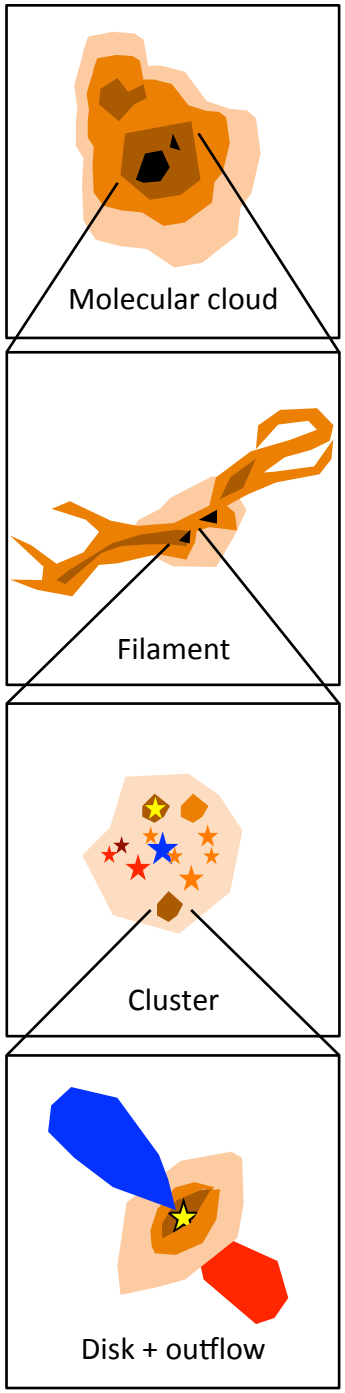


Towards a statistical understanding of the star formation process

Álvaro Sánchez-Monge
– Institute of Space Sciences (ICE-CSIC) –

in collaboration with:
Mitra Aghababaei – Flavia Amaral – Maite Beltrán – Henrik Beuther – Gemma Busquet
Riccardo Cesaroni – Asunción Fuente – Gary Fuller – Adam Ginsburg – Josep Miquel Girart
Fanyi Meng – Thomas Möller – Sergio Molinari – Wiebke Riedel – Mahya Sadaghiani
Peter Schilke – Andreas Schwörer – Jose Maria Torrelles – Tianwei Zhang – Qizhou Zhang
the ALMAGAL consortium – and many others

Institute of Space Sciences
EXCELENCIA MARÍA DE MAEZTU
CSIC
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

Stars do not form in isolation

Star (cluster) formation

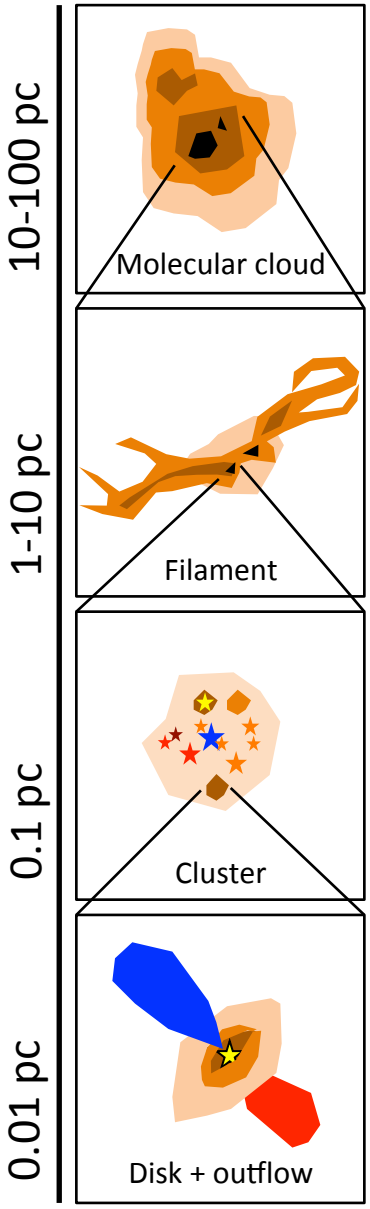
Super star clusters: 100+ high-mass stars

Stars do not form in isolation
Most of them are formed in clusters

Clusters with 1000 members contain already a 10 $M_\odot$ star
50% of stars have formed in a cluster containing at least a 10 $M_\odot$ star !

Adams 2010, ARA&A, 48, 47

From clouds to stars



Questions on Star (Cluster) Formation

Q. How do molecular clouds fragment into stellar clusters?

Q. Do all stellar clusters form in the same way?

Q. How do (proto-)stellar clusters evolve with time?

Q. How is mass transported from the large clouds down to stars?

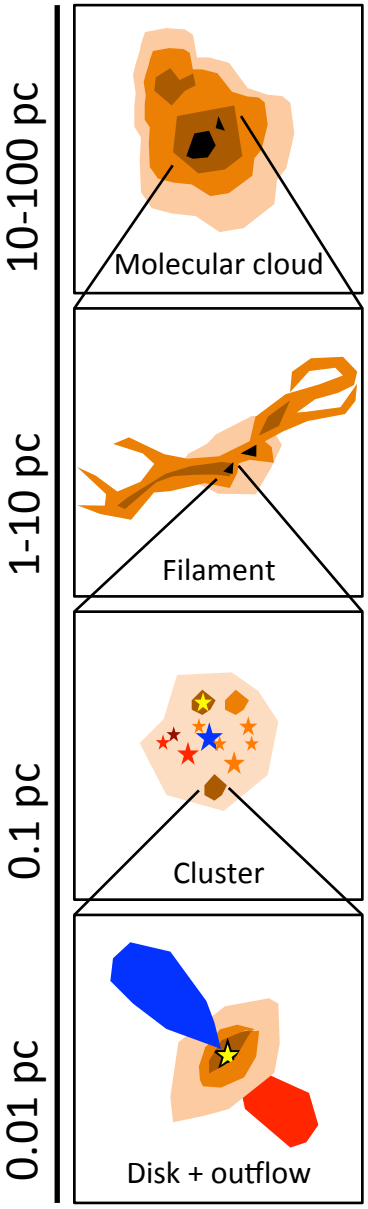
Q. What is the role of gravity, turbulence and magnetic fields?

Q. How does feedback originate and affect the whole process?

Q. What is the role of proto-stellar/planetary disks?

Q. How does chemistry evolve from simple to organic/pre-biotic?

From clouds to stars



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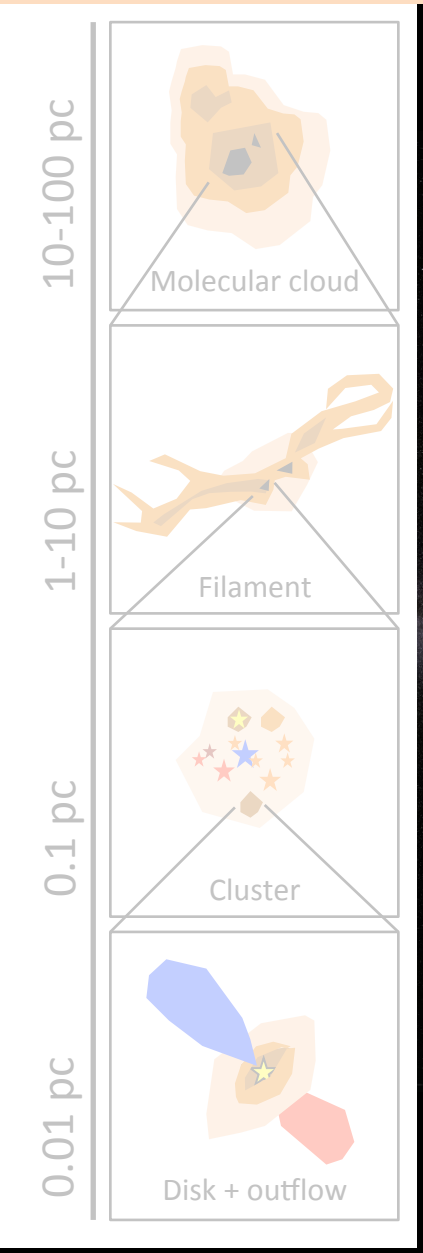
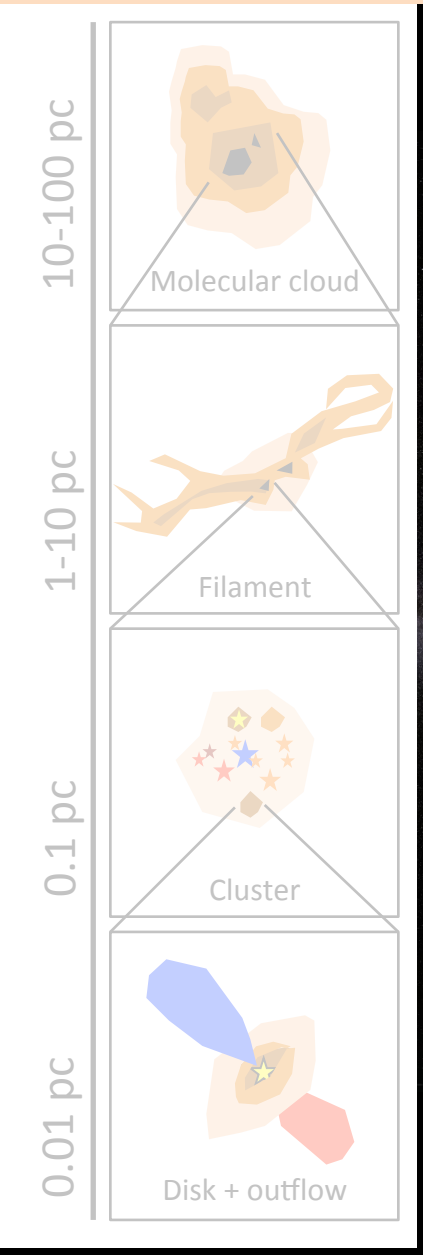
Mass transport through filaments



Milky Way as seen in the *GigaGalaxy Zoom* project (credit: ESO/S. Bruiner)

Mass transport through filaments



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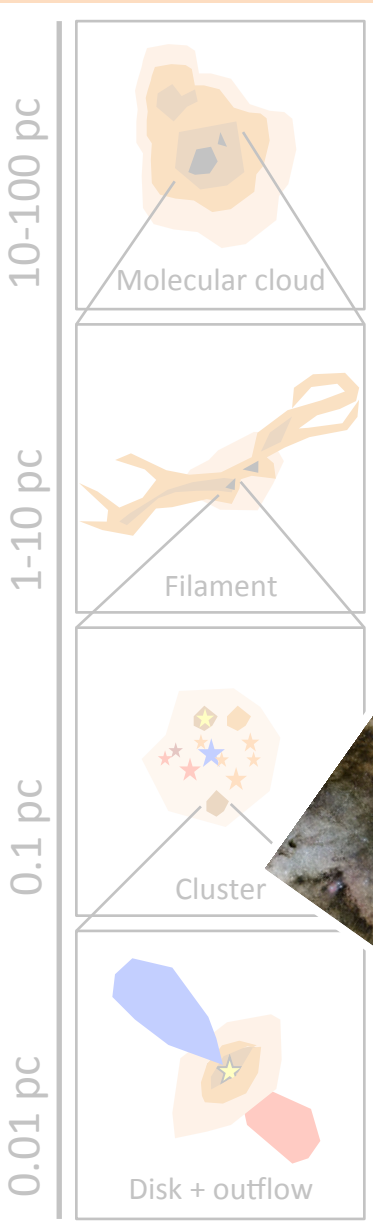

RVB color-composite image
GigaGalaxy Zoom project (credit: ESO/S. Guisard)

Mass transport through filaments

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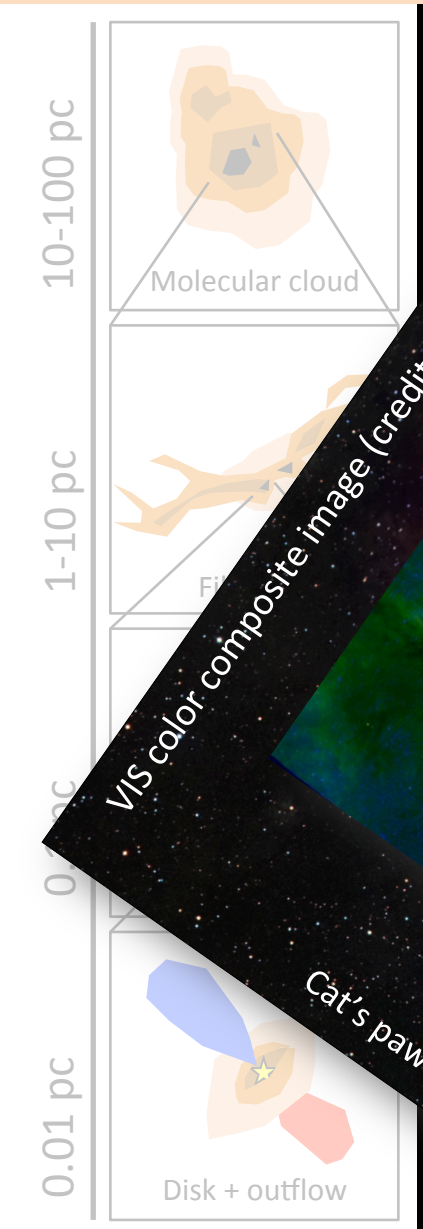
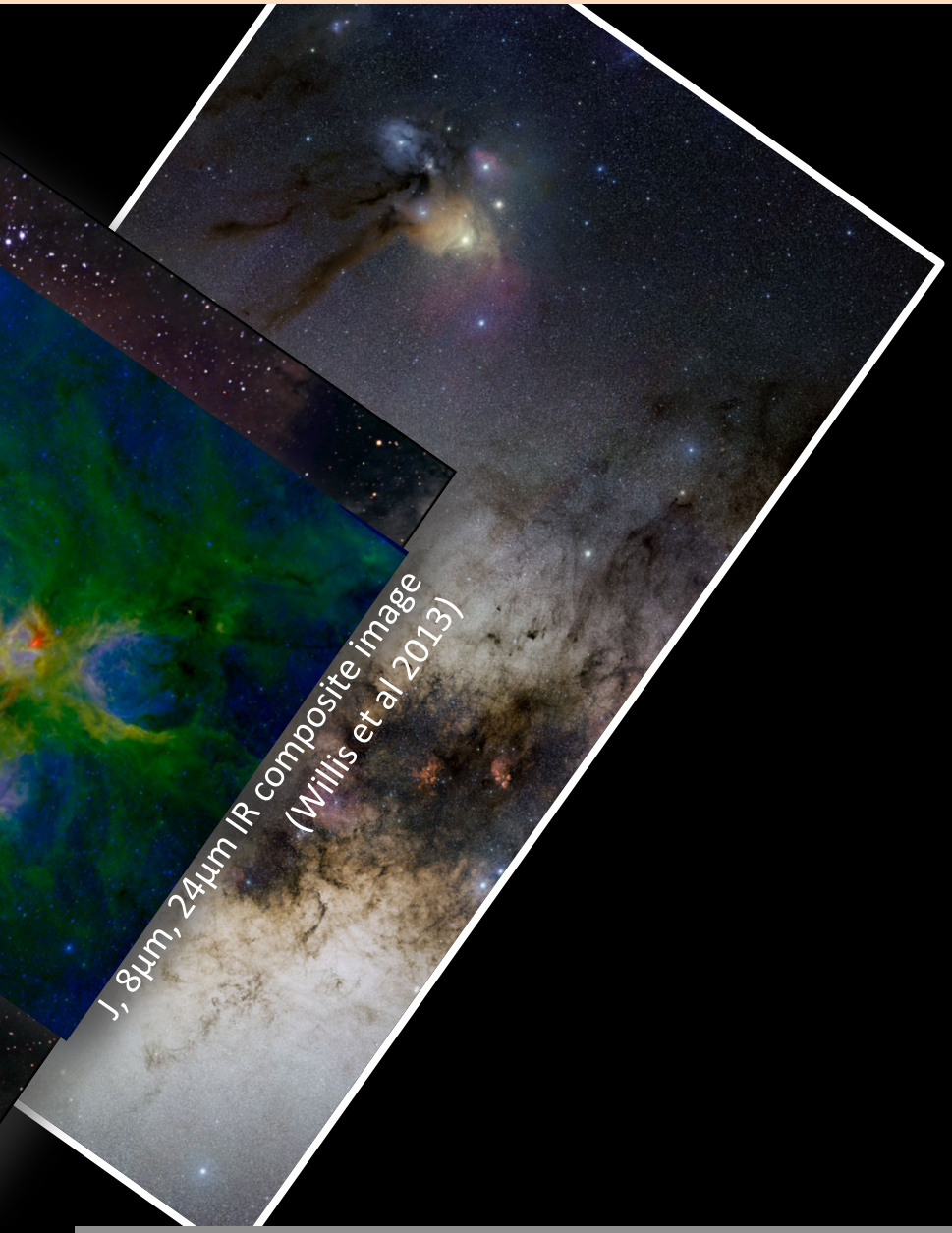
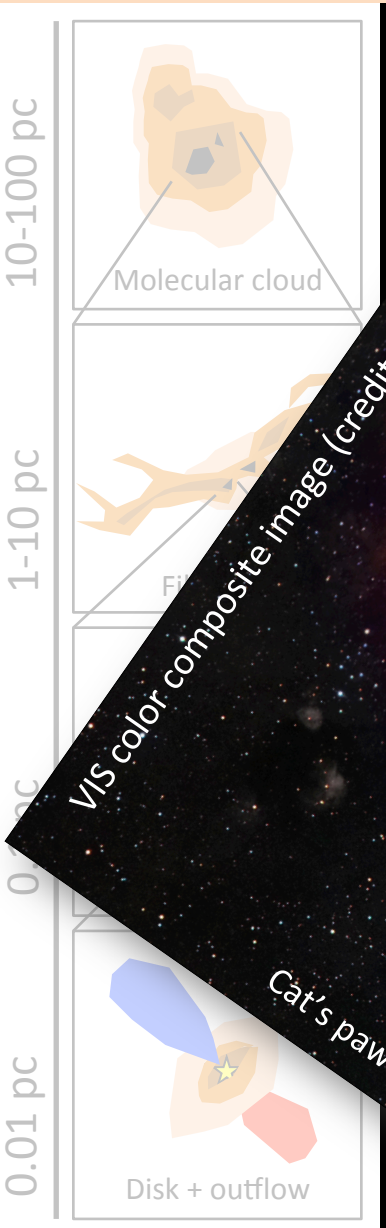




Mass transport through filaments



NGC 6334 star forming complex

VIS color composite image (credit: M. Caligiuri)

Cat's paw (NGC 6334)

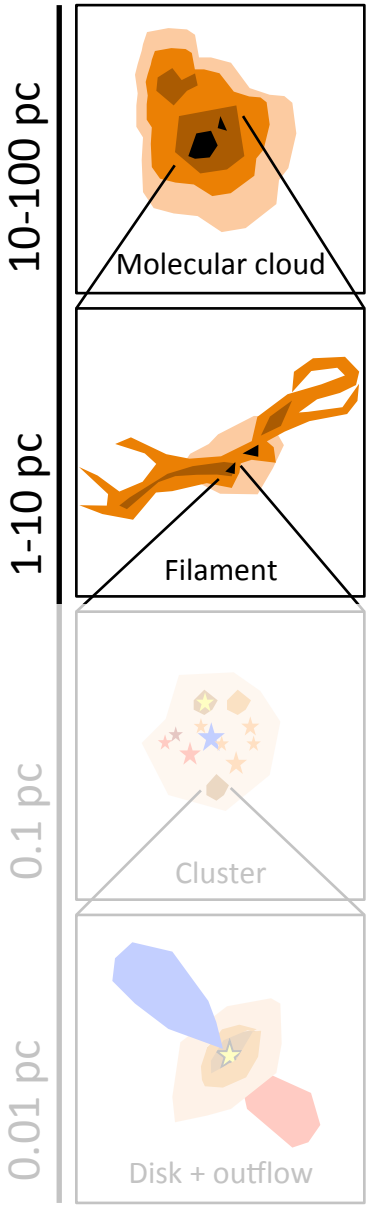
ATLASGAL 870 µm (Schuller et al 2009)

10 pc

J, 8µm, 24µm IR composite image (Willis et al 2013)

distance of 1.3 kpc (maser parallax; Wu et al 2014, Chibueze et al 2014)

Mass transport through filaments



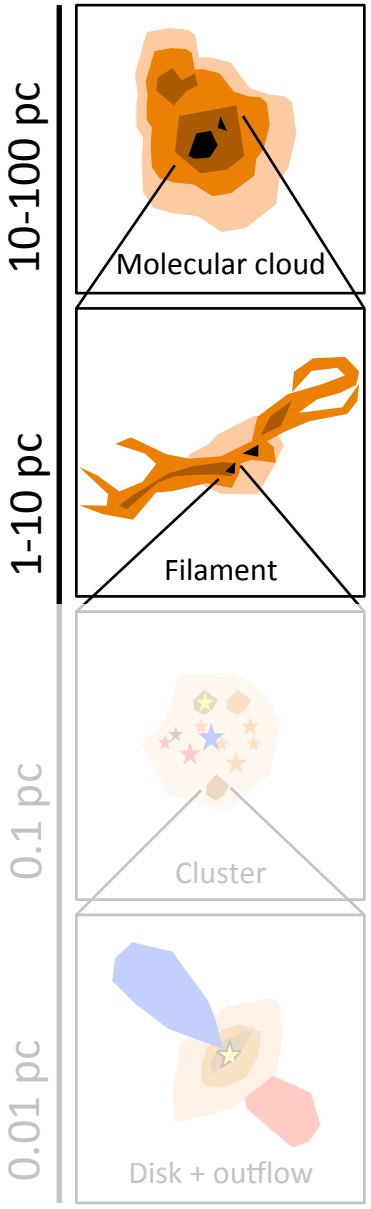
NGC 6334 star forming complex

10 pc

Hi-GAL/*Herschel* 250 µm (Molinari et al 2010)

distance of 1.3 kpc (maser parallax; Wu et al 2014, Chibueze et al 2014)

Mass transport through filaments



NGC 6334 star forming complex

Long filament of about 60 pc, with a mass of about $2 \cdot 10^4$ $M_\odot$
Central filament is 12 pc x 0.3 pc

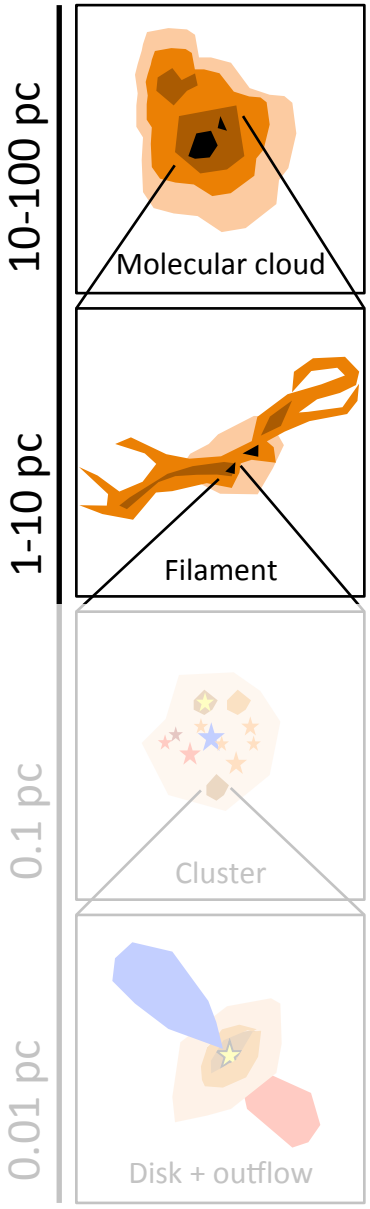
Active (high-mass) star formation occurs within the central filament
… but how does mass flow from large-scales to stars?

10 pc

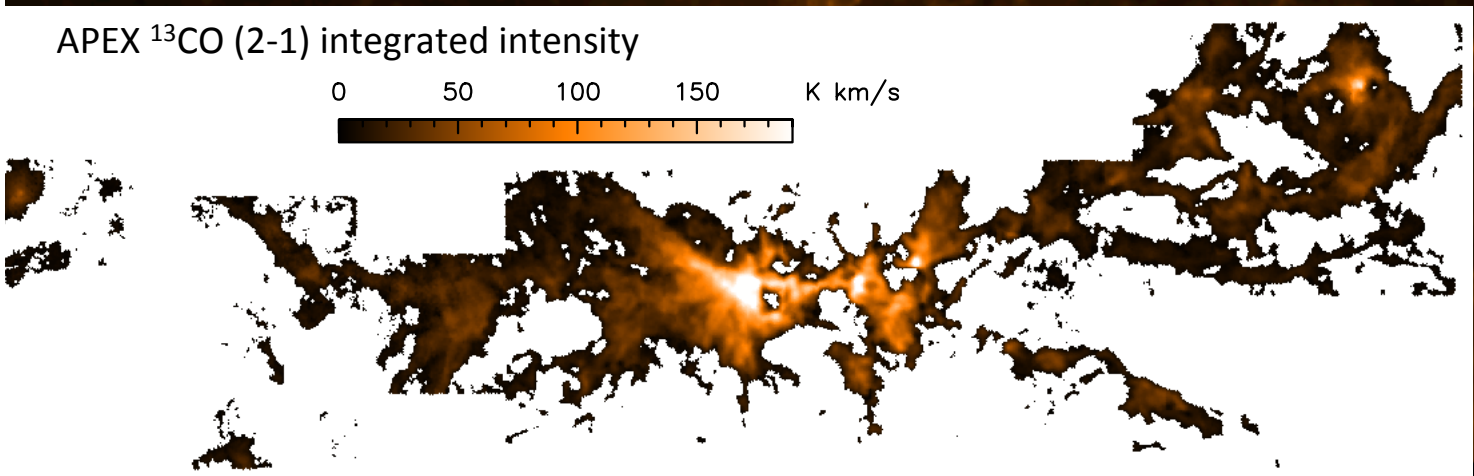
Hi-GAL/*Herschel* 250 µm (Molinari et al 2010)

distance of 1.3 kpc (maser parallax; Wu et al 2014, Chibueze et al 2014)

Mass transport through filaments



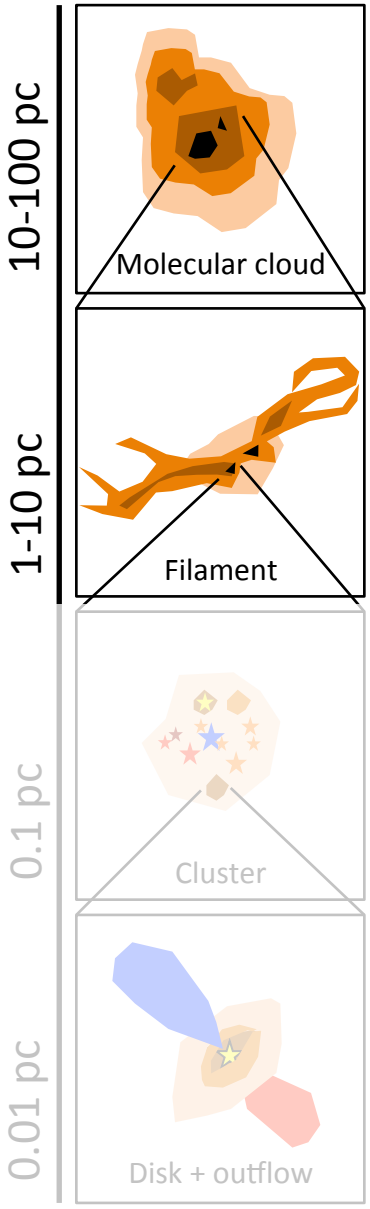
The mass flow can be studied with molecular line observations



10 pc

Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, … Sánchez-Monge et al. (2022)

Mass transport through filaments



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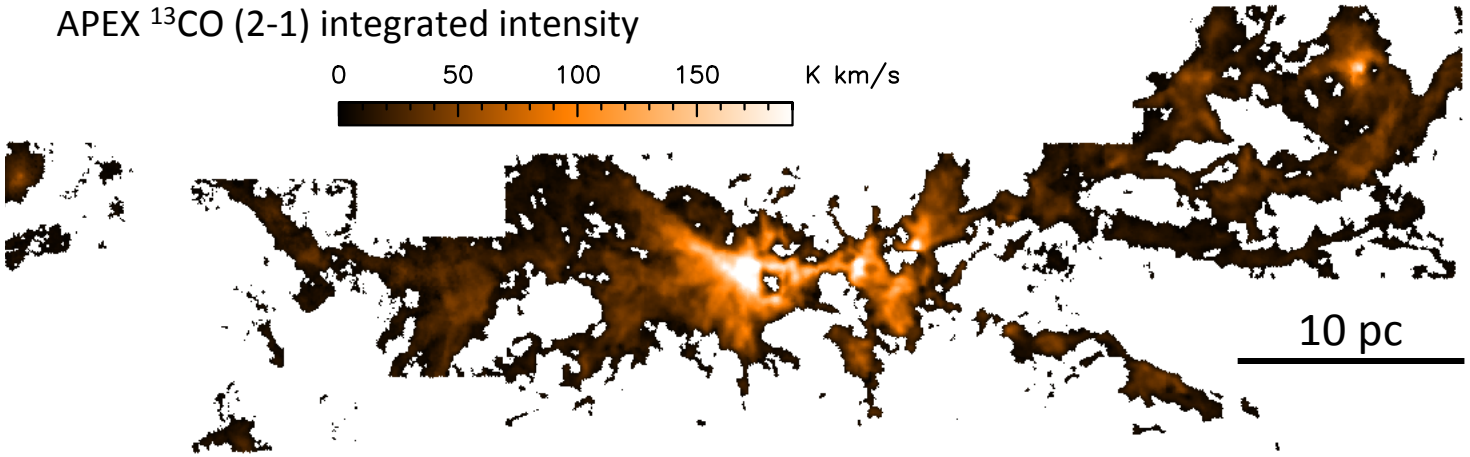

Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, … Sánchez-Monge et al. (2022)

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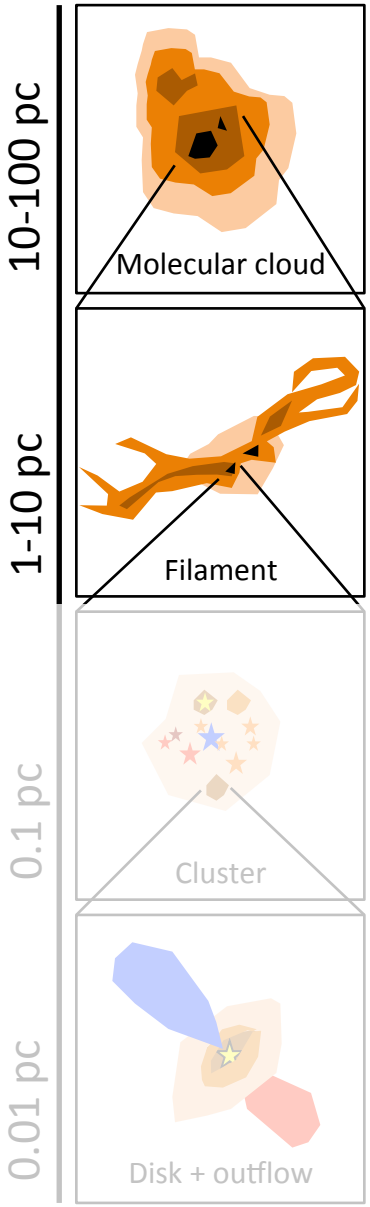
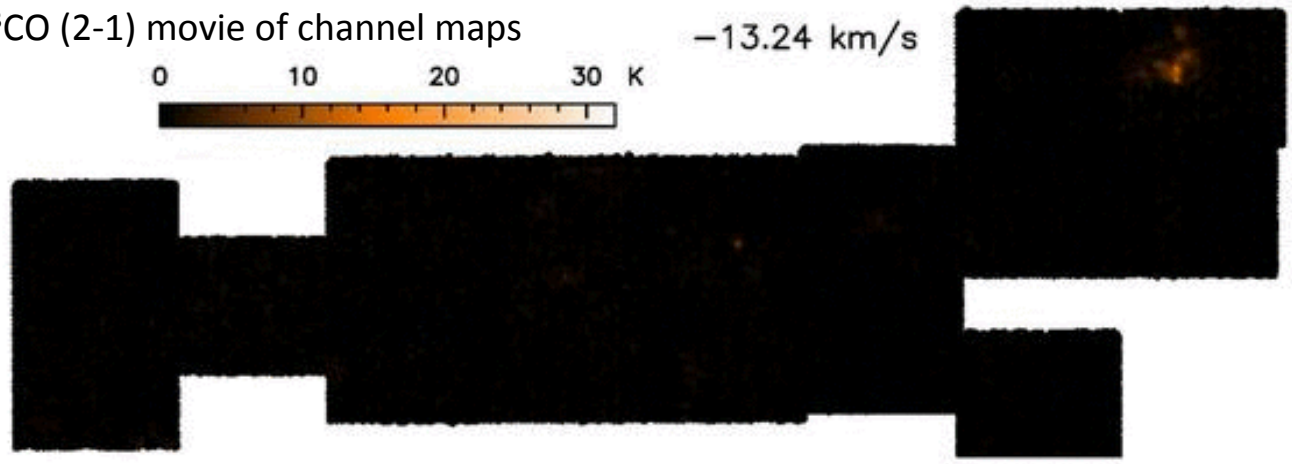


The mass flow can be studied with molecular line observations

APEX ^{13}CO (2-1) movie of channel maps

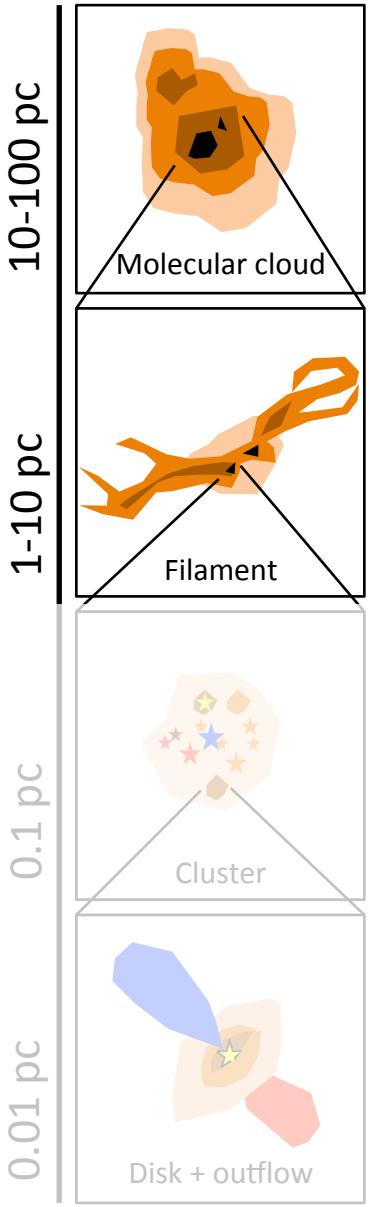


Velocity gradient on large scales

… and along filamentary structures

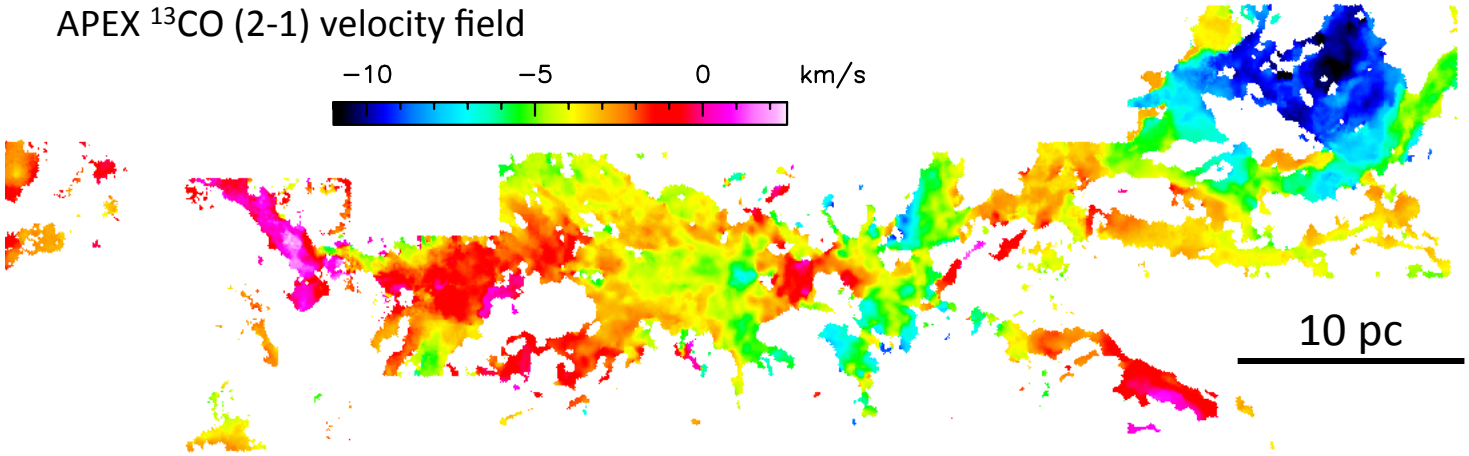
Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, … Sánchez-Monge et al. (2022)

Mass transport through filaments



The mass flow can be studied with molecular line observations

APEX ^{13}CO (2-1) velocity field

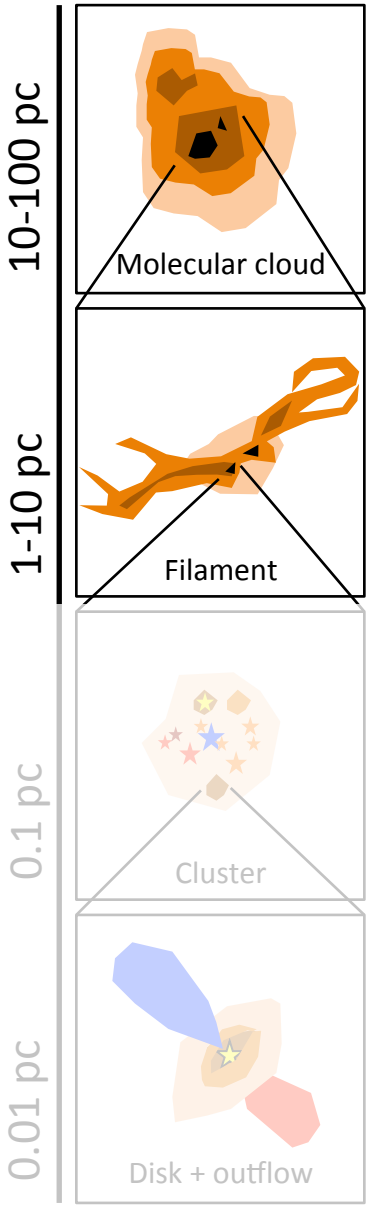


Velocity gradient on large scales … and along filamentary structures

Average velocity gradient : 1 km/s/pc

Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, … Sánchez-Monge et al. (2022)

Mass transport through filaments

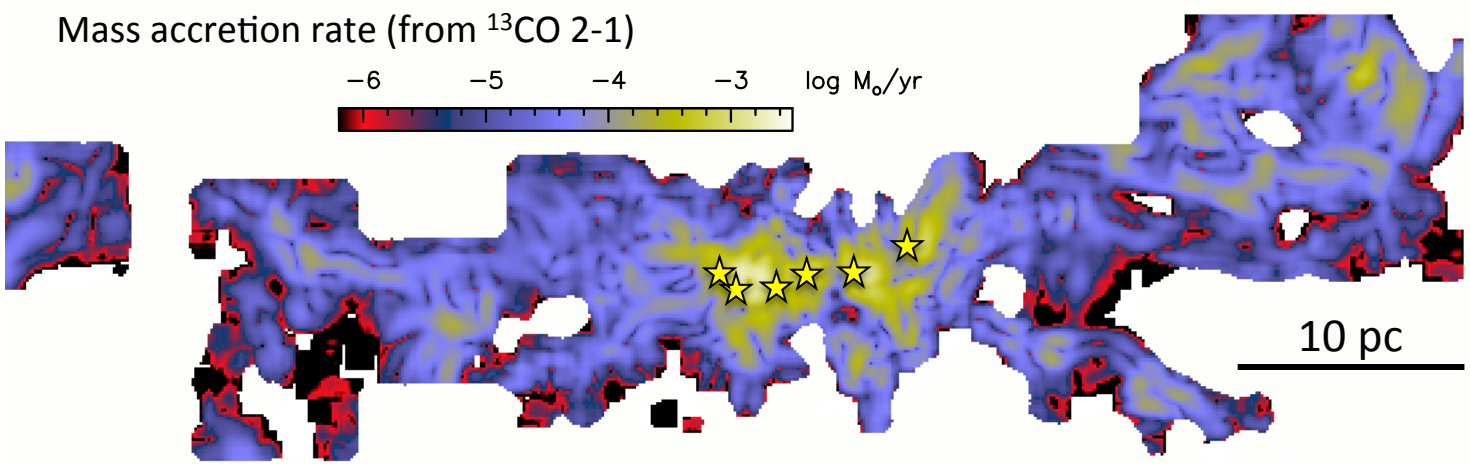


High accretion rates (10^{-3} $M_\odot$/yr) toward dense sites of star formation

The mass flow can be studied with molecular line observations

Throughout the filament, accretion rates about 10^{-5} – 10^{-4} $M_\odot$/yr

Mass accretion rate (from ^{13}CO 2-1)

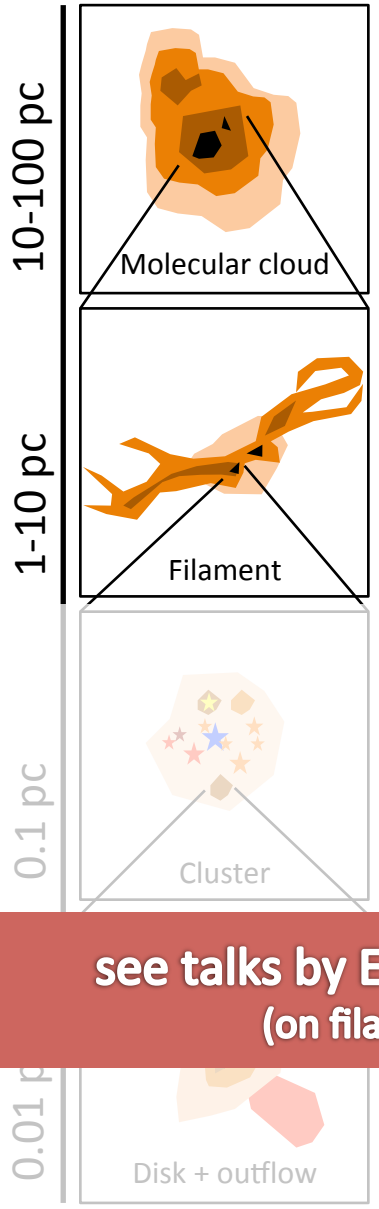


Mass accretion rate can be derived as: $\dot{M} = (M/L \times v_{||}) / \tan(\alpha)$

with: $v_{||}$ velocity gradient parallel to the filament, M/L mass per line density, and $\alpha = 45^o$

Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, … Sánchez-Monge et al. (2022)

Mass transport through filaments

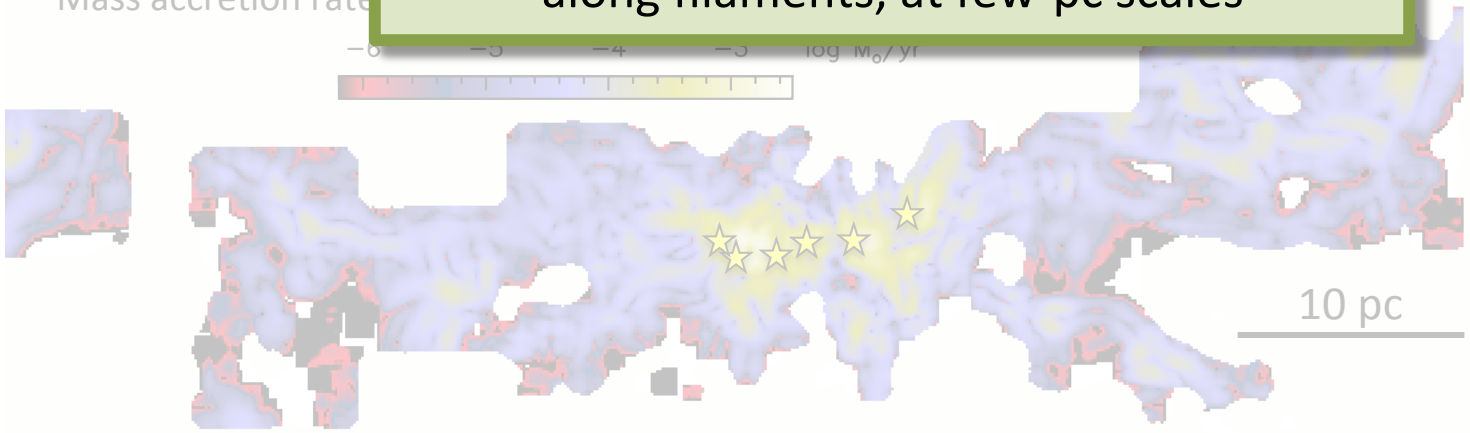


High-accretion ra
Throughout the

Mass accretion rate

Take home messages

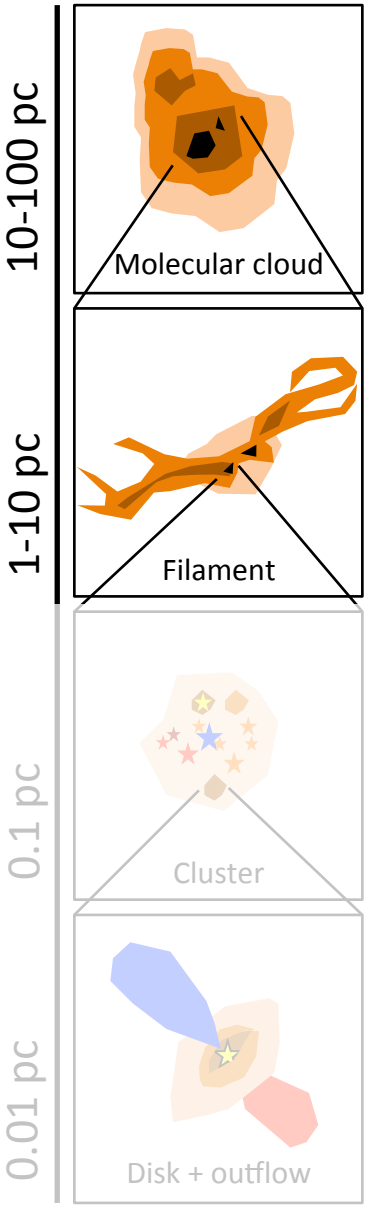
Mass accretion rates of 10^{-5} – 10^{-3} $M_\odot$/yr along filaments, at few-pc scales

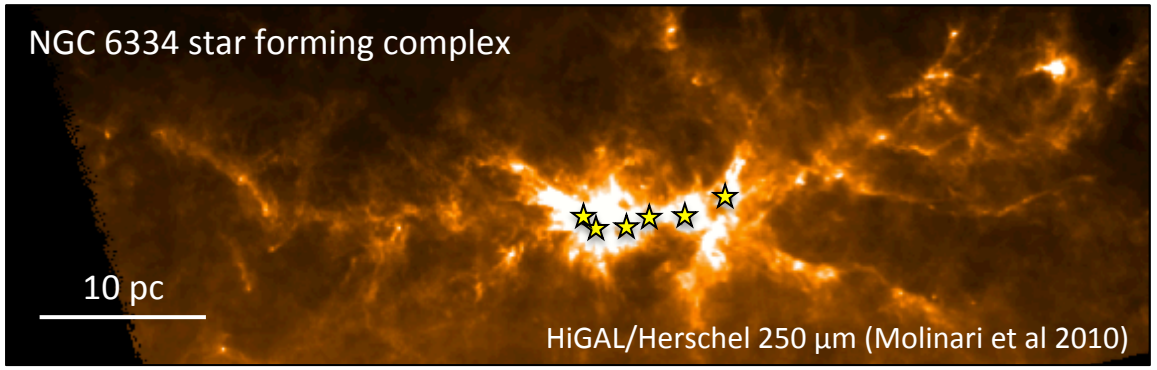


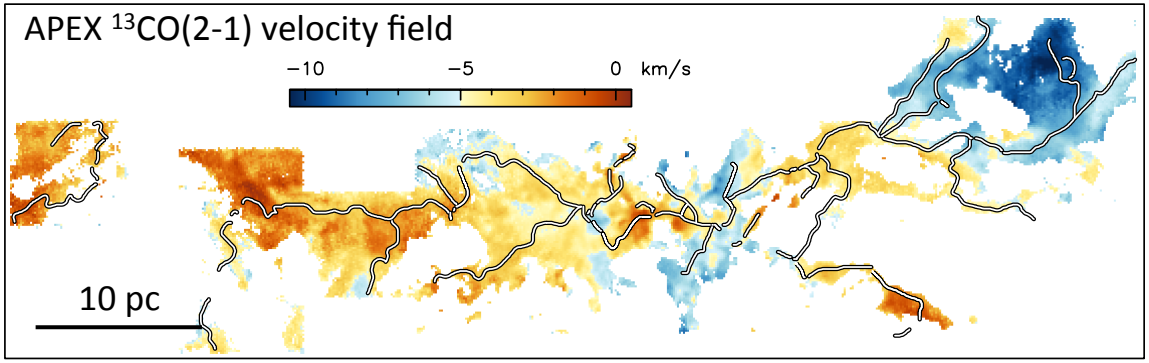
see talks by Emma Mannfors, Mika Juvela, Dana Makarova, Jonathan Oers, ...
(on filament properties, hub-filament systems and column density estimates)

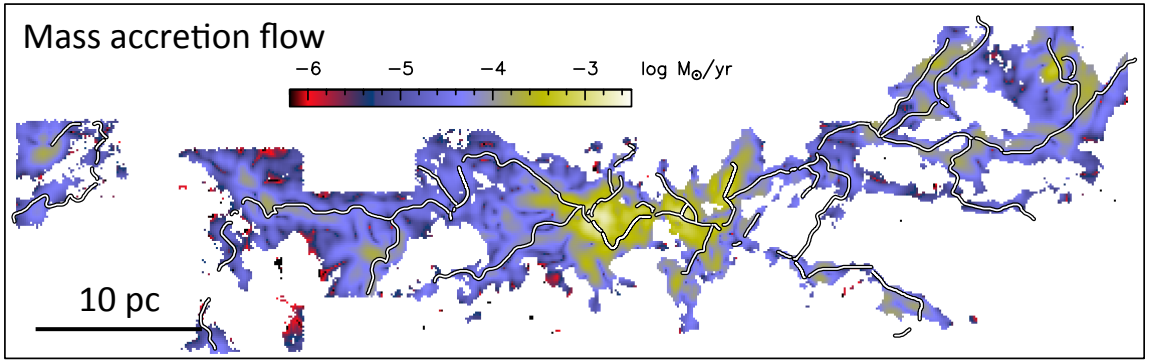
Zernickel et al. (2013) / Zernickel (2015, PhD) / Sánchez-Monge et al (2015) / Arzoumanian, ... Sánchez-Monge et al. (2022)

Mass transport through filaments



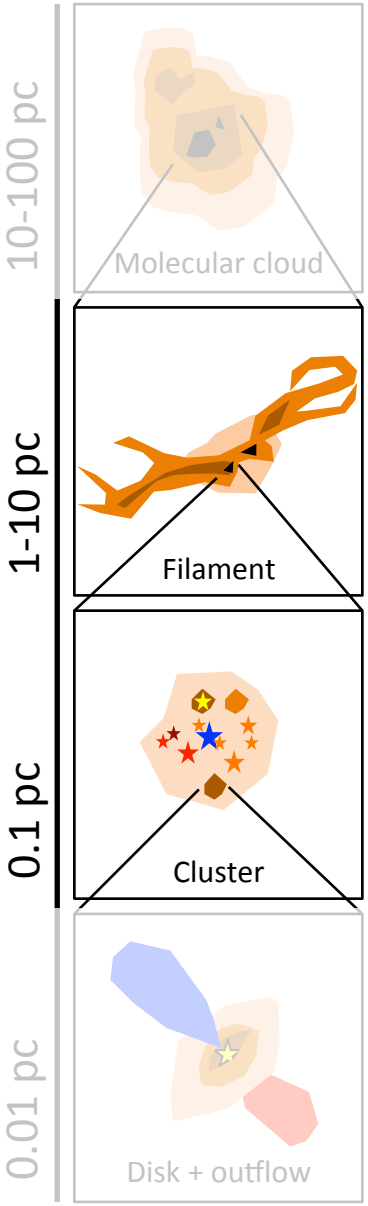


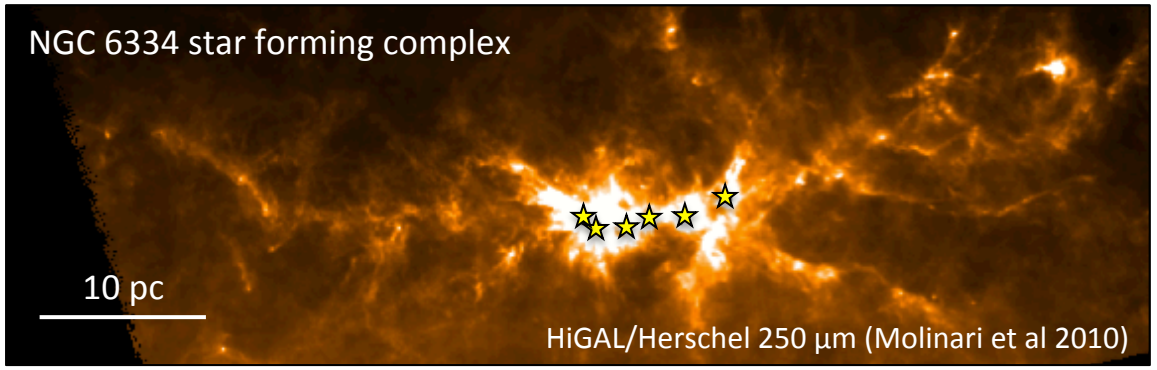


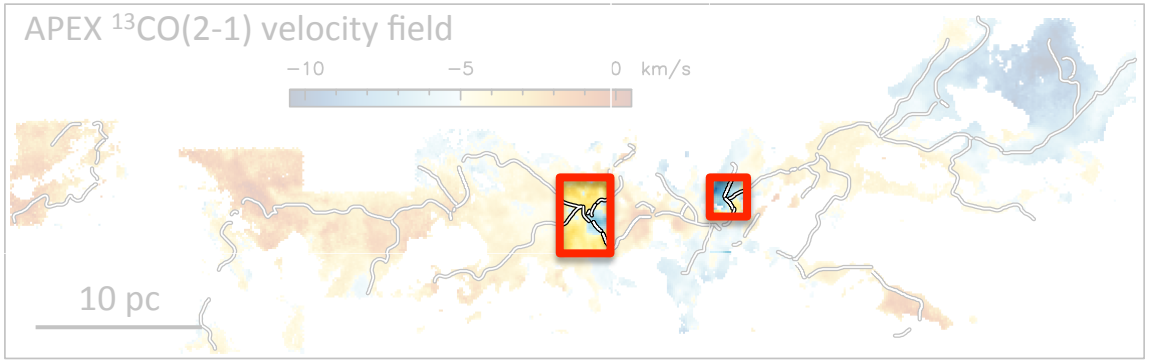


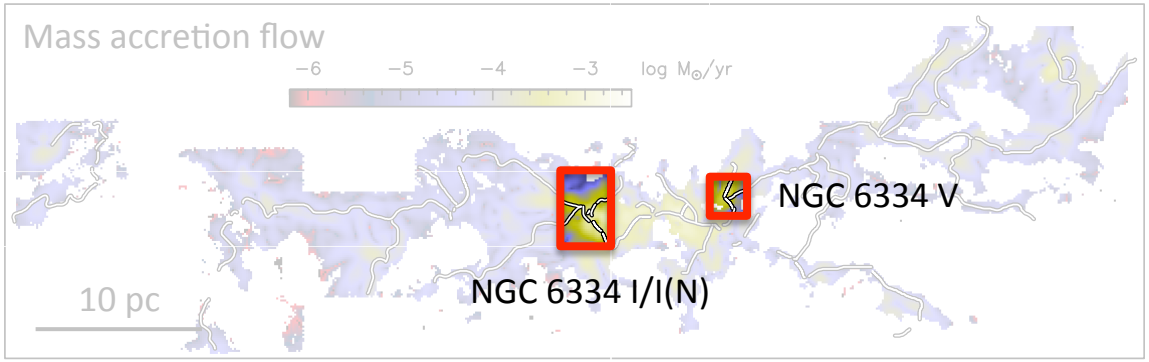
Accretion of material – from large clouds to clusters and stars

Formation of clusters and their properties



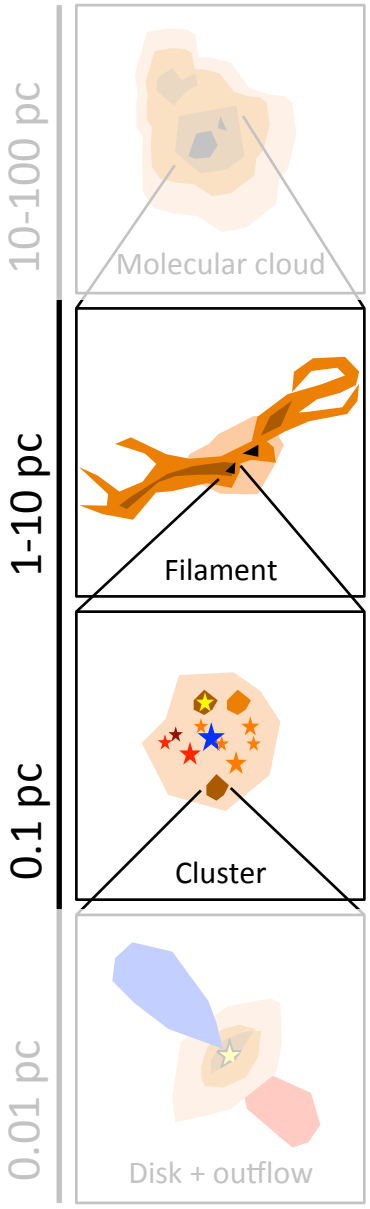


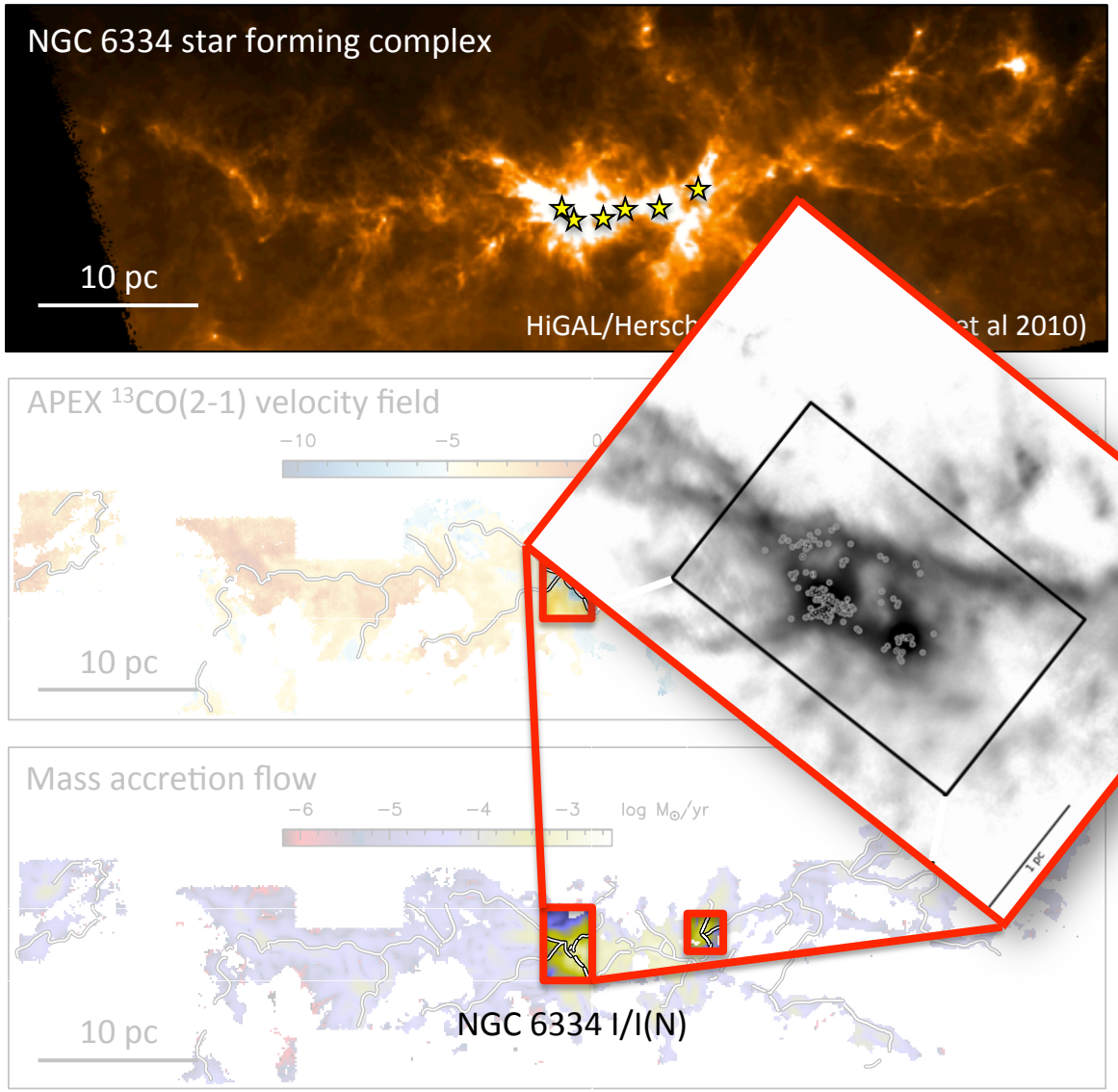




Zooming into the densest structures

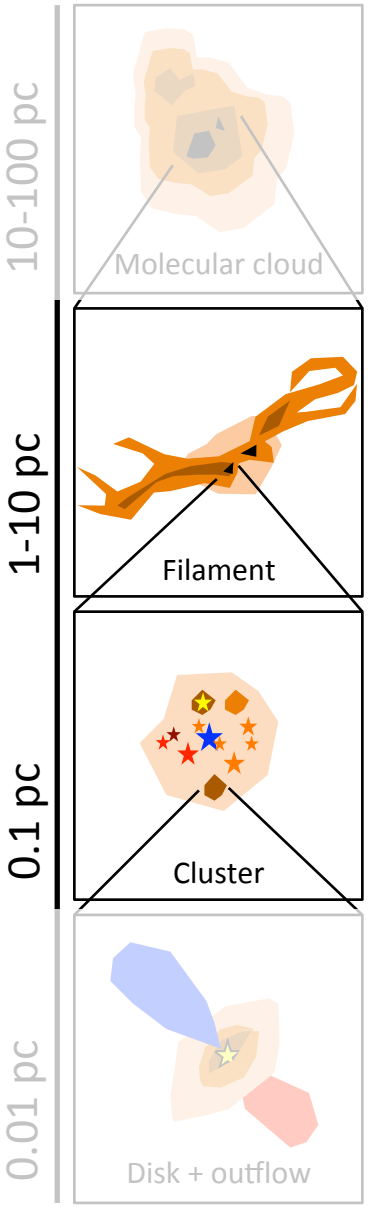
Formation of clusters and their properties

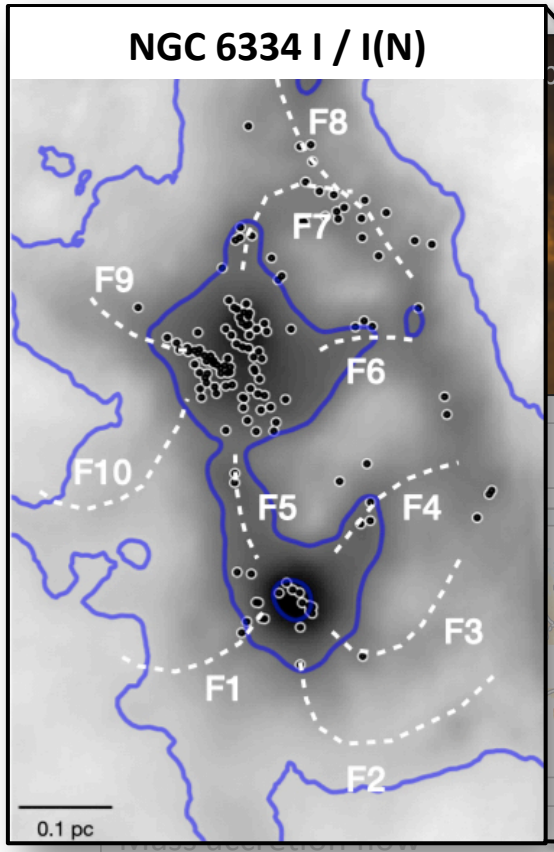


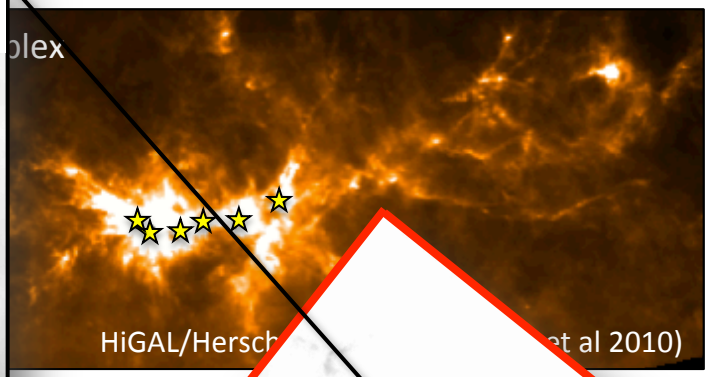


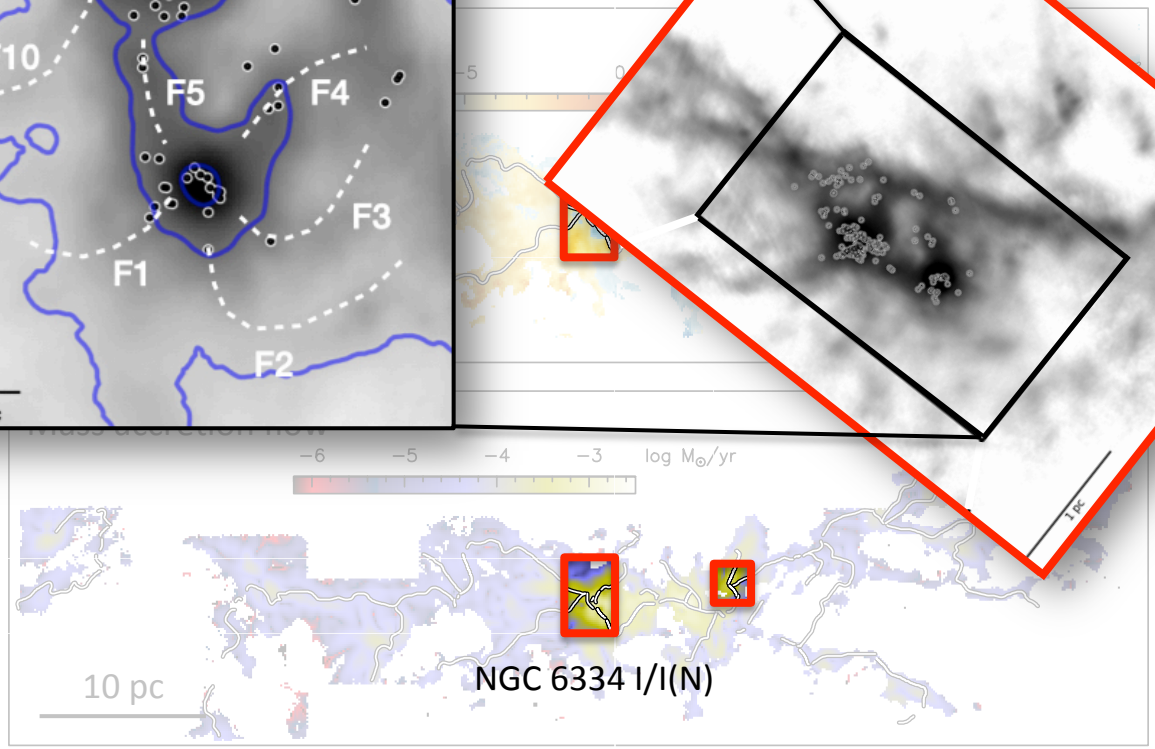
Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

Formation of clusters and their properties





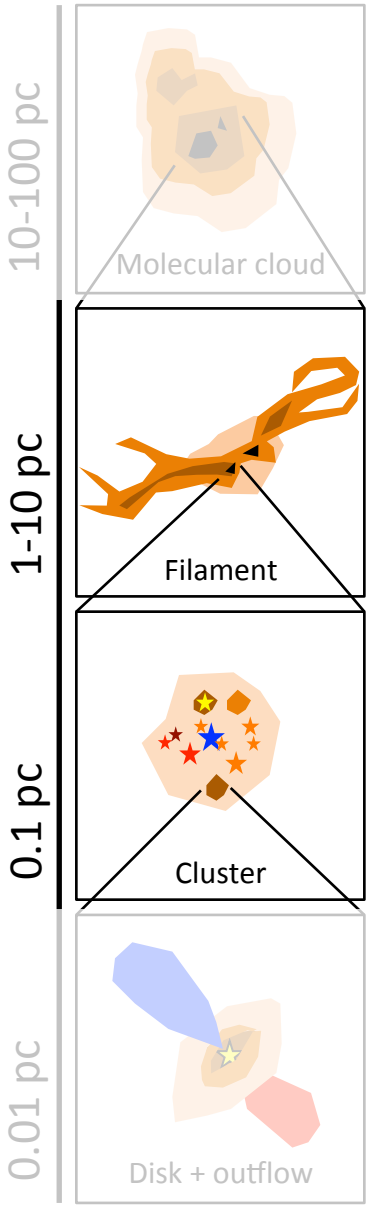


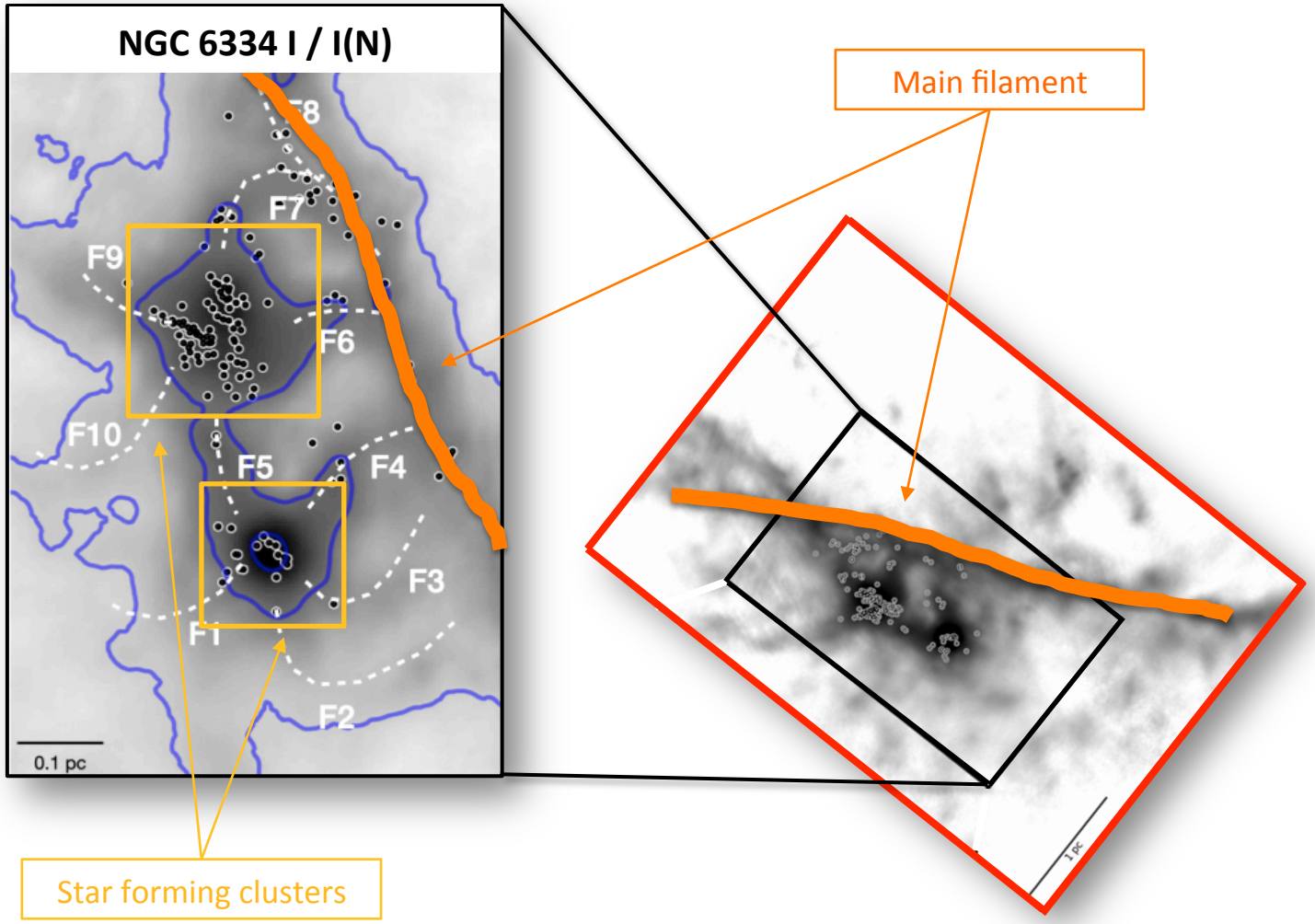


Zooming into densest structures

Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

Formation of clusters and their properties

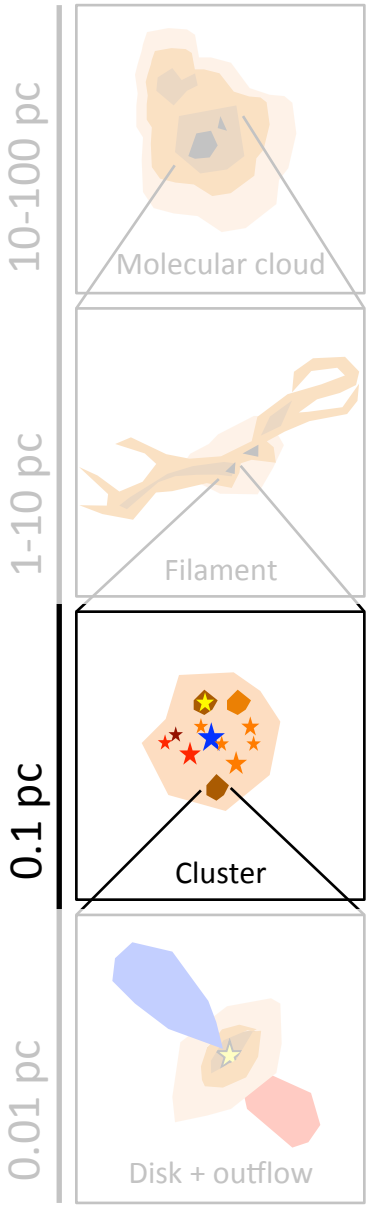


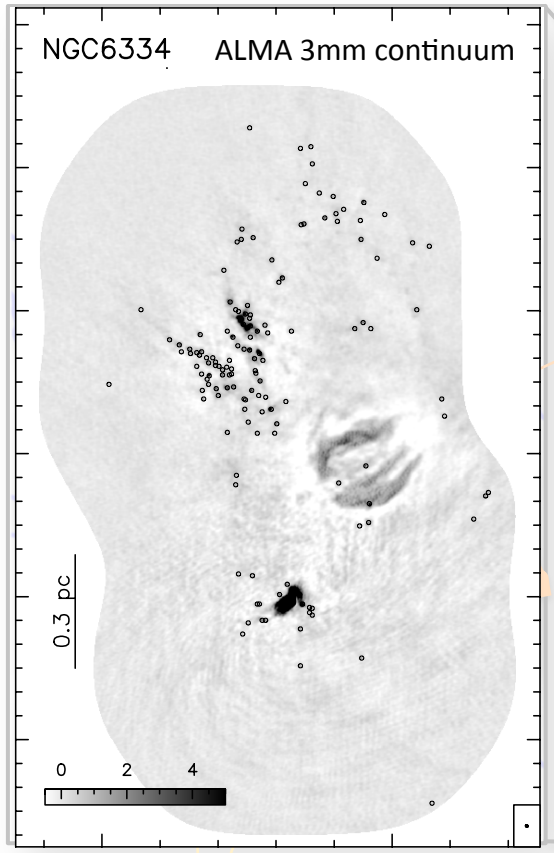


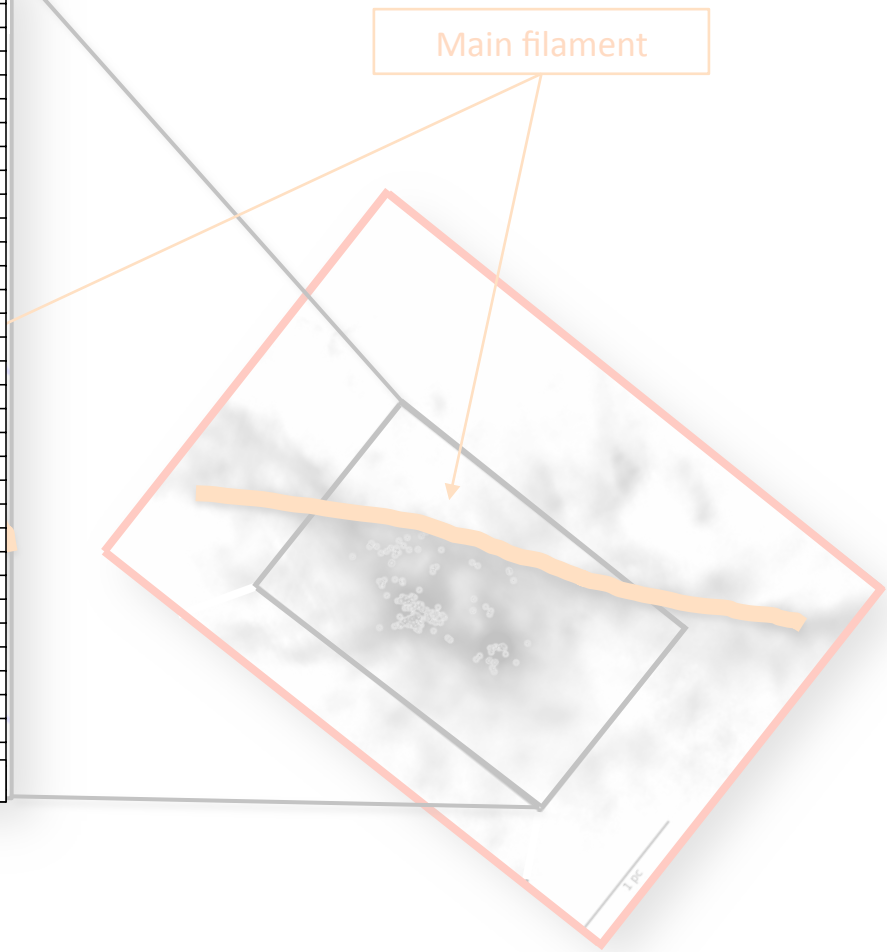
Accretion from filaments to star clusters is about 1-3 x 10^{-3} $M_{\odot}$/yr
In agreement with the mass flow at large scales

Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

Formation of clusters and their properties





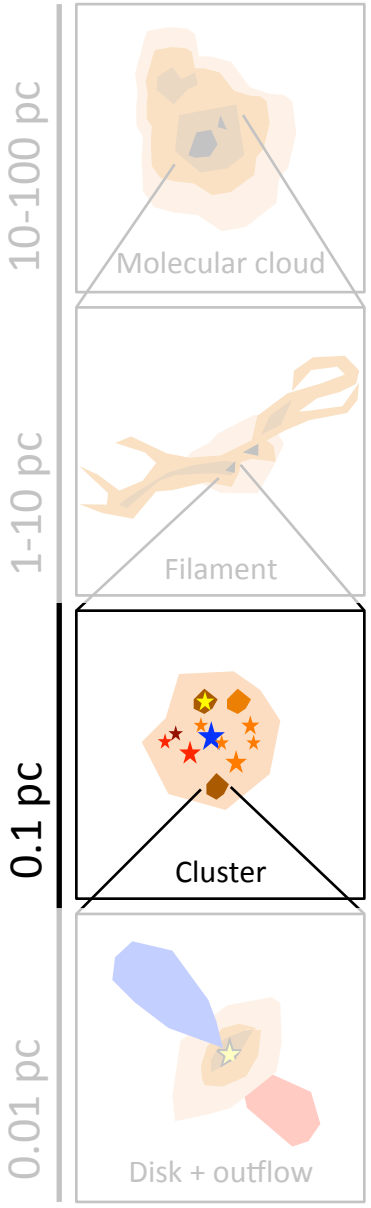


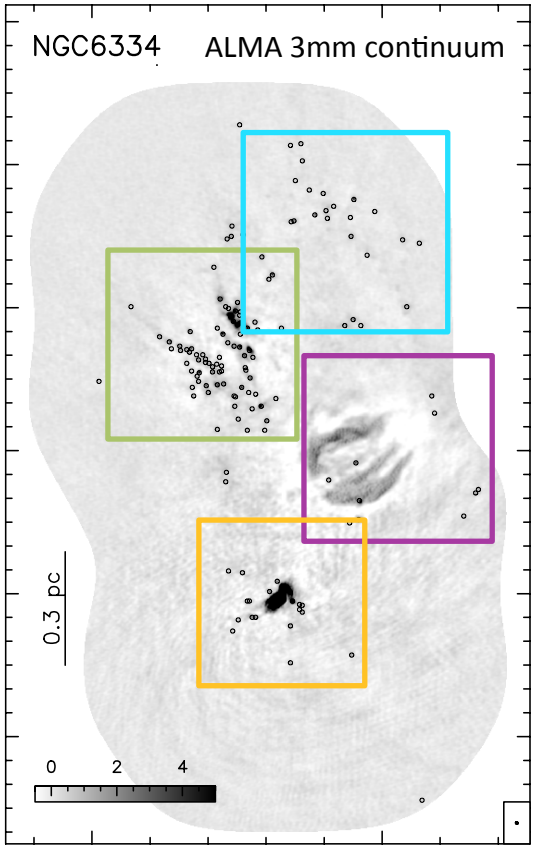
Star forming clusters

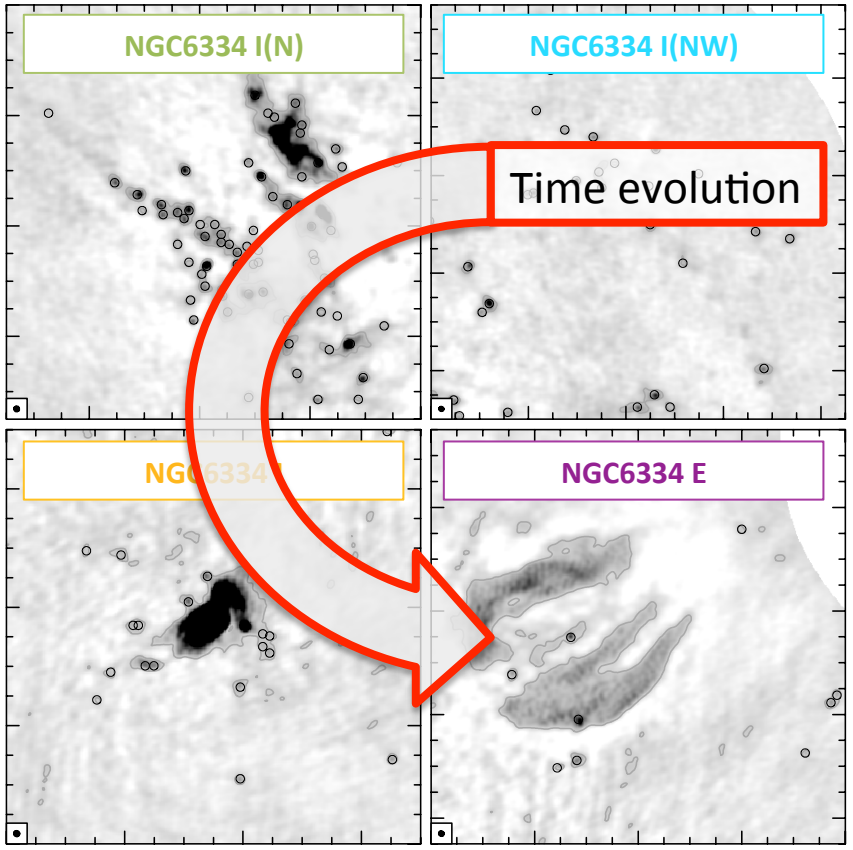
What are the properties of the forming clusters?

Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

Formation of clusters and their properties



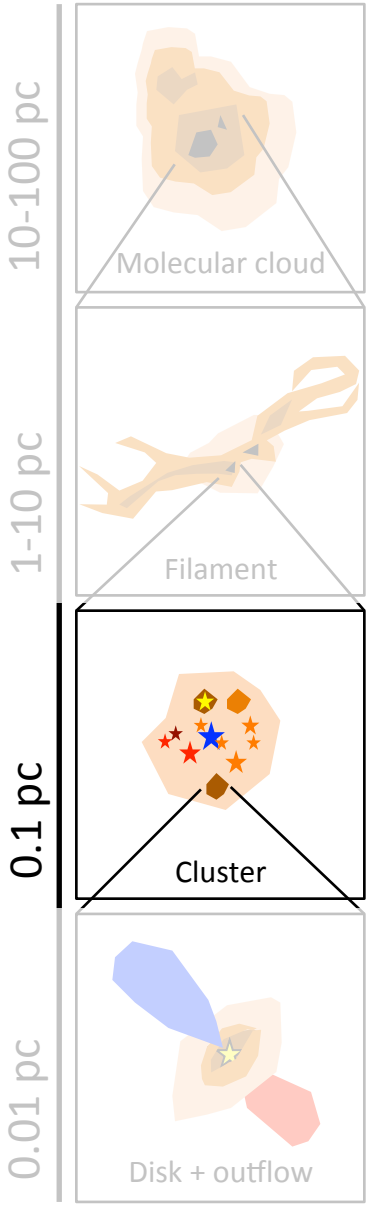


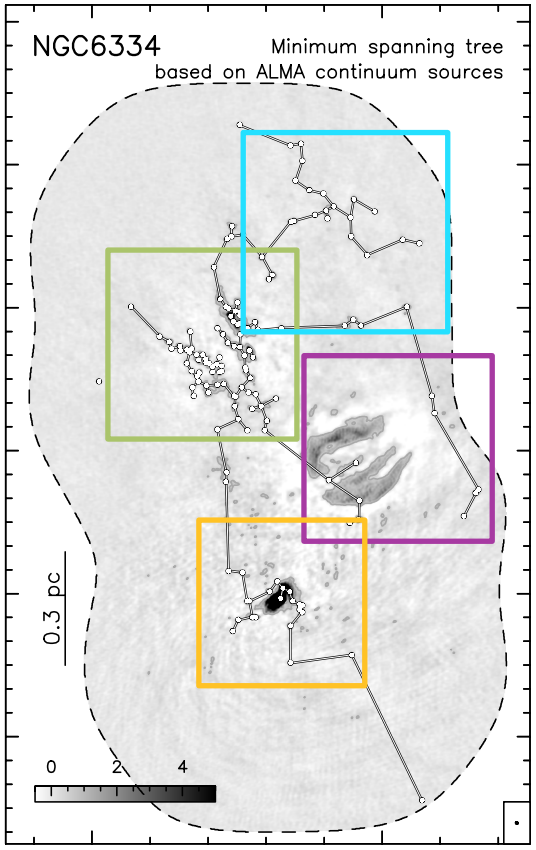


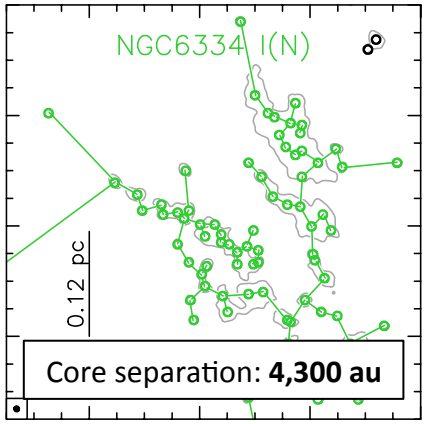
- Four clusters identified with different clustering/machine learning techniques in different evolutionary stages (from less to more evolved: NW → I(N) → I → E)

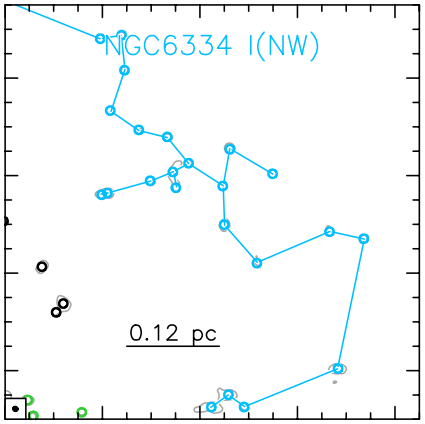
Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

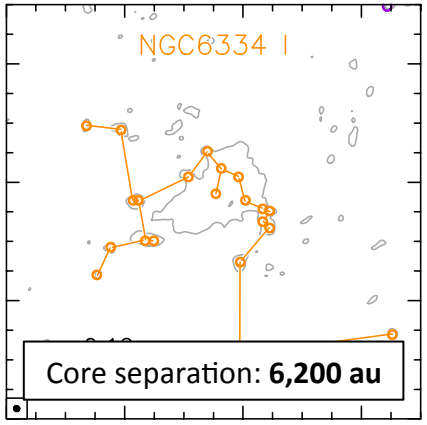
Formation of clusters and their properties

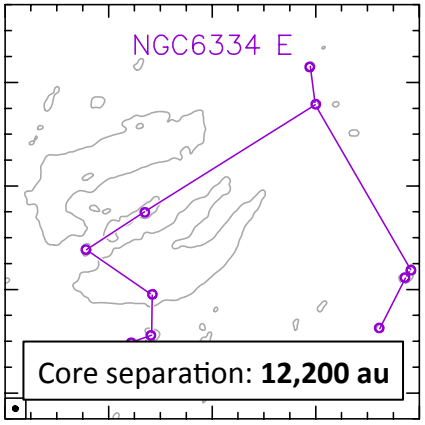








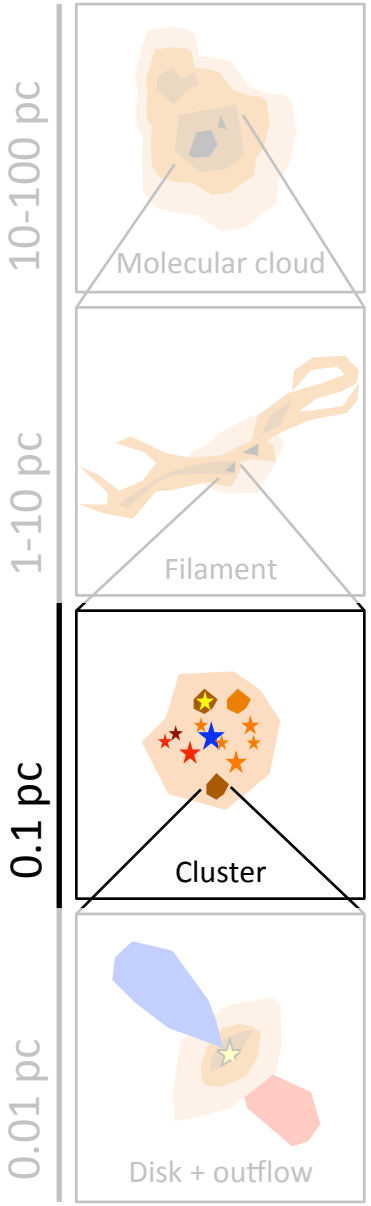


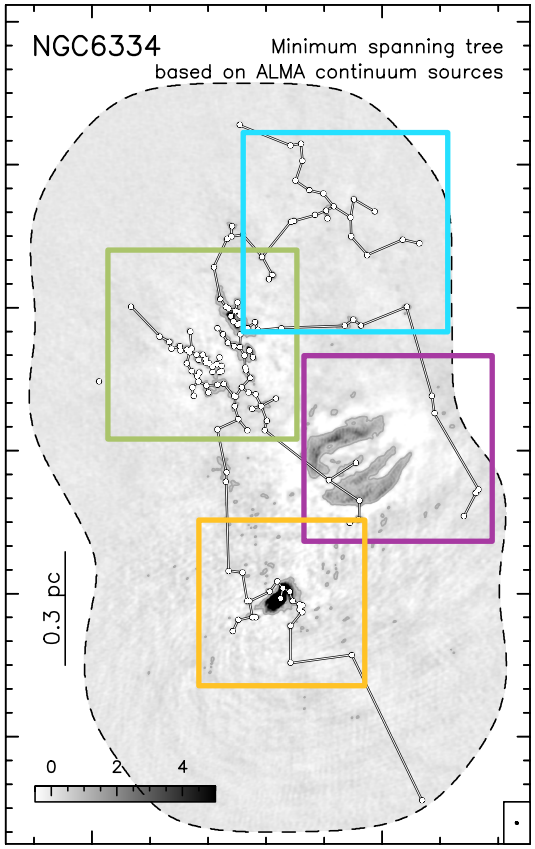


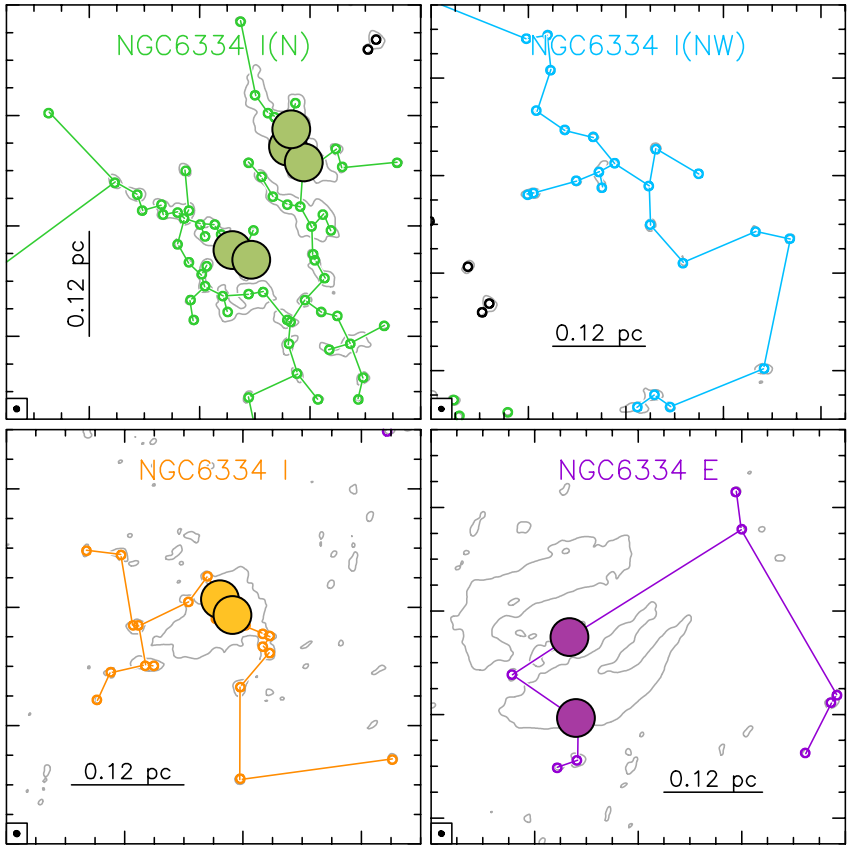
- Four clusters identified with different clustering/machine learning techniques in different evolutionary stages (from less to more evolved: NW → I(N) → I → E)
- Spatial distribution: cores drift away with time (e.g., due to dynamic effects)

Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

Formation of clusters and their properties







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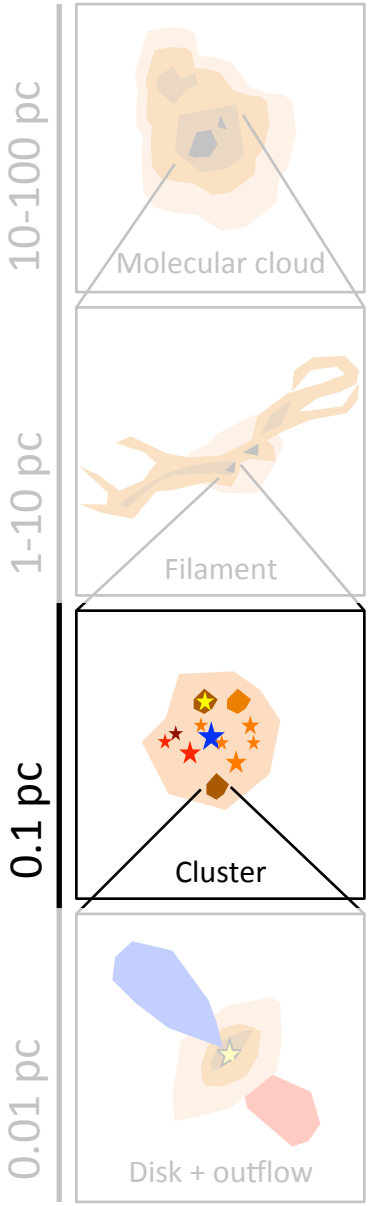

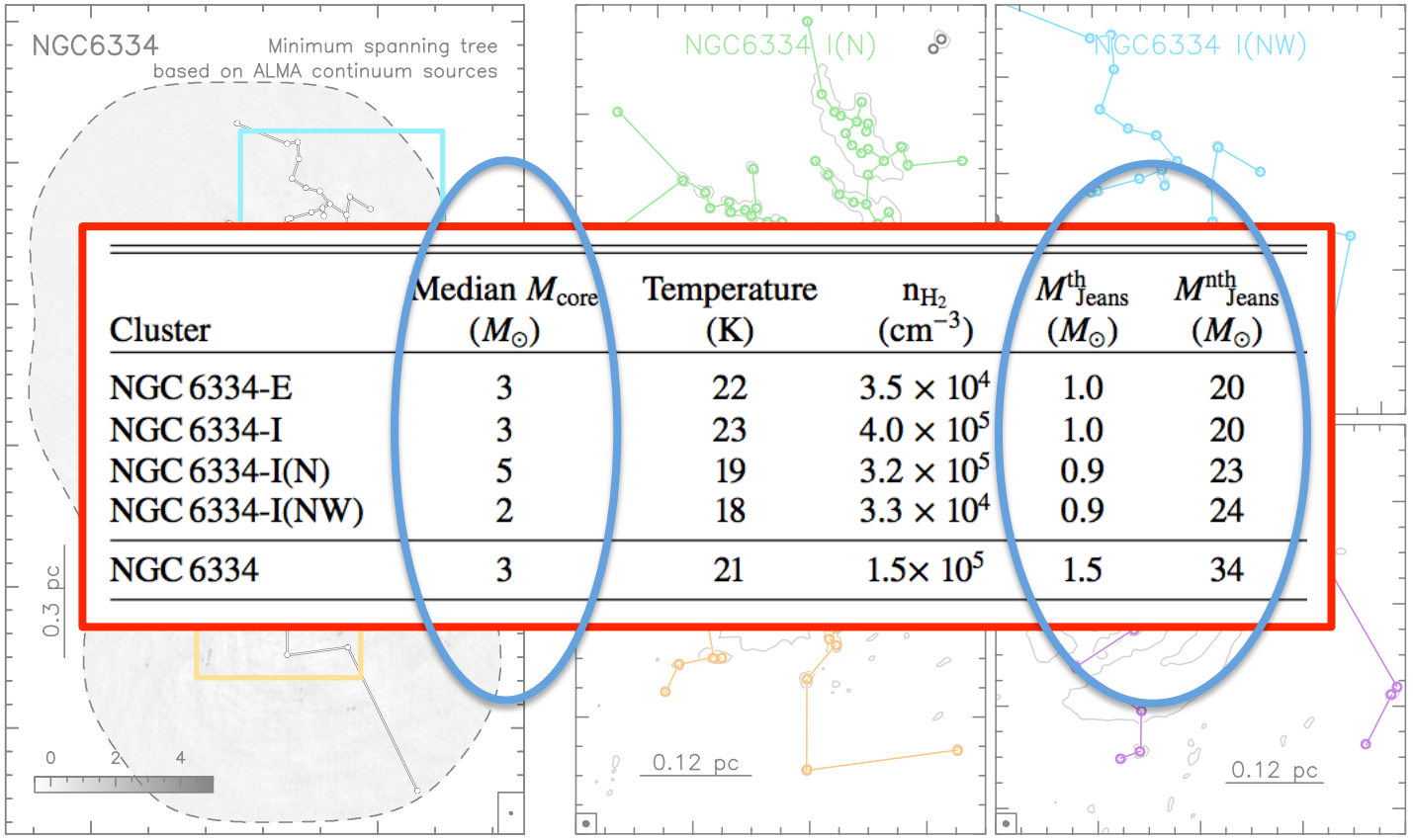

Cluster	Median M_{core} ($M_\odot$)	Temperature (K)	n_{H_2} (cm^{-3})	M^{th}_{Jeans} ($M_\odot$)	M^{nth}_{Jeans} ($M_\odot$)
NGC 6334-E	3	22	3.5×10^4	1.0	20
NGC 6334-I	3	23	4.0×10^5	1.0	20
NGC 6334-I(N)	5	19	3.2×10^5	0.9	23
NGC 6334-I(NW)	2	18	3.3×10^4	0.9	24
NGC 6334	3	21	1.5×10^5	1.5	34

- Four clusters identified with different clustering/machine learning techniques in different evolutionary stages (from less to more evolved: NW → I(N) → I → E)
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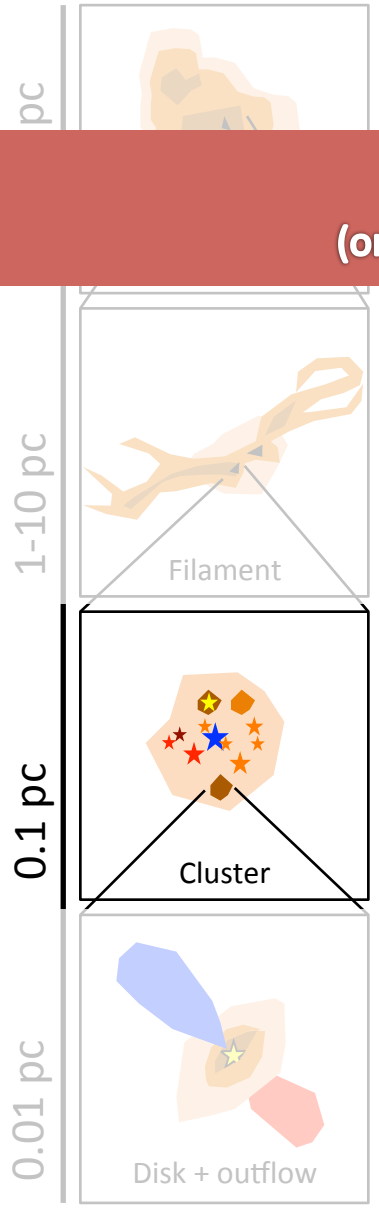
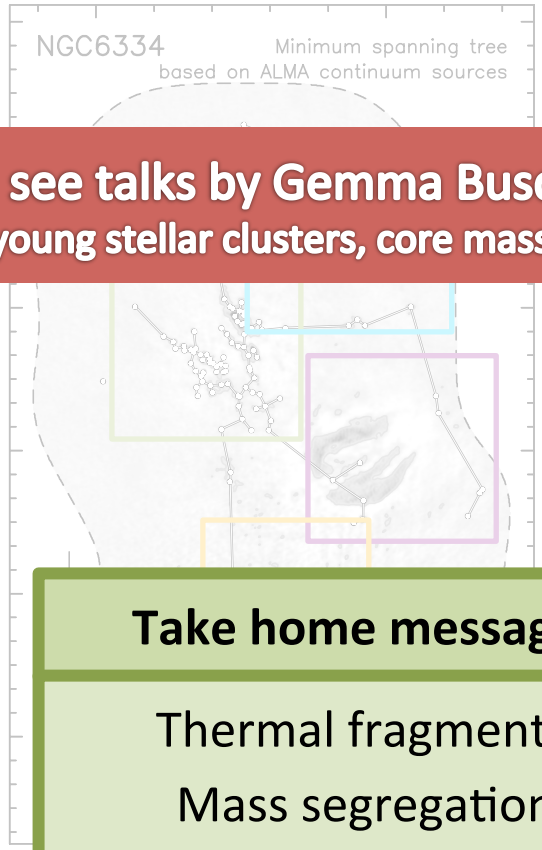
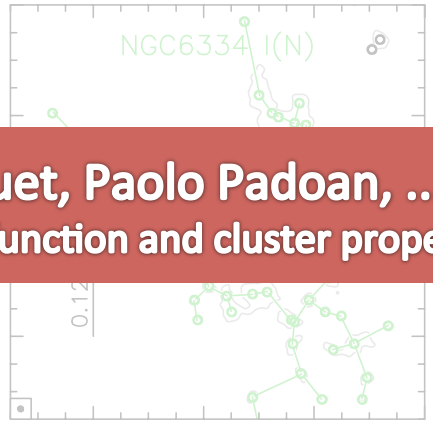
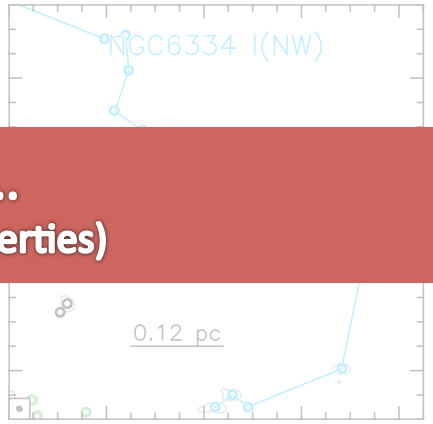
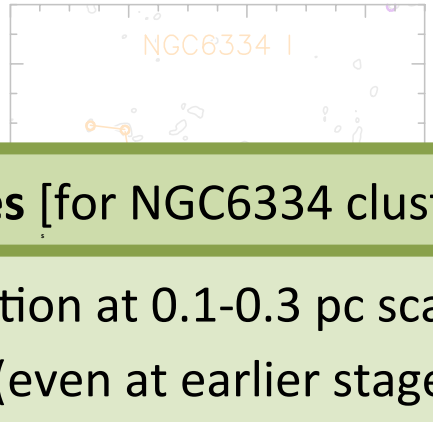
Formation of clusters and their properties

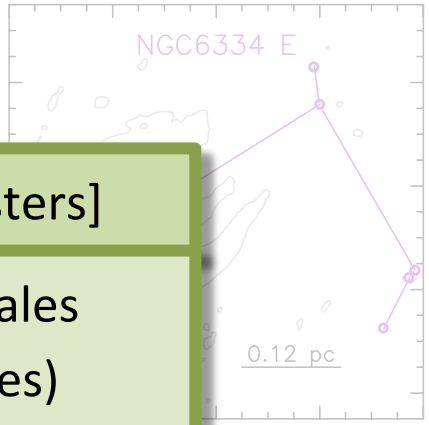












see talks by Gemma Busquet, Paolo Padoan, ...
(on young stellar clusters, core mass function and cluster properties)

Take home messages [for NGC6334 clusters]

Thermal fragmentation at 0.1-0.3 pc scales

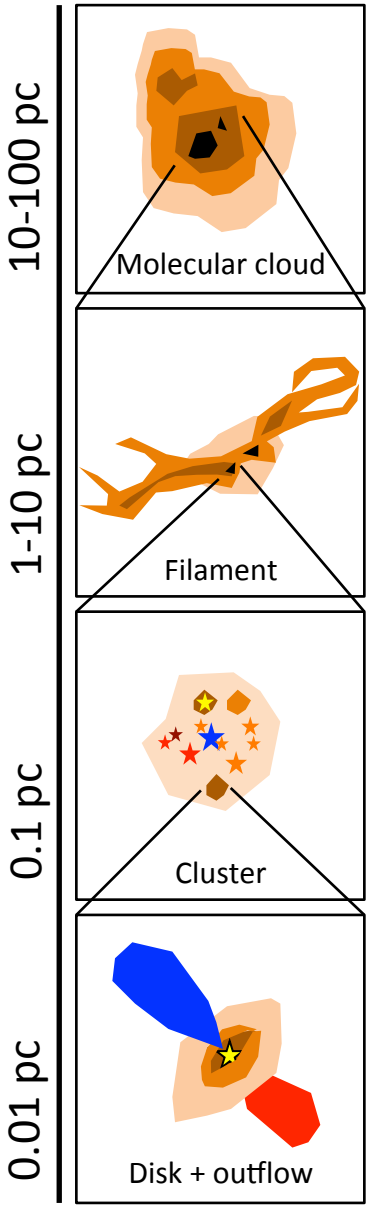
Mass segregation (even at earlier stages)

Cores drift away with time

- echniques
in different evolutionary stages (from less to more evolved: NW → I(N) → I → E)
- Spatial distribution: cores drift away with time (e.g., due to dynamic effects)
- Mass segregation: massive cores are located at the center since its formation
- Observed fragmentation in agreement with thermal fragmentation

Sadaghiani, Sánchez-Monge et al (2020) / Sadaghiani (2021, PhD) / Aghababei, Sánchez-Monge et al (2023, in prep)

From clouds to stars



Questions on Star (Cluster) Formation

Q. How do molecular clouds fragment into stellar clusters?

Q. Do all stellar clusters form in the same way?

Q. How do (proto-)stellar clusters evolve with time?

Q. How is mass transported from the large clouds down to stars?

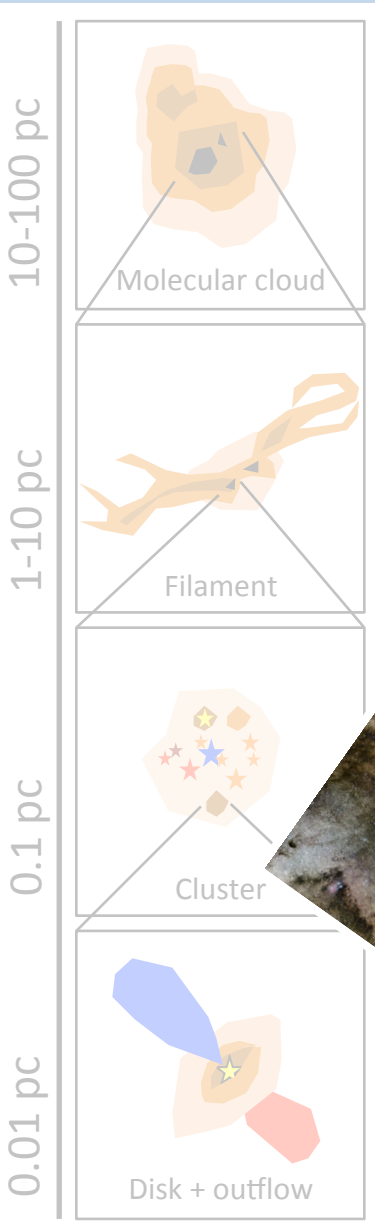
Q. What is the role of gravity, turbulence and magnetic fields?

Q. How does feedback originate and affect the whole process?

Q. What is the role of proto-stellar/planetary disks?

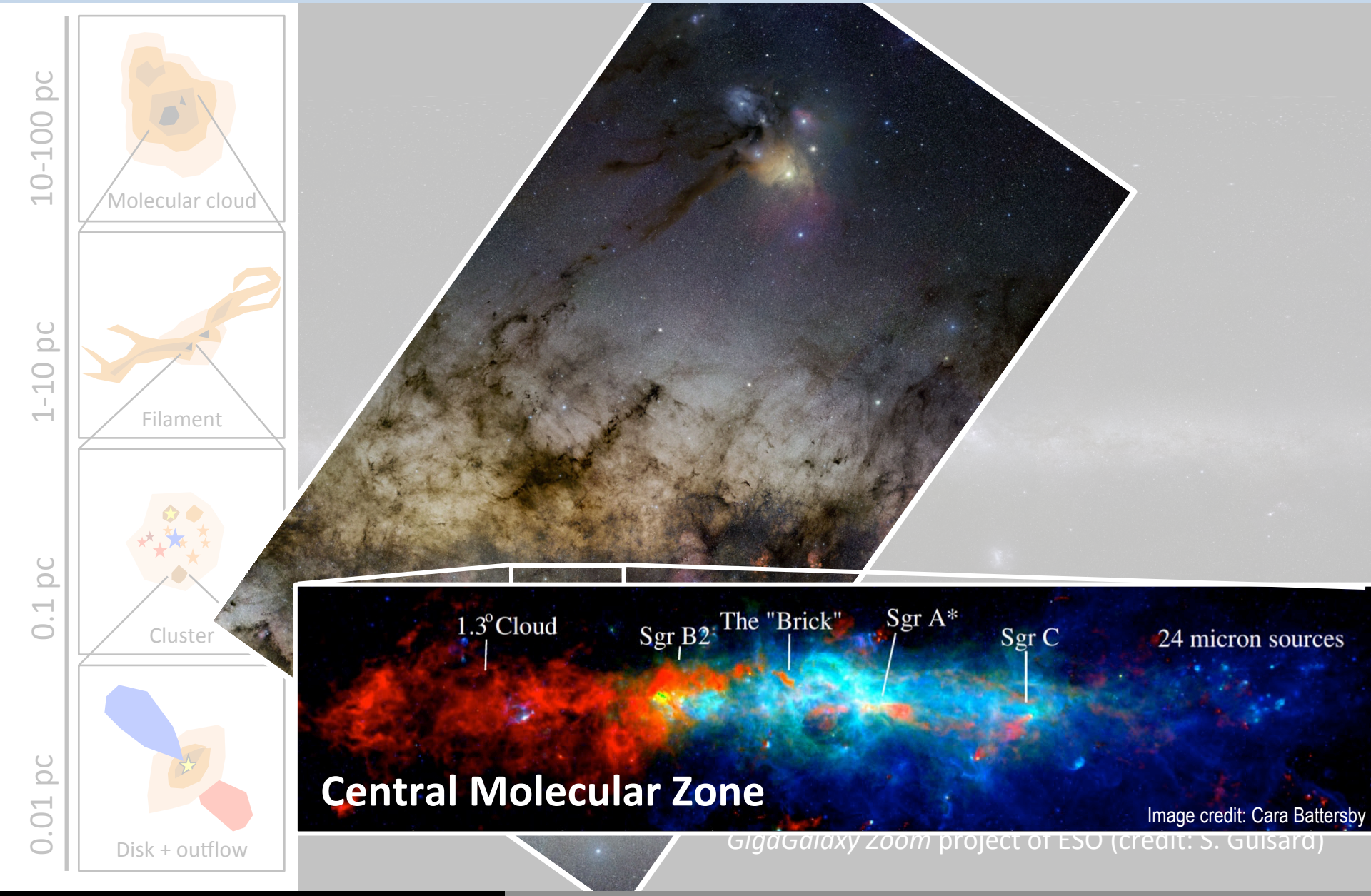
Q. How does chemistry evolve from simple to organic/pre-biotic?

Formation of super-stellar clusters



RVB color-composite image
GigaGalaxy Zoom project of ESO (credit: S. Guisard)

Formation of super-stellar clusters



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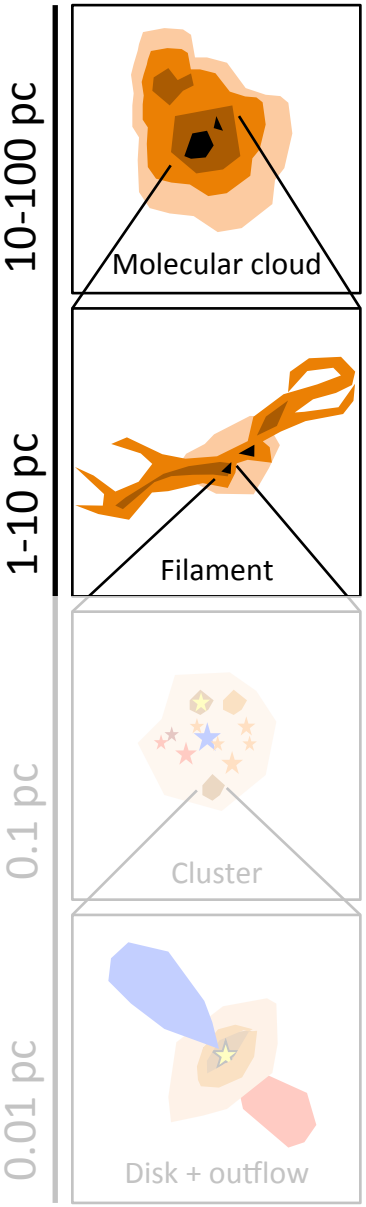
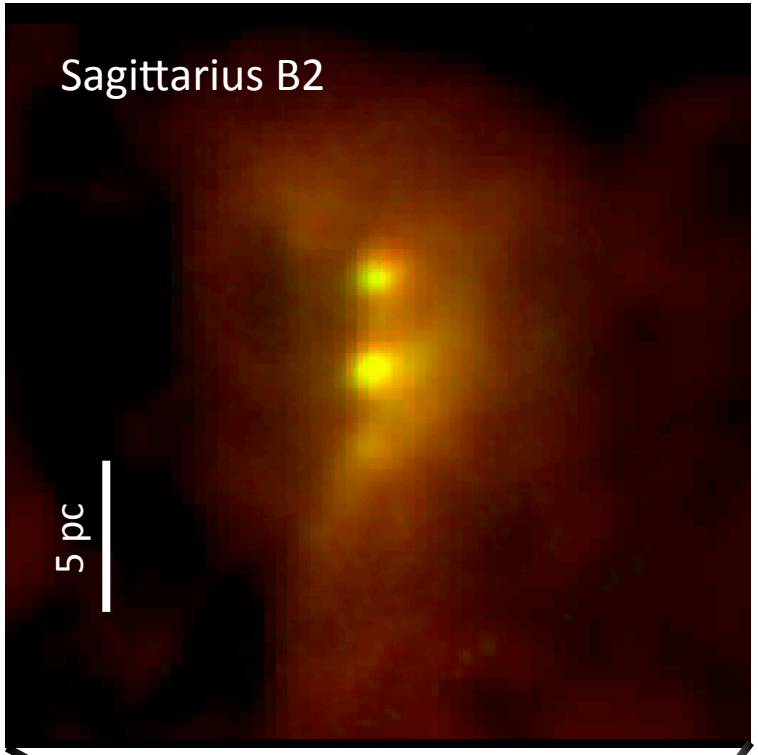
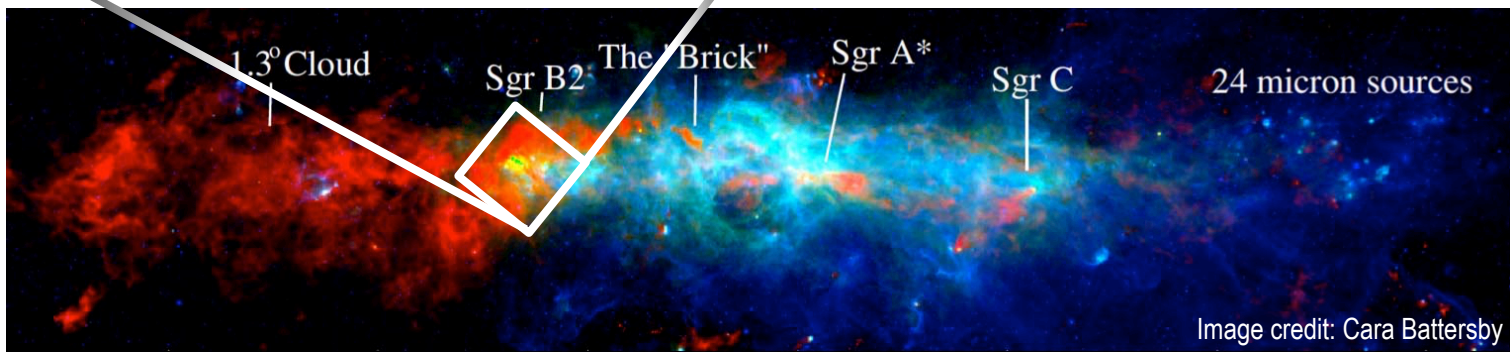


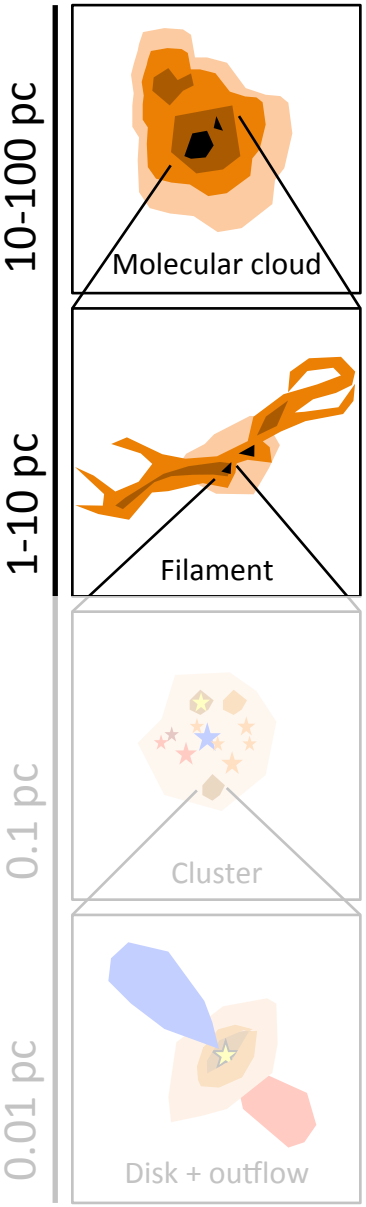


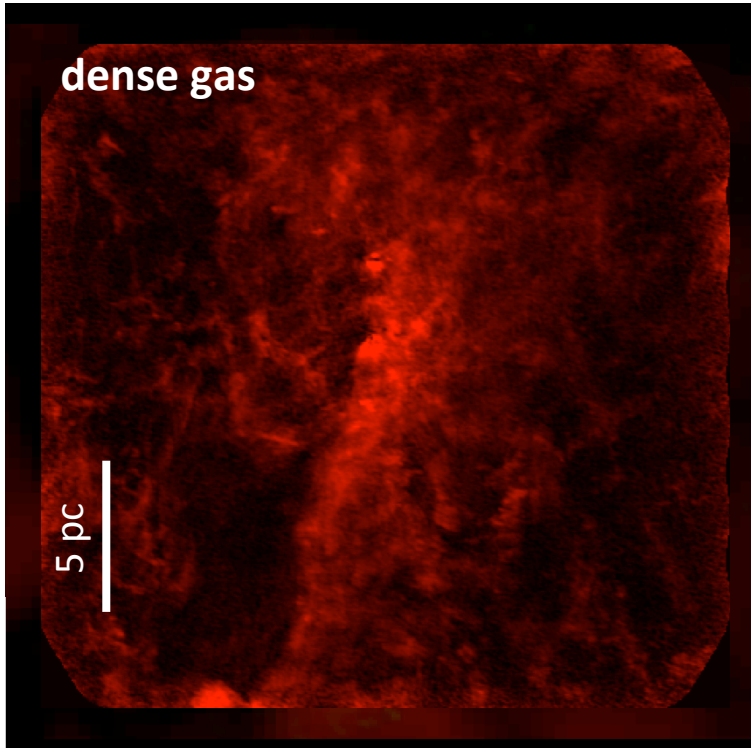
Herschel / Hi-GAL and CSO (250 μm, 350 μm)



Sagittarius B2:
the most massive cloud in the Milky Way with 10^7 $M_\odot$ in a cloud of 20 pc in size

Formation of super-stellar clusters





Herschel / Hi-GAL and CSO (250 μm, 350 μm)
Red: ALMA HC_3N (9-8)

Sagittarius B2 molecular cloud
- distributed star formation
- 300+ dense cores identified
- filamentary structures in dense gas

Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
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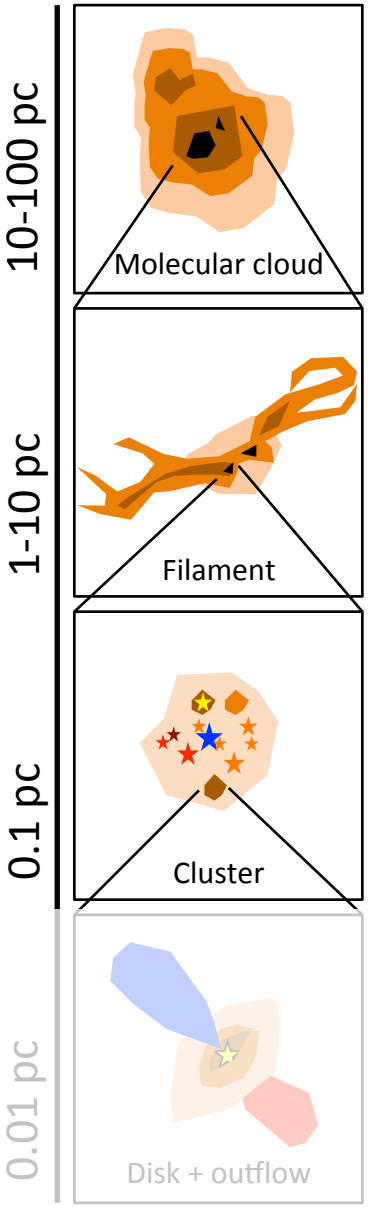
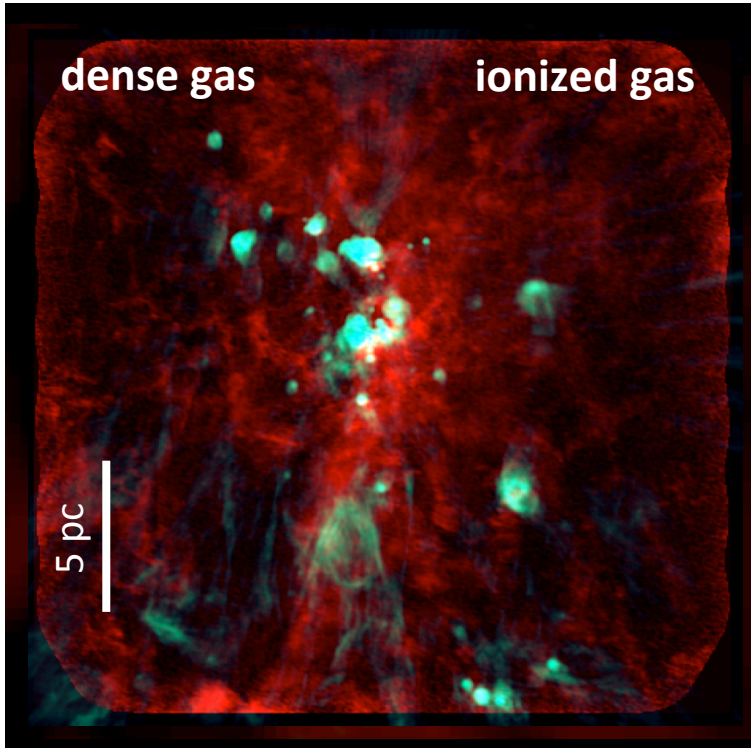
Formation of super-stellar clusters





Herschel / Hi-GAL and CSO (250 μm, 350 μm)
Red: ALMA HC_3N (9-8)
Turquoise: VLA 5 GHz continuum

Sagittarius B2 molecular cloud

- distributed star formation
- 300+ dense cores identified
- filamentary structures in dense gas

- 90+ massive stars with HII regions (some with synchrotron radiation)

Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
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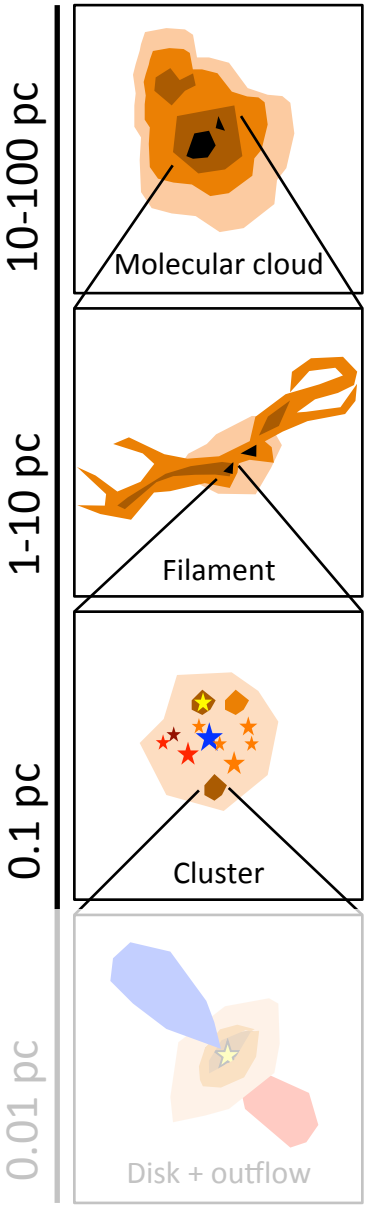

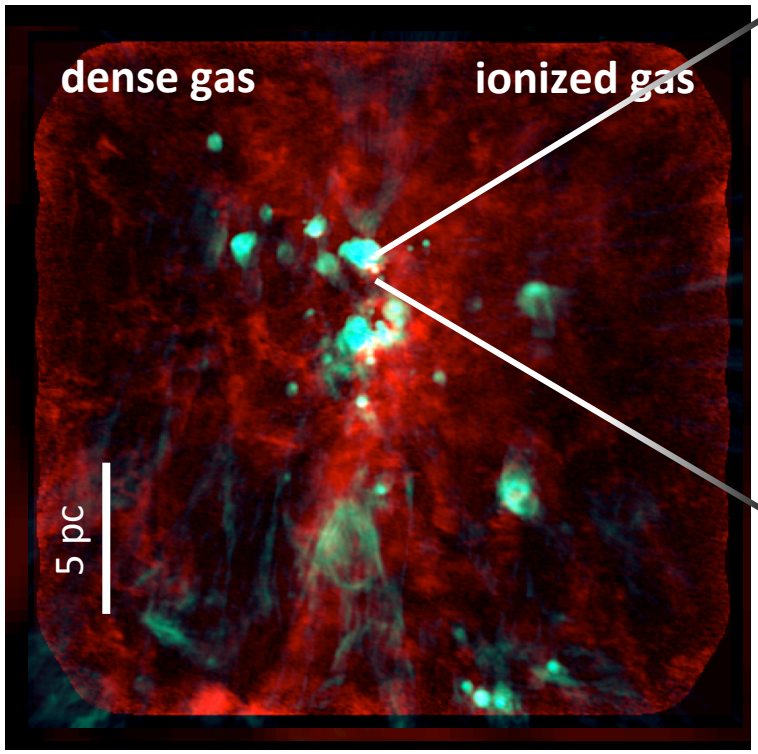

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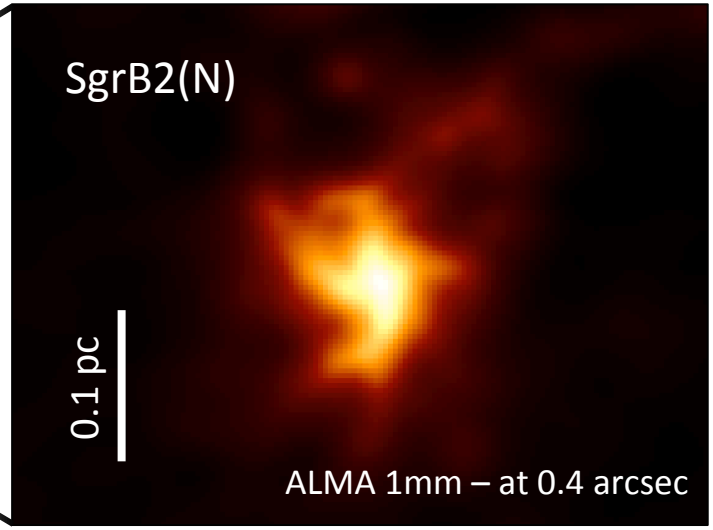

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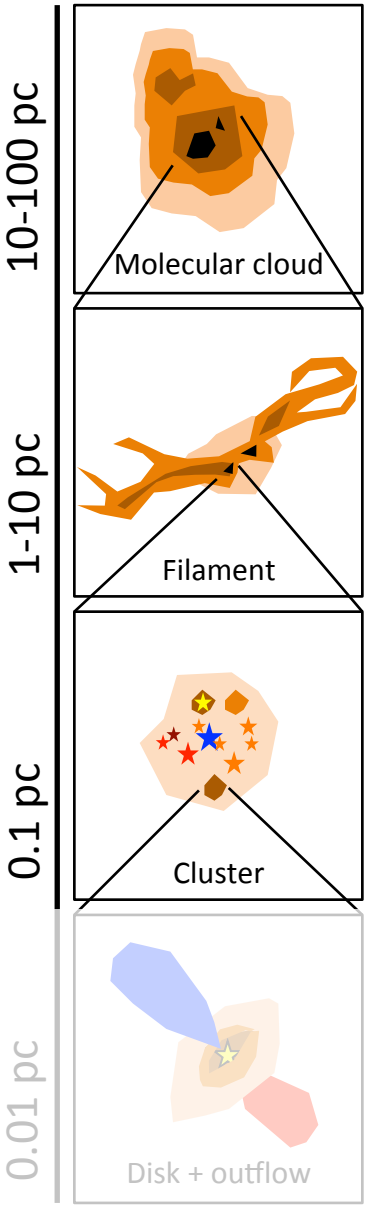

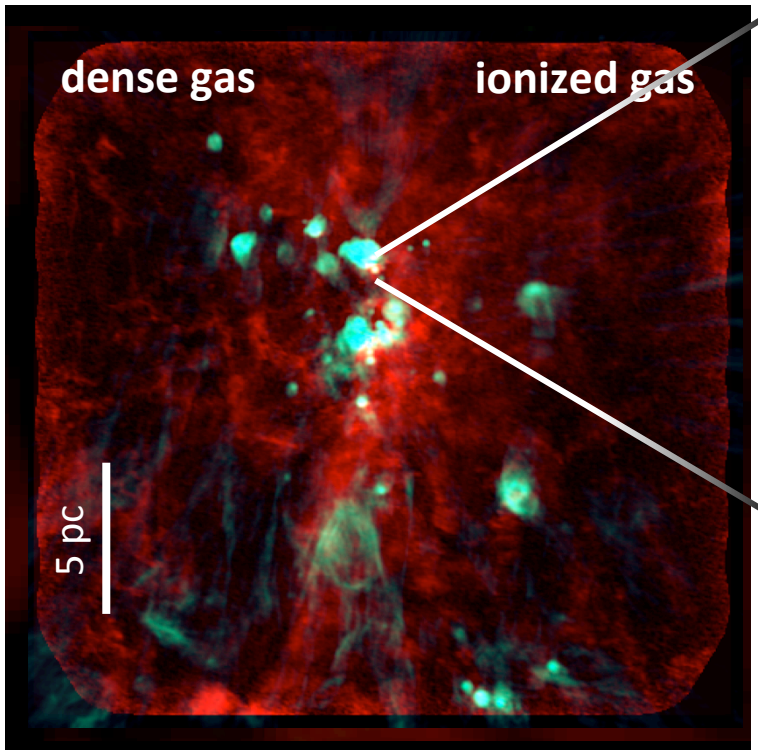

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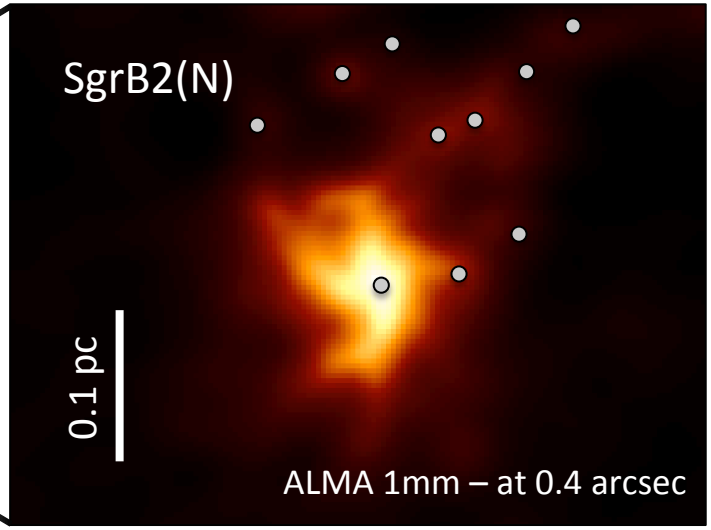

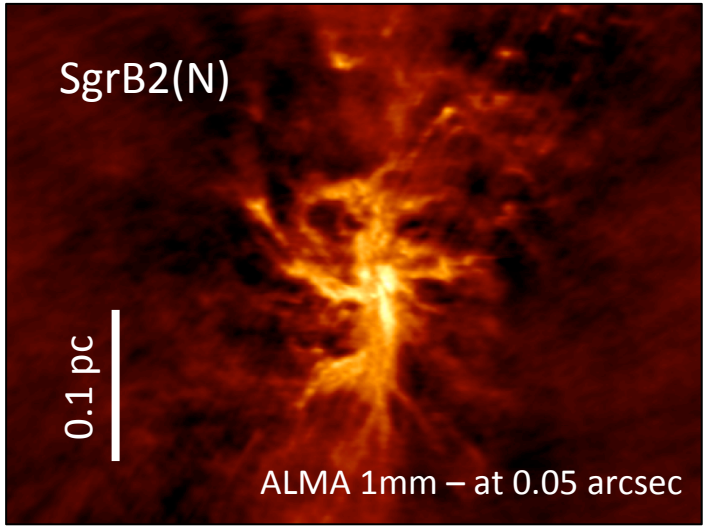

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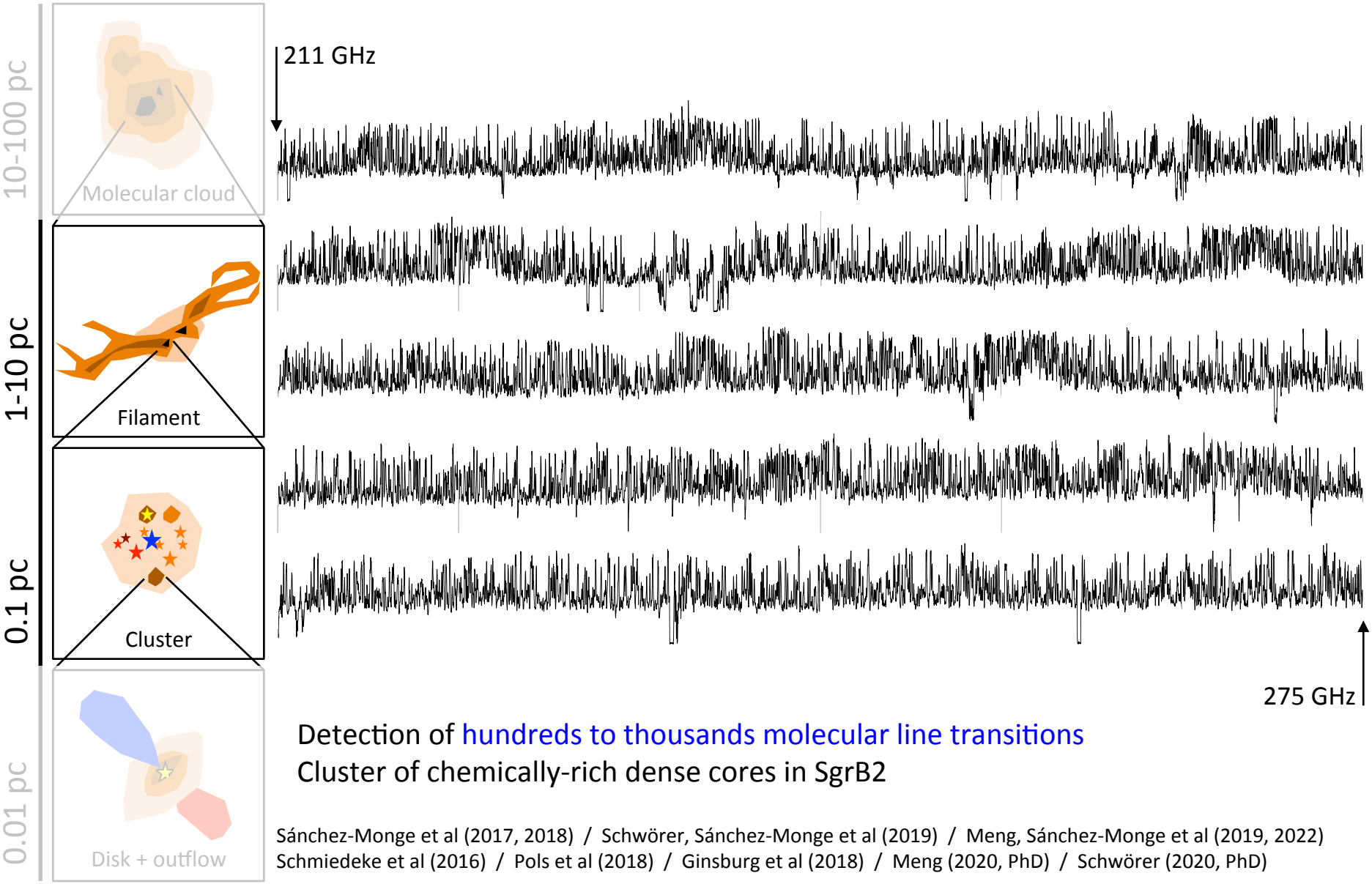

Detection of hundreds to thousands molecular line transitions
Cluster of chemically-rich dense cores in SgrB2

Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
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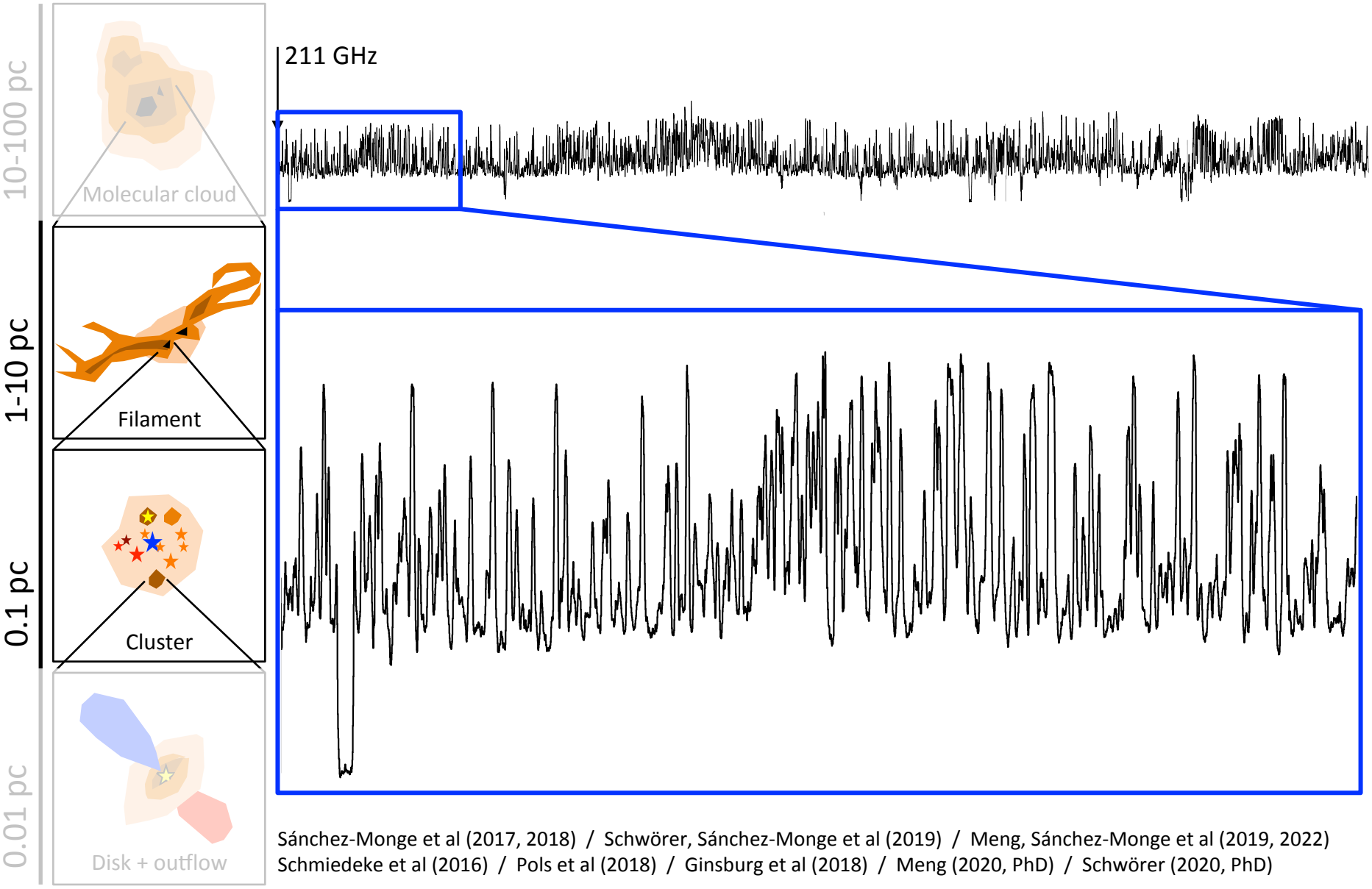

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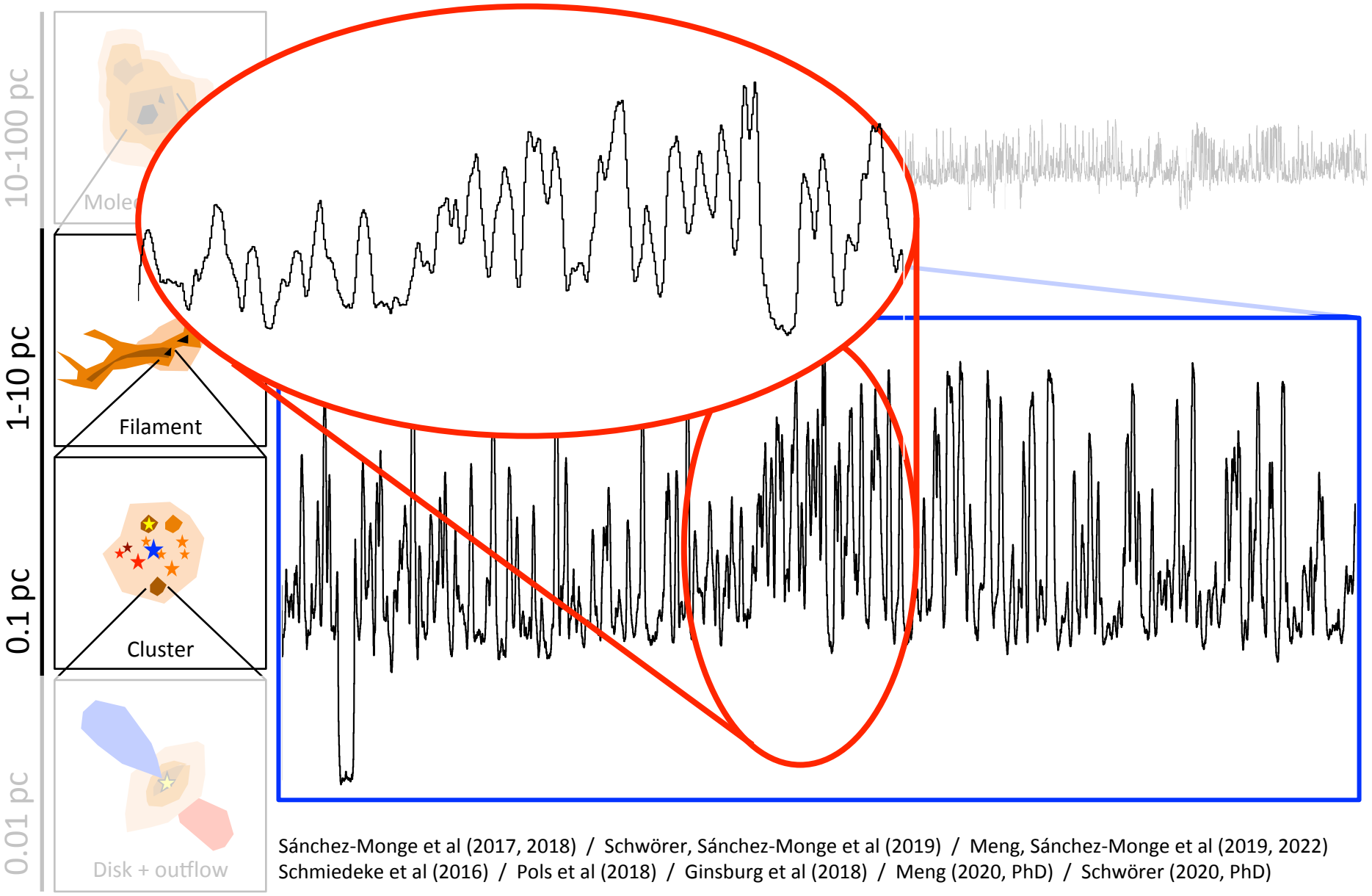

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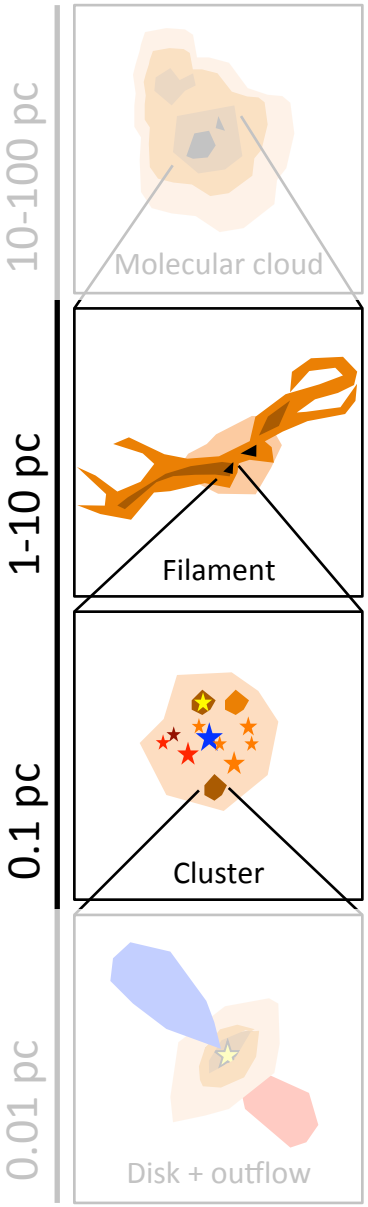

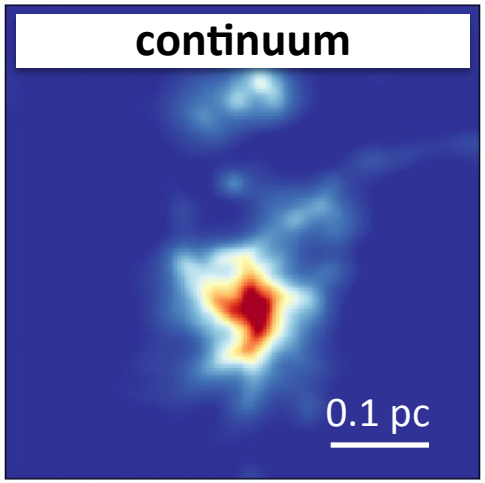

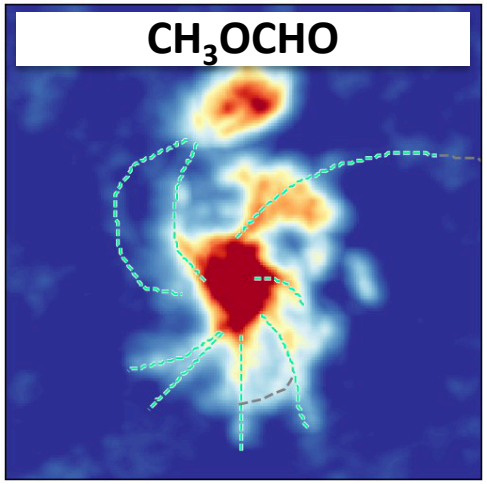

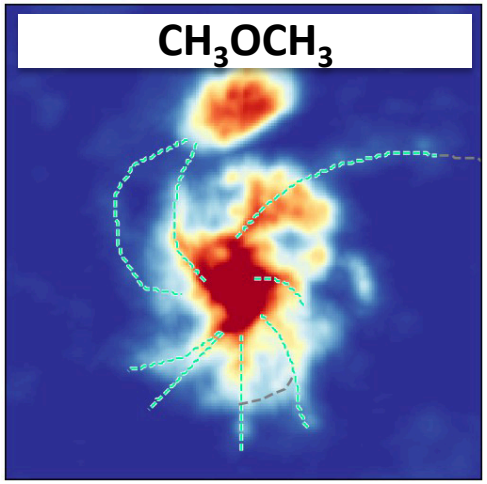

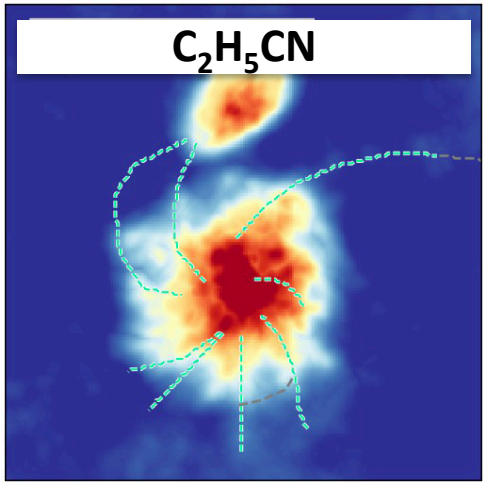

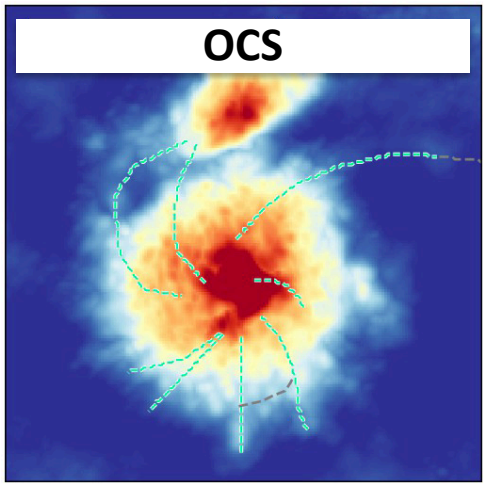

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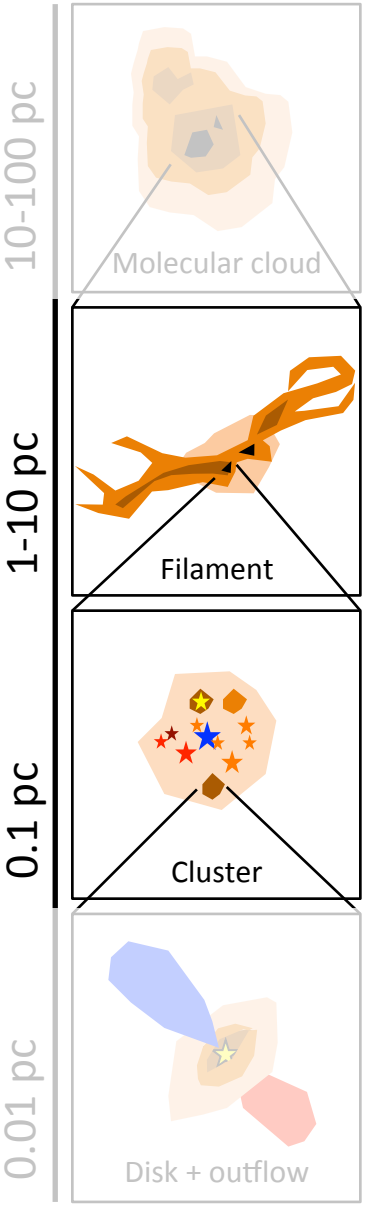
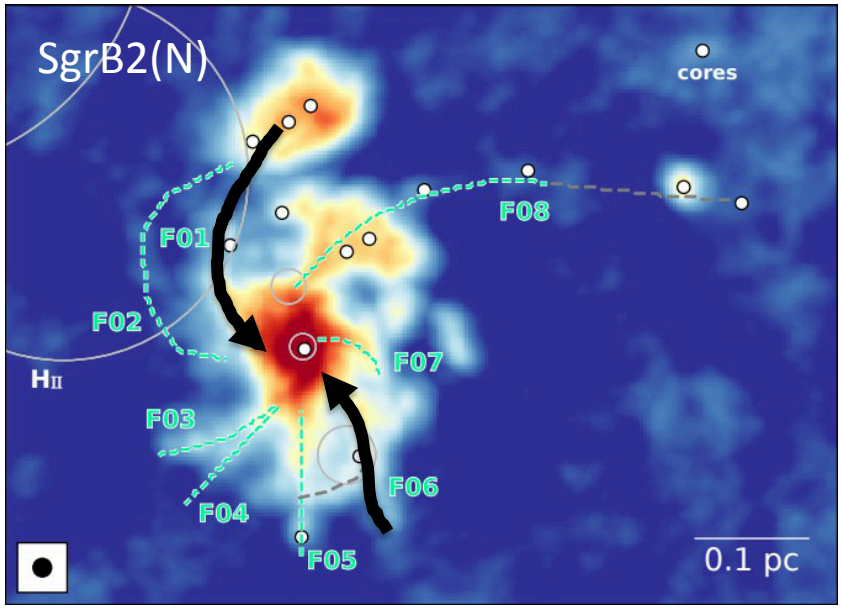
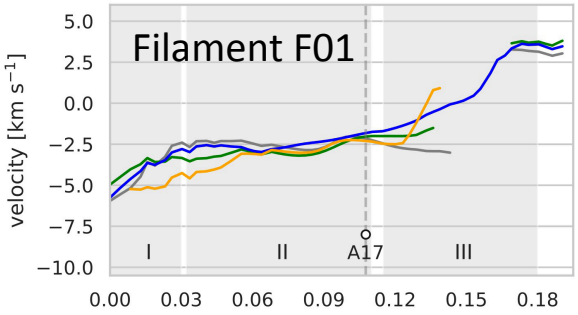
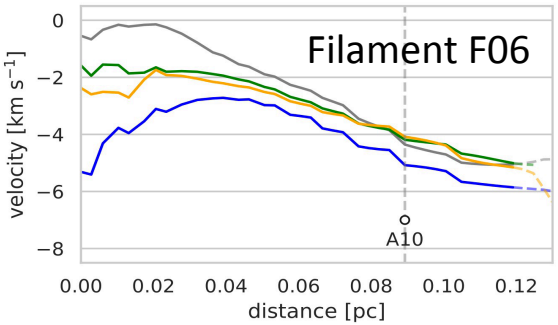
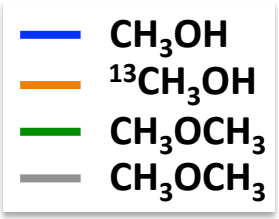
Formation of super-stellar clusters









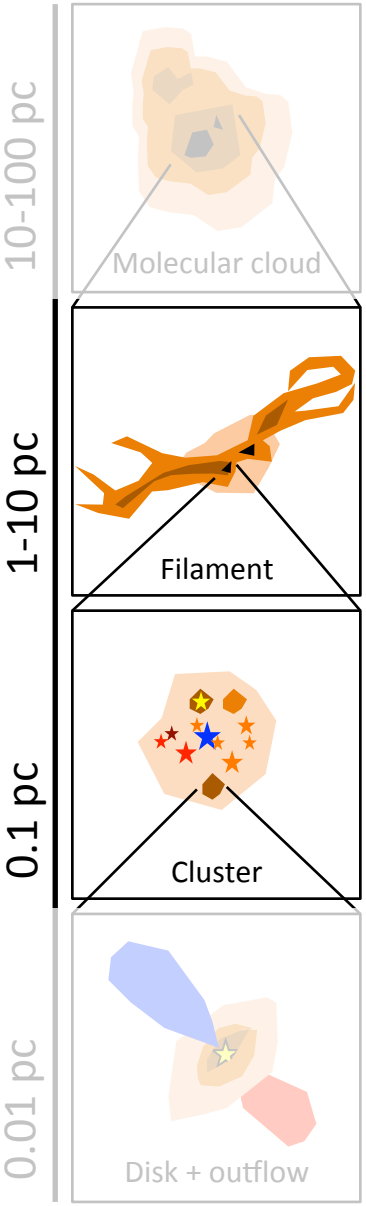


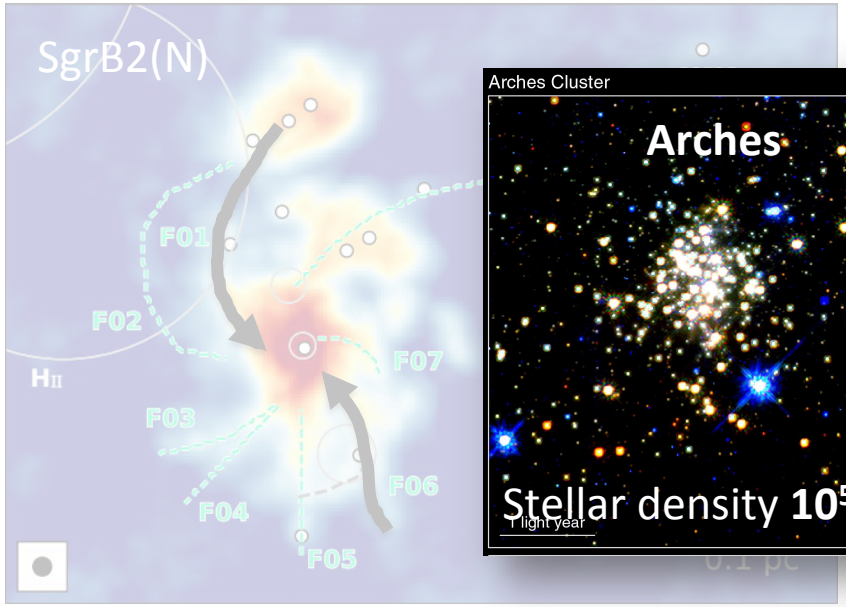
Velocity gradients : 20-100 km s^{-1} pc^{-1}
Mass accretion rates : **0.16 $M_\odot$ yr^{-1}**
(while 10^{-5} – 10^{-3} $M_\odot$ yr^{-1} in NGC6334)

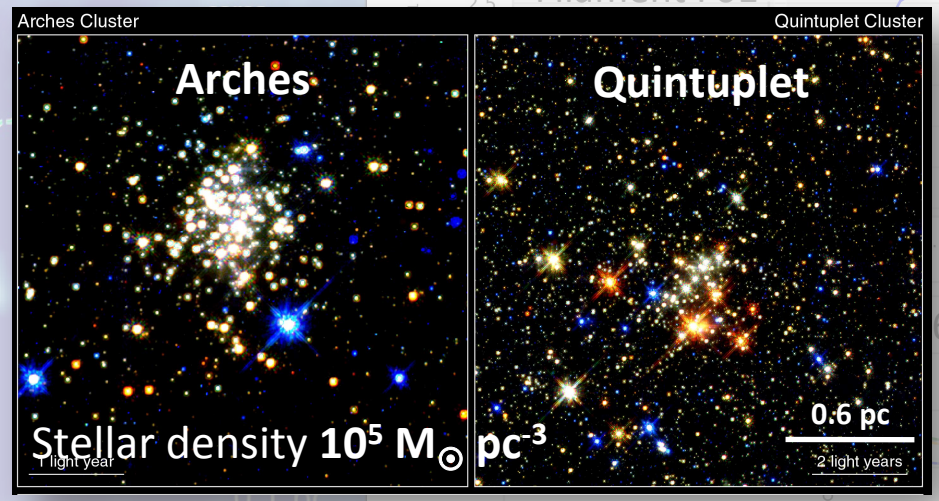
Mass in the region : 10^4 $M_\odot$
Large densities : **10^5-10^7 $M_\odot$ pc^{-3}**

Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
Schmiedeke et al (2016) / Pols et al (2018) / Ginsburg et al (2018) / Meng (2020, PhD) / Schwörer (2020, PhD)

Formation of super-stellar clusters







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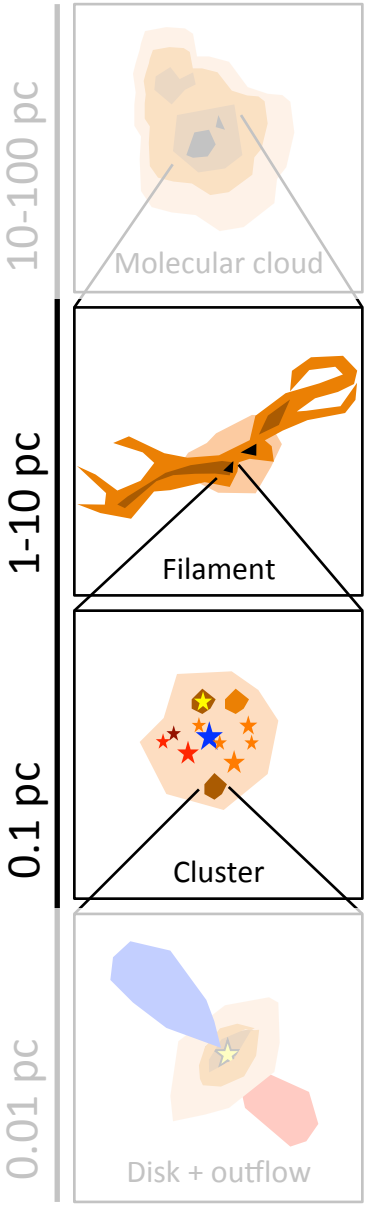
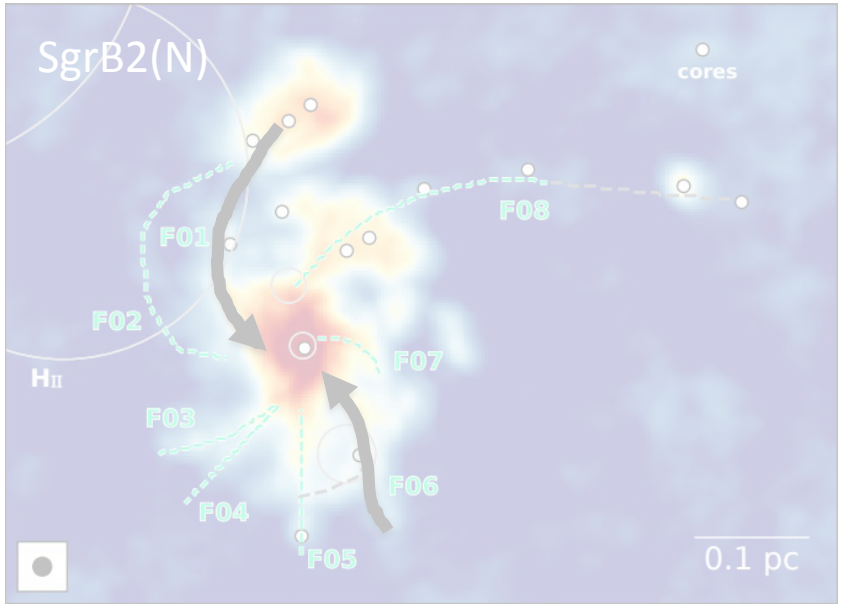
Mass in the region : 10^4 $M_\odot$
Large densities : **10^5-10^7 $M_\odot$ pc^{-3}**

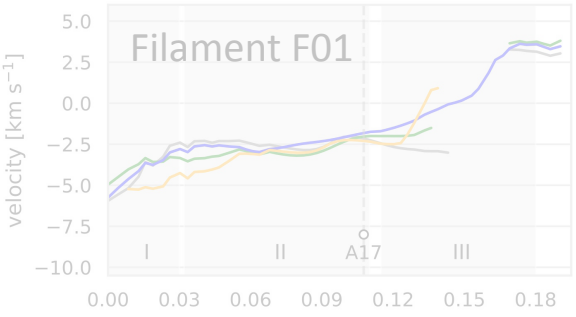
SgrB2(N) has the potential to form a super-stellar cluster

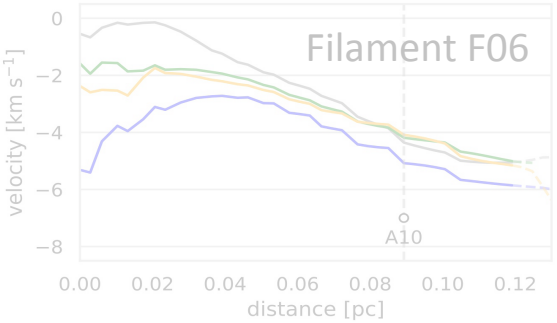
Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
Schmiedeke et al (2016) / Pols et al (2018) / Ginsburg et al (2018) / Meng (2020, PhD) / Schwörer (2020, PhD)

Formation of super-stellar clusters









Take home messages [for SgrB2]

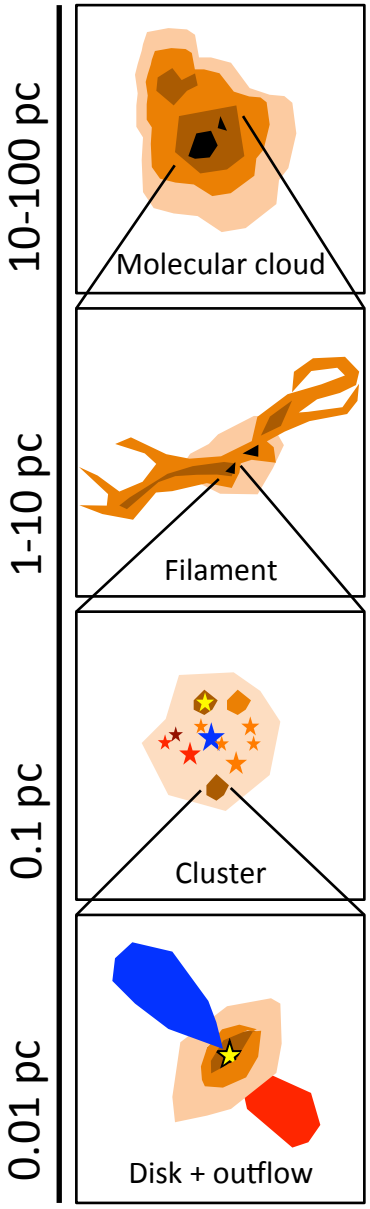
Converging filaments, with 0.16 $M_\odot$/yr accretion rates

Clusters of chemically-rich dense cores

SgrB2(N) only known precursor of a **super star cluster**

Sánchez-Monge et al (2017, 2018) / Schwörer, Sánchez-Monge et al (2019) / Meng, Sánchez-Monge et al (2019, 2022)
Schmiedeke et al (2016) / Pols et al (2018) / Ginsburg et al (2018) / Meng (2020, PhD) / Schwörer (2020, PhD)

From clouds to stars



Questions on Star (Cluster) Formation

Q. How do molecular clouds fragment into stellar clusters?

Q. Do all stellar clusters form in the same way?

Q. How do (proto-)stellar clusters evolve with time?

Q. How is mass transported from the large clouds down to stars?

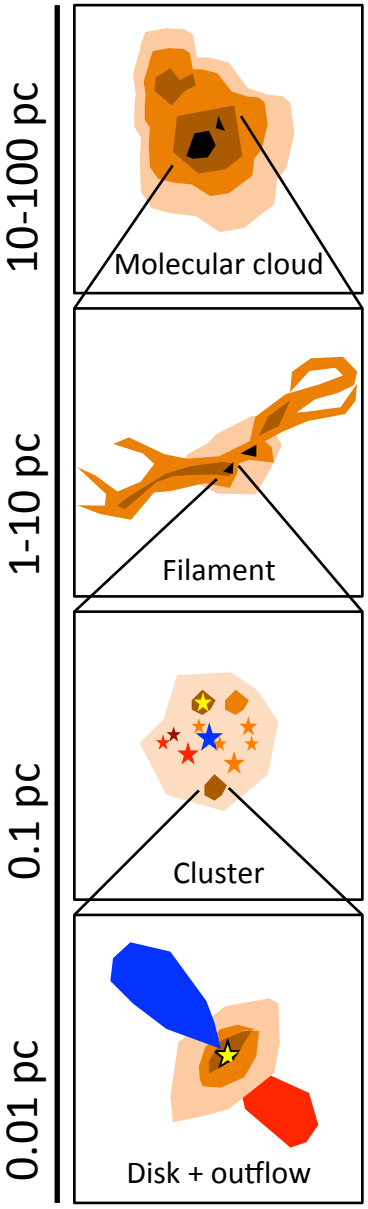
Q. What is the role of gravity, turbulence and magnetic fields?

Q. How does feedback originate and affect the whole process?

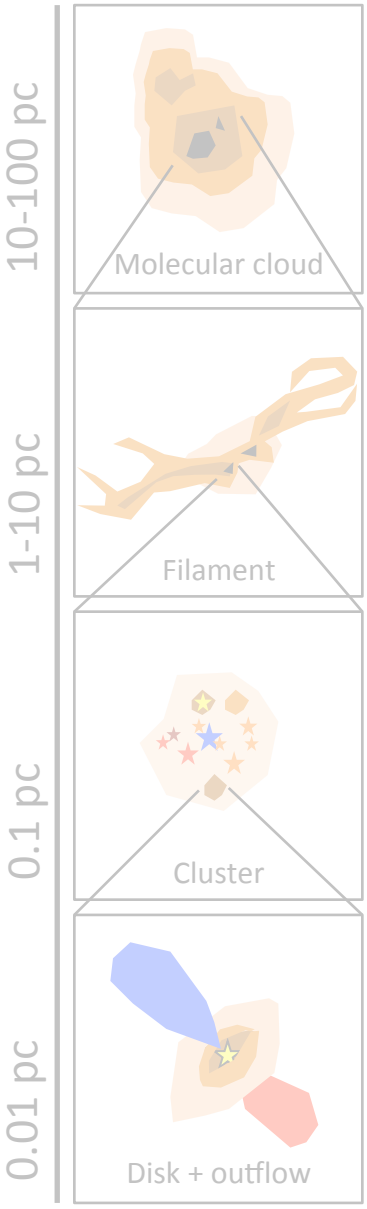
Q. What is the role of proto-stellar/planetary disks?

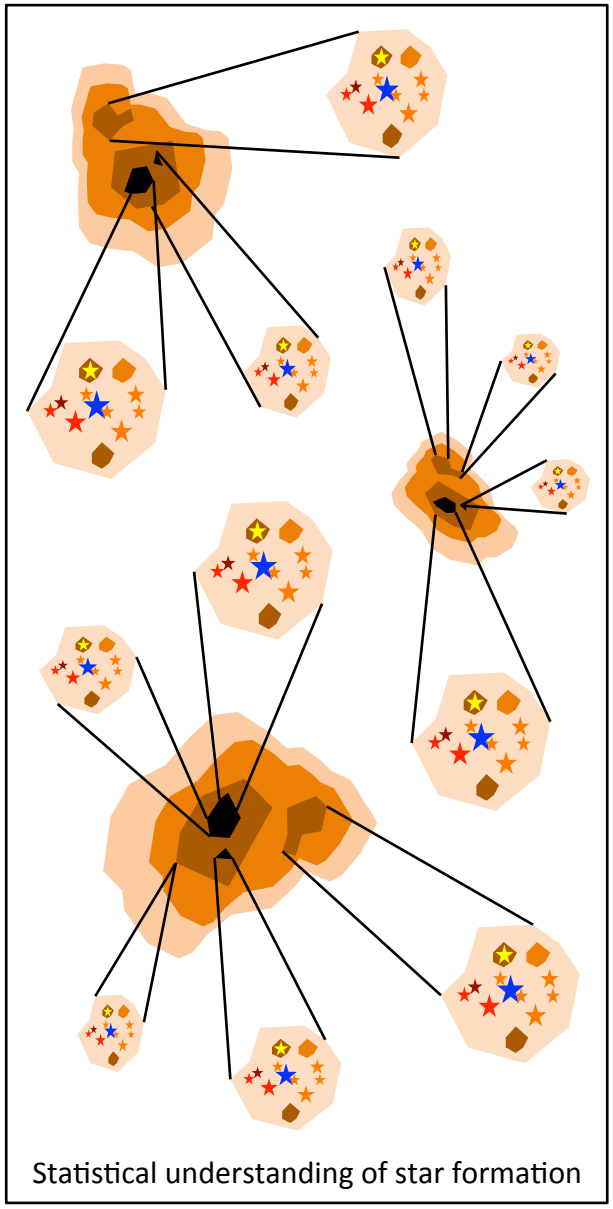
Q. How does chemistry evolve from simple to organic/pre-biotic?

Statistical characterization of star formation



Statistical characterization of star formation





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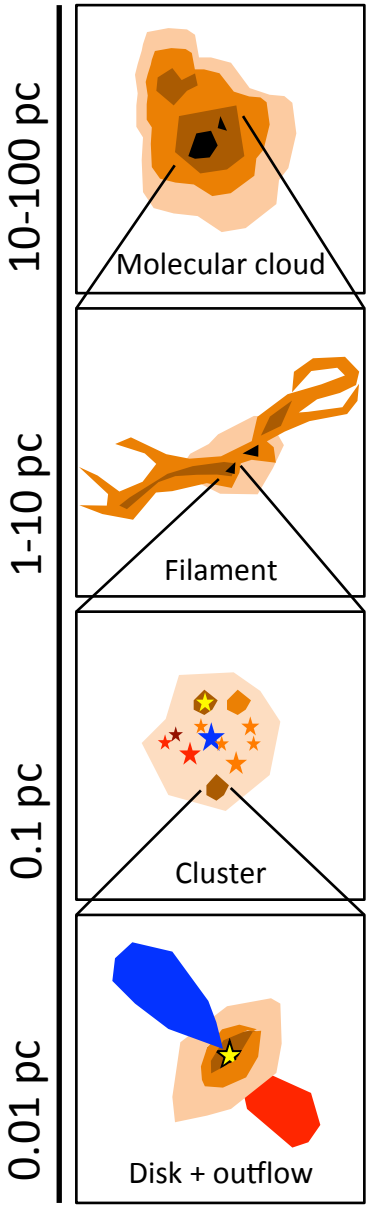
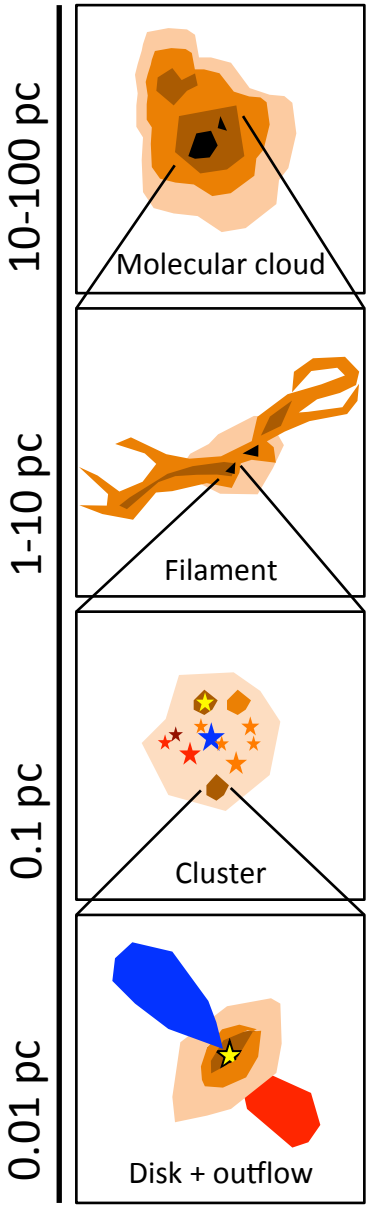


Towards a statistical characterization of star formation

15 regions – Sánchez-Monge et al 2013, MNRAS, 432, 3288
19 regions – Palau, … Sánchez-Monge et al 2014, ApJ, 785, 42
19 regions – Palau, … Sánchez-Monge et al 2015, MNRAS, 453, 3785
20 regions – Beuther, … Sánchez-Monge et al 2018, A&A, 617, A100
35 regions – Csengeri et al 2018, A&A, 617, A89

Statistical characterization of star formation



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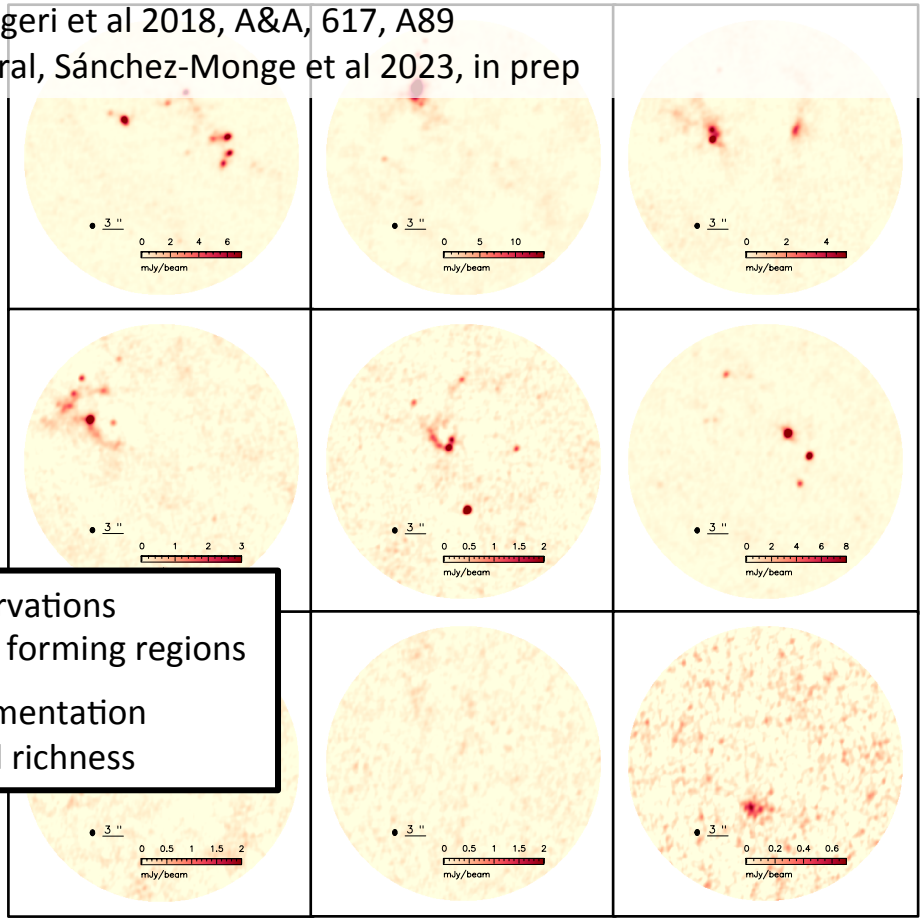
66 regions – Amaral, Sánchez-Monge et al 2023, in prep

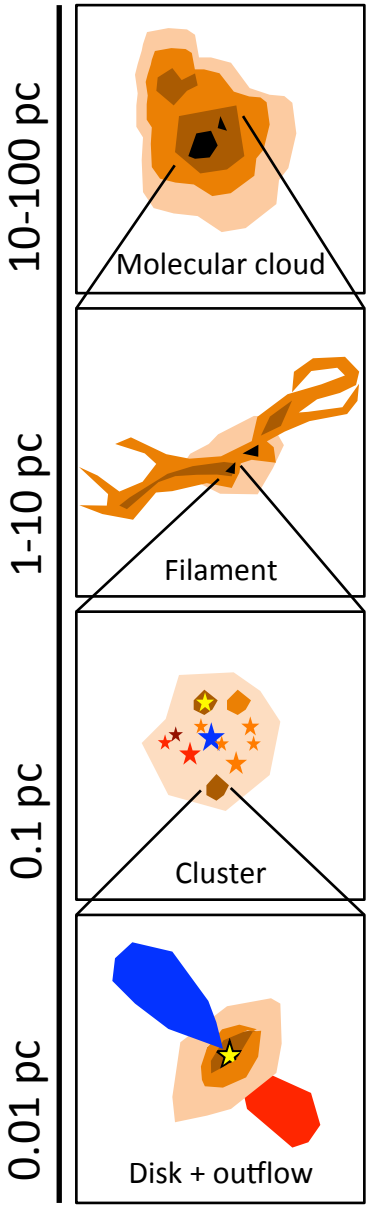


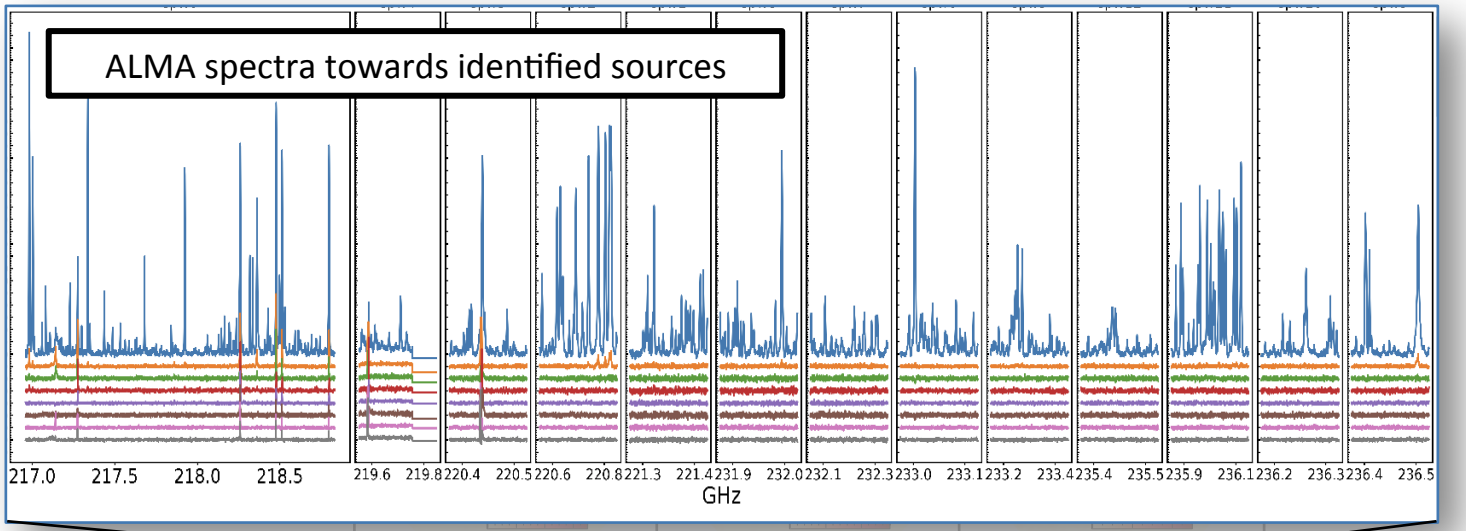
ALMA observations
of **66** high-mass star forming regions

studying fragmentation
and chemical richness

+ 57 regions more

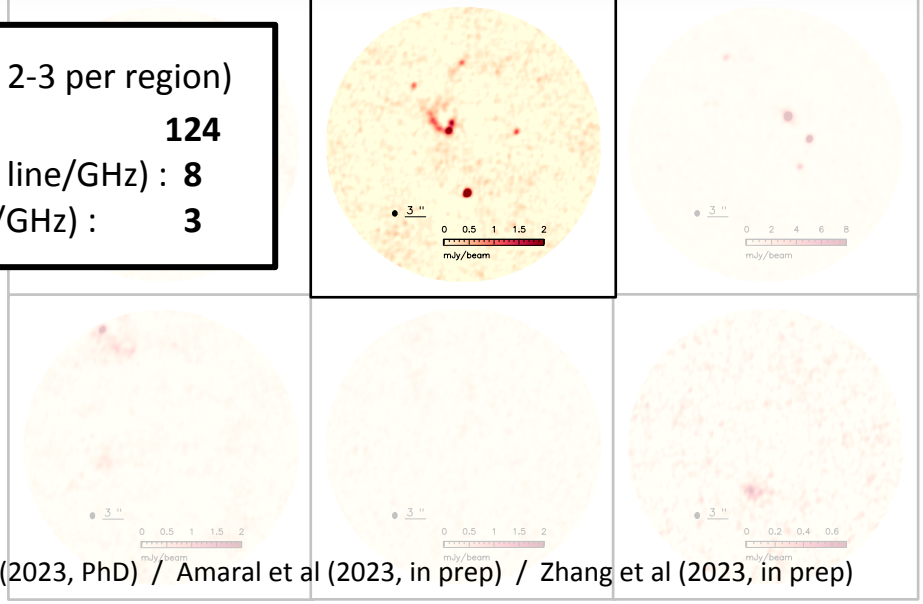
Statistical characterization of star formation





Total sources: **135** (≈ 2-3 per region)

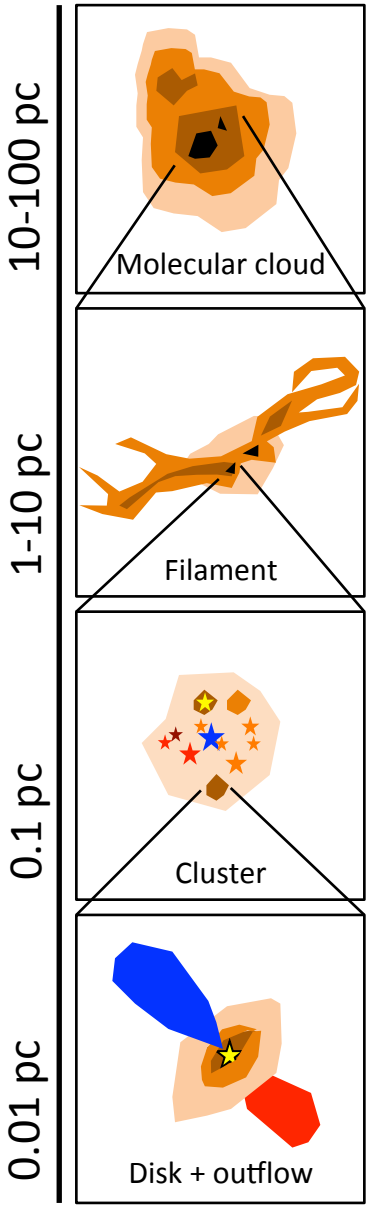
- Line poor : **124**
- Intermediate (10 line/GHz) : **8**
- Line rich (50 line/GHz) : **3**



+ 57 regions more

Amaral (2023, PhD) / Zhang (2023, PhD) / Amaral et al (2023, in prep) / Zhang et al (2023, in prep)

Statistical characterization of star formation



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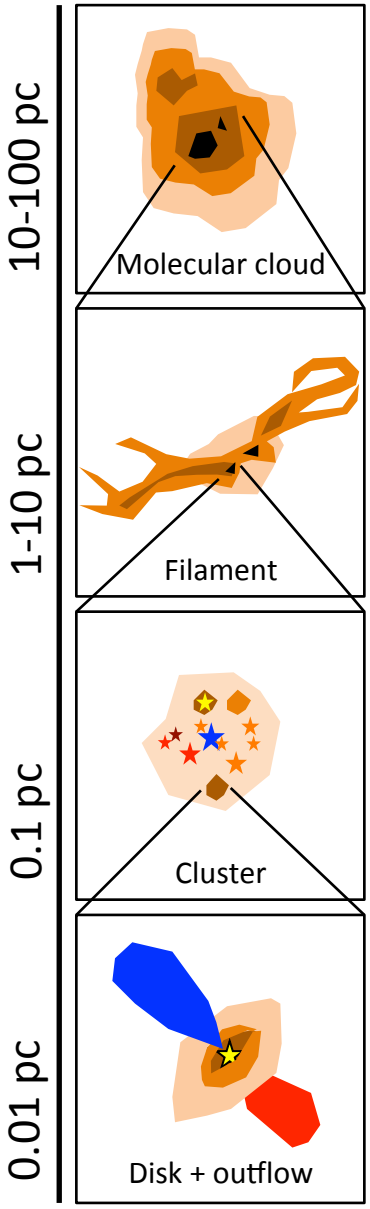

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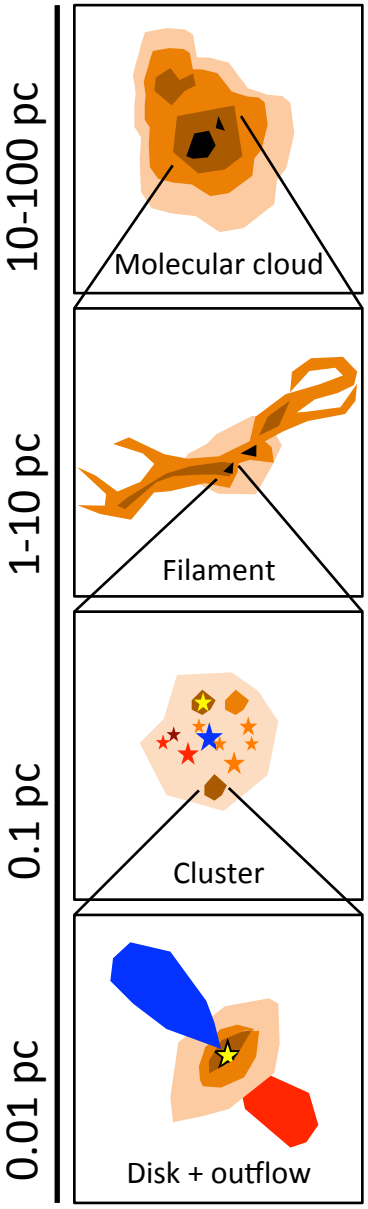
66 regions – Amaral, Sánchez-Monge et al 2023, in prep
146 regions – ATOMS Large Program
1017 regions – **ALMAGAL Large Program**

ALMA evolutionary study of high-mass proto-cluster formation in the Galaxy

Main scientific goals:
- Cluster fragmentation
- Accretion and feedback processes
- Physical and chemical evolution
- Disk properties

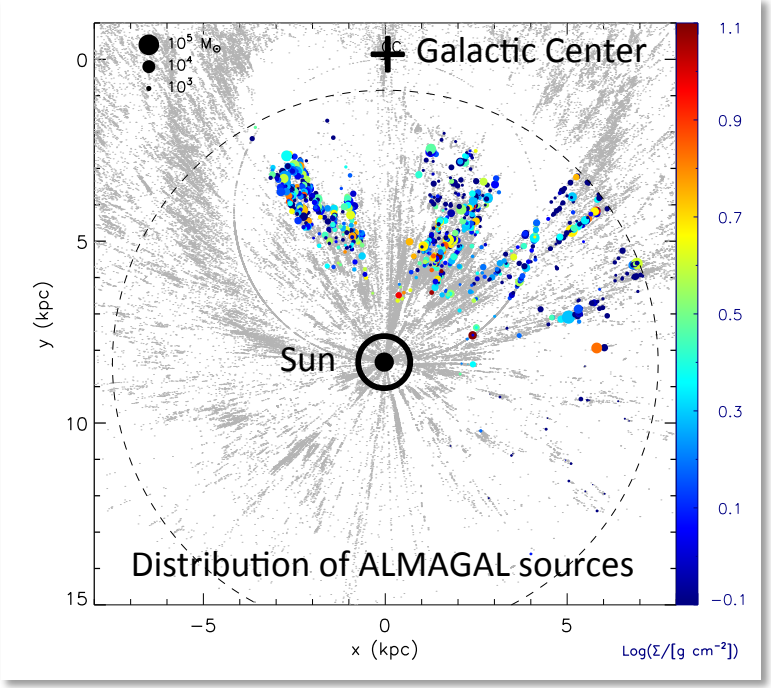
ALMAGAL consortium
75+ people from 13 countries

Statistical characterization of star formation



ALMAGAL

ALMA evolutionary study of high-mass proto-cluster formation in the Galaxy



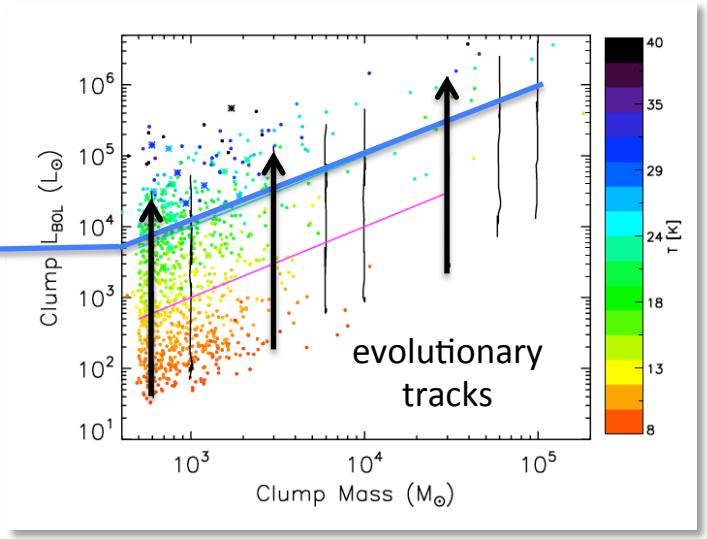
1017 observed sources…

… distributed throughout the Galaxy

Star cluster formation in:

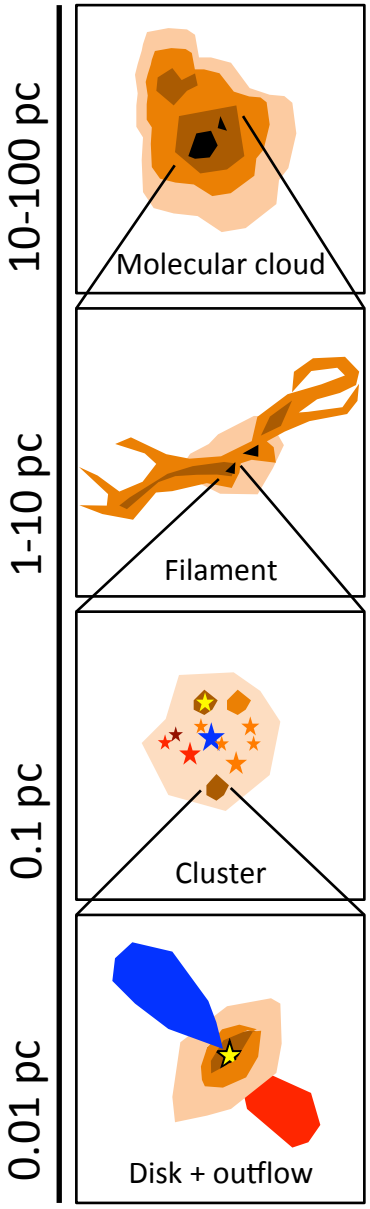
- inner / outer Galaxy
- within/ outside spiral arms
- …

ZAMS



… in different evolutionary stages

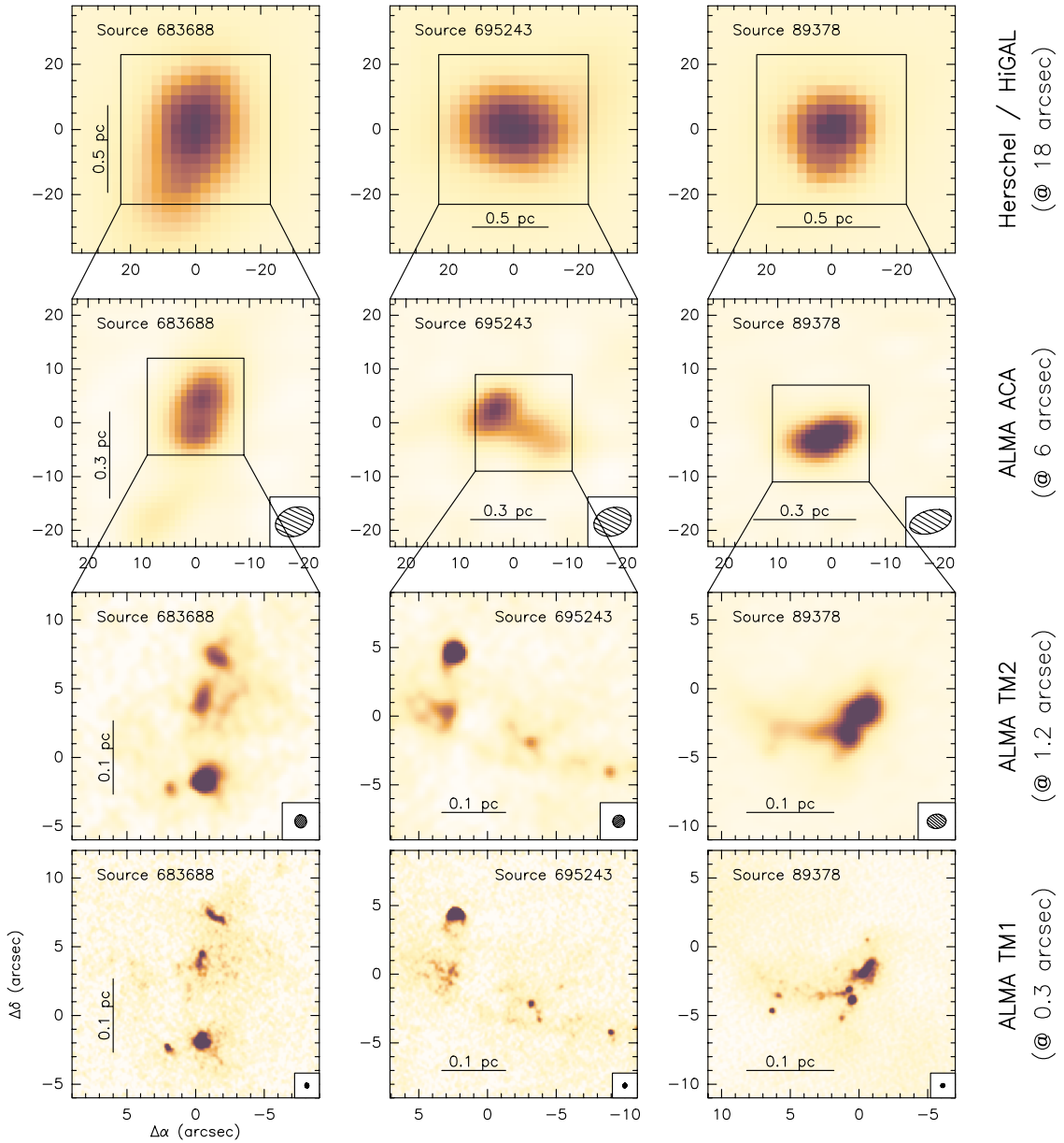
Statistical characterization of star formation



+ 1013 regions more

Spatial resolution 1000 au

Mass sensitivity 0.1 $M_\odot$



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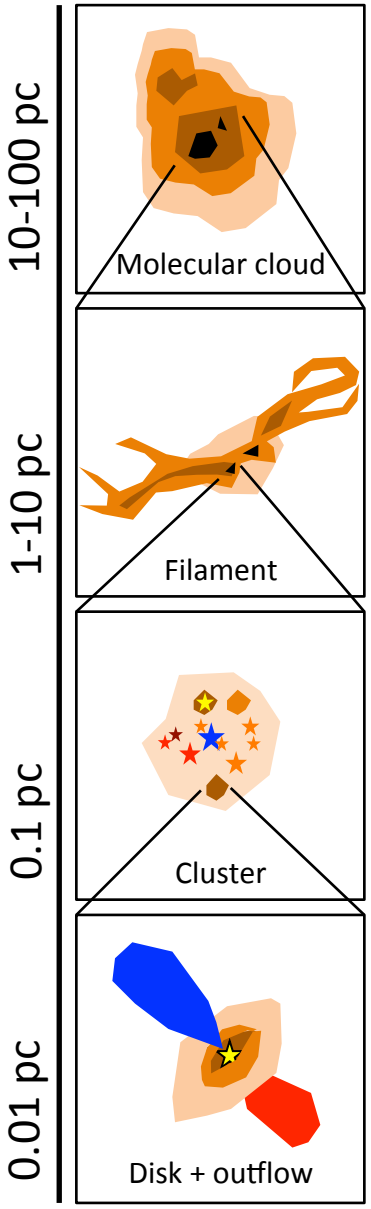

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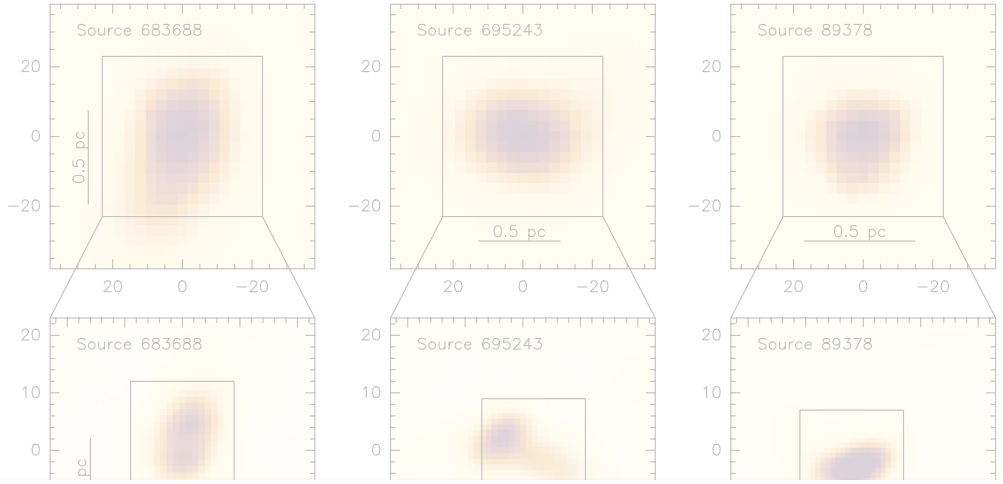
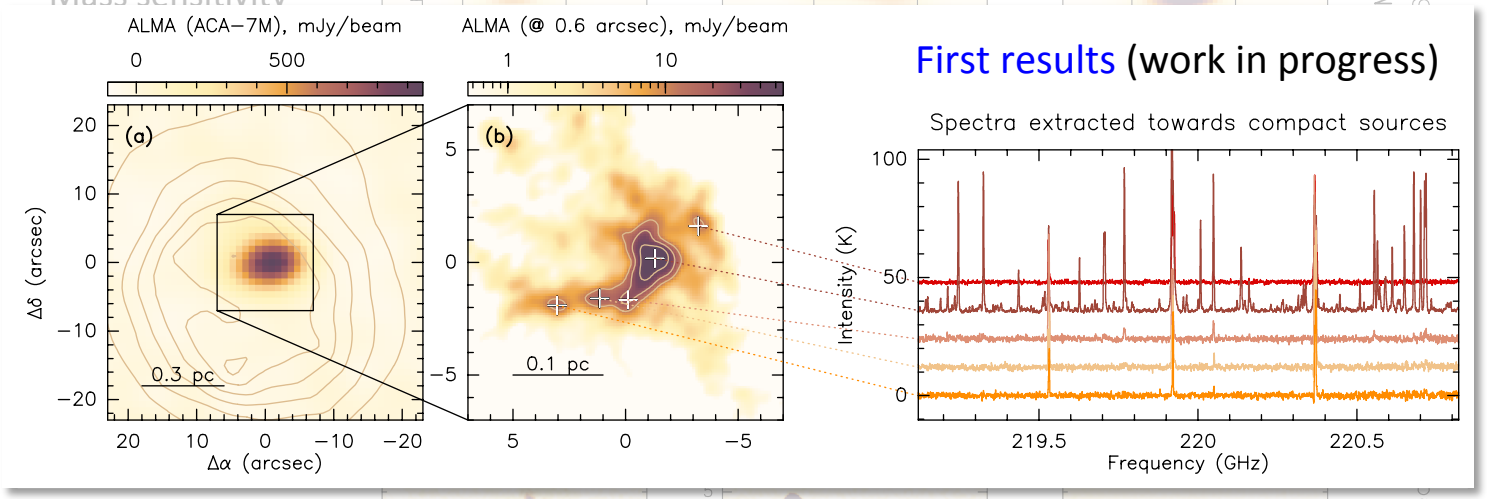
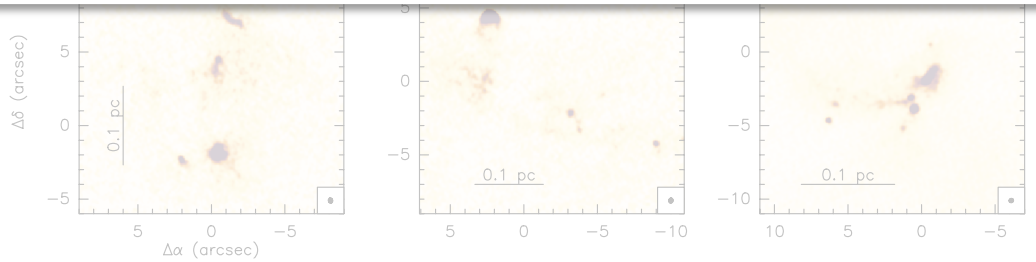
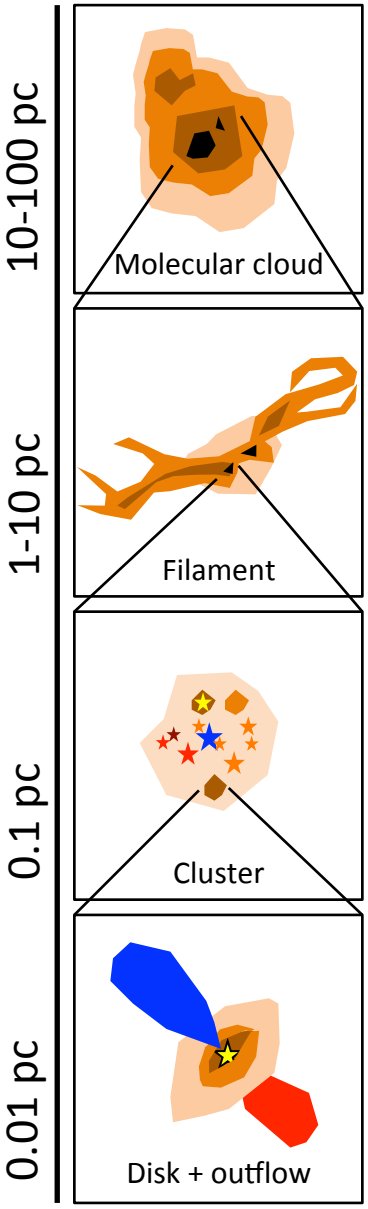


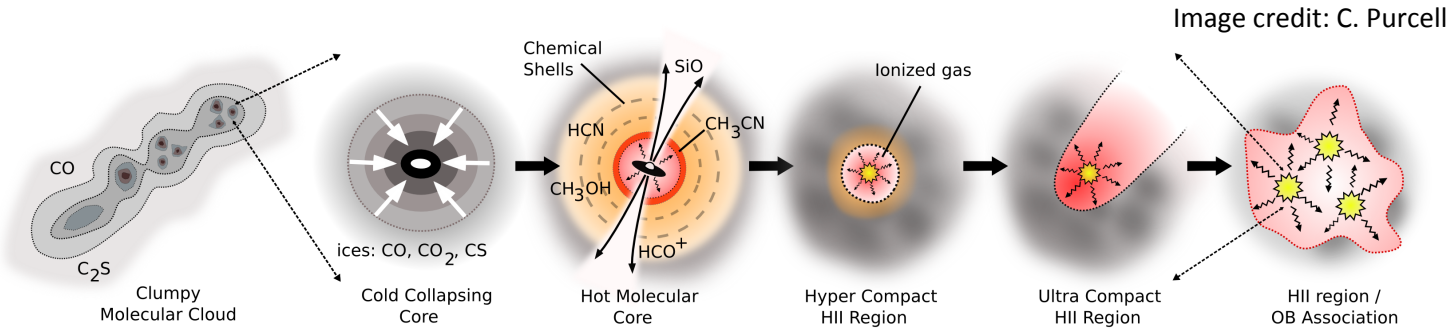




Evolutionary stages in star formation



Establishing **evolutionary stages** in (high-mass) star formation



Molecular cloud

Cold core

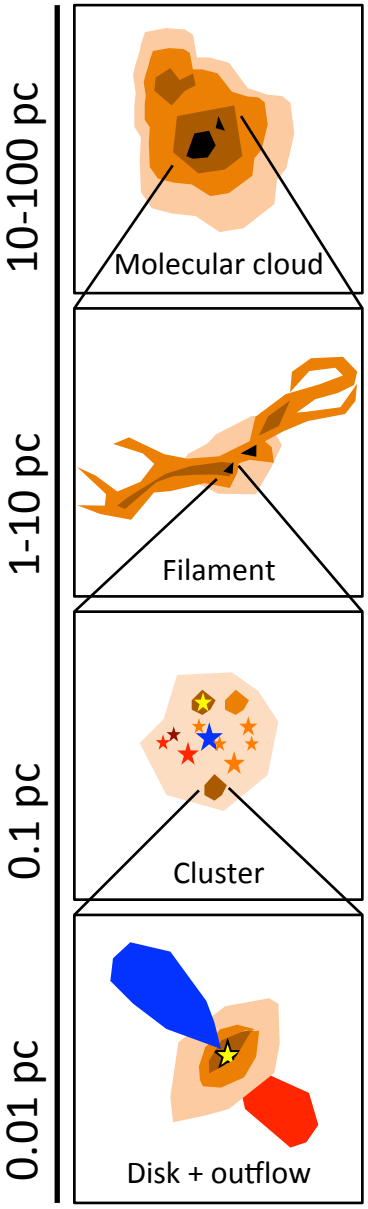
Hot core

HC HII region

UC HII region

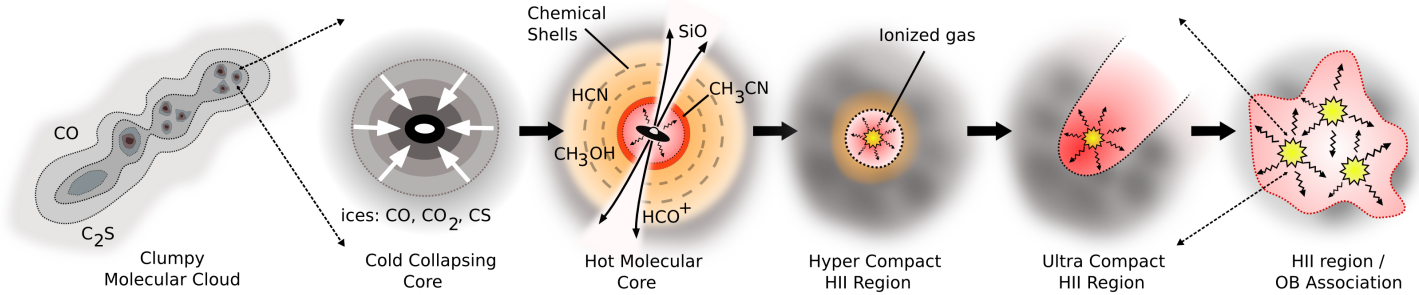
Stellar cluster

Evolutionary stages in star formation



Establishing **evolutionary stages** in (high-mass) star formation

Image credit: C. Purcell



Molecular cloud

Cold core

Hot core

HC HII region

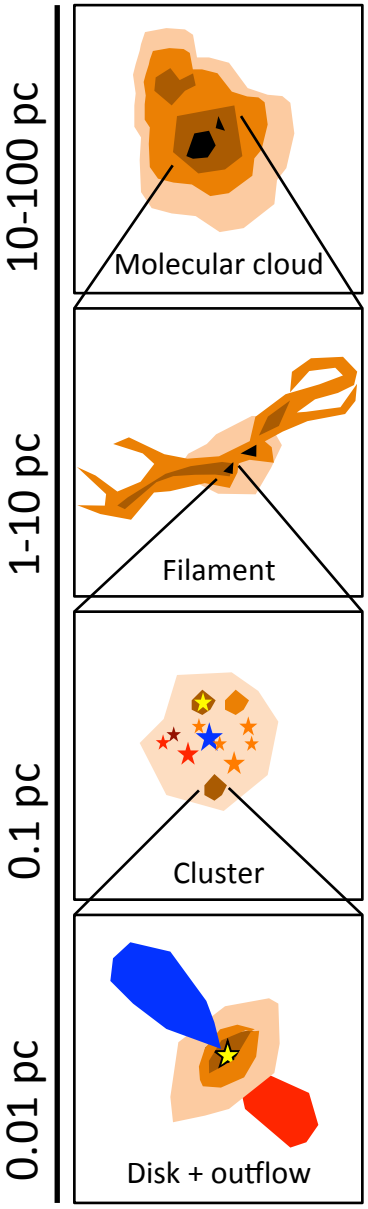
UC HII region

Stellar cluster

Time evolution

(total process takes about 10^5-10^6 yr)

Evolutionary stages in star formation



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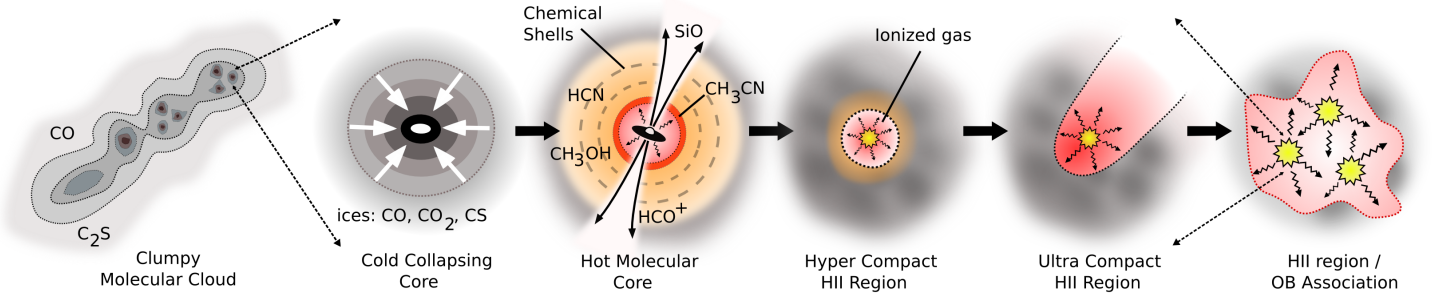


Molecular cloud — Cold core — Hot core — HC HII region — UC HII region — Stellar cluster

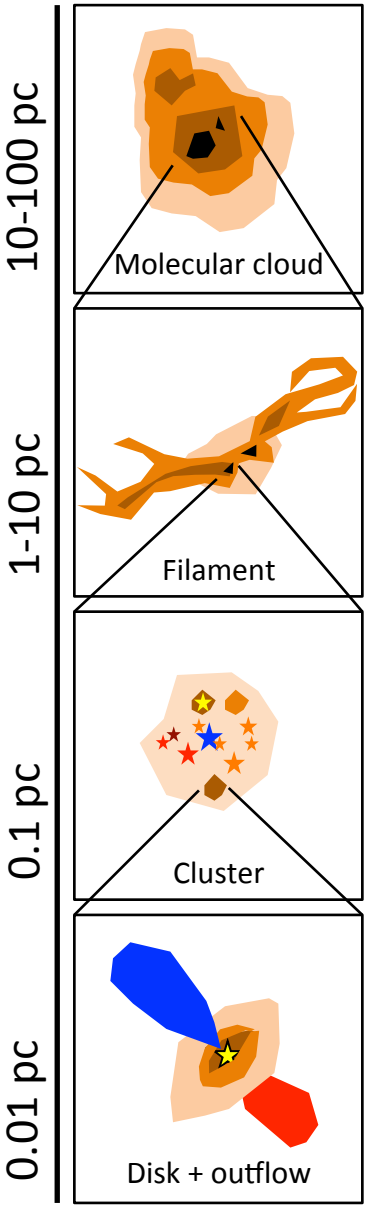
Physical properties change – e.g.: temperature increases

Chemical content changes – e.g.: complex molecules form

Time evolution

(total process takes about 10^5-10^6 yr)

Evolutionary stages in star formation



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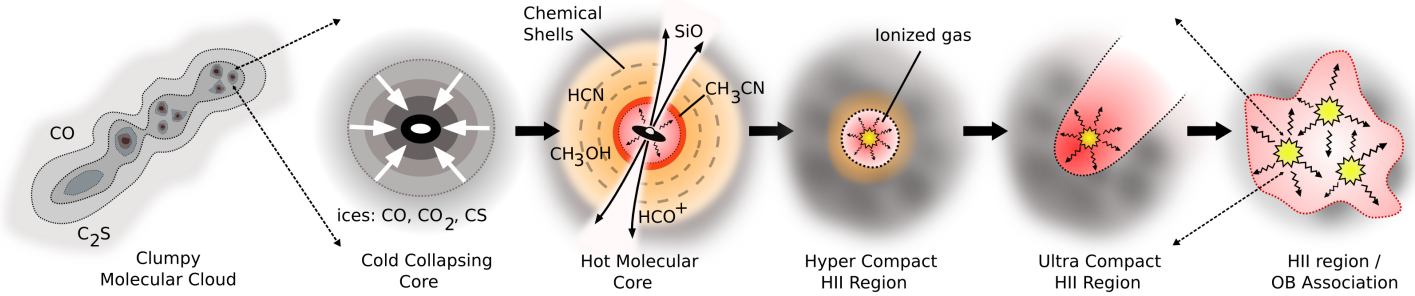


Molecular cloud | Hot core | UC HII region

HC HII region | Stellar cluster

Cold core

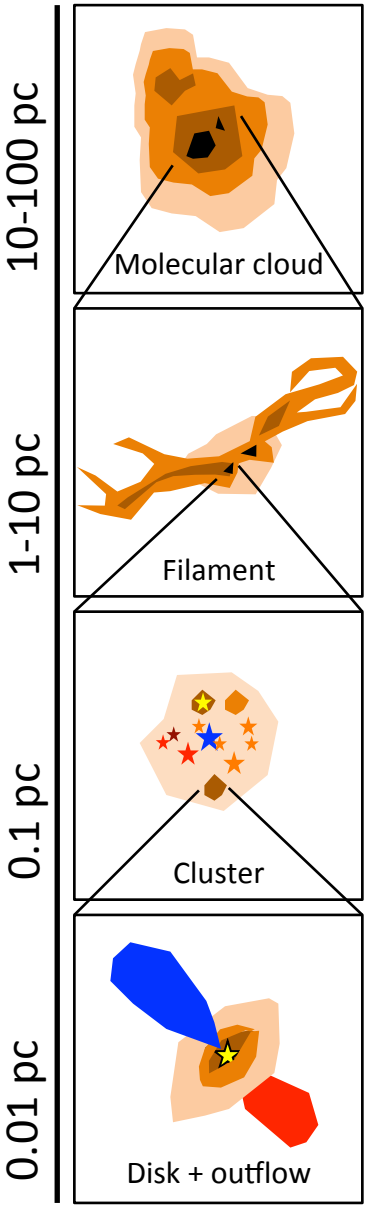
Temperatures ≈ 20-40 K
Chemistry: Deuterated, N_2H^+, CCS

Physical properties change – e.g.: temperature increases
Chemical content changes – e.g.: complex molecules form

Time evolution

(total process takes about 10^5-10^6 yr)

Evolutionary stages in star formation



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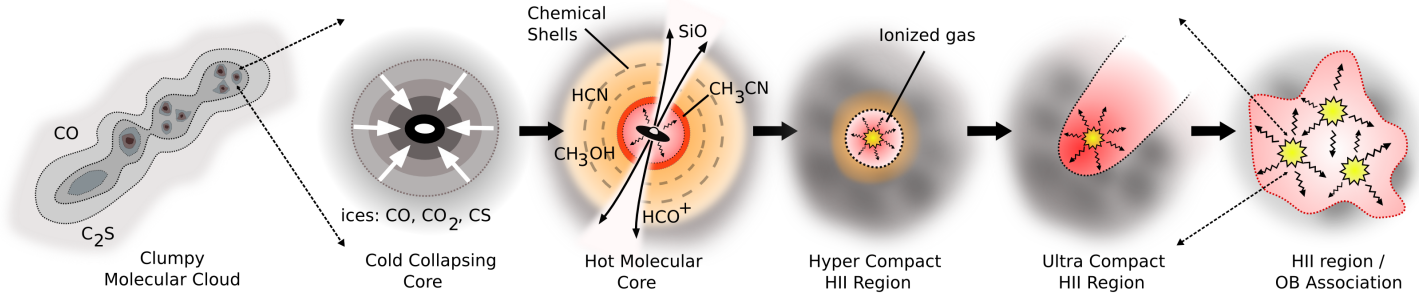


Molecular cloud

Cold core

Temperatures ≈ 20-40 K
Chemistry: Deuterated, N_2H^+, CCS

Hot core

Temperatures ≈ 150-400 K
Chemistry: CH_3OH, CH_3CN, COMs

HC HII region

UC HII region

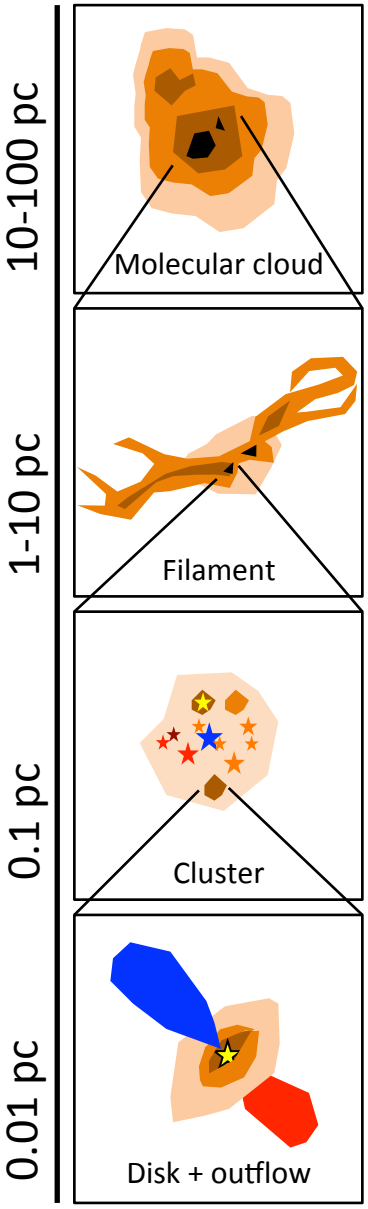
Stellar cluster

Physical properties change – e.g.: temperature increases
Chemical content changes – e.g.: complex molecules form

Time evolution

(total process takes about 10^5-10^6 yr)

Evolutionary stages in star formation



Establishing **evolutionary stages** in (high-mass) star formation

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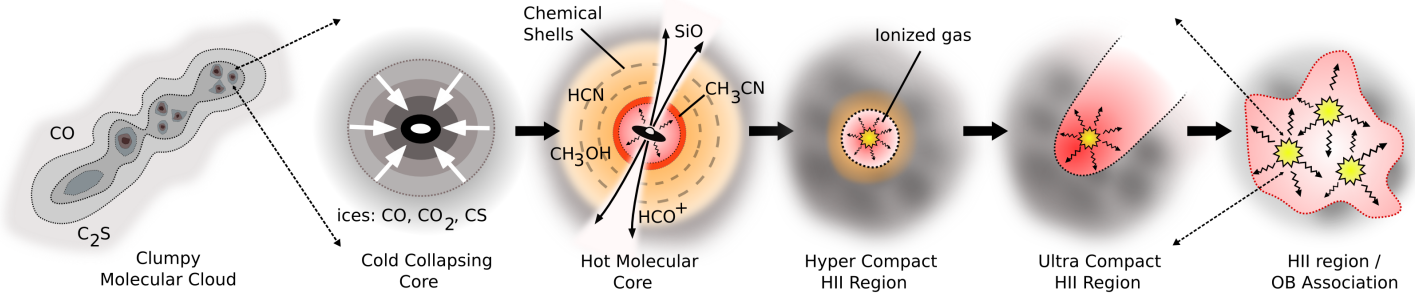


Molecular cloud

Cold core

Temperatures ≈ 20-40 K
Chemistry: Deuterated, N_2H^+, CCS

Hot core

Temperatures ≈ 150-400 K
Chemistry: CH_3OH, CH_3CN, COMs

UC HII region

HC HII region

Temperatures ≈ 10^3-10^4 K
Chemistry: Hα, C^+, CO^+

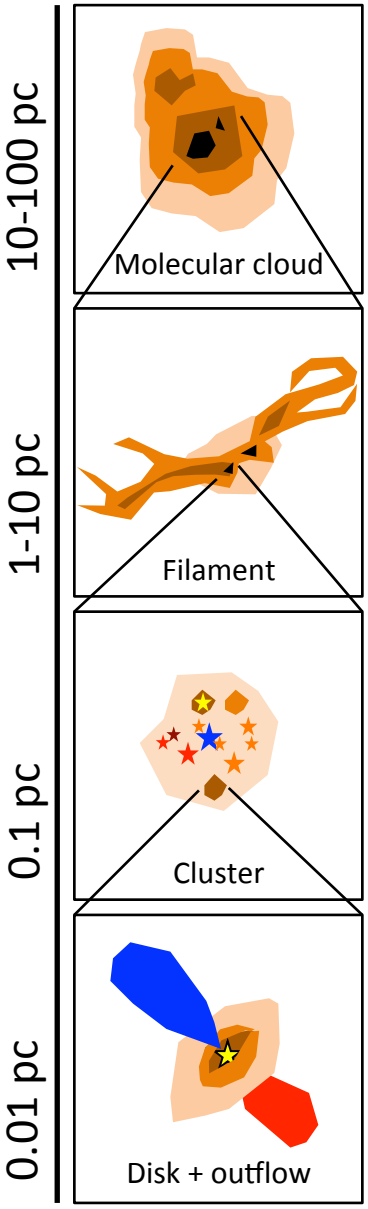
Stellar cluster

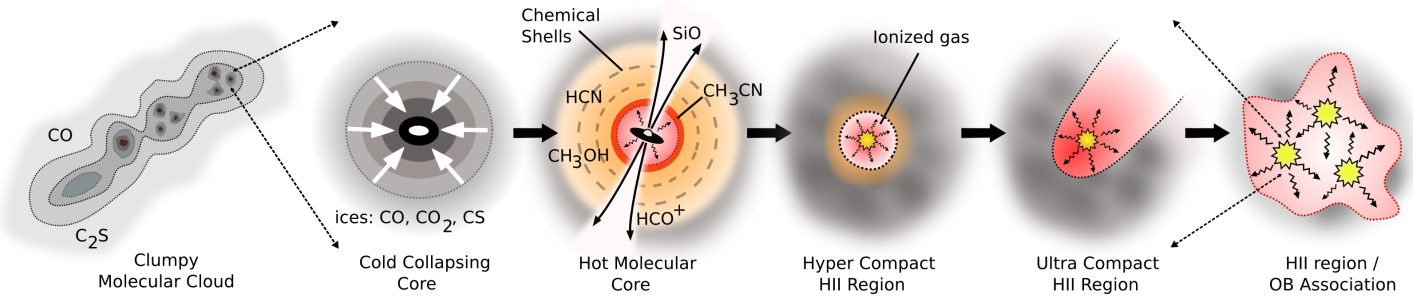
<u>Physical properties change</u> – e.g.: temperature increases
<u>Chemical content changes</u> – e.g.: complex molecules form

Time evolution

(total process takes about 10^5-10^6 yr)

Molecular fingerprints of evolution





Scientific goals:

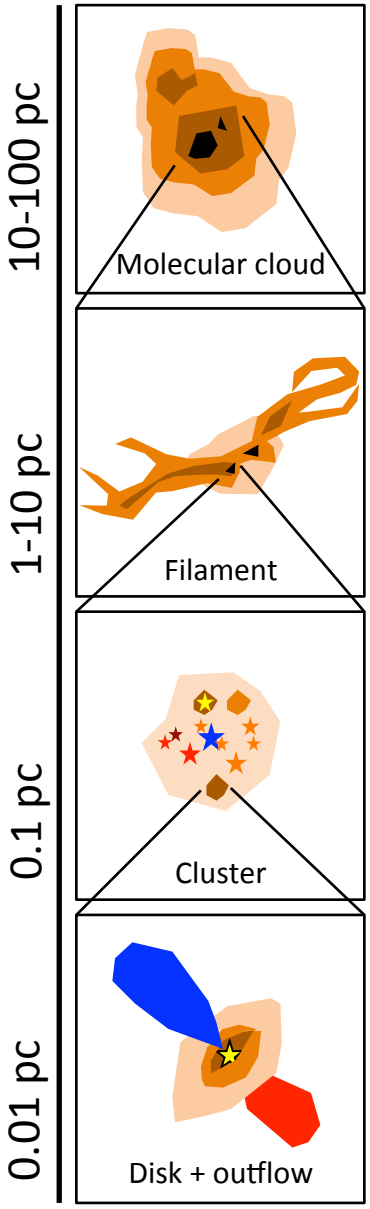
- Understanding the chemical evolution in the formation of a (high-mass) star
- Searching for molecular fingerprints of the evolution process

Model setup:

Simple physical model,
which enables to generate a large set of different models
and to produce synthetic spectra that is directly comparable to observations

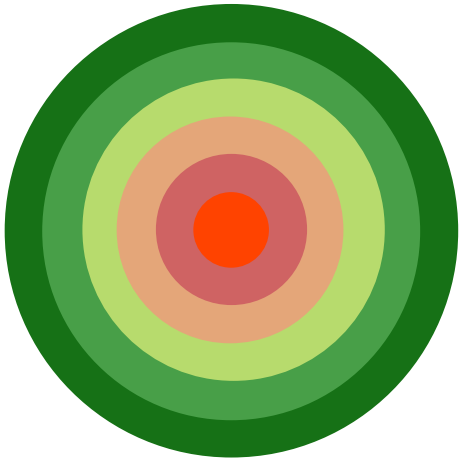
Choudhury et al (2015) / Stéphan et al (2018) / Riedel (2021, Master thesis) / Ngo (2022, PhD)

Molecular fingerprints of evolution



Riedel (2021, Master thesis)

Sketch of the dense core model



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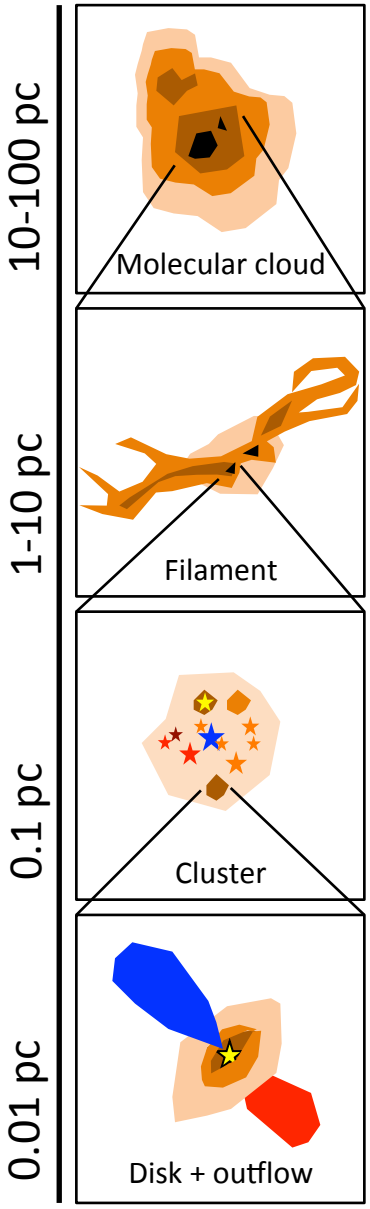

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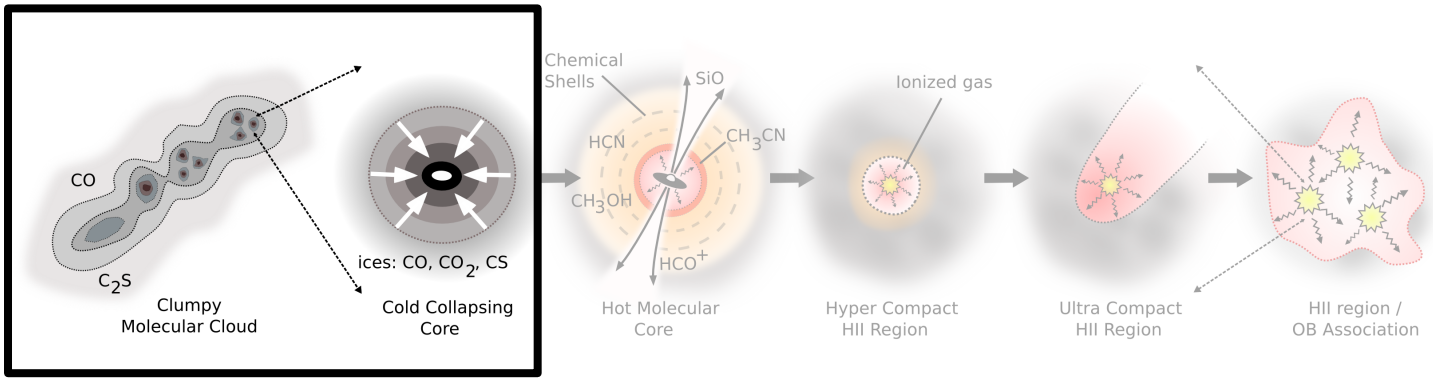
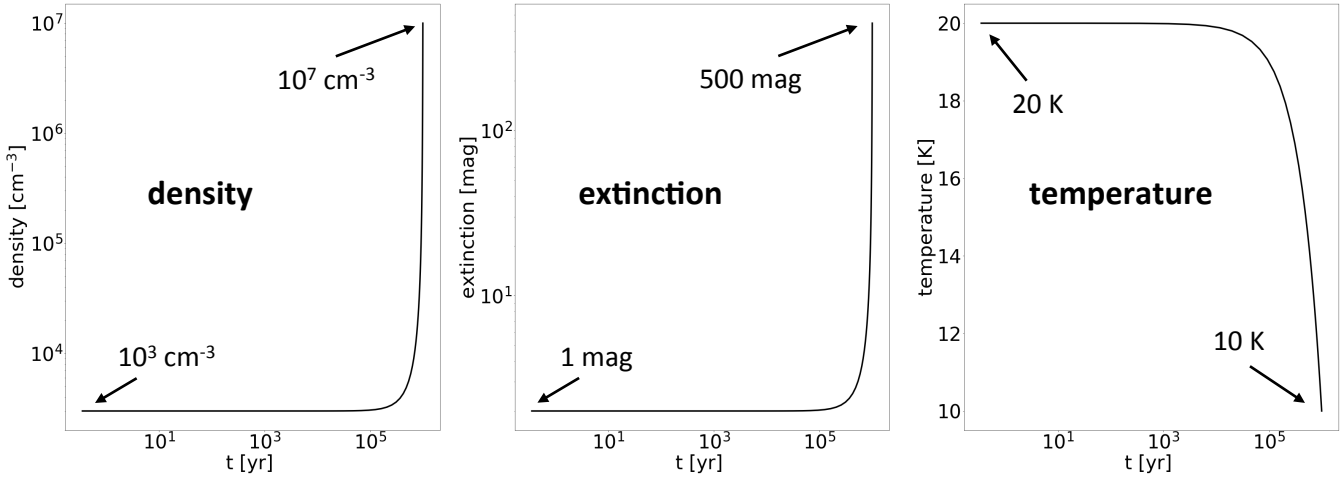
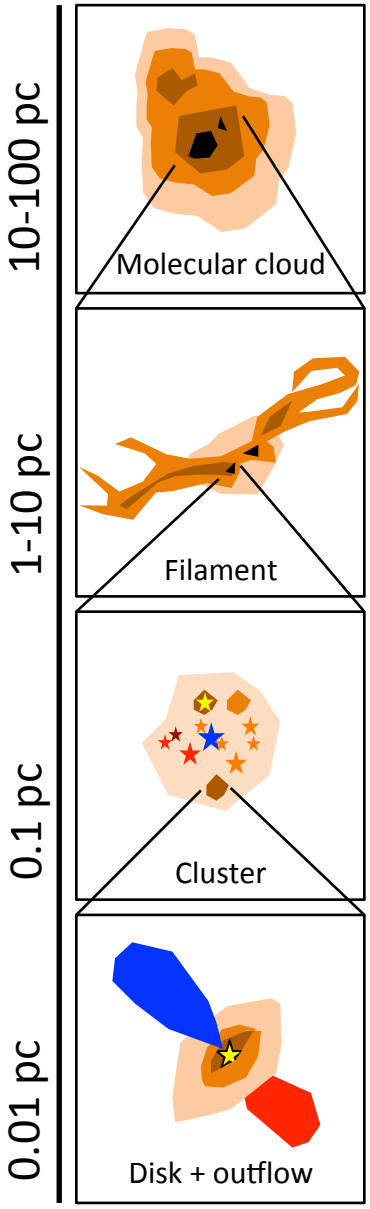


Cold collapse phase

Molecular cloud collapses to a central density of 10^7 cm^{-3} (within 1 Myr)
Collapse can be slowed down (e.g., rotation, magnetic fields)
- Parametrized by a retardation factor



Molecular fingerprints of evolution



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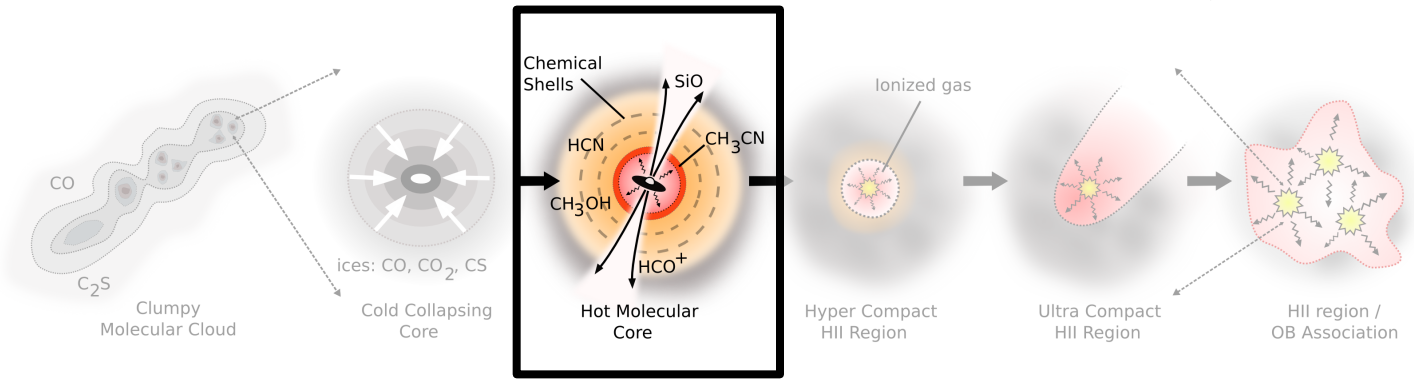
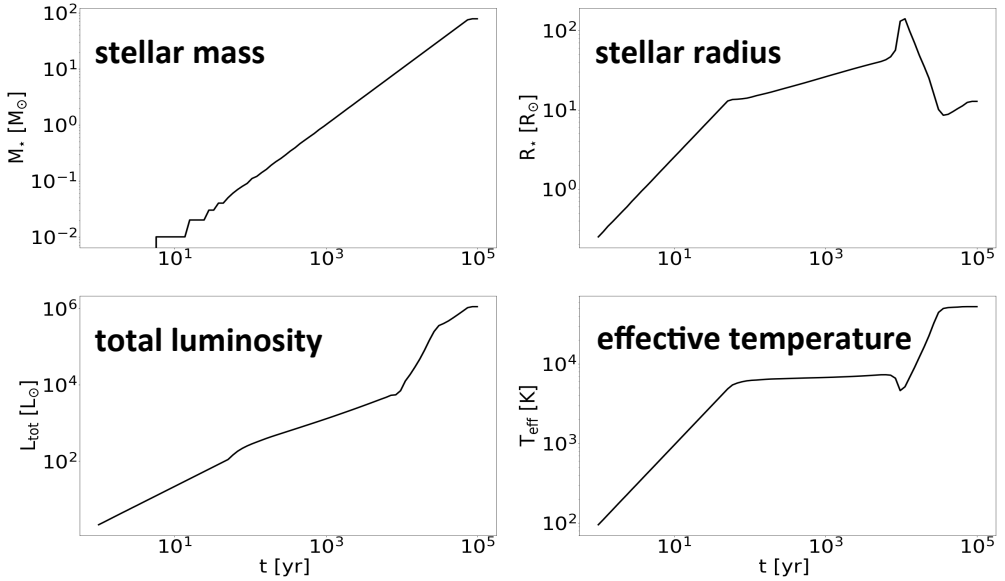


Warm-up phase

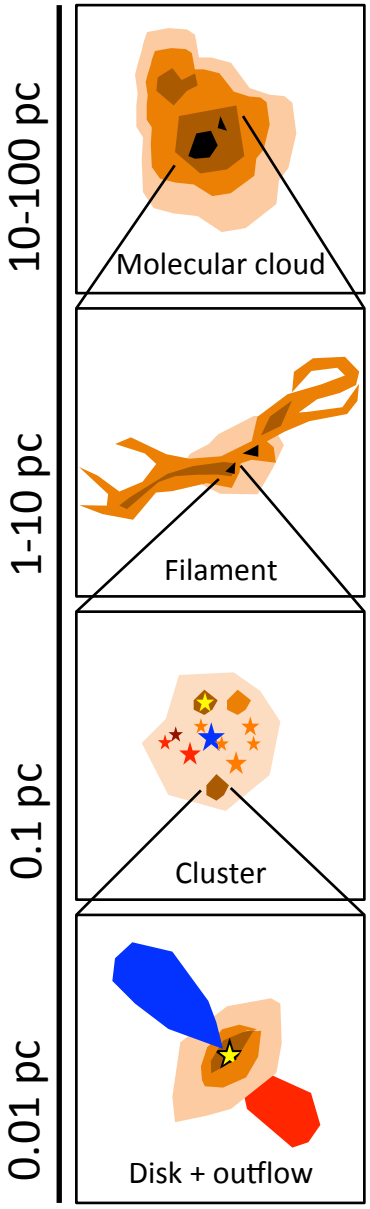
Luminosity evolution of a high-mass protostar accreting at 10^{-3} $M_\odot$ yr^{-1}

- Stellar evolution taken from numerical simulations by Hosokawa et al 2009



The Saptarsy⌘ chemical code

⌘ from Sanskrit, the seven sages (see also Ursa Major and Pleiades)



Saptarsy: spatial and temporal variations
in the chemical structure of star forming cores

See details at:
- Choudhury et al 2015, A&A, 575, A68
- Dirk Schäfer 2017, Master Thesis
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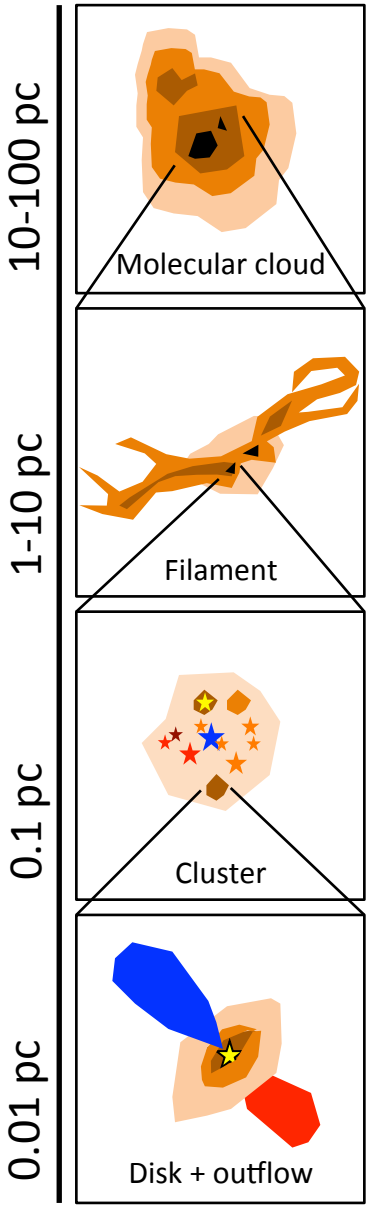

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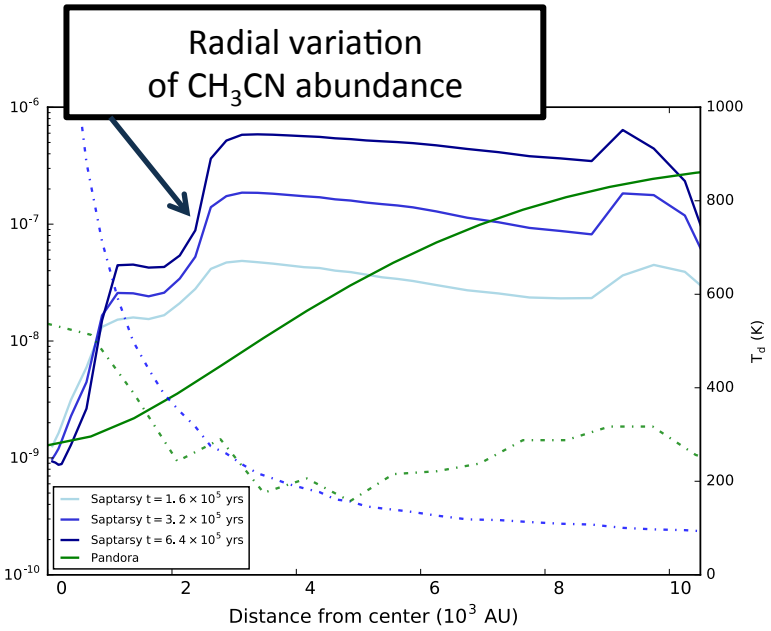

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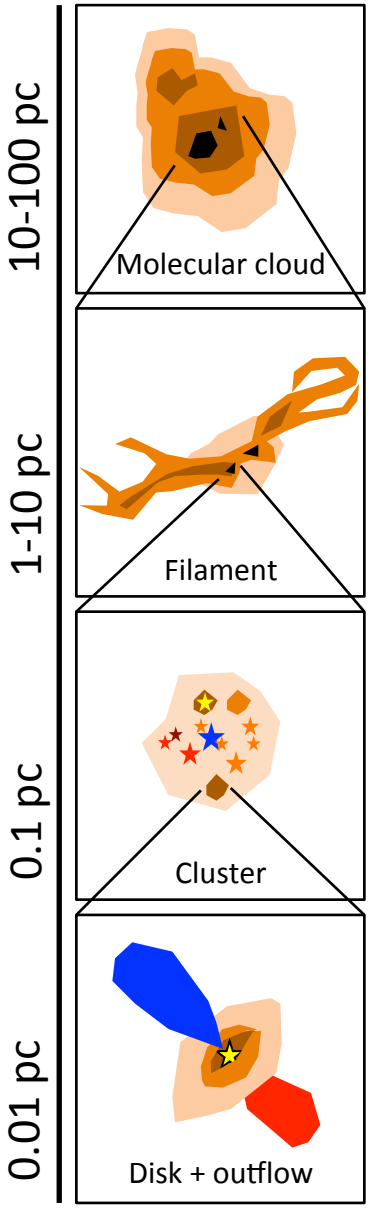

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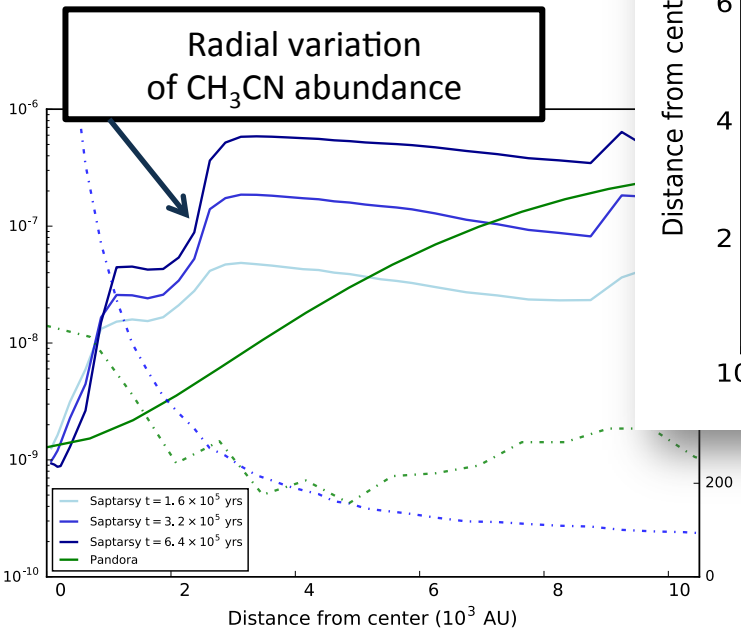

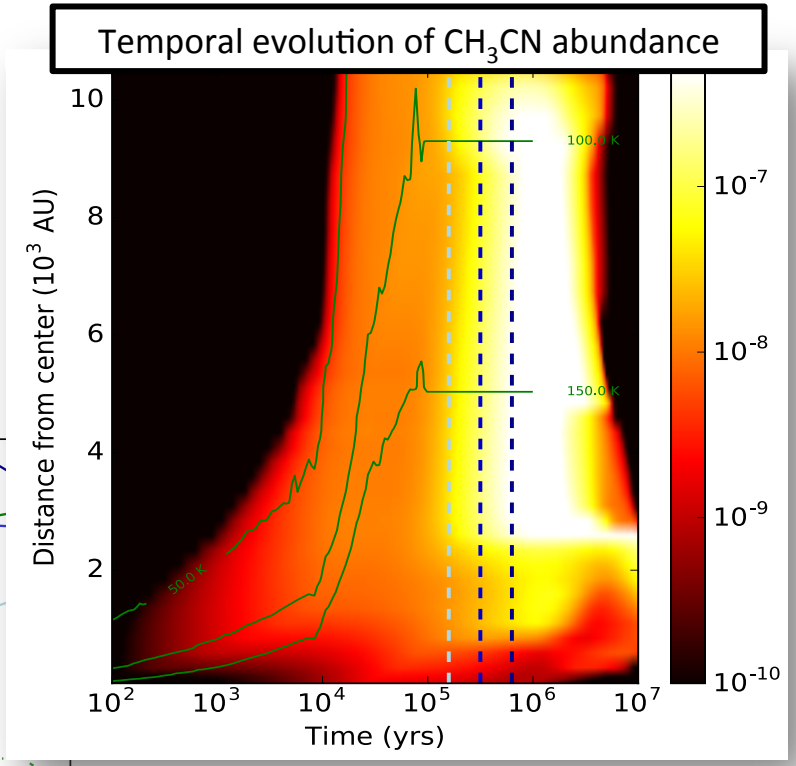

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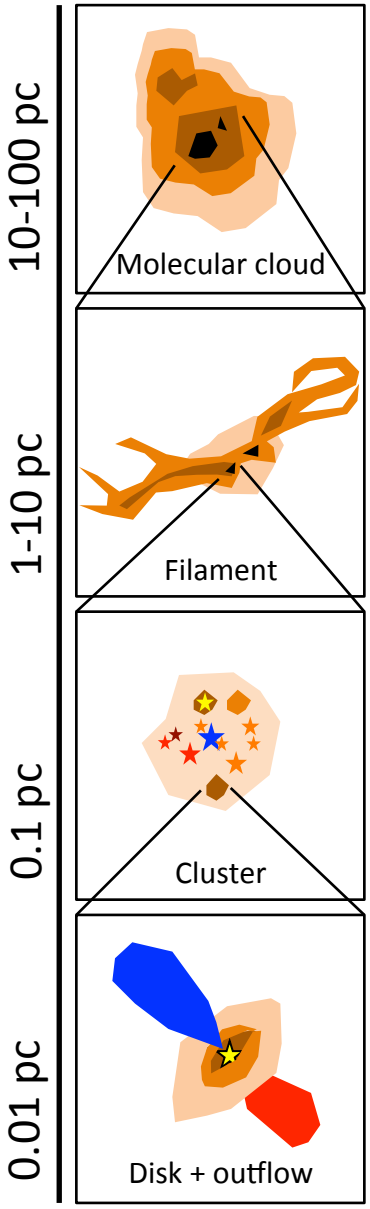

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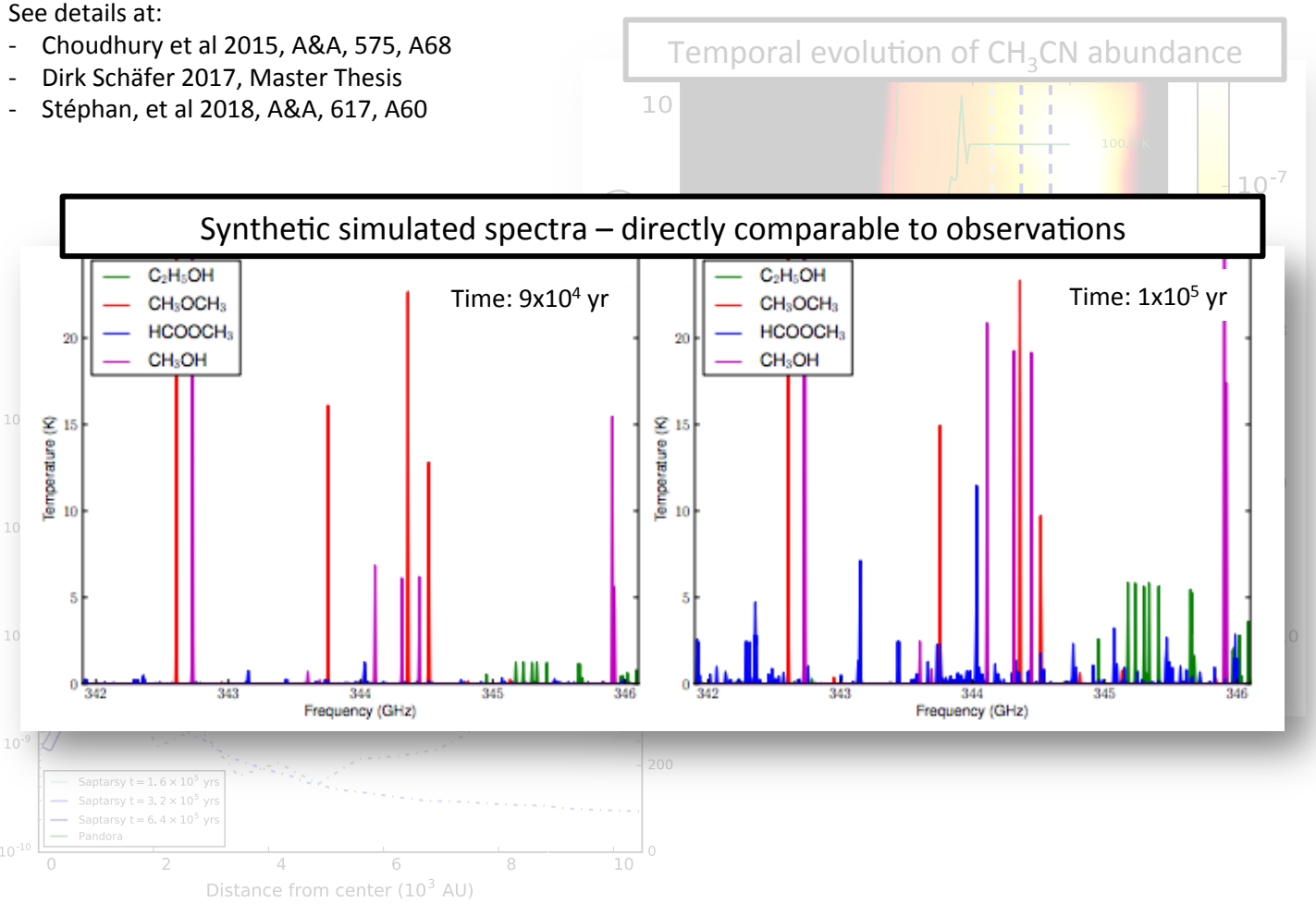
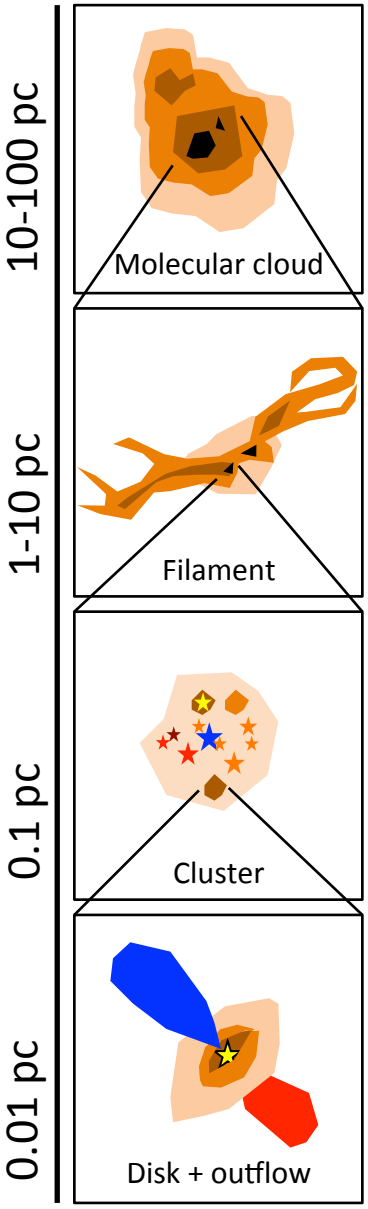
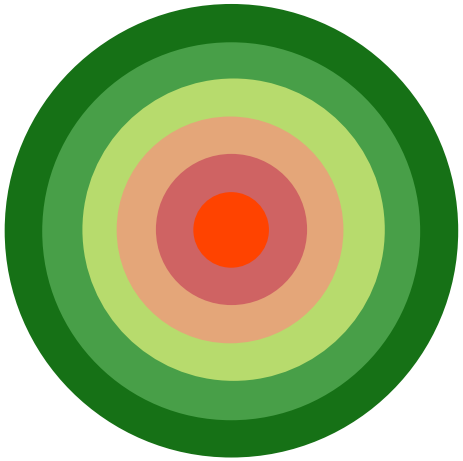


Molecular fingerprints of evolution



Riedel (2021, Master thesis)

Sketch of the dense core model



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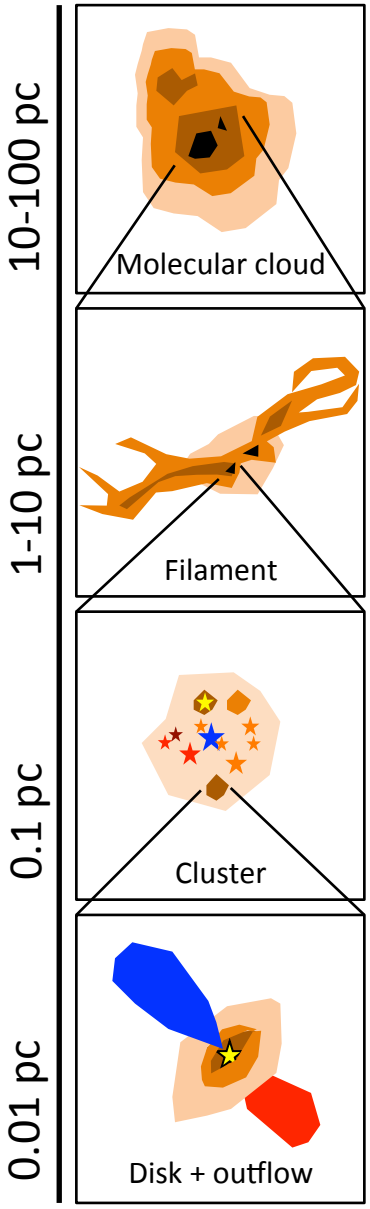

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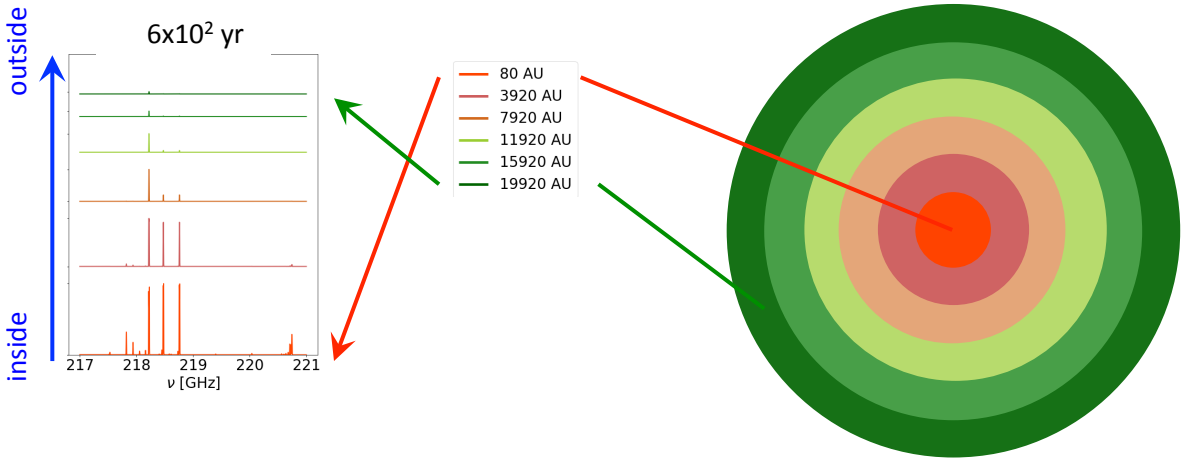
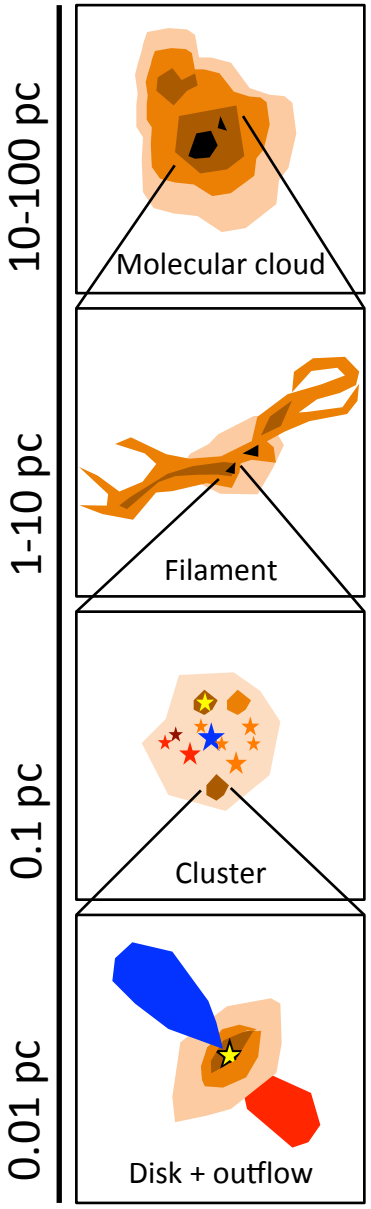


For one model, we generate synthetic spectra
- at **different radii (positions)** at a given time

Molecular fingerprints of evolution



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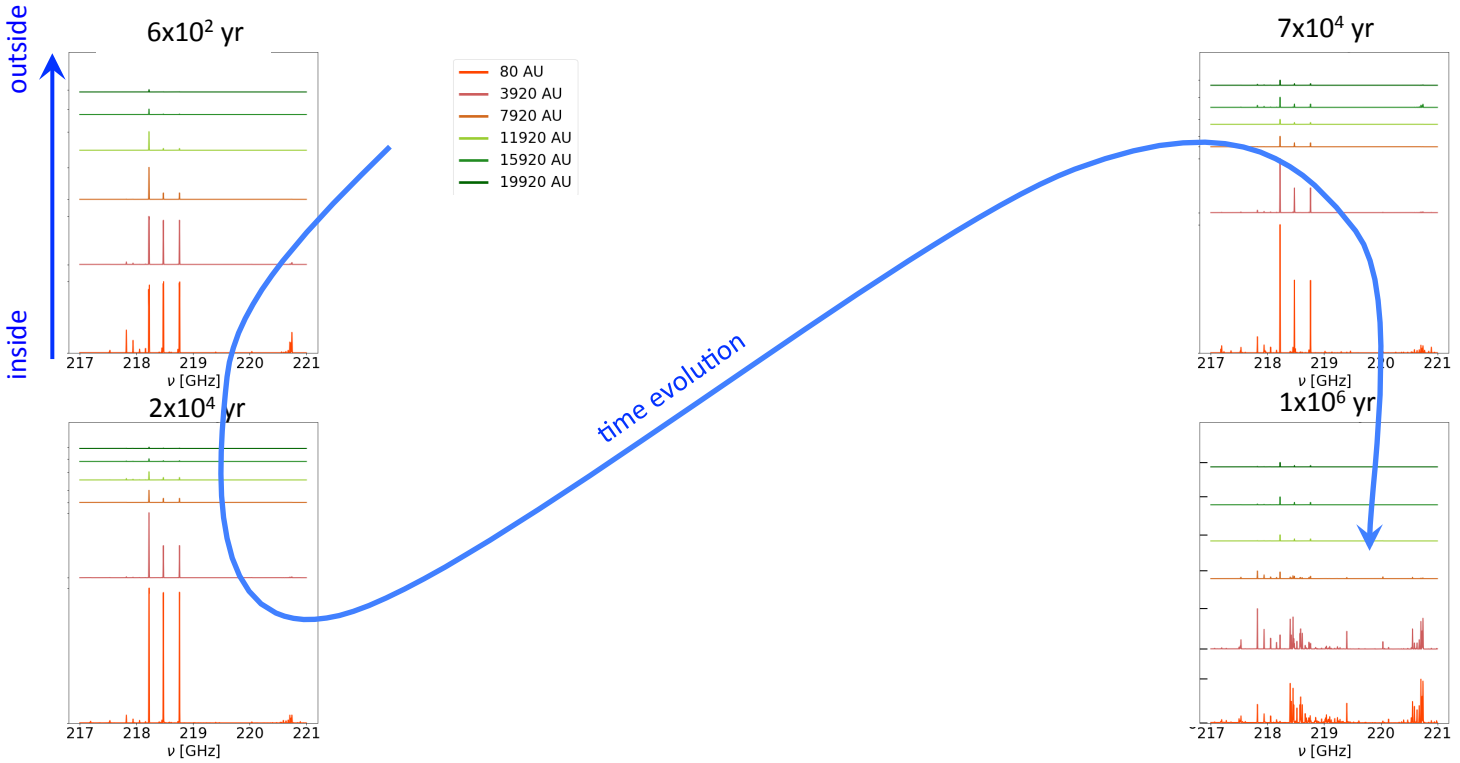
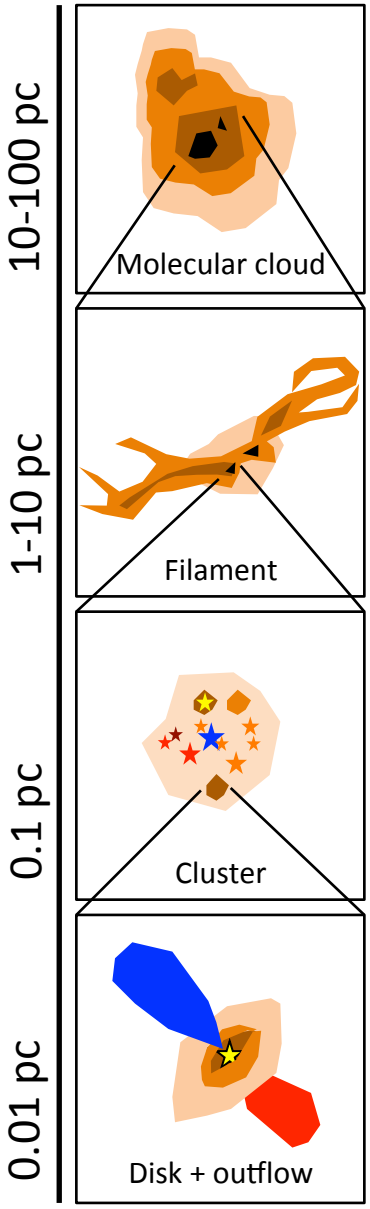


For one model, we generate synthetic spectra
- at **different radii (positions)** at a given time
- and we can explore **different times**

Molecular fingerprints of evolution



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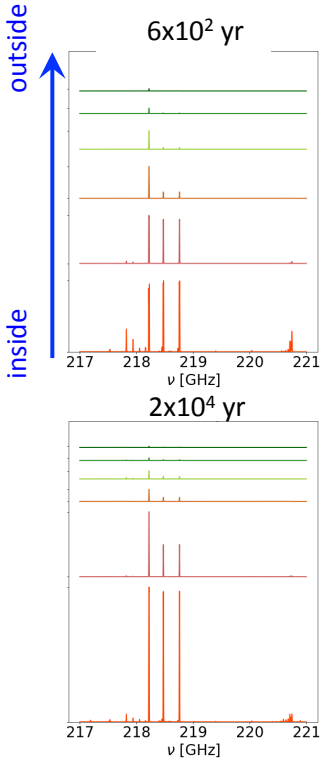
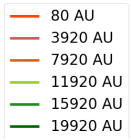
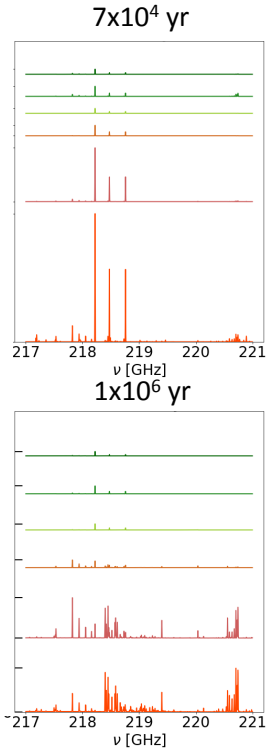


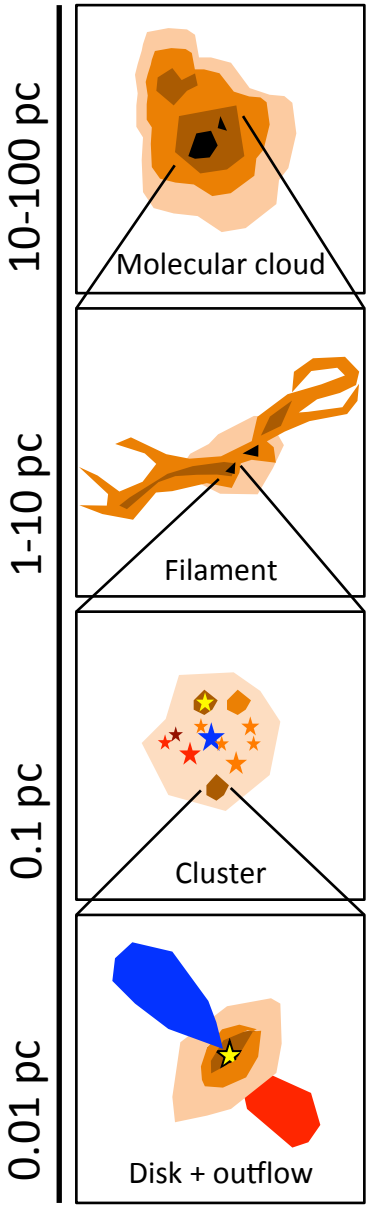




For one model, we generate 100+ spectra with 1000+ channels

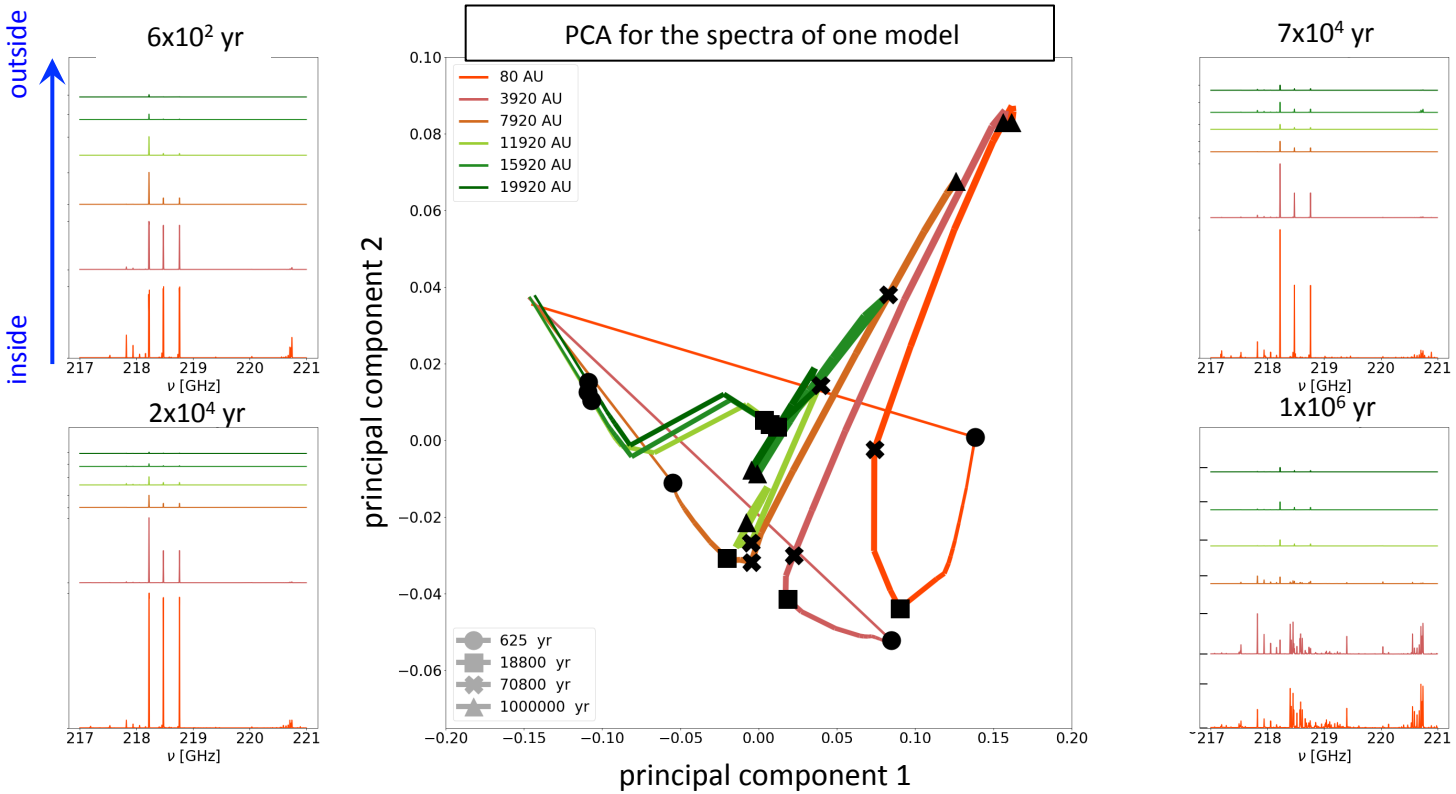
For one model, we generate synthetic spectra
- at **different radii (positions)** at a given time
- and we can explore **different times**

Molecular fingerprints of evolution



Principal Component Analysis (PCA) to reduce dimensionality

→ We use PCA on the synthetic spectra



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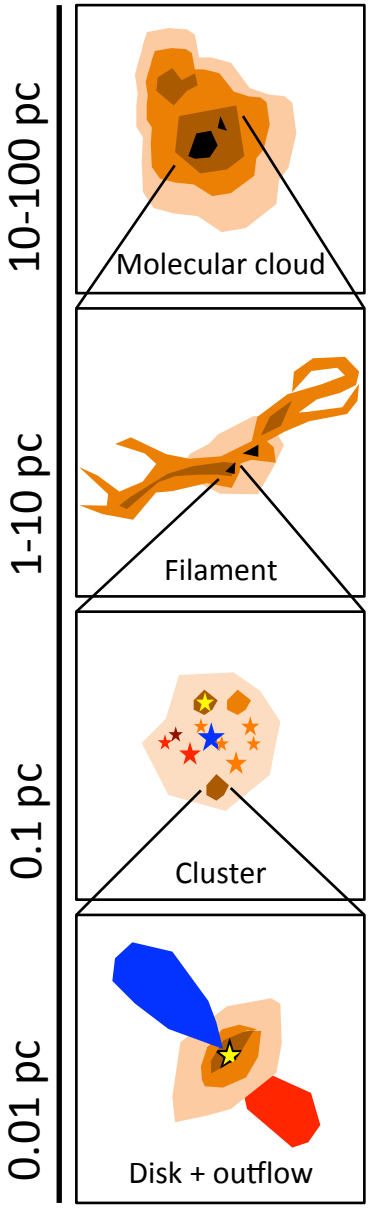
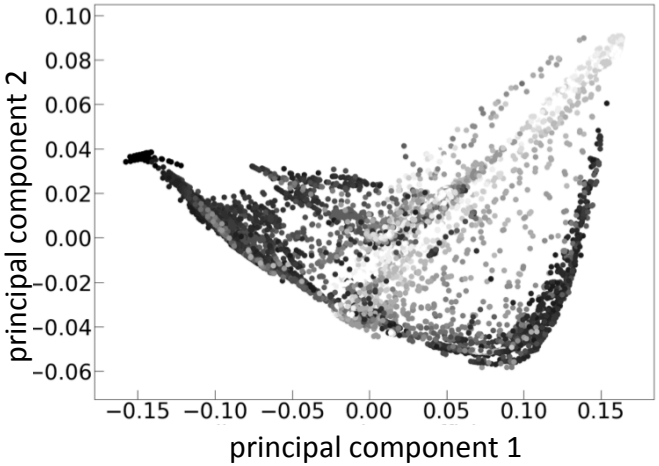


Riedel (2021, Master thesis)

Principal Component Analysis (PCA) to reduce dimensionality

Including the synthetic spectra for the **50 different models**
2D-represeantion of the first 5 principal components



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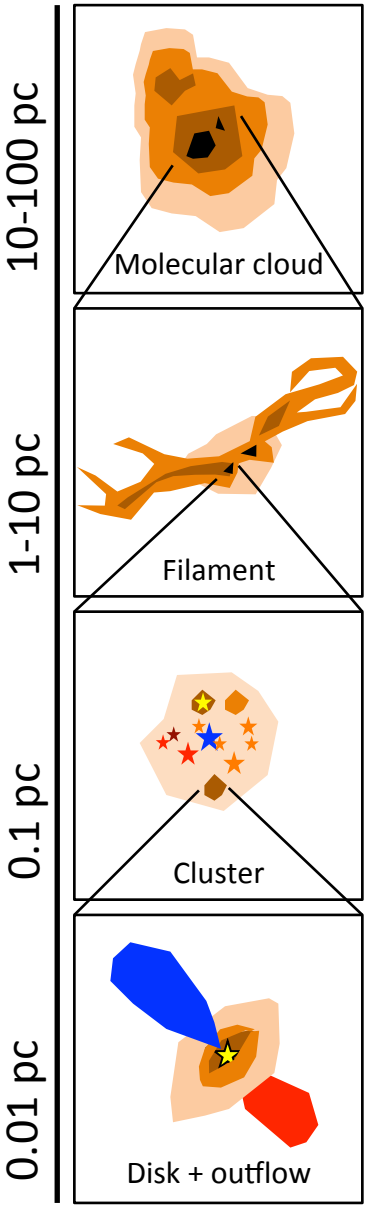

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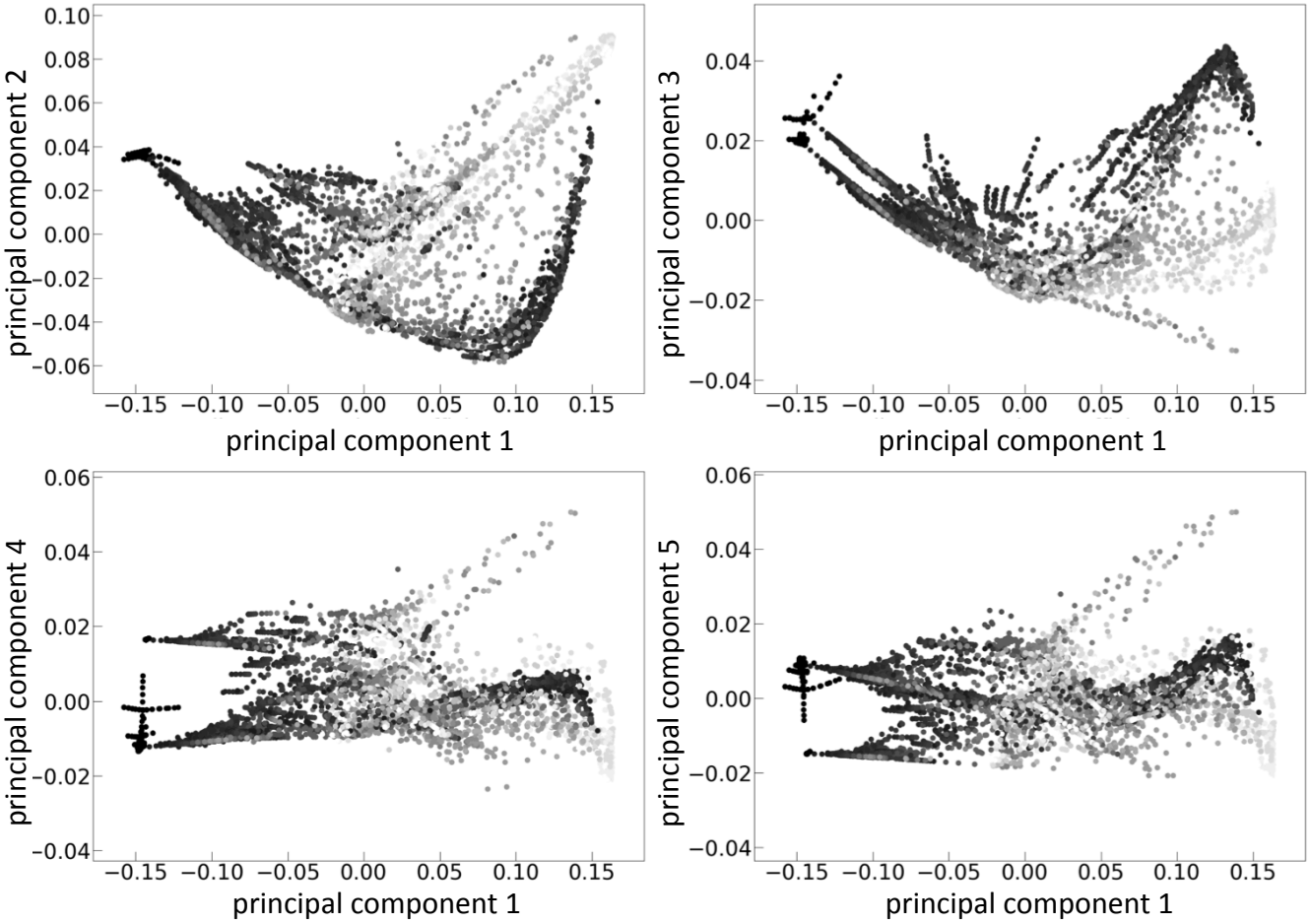

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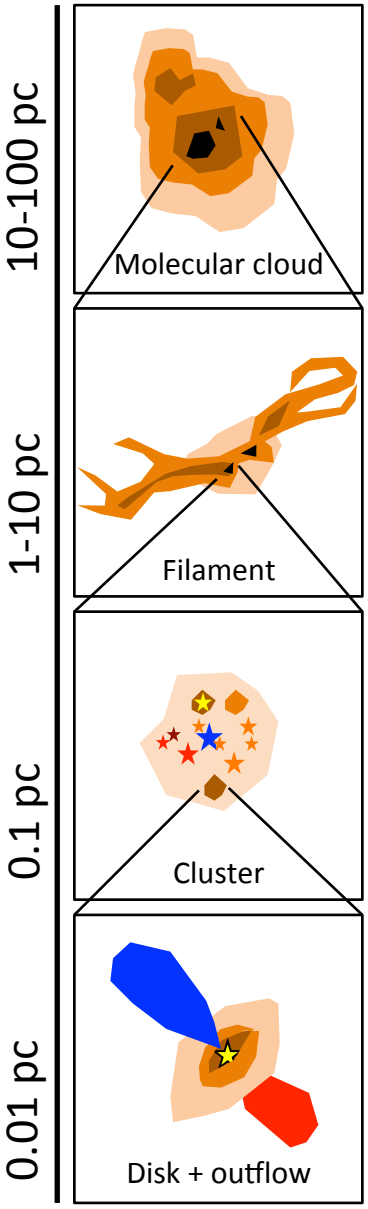
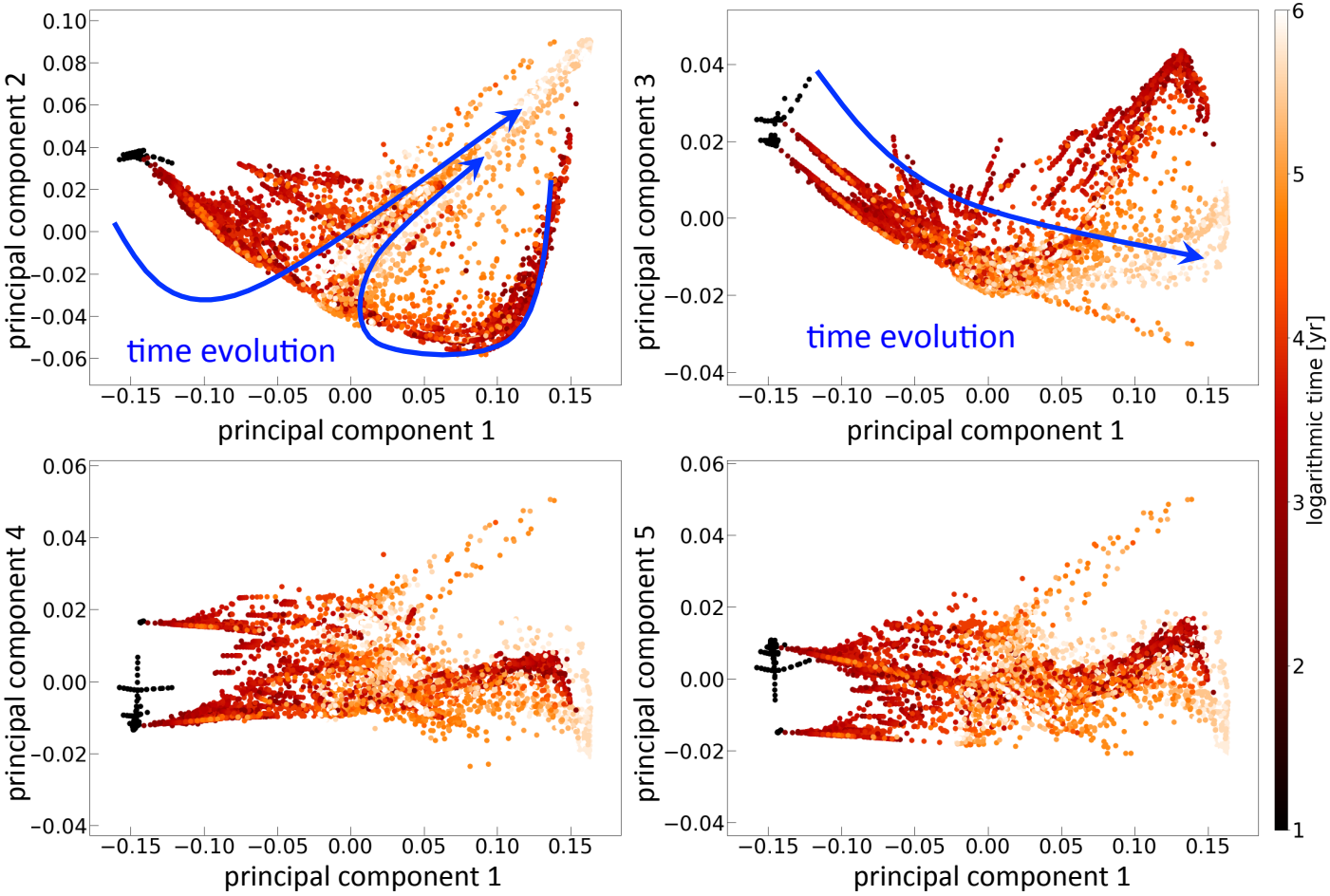


Riedel (2021, Master thesis)

Principal Component Analysis (PCA) to reduce dimensionality

PCAs : Colored as a function of time (**evolution**)



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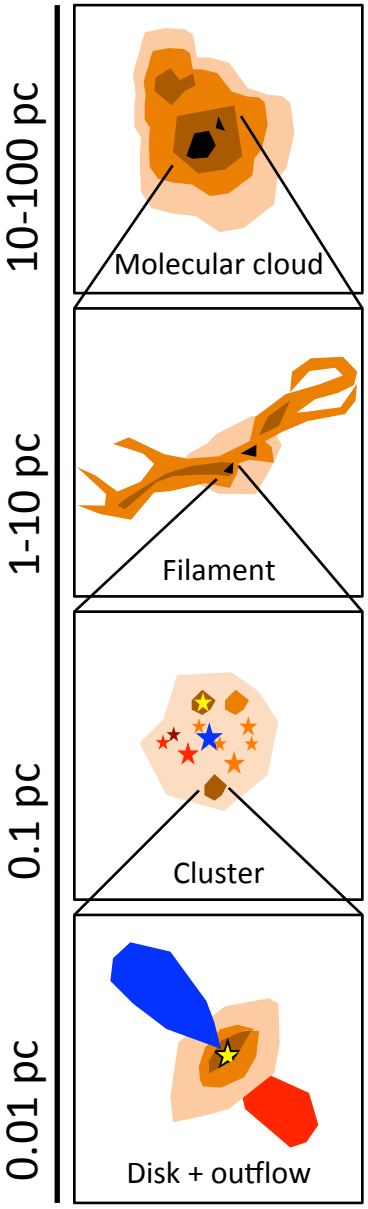
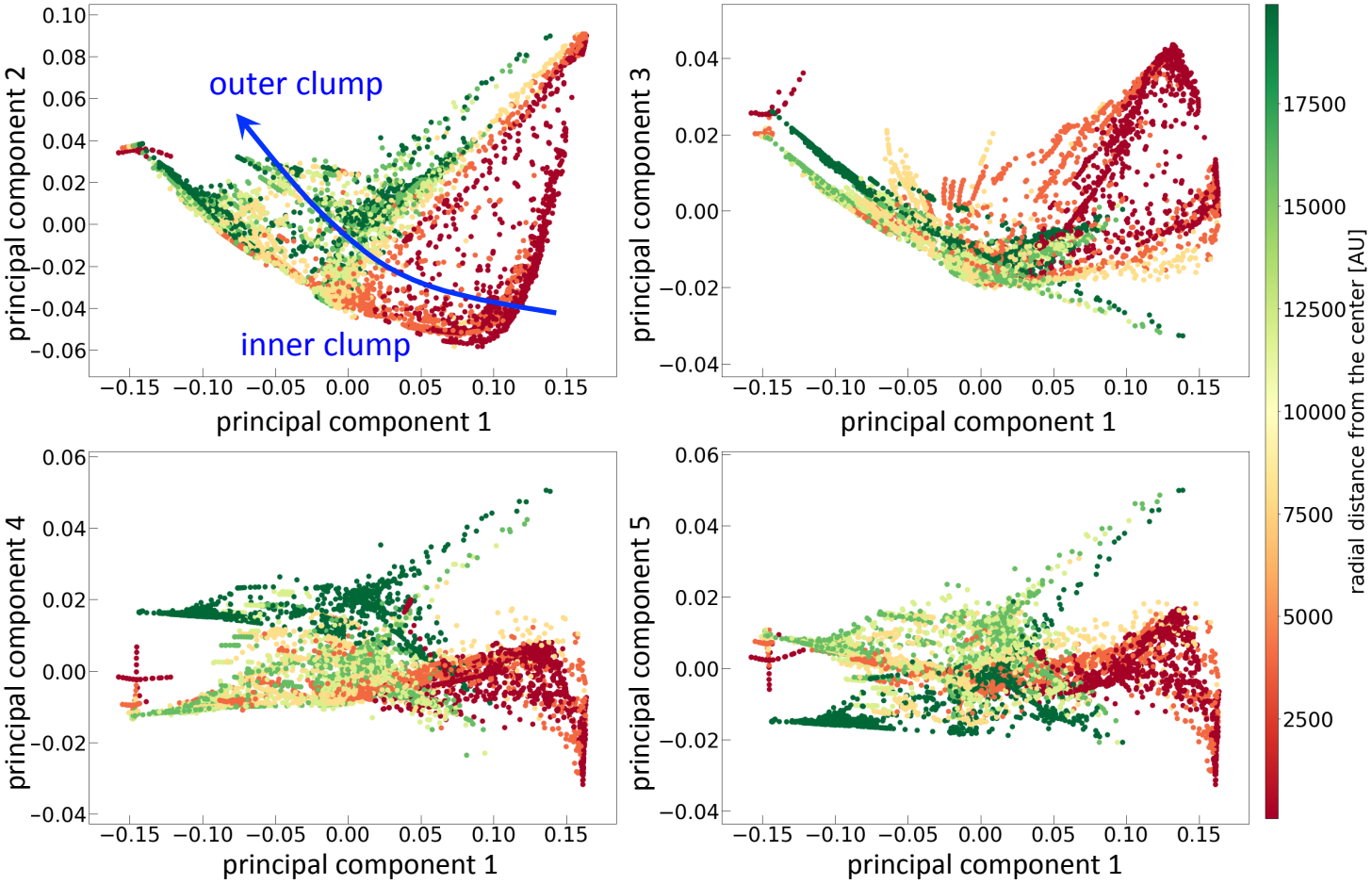


Riedel (2021, Master thesis)

Principal Component Analysis (PCA) to reduce dimensionality

PCAs : Colored as **spatial location** within the clump



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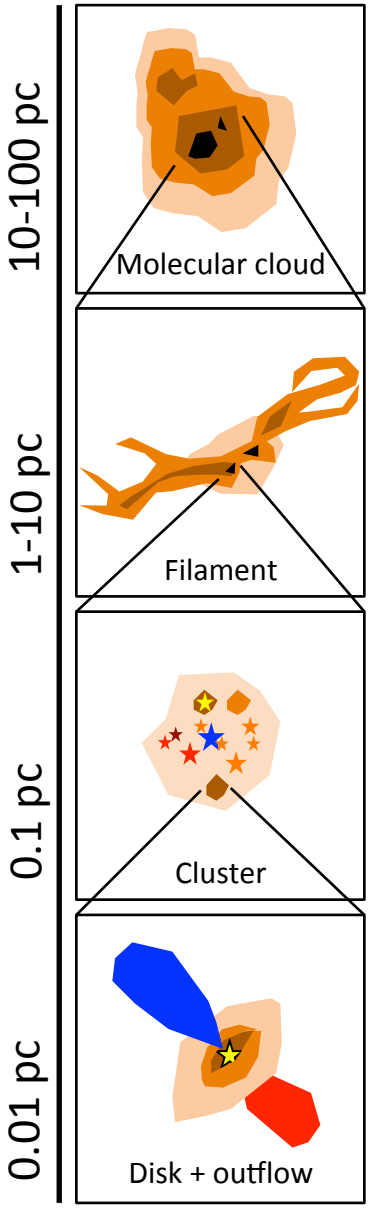


Riedel (2021, Master thesis)

We can compare the modeled synthetic spectra with large sets of observations

ALMA evolutionary study of high-mass proto-cluster formation in the Galaxy

1017 star-forming clusters

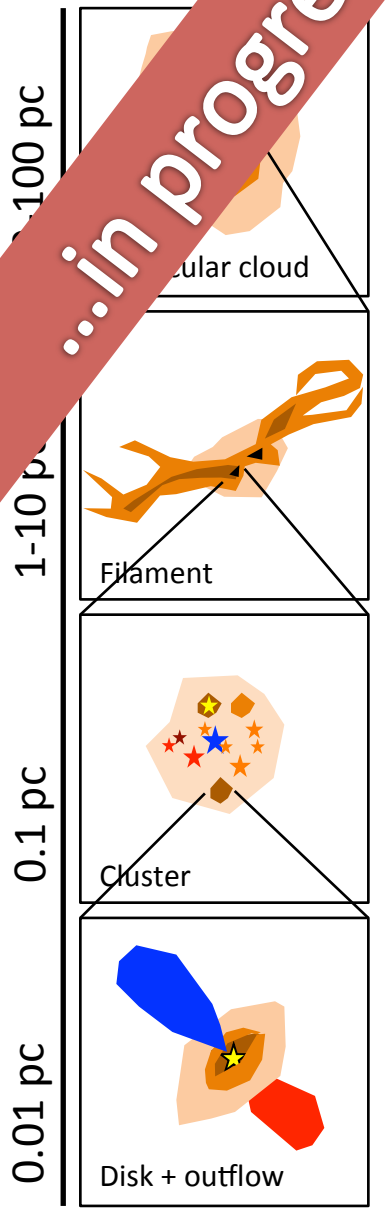
catalogue of about 10,000 dense cores at different evolutionary stages

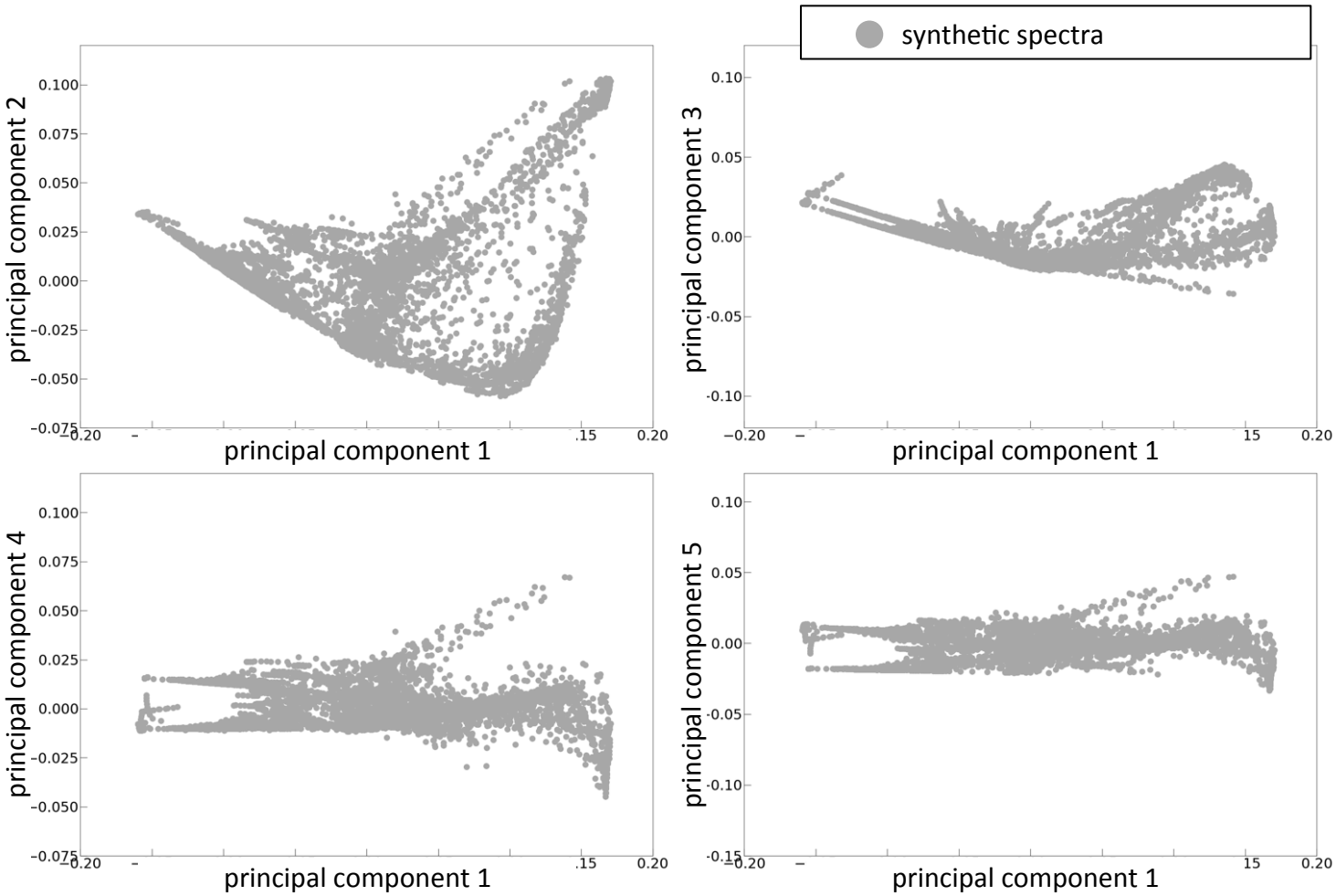
M…cular fingerprints of evolution

…in progress

Riedel (2021, Master thesis)

Comparison of PCA from synthetic spectra and observed spectra





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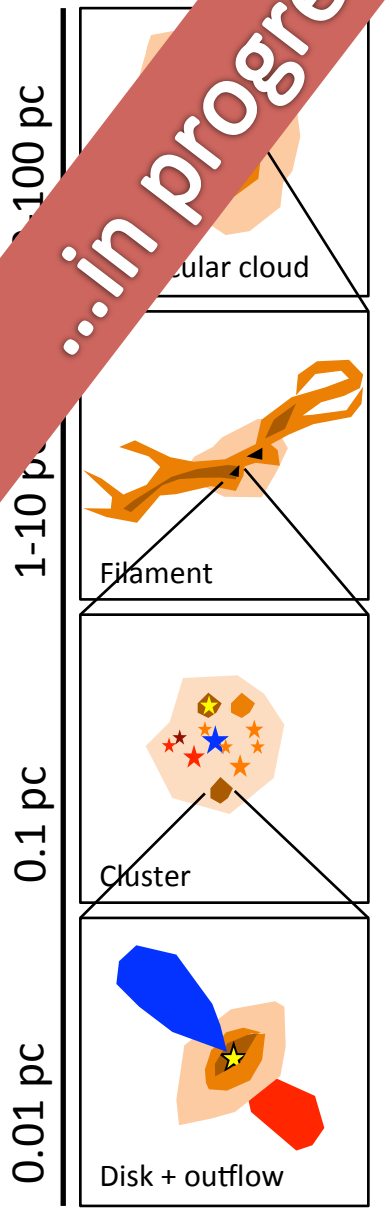
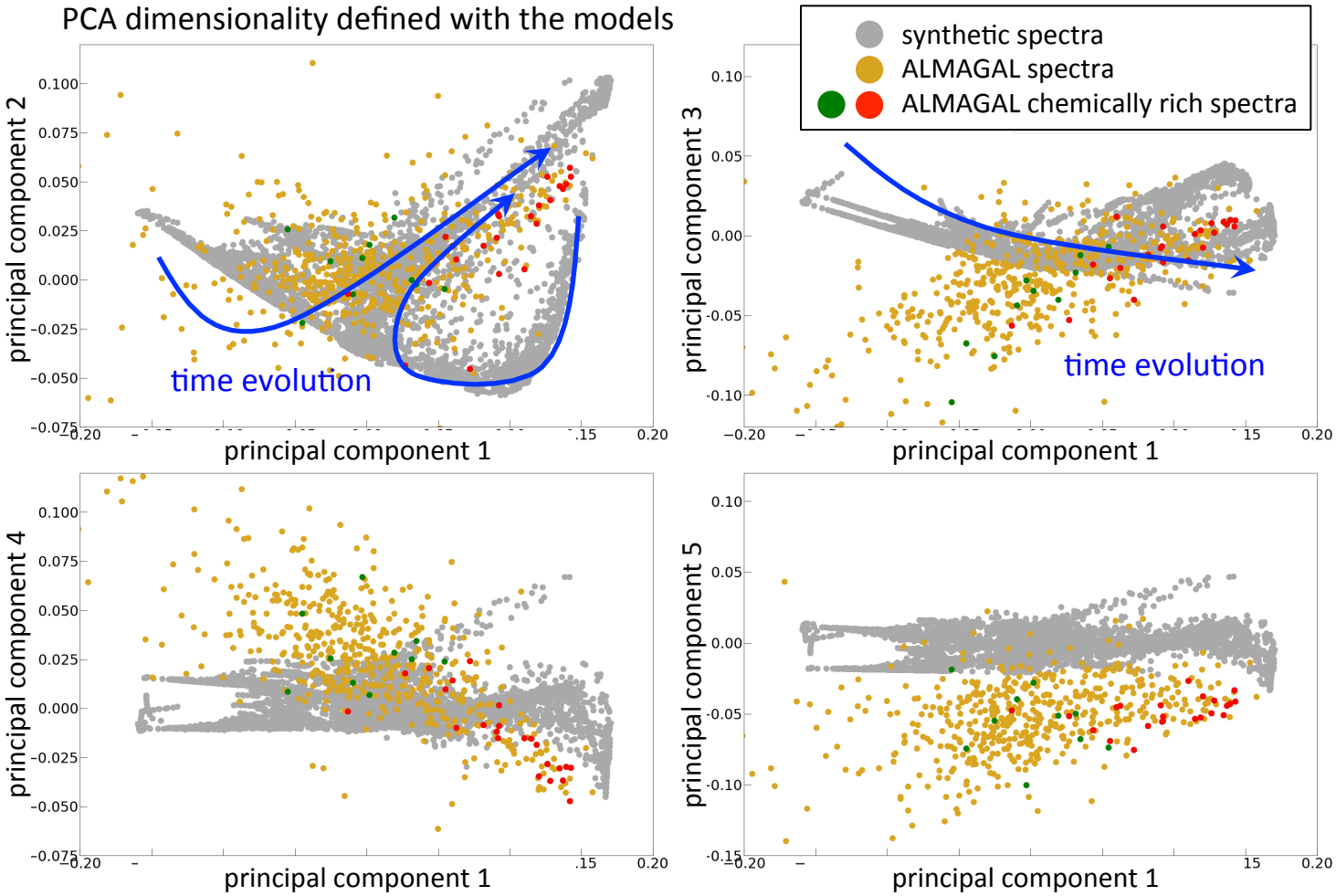


Riedel (2021, Master thesis)

Comparison of PCA from synthetic spectra and observed spectra

ALMAGAL observed spectra projected onto the PCA dimensionality defined with the models



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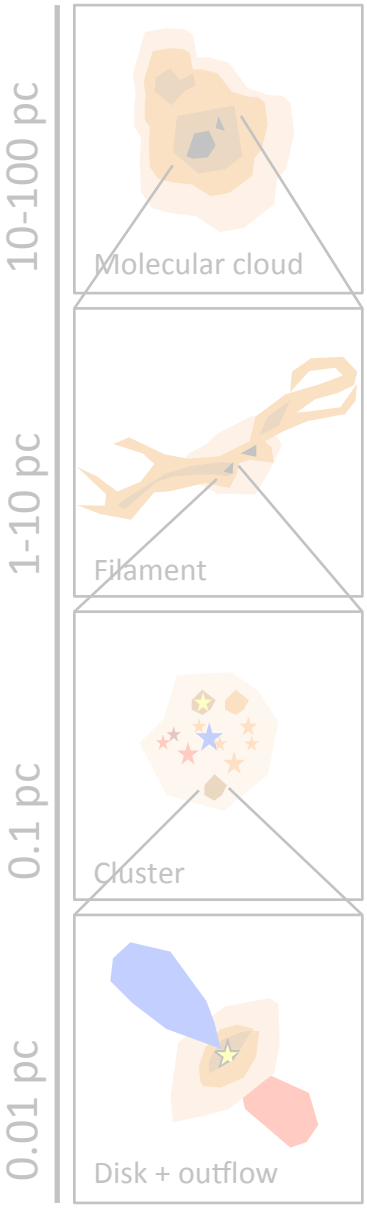

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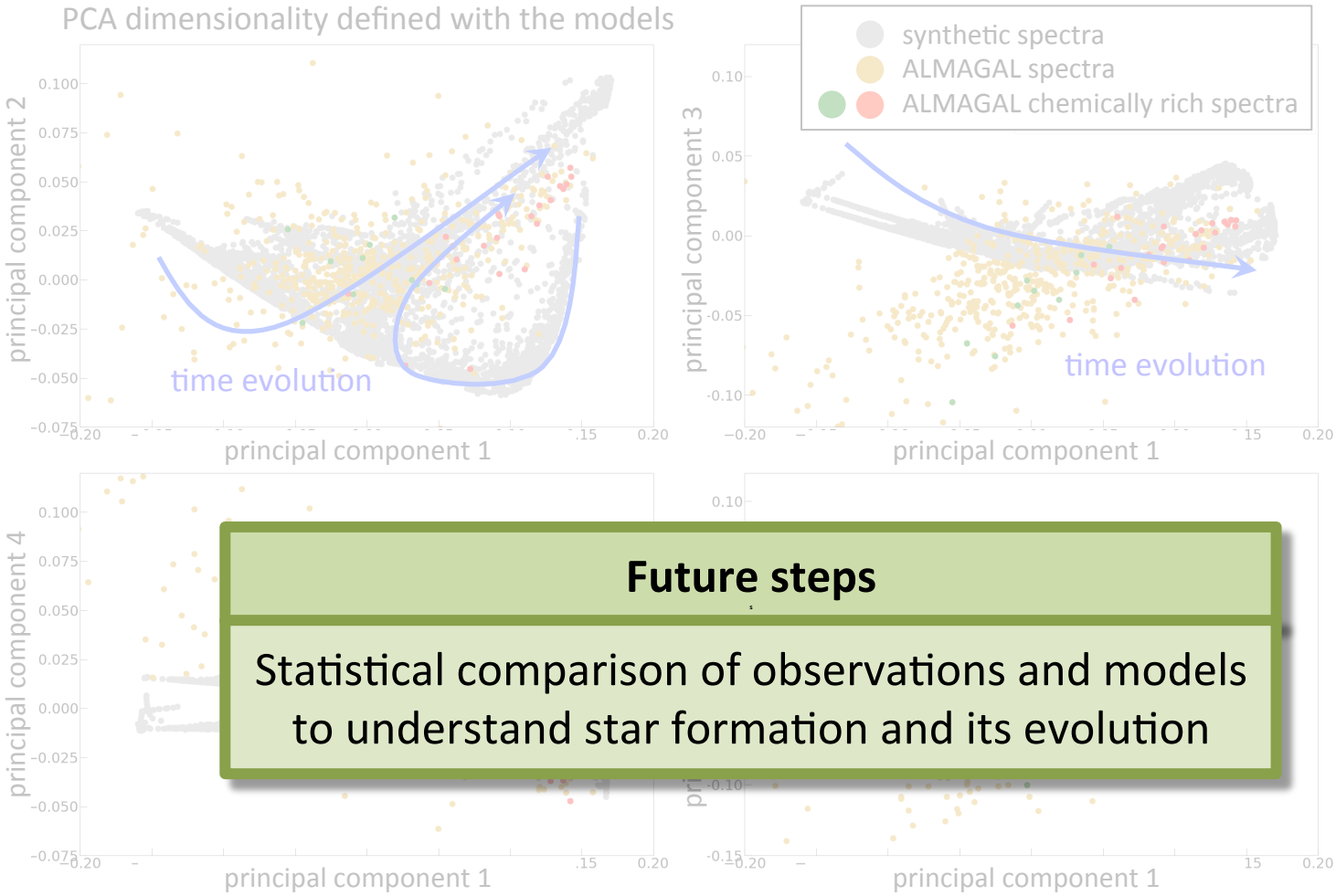
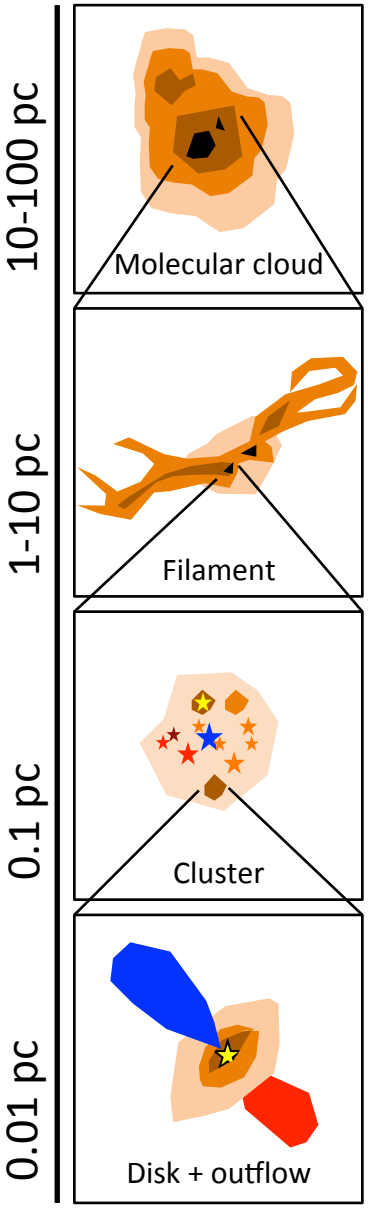


Future steps

Statistical comparison of observations and models to understand star formation and its evolution

From clouds to stars



Mass accretion rates

Low-density regions: $10^{-5} – 10^{-4}$ $M_\odot$/yr

Massive clusters: 10^{-3} $M_\odot$/yr

Super-star clusters: 10^{-1} $M_\odot$/yr

Clusters

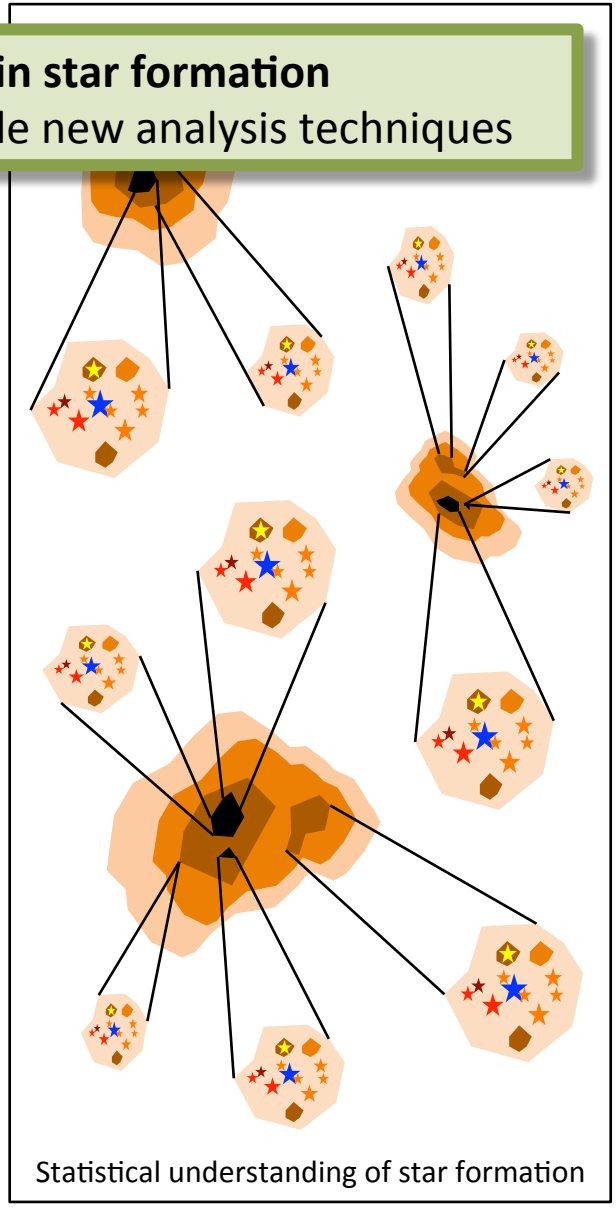
Thermal fragmentation at 0.1-0.3 pc

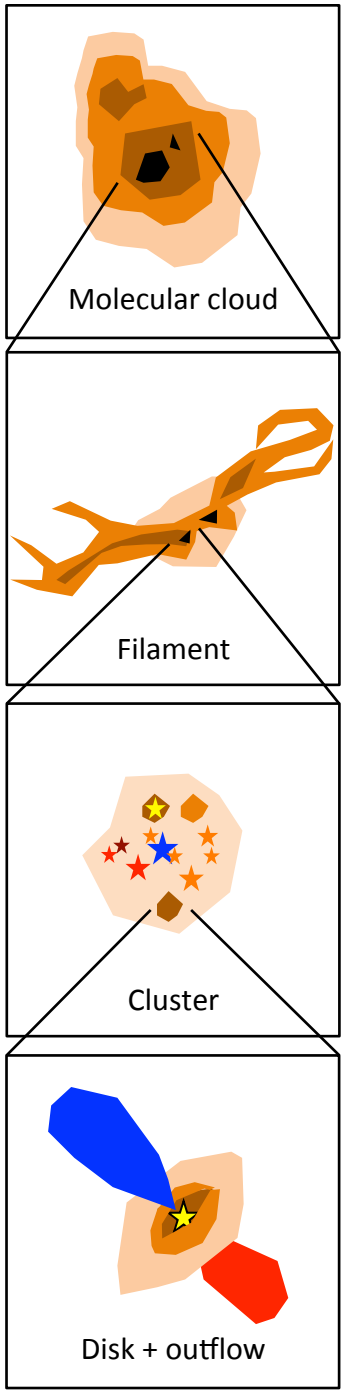
Mass segregation (even primordial)

Cores drift away with time

Statistics in star formation

Large surveys enable new analysis techniques

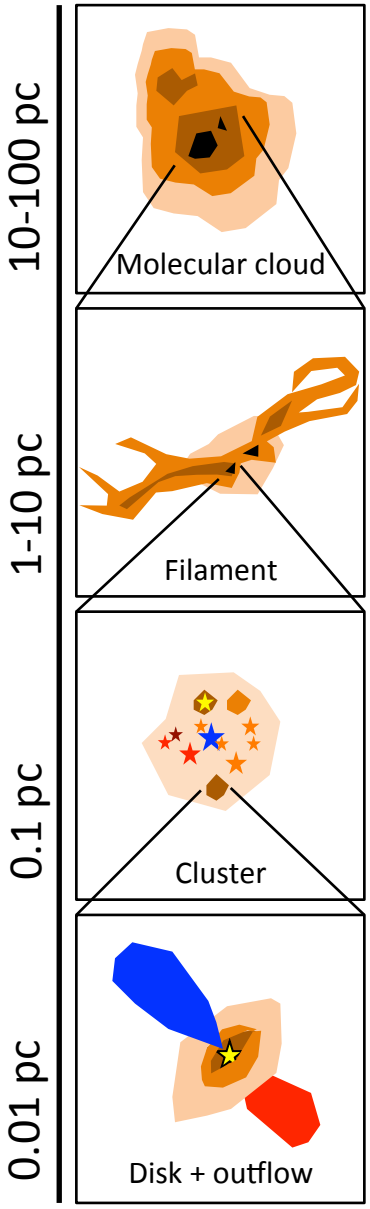




Thank you for your attention

Institute of Space Sciences
EXCELENCIA MARÍA DE MAEZTU
CSIC
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

Molecular fingerprints – model setup



Flowchart of the working pipeline

initial abundances

Spitzer collapse
$n_H(t)$; $A_V(t)$; $T(t)$

Saptarsy

Cold collapse phase
chemical evolution
(compute abundances)

Plummer
profile $n_H(r, t)$
$L(t)$

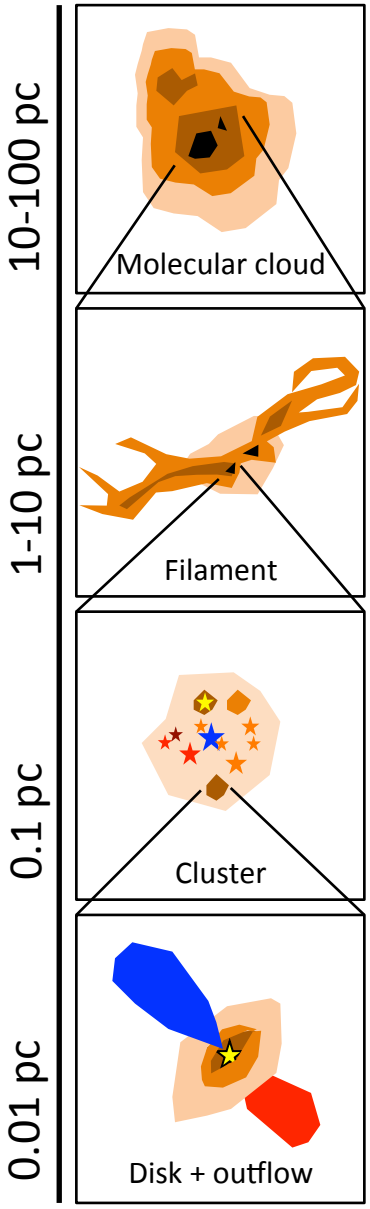
RADMC-3D

Compute:
$T_d(r, t)$; $T_g(r, t)$; G_0

Saptarsy

Warm-up phase
chemical evolution
(compute abundances)

Molecular fingerprints – model setup



Flowchart of the working pipeline

initial abundances

Spitzer collapse
$n_H(t)$; $A_V(t)$; $T(t)$

Saptarsy

Cold collapse phase
chemical evolution
(compute abundances)

Plummer
profile $n_H(r, t)$
$L(t)$

RADMC-3D

Compute:
$T_d(r, t)$; $T_g(r, t)$; G_0

Saptarsy

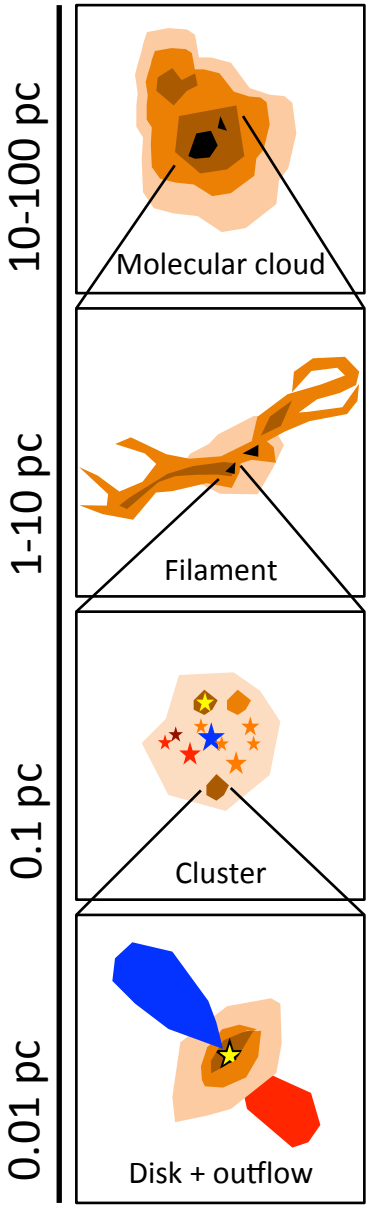
Warm-up phase
chemical evolution
(compute abundances)

Molecular densities
$n_X(r, t)$

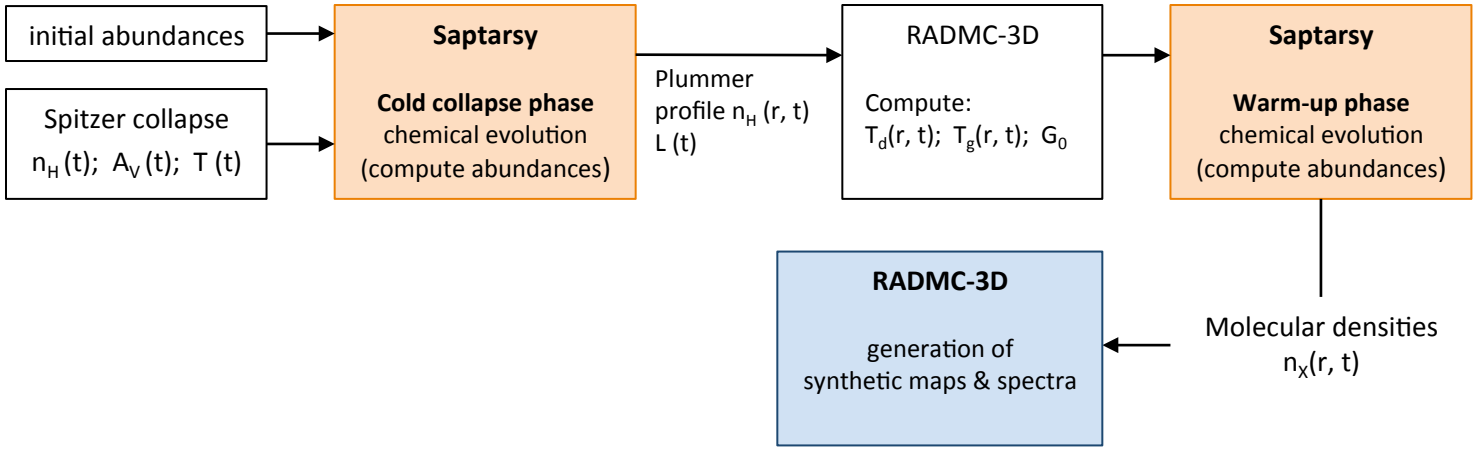
RADMC-3D

generation of
synthetic maps & spectra

Molecular fingerprints – model setup



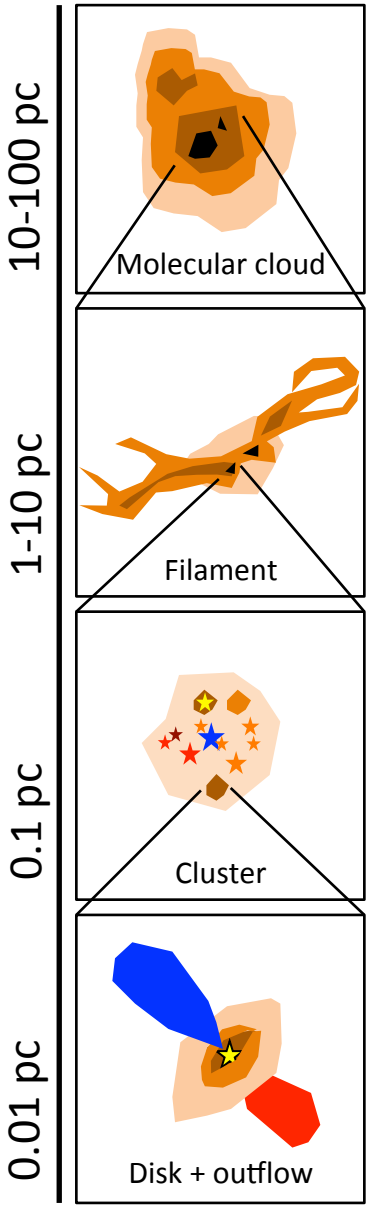
Flowchart of the working pipeline



Not MPI parallelized

Too slow for large and complex spectra

Molecular fingerprints – model setup



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Warm-up phase
chemical evolution
(compute abundances)

Molecular densities
$n_X(r, t)$

connection script

$N_H(r, t)$
dust mass opacity
spectral index

molfit files

XCLASS

generation of
synthetic spectra

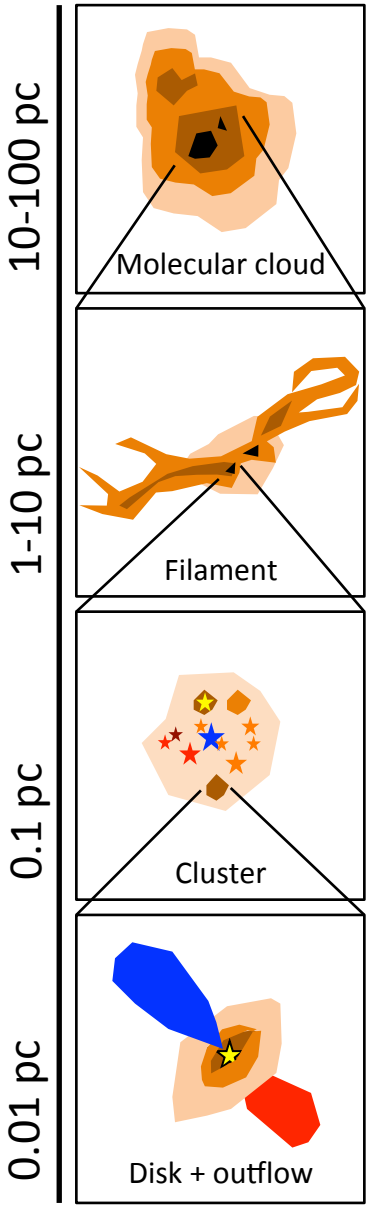
see Möller et al 2017

Analysis
- PCA analysis
- Comparison with observations

XCLASS *molfit* files (with multiple layers)
describing the molecular abundance distribution

```
% Number of molecules    1
%
% schema:
%
% name of molecule       number of components
% f  l  u  size     f  l  u  T_rot     f  l  u  N_tot     f  l  u  Dv     f  l  u  Vlsr     Aflag
%
CO;v=0;         1
  n  0  0  0.5      n  0  0  150.0     n  0  0  1.0e+16  n  0  0  5.0    n  0  0  -10.0     c
```

Molecular fingerprints – creation of models



49 different models considered:

- 1 reference model
- 10 models with different **total luminosity**
- 8 models with different **density distribution profile**
- 10 models with different **maximum density**
- 10 models with different **retardation factor** (slow-down collapse)
- 10 models with different **rate of luminosity increase**