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SNAPSHOTS OF THE EARLY EVOLUTION OF HIGH-MASS PROTOSTARS

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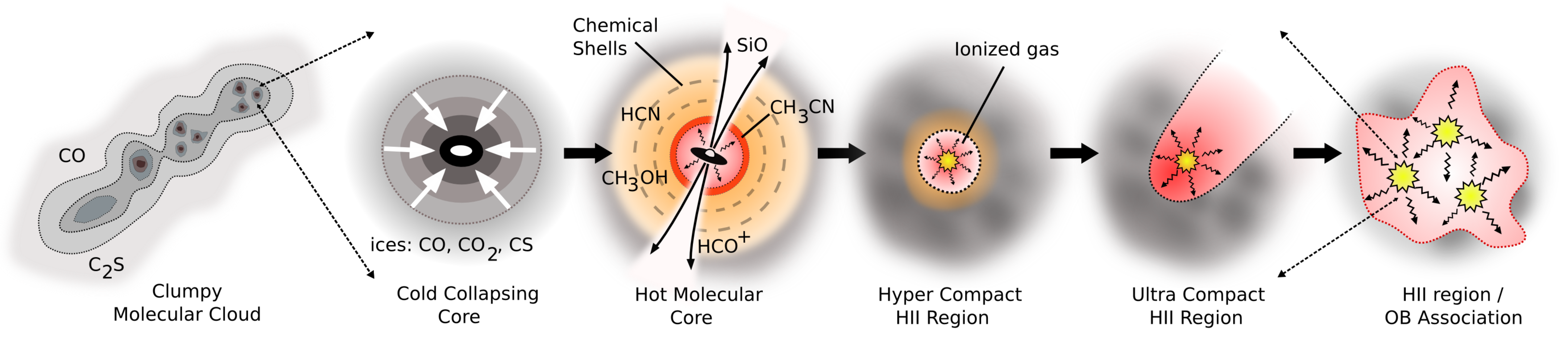
THE TIMELINE OF MASSIVE STAR FORMATION

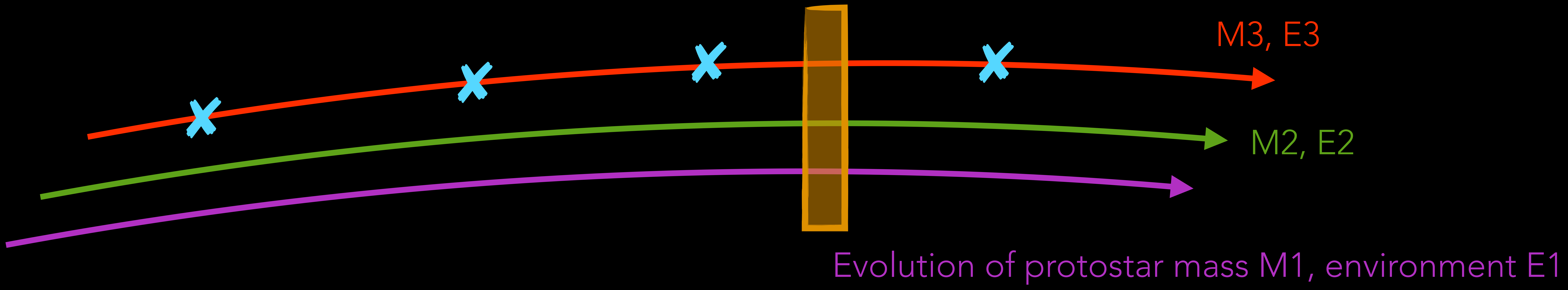


C. Purcell, http://web.science.mq.edu.au/~cpurcell/public/index.php

- Evolution morphologically and chemically: release of molecular species from ice mantles through shocks or heating
- Not a single path, huge range of masses, environments: luminosity a function of size and evolution, arm vs. inter-arm regions, nearby sources of feedback
- Not complete picture: Sub-phases, transitions between regimes

UNDERSTANDING EVOLUTIONARY TRACERS

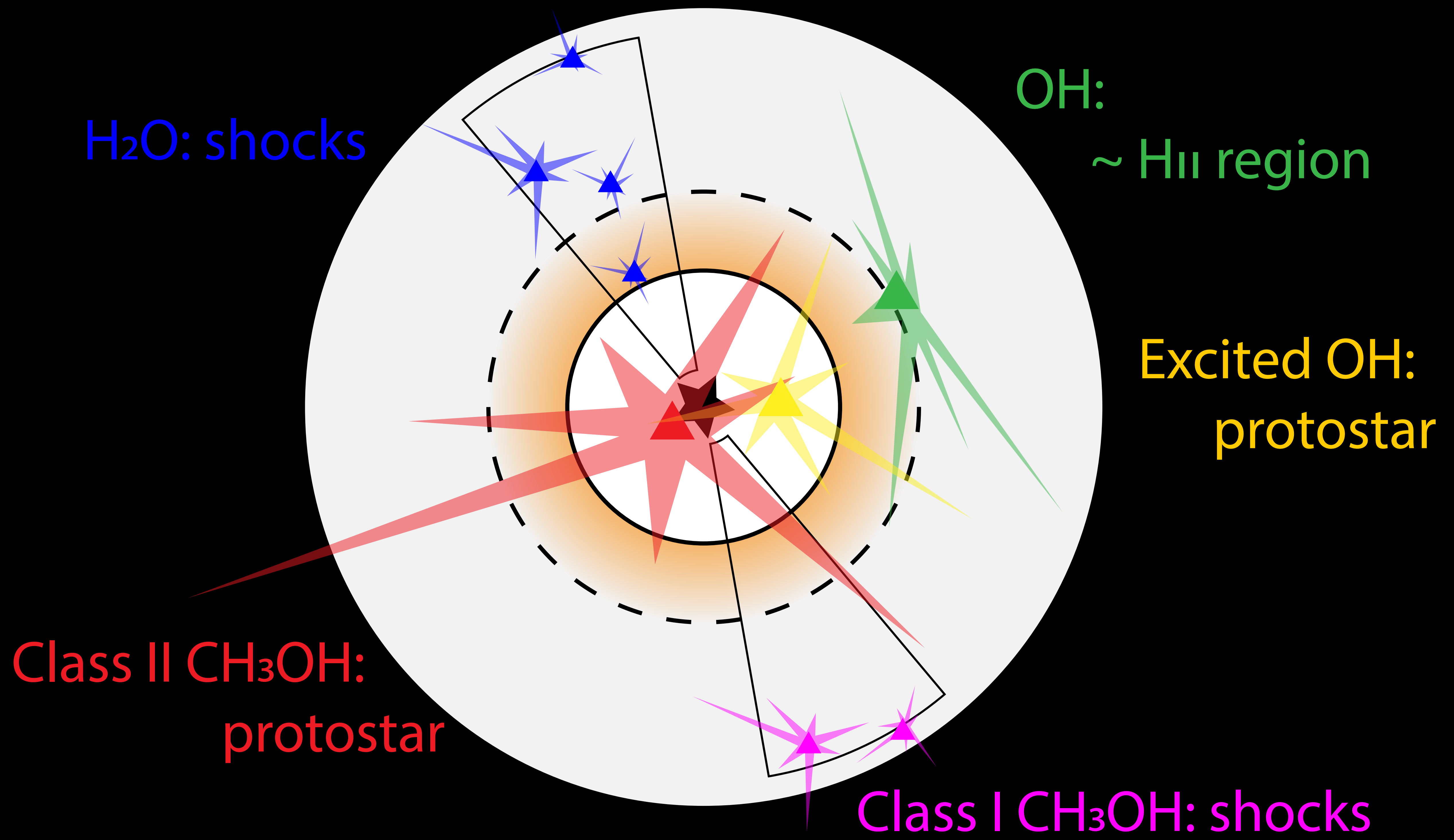
- Tracers: class II methanol masers, 70-micron extinction
- Part I: Protostellar: sufficiently luminous to host maser, but not yet destroyed methanol in immediate surroundings - large sample, low-resolution, narrow phase of evolution (Jones et al., MNRAS submitted)
- Part II: 70-micron dark: “starless” (or very young protostars) - small sample, high spectral detail and resolution, follow one type of object

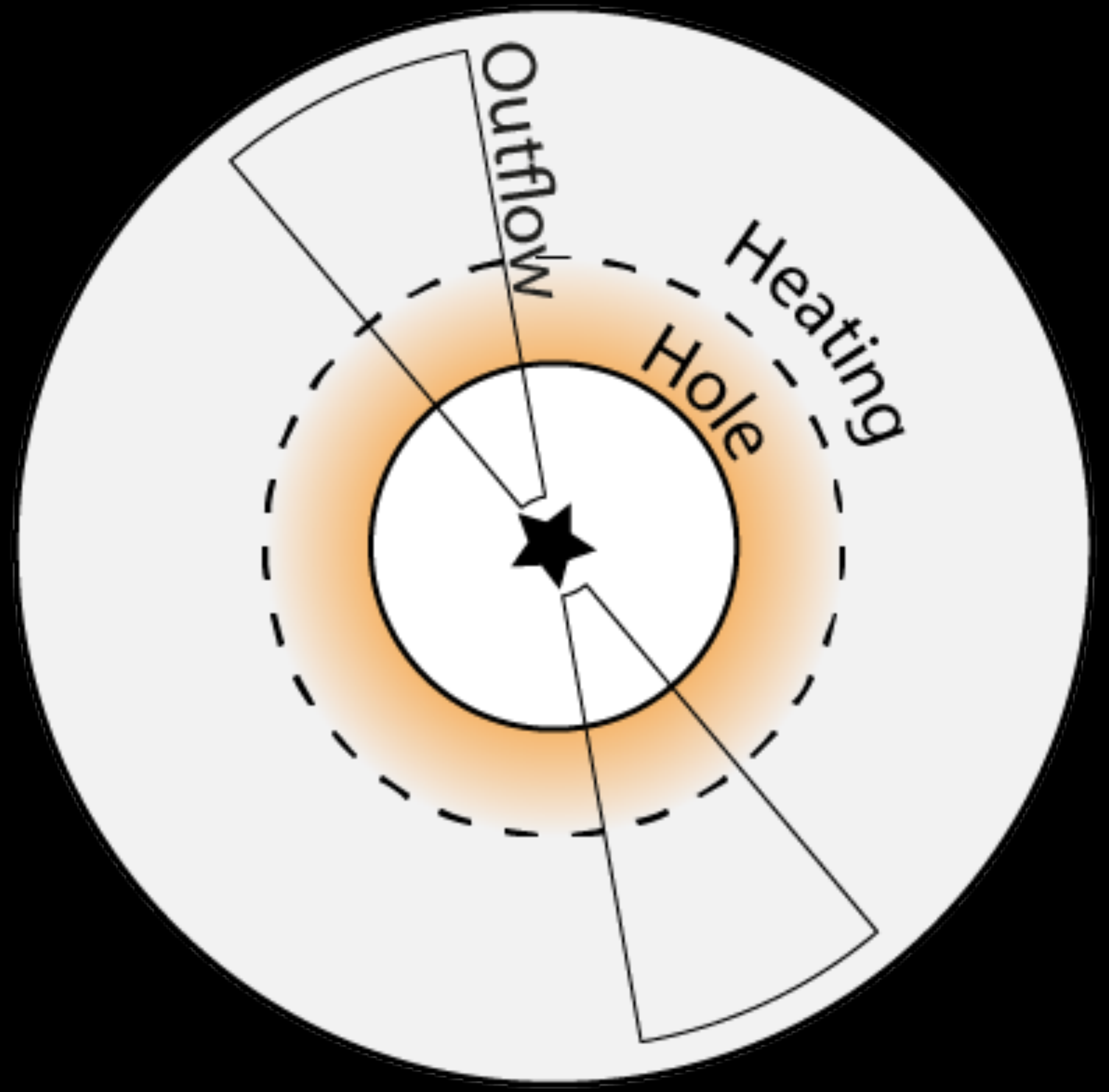


PART I: PROTOSTELLAR OBJECTS HOSTING CLASS II METHANOL MASERS

- Class II methanol masers: exclusive tracers of high-mass protostars
- Main transition at 6.7GHz, also at 12.2GHz
- Co-located with central protostar
- Pumped by IR re-radiation of strong UV from massive protostar

PART I: STAR FORMATION MASERS





[WARNING: Not all at the same time]

PART I: ANALYSIS

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PART I: DATA

Parkes detetction
ATCA accurate position
Parkes deep spectra

Methanol MultiBeam Survey (MMB)

~1000 6.7GHz class II methanol masers
Southern Galactic Plane

Survey: Green et al. 2009;
Data releases: Caswell et al. 2010, Green et al. 2010, Caswell et al. 2011, Green et al. 2012, Breen et al. 2015

Distances: Green & McClure-Griffiths 2011, Green et al. 2017

***Herschel* Infrared Galactic Plane Survey (Hi-GAL)**

70, 160, 250, 350, 500µm
Full Galactic Plane

Molinari et al. (2010a, 2010b, 2016 + priv. comm. for full GP catalogues)

Single-wavelength photometry catalogues

CuTEx extractions

General protostellar sample (Hi-GAL)

Elia et al. 2017
5497 with reliable distance

Galactic protostellar MYSOs hosting class II methanol masers

Compact source at 70, 160, 250, 350µm

647 objects

Excited-state hydroxyl masers (6035MHz)

MMB co-observed
Southern Galactic Plane

Avison et al. 2015

Survey: Dawson et al. 2014;
Positions: Qiao et al. 2016, 2018

Ground-state hydroxyl masers (SPLASH)

Untargeted
$334^{o} < l < 344^{o}$
$355^{o} < l < 5^{o}$

12.2GHz class II methanol masers

MMB targeted follow up
Southern Galactic Plane

Breen et al. 2012a, 2012b, 2014, 2016

H_2O Southern Galactic Plane Survey (HOPS)

Untargeted water masers
Low sensitivity
~Southern Galactic Plane

HOPS: Walsh et al. 2011, 2014;
Association with MMB: Breen et al. 2018

Titmarsh et al. 2014,2016 water masers

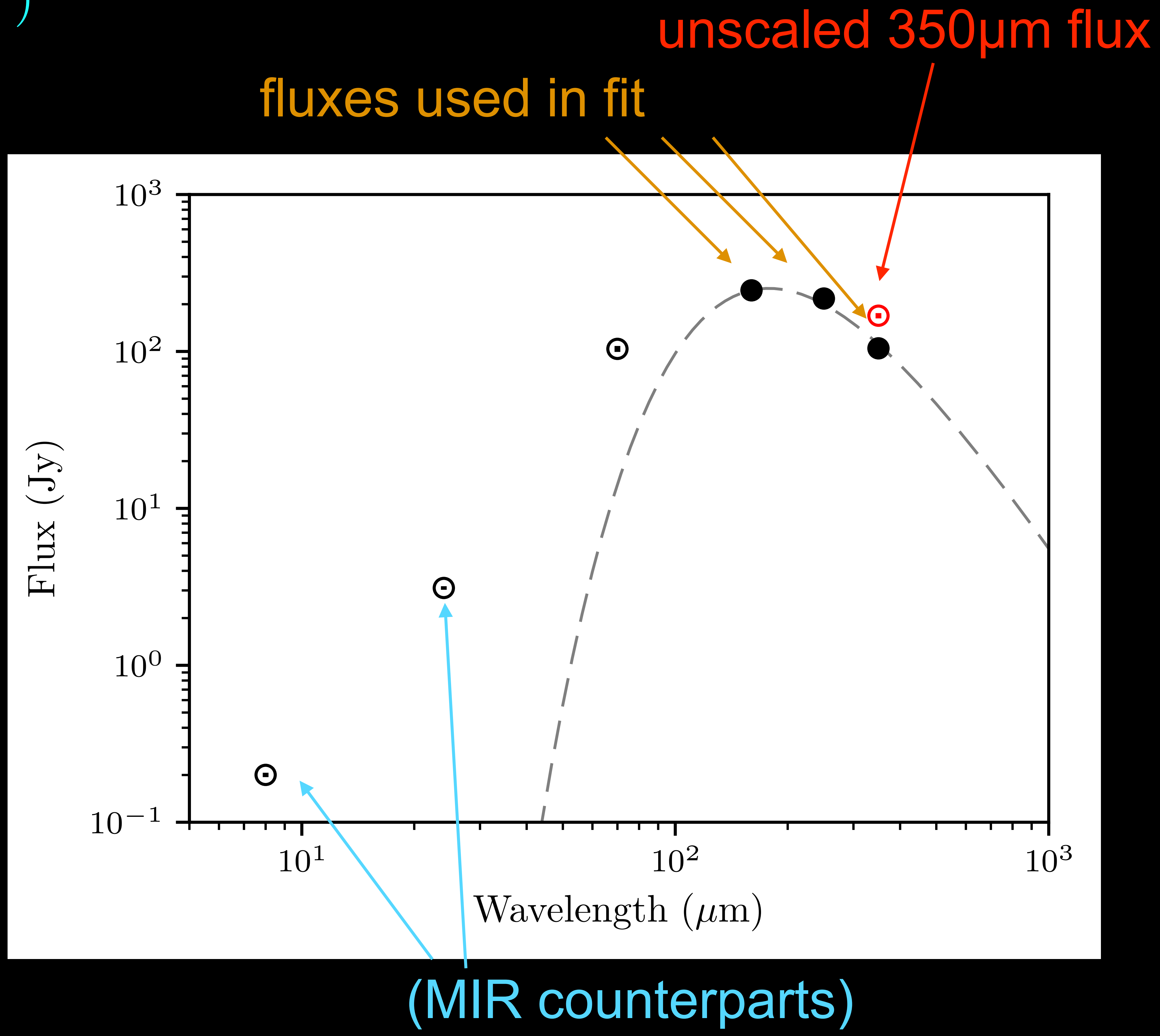
MMB targeted
High sensitivity
$341^{o} < l < 20^{o}$

Titmarsh et al. 2014, 2016

PART I: DERIVATION OF FIR PROPERTIES

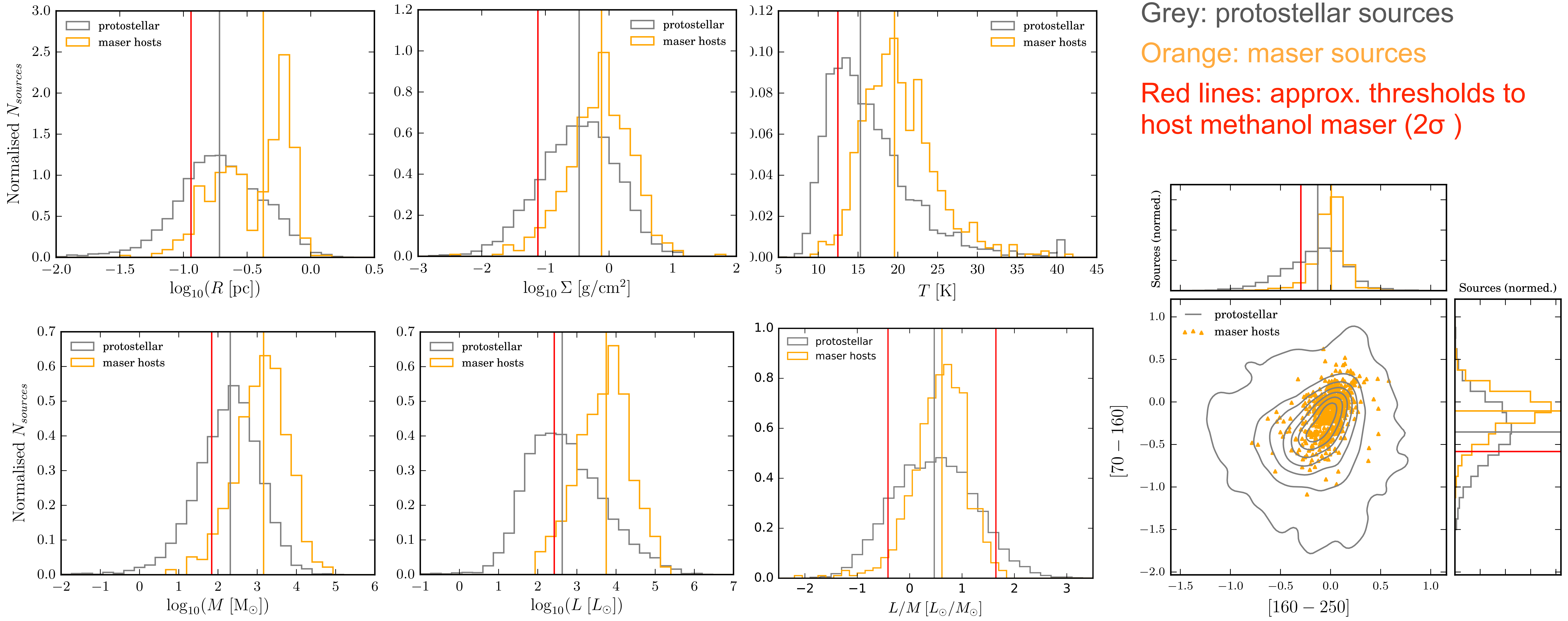
$$S_\nu = \frac{M}{d^2}\kappa_0\left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$$

- Single temperature modified blackbody (spectral index 1.8)
- Unresolved at 350microns, scale: $F_\nu^{SED} = F_\nu \times \frac{FWHM_{250}^{dec}}{FWHM_\nu^{dec}}$
- FIR luminosity: integrated between 70 and 500 microns
- Fit to obtain mass surface density and temperature
- Noted inconsistencies with other work: reference dust mass opacity, spectral index - end up negligible during comparisons



PART I: MANY HISTOGRAMS

On average, methanol maser hosts are more luminous (total and single band), hotter, more massive, steeper colour, higher mass surface density and occupy a narrower band in L/M than a general protostellar MYSO



Grey: protostellar sources

Orange: maser sources

Red lines: approx. thresholds to host methanol maser (2σ)

PART I: MANY COMBINATIONS

Usual spaces: mass-radius, mass- mass surface density, mass-luminosity…

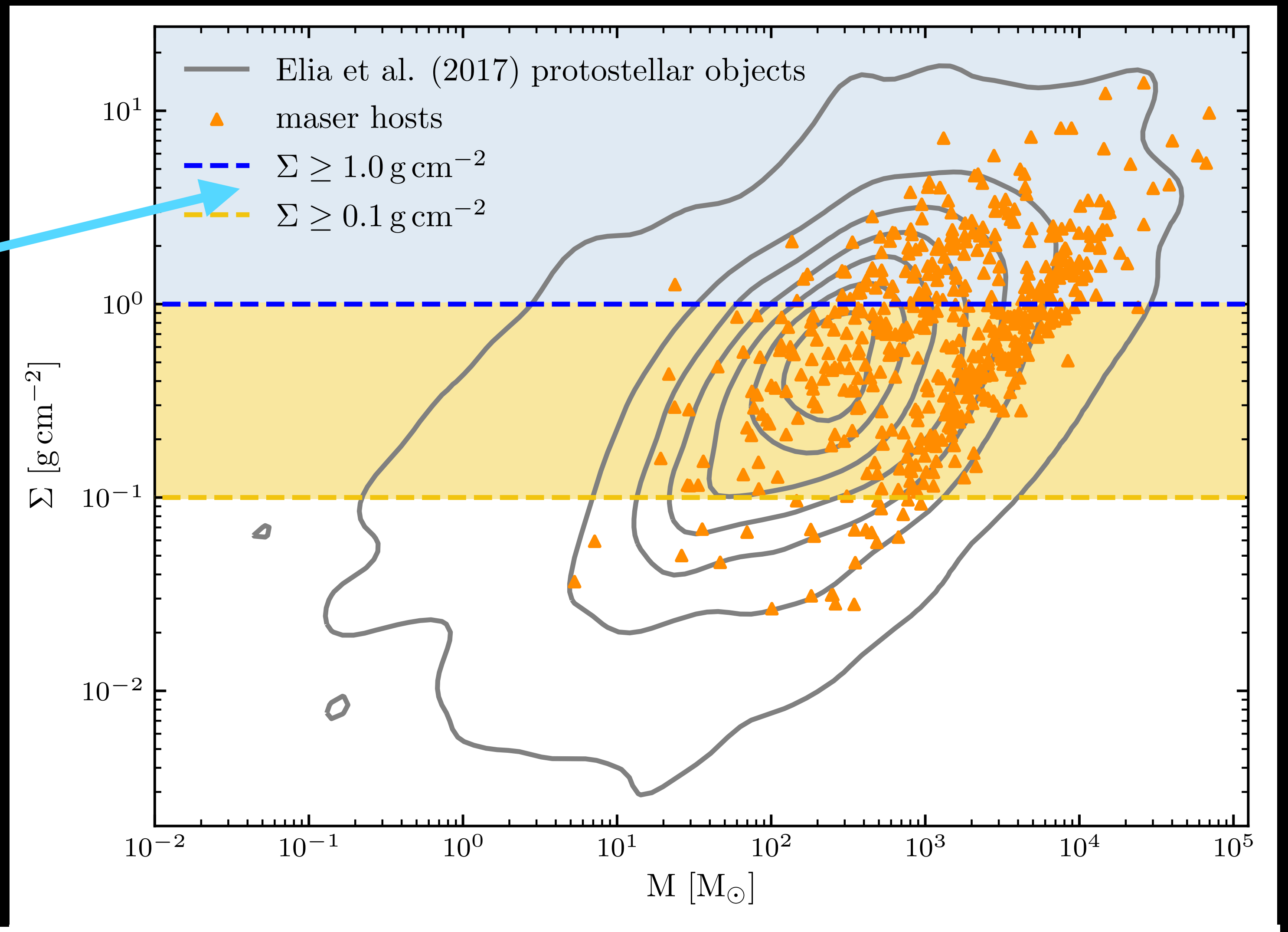
40% of maser sources above Σ=1.0g/cm²
(only 20% of protostellar sources)

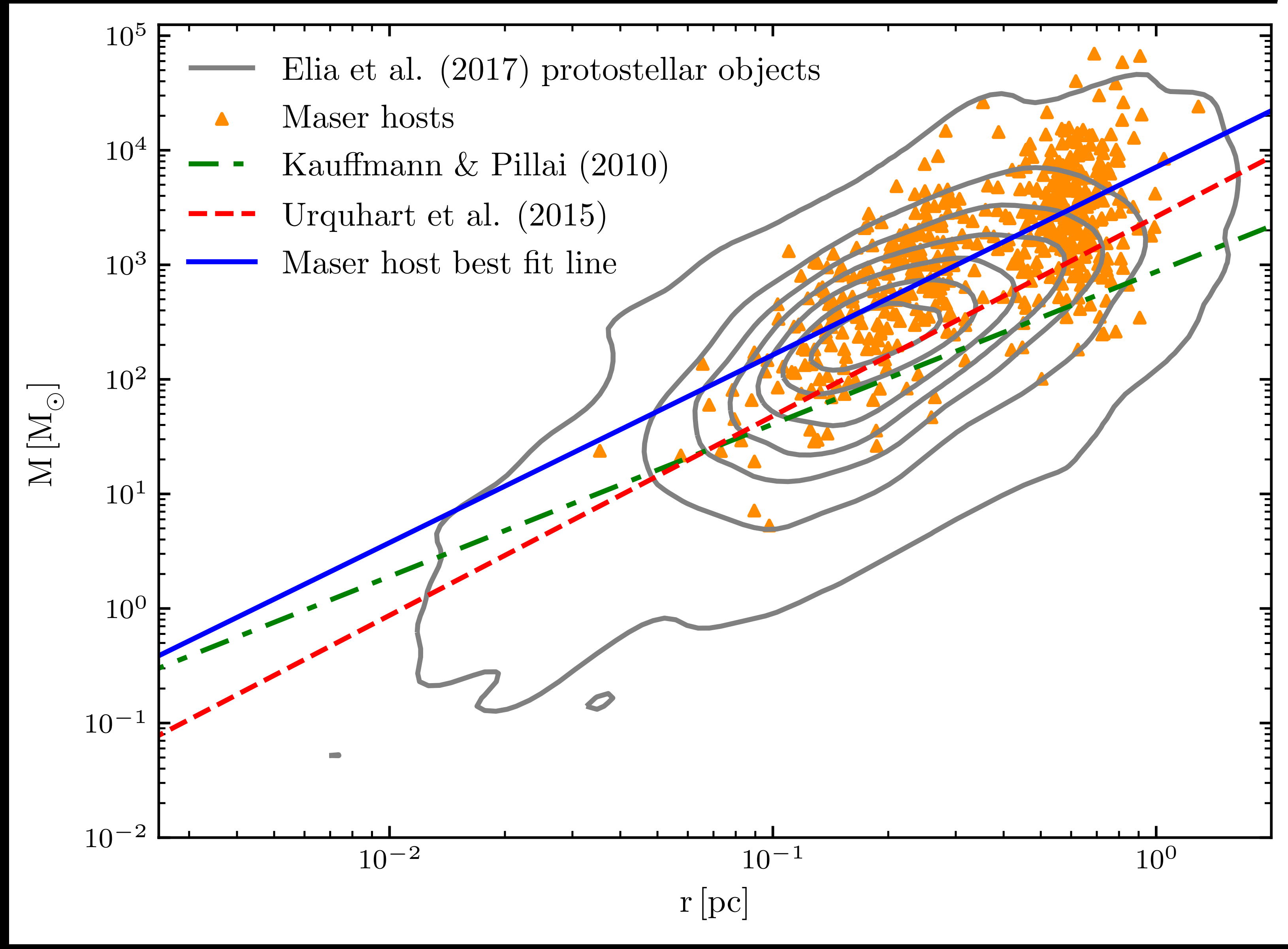
Line of best fit in M-R:

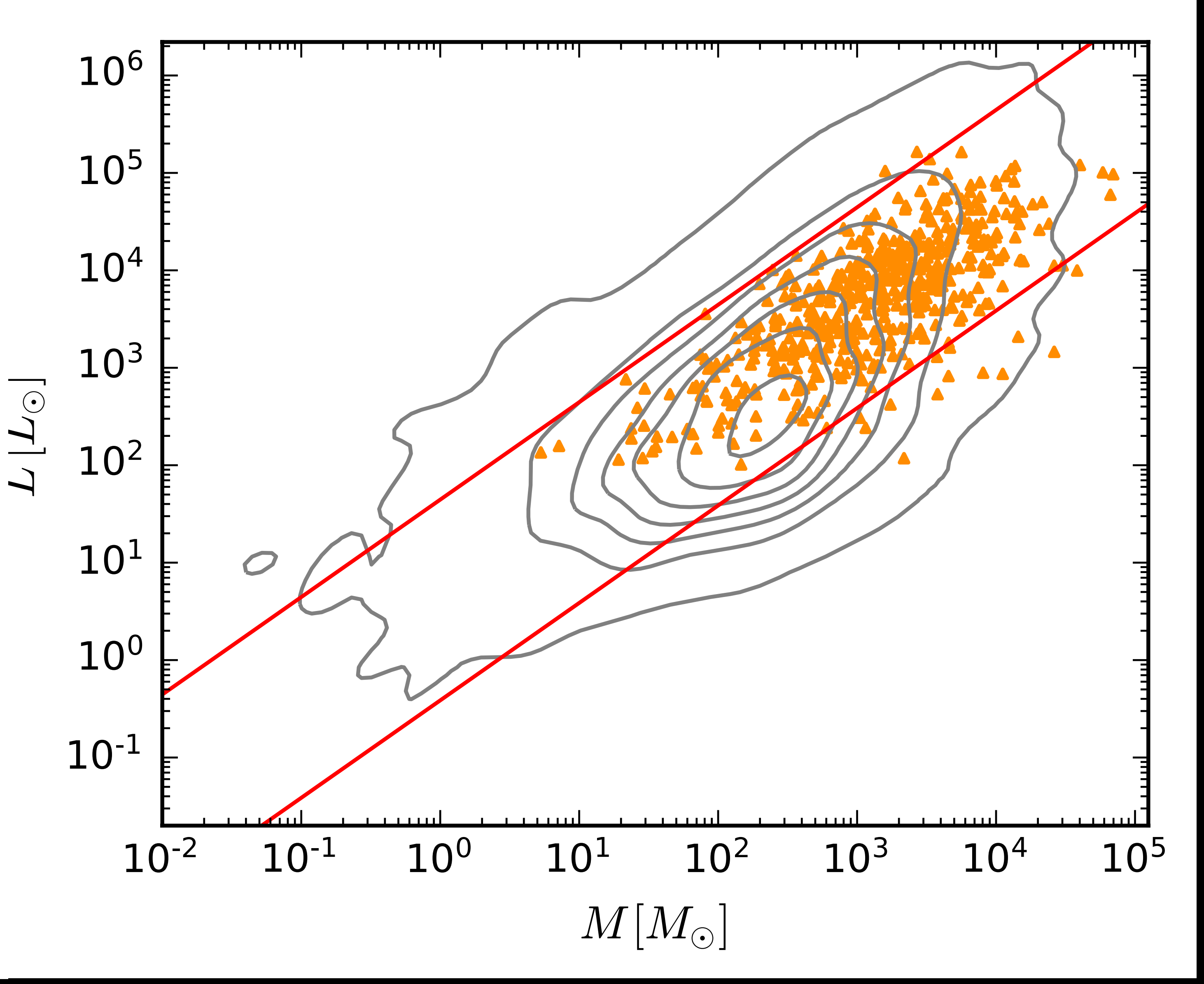
$$\log(M) = 1.64 \log(r) + 3.85$$

Reference comparison:
Urquhart et al. (2015)

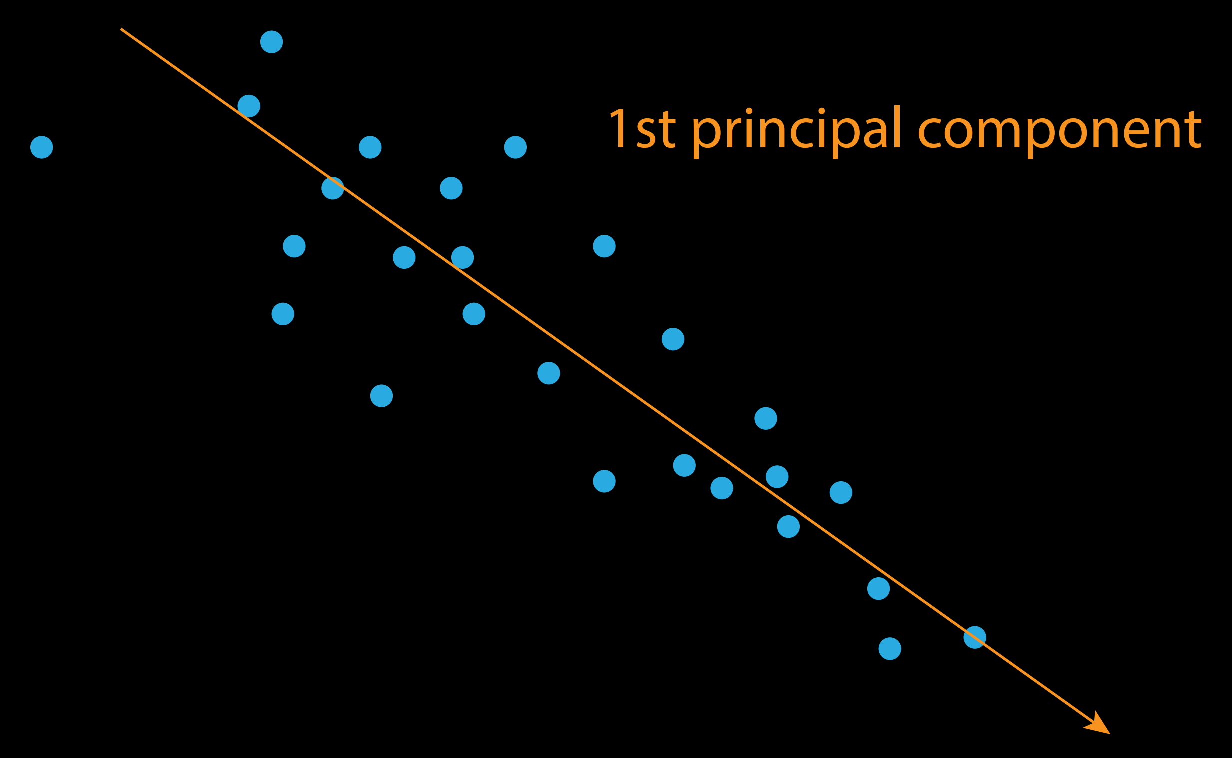
$$\log(M) = 1.74 \log(r) + 3.42$$







PART I: PRINCIPAL COMPONENT ANALYSIS



Mutual trends in multiple parameters

Example: increase in luminosity with size and temperature

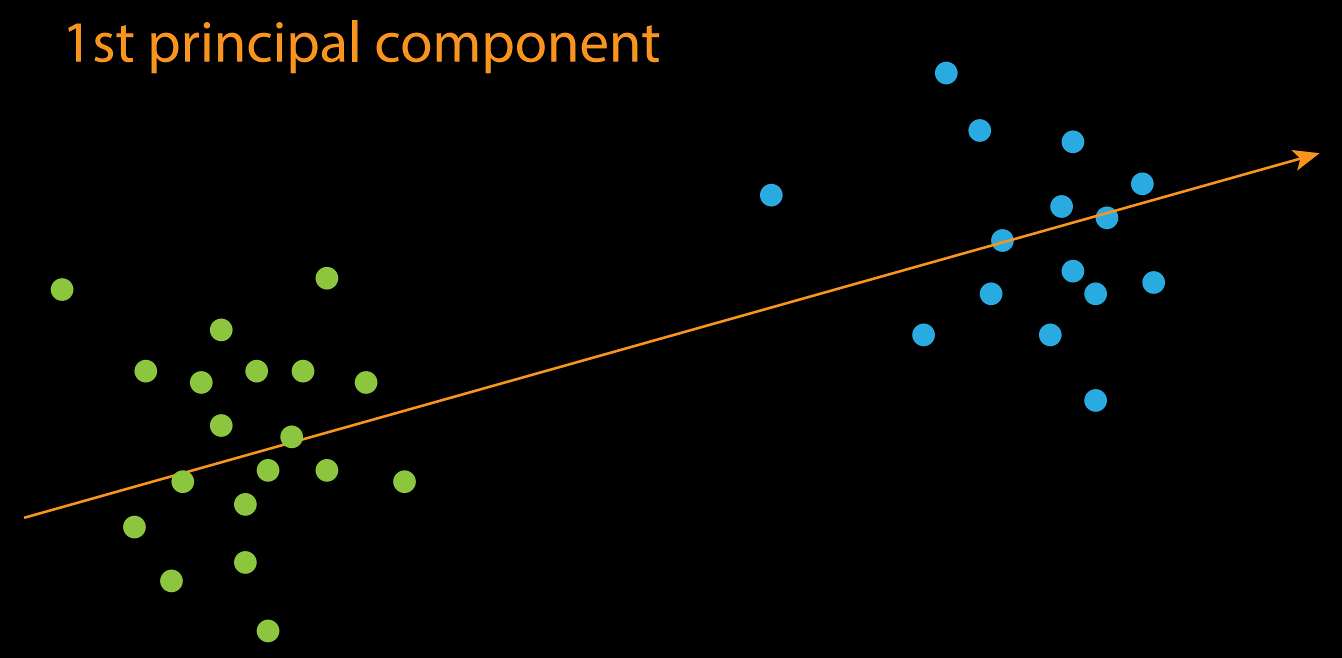
Intra-sample trend

- Reduce dimensionality of data by defining new variables that each account for a decreasing amount of total variance
- Can recover two types of trend

Separation of two distinct types of object

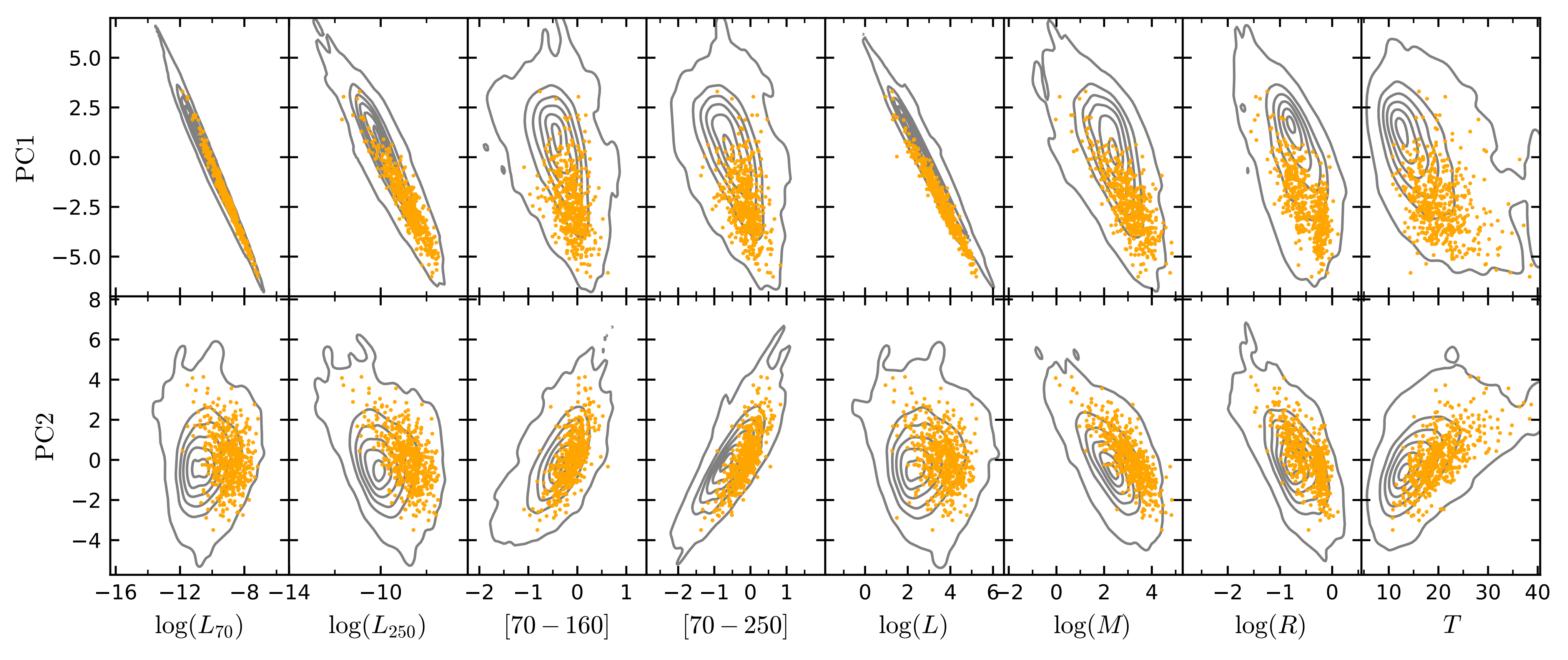
Example: different locations along an evolutionary trend

Inter-sample trend



PART I: PRINCIPAL COMPONENT ANALYSIS

Eight input properties: log(L70), log(L250), log(LFIR), [70-160], [70-250], log(M), log(R), T



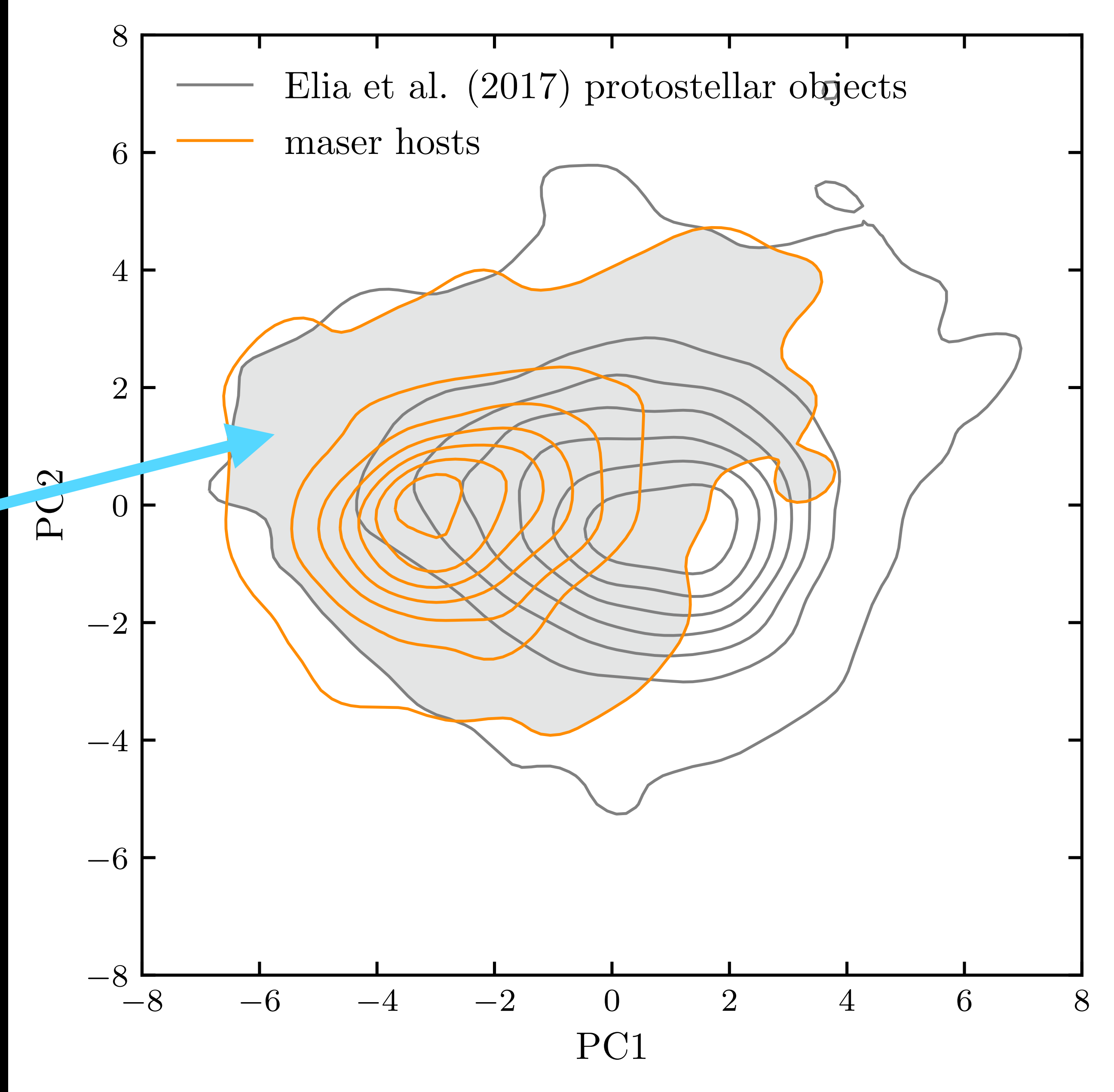
- **PC1: size trend** (*increase of each luminosity alongside M and R*)

- **PC2: evolutionary trend (***increase in 70μm emission with T, decrease in M and R)*

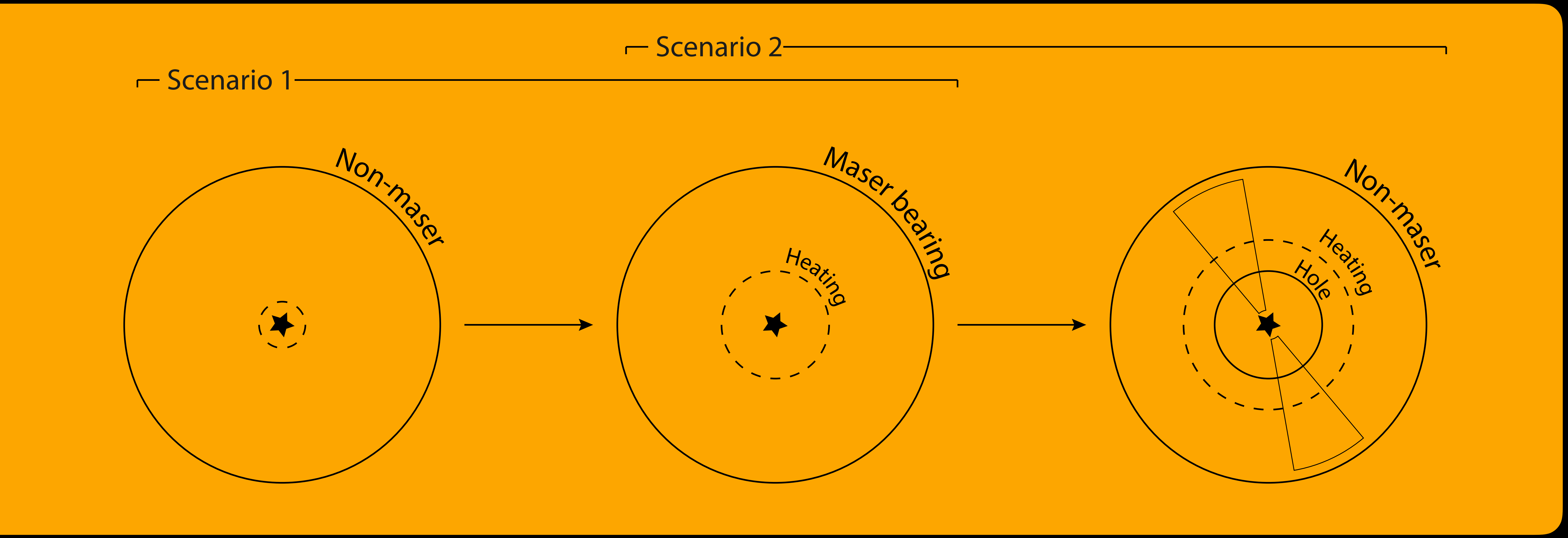
Intra-sample trends are stronger than offset between protostellar and maser objects

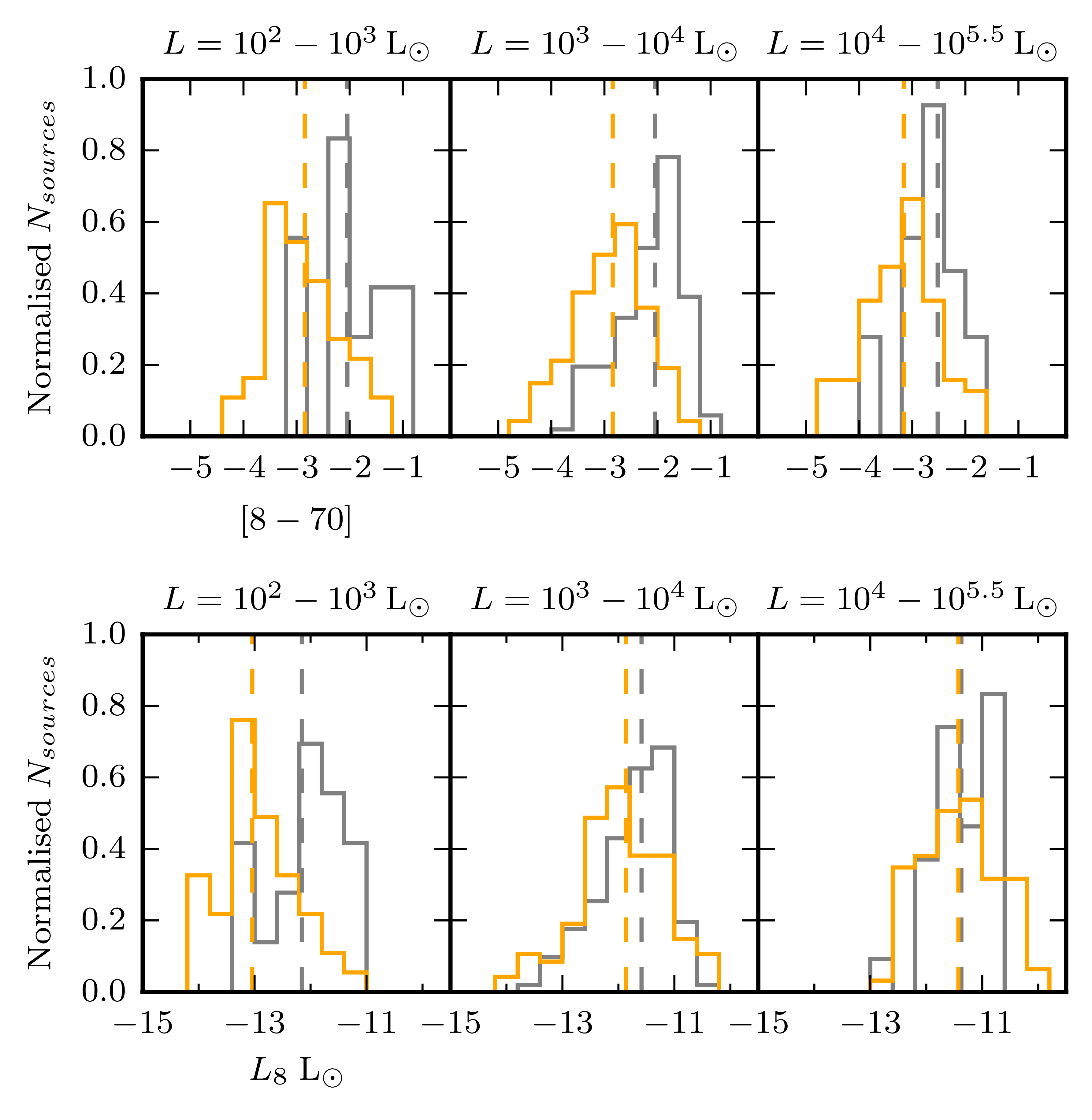
Overlap: **as many things don't have detected methanol masers as do, despite falling in the same clump parameter space**

In total, 896 matched "maserless" objects



PART I: PHYSICAL SCENARIOS





Mid-infrared:

Scenario 1: less visibility at 8μm (not enough heating)

Scenario 2: more visibility if more evolved (more heating, less dust, holes)

Spitzer GLIMPSE 8μm:

Higher percentage of non-maser objects assigned an 8μm counterpart, and stronger (relative to clump FIR luminosity)

PART I: SECONDARY MASERS

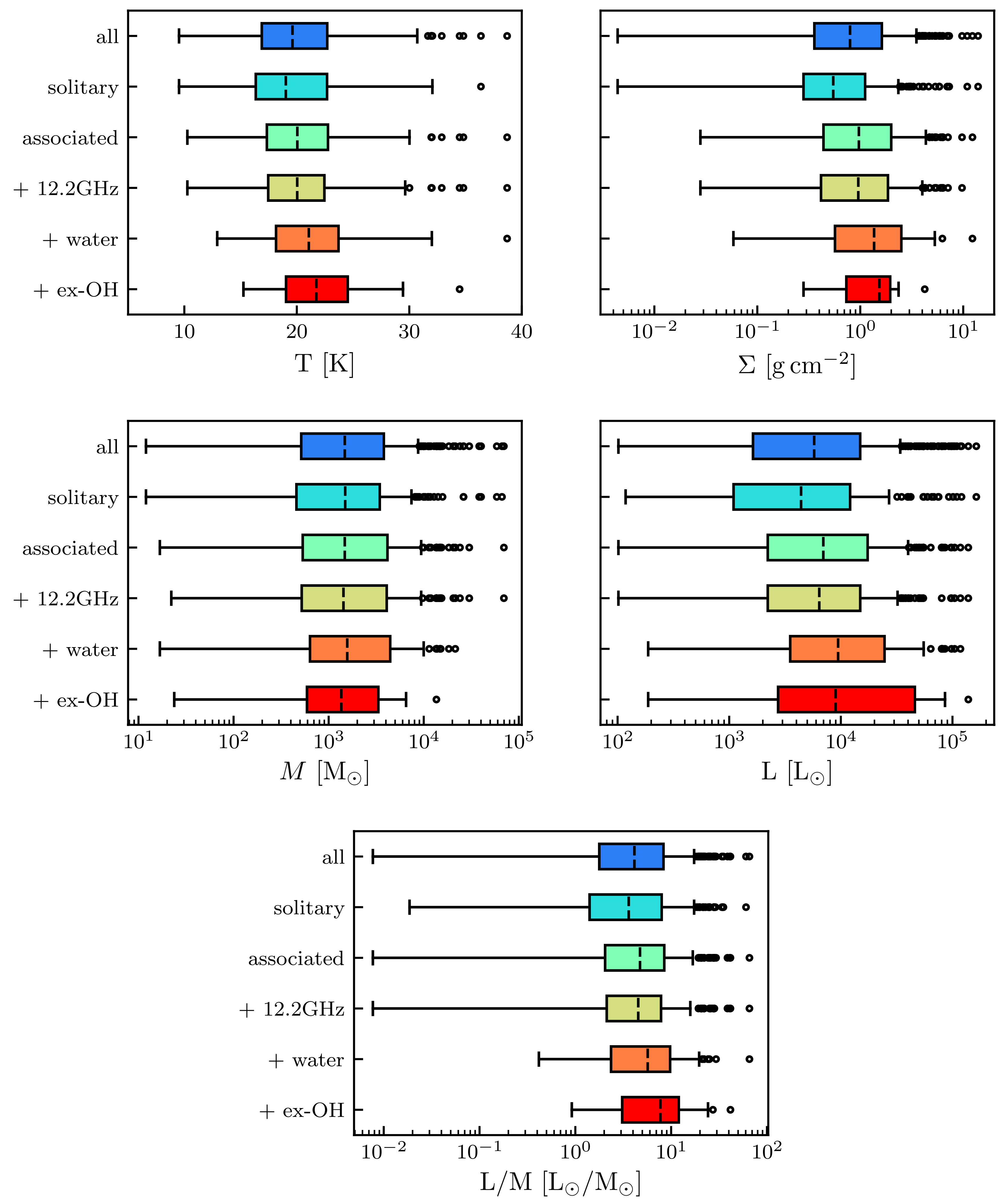
- Compare evolutionary state of each type of secondary maser through IR properties

- 6.7GHz masers with any type of secondary masers are generally more evolved

  - 12.2 have small ~1K temperature increase (borderline significance, see Breen et al. 2018 paper)

  - Hydroxyl masers: much more evolved (increased colour, temperature, L/M etc)

  - Water masers: greater L/M



PART I: TIMELINE OF SECONDARY MASERS

- Relative lifetime from fraction of 6.7GHz hosts also hosting each secondary maser
- Use average L/M for each secondary maser to determine offset
- Assumes masers are part of evolutionary sequence: switch on/off during **one** sub-phase of 6.7GHz masing

[WARNING: early stage analysis]

PART II: AN SMA/ALMA STUDY OF SDC24

- SMA: Study of objects along a single evolutionary path *(PI: Ya-Wen Tang, ASIAA)*
- ALMA: Study of mass assembly in cores, from clump to core scale *(PI: Alessio Traficante, IAPS-INAF)*
- Aim: Fully characterise an object with torturously comprehensive spectral coverage
- SDC24.013+0.488: very young object - precursor to association like SDC335*?

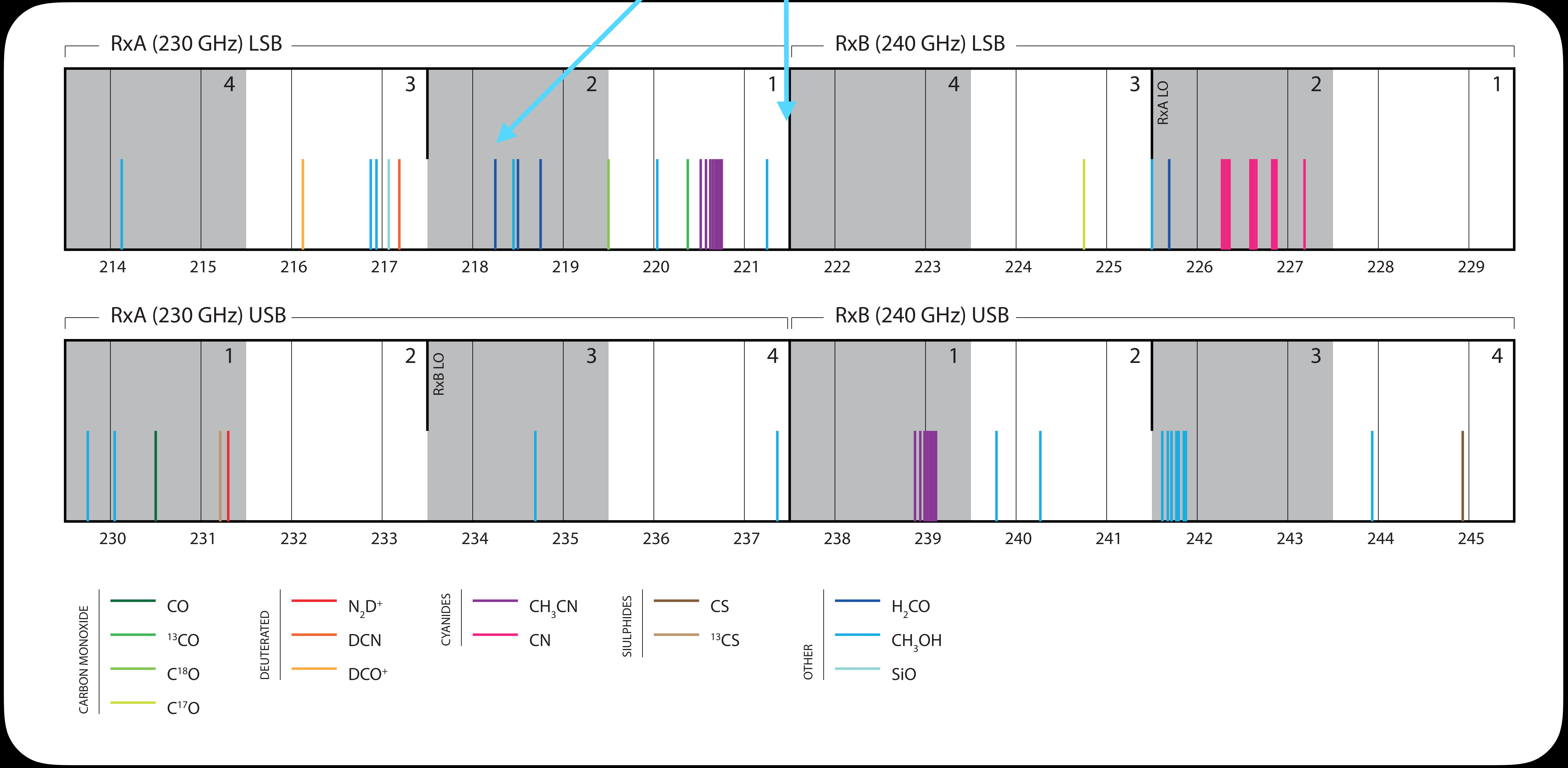
Source	d (kpc)	R (pc)	M ($M_\odot$)	n ($\times 10^4$ cm^{-3})	F_{70} (Jy)	∇v (km/s/pc)
SDC24	5.2	0.8	2700	2.2	<1	0.2
SDC18	4.6	0.8	2500	2.0	31	0.7
SDC335	3.3	0.6	2600	5.0	792	1.1

**Michael Anderson's talk on hub-filament systems*

PART II: DATA

ALMA PI: Alessio Traficante, 13 sources at ~1.5″ resolution, 12m+ACA+TP

+ band 3 HCN, HCO+ H13CO+

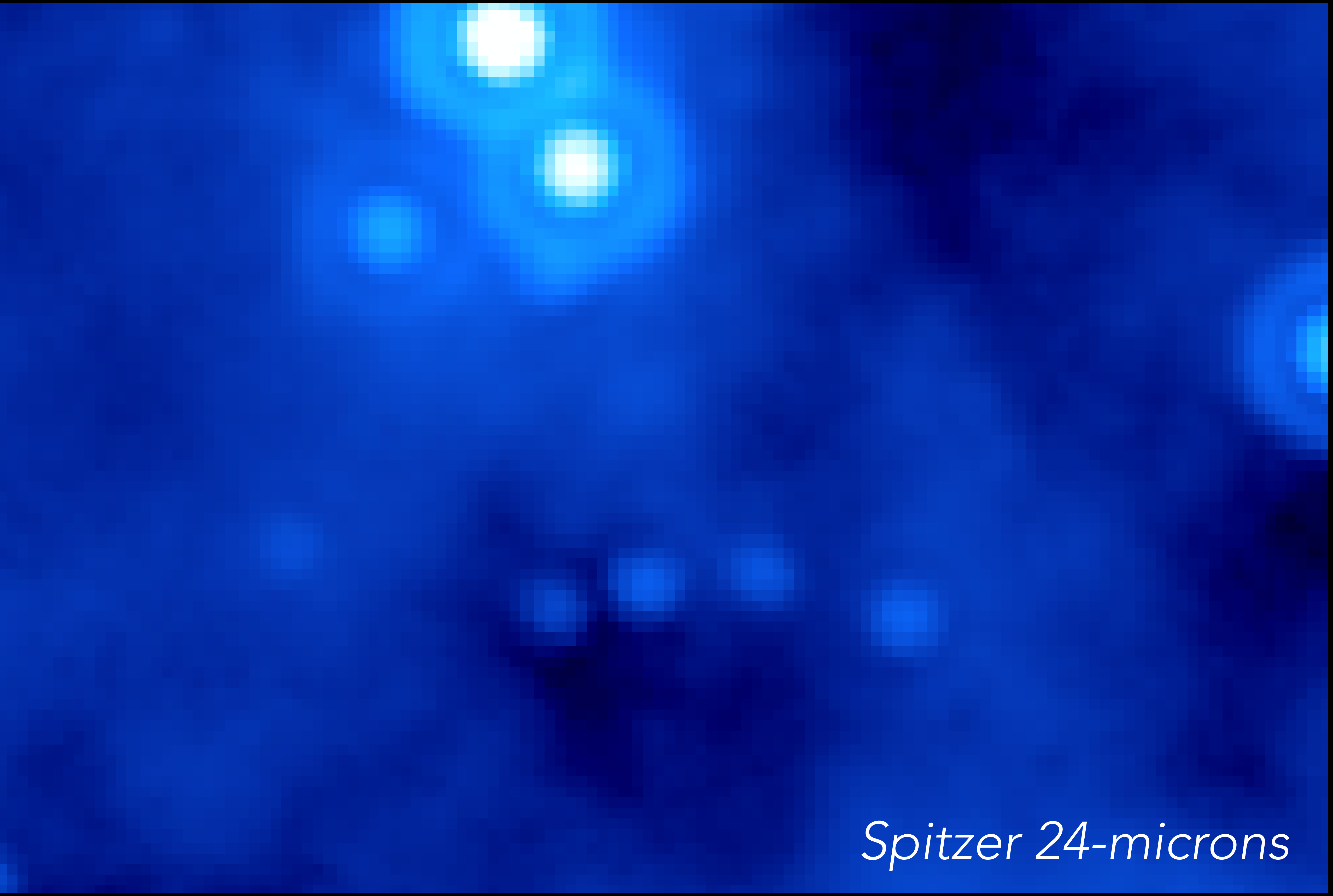


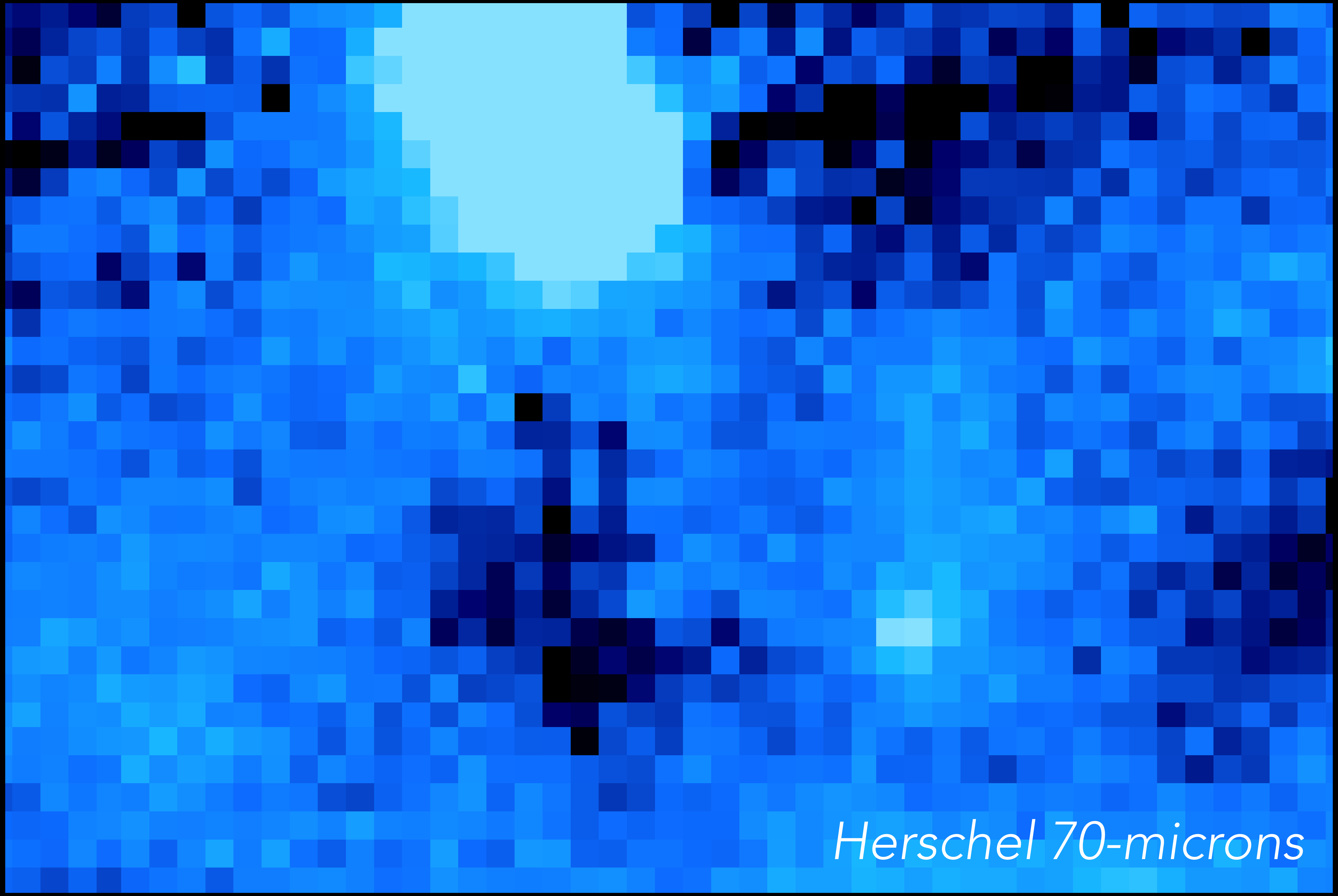
SMA PI: Ya-Wen Tang (ASIAA)

3″ (0.1pc) resolution from compact + subcompact tracks, 0.6mJy/beam sensitivity

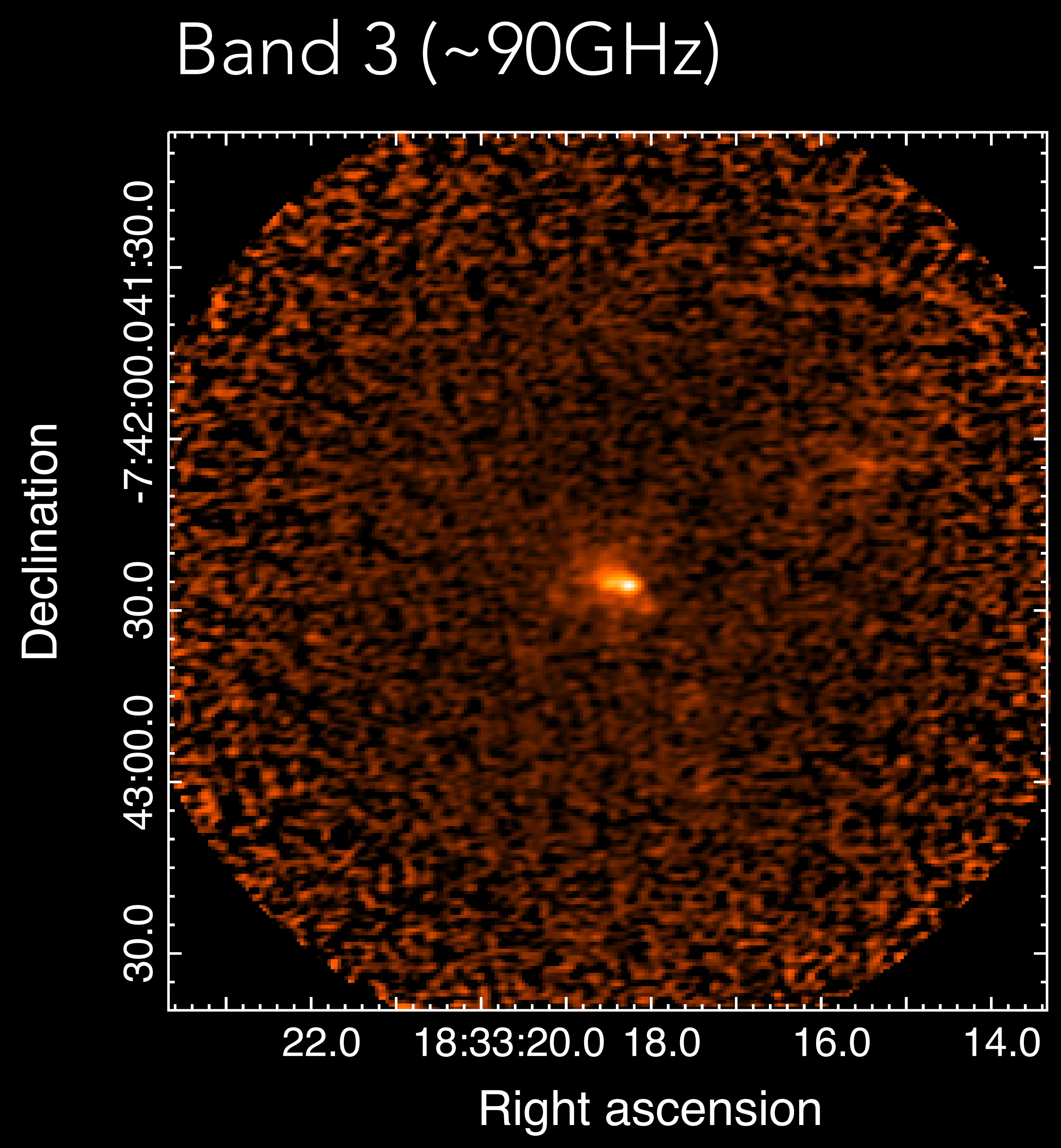
"SDC24 is really boring"

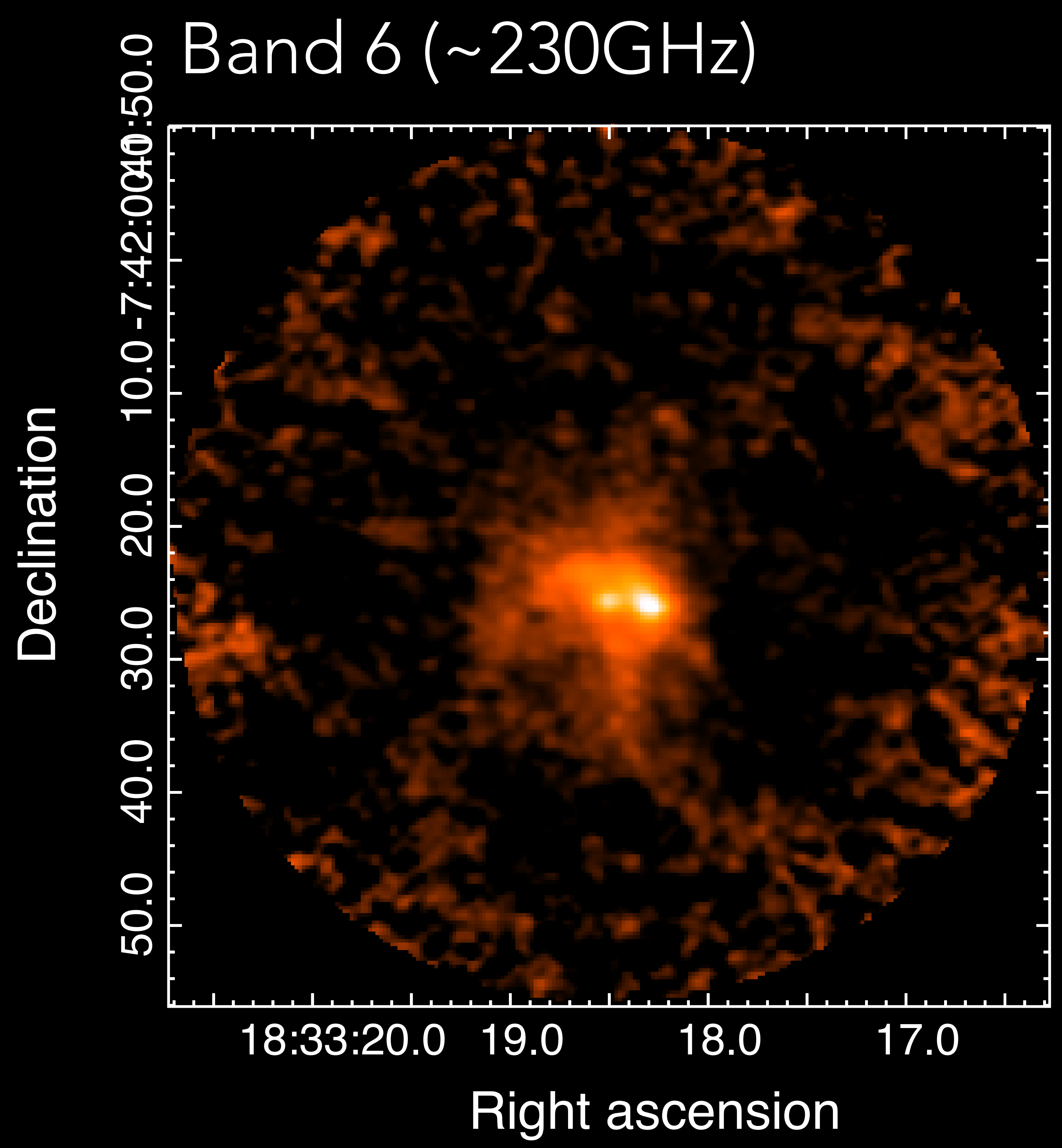
–BETH JONES (2016)





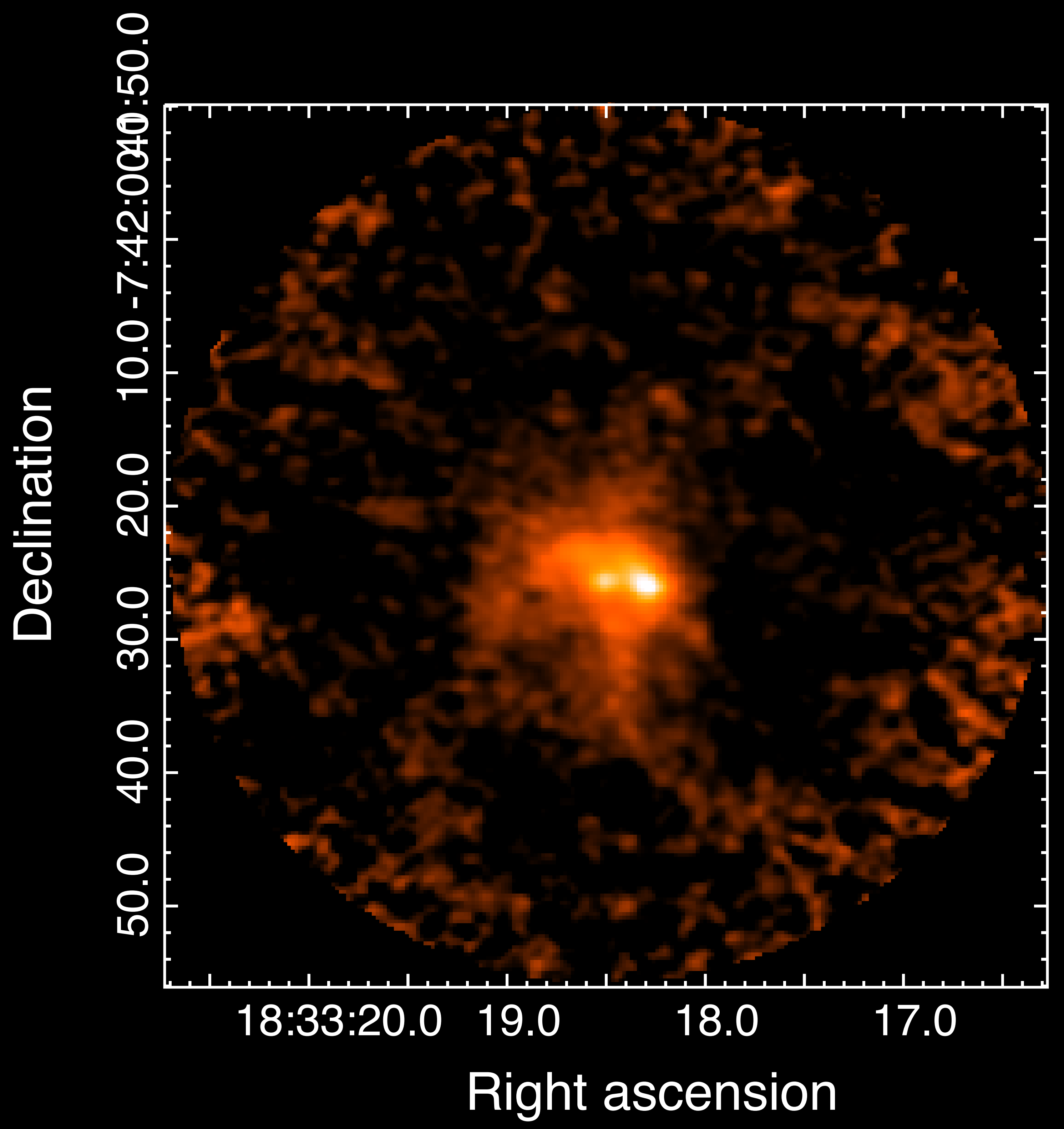
PART II: CONTINUUM CORES

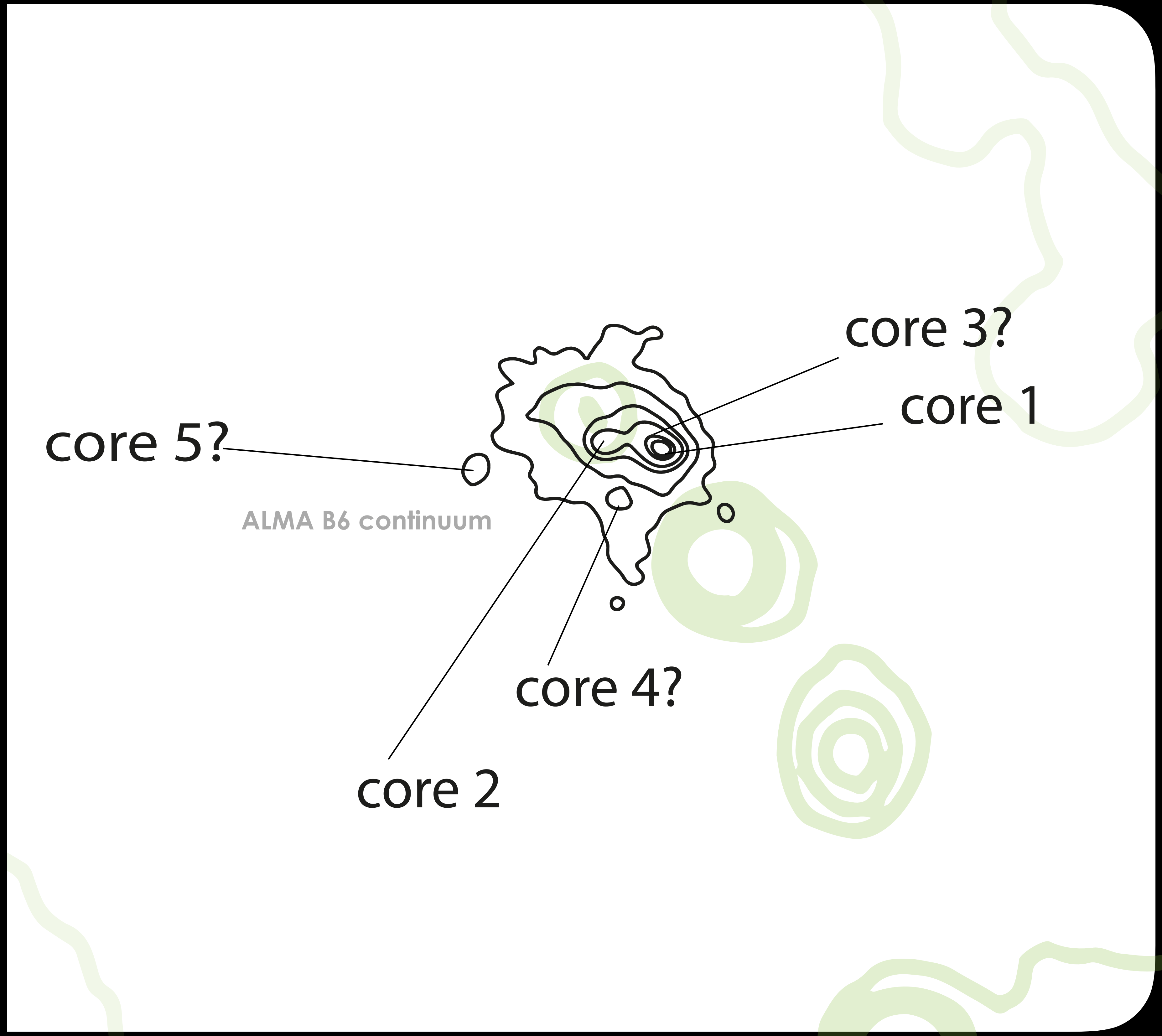




- Only two bright cores
- Filament in weak continuum
- Elongation of core 1: core 3
- Tentative hints of cores 4 and 5

PART II: CONTINUUM CORES



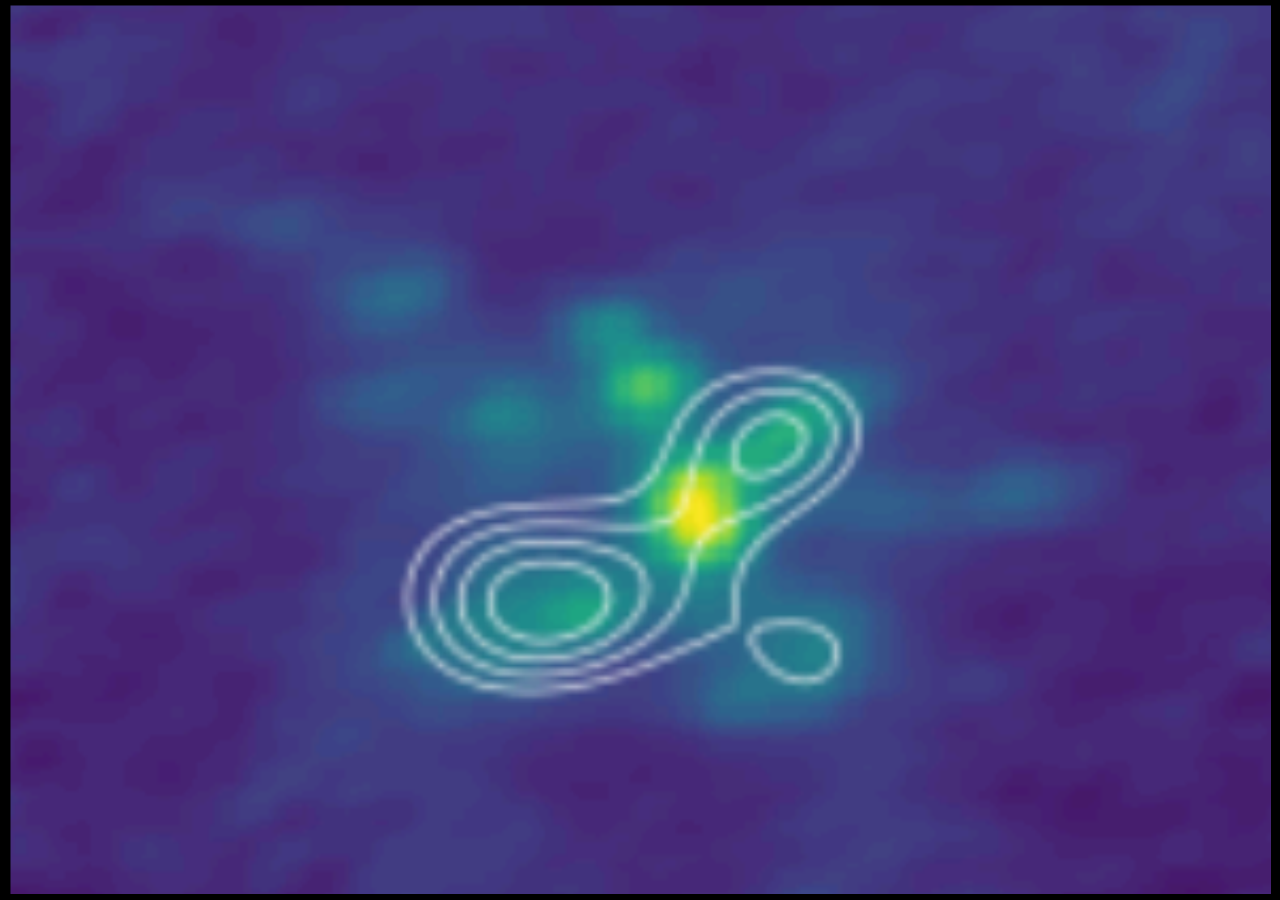


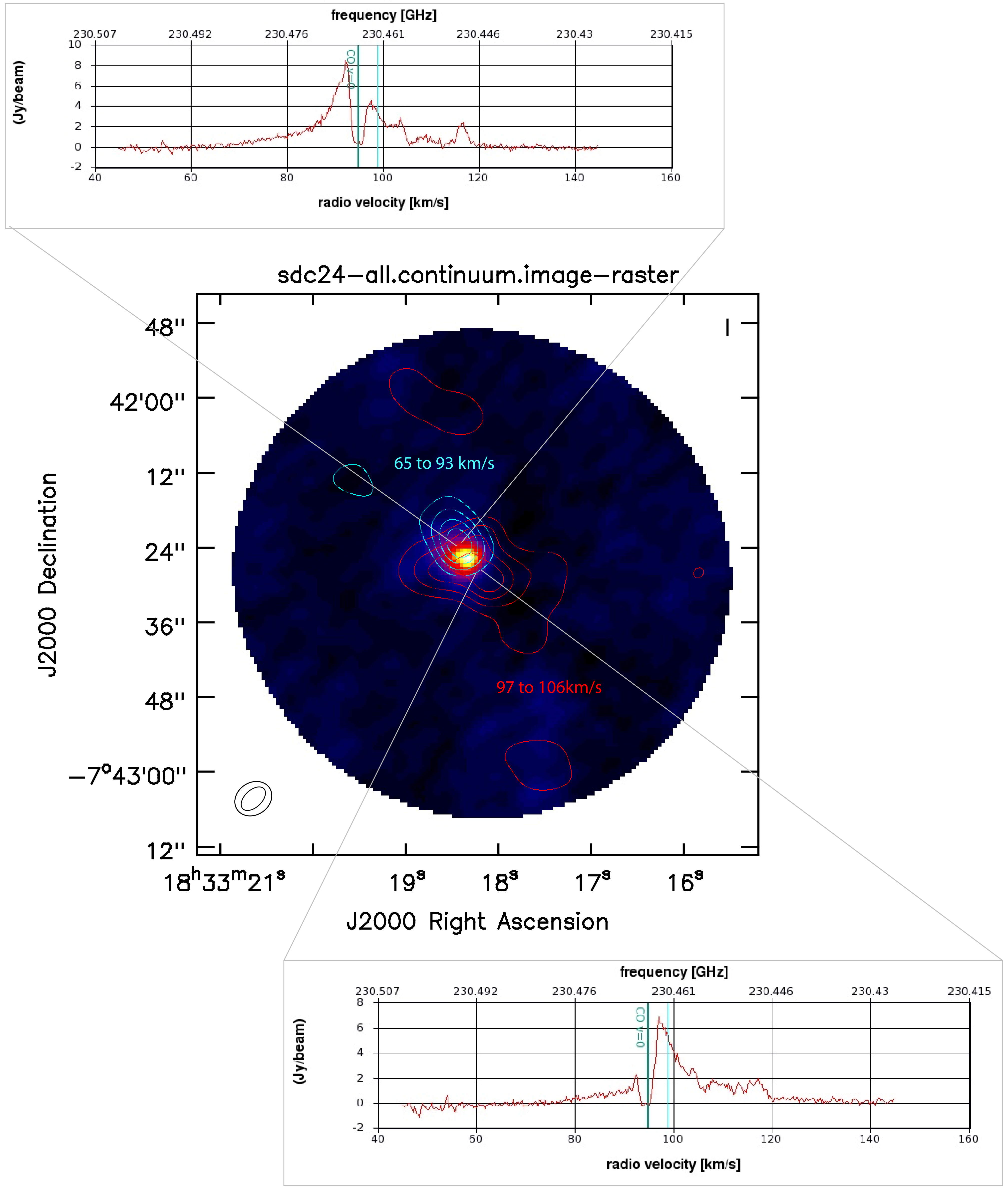
- Only two bright cores
- Filament in continuum
- Elongation of core 1: core 3
- Tentative hints of cores 4 and 5
- Core finding in uv space (UVMULTIFIT, Nordic ARC Node; *Avison et al., in prep*)

MIPSGAL 24 microns

PART II: CO

- Spectrum from SMA: an outflow!
- Maps from ALMA: oh no…
- Not entirely unexpected: SiO with SMA



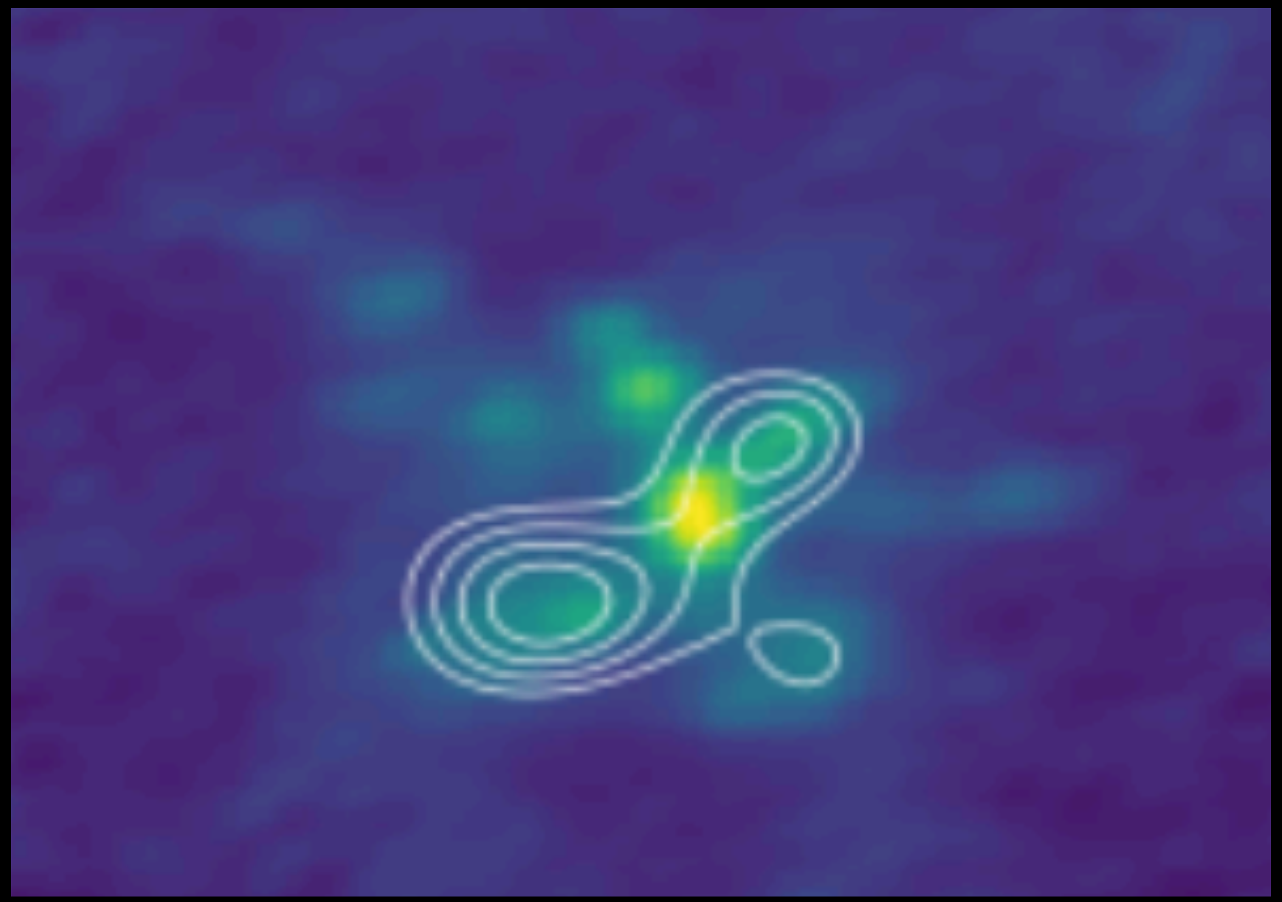


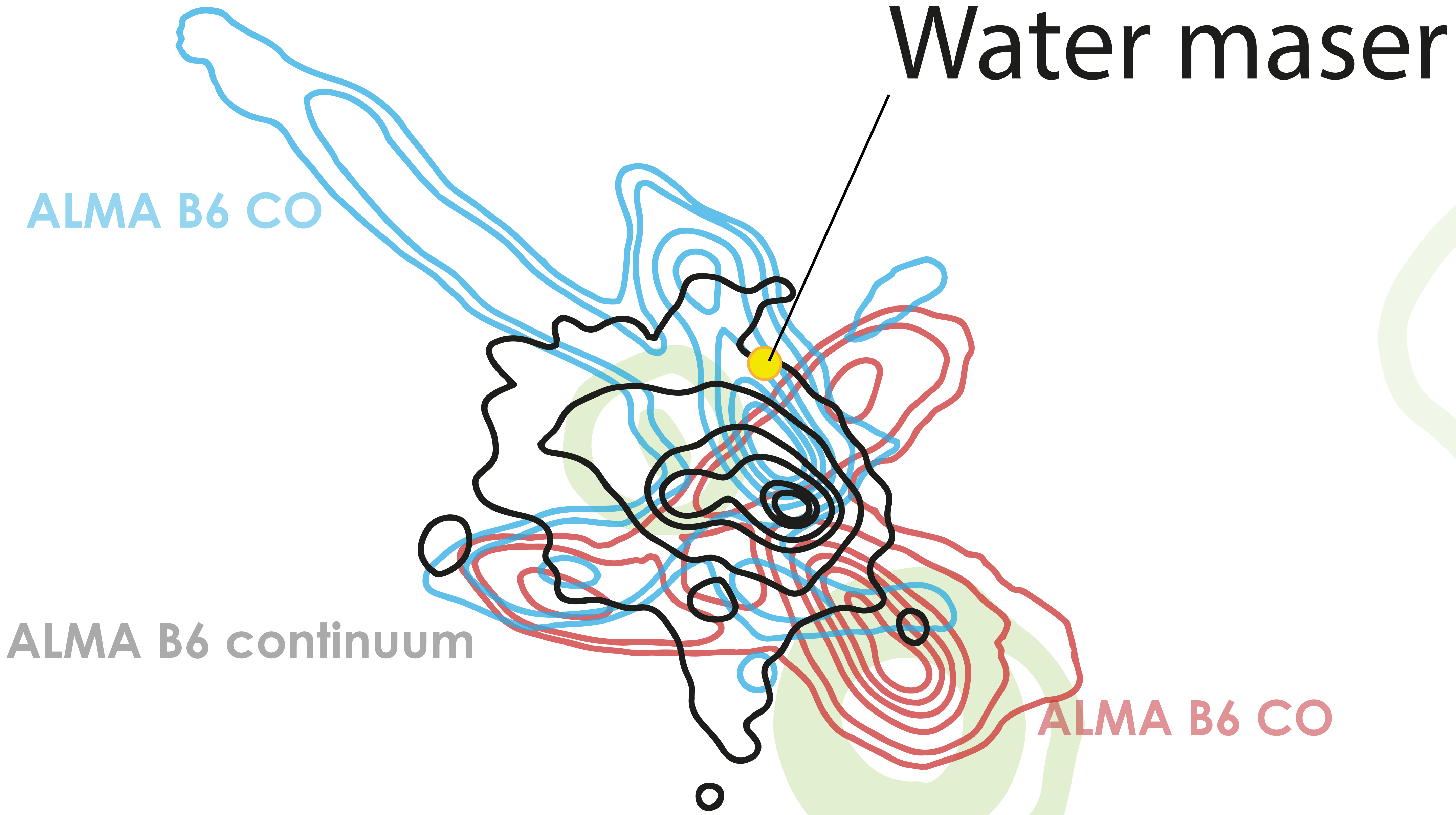
SDC24 in CO with SMA (background image: continuum)

Continuum beam: 4.67*2.76 arcsec, -46.7deg
CO beam: ~5*5 arcsec
Velocity resolution: 0.25km/s
Blue contours: integrated emission from 65 to 93 km/s
Red contours: Integrated emission from 97 to 106km/s

PART II: CO

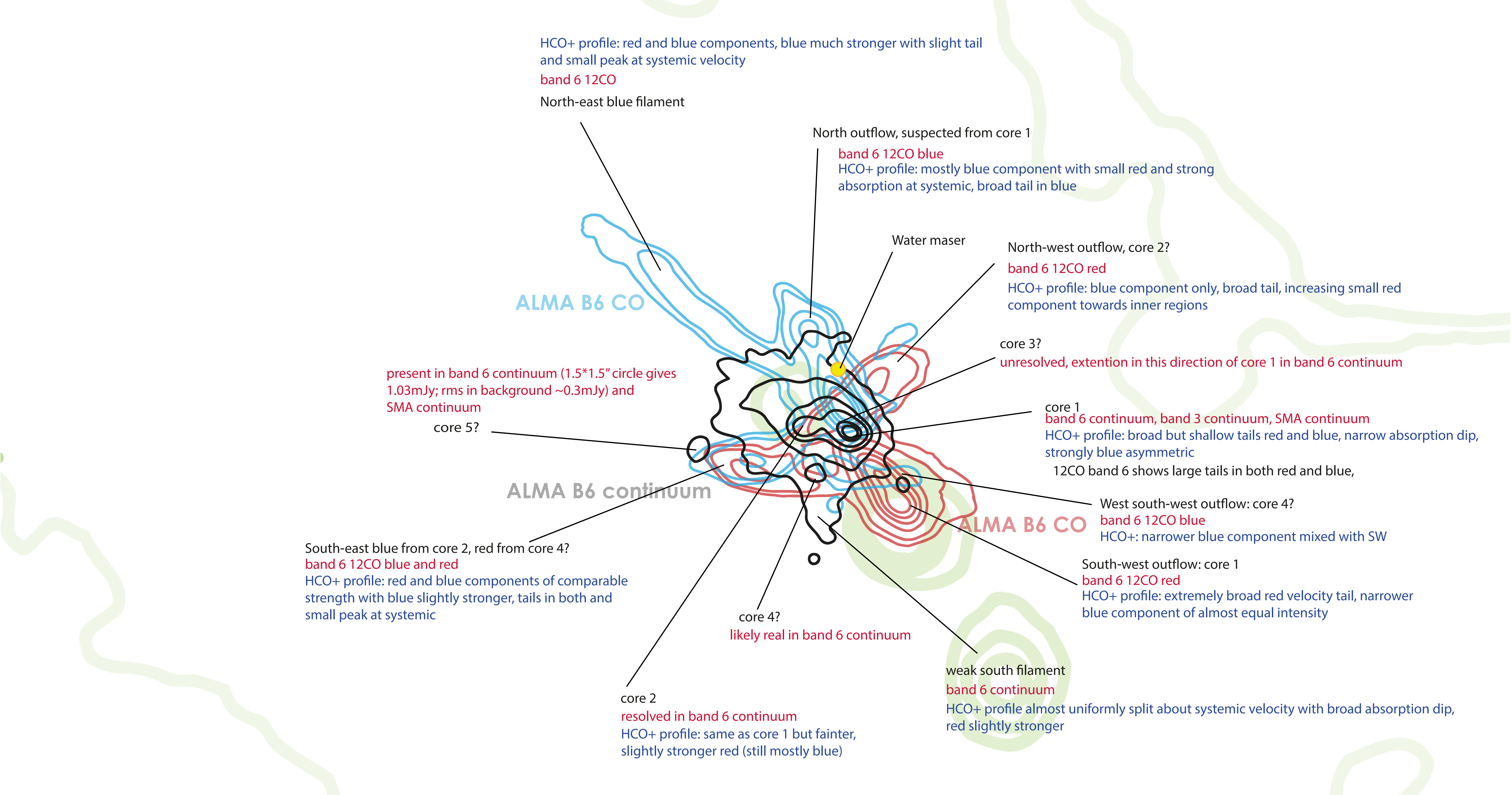
- Spectrum from SMA: an outflow!
- Maps from ALMA: not just one…
- Not entirely unexpected: SiO with SMA





“SDC24 is super complicated”

–ALESSIO TRAFICANTE (2016), BETH JONES (2019)



PART II: GOING FORWARDS...

- Outflow analysis: SDC24 -> SDC28 and SDC31 *(B. Jones++ (2019, in prep.) and A. Avison++ (2020?))*
- SDC18: spectral analysis from SMA data -> wSMA with 64GHz bandwidth
- Fragmentation *(Traficante++, in prep.)*, infall/mass assembly, ALMAGAL...

CONCLUSIONS

- Characterised the properties of 647 protostellar MYSOs hosting 6.7GHz masers
- Identified differences with general Galactic protostellar population, but also found a set of 896 objects that could also host a methanol maser
- **Favour the scenario that these protostellar clumps lacking a methanol maser are more evolved***
- Selection of an "early stage" source from 70micron maps shows several young protostars already with outflows underneath.
- **Interferometric observations are required to fully define the evolutionary state of a clump - the underlying complexity may not be obvious from larger scale tracers**

(THAT WAS THE LAST SLIDE... YOU WENT TOO FAR)