The SOFIA Massive (SOMA) Star Formation Survey

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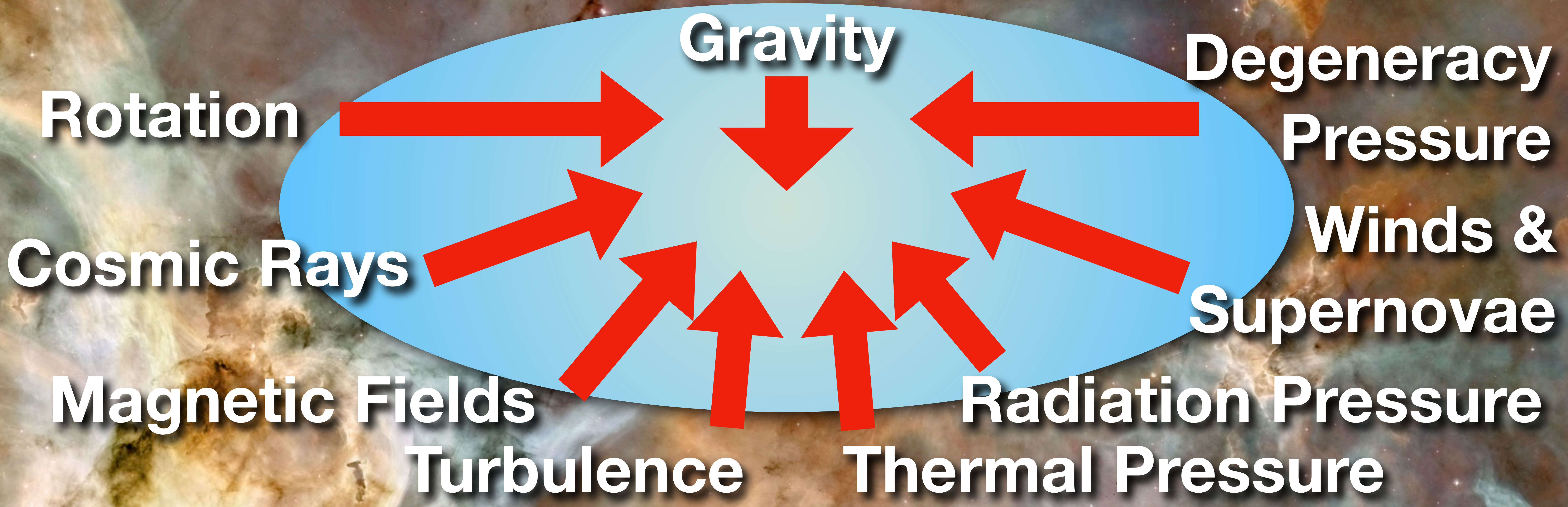
The Importance of Massive Stars

From Clouds to Stars



Definitions:

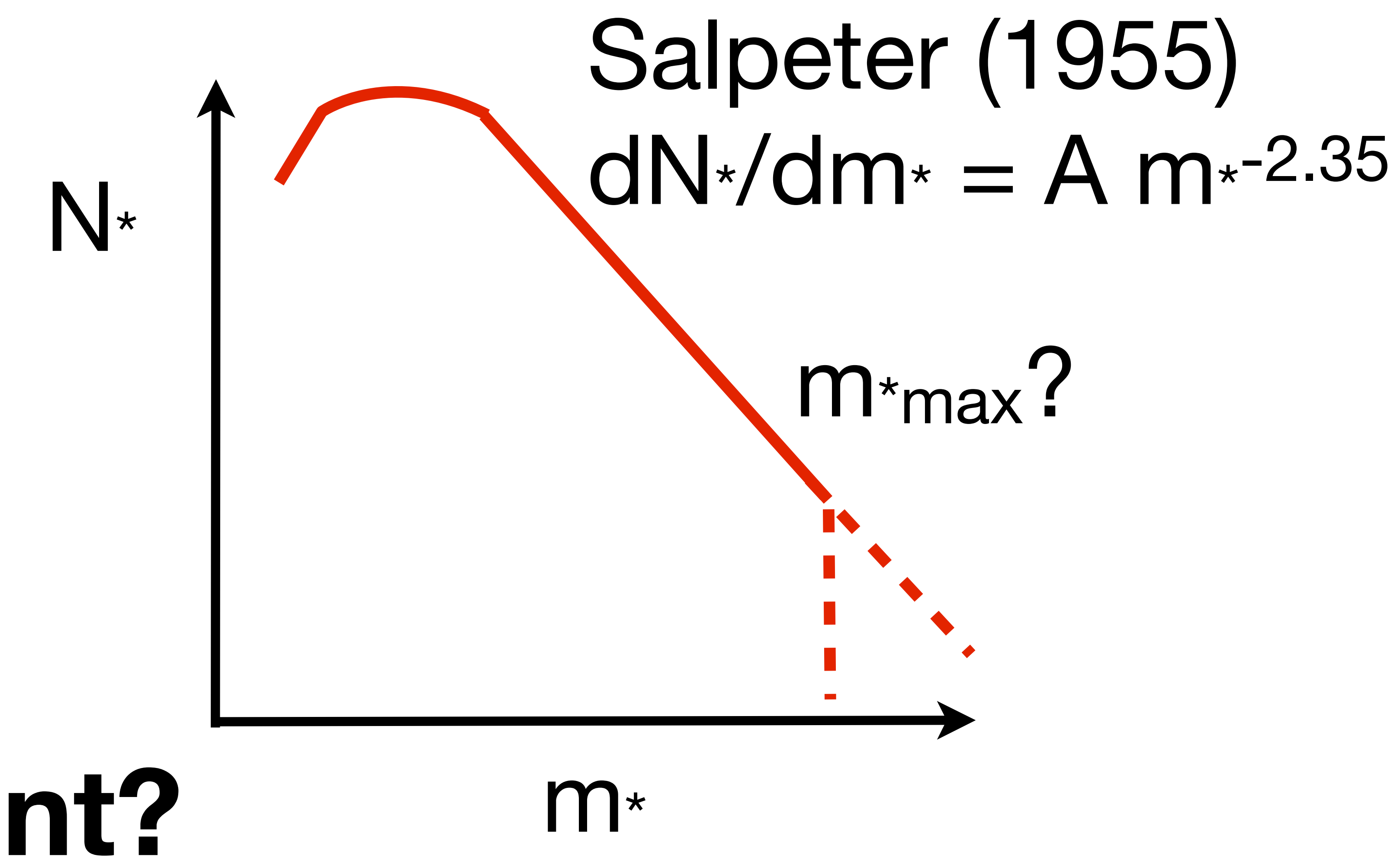
Core → star or binary (from central disk)

Clump → star cluster

Cloud (GMC) → OB association

Open Questions

- Galaxy scale: What sets the SFR in galactic disks?
- GMC properties & lifecycle: Gravitationally bound? Lifetimes?
- Initiation of SF: 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 $dm_*/dt \sim 10^{-5} - 10^{-2}\ M_\odot\ yr^{-1}$

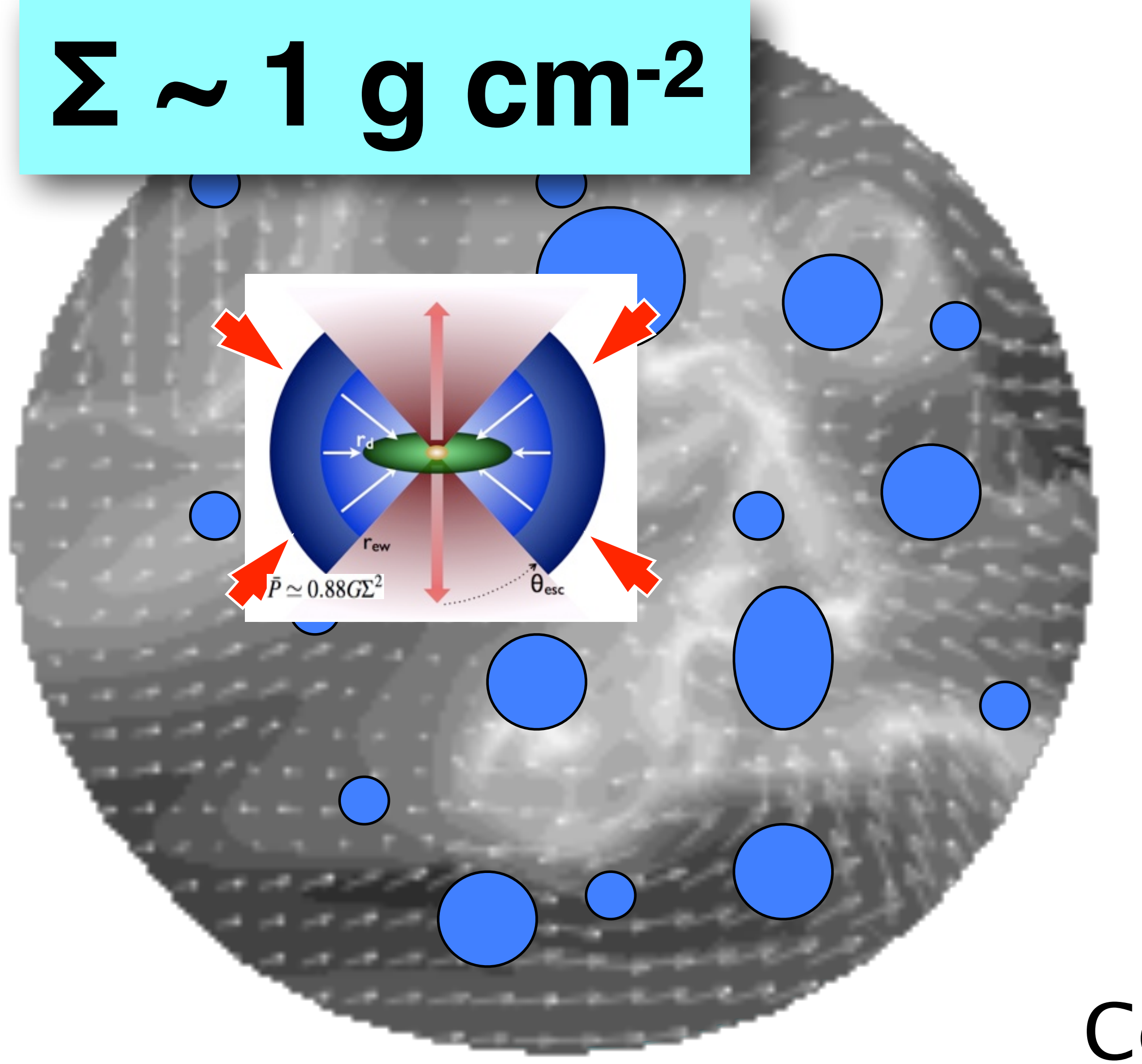
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

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)

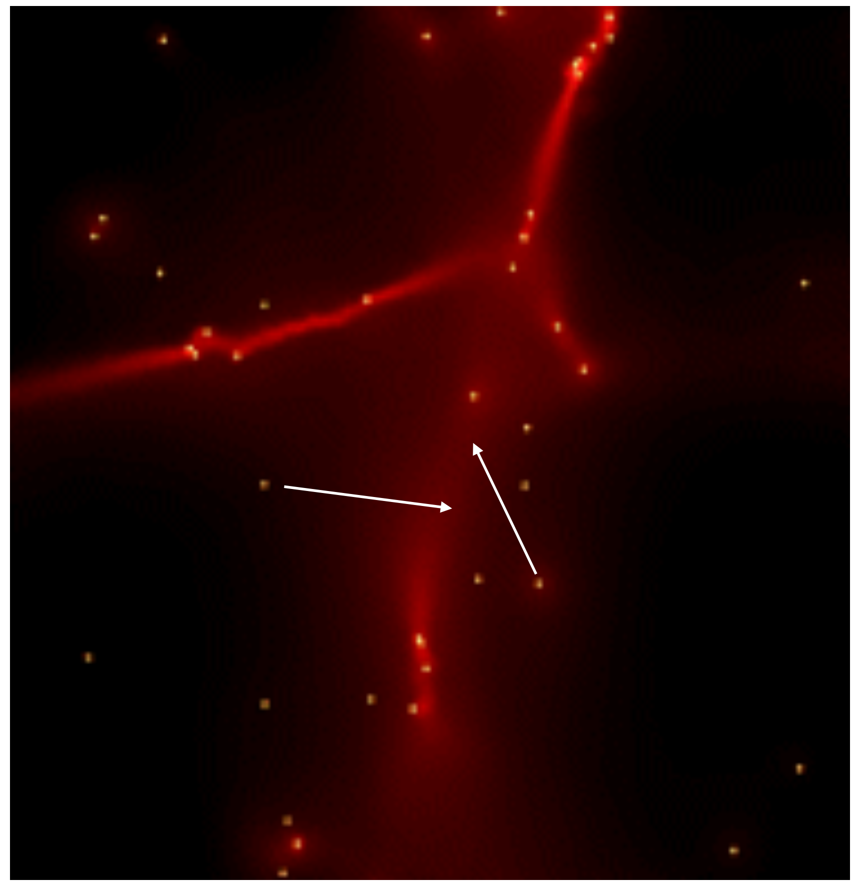
Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

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

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

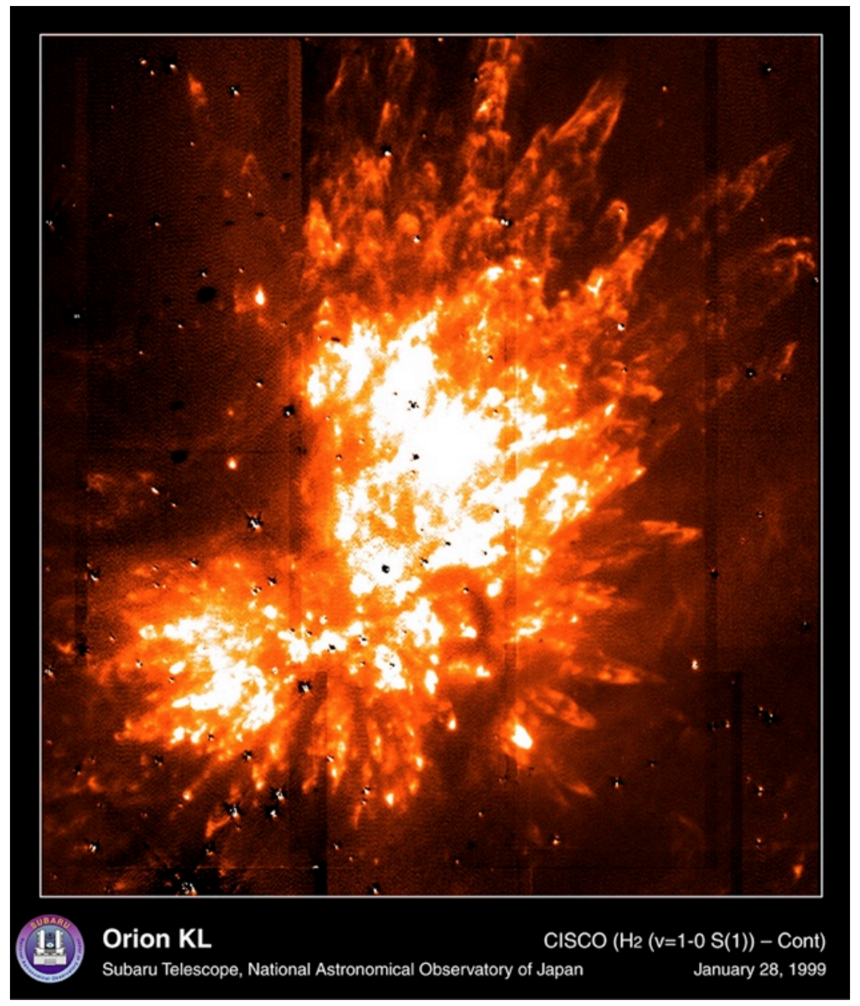


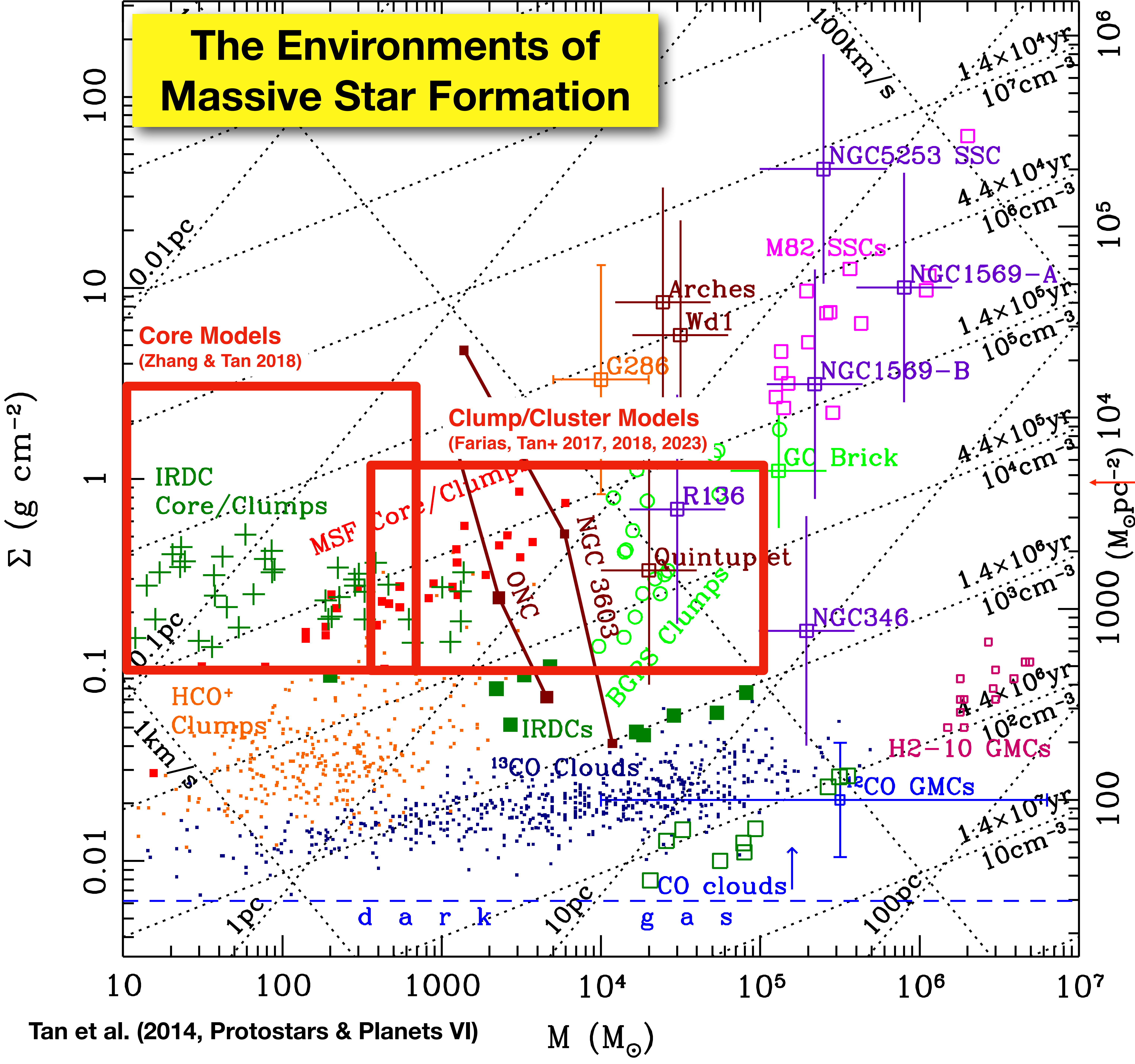
Originally based on simulations including only thermal pressure.

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)





Σ - M Diagram

Physical Properties of Star-Forming Regions

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

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

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

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

$A_V=230$

$A_{8\mu m}=8.1$

$N_H=4.2\times10^{23} cm^{-2}$

$\Sigma=4800\ M_\odot\ pc^{-2}$

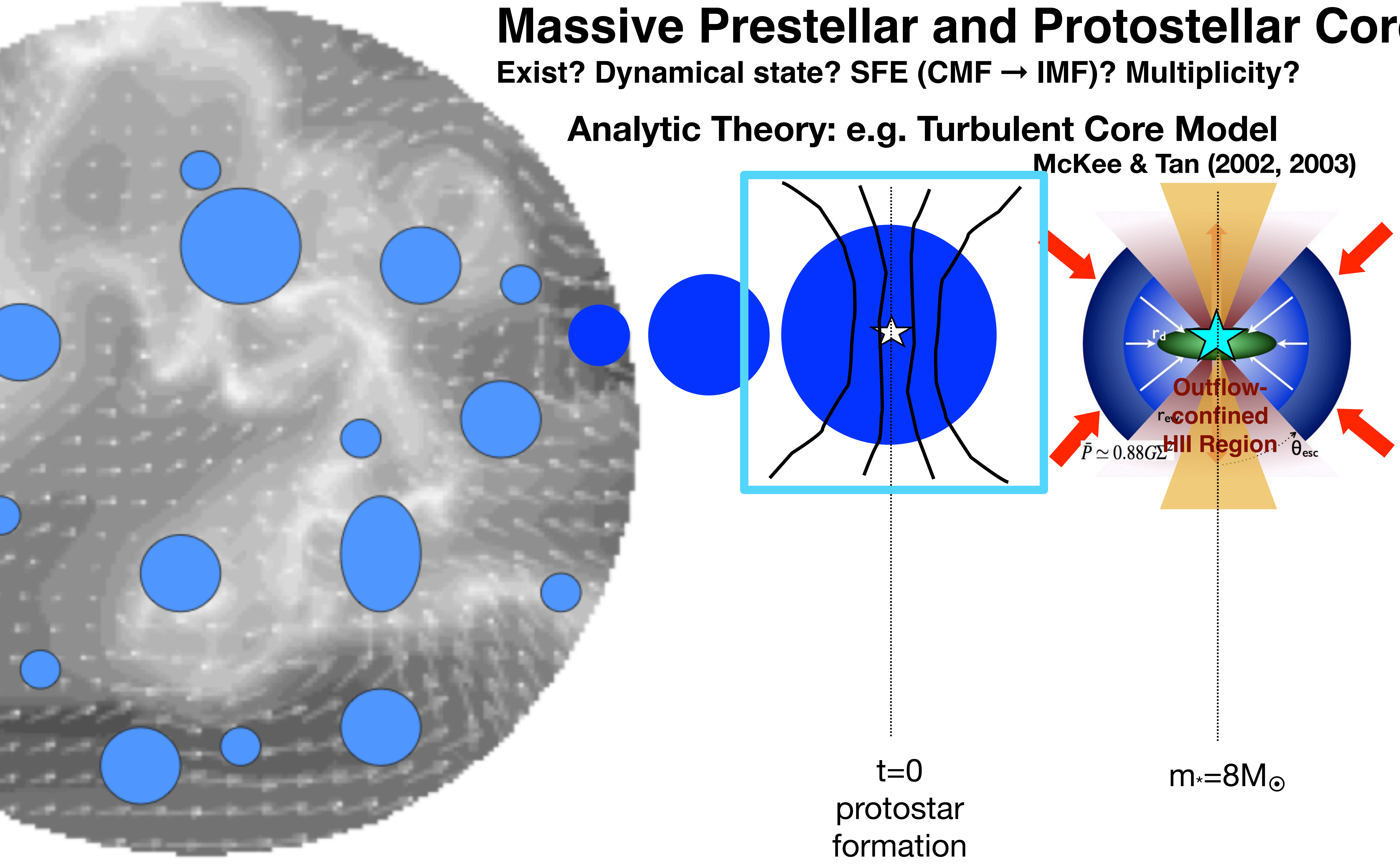
Tan et al. (2014, Protostars & Planets VI)

Massive Prestellar and Protostellar Cores

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

Analytic Theory: e.g. Turbulent Core Model

McKee & Tan (2002, 2003)

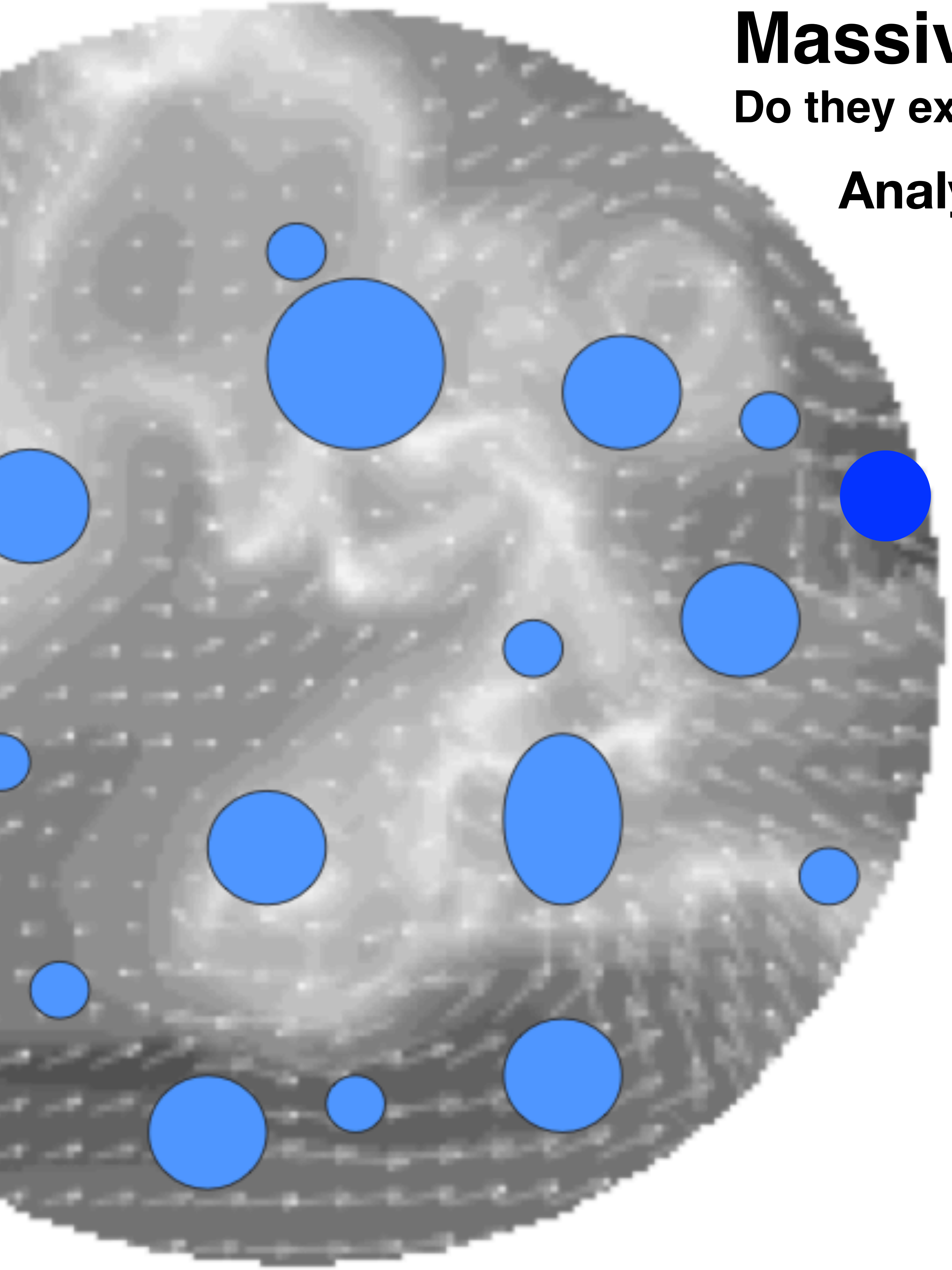


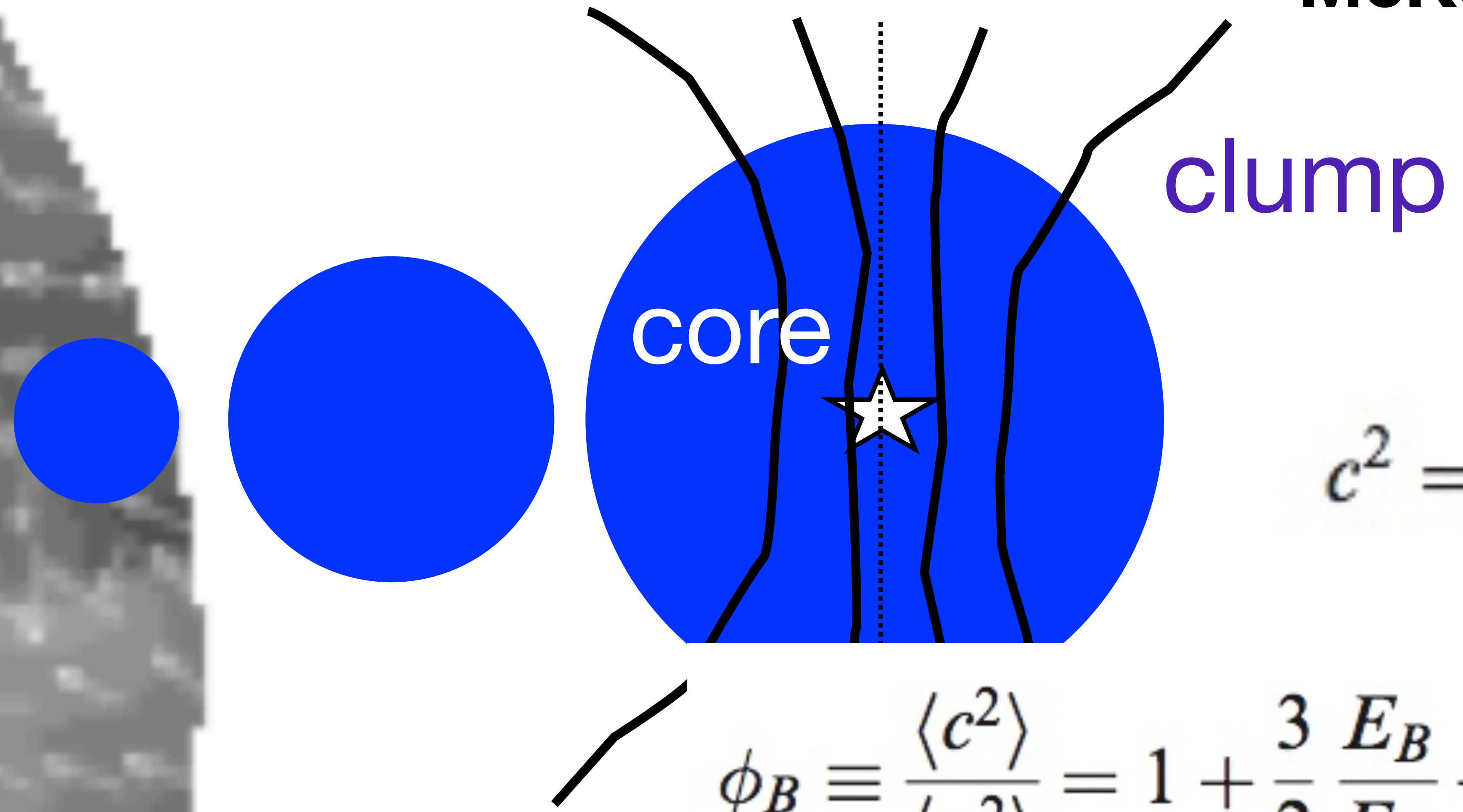
Massive Prestellar Cores

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

Analytic Theory: e.g. Turbulent Core Model

McKee & Tan (2002, 2003)





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

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

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

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

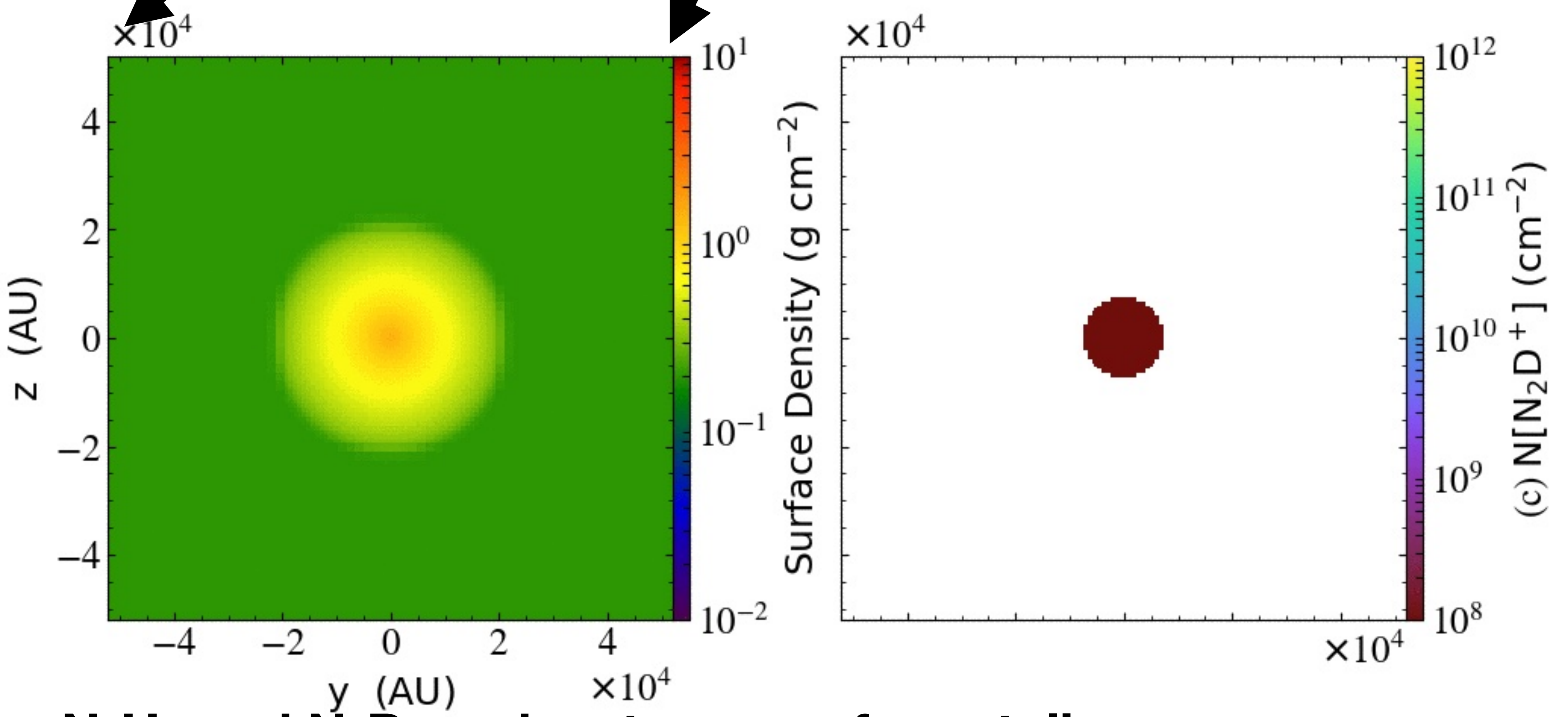
$n_{H,s} \to 1.1\times10^{6}\ \mathrm{cm^{-3}}$

t=0
protostar
formation

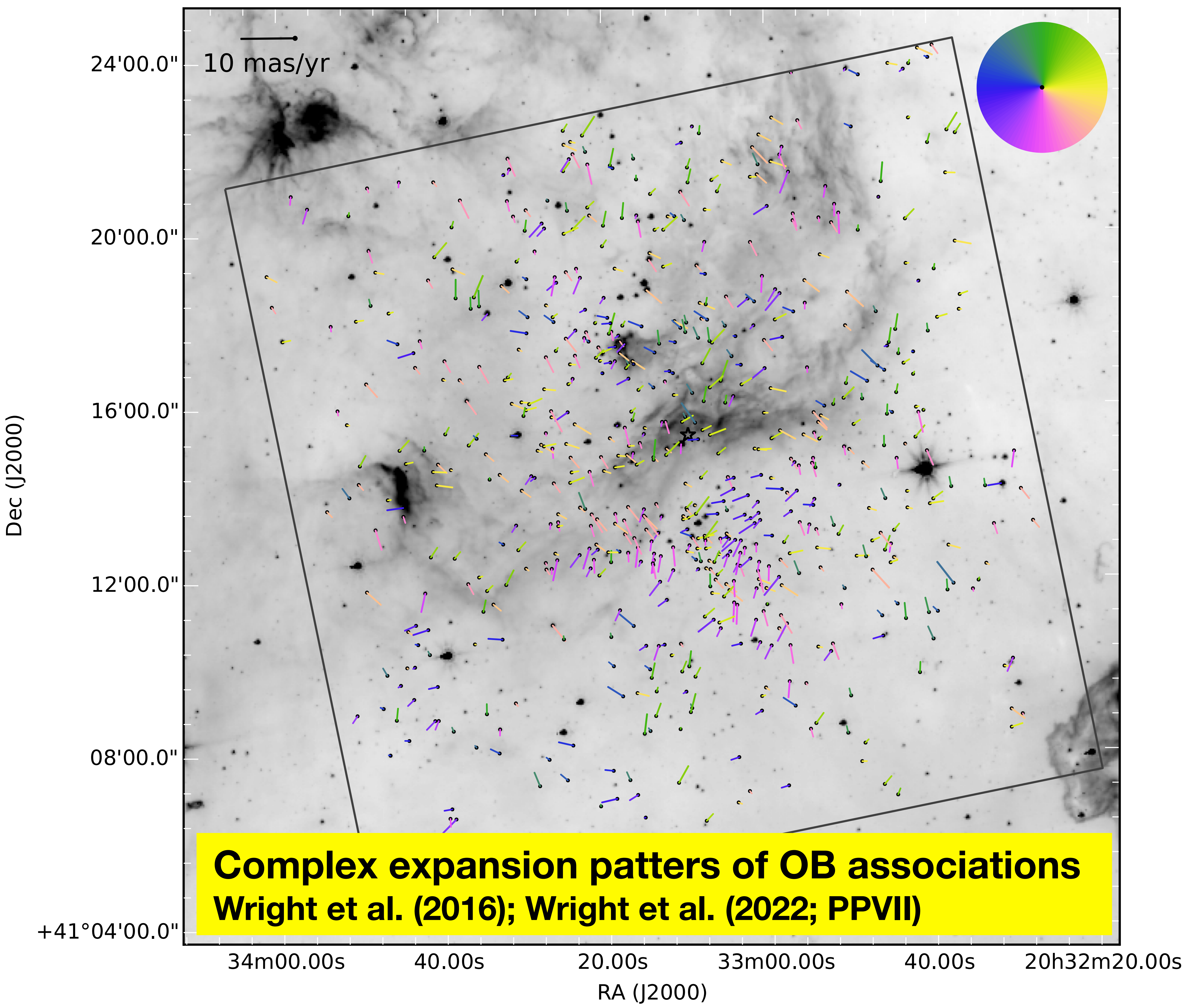
Filaments, Clumps & Cores from Collision of Magnetized GMCs

Wu et al. 2015, 2017a, b, 2020
Hsu et al. 2023
García-Alvarado et al., in prep.

A natural mechanism to provide a large scale environment with disturbed kinematics and some relatively isolated massive cores



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



Complex expansion patters of OB associations
Wright et al. (2016); Wright et al. (2022; PPVII)

Butler, Tan & Kainulainen (2014); NASA/JPL/Spitzer

Protocluster and Core Mass Function Studies

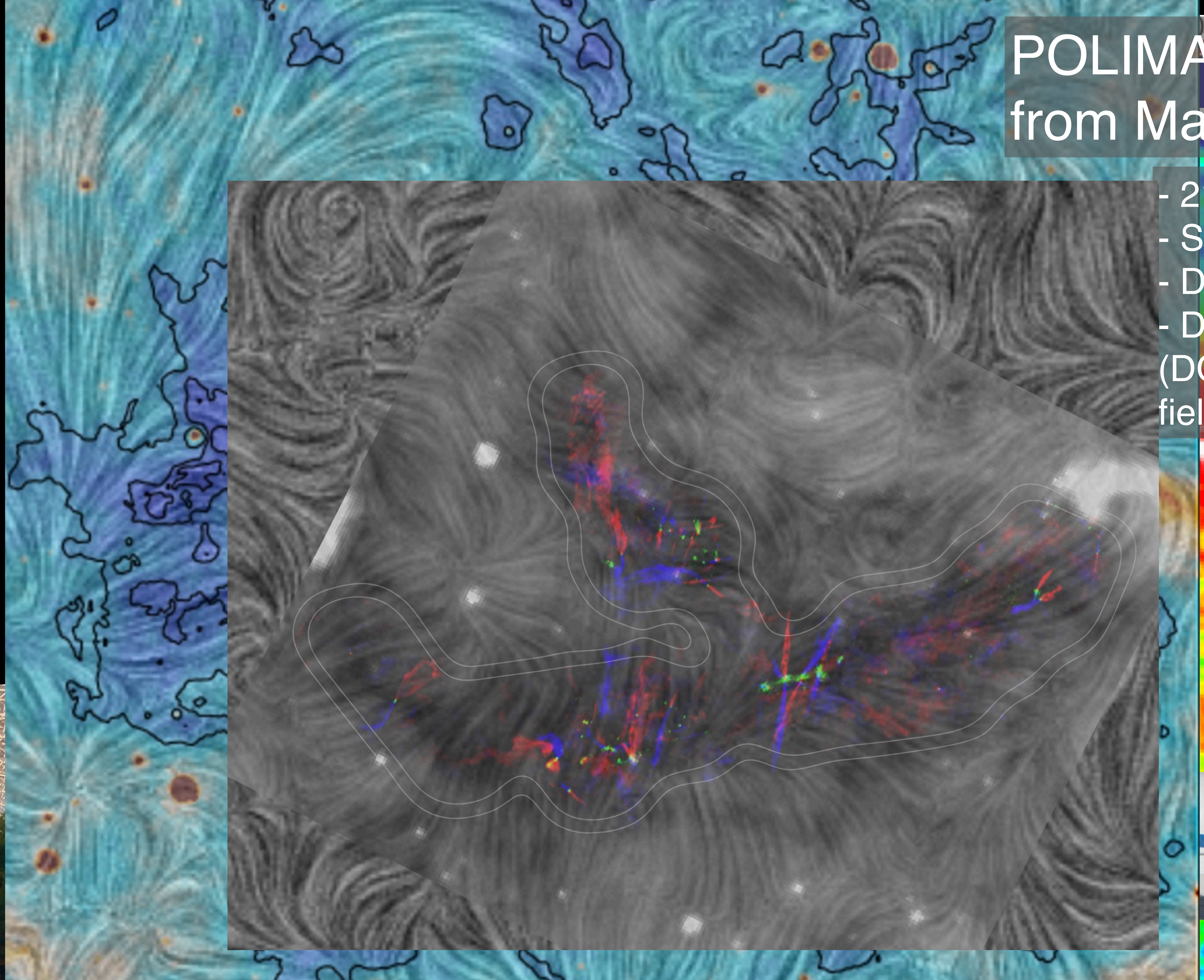
Magneto-Kinematic Mapping of IRDCs

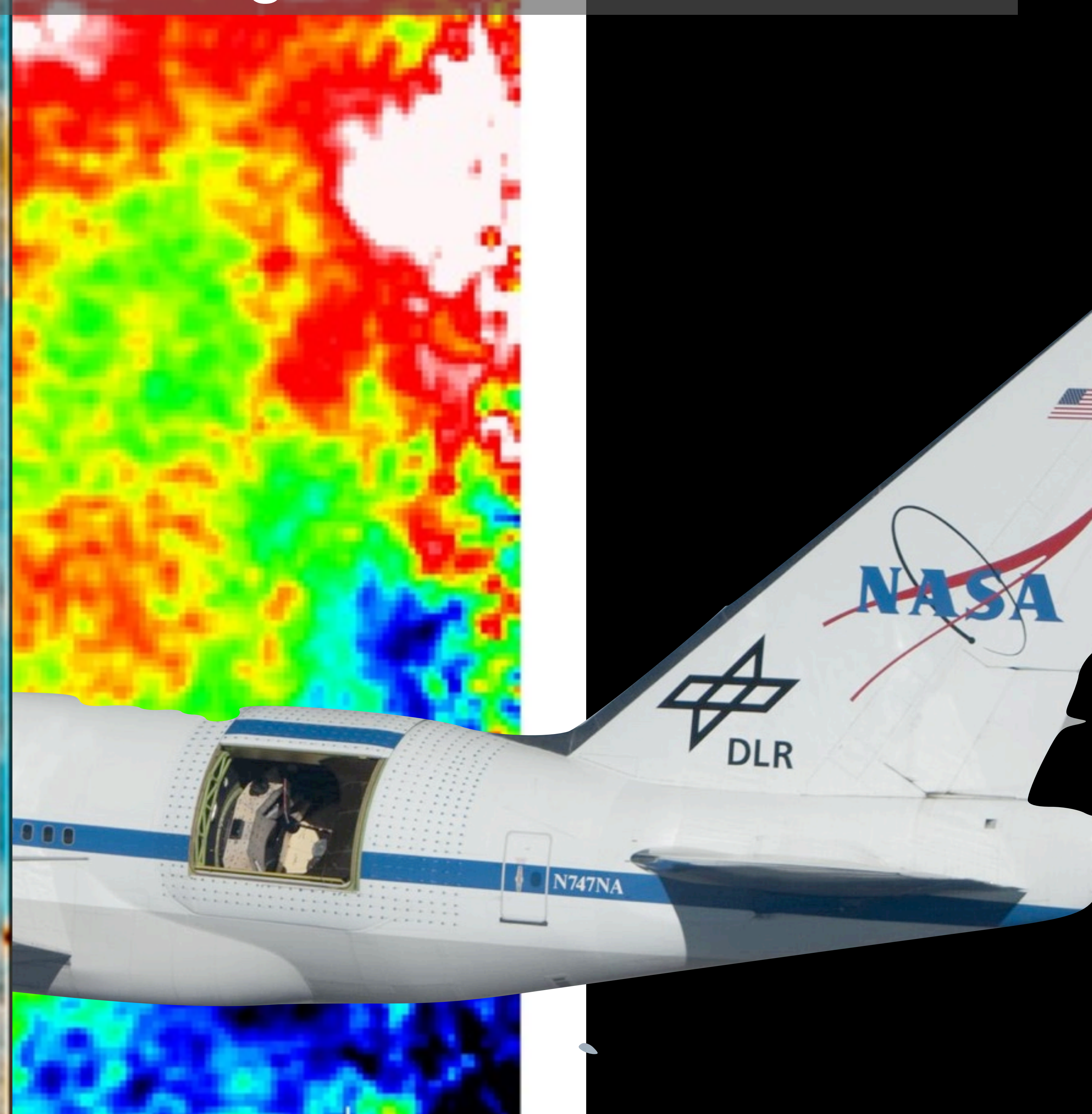
POLIMAP - Polarized Light from Massive Protoclusters

GBT-Argus
^{13}CO(1-0)
~7”
Law, Tan, Skalidis, Morgan 2024

POLIMAP - Polarized Light from Massive Protoclusters

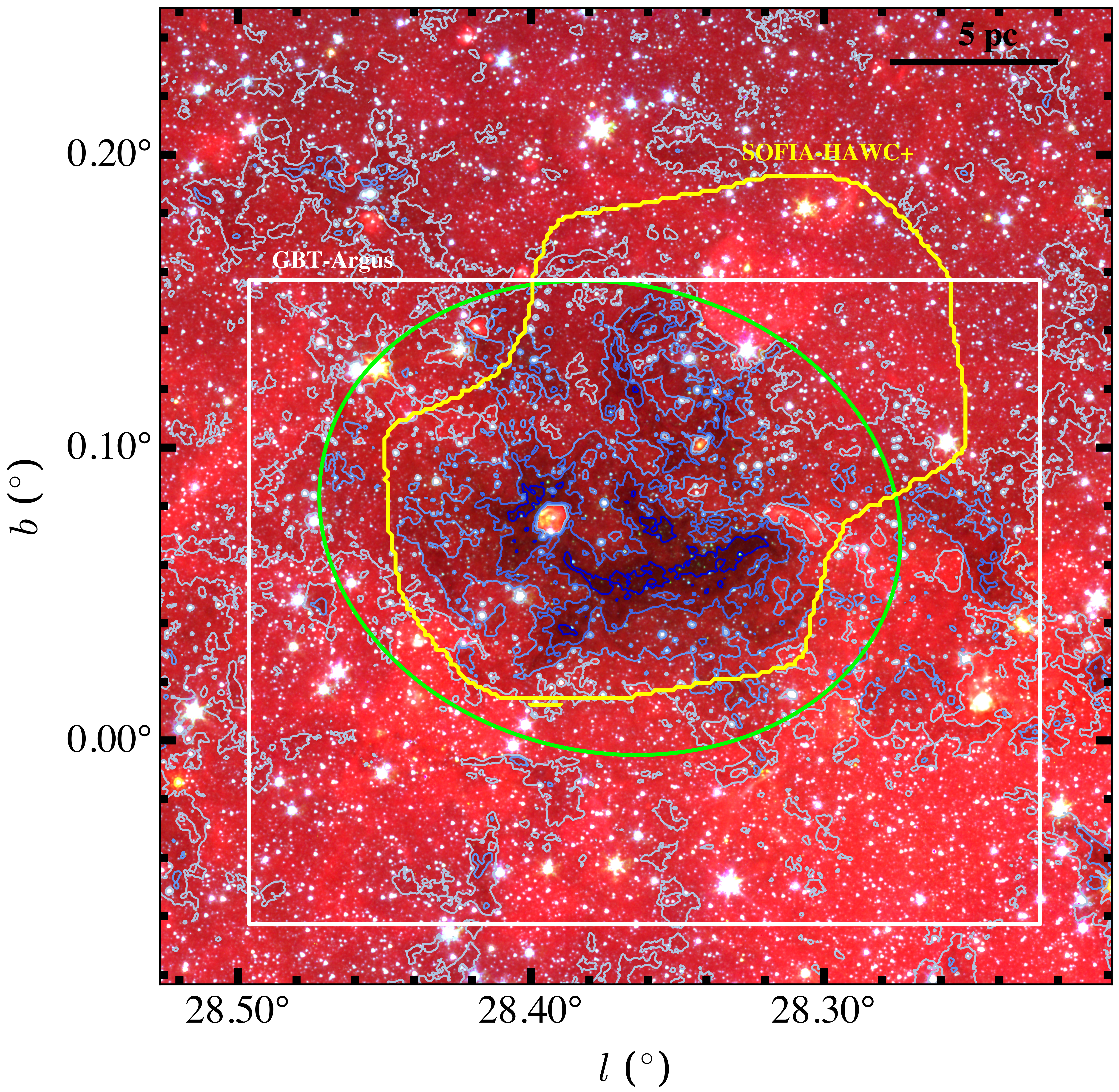
- 214µm polarized dust emission
- SOFIA-HAWC+ (18”)
- Dust grains align with B-fields
- Davis-Chandrasekhar-Fermi (DCF) methods to estimate B-field strength

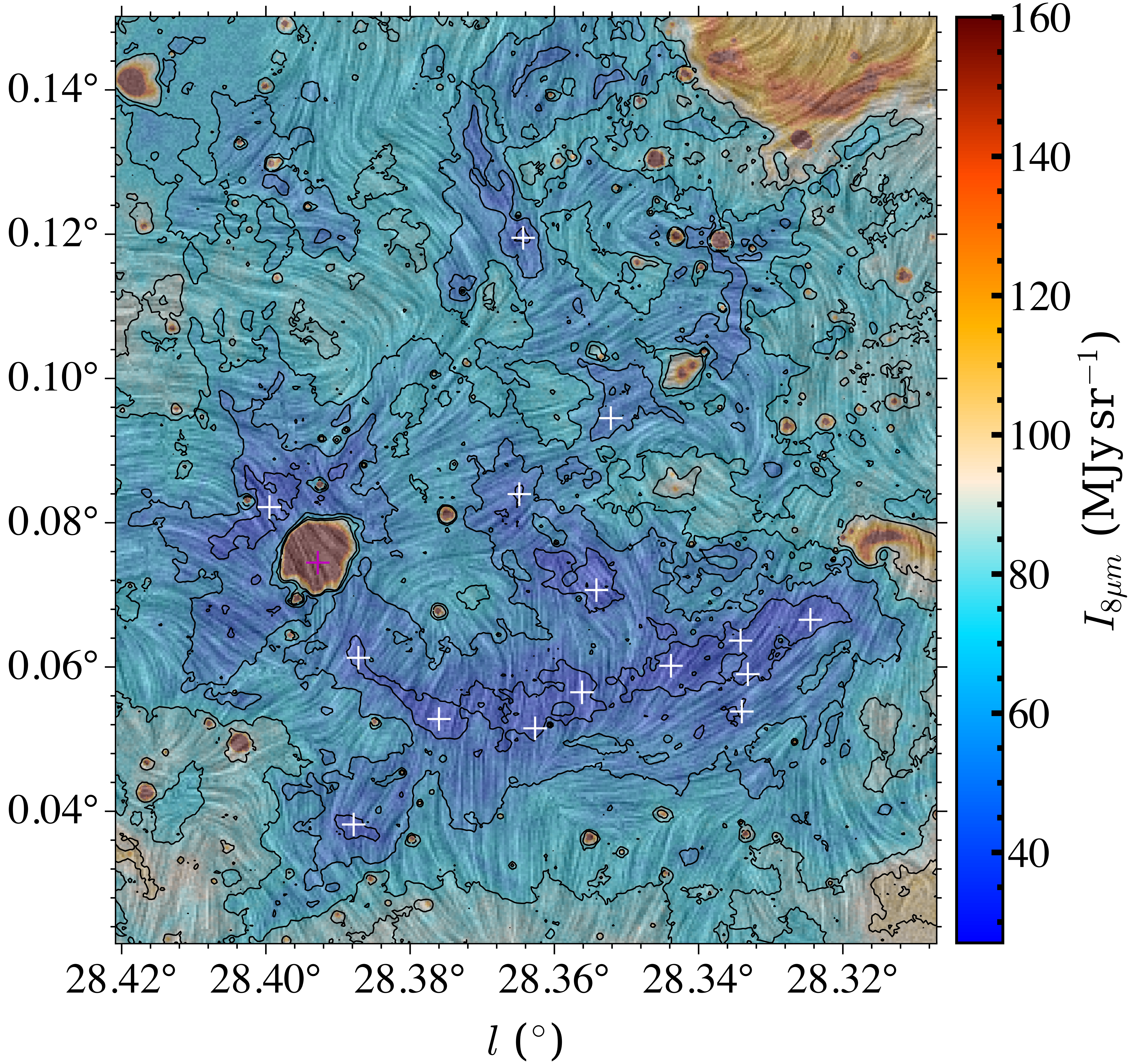




POLIMAP - Polarized Light from Massive Protoclusters

Law, Tan et al. (2024)

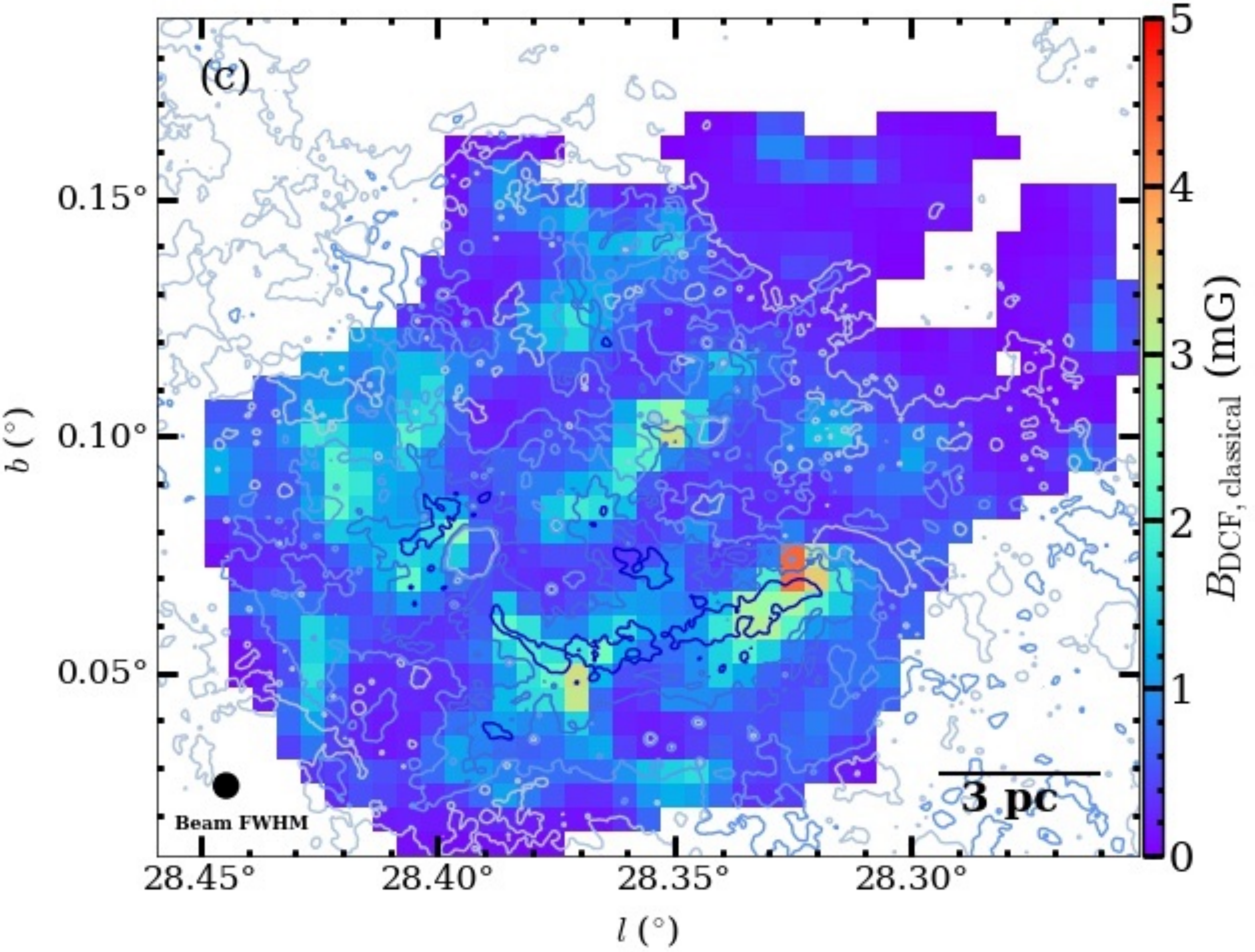


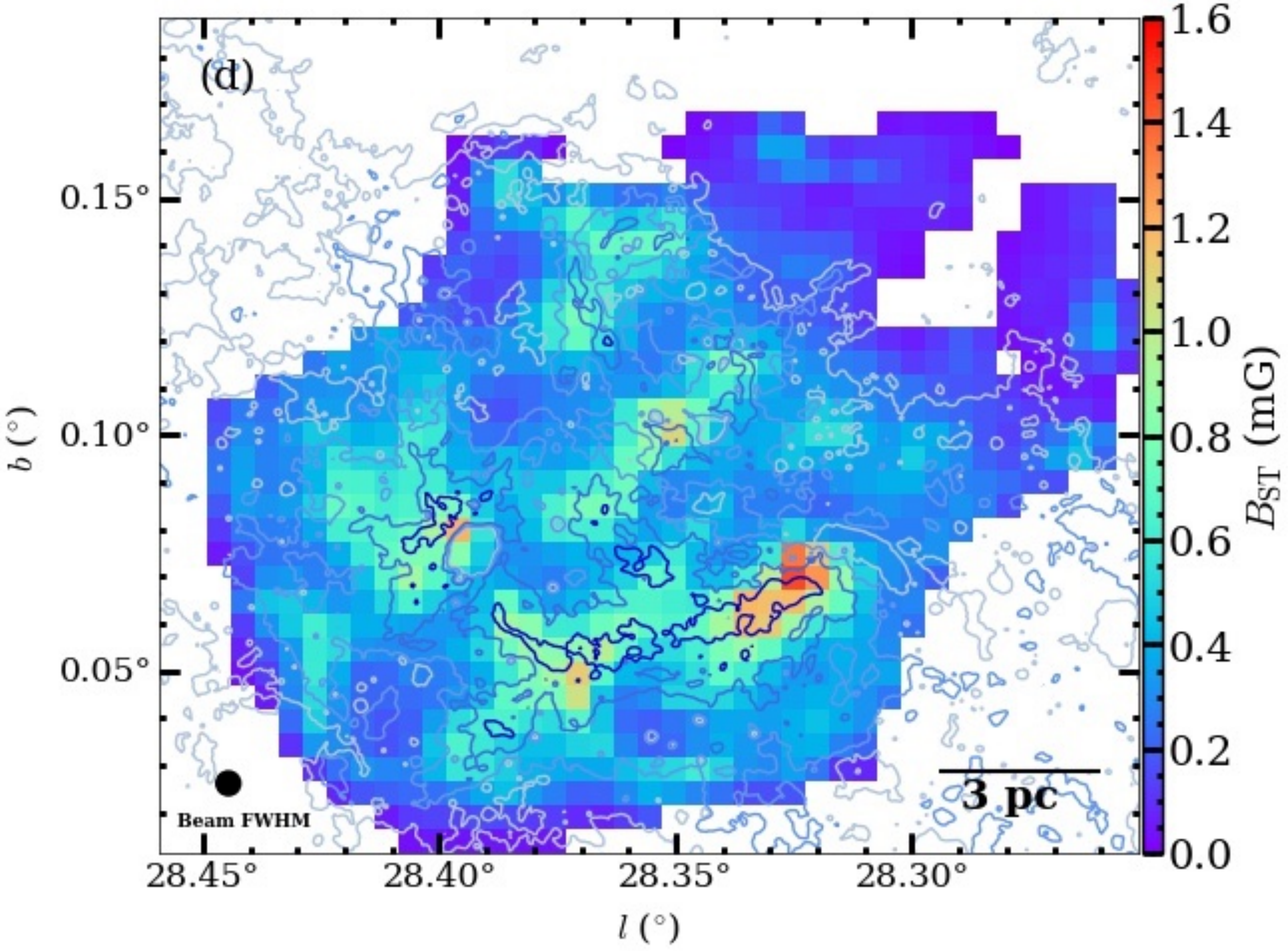


POLIMAP - Polarized Light from Massive Protoclusters

Law, Tan et al. (2024)

Magnetic field strength mapping





POLIMAP - Polarized Light from Massive Protoclusters

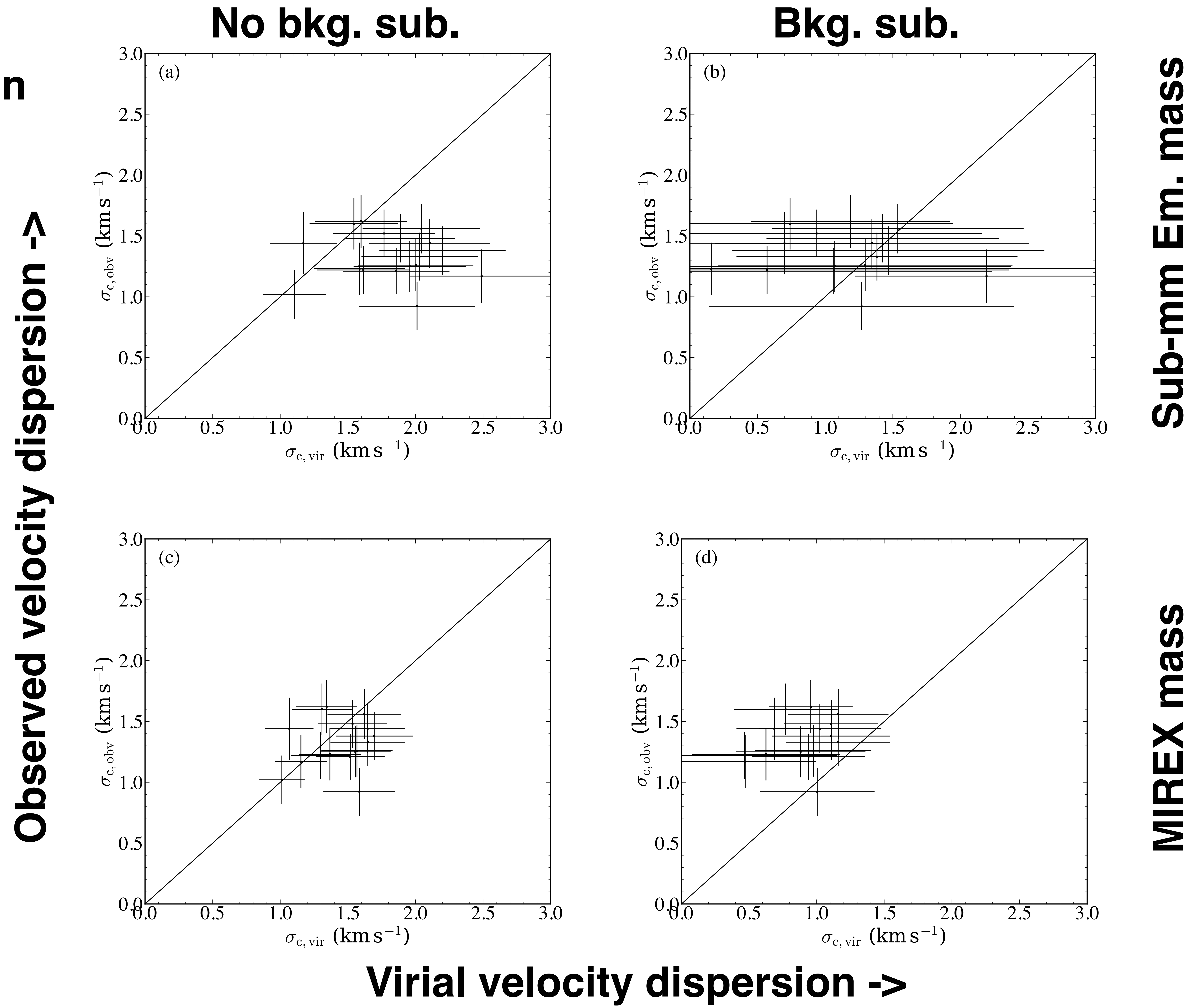
Law, Tan et al. (2024)

Mass-to-flux ratio mapping

POLIMAP - Polarized Light from Massive Protoclusters

Law, Tan et al. (2024)

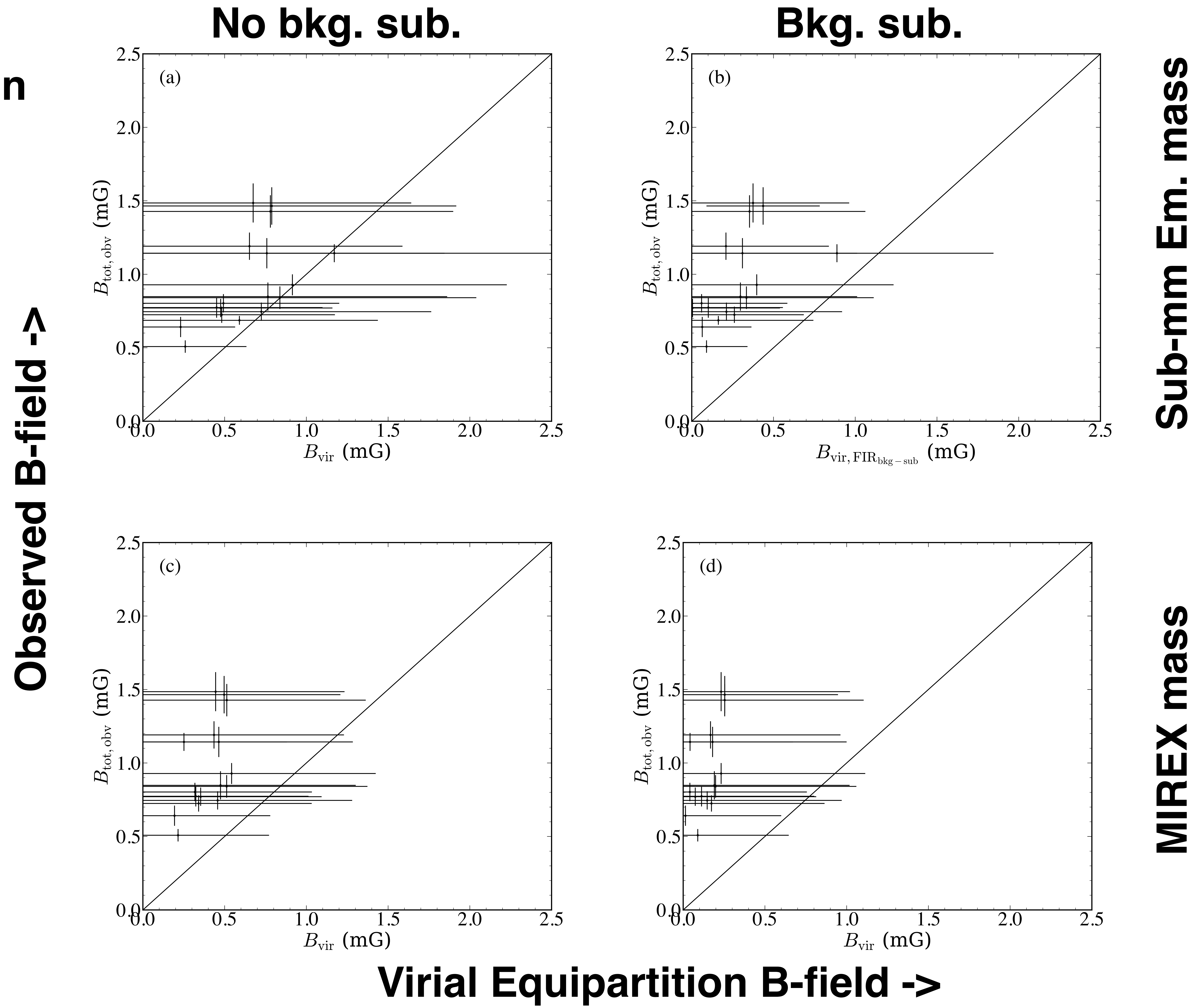
Testing Turbulent Core Accretion



POLIMAP - Polarized Light from Massive Protoclusters

Law, Tan et al. (2024)

Testing Turbulent Core Accretion



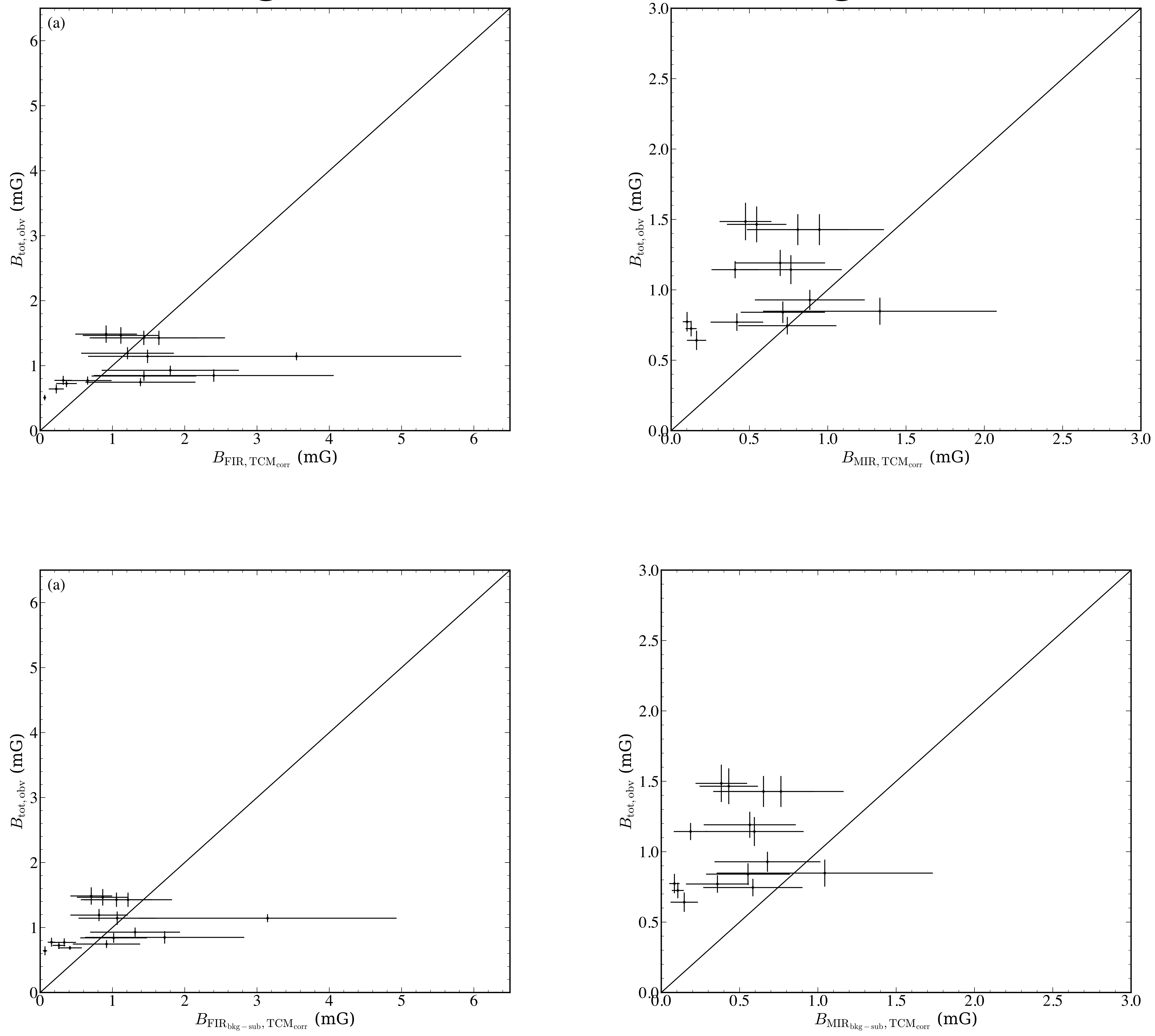
POLIMAP - Polarized Light from Massive Protoclusters

Law, Tan et al. (2024)

Testing Turbulent Core Accretion

No bkg. sub. **Bkg. sub.**

Observed B-field ->



Sub-mm Em. mass

MIREX mass

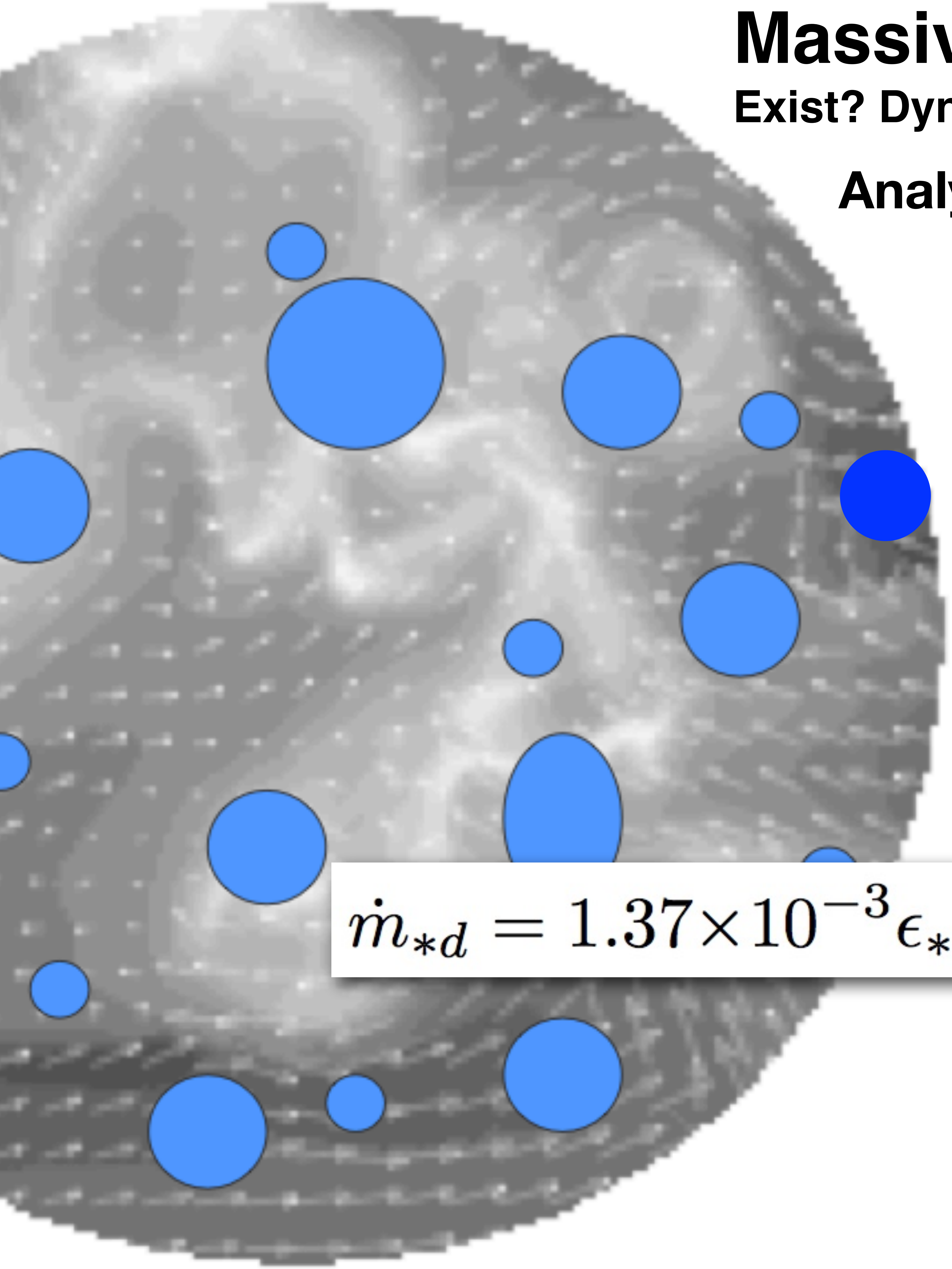
Virial B-field ->

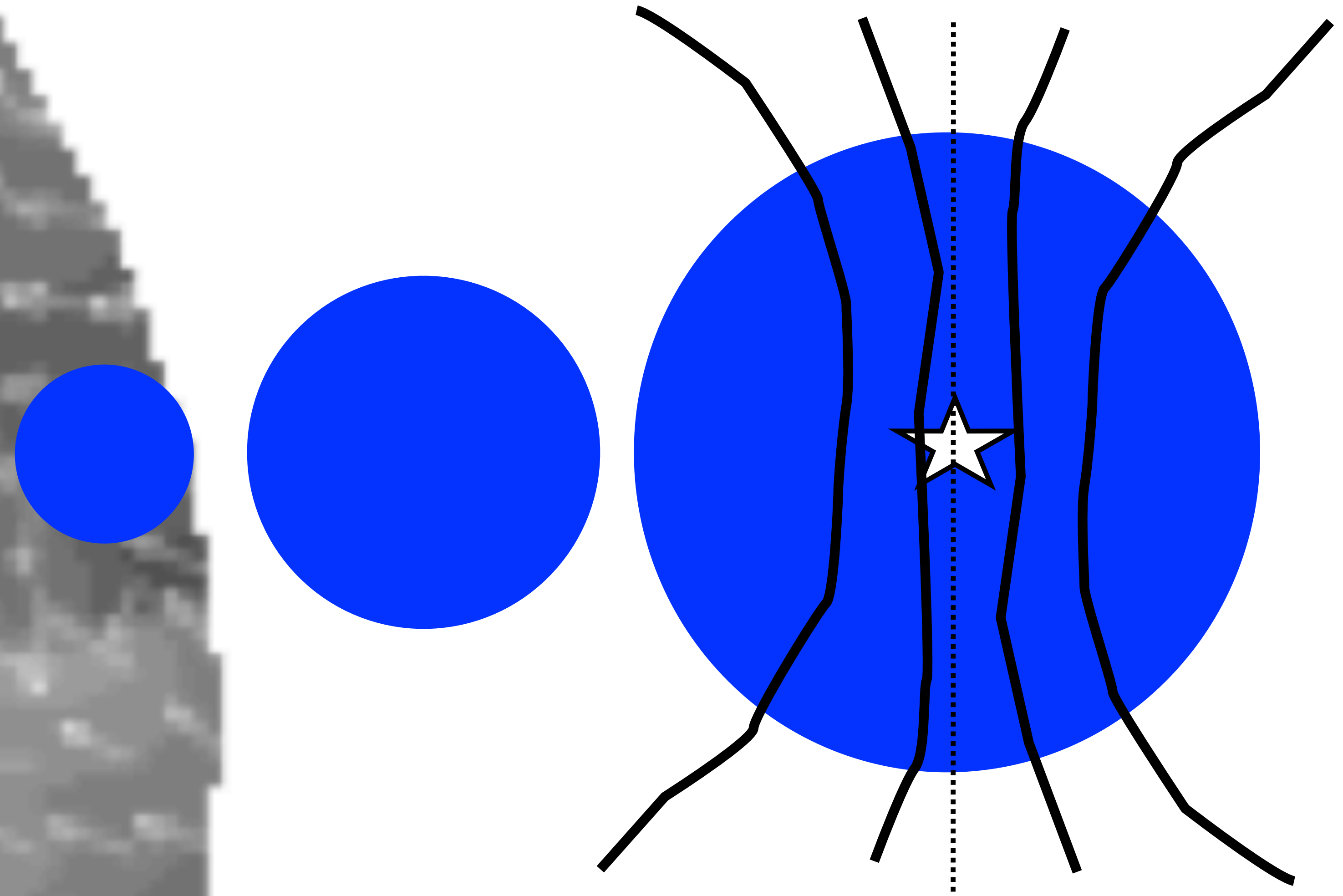
Massive Protostellar Cores

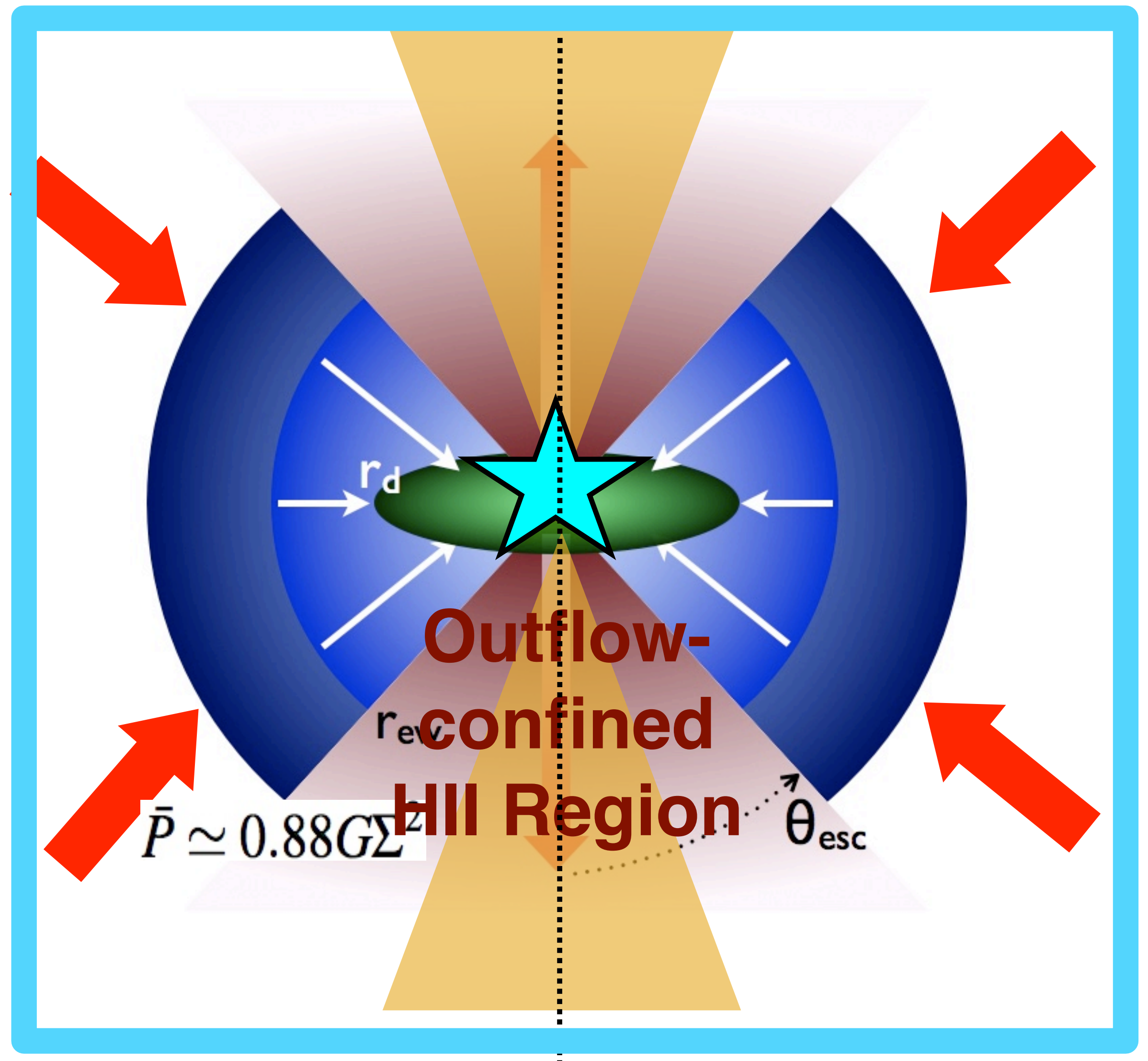
Exist? Dynamical state? SFE (CMF->IMF)? Multiplicity?

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_*=8$M_\odot$

Massive Protostellar Cores: simulations

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

Seifried et al. (2012)
$M_c = 100M_\odot$, R_c=0.25pc,
$n_H = 4.4x10^4 cm^{-3}$, B~1mG

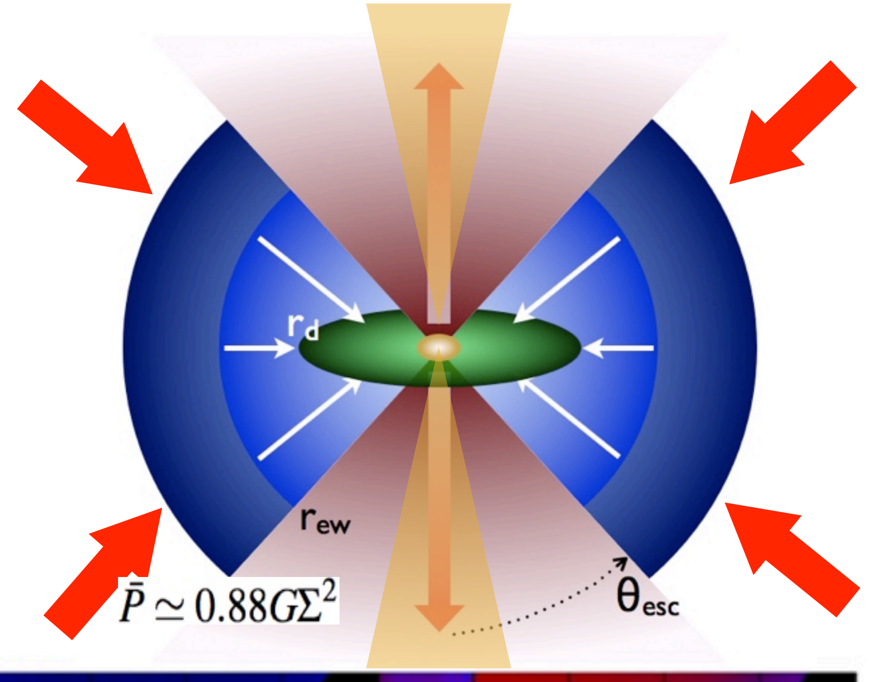
Myers et al. (2013)
$M_c = 300M_\odot$, R_c=0.1pc,
$n_H = 2.4x10^6 cm^{-3}$, B>~1mG

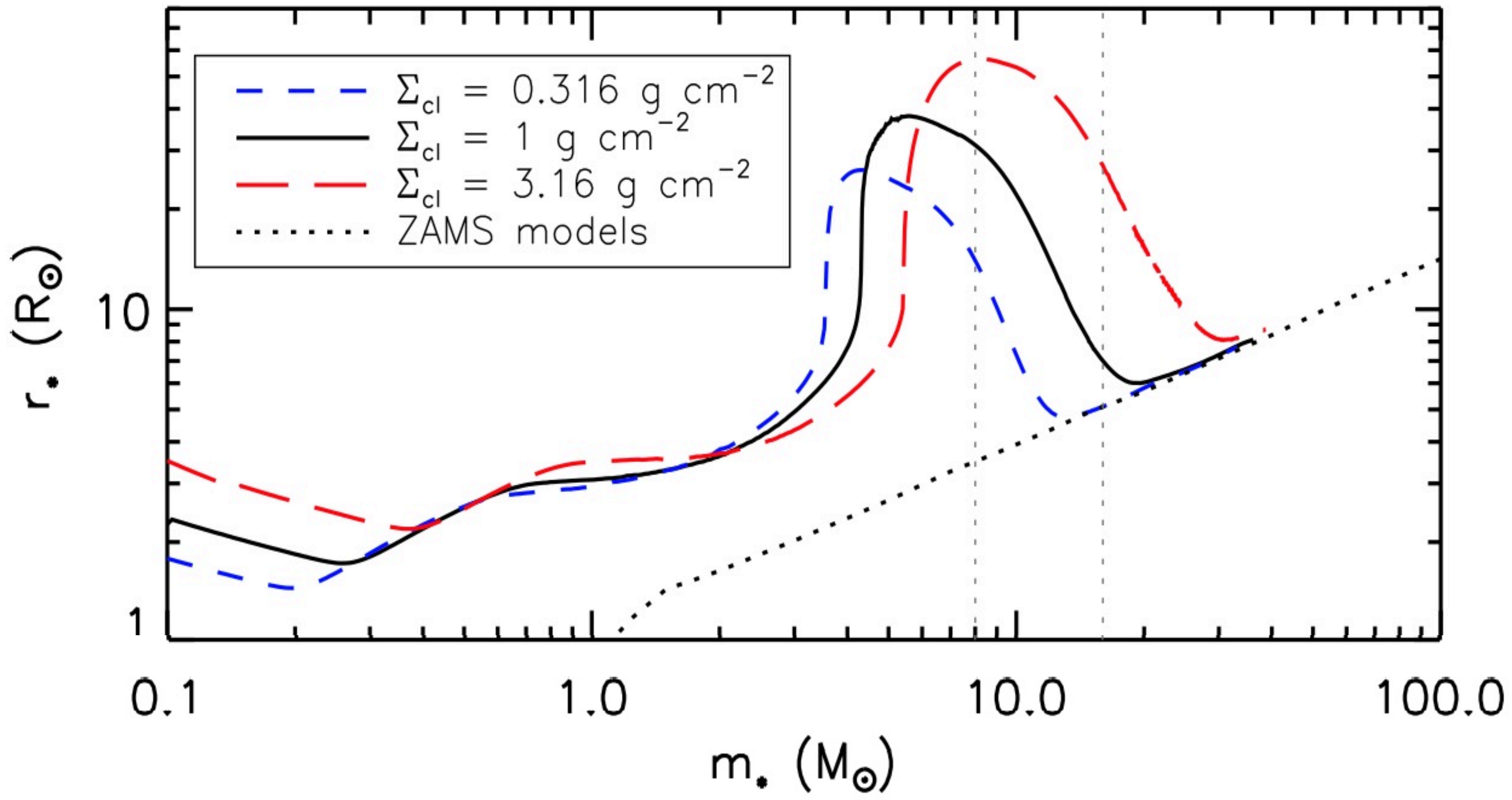
Commerçon et al. (2022)
$M_c = 100M_\odot$, R_c=0.2pc,
$n_H = 8.6x10^4 cm^{-3}$, μ = 2, 5

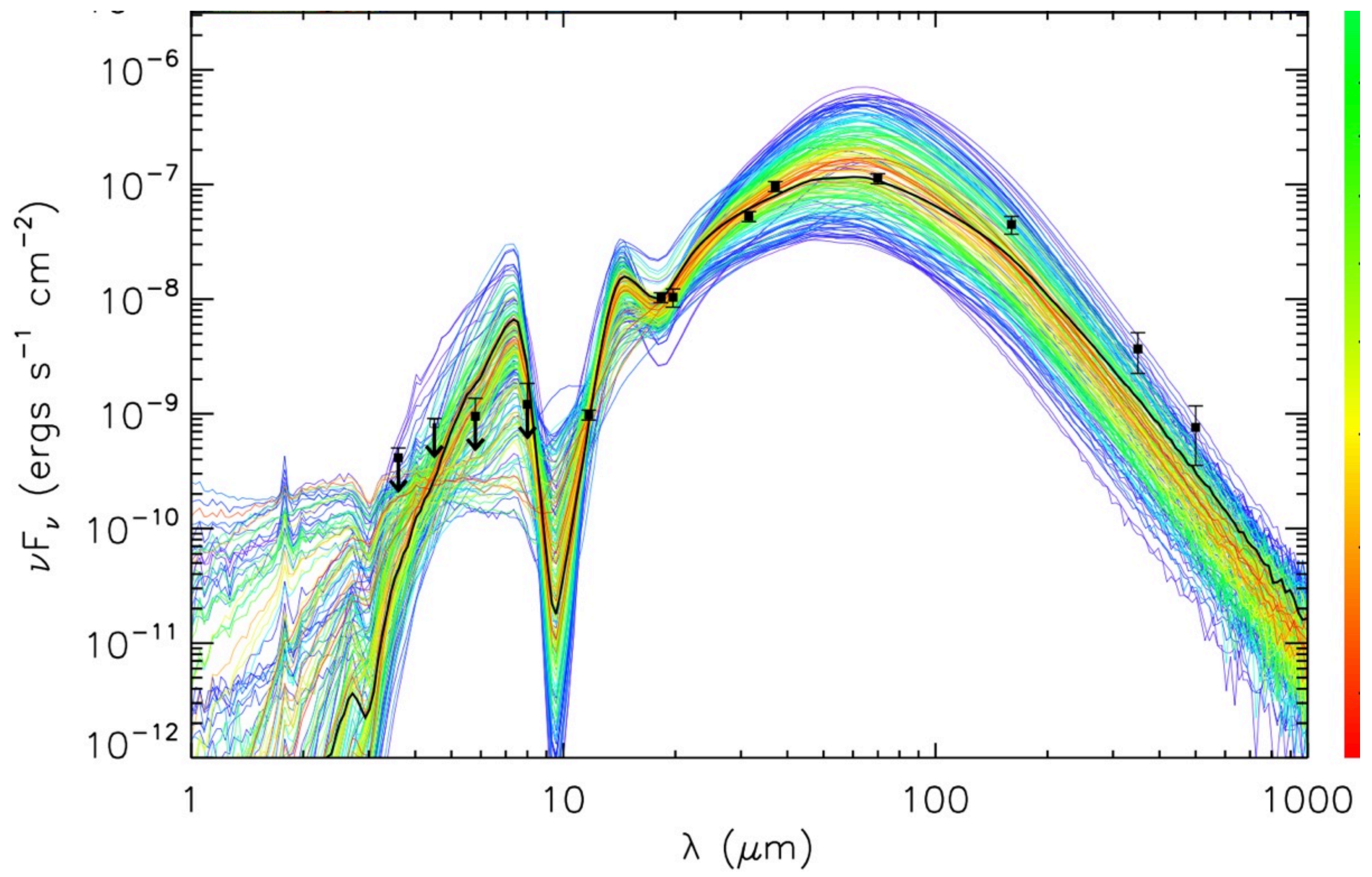
Massive Protostellar Cores: protostellar evolution & radiative transfer models

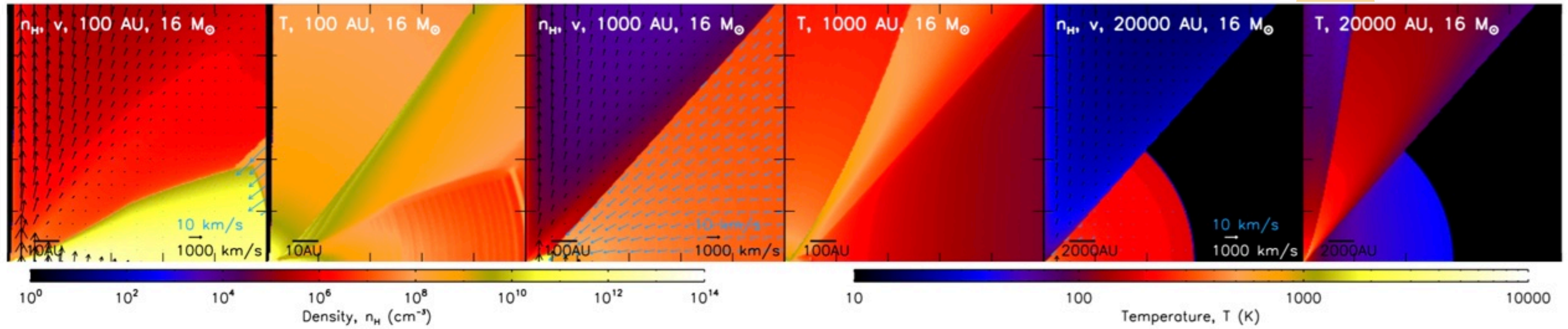
Zhang & Tan (2011), Zhang, Tan & McKee (2013), Zhang, Tan & Hosokawa (2014), Zhang & Tan (2018)

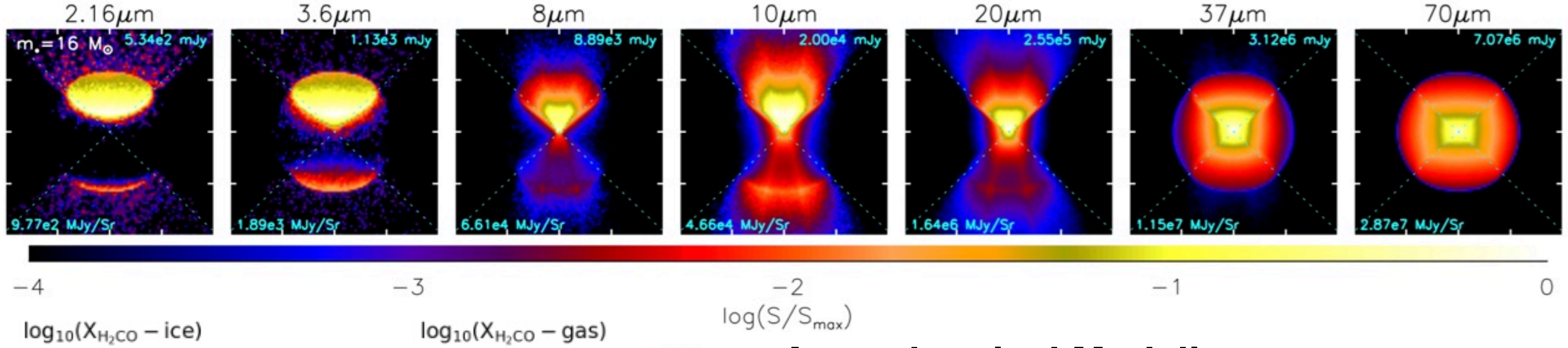
Three primary parameters of Turbulent Core Model: Σ_{clump}, M_{core}, m_*

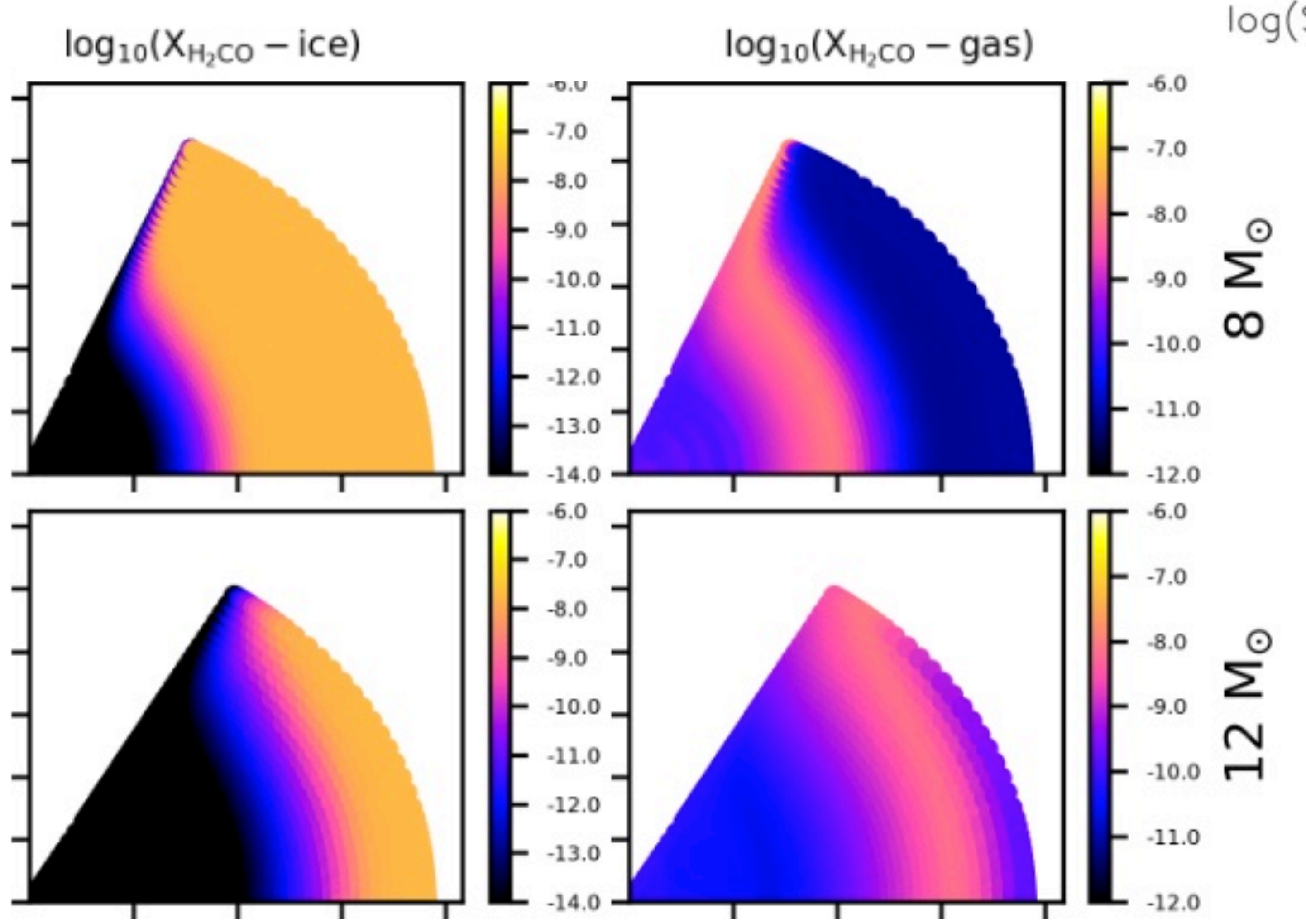




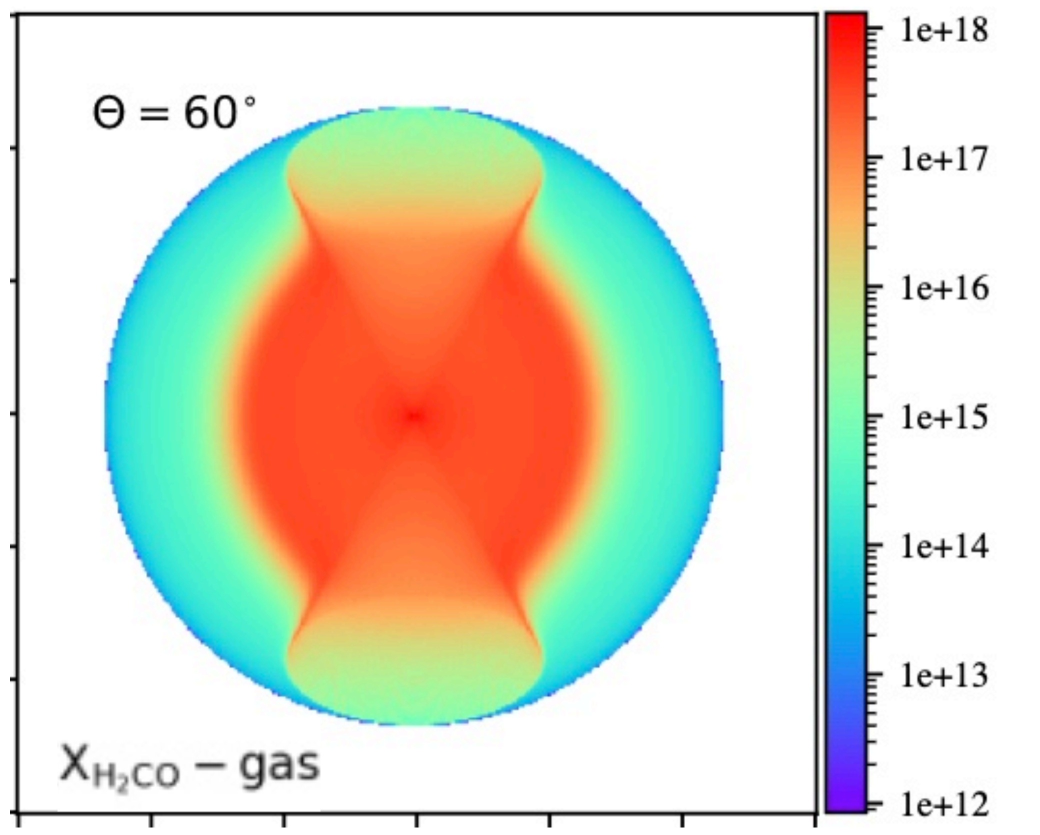




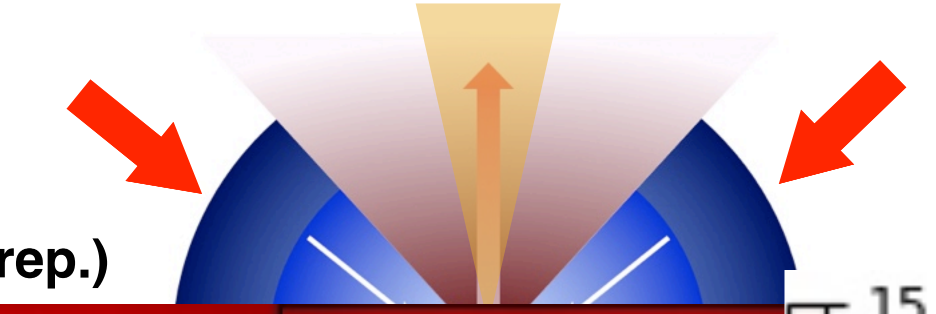




Astrochemical Modeling (Gorai et al., in prep.)



Massive Protostellar Cores: MHD simulations



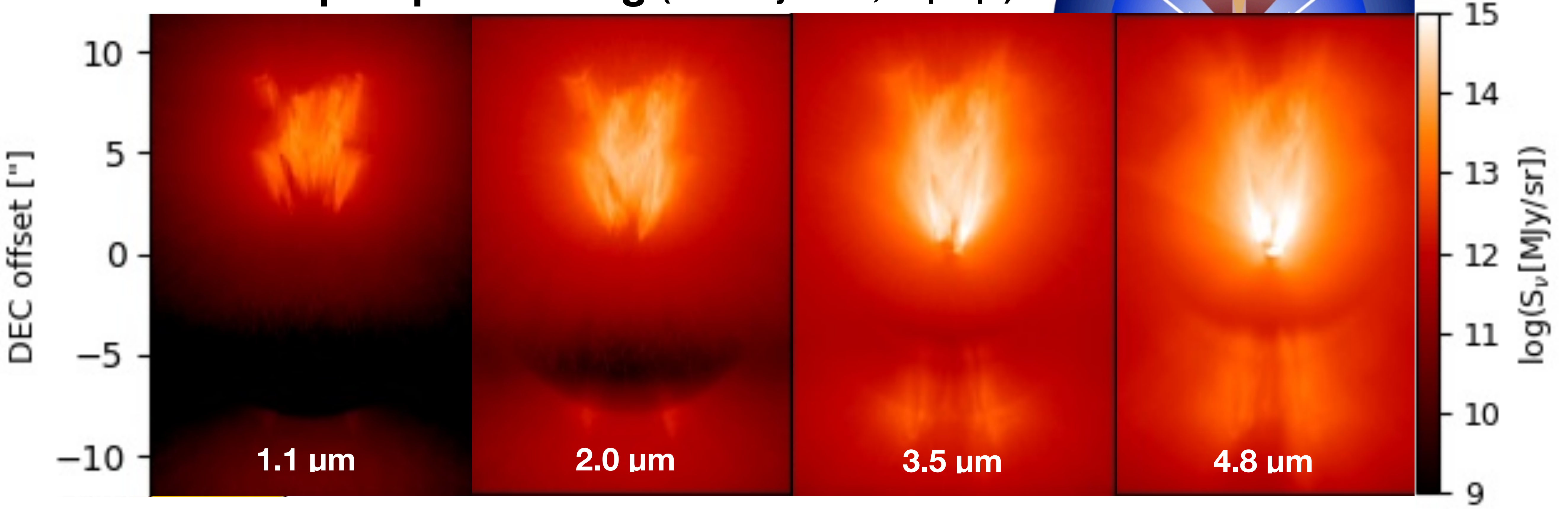
Jan Staff
1977 - 2023

Staff, Tanaka & Tan (2019), Staff et al. (2023)

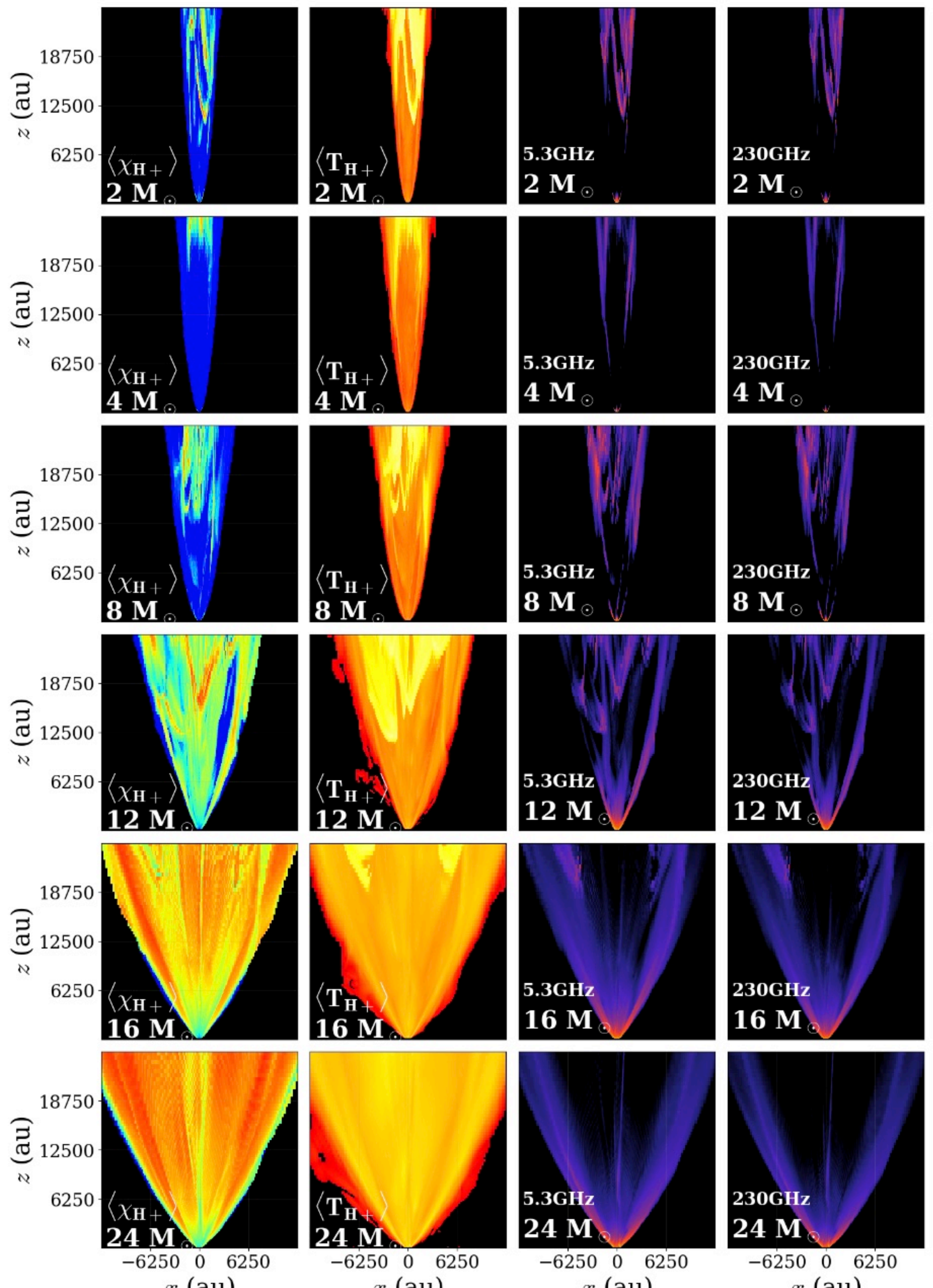
Σ_{clump} = 1 g cm^{-2}
M_{core} = 60 $M_\odot$
m_* = 1 - 24 $M_\odot$

Time = 0 yea

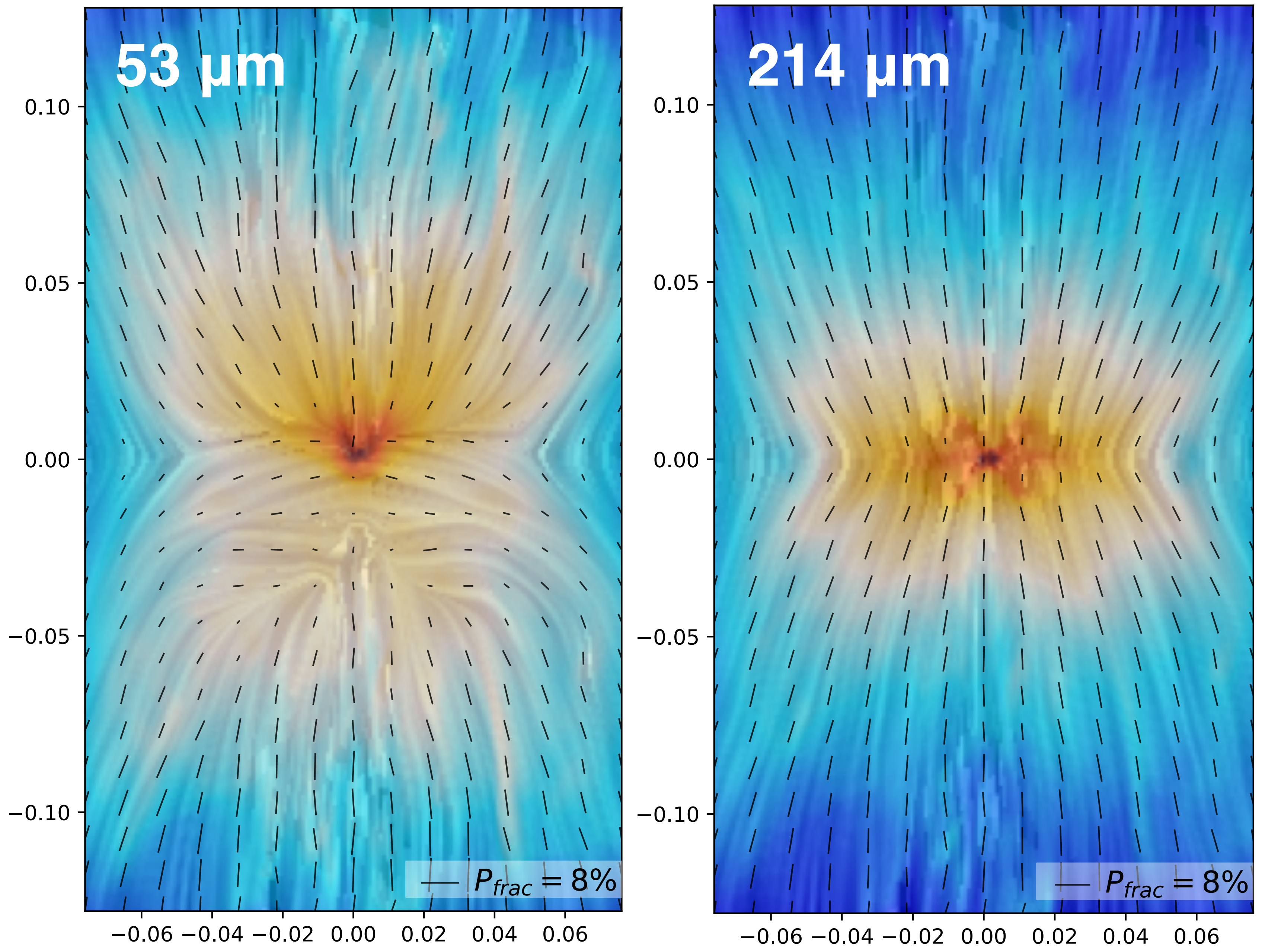
Continuum RT postprocessing (Ramsey et al., in prep.)



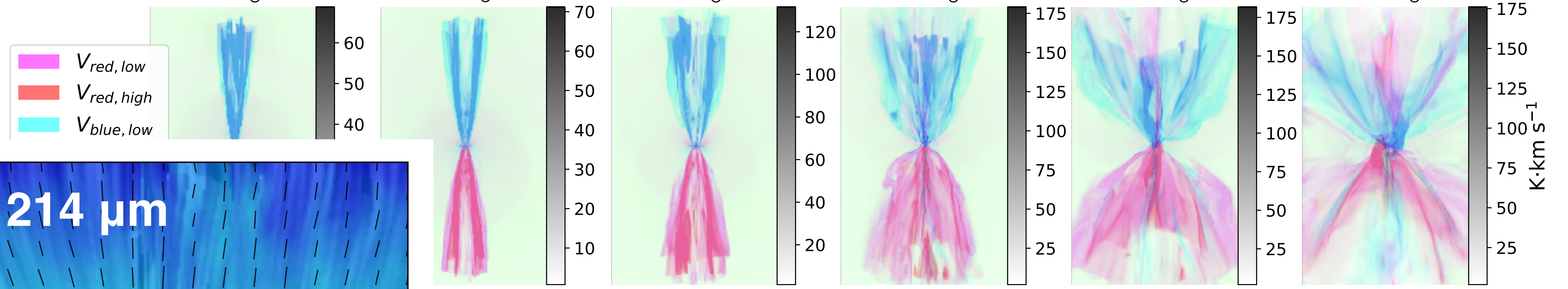
Shock-ionization & free-free emission (Gardiner et al. 2024)



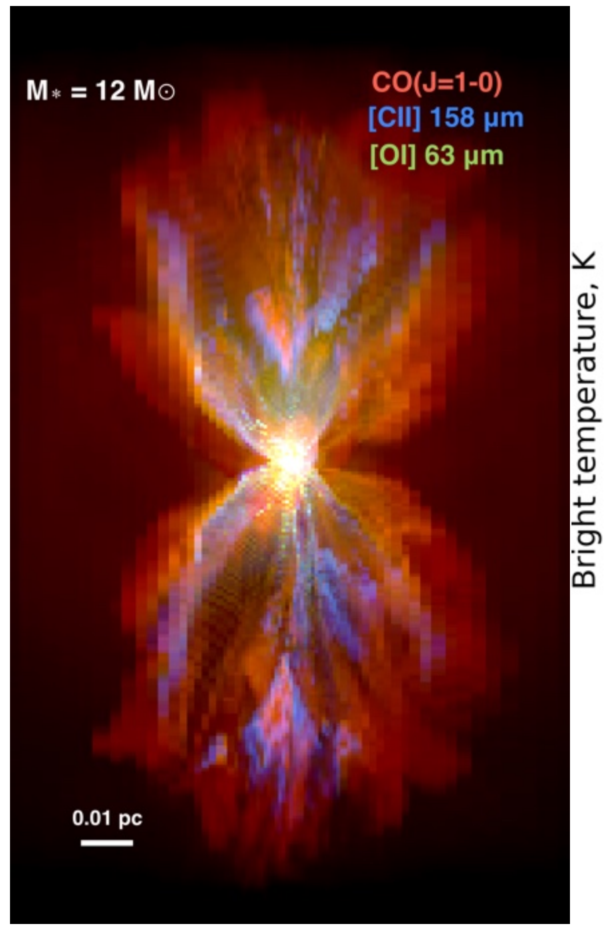
Polarized dust emission
(Küffmeier, Xu et al., in prep.)

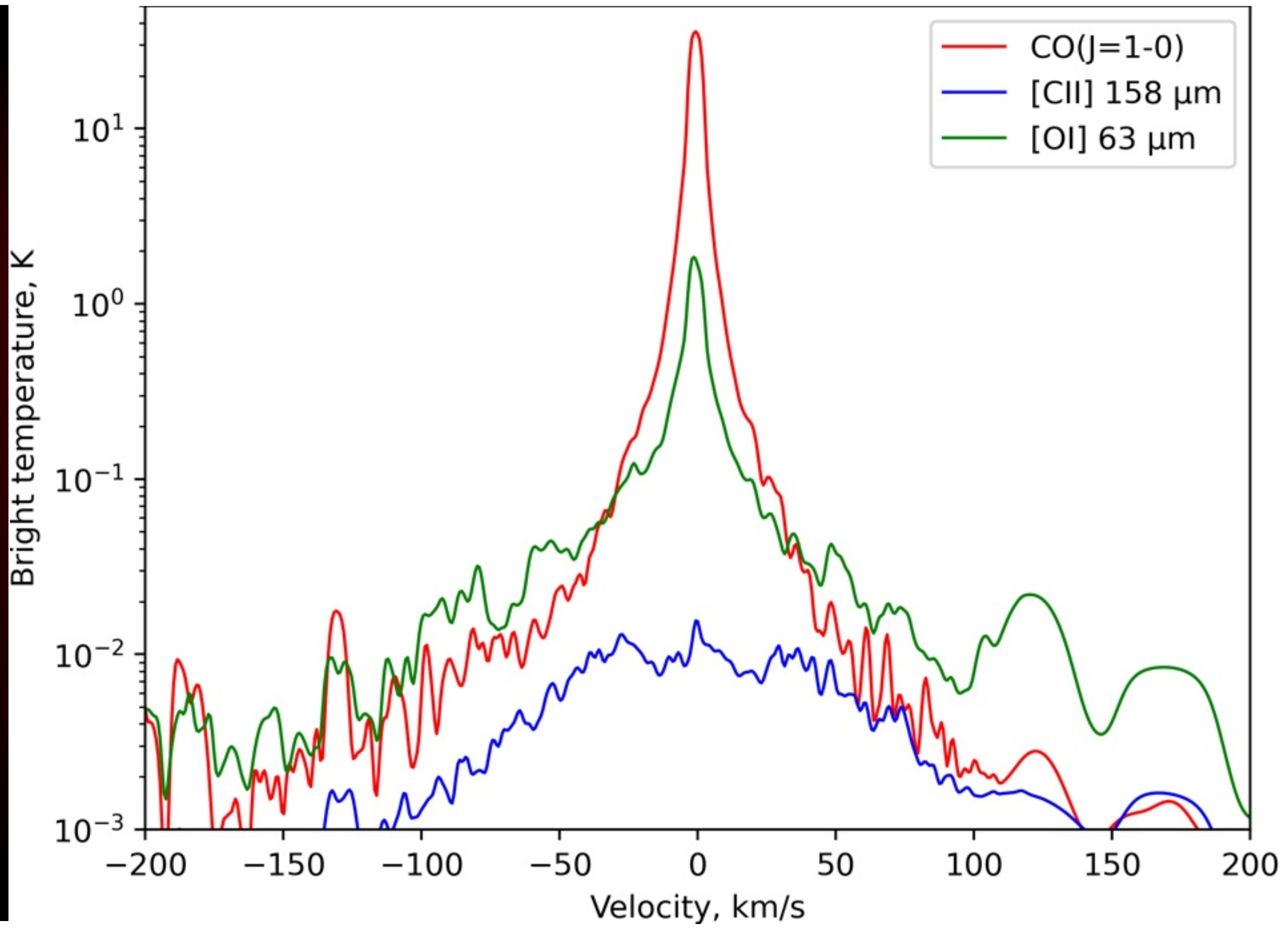


CO line emission (Xu et al. 2024; Stelea et al., in prep.)



PDR modeling (Obolentseva, Bisbas+)



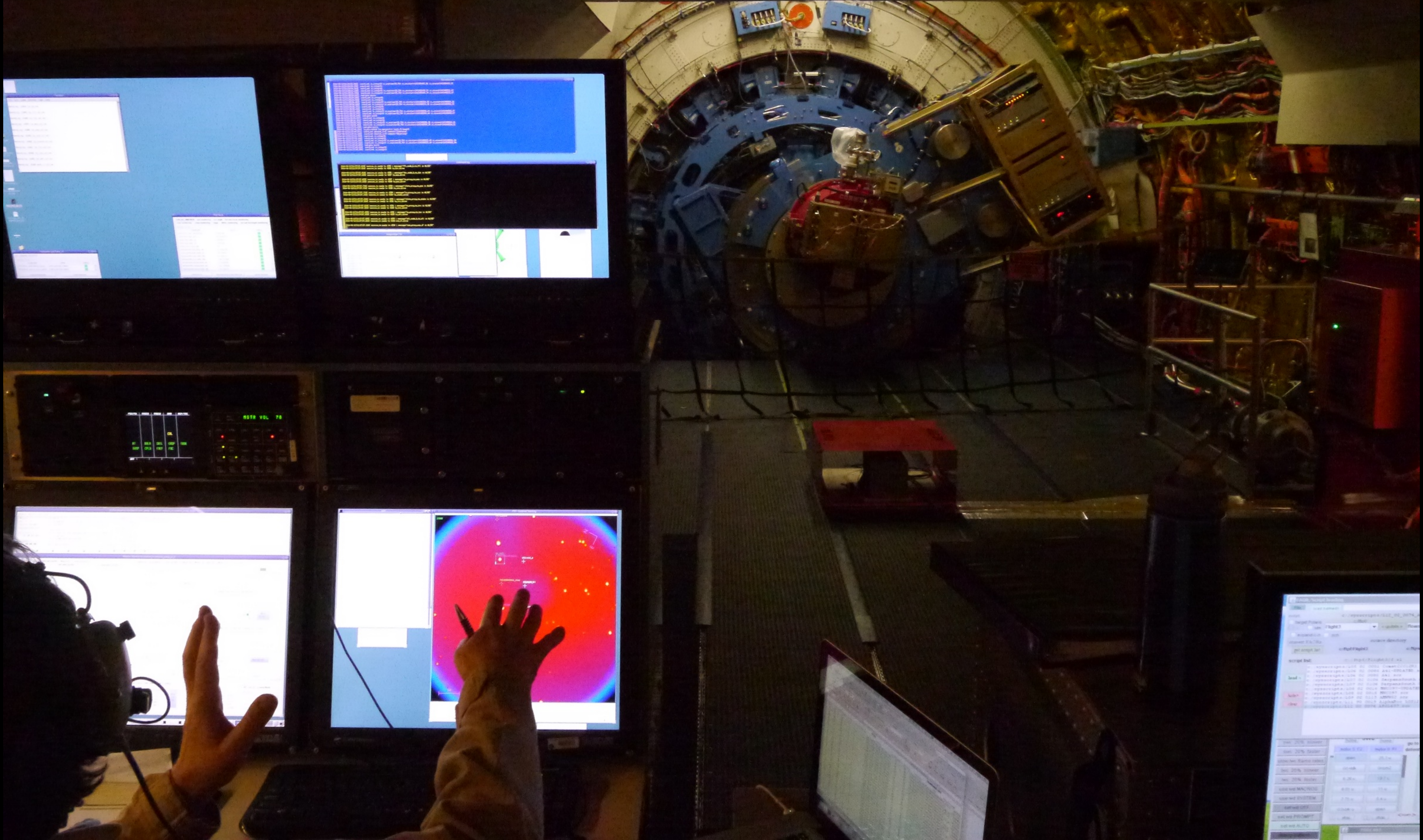


Massive Protostar Observations

The SOFIA Massive (SOMA) Star Formation Survey


N747NA


SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
NASA
DLR
N747NA



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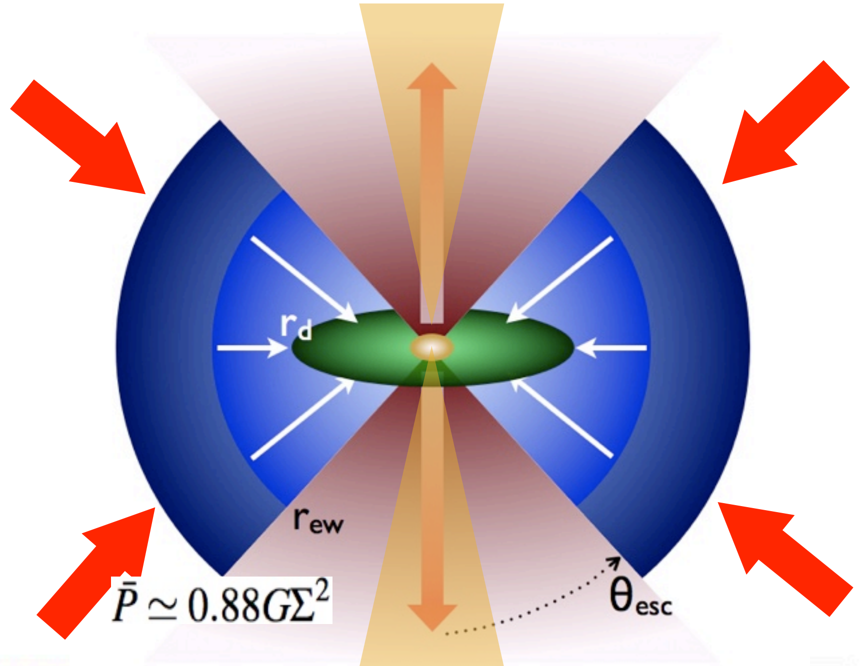
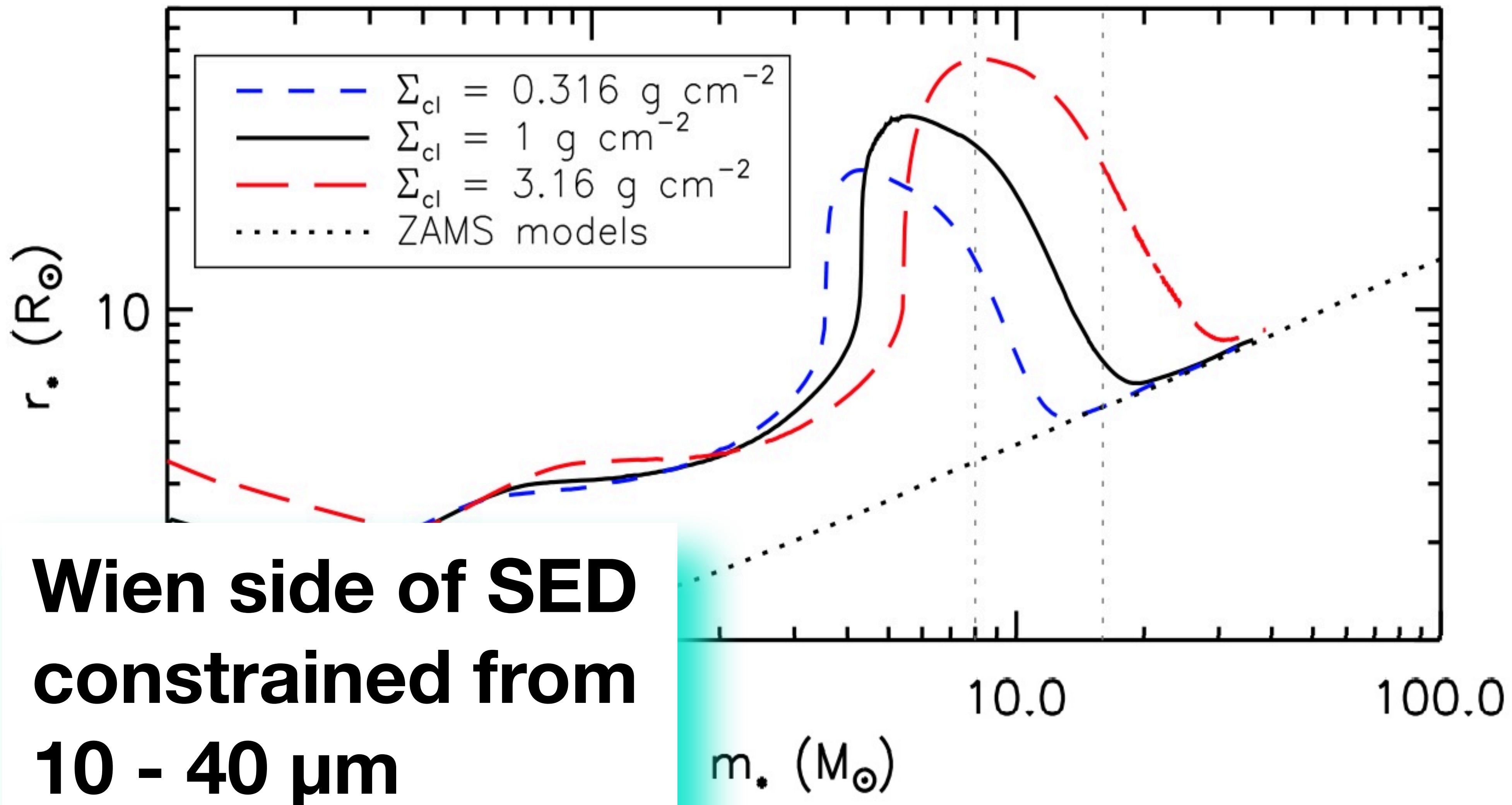
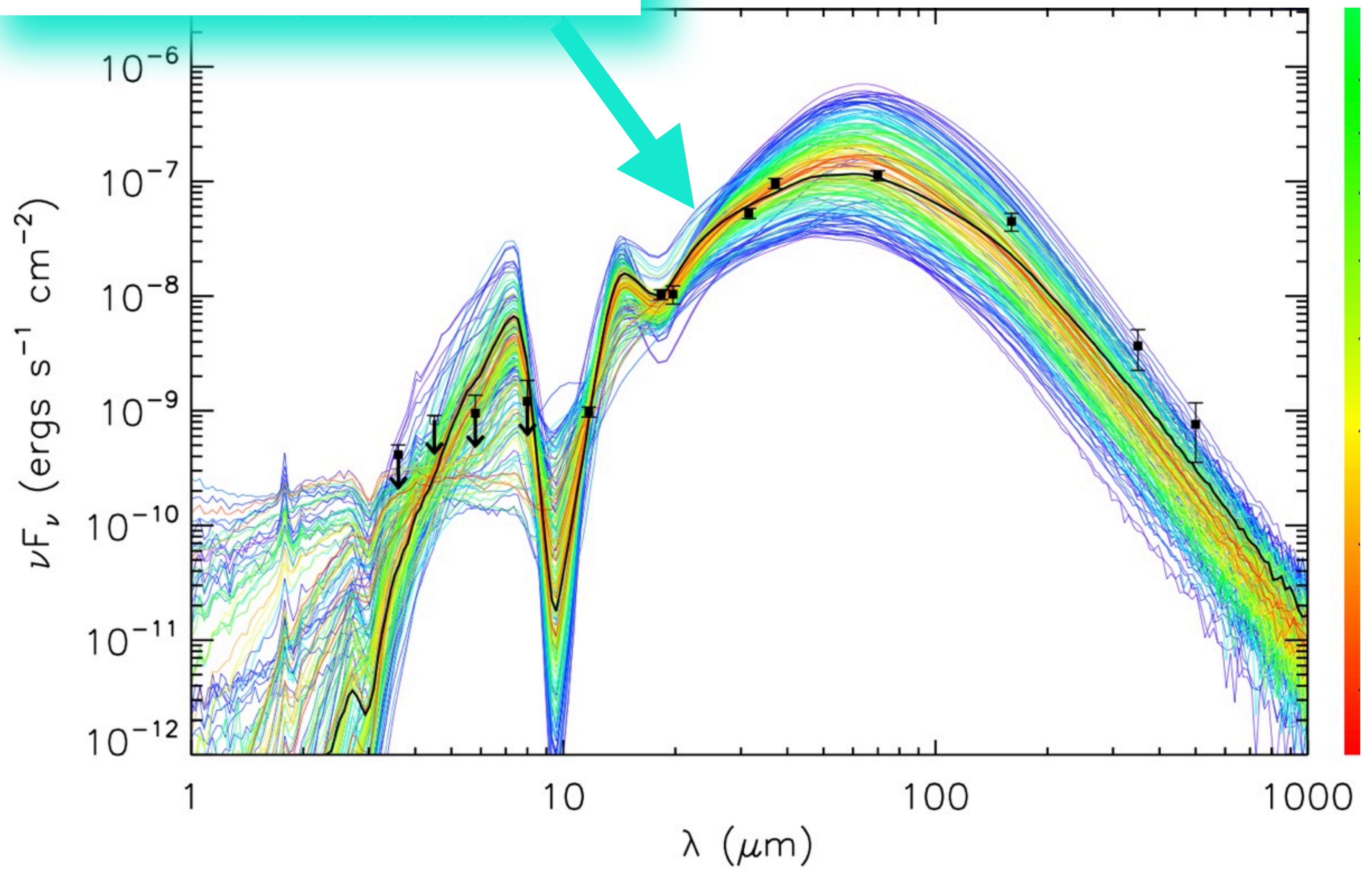
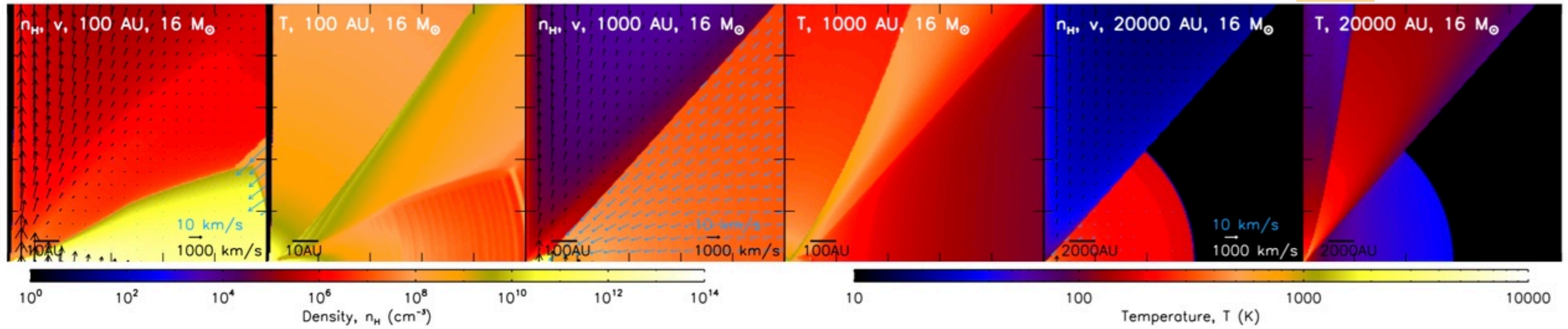
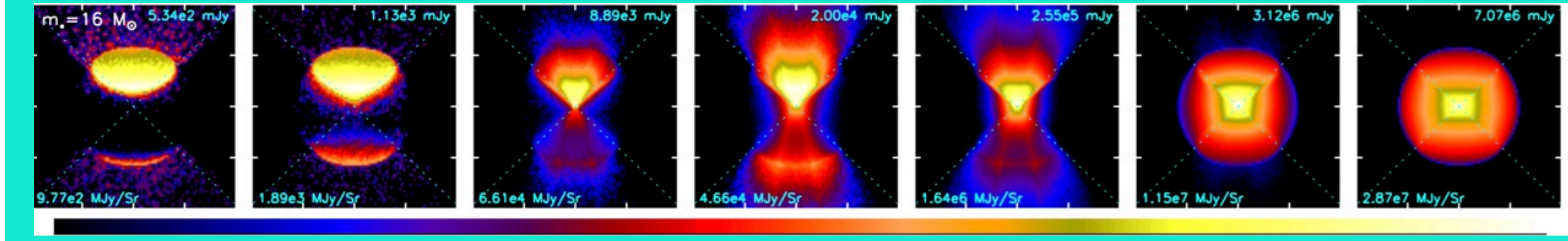




Wien side of SED constrained from 10 - 40 μm

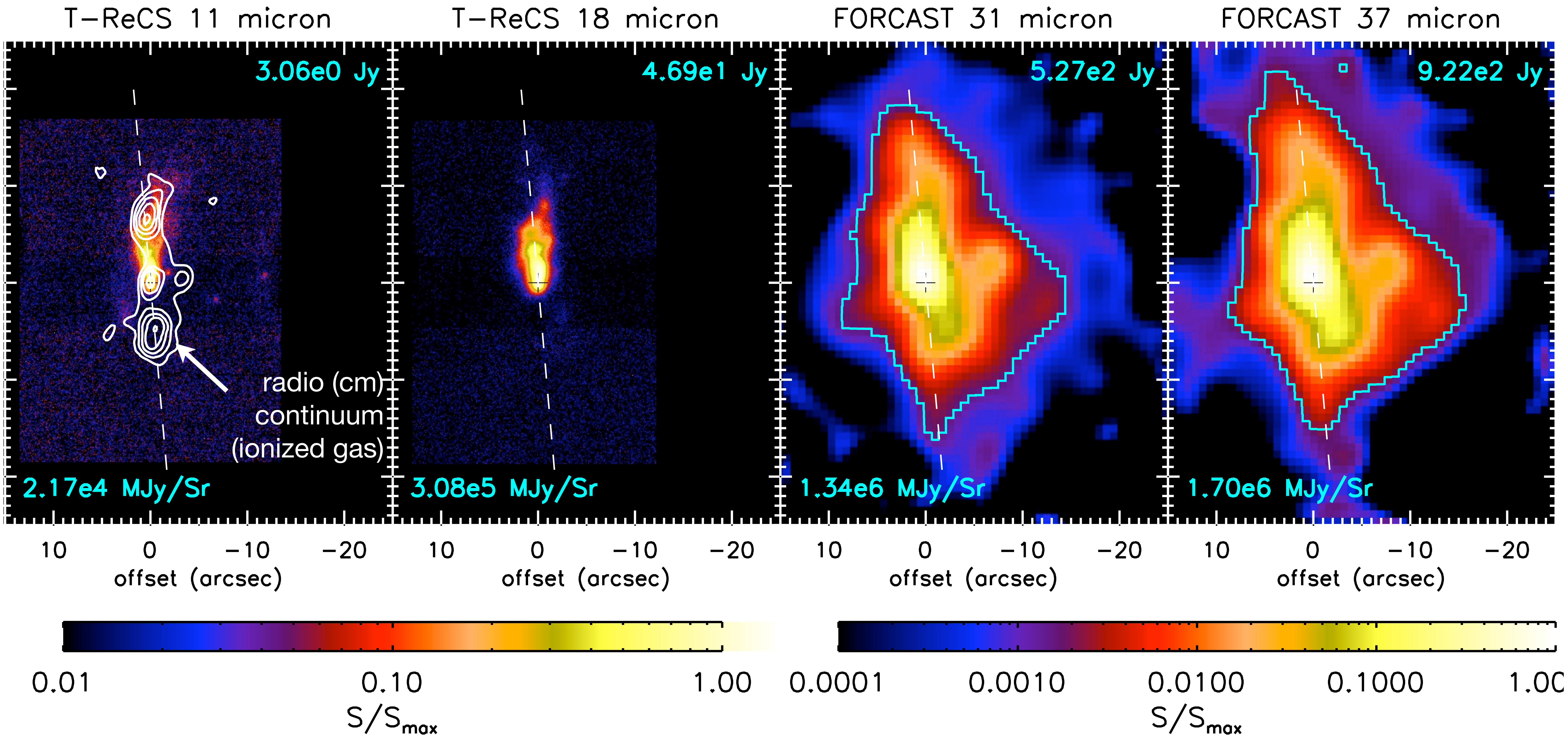






Prediction: increasing symmetry from MIR-FIR

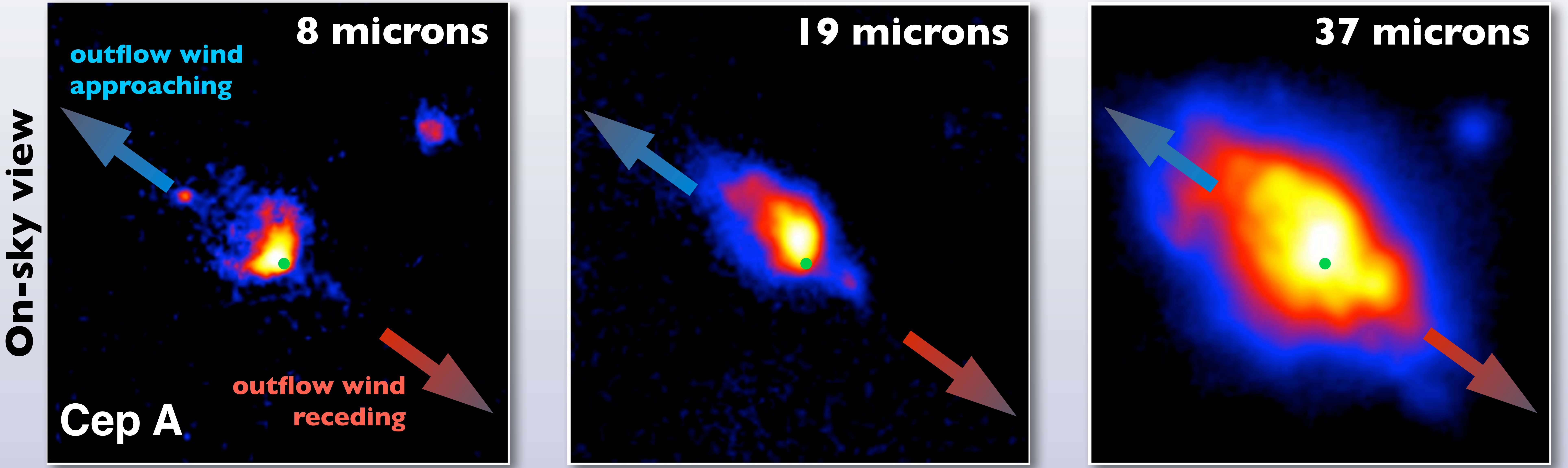
Massive Protostar G35.2N: d=2.2kpc; $L \sim 10^5 L_\odot$

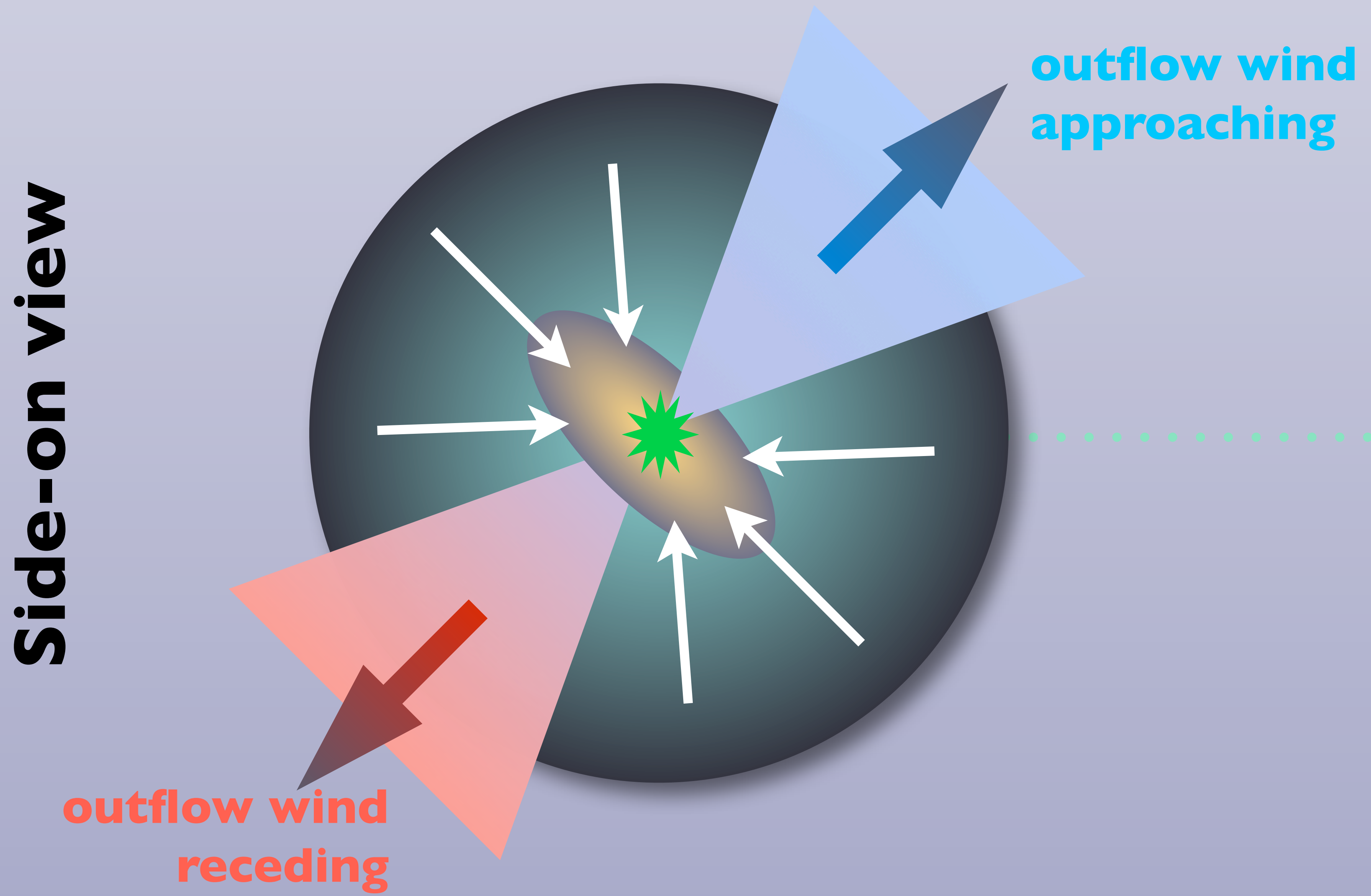


De Buizer (2006)

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

Peering to the Heart of Massive Star Birth



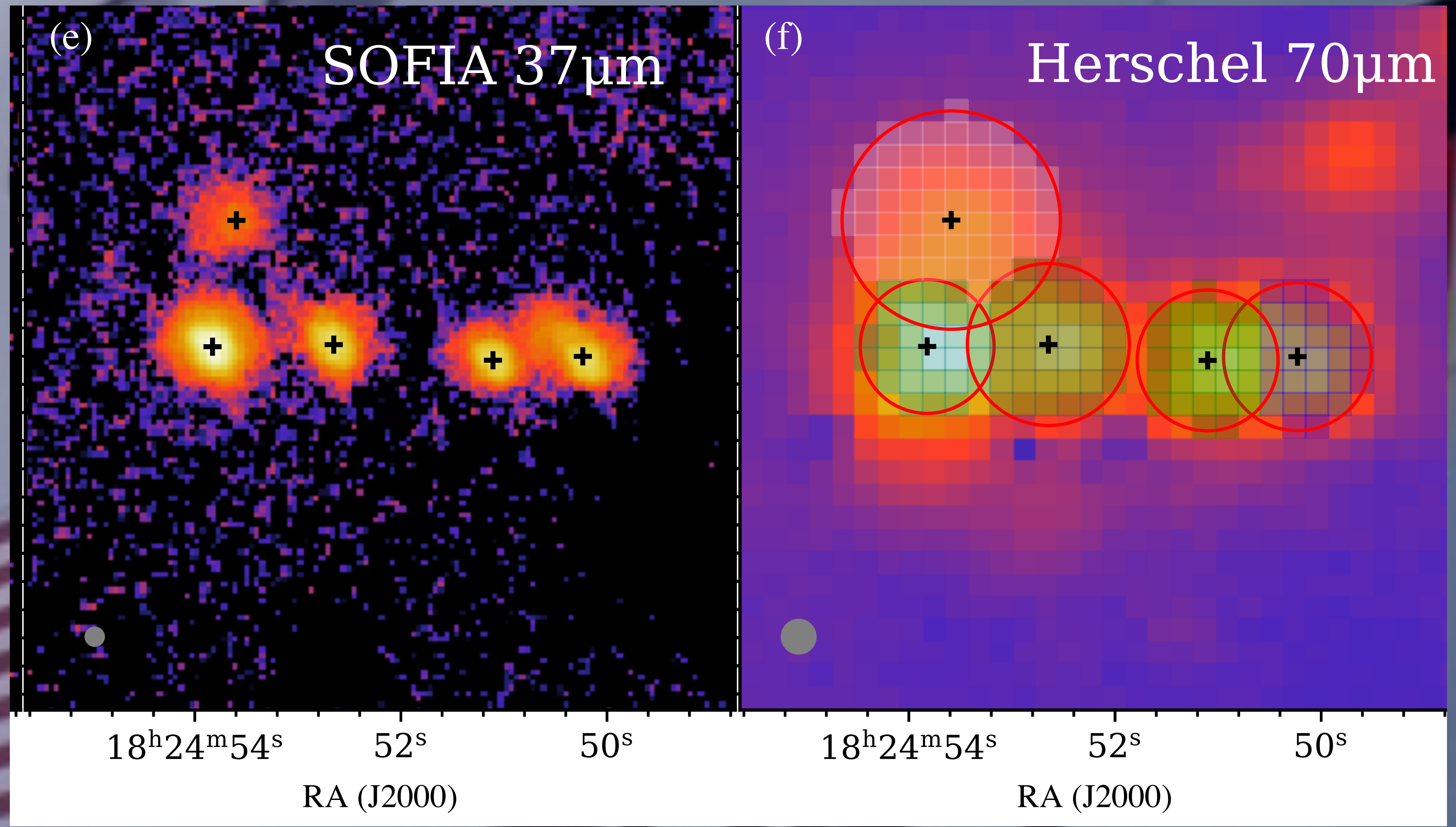


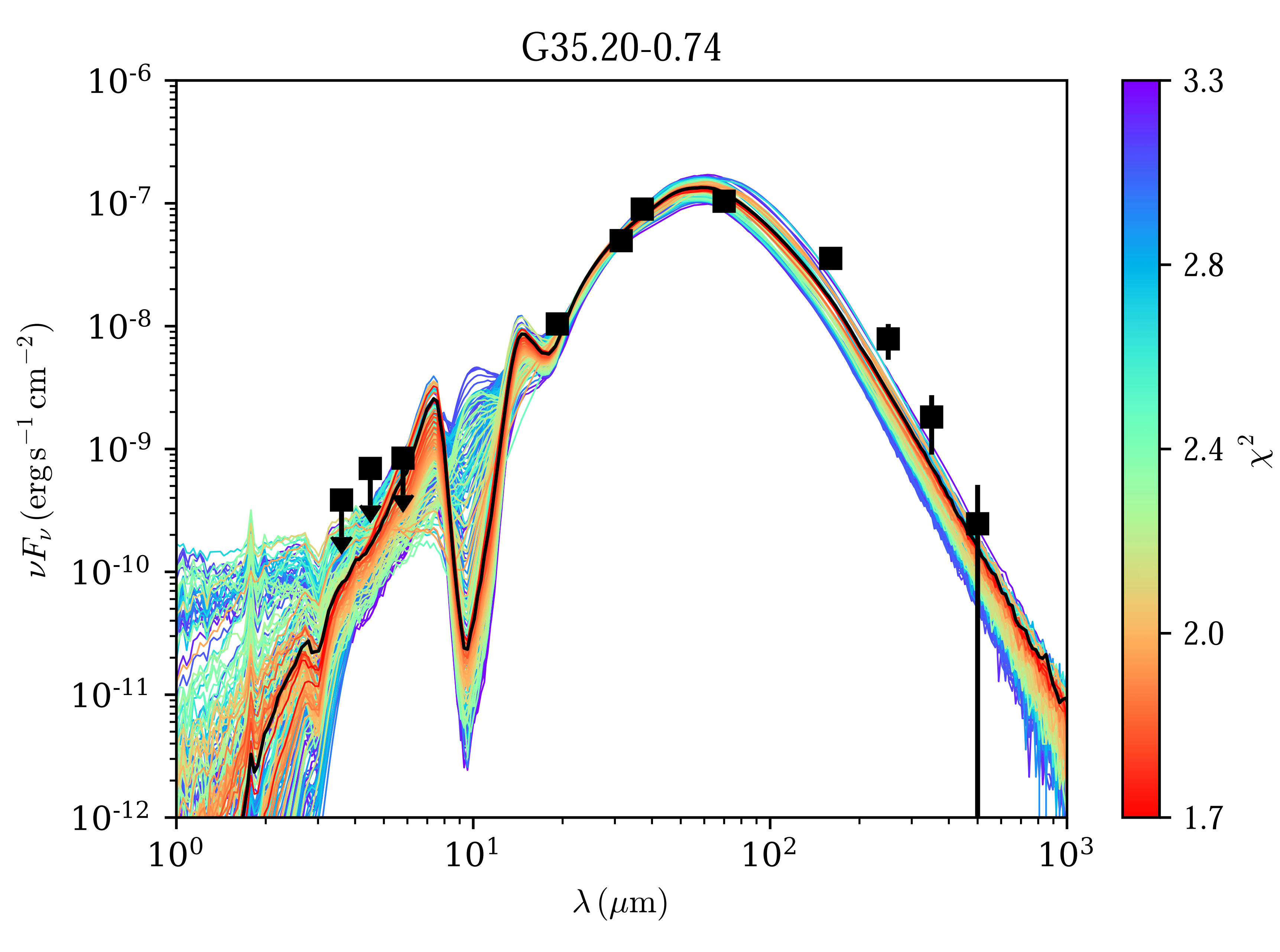
De Buizer, Liu, Tan et al. (2017)

The SOFIA Massive (SOMA) Star Formation Survey

http://www.cosmicorigins.space/soma

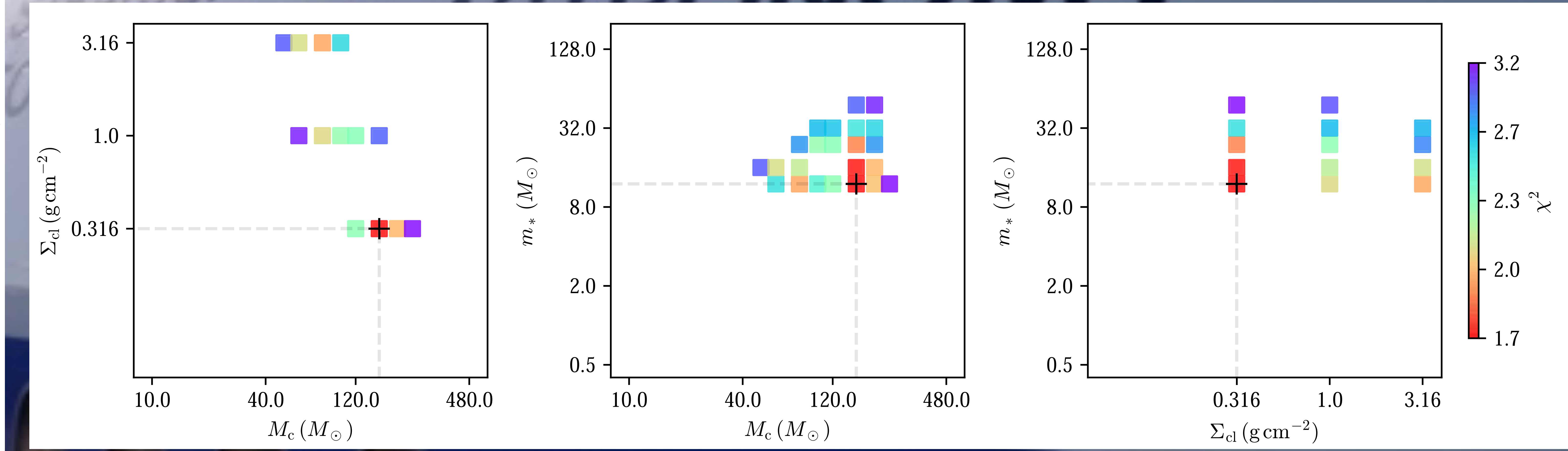
SOMA I	De Buizer et al. (2017)	8 High-Mass Protostars
SOMA II	Liu et al. (2019)	7 Highest Luminosity Protostars
SOMA III	Liu et al. (2020)	14 Intermediate-Mass Protostars
SOMA IV	Fedriani et al. (2023)	11 “Isolated” High-Mass Protostars
SOMA V	Telkamp et al., in prep.	~35 “Clustered” HMPs & IMPs from 7 regions



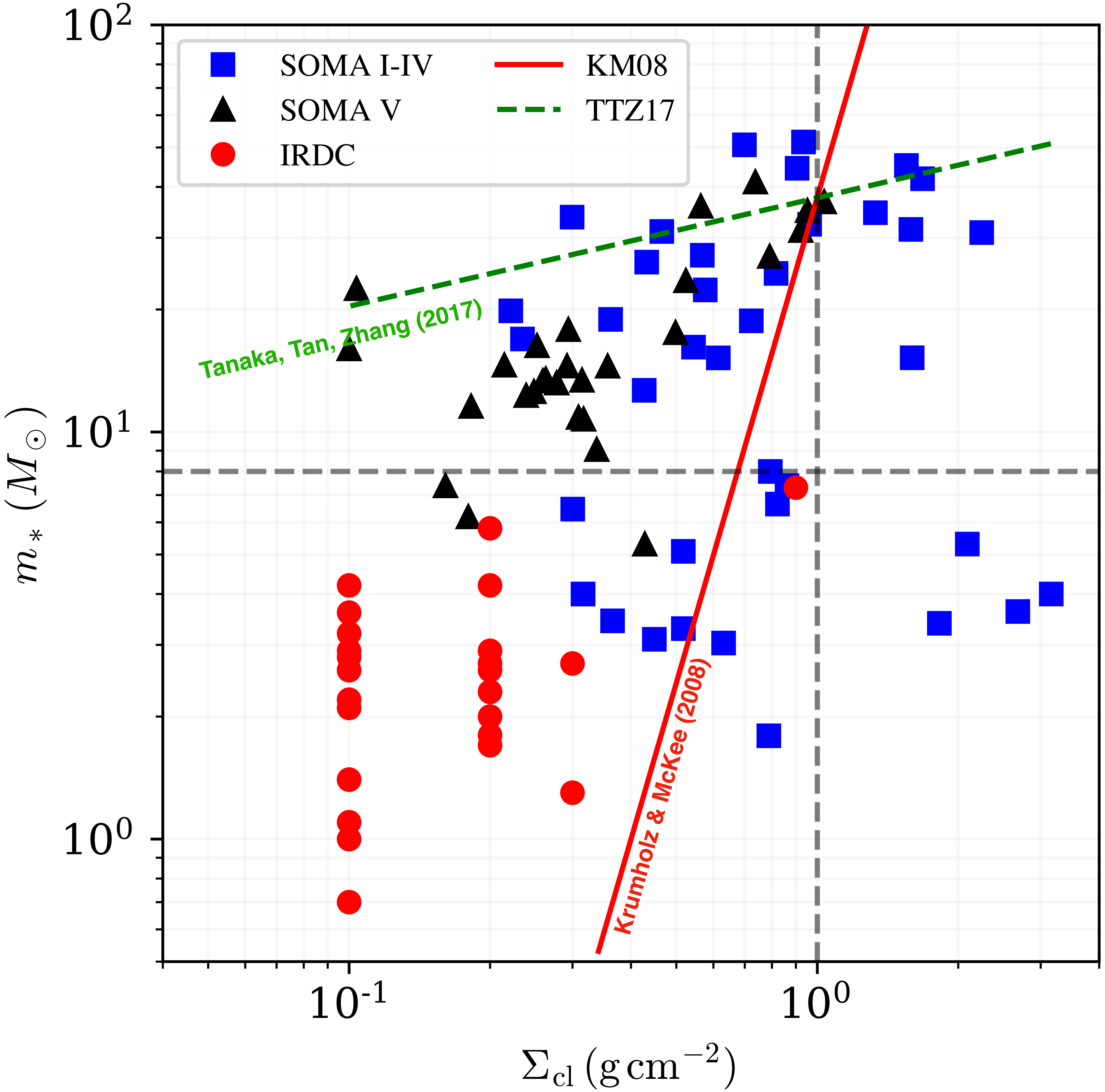


Primary (TCA): Σ_{clump}, M_{core}, m_*

Secondary: θ_{view}, A_V

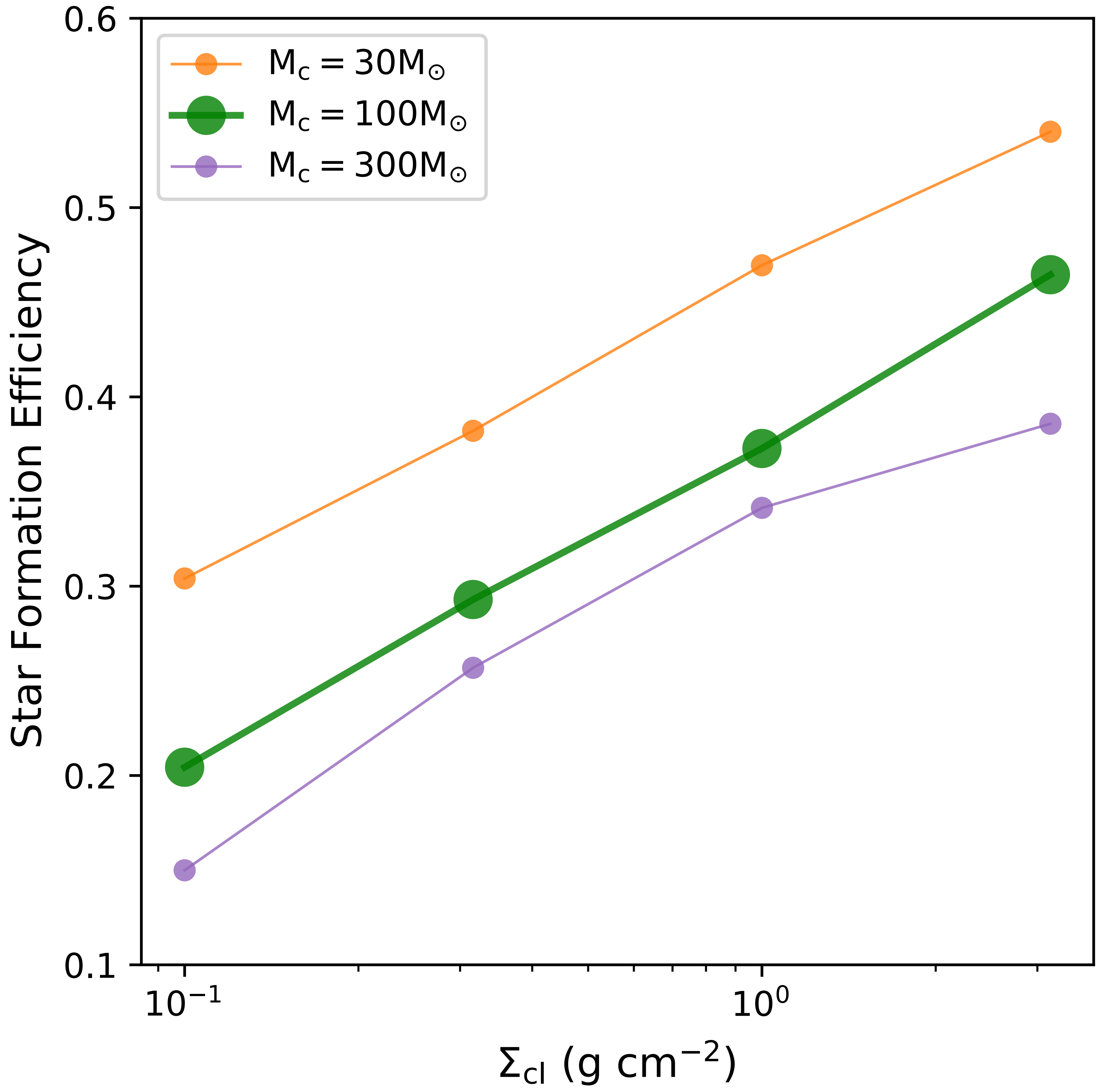


Conditions for Massive Star Formation? m* vs Σ_{clump}



Massive protostars can form where Σ_{cl} < 1 g cm^{-2}
m* > 25 $M_\odot$ generally favors high Σ_{cl} >0.3 g cm^{-2}

- **B-fields limit fragmentation (Butler & Tan 2012)**
- **Internal protostellar feedback limits core SFE (Tanaka, Tan & Zhang 2017)**



SOMA+

SOMA Archival: Analysis of SOFIA-FORCAST data archive (Crowe+ in prep.; Tarafder+ in prep.; Zhang+ in prep.)

SOMA Imaging: FORCAST image fitting (Yang+ in prep.; Mifsut Benet+ in prep.)

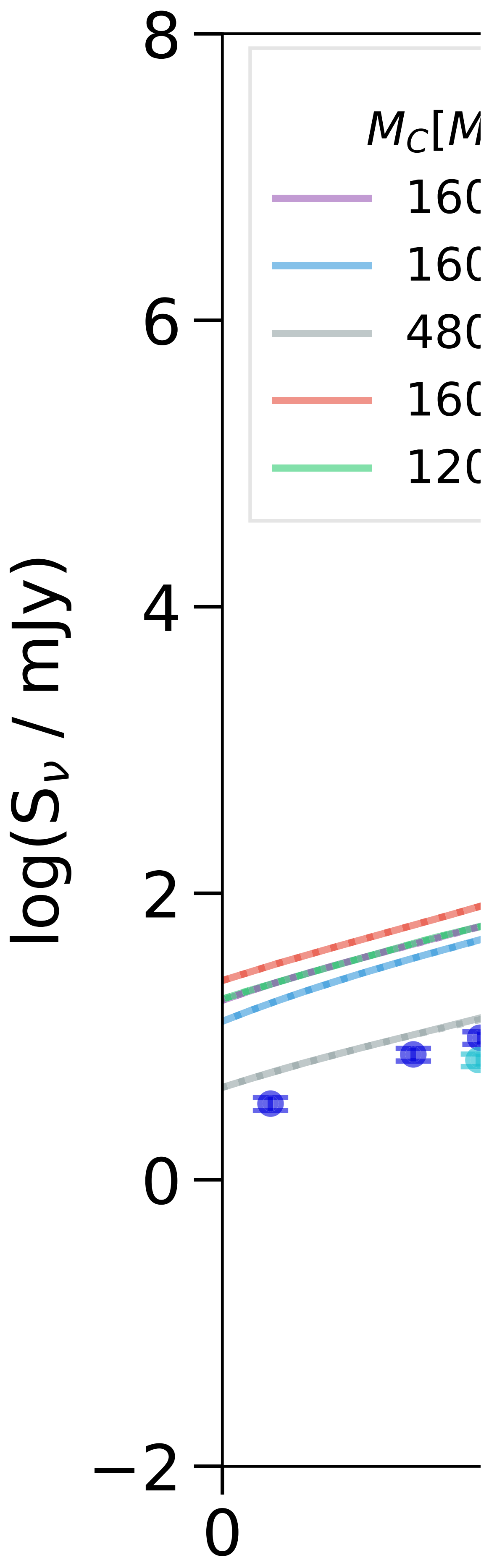
SOMA Radio: VLA/ATCA all sources observed (Rosero et al. 2019; Sequeira-Murillo+)

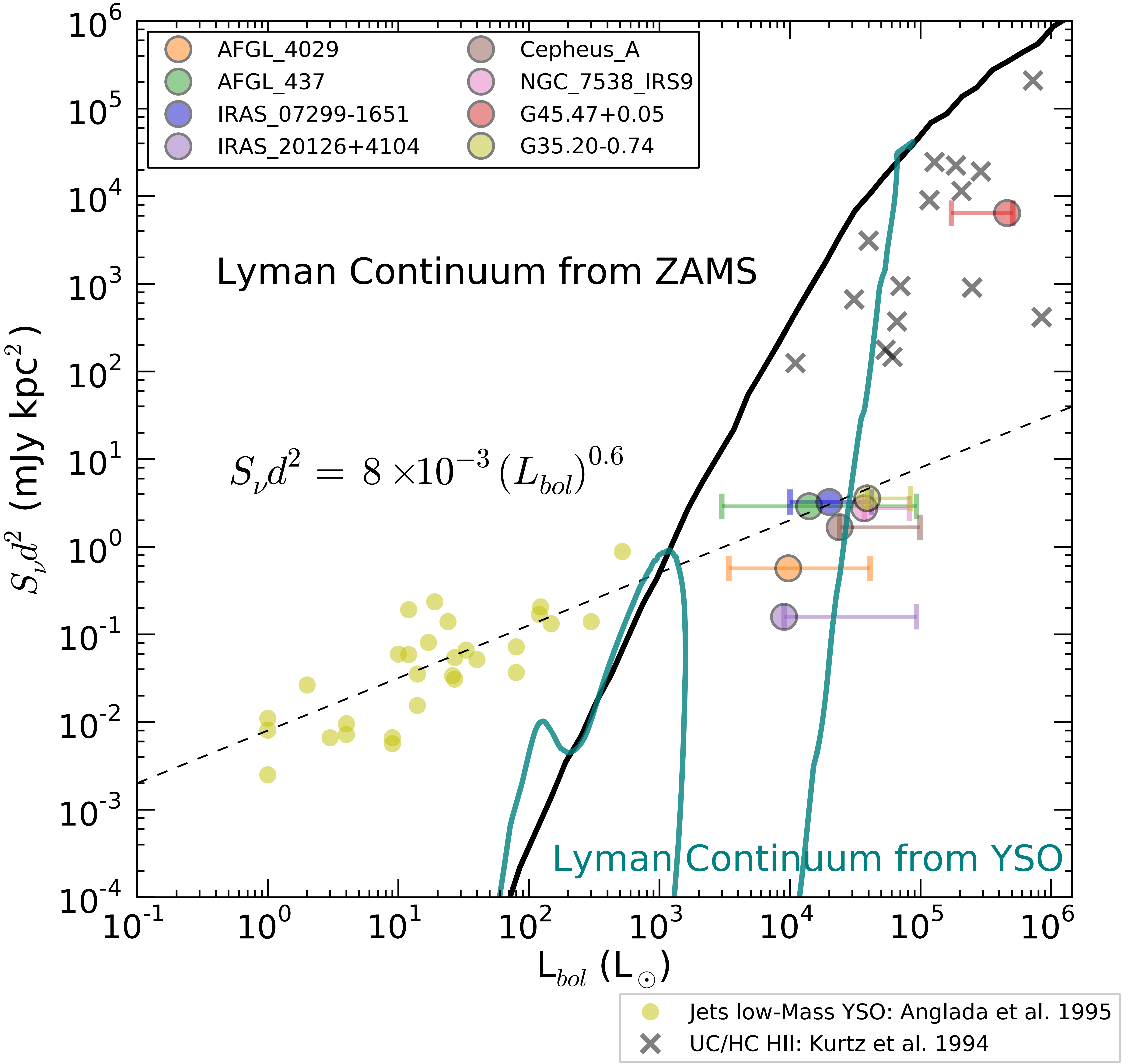
SOMA-Radio

VLA/ATCA all sources observed:
Rosero+ 2019
Rosero+ in prep.
Sequeira-Murillo+ in prep.
Vohra+ in prep.

~3 - 10 mJy; 0.3”
K-band (1.3 cm) (9.9 and 23.9 GHz)
C-band (6 cm), (5.3 and 6.3 GHz)

Radio fluxes to break IR-SED model degeneracies.





SOMA+

SOMA Archival: Analysis of SOFIA-FORCAST data archive (Crowe+ in prep.; Zhang+ in prep.)

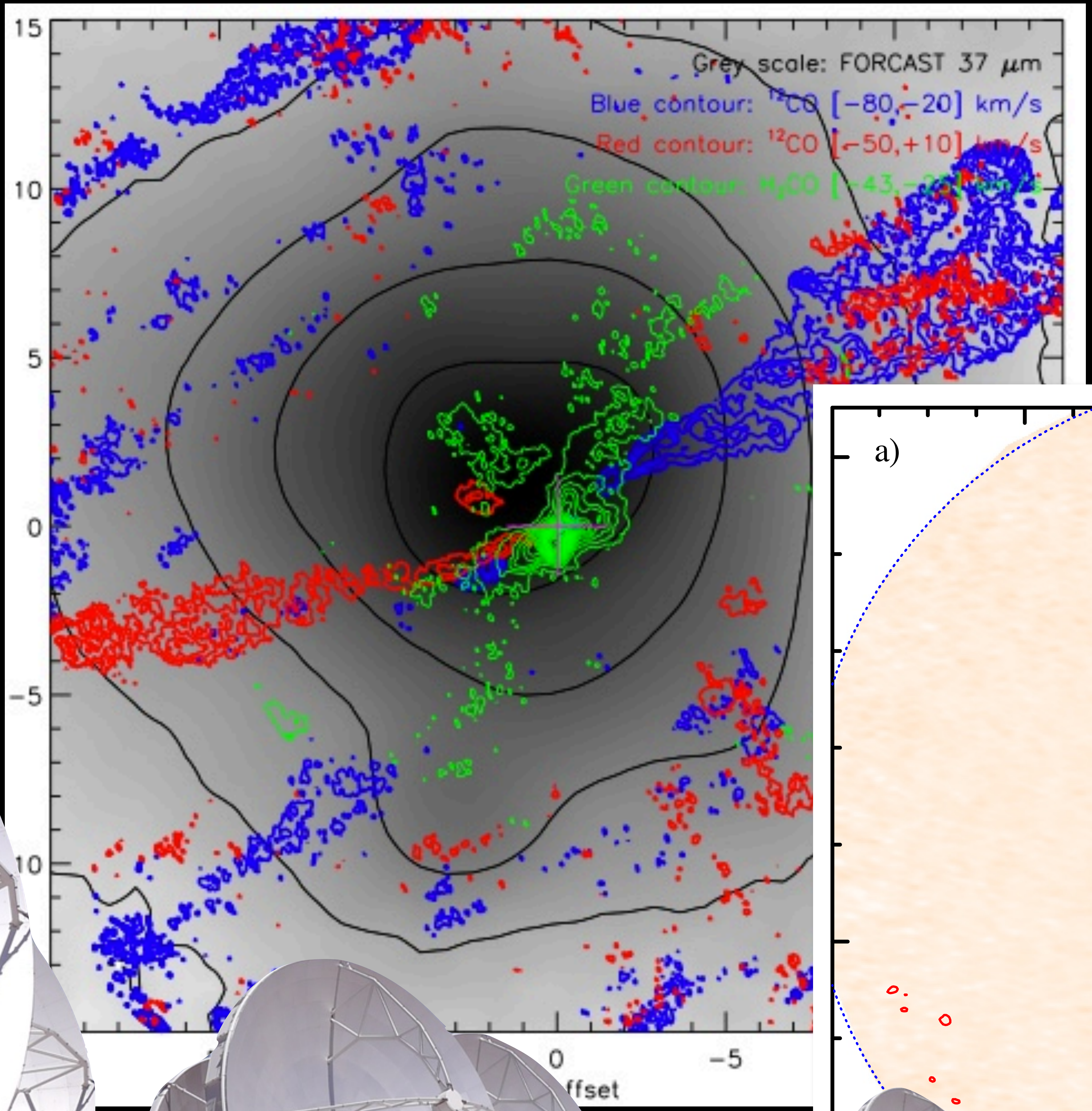
SOMA Imaging: FORCAST image fitting (Yang+ in prep.; Mifsut Benet+ in prep.)

SOMA Radio: VLA/ATCA all sources observed (Rosero et al. 2019; Sequeira-Murillo+)

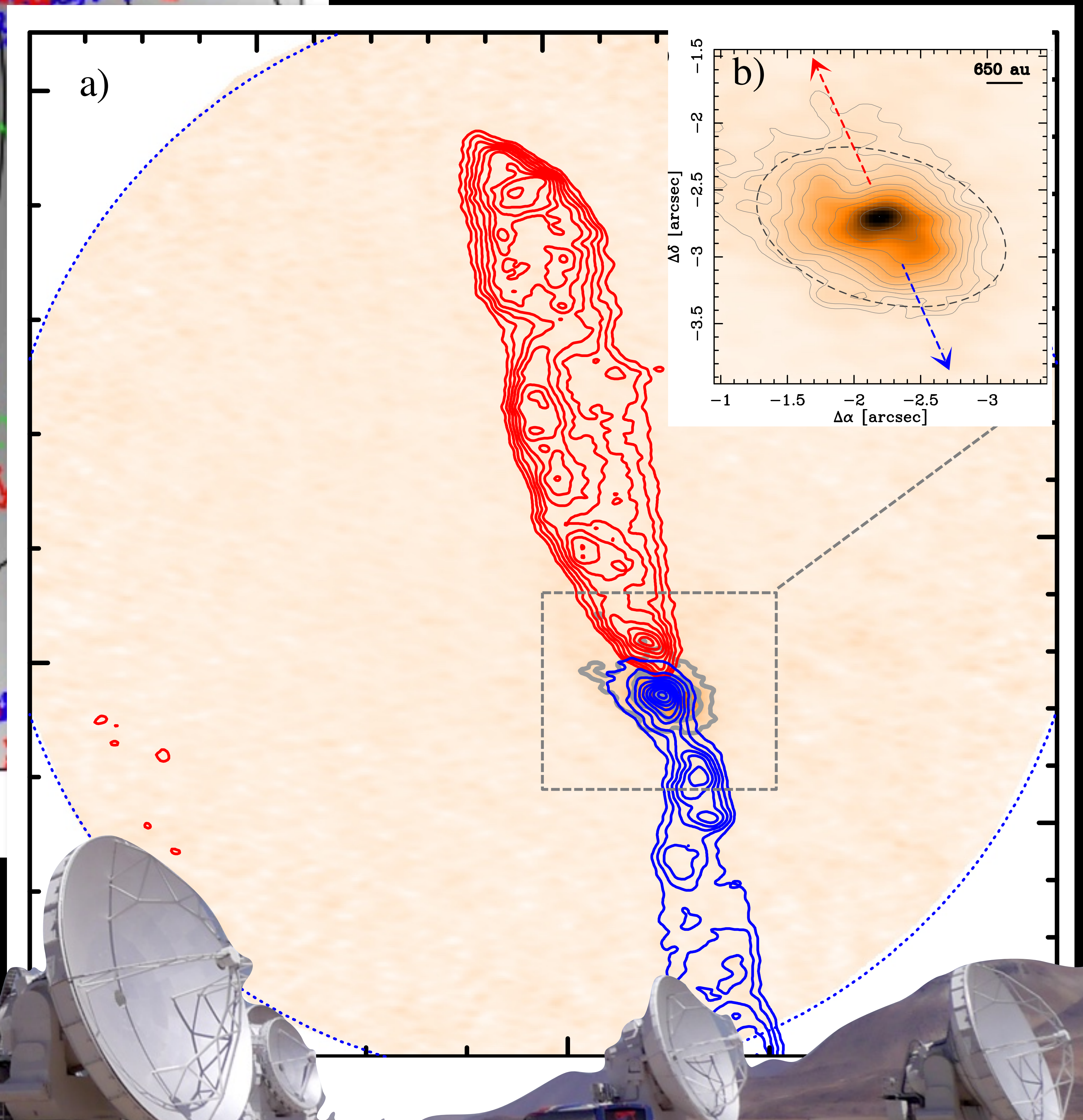
SOMA mm/submm: ALMA (Band 6) - hi-res 5 observed (Zhang et al. 2019a, b, 2022; Law et al. 2022)
- med-res 8 observed (Zhang et al. 2019c)
- low-res ~15 observed
Chemistry - SMA, IRAM30m, GBT, Yebes

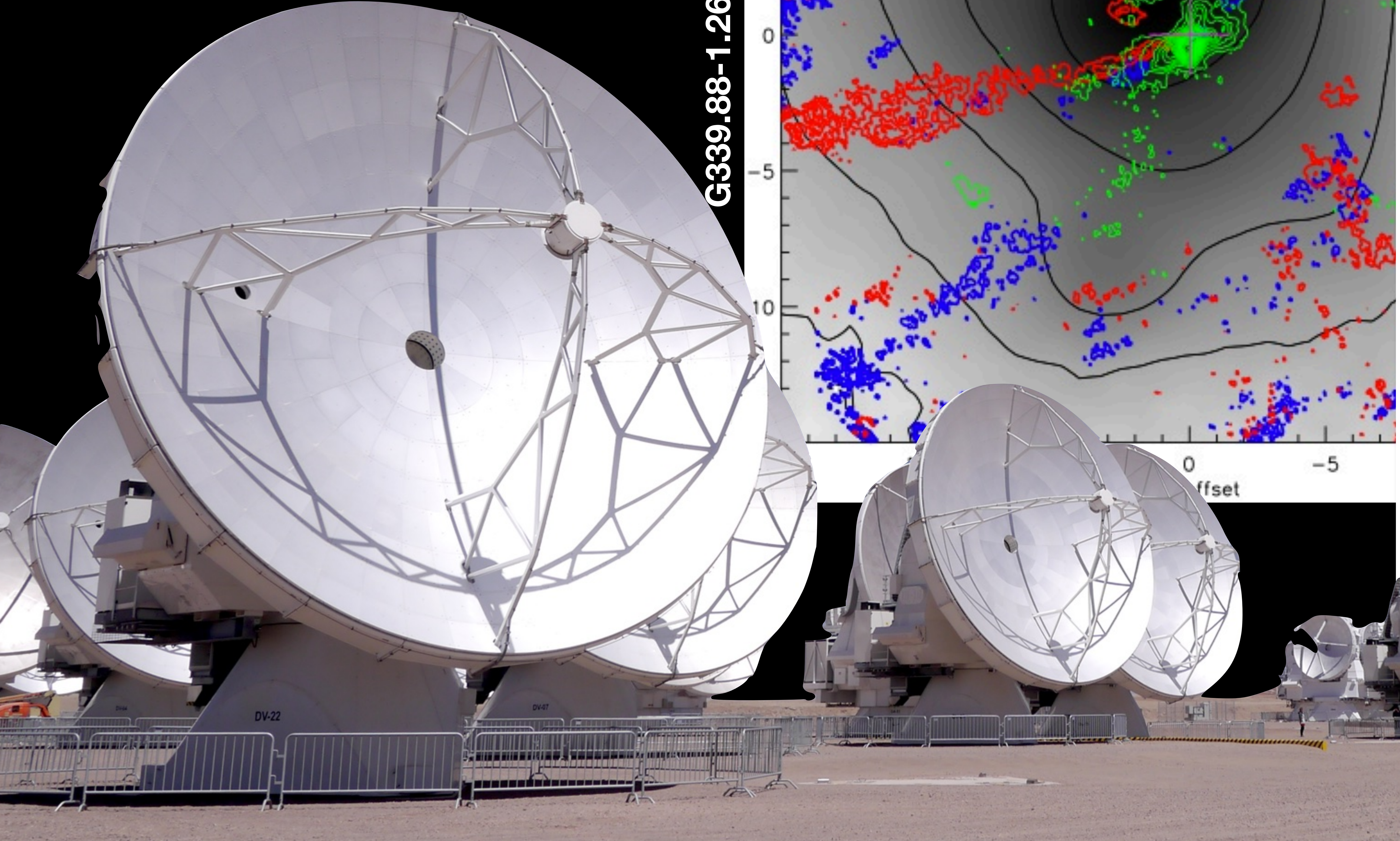
"Ordered" Massive Star Formation

G339.88-1.26, Zhang, Tan et al. 2019



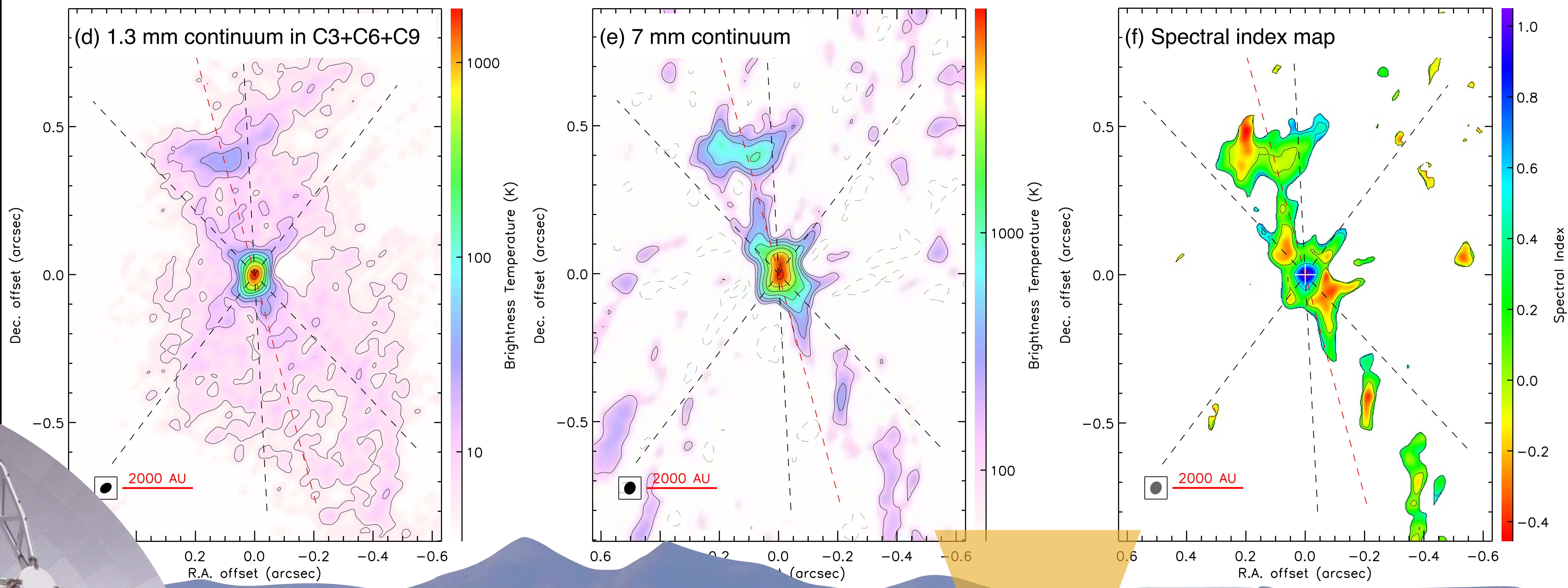
G328.3-0.5, Csengeri et al. 2018





“Ordered” Massive Star Formation

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



“Ordered” Massive Binary Star Formation

IRAS 07299-1651, Zhang, Tan et al. 2019

"Isolated" Massive Star Formation

G28.20-0.05, Law et al. 2022

SOMA+

SOMA Archival: Analysis of SOFIA-FORCAST data archive (Crowe+ in prep.; Zhang+ in prep.)

SOMA Imaging: FORCAST image fitting (Yang+ in prep.; Mifsut Benet+ in prep.)

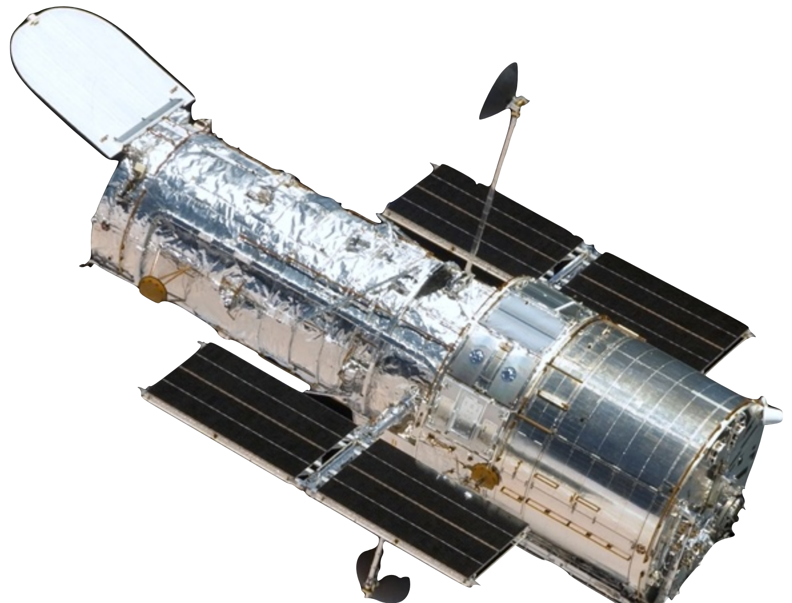
SOMA Radio: VLA/ATCA all sources observed (Rosero et al. 2019; Sequeira-Murillo+)

SOMA mm/submm: ALMA (Band 6) - hi-res 5 observed (Zhang et al. 2019a, b, 2022; Law et al. 2022)
- med-res 8 observed (Zhang et al. 2019c)
- low-res ~15 observed
Chemistry - SMA, IRAM30m, GBT, Yebes

SOMA POL: ~few sources observed with HAWC+; JCMT-POL2 (Pattle, Law+)

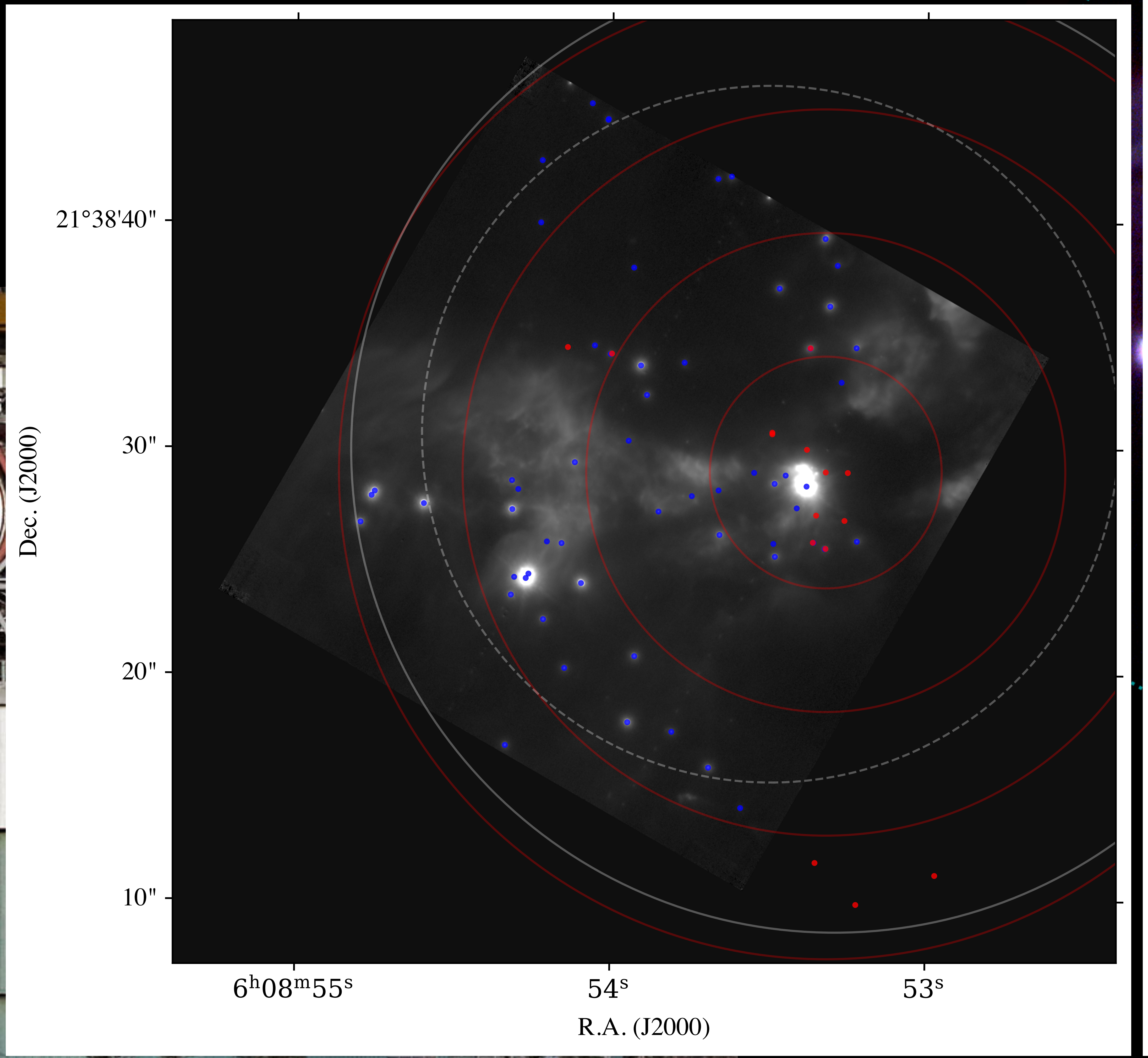
SOMA FIFI-LS: 17 sources observed - Atomic Outflows [OI] (Oakey, Reyes Rosa, Yang+)

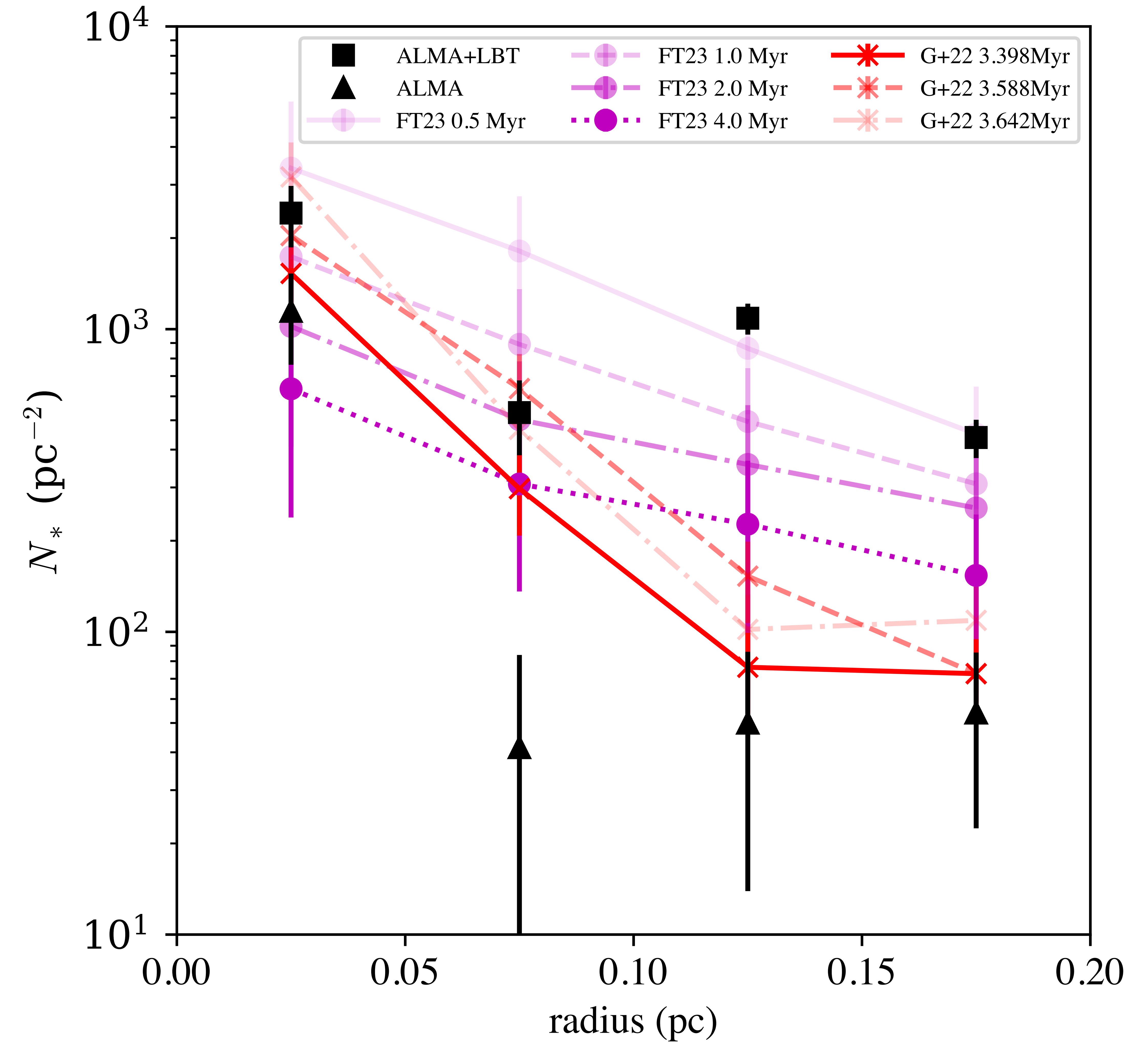
SOMA NIR: HST/WFC3 18 observed (Fedriani et al. 2019 for G35.2)
LBT/LUCI ~20+ observed; remainder in progress (Fedriani+ in prep.)



“Crowded” Massive Star Formation

AFGL 5180, Crowe, Fedriani et al. 2024





SOMA Survey: Conclusions and Outlook

- If massive stars form by (turbulent) core accretion, we expect ordered outflow cavities. In high density regions, cores predicted to have high mass surface densities so even ~40μm emission controlled by these cavities.

- The SOMA survey is using SOFIA-FORCAST to image >50 massive & intermediate-mass protostars in a range of environments and evolutionary stages, to test formation theories, via RT modeling (SEDs, images) and astrochemical modeling.

- >100 sources analyzed to date. Follow-up in progress with ALMA, VLA, HST…