Formation of Clusters containing High-Mass Stars

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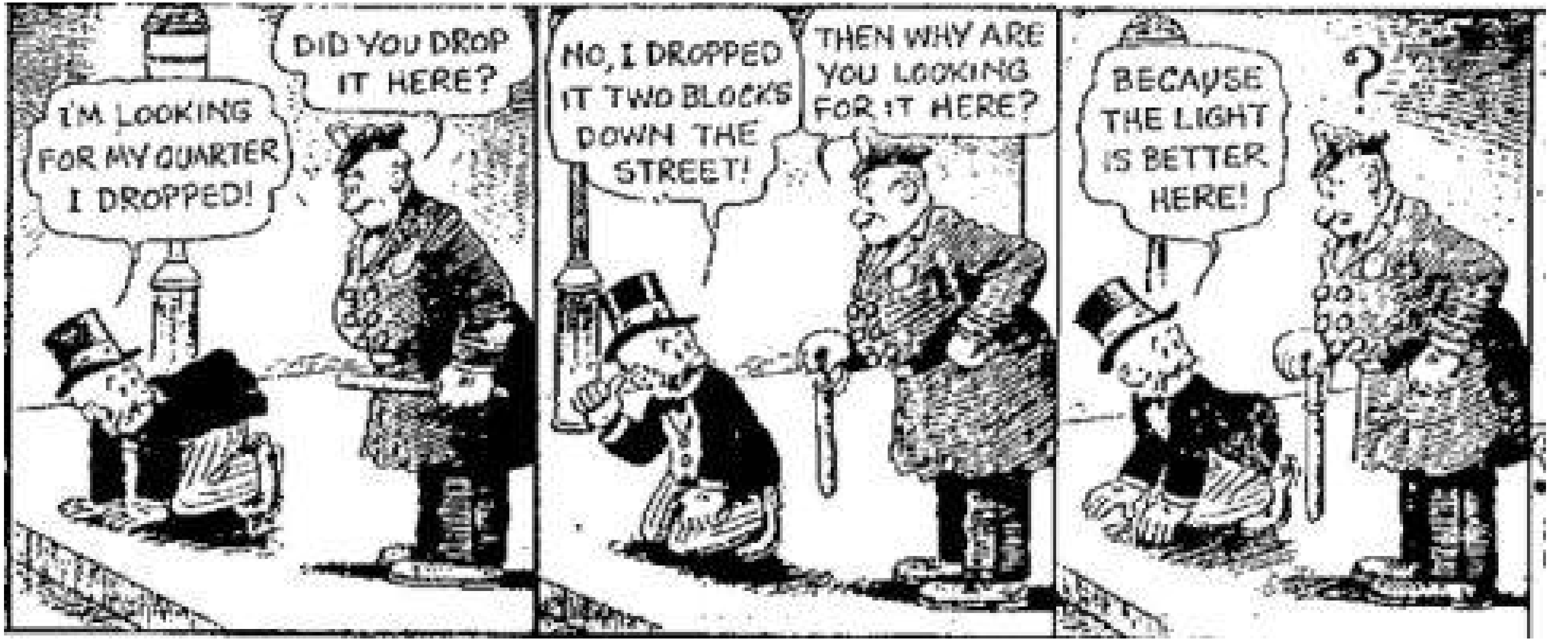
with input from Mahya Sadaghiani, Atefeh Aghababaei, Benedikt Helmstaedter, Niraj Kandpal and Álvaro Sánchez-Monge

Old joke



I'M LOOKING FOR MY QUARTER I DROPPED!
DID YOU DROP IT HERE?
NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!
THEN WHY ARE YOU LOOKING FOR IT HERE?
BECAUSE THE LIGHT IS BETTER HERE!
?

Old science

I AM TRYING TO UNDERSTAND HOW STARS FORM
DO THEY FORM AS SINGLE STARS, HERE?
NO, MOST STARS FORM IN CLUSTER, OVER THERE.
THEN WHY DO YOU LOOK AT SINGLE STARS?
BECAUSE THEY ARE CLOSER AND EASIER TO OBSERVE.
?

Which fraction of stars form in clusters with high-mass stars?

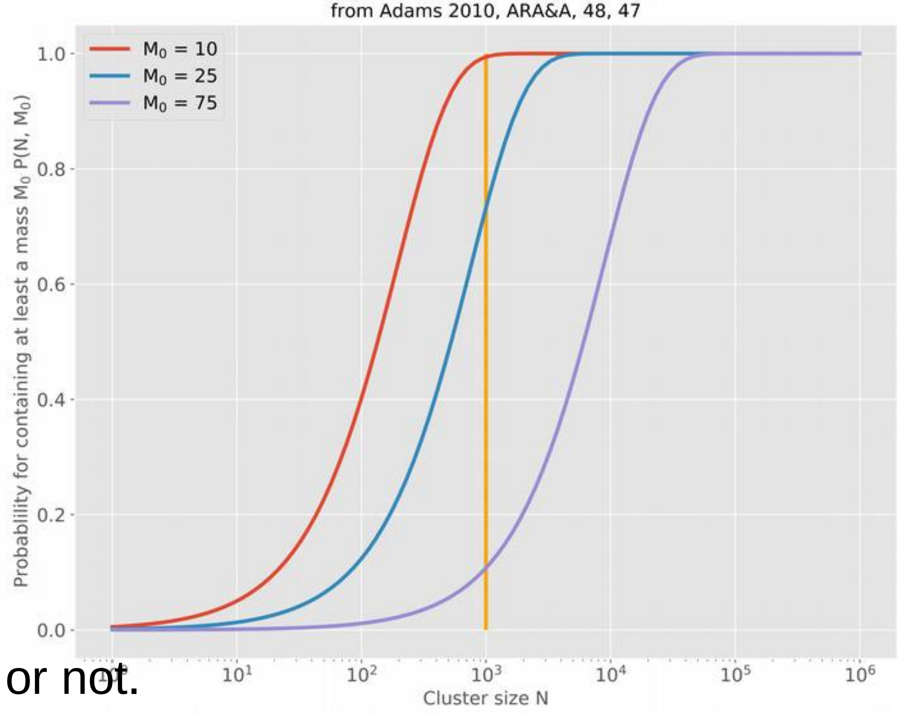
Probability of star coming from a cluster with N members $\frac{dP}{dN} \propto \frac{1}{N}$ (following Adams 2010)

N between 1 (single star) and 10^6 (globular cluster)

⇒ 50% of all stars come from a cluster with at least 1000 stars,

which contain at least a 10 $M_\odot$ star

⇒ a significant amount of stars form in an environment with at least one high-mass star



We are interested in the early stages, so for this purpose it does not matter if the cluster is bound or not.

Why does it matter? Interaction!

- Close encounters between all stars and protostars
  - influence the binarity properties
  - eject stars from the mass reservoir
  - truncate disks and thus affect accretion
- Radiation feedback by high-mass stars
  - influences the Jeans Mass
  - photoevaporate disks

Talks by
Rainer Köhler
Richard Parker

Talk to Asmita Bhandare

Poster by Megan Reiter

Low mass stars forming in high-mass clusters have received little observational attention

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Outer Solar System Possibly Shaped by a Stellar Fly-by

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Abstract

The planets of our solar system formed from a gas-dust disk. However, there are some properties of the solar system that are peculiar in this context. First, the cumulative mass of all objects beyond Neptune (trans-Neptunian objects [TNOs]) is only a fraction of what one would expect. Second, unlike the planets themselves, the TNOs do not orbit on coplanar, circular orbits around the Sun, but move mostly on inclined, eccentric orbits and are distributed in a complex way. This implies that some process restructured the outer solar system after its formation. However, some of the TNOs, referred to as Sednoids, move outside the zone of influence of the planets. Thus, external forces must have played an important part in the restructuring of the outer solar system. The study presented here shows that a close fly-by of a neighboring star can simultaneously lead to the observed lower mass density outside 30 au and excite the TNOs onto eccentric, inclined orbits, including the family of Sednoids. In the past it was estimated that such close fly-bys are rare during the relevant development stage. However, our numerical simulations show that such a scenario is much more likely than previously anticipated. A fly-by also naturally explains the puzzling fact that Neptune has a higher mass than Uranus. Our simulations suggest that many additional Sednoids at high inclinations still await discovery, perhaps including bodies like the postulated planet X.

Key words: Kuiper belt: general – minor planets, asteroids: general – open clusters and associations: general – planetary systems – planets and satellites: formation – protoplanetary disks

A&A 545, A4 (2012)
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Astronomy & Astrophysics

Solar system genealogy revealed by extinct short-lived radionuclides in meteorites

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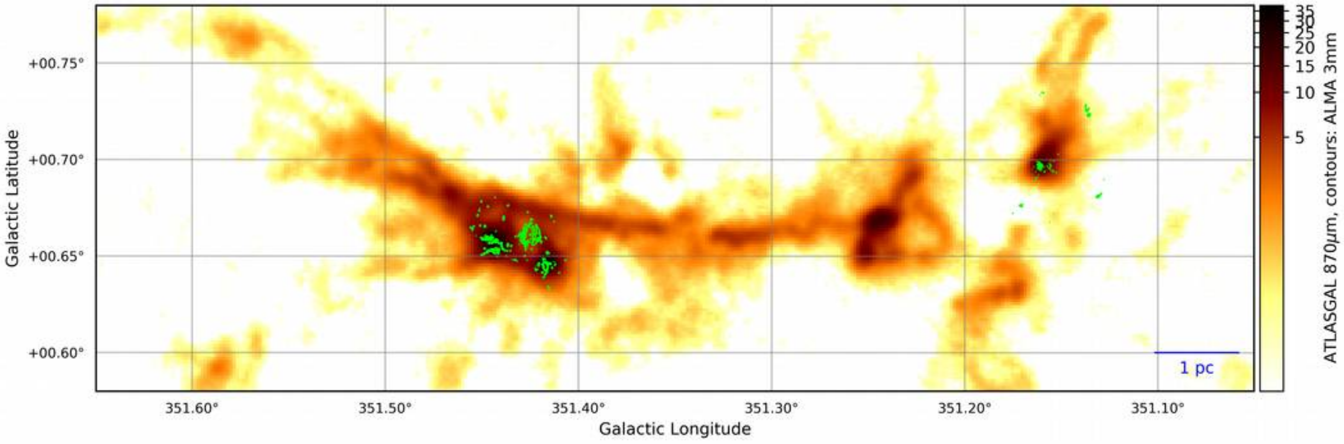
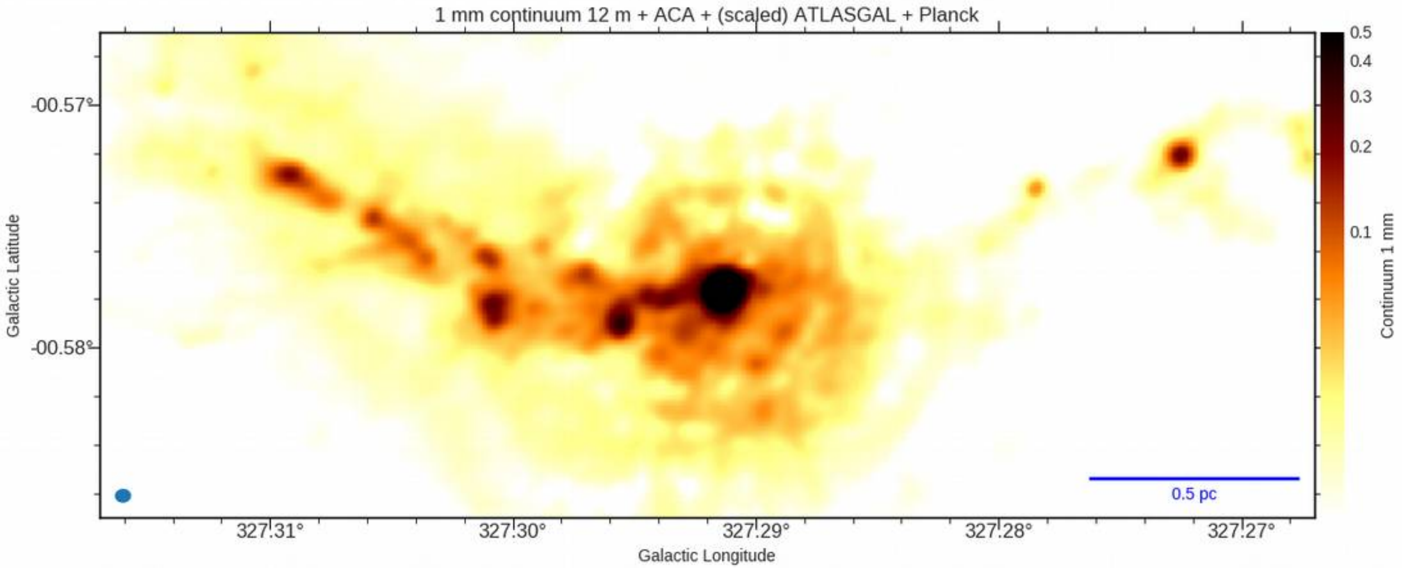
ABSTRACT

Context. Little is known about the stellar environment and the genealogy of our solar system. Short-lived radionuclides (SLRs, mean lifetime τ shorter than 100 Myr) that were present in the solar protoplanetary disk 4.56 Gyr ago could potentially provide insight into that key aspect of our history, were their origin understood.
Aims. Previous models failed to provide a reasonable explanation of the abundance of two key SLRs, ^{26}Al (τ_{26} = 1.1 Myr) and ^{60}Fe (τ_{60} = 3.7 Myr), at the birth of the solar system by requiring unlikely astrophysical conditions. Our aim is to propose a coherent and generic solution based on the most recent understanding of star-forming mechanisms.
Methods. Iron-60 in the nascent solar system is shown to have been produced by a diversity of supernovae belonging to a first generation of stars in a giant molecular cloud. Aluminum-26 is delivered into a dense collected shell by a single massive star wind belonging to a second star generation. The Sun formed in the collected shell as part of a third stellar generation. Aluminum-26 yields used in our calculation are based on new rotating stellar models in which ^{26}Al is present in stellar winds during the star main sequence rather than during the Wolf-Rayet phase alone. Our scenario eventually constrains the time sequence of the formation of the two stellar generations that just preceded the solar system formation, along with the number of stars born in these two generations.
Results. We propose a generic explanation for the past presence of SLRs in the nascent solar system, based on a collect-injection-and-collapse mechanism, occurring on a diversity of spatial/temporal scales. In that model, the presence of SLRs with a diversity of mean lifetimes in the solar protoplanetary disk is simply the fossilized record of sequential star formation within a hierarchical interstellar medium. We identify the genealogy of our solar system's three star generations earlier. In particular, we show that our Sun was born together with a few hundred stars in a dense collected shell situated at a distance of 5–10 pc from a parent massive star having a mass greater than about 30 solar masses and belonging to a cluster containing ~1200 stars.

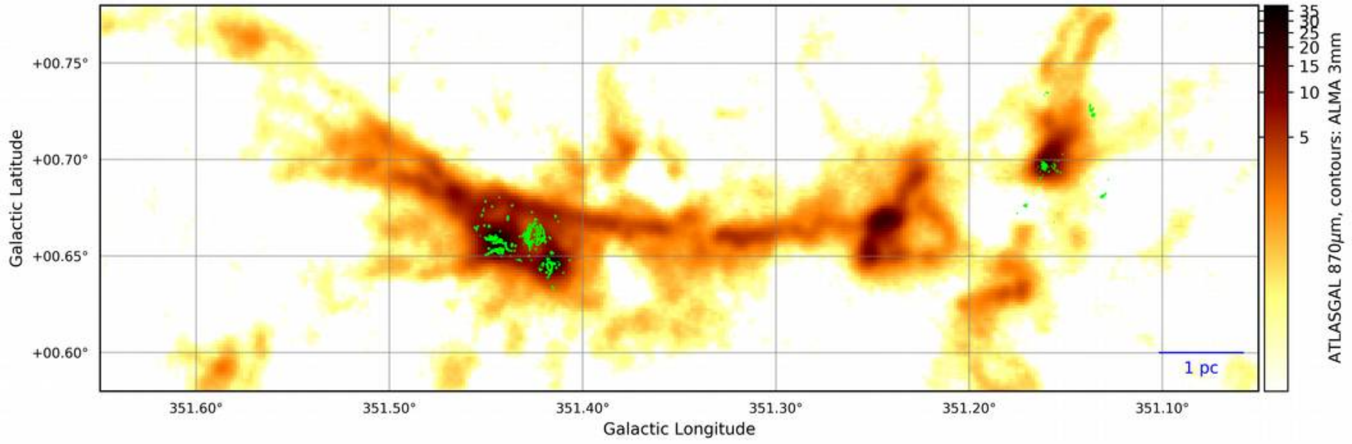
Key words. planets and satellites: formation – meteorites, meteors, meteoroids – ISM: clouds – gamma-ray burst: general – stars: rotation



NGC 6334
Distance 1.3 kpc

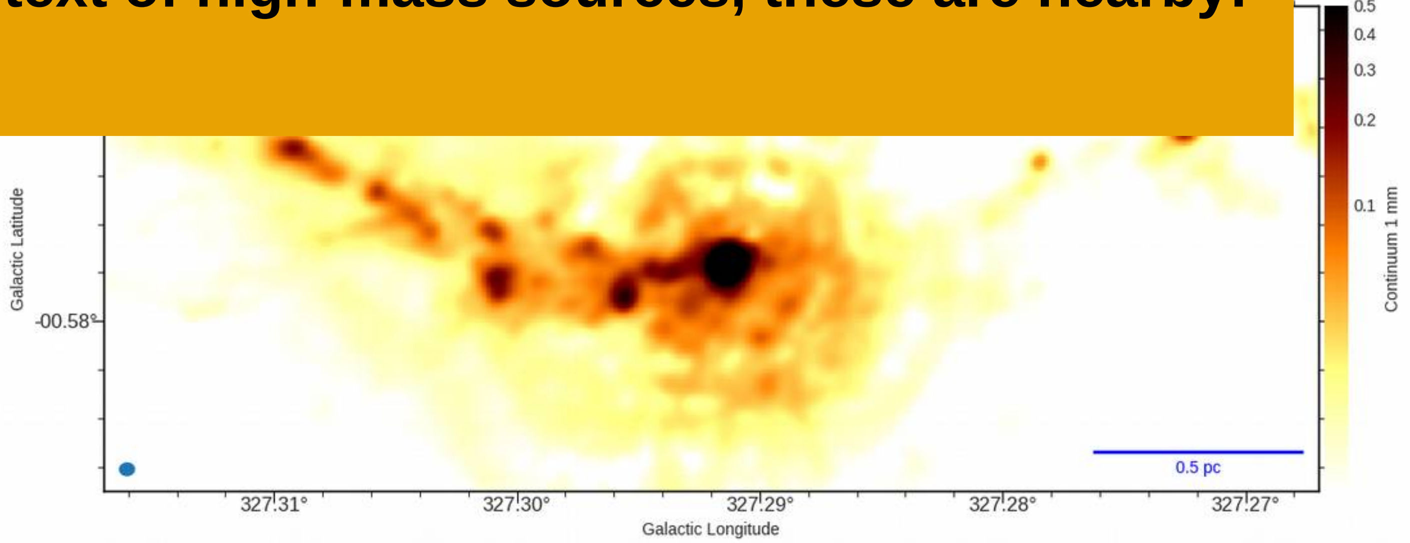


G327.3-0.6
Distance 3.3 kpc



NGC 6334
Distance 1.3 kpc

In the context of high-mass sources, these are nearby!

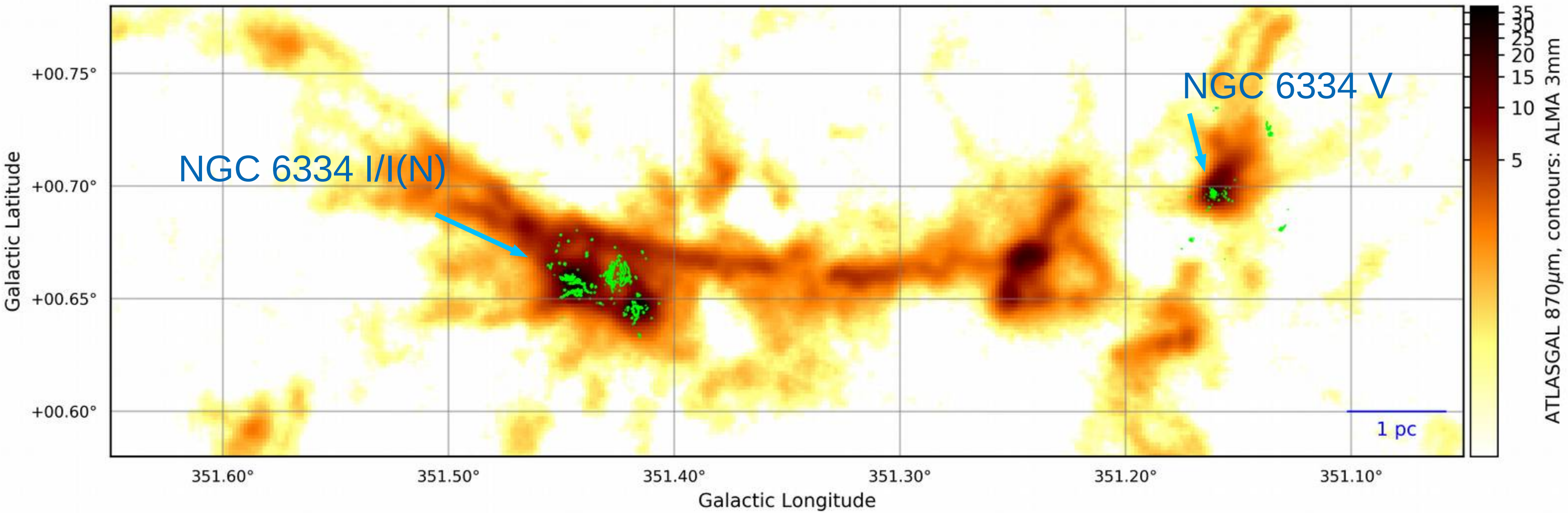


G327.3-0.6
Distance 3.3 kpc

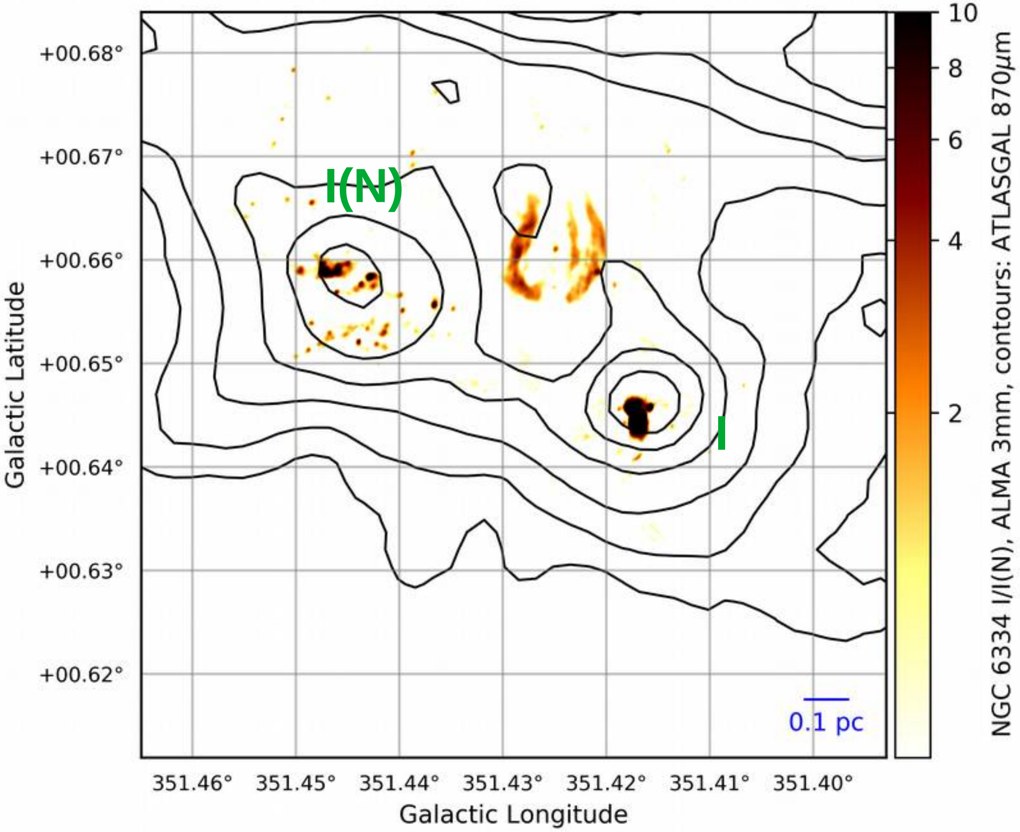
NGC 6334 Small scale structure

Pioneering work by Sandell 2000, Hunter et al. 2014, 2017, 2018, Brogan et al. 2016

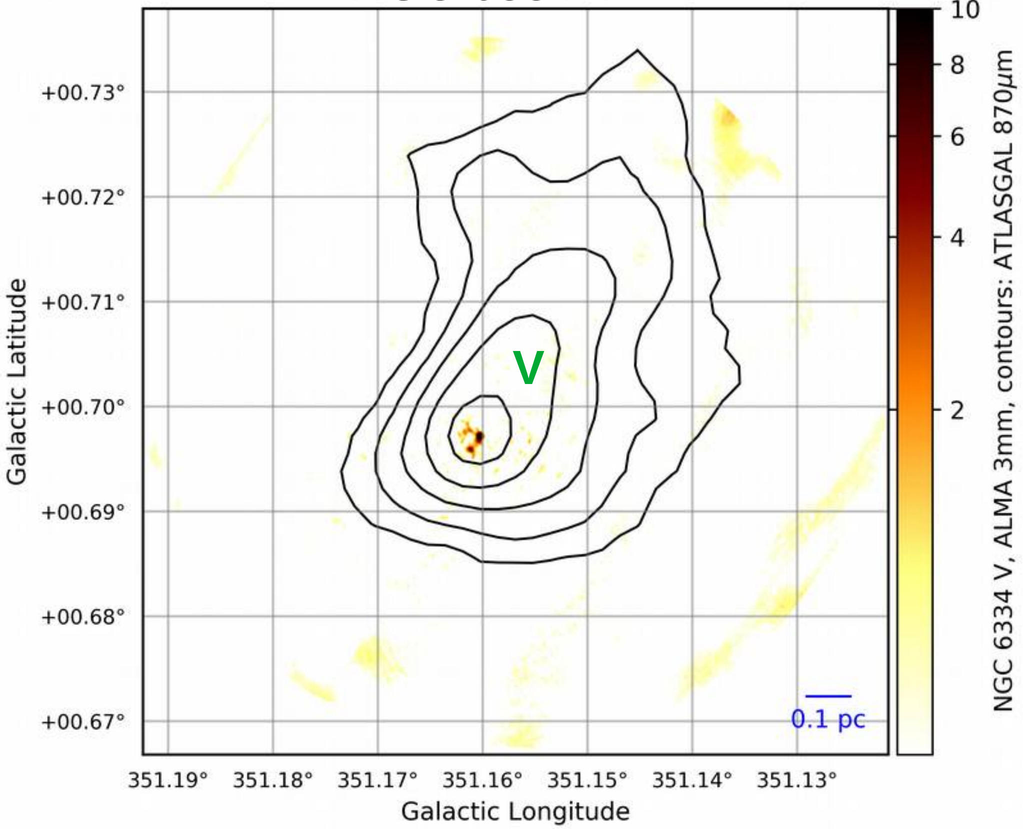
ALMA data shown: PI Baobab Liu, PhD Mahya Sadaghiani, Master Atefeh Aghababaei


NGC 6334 I/I(N)
NGC 6334 V
+00.75°
+00.70°
+00.65°
+00.60°
Galactic Latitude
351.60°
351.50°
351.40°
351.30°
351.20°
351.10°
Galactic Longitude
1 pc
35
30
25
20
15
10
5
ATLASGAL 870μm, contours: ALMA 3mm

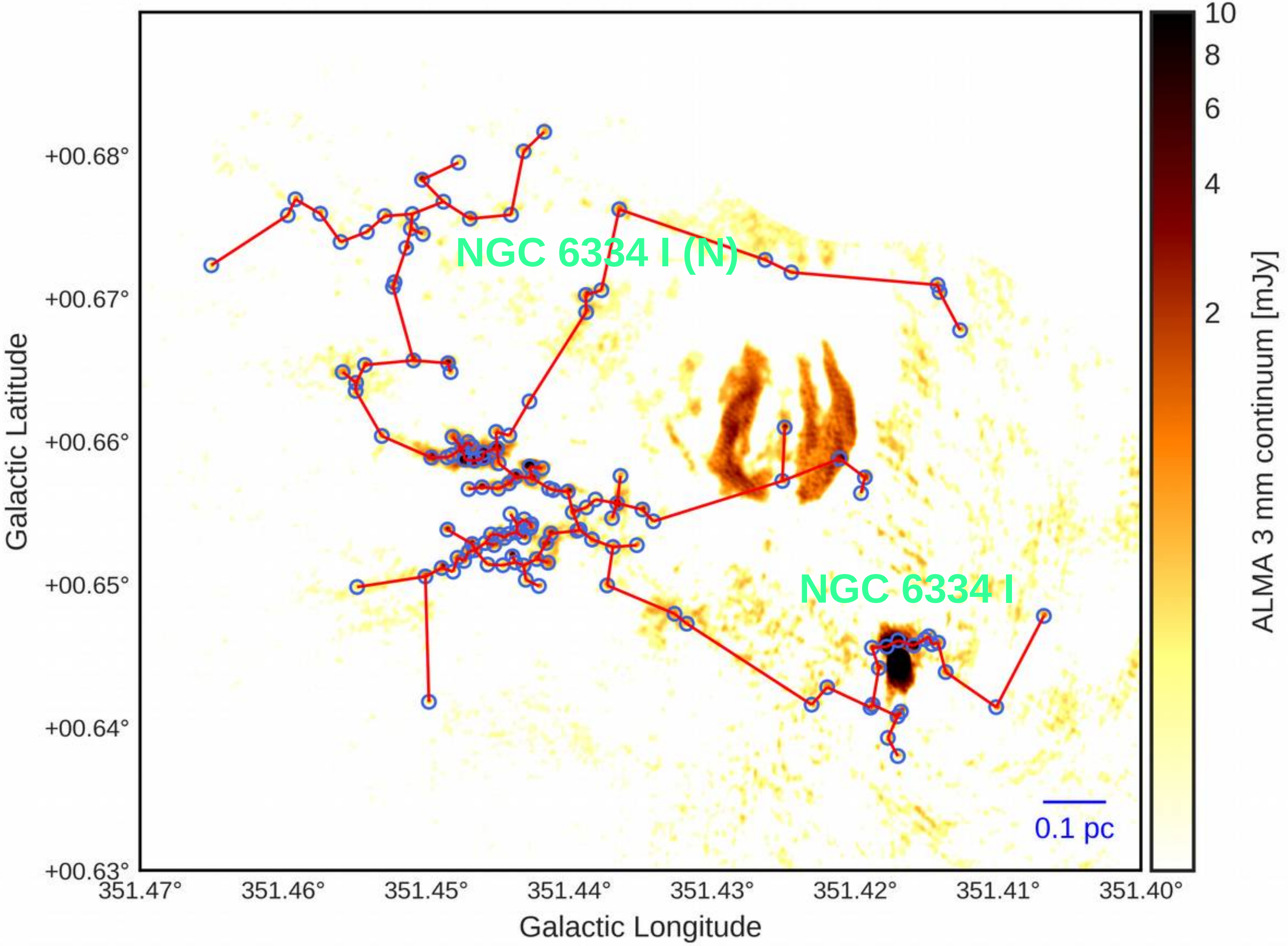
NGC 6334 I/I(N)



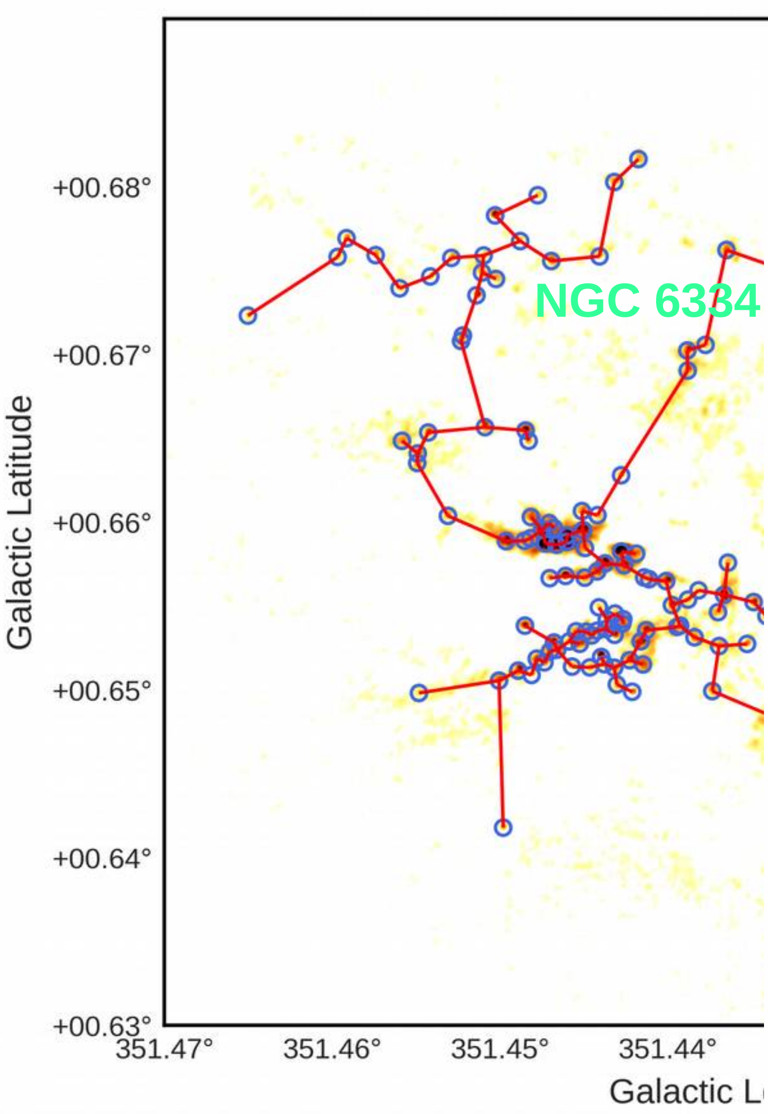
NGC 6334 V

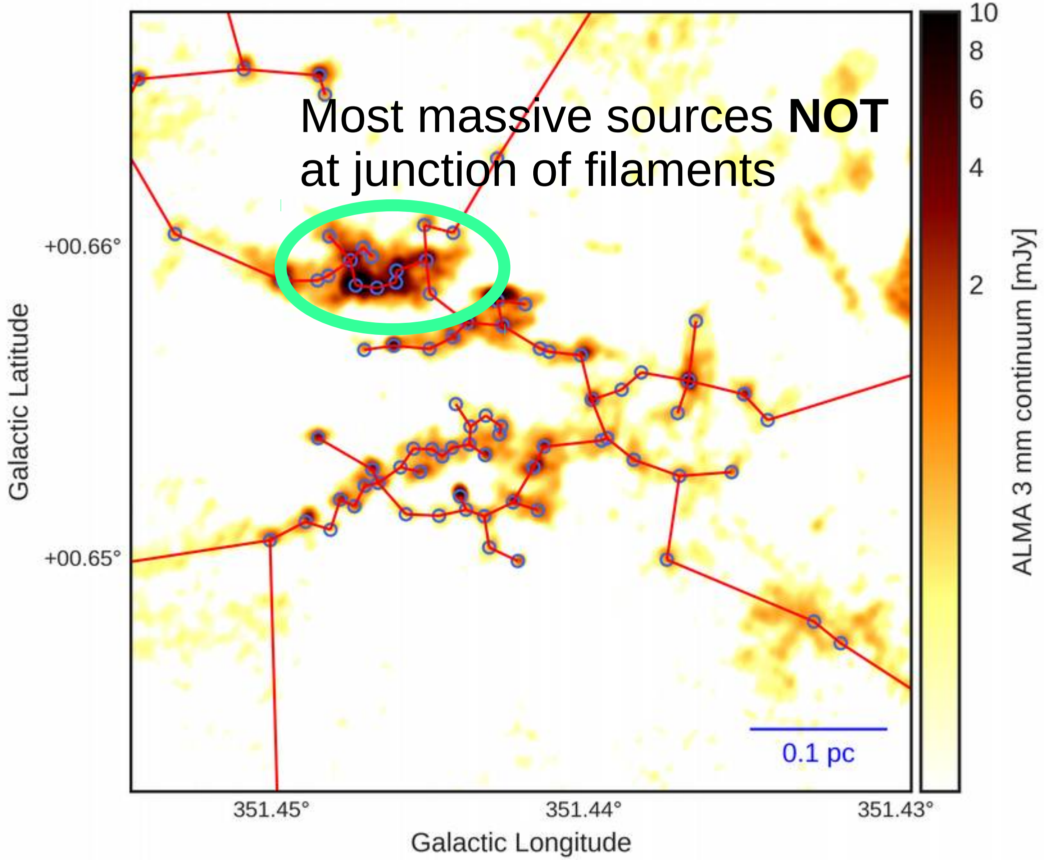


Mahya Sadaghiani

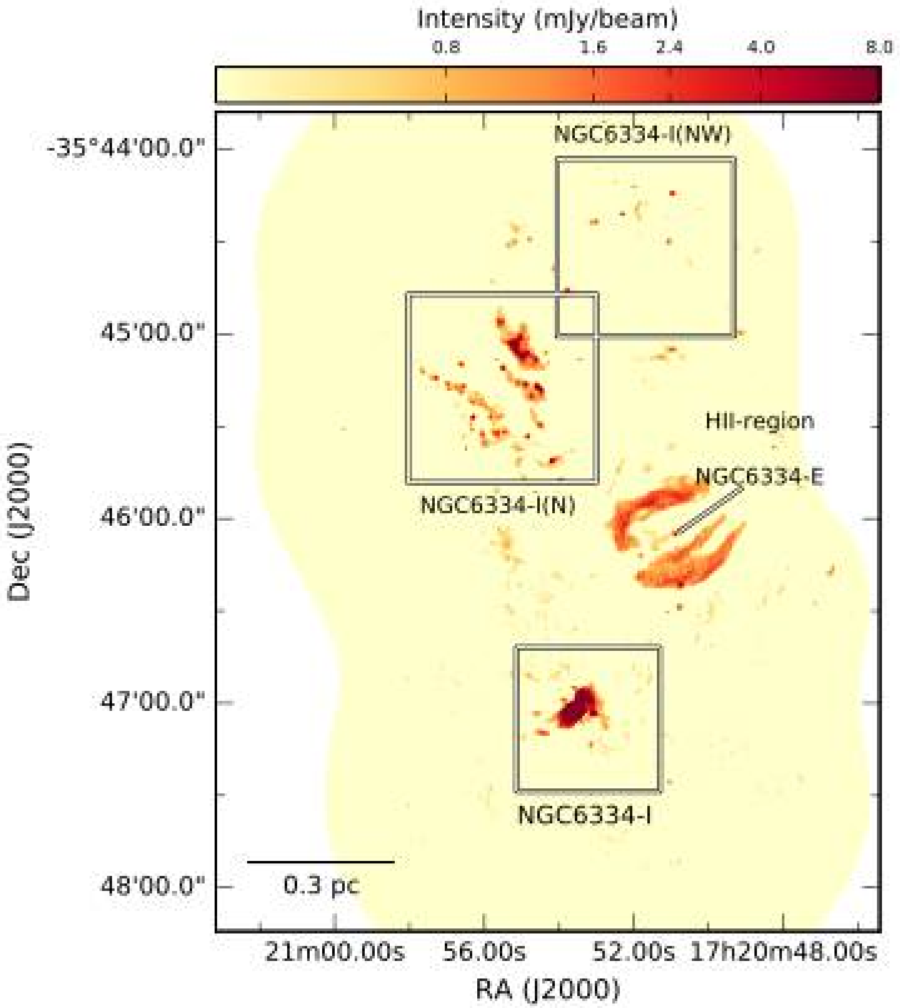


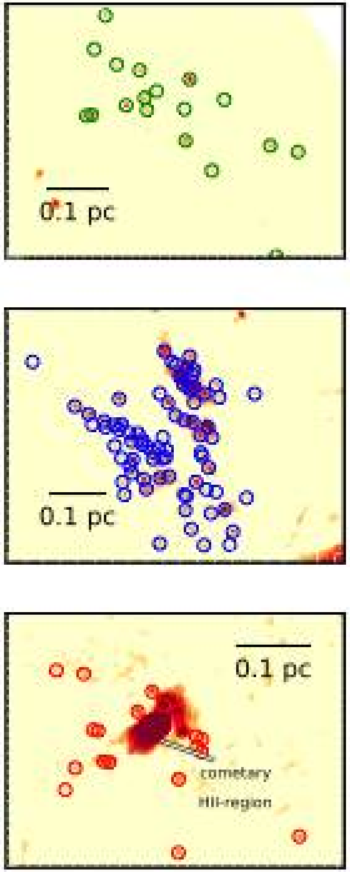
Mahya Sadaghiani





Subclusters





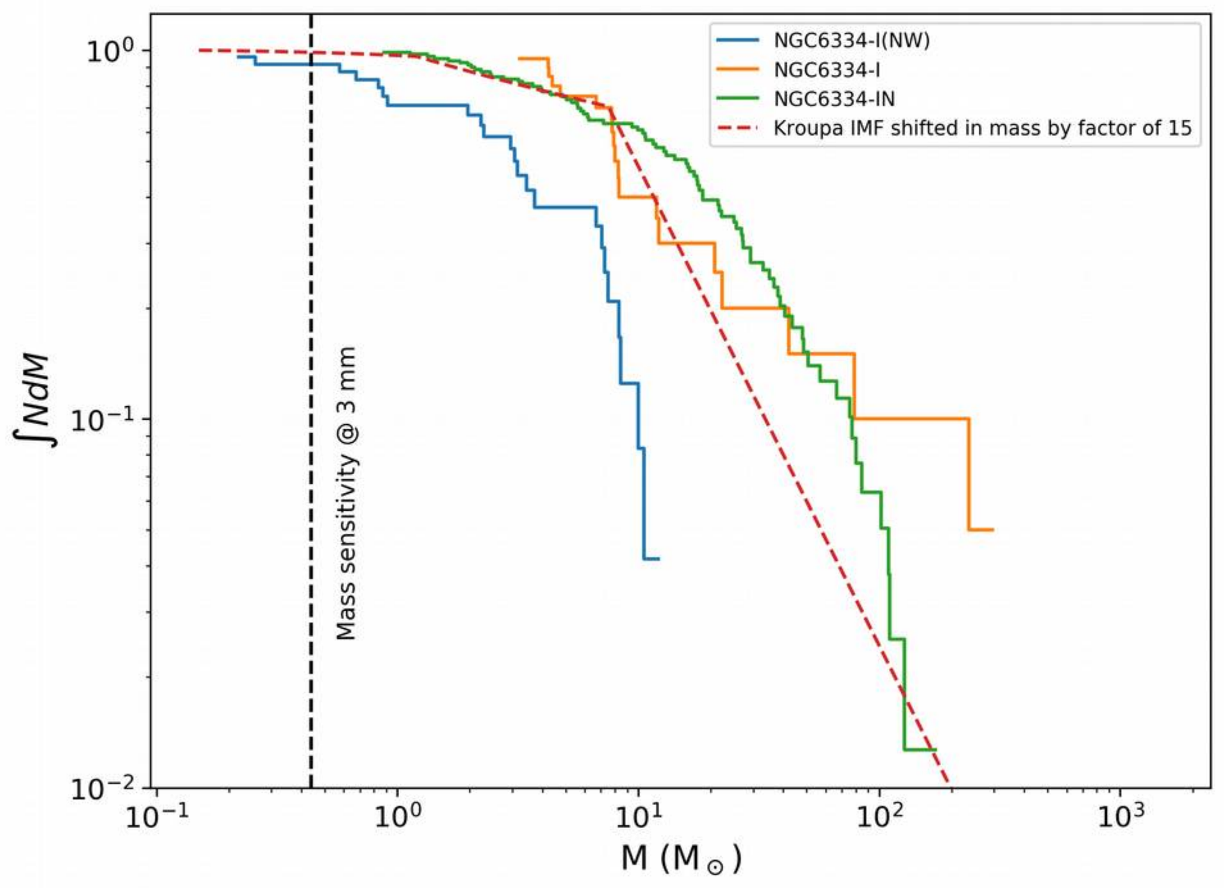
Subclusters determined by machine learning clustering algorithms

Cumulative Core Mass Function

Uncertainty due to unknown temperatures

No drastic departures from Kroupa IMF apparent, although I might be a bit top-heavy (but low numbers)

no dearth of low mass stars as in Zhang et al. 2015 toward G28.34+0.06 P1



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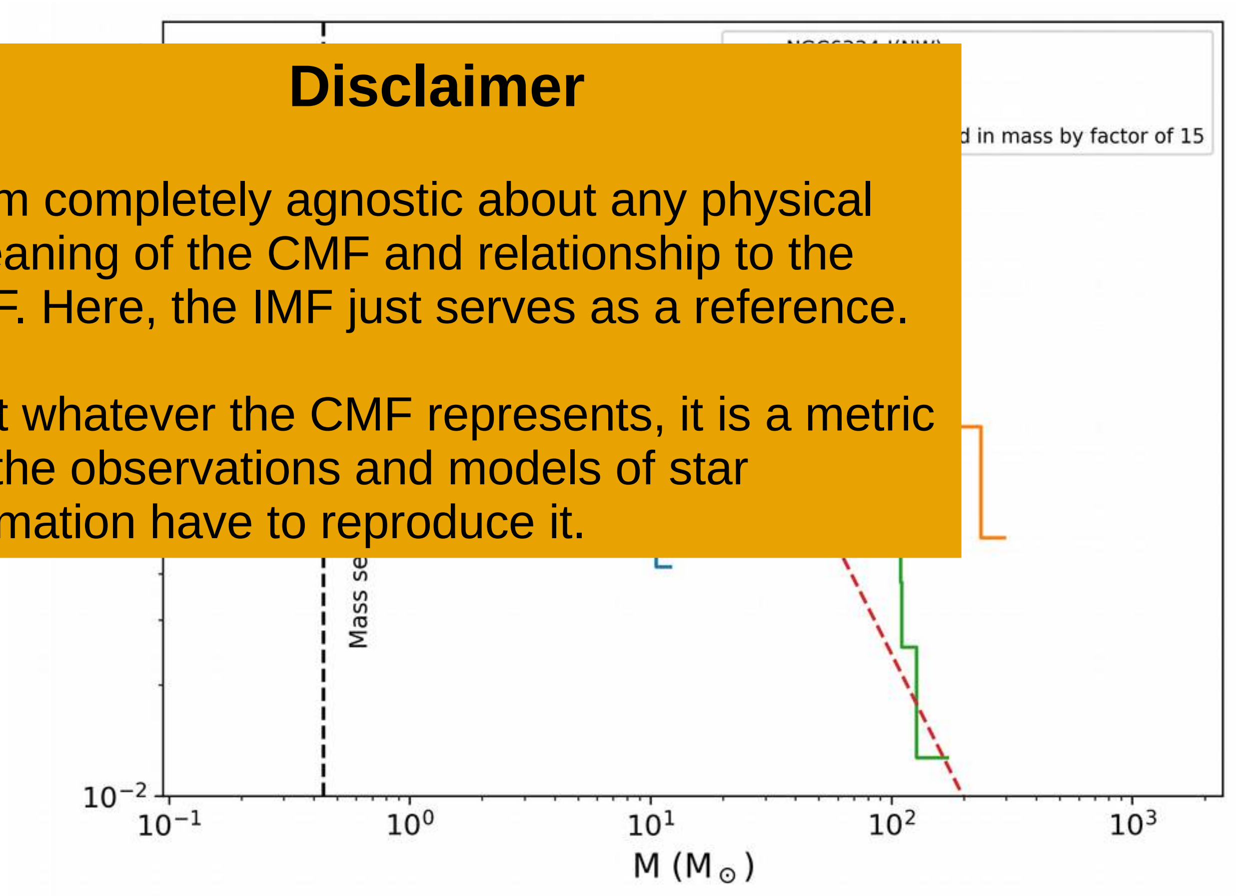
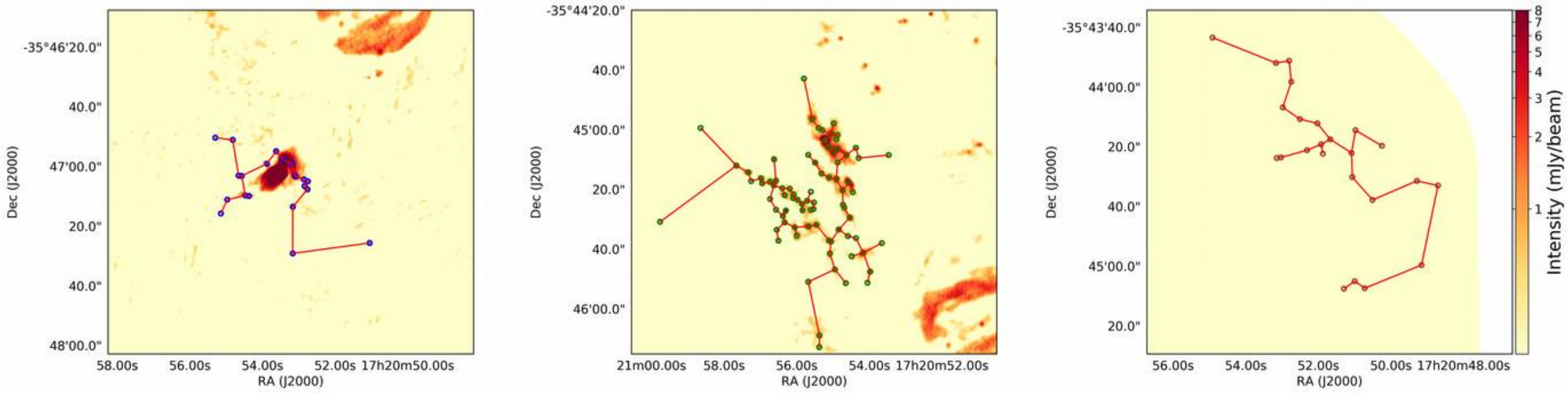


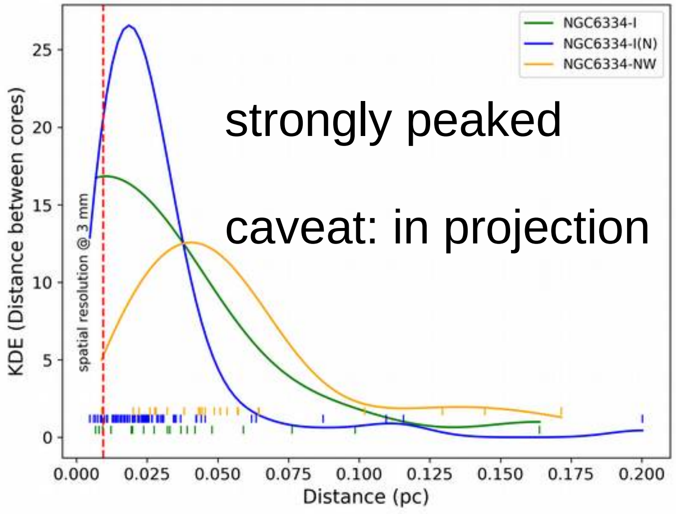
Disclaimer

I am completely agnostic about any physical meaning of the CMF and relationship to the IMF. Here, the IMF just serves as a reference.

But whatever the CMF represents, it is a metric of the observations and models of star formation have to reproduce it.

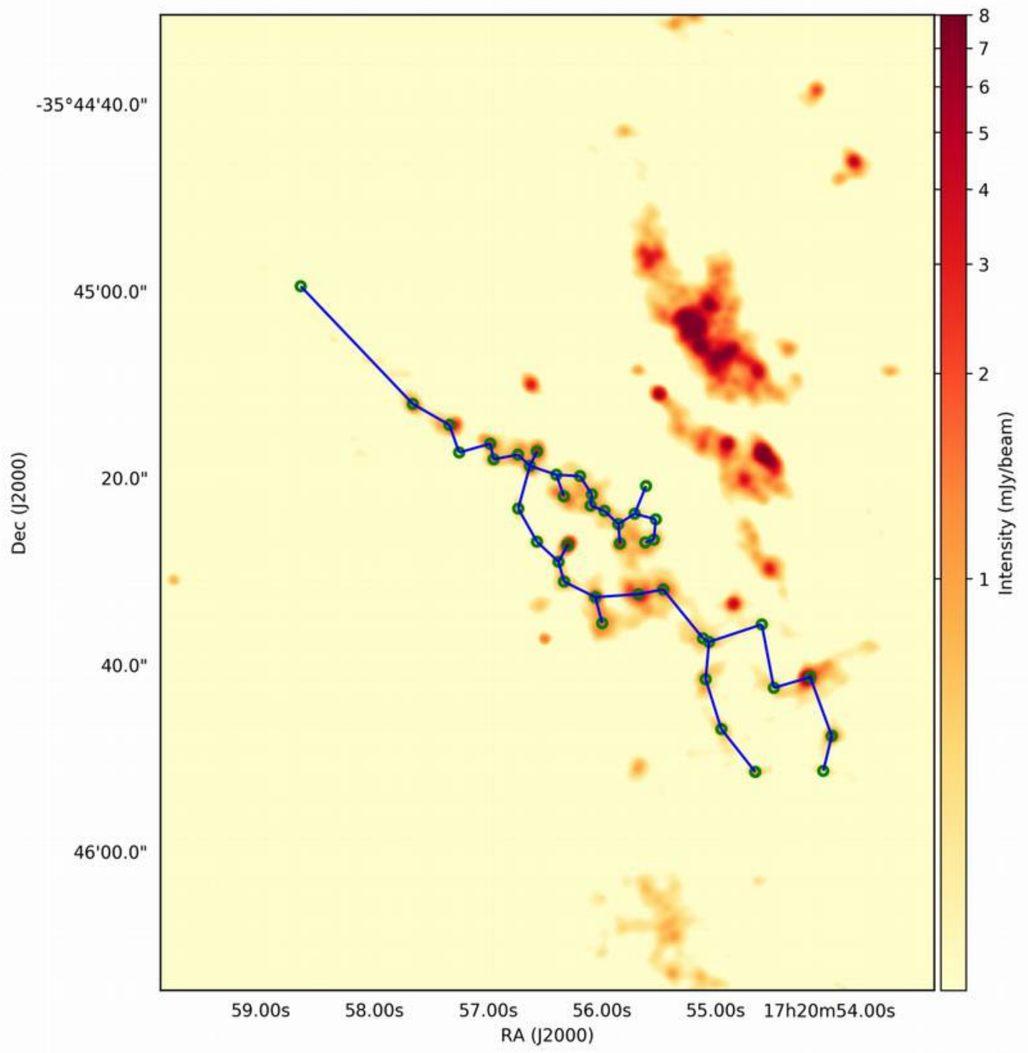


Minimum spanning tree: average separation



Cluster	No.	Mean distance [pc] (lower limit)	Median distance [pc] (lower limit)
NGC 6334-I	20	0.039	0.032
NGC 6334-I(N)	79	0.027	0.021
NGC 6334-I(NW)	24	0.057	0.045

$$\lambda_{\rm cr} = 1.24\ {\rm pc}\left(\frac{\sigma}{1\ {\rm km\ s^{-1}}}\right)\left(\frac{n_c}{10^5 {\rm cm^{-3}}}\right)^{-0.5} = 0.018\ {\rm pc\ (turbulent)}$$



M/l < 2650 $M_\odot$/pc (observed)

Critical M/l ratios from filament fragmentation

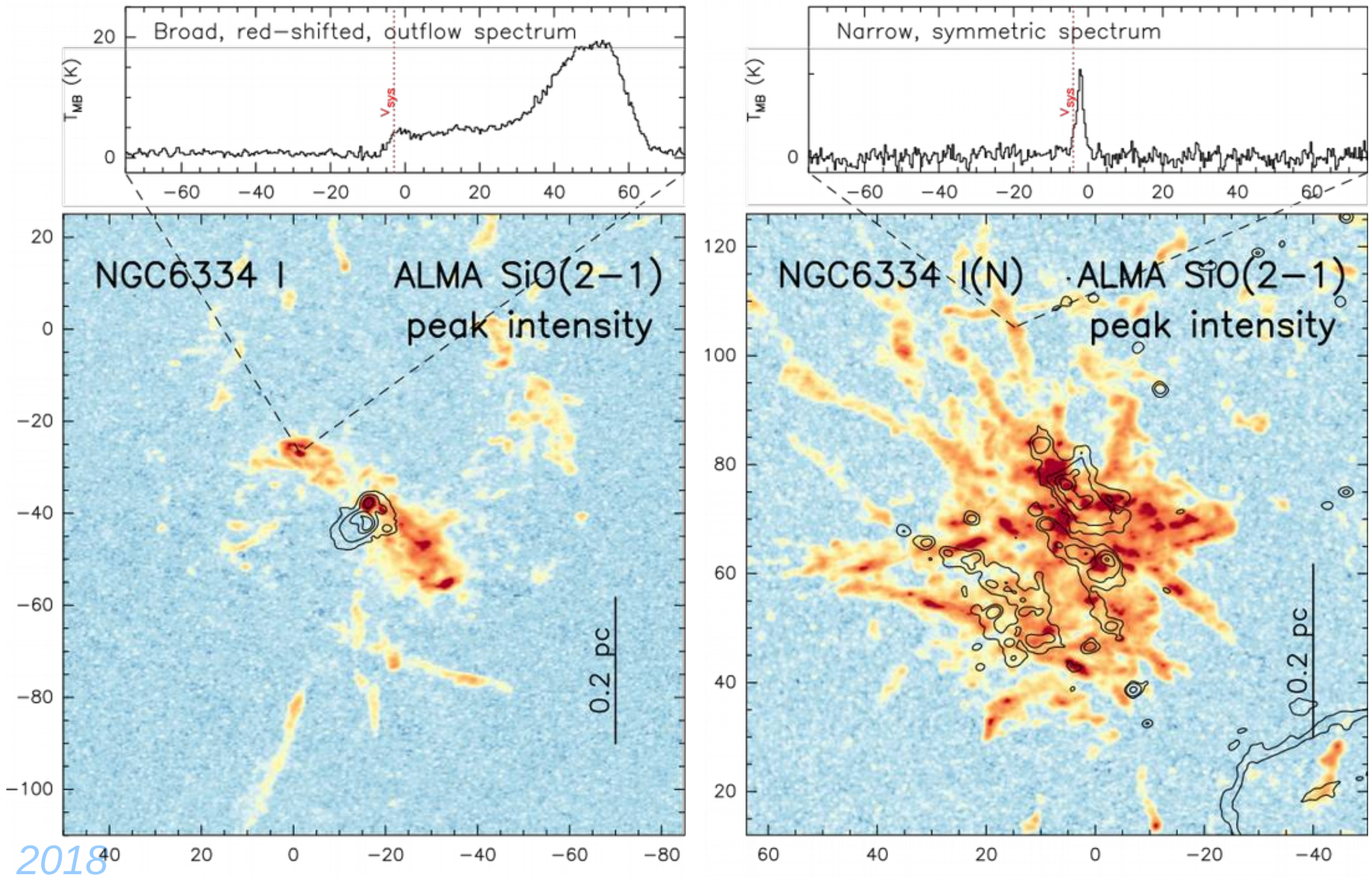
$$\frac{M}{l} = \frac{2\sigma^2}{G}$$

M/l = 50 $M_\odot$/pc (thermal support)

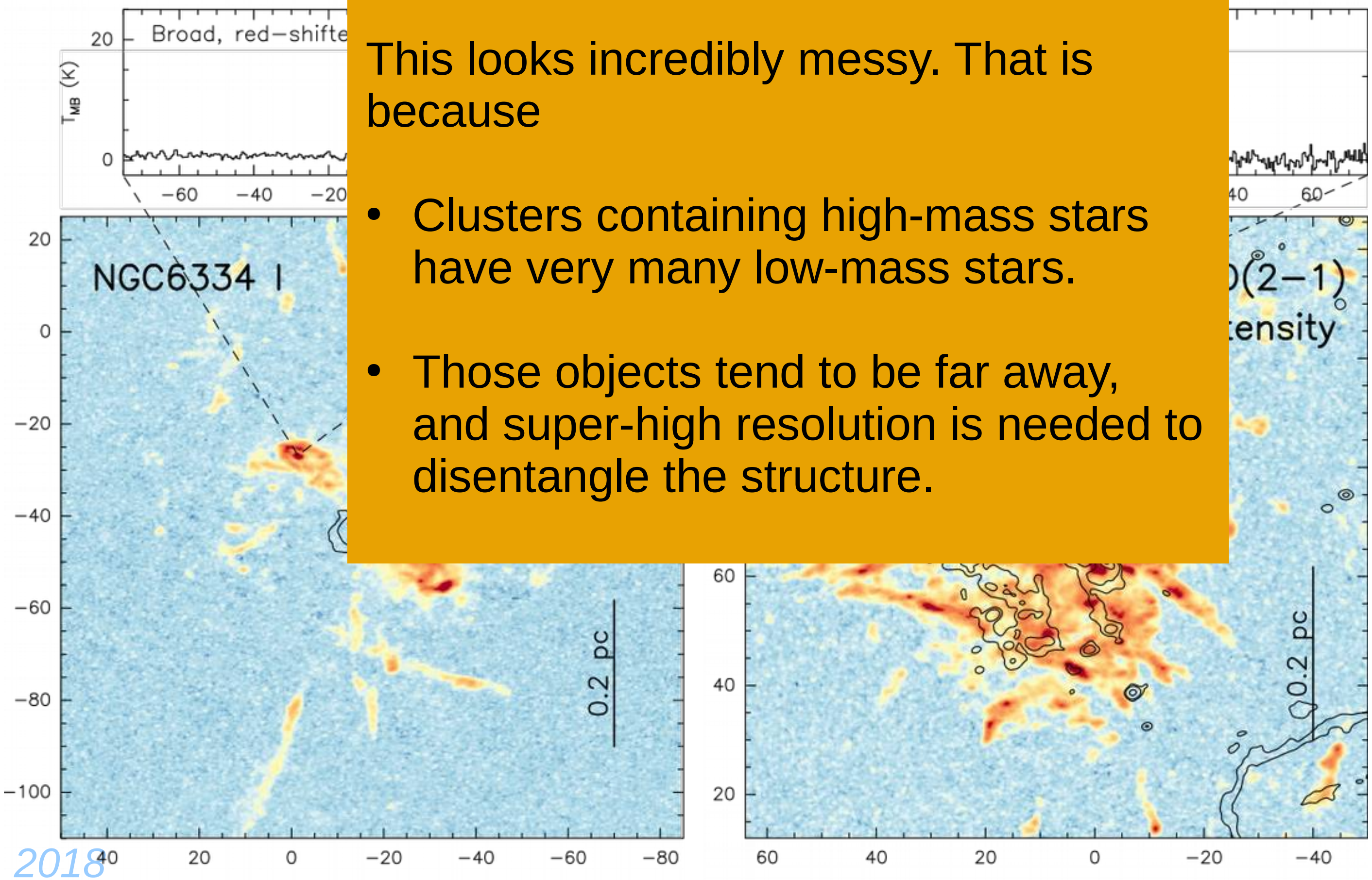
M/l = 1860 $M_\odot$/pc (turbulent support)

About 50% of the total filament mass in both subbranches are in the cores.

SiO reveals network of (mostly) outflows



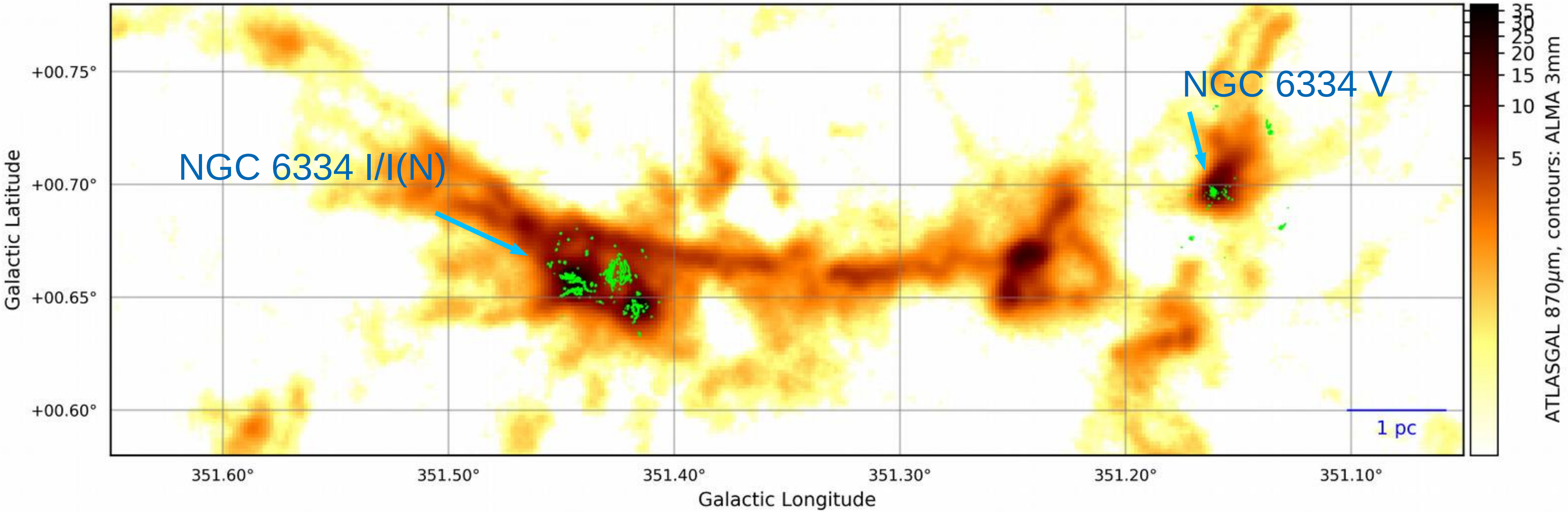
SiO revea … s



Note

This looks incredibly messy. That is because

- Clusters containing high-mass stars have very many low-mass stars.
- Those objects tend to be far away, and super-high resolution is needed to disentangle the structure.


NGC 6334 I/I(N)
NGC 6334 V
Galactic Latitude
+00.75°
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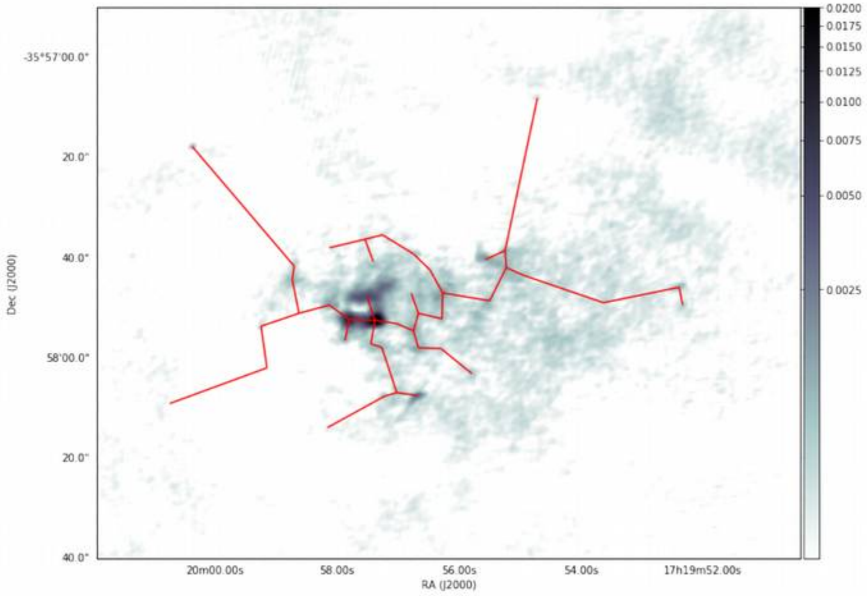
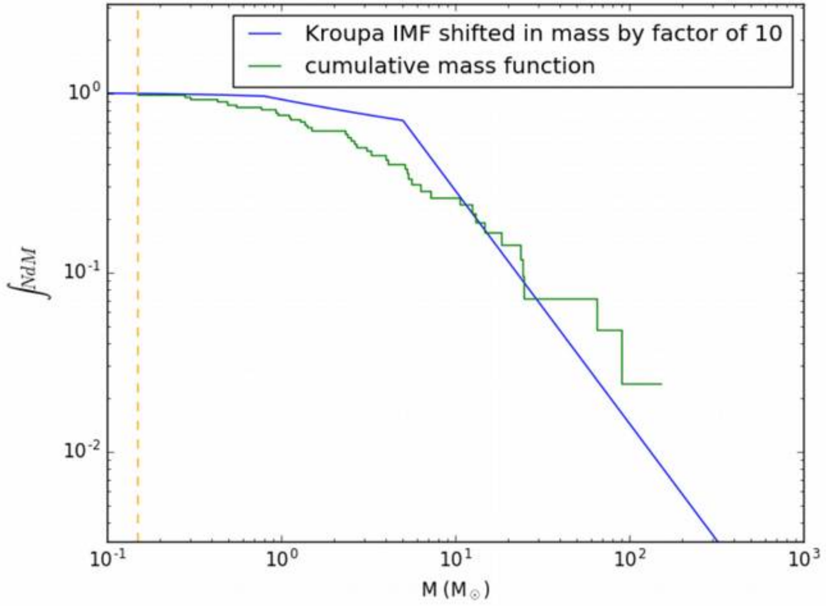
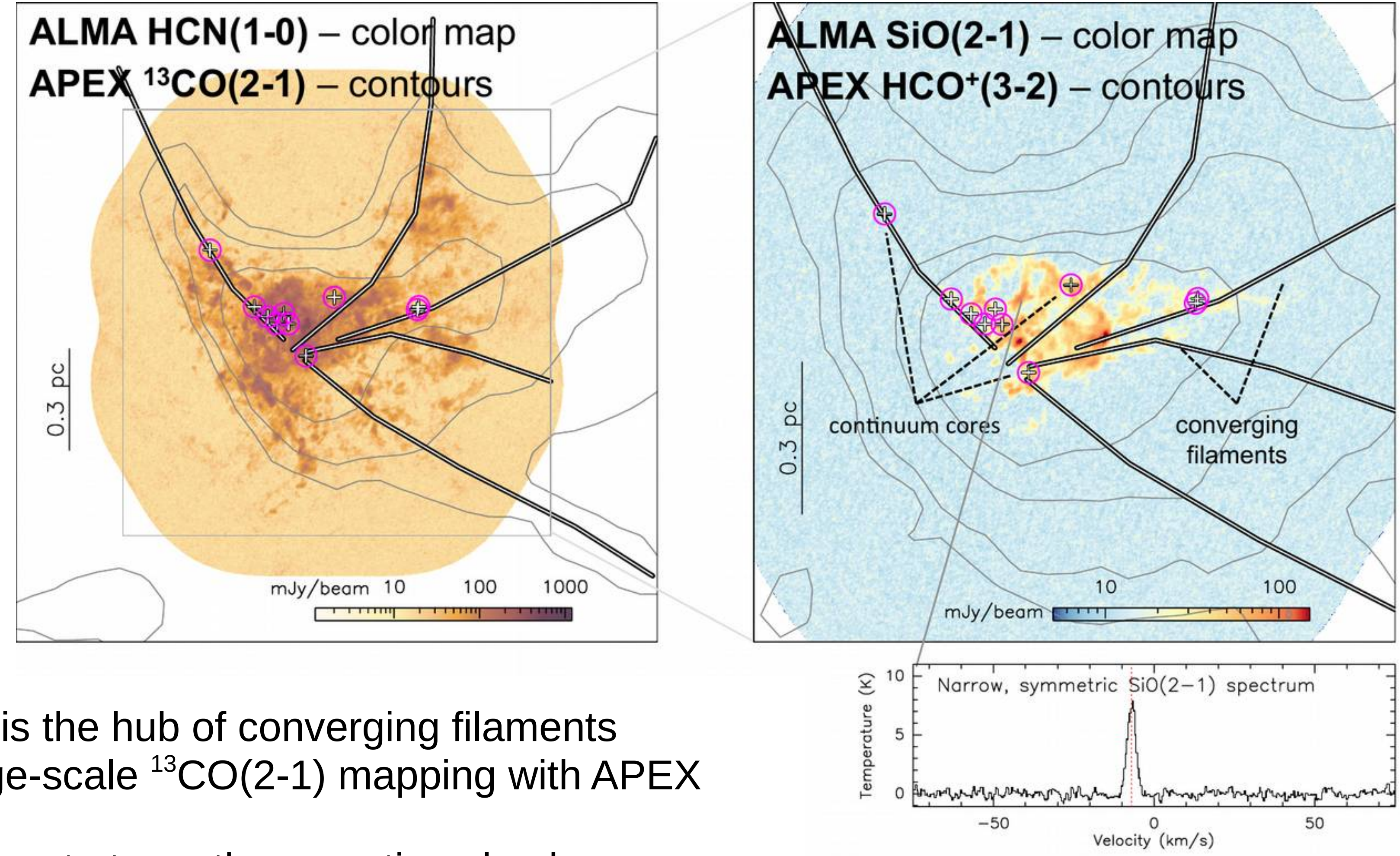
+00.60°
351.60°
351.50°
351.40°
351.30°
351.20°
351.10°
Galactic Longitude
1 pc
ATLASGAL 870μm, contours: ALMA 3mm
35
30
25
20
15
10
5

Atefeh Aghababaei

NGC6334 - V







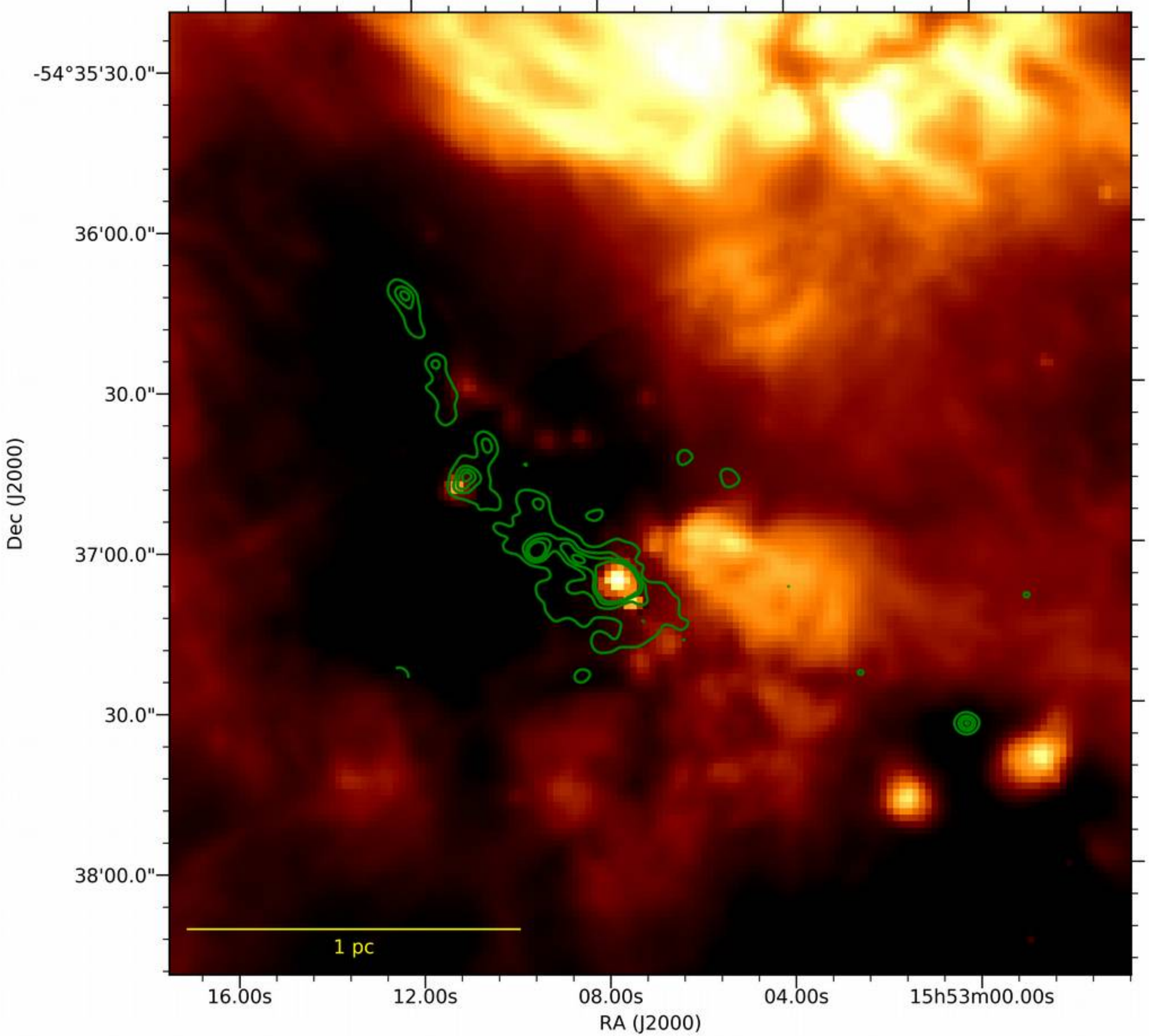
NGC 6334 V is the hub of converging filaments traced by large-scale $^{13}CO(2\text{-}1)$ mapping with APEX

SiO here seems to trace the accretion shock

G327.3-0.6

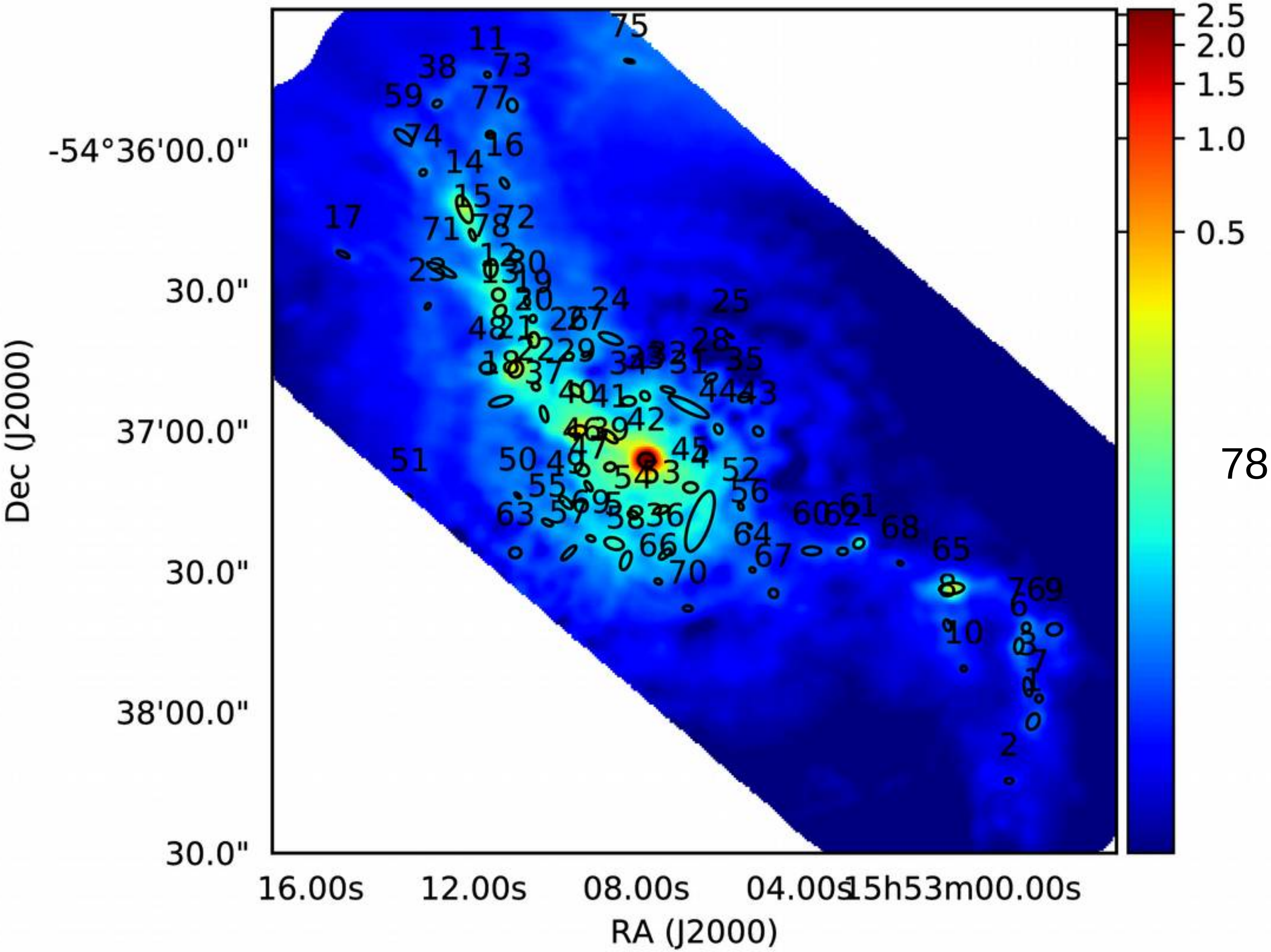
(G327 to friends)

ALMA 1.3 mm (green contours) on Spitzer 4.5 µm



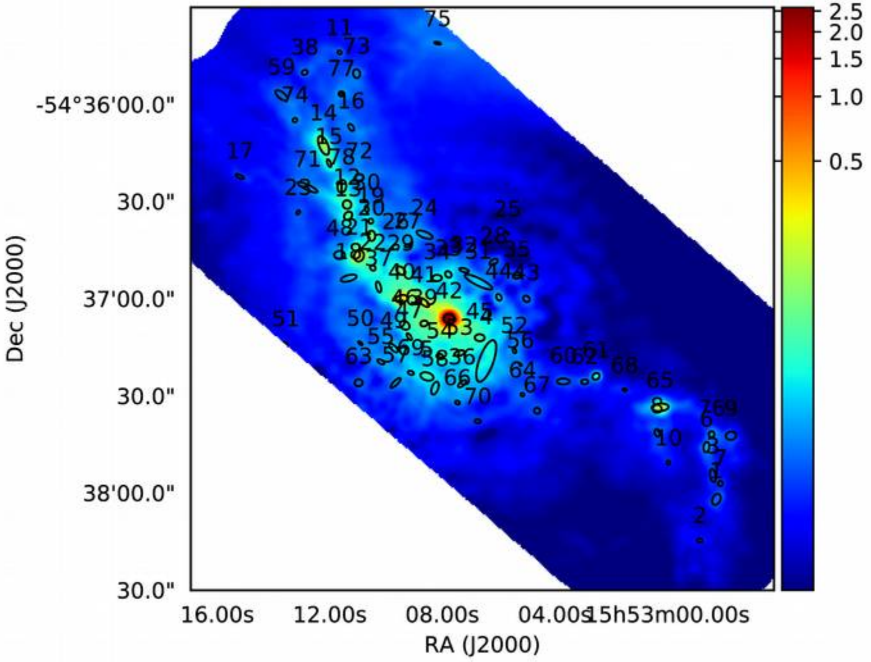
Benedikt Helmstaedter

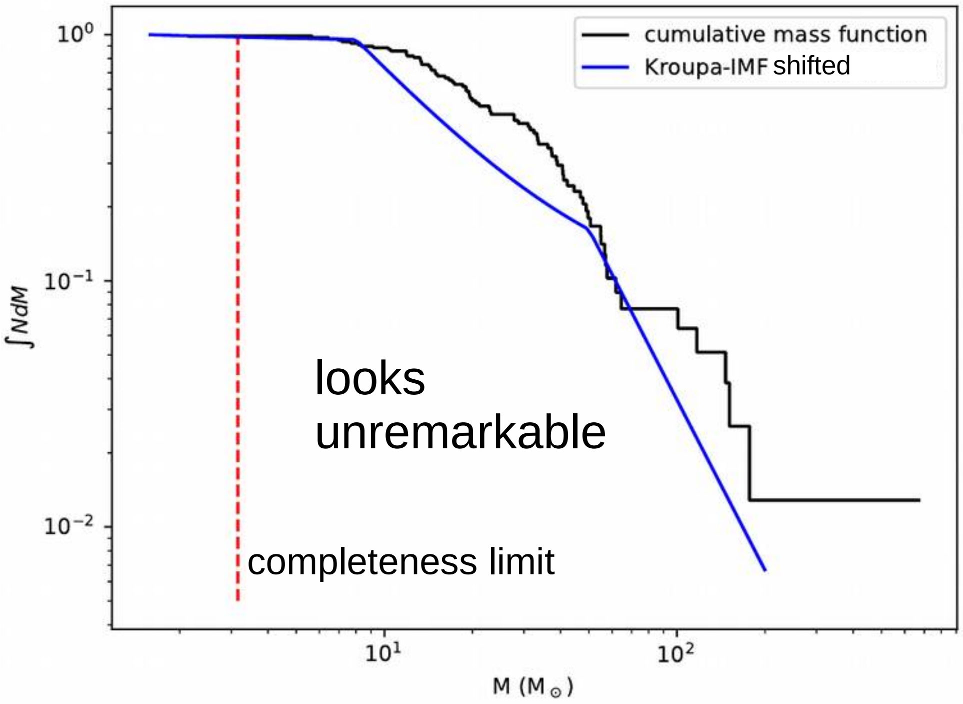
G327 – ALMA 1.3 mm observations

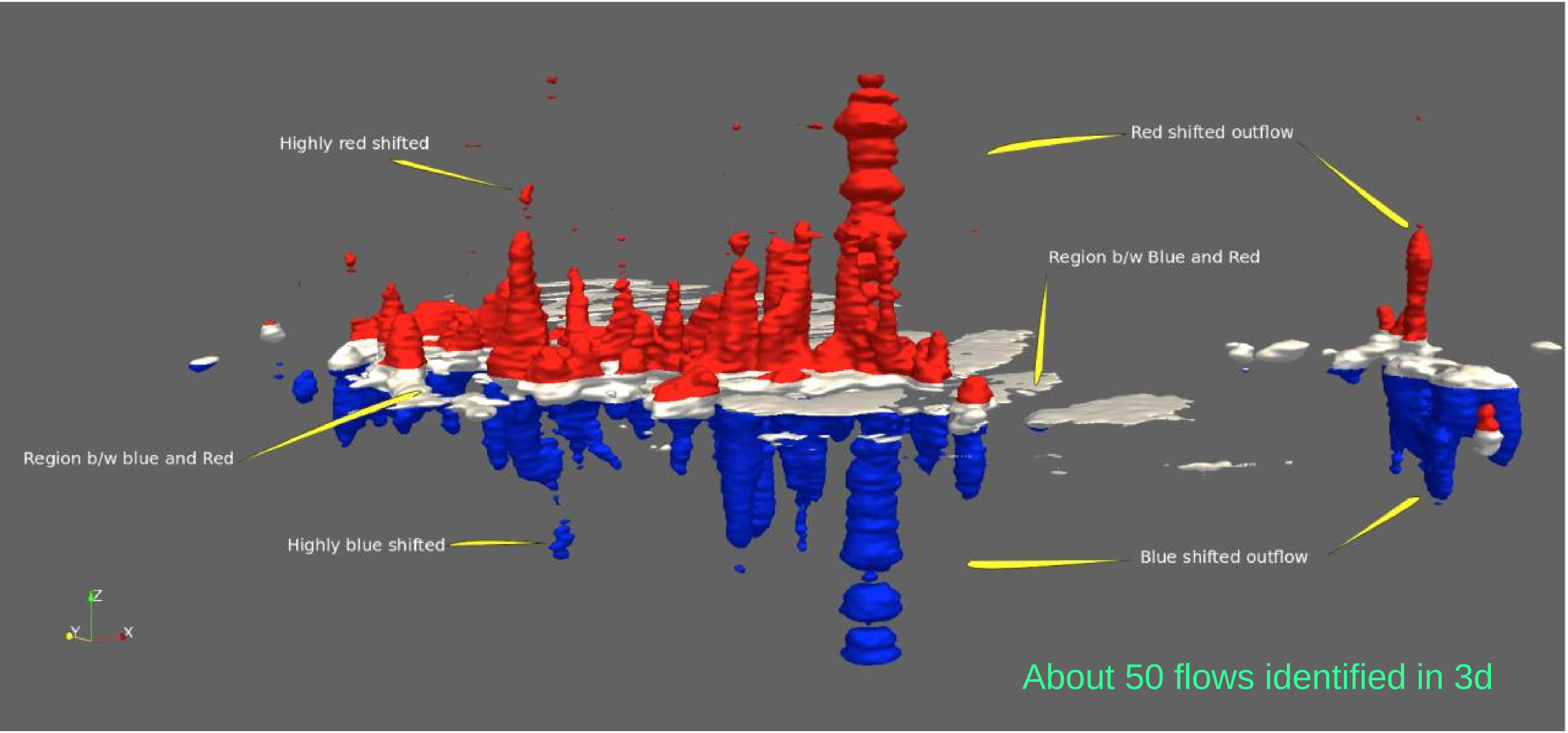


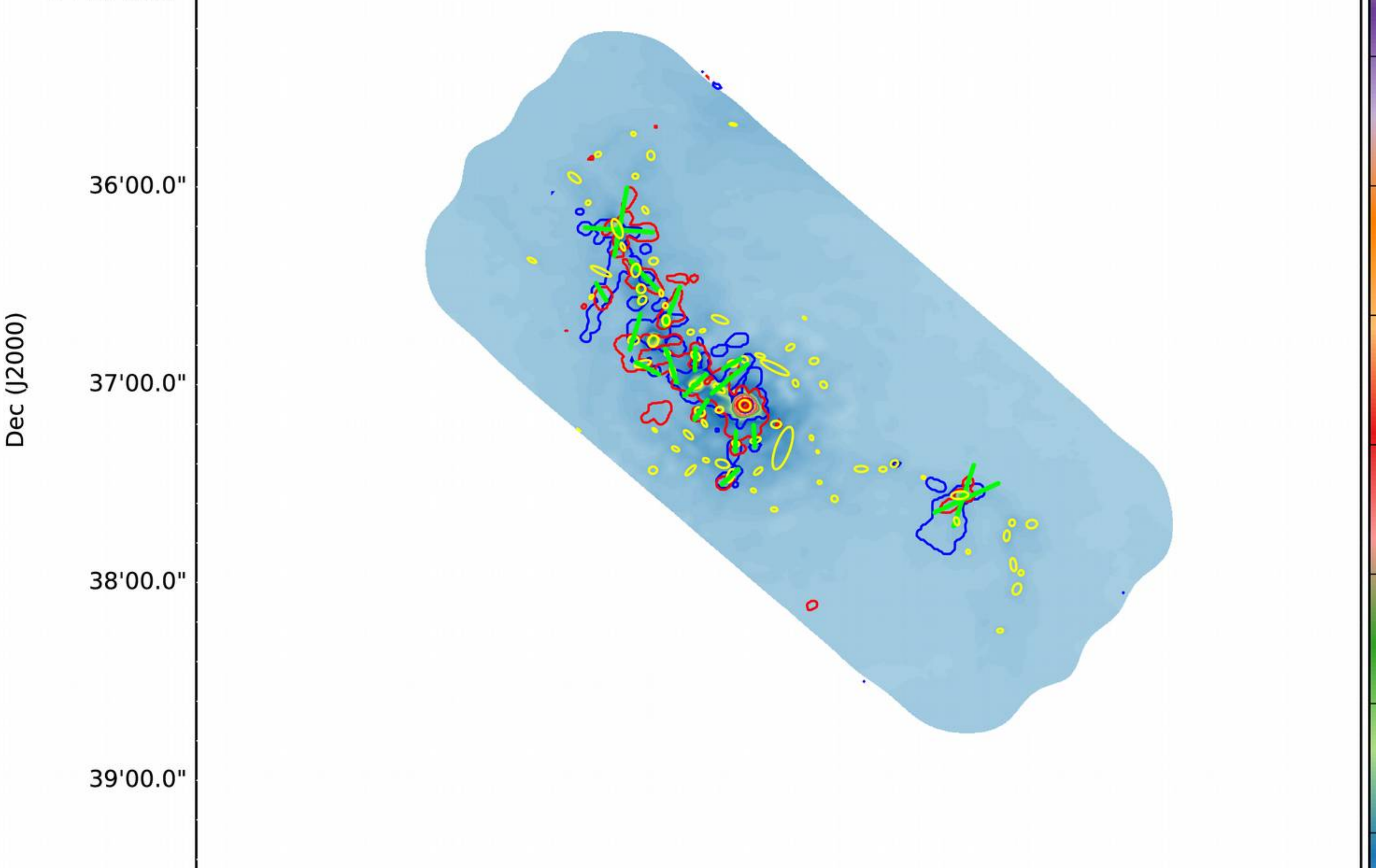
78 sources found

G327 cumulative clump mass function






Highly red shifted
Red shifted outflow
Region b/w Blue and Red
Region b/w blue and Red
Highly blue shifted
Blue shifted outflow
Z
Y
X
About 50 flows identified in 3d


36'00.0"
37'00.0"
38'00.0"
39'00.0"
Dec (J2000)

Future Research

- **Existing data**
  - Characterize outflow properties (e.g. orientation relative to filament, momentum, energy etc.)
  - Understand mass flow within the filaments
  - Velocity dispersion of cores
- **More data**
  - **Deeper:** what does the CMF look like at even lower mass?
  - **Higher resolution:** characterize multiplicity
  - **Both:** find and characterize disks, particularly in high stellar density regions
  - More sources

Stay tuned…

Thank you for your attention!