The InterStellar Medium science with ALMA

(mostly Galactic perspective)

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What is ISM?

"ISM is anything not in stars" (Osterbrok 1984)

Constituents:

a) Gas:

Hydrogen
Helium
Oxigen, Carbon, other species (<0.1 %)

b) Dust Particle

1% in mass
Fundamental

c) InterStellar Radiation Field (ISRF)

But also ….
Cosmic Rays
Magnetic Fields

Stable Phases of Gas in ISM

Klessen & Glover, 2014

	Thermal Phase	T (K)	N (cm-3)	X	Tracers
a)	Molecular clouds H2	10-20	> 100	$<10^{-6}$	Mm-wavelength molecular emission lines (CO)
a)	Cold Neutral Medium (CNM)	~50-100	~20-50	$\sim10^{-4}$	HI 21 cm emission line
a)	Warm Neutral Medium (WNM)	~8000	~0.2-0.5	~0.1	HI 21 cm emission line
	Warm Ionized Medium (WIM)	6000-10000	~0.2-0.5	0.8-1	Halpha 6563 Pulsar dispersion
b)	Hot Ionized Medium (HIM)	$\sim 10^6$	< 0.01	1	High excitation absorption lines towards hot stars (OIV, NV, CIV), soft X-ray

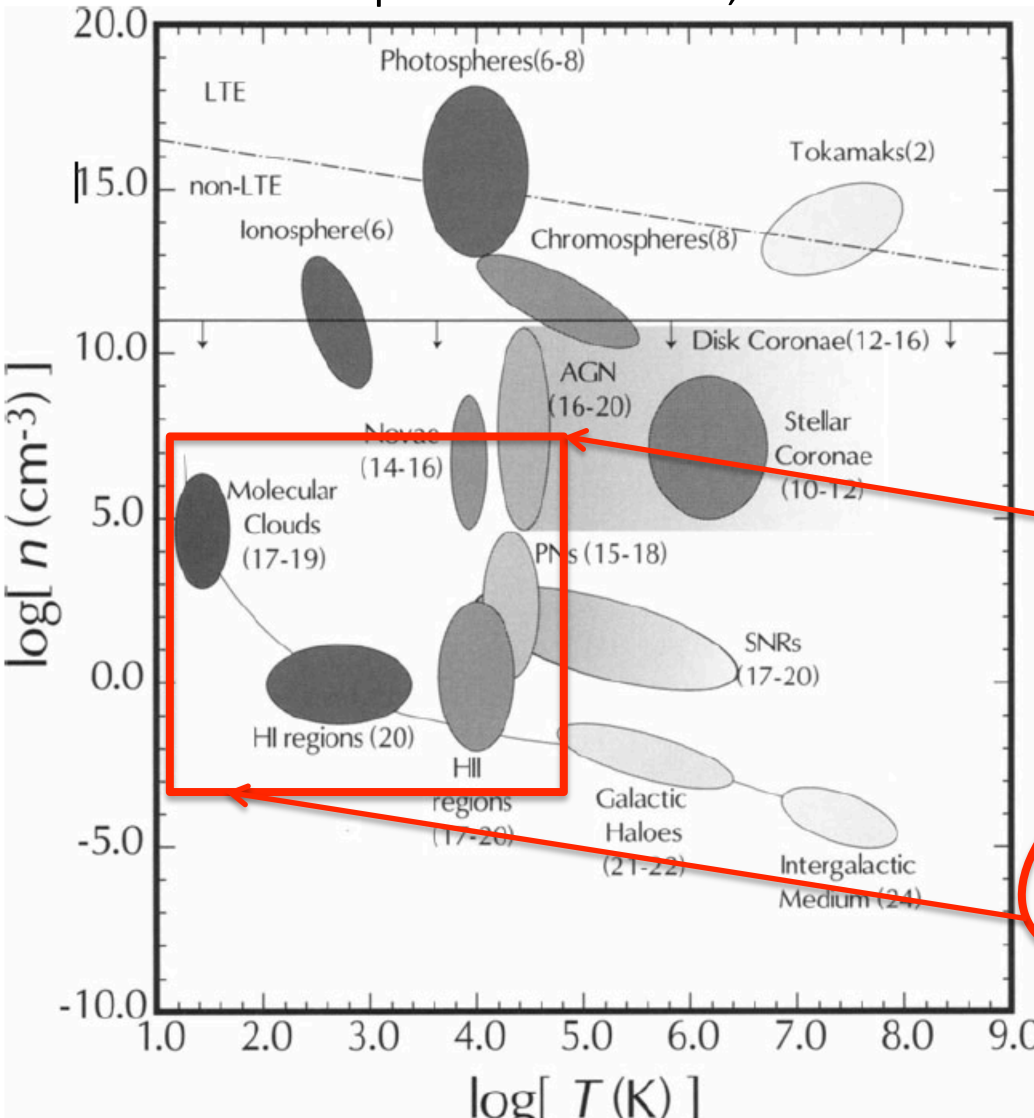
a) Original introduced Field, Goldsmith & Habing 1969

Atomic ISM is in thermal equilibrium → 2 phases + 1 Molecular

b) McKee & Ostriker 1977, supernovae and ionation from O/B → Ionized medium

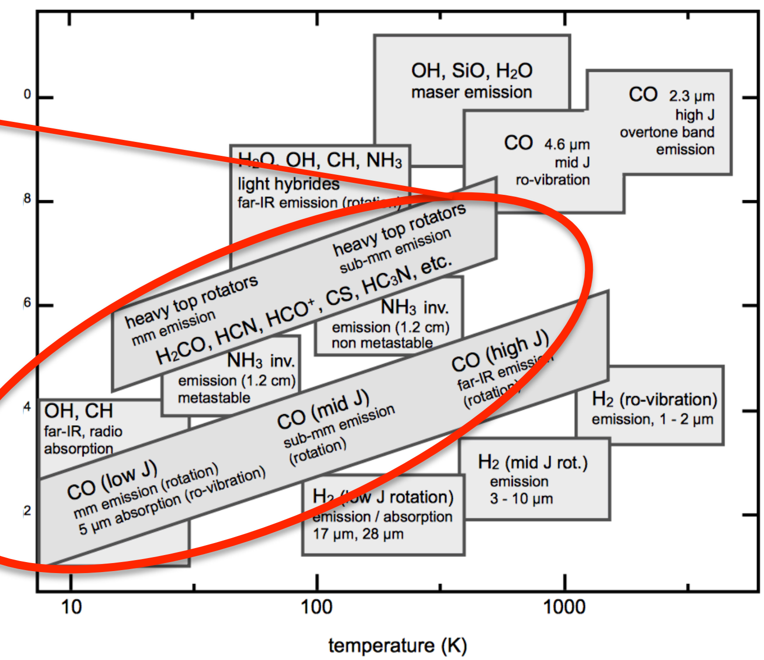
Physical Properties of ISM

From Dopita & Sutherland, 2003



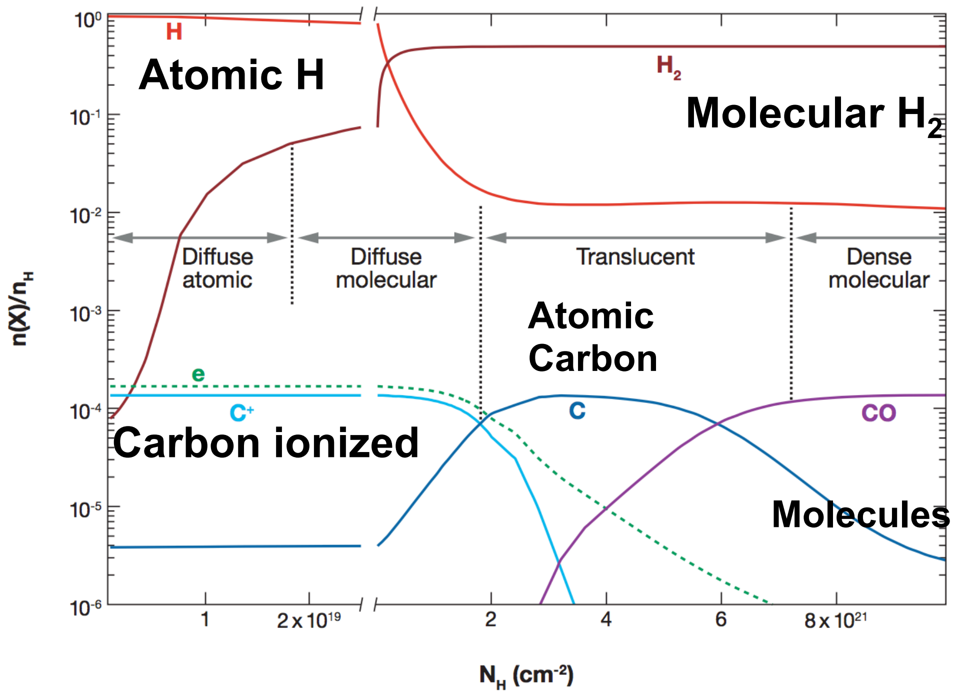
Densities and Temperatures of phases of ISM. () -> typical sizes

Observational tracers for structures and dynamic of ISM



Klessen & Glover, 2014

Classification of CNM – Different types



Snow & McCall, 2006

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n{}_{H_2} < 0.1$	$f^n{}_{H_2} > 0.1$ $f^n{}_{C+} > 0.5$	$f^n{}_{C+} < 0.5$ $f^n{}_{CO} < 0.9$	$f^n{}_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

Dust in ISM

Observed initially from the absorption of optical light.

Constitute about ~1% of total mass of ISM

Fundamental:

-) Allow the gas to cool down.

Protect against UV radiation field (shielding)

-) Allow chemisty: catalyst of formation of some molecules in the ISM.

Active Surface for chemical reations

-) Seeds for planet formation.

Dust in ISM – New view offered by Herschel

Dust thermal continuum emission from grains in radiative equilibrium with the local radiation field

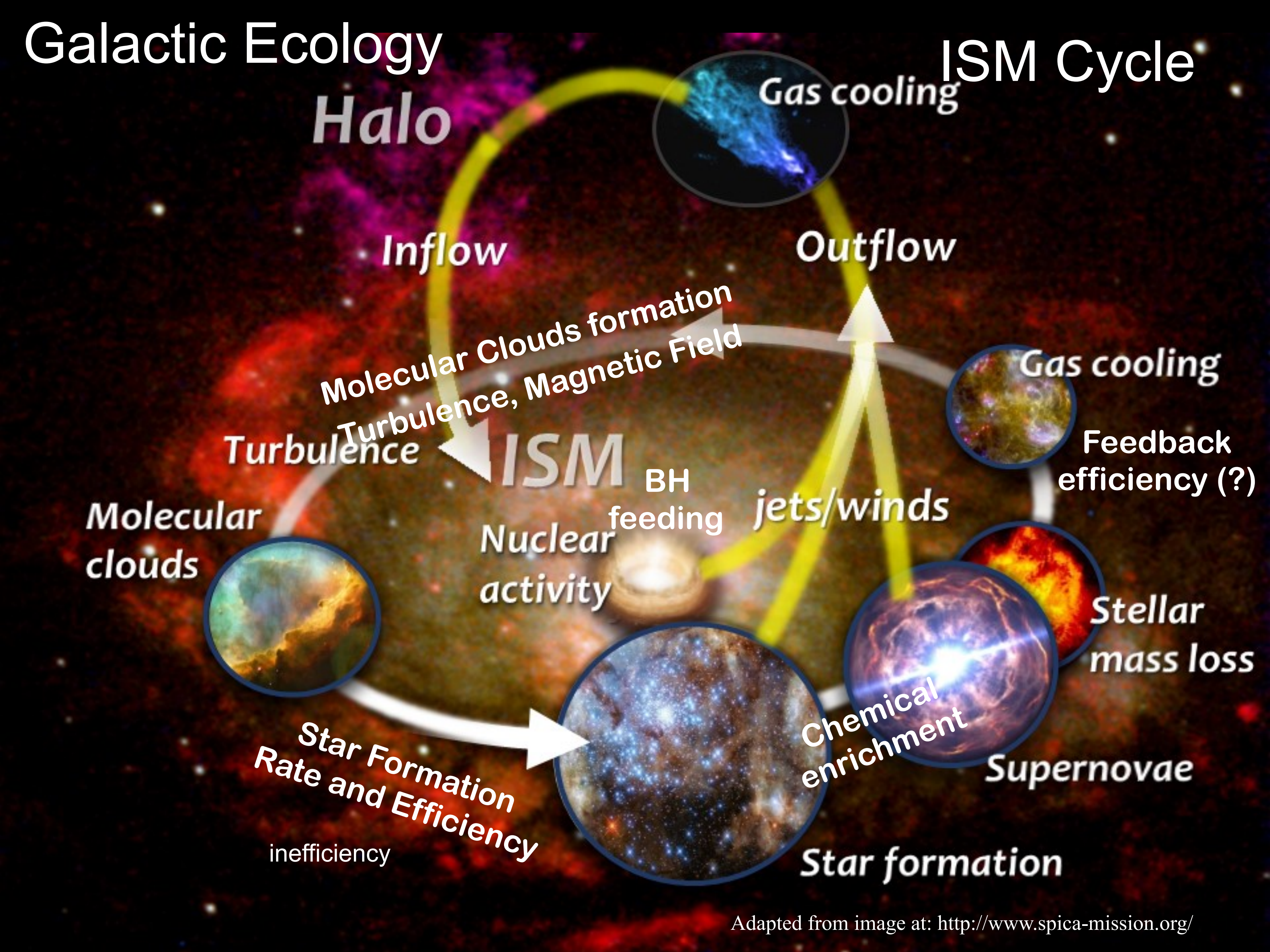
Dust in ISM shows a rich filamentary appearance

Covering a wide range of spatial scales and intensities

Other recurrent morphologies associated also to shells, arcs, bubbles. (hot dust warmed by ionizing radiation)

Snapshot of Galactic Plane (Hi-GAL data) :
RGB : blue, green, red (70, 160, 250 µm) Reprocessed during VIALACTEA project

Consortium/ASI; Map-Making by UNIMAP (L.Piazzo, Univ. Sapienza Roma); Mosaics by E.Schisano (INAF-IAPS); Process by G. Li Causi (INAF-IAPS)


Galactic Ecology
ISM Cycle
Halo
Gas cooling
Inflow
Outflow
Molecular Clouds formation
Turbulence, Magnetic Field
Gas cooling
Turbulence
ISM
BH
feeding
jets/winds
Feedback
efficiency (?)
Molecular
clouds
Nuclear
activity
Stellar
mass loss
Chemical
enrichment
Star Formation
Rate and Efficiency
Supernovae
inefficiency
Star formation
Adapted from image at: http://www.spica-mission.org/

ISM is a dynamic environment

Cauldron where stars are born.

Medium for receiving the enriched products of stellar nucleosynthesis expelled by stars during their evolution (AGB, supernovae)

Energy continuosly flows throws the ISM: radiative energy
mechanical pressure,
hot winds
supersonice turbolence

Interchange between gas in ISM and stars drives the Evolution of Galaxy

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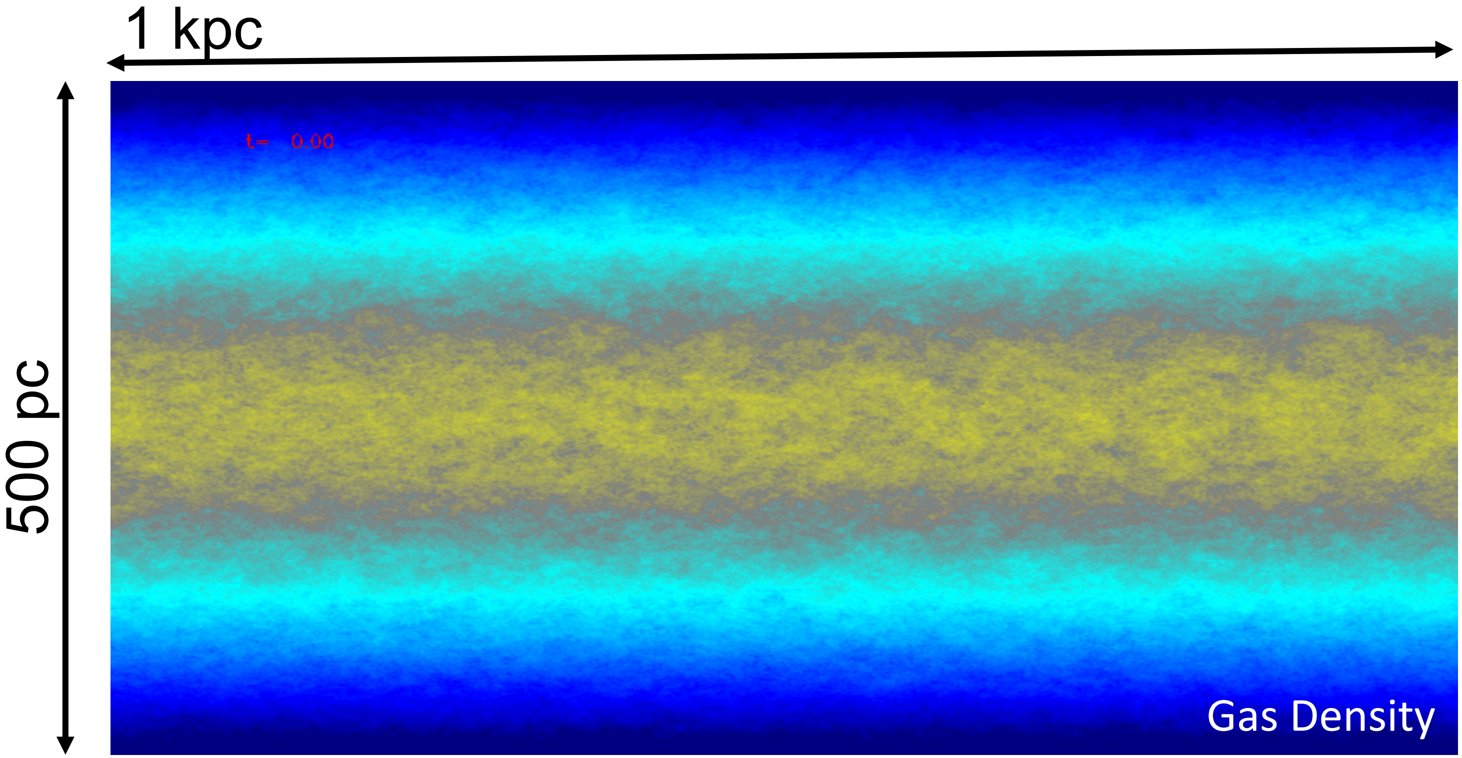
The ISM Cycle in a galaxy



← Thin layer at midplane

Galaxy Evolution!

Thermal instability → CNM + WNM

Kim et al. 2011

Formation of cold (x 100 denser) clouds, surrounded by war, diffuse medium.

Collapse leads to star formation → lead to energy injection from high-mass stars.

Feedback energy disperse the cold dense gas and warm up diffuse medium

Vertical and horizontal dispersion → Turbulence, cloud collisions, colliding flows

Some open questions

1) Formation of clouds, atomic and molecular. Where do they come from?

2) Key events in molecular clouds for the star formation to happen in molecular clouds.

3) Role of magnetic field and turbulence in Galactic Ecology.

1) + 2) + 3) + feedback →

Characterize the self-regulating process acting in ISM which helps to control the evolution of galaxies through cosmic time.

Star burst Galaxy: SFR ~ 300 M_{sun} / yr → Milky Way SFR: 1-2 M_{sun} / yr

In the past galaxies were wilder!

Investigation of ISM

Central in these topic is Wife Field Spectral line surveys of ISM across a range of frequency bands

Follow-up of sources of particular interest:

-) Higher spatial resolution,
-) Higher sensitivity
-) Polarization for B field

ALMA, SKA

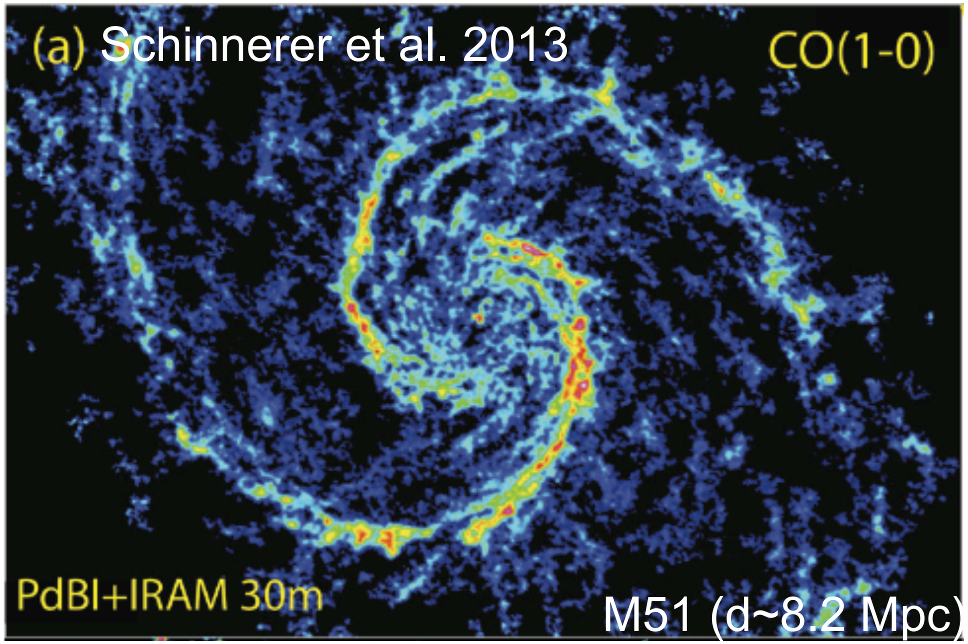
-) Molecular clouds in other Galaxyes

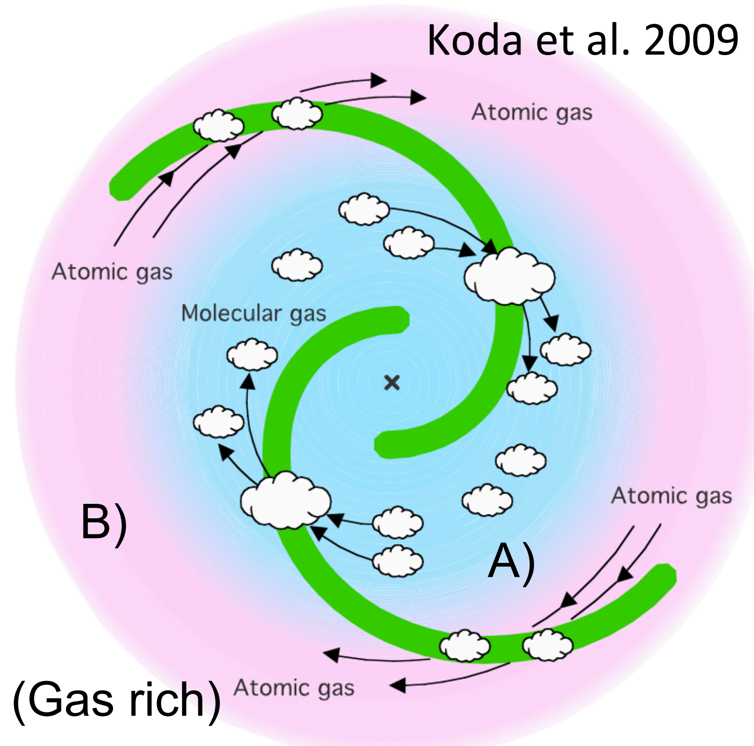
-) First steps towards the star formation process

-) Astrochemisty (in the circumstellar environment)

Formation of molecular clouds
-
Cloud structures
-
Extending towards nearby galaxies

Distribution of the ISM in spiral galaxies





A) Gather and collect scenario in the Inner Disc (Gas rich)

Spiral arm streaming motion coagulate GMC into more massive clouds in the arm. After the passage it shreds them back into smaller clouds in the interarm region.

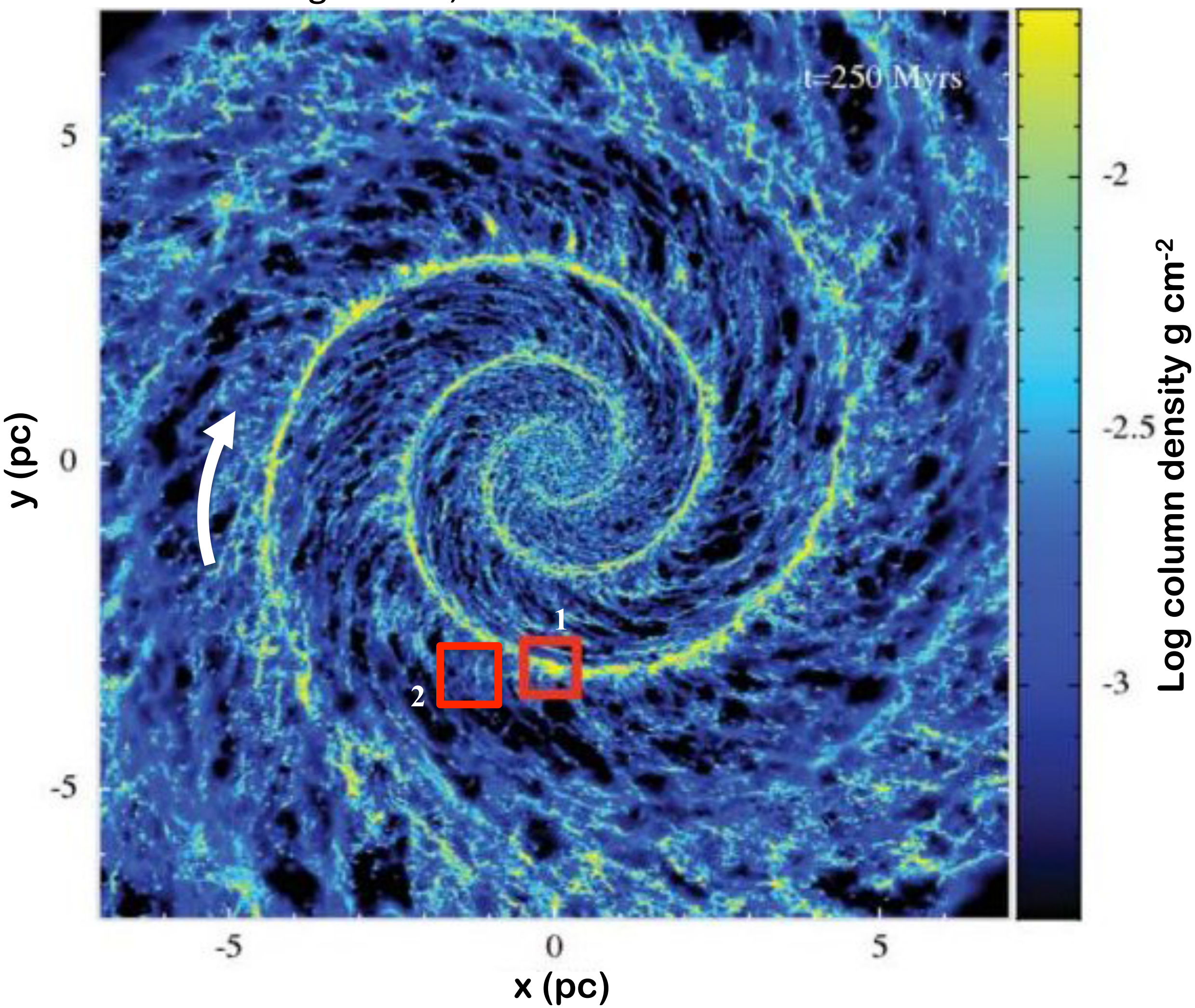
B) Outer Disc (gas poor)

Classic Phase transition: atomic gas HI collected → H_2 molecular gas → atomic gas

New ALMA data incoming.
New targets, like M83, and better sensitivity and angular resolution CO(1-0) and CO(2-1) - Koda project 2017.1.00079 -

Filamentary appearance of ISM - simulation

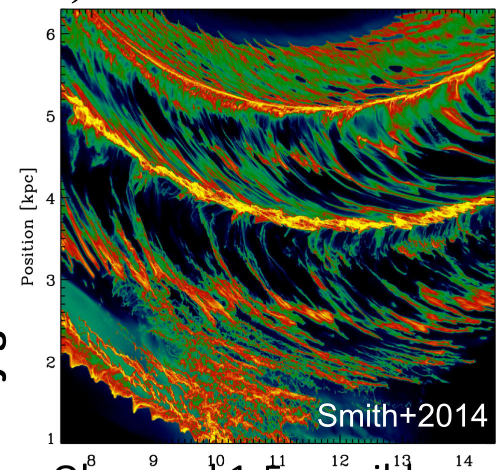
Dobbs & Pringle 2013, Smith et al 2014



Material accumulate in the spiral arm gravitational well

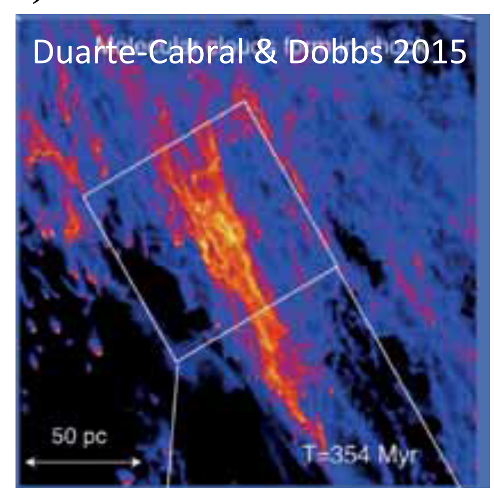
Galactic shear stretching the material

1) Dense "bones" on Arm



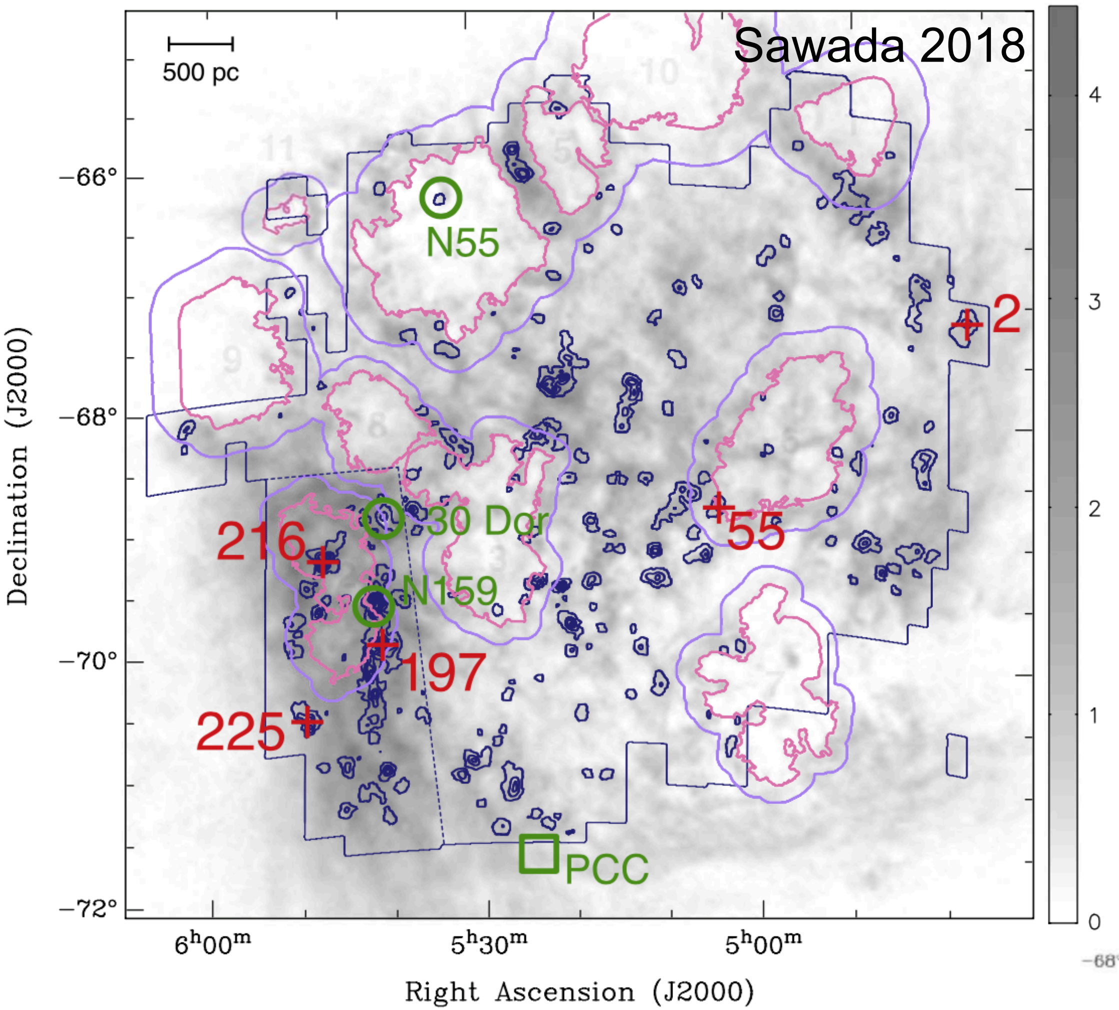
Observed 1-5 possible candidates
Goodman+2014, Zucker+2015

2) Inter-arm features



Observed ~ 10 candidates
Ragan+ 2014, Wang+ 2015

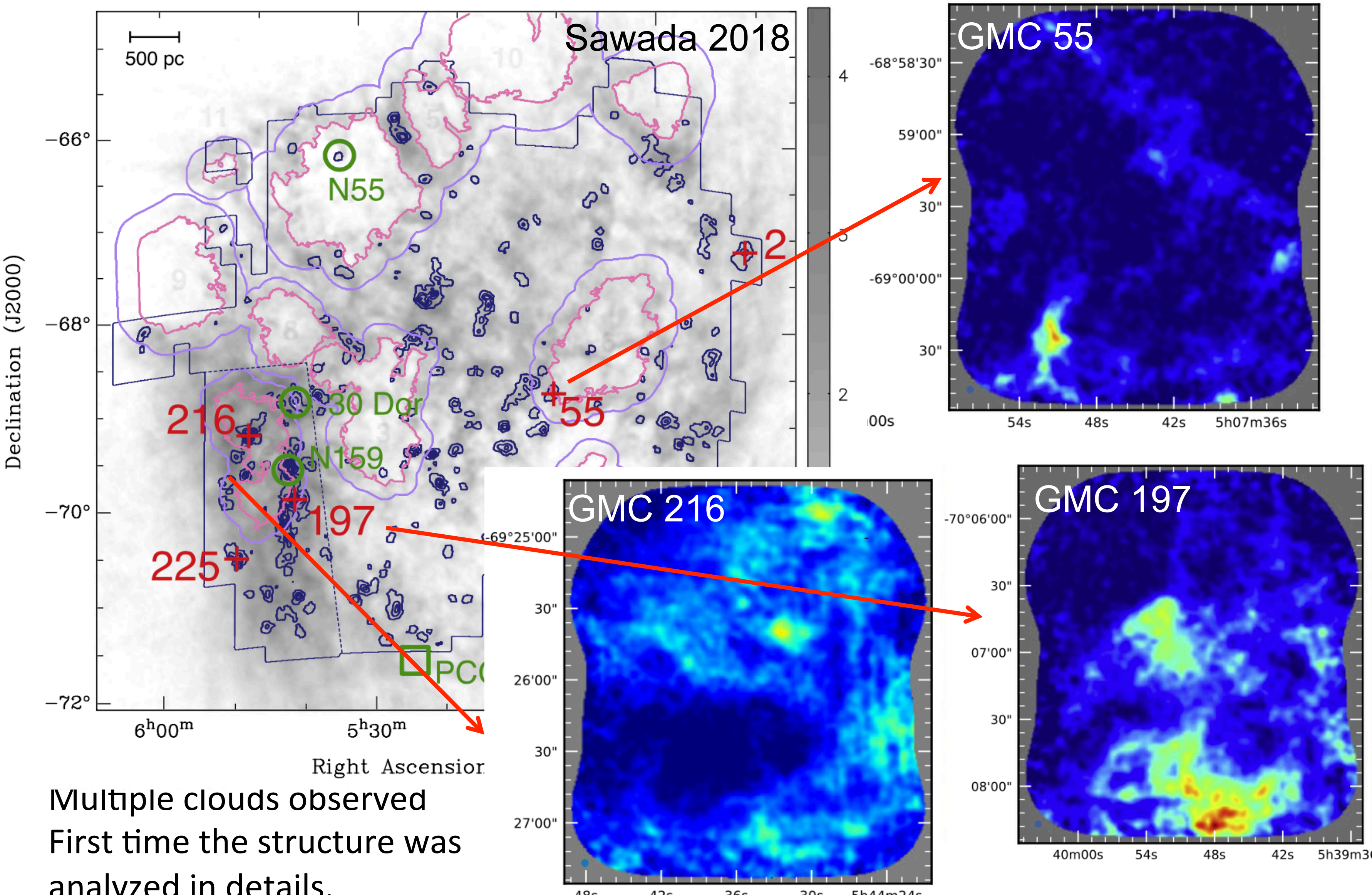
Molecular clouds – Census in LMC



Green and Red are fields observed by ALMA (data archives)

HI 21 cm grayscale
CO (pink contour)
Super Giant Shells (purple)

Molecular clouds in LMC – internal structure

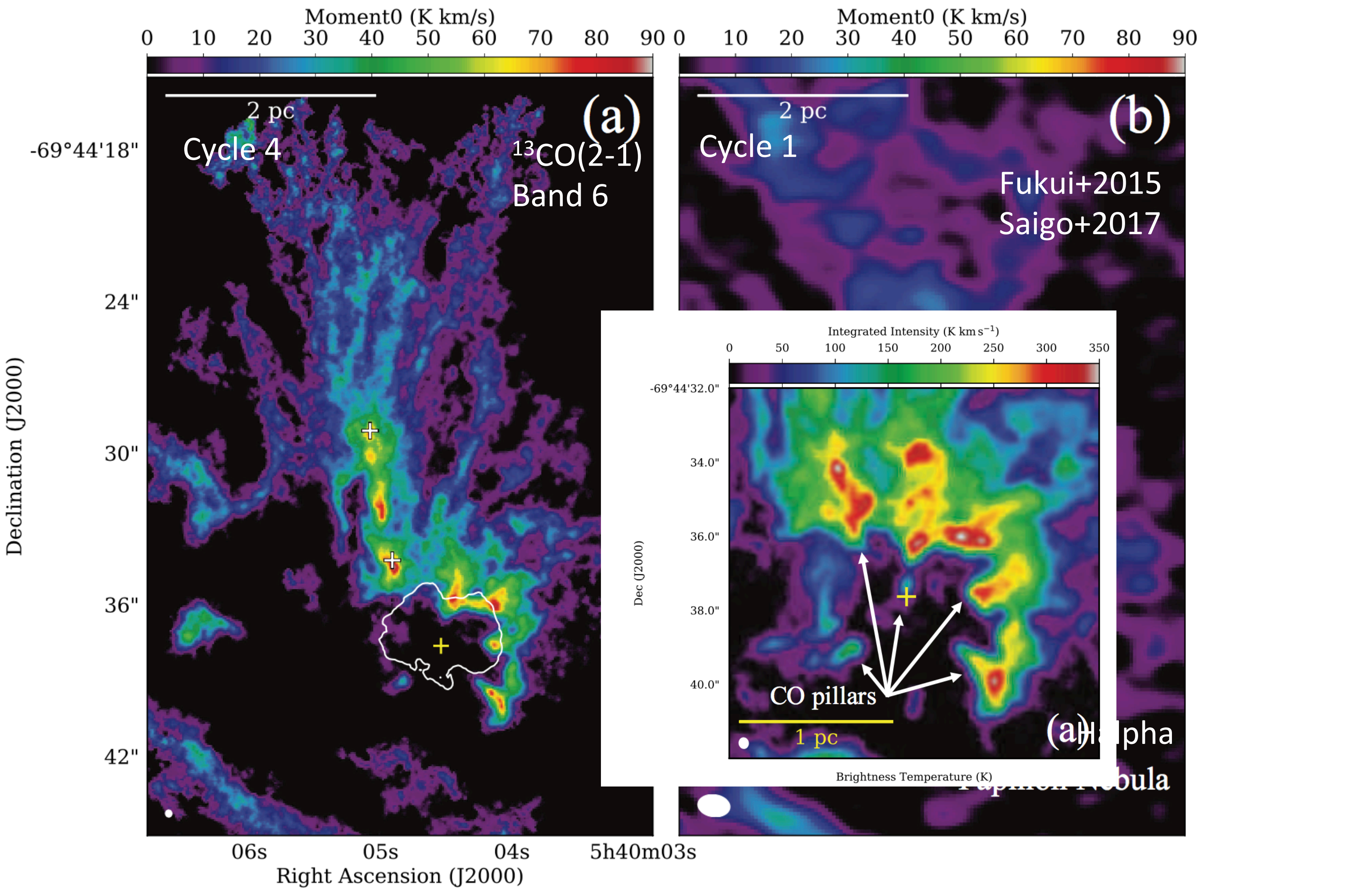


Multiple clouds observed

First time the structure was analyzed in details.

More structured more evolved

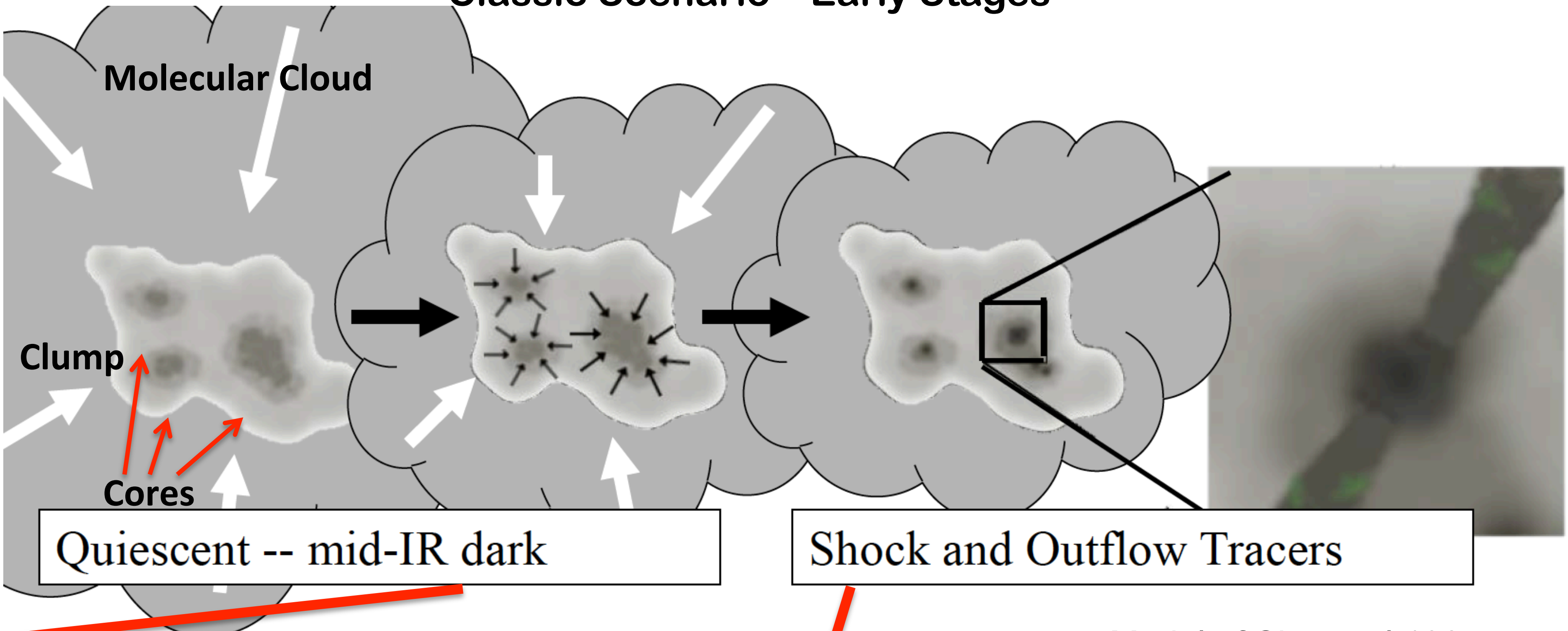
Filament in LMC

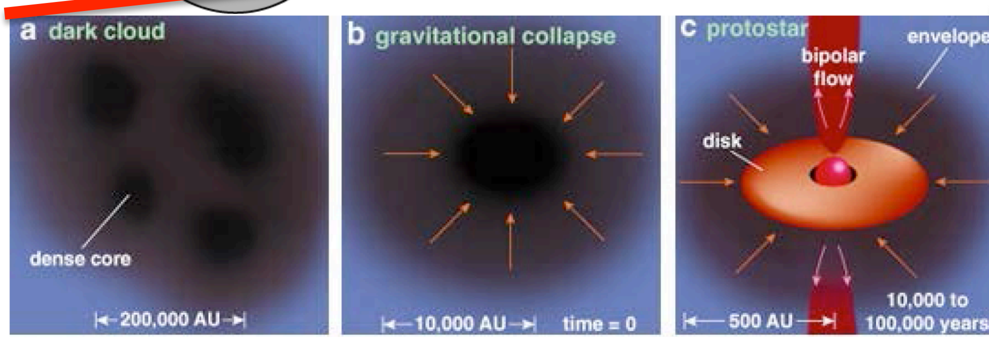


From molecular clouds to stars
-
Early stages of Star formation

From clouds to stars

Classic Scenario – Early Stages





M* ~ Msun

Model of Shu et al.1987
Protostars to MS star evolution
Isolated

M* > 8 Msun

Competitive accrection
vs (?)
Core -Turbulent model
Clustered

Star formation is a very inefficient process in our Galaxy
SFR ~ 1-2 Msun year^{-1}

See Leurini's talk

Filaments and Star Formation

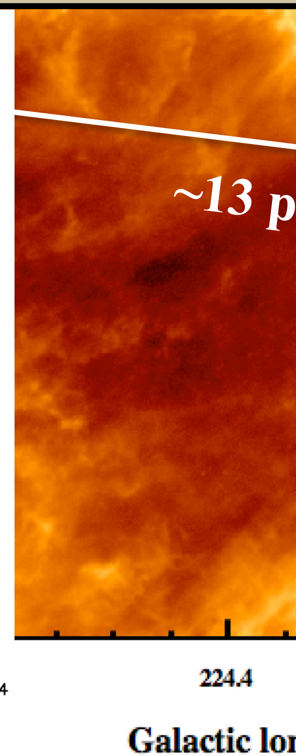
Star formation is mostly associated with filaments

(reported for young stars back to Schneider & Elmegreen 1979)

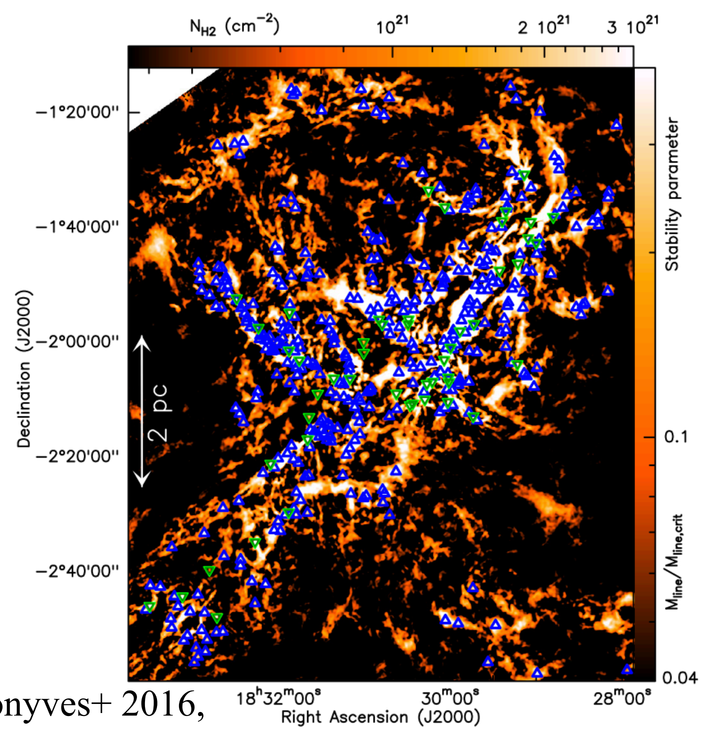
But also primordial condensation ($\tau^{pre} \leq 1$ Myr) are located on filaments

On situ formation $\geq 75\%$ early objects

Not all filaments are star forming



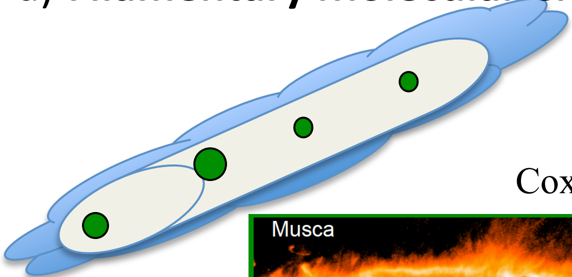
Molinari+2010, Schisano+ 2014



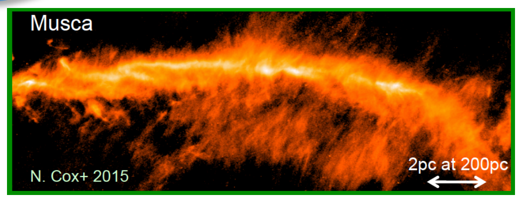
Konyves+ 2016, André+ 2010. 2014

Morphology of Molecular clouds: filaments

a) Filamentary Molecular Cloud

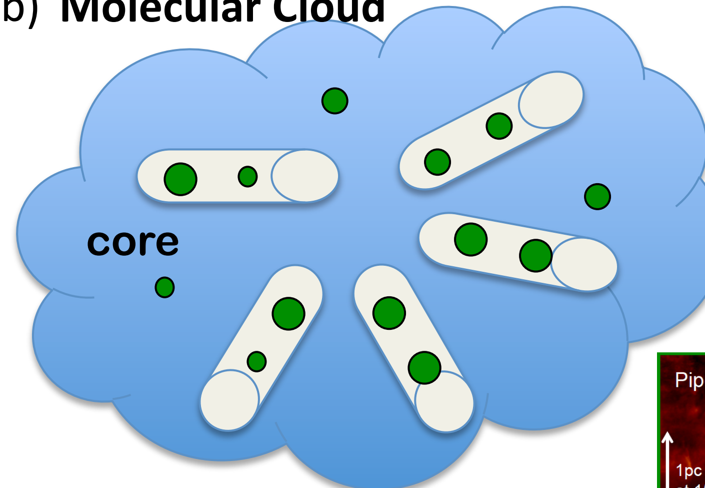


Cox+, 2014

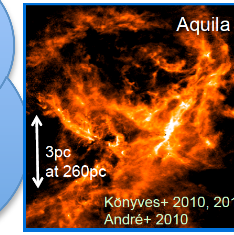


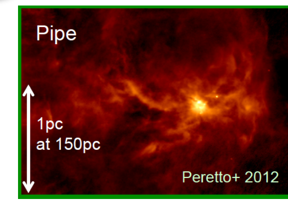
Jackson+, 2010

b) Molecular Cloud



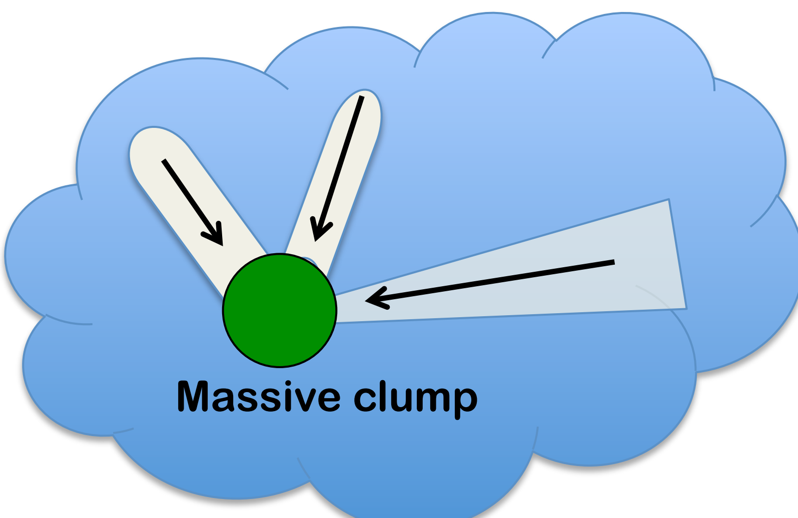
André+, 2014



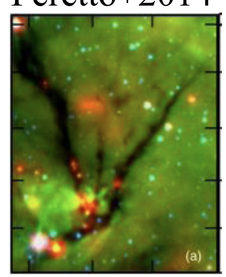


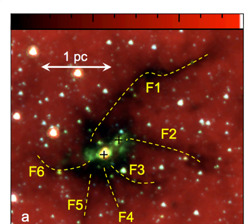
Peretto+, 2011

c) Central hub with network filaments



Peretto+2014



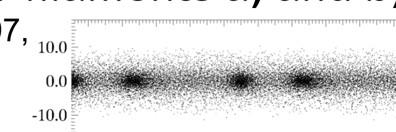


Filaments are a <u>structure</u> to model

(Ostriker+1964, Stodolkiewicz+1963, Fiege & Pudritz 2000, Meyers+ 2009, Toala et al. 2012, Pon et al. 2012, Fishera & Martin 2012, Heitsch+2016, Meyers+2017)

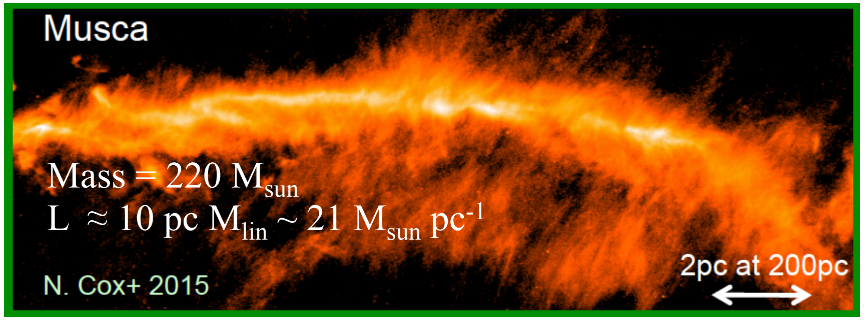
Fragmentation of filaments a) and b)

(Inutsuka & Miyama 1997, Nagai+1998, Kainulainen+2013)



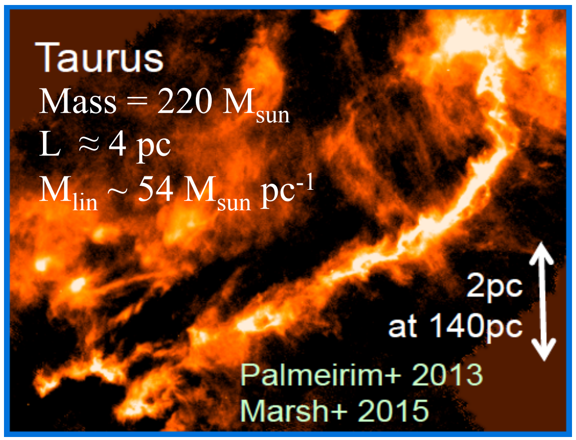
Filaments c) as transient, dynamical features channeling material.

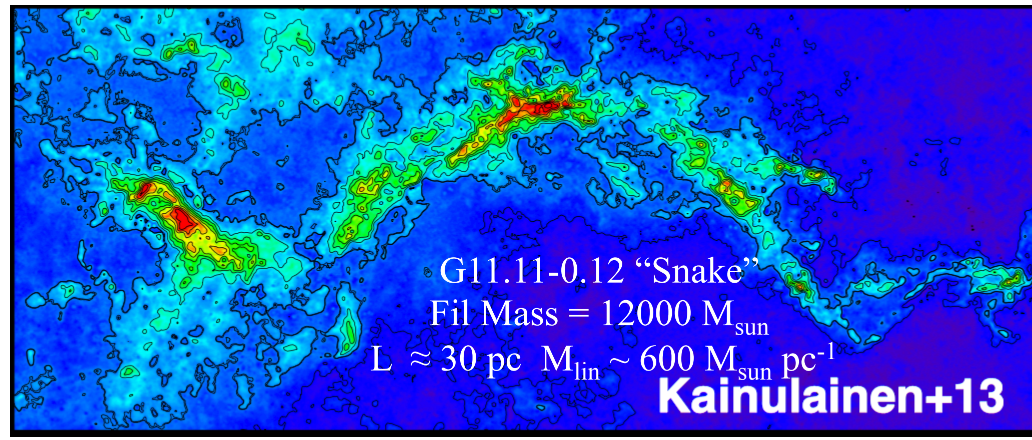
Filamentary clouds - multi-scale features?

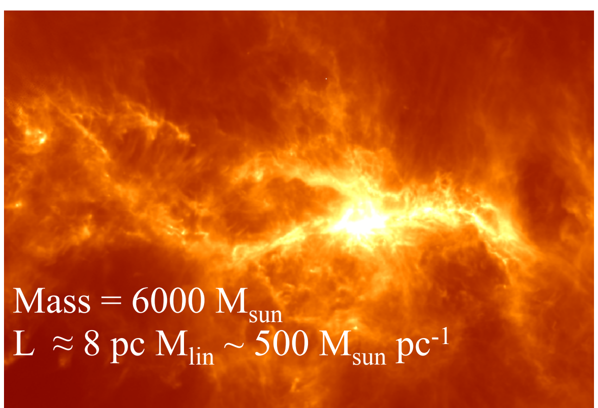


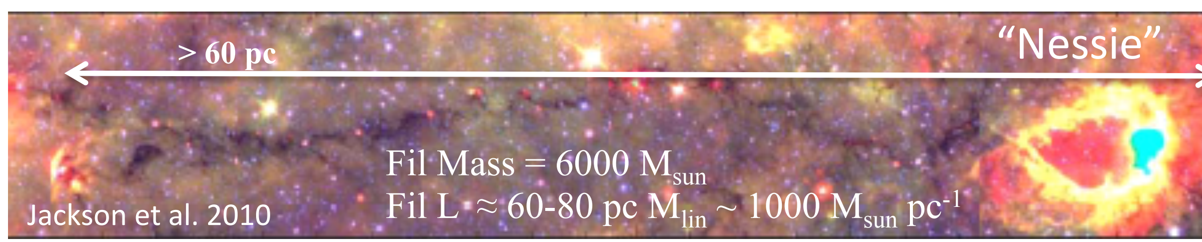
Almost linear objects exists on a wide range of spatial scales and linear mass

Is there an invariance on physics of these structures?



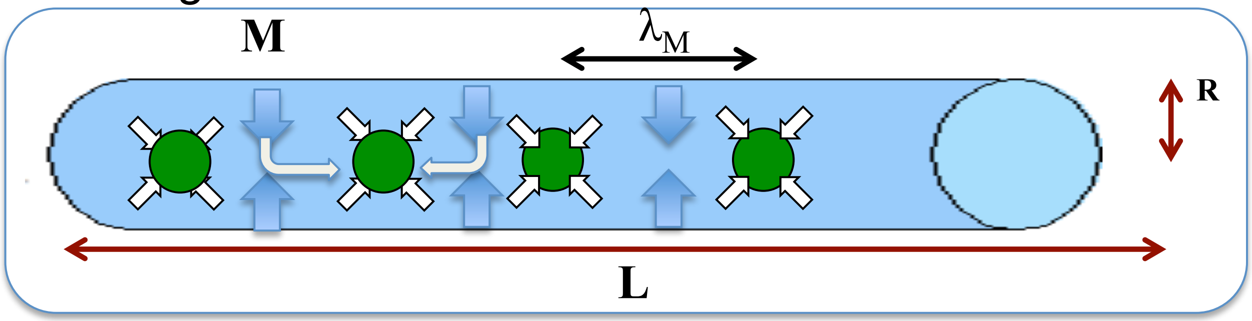






Filament Fragmentation

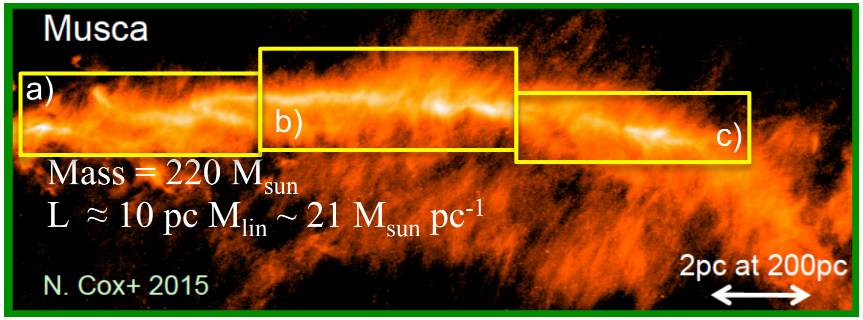
SF at very initial stages

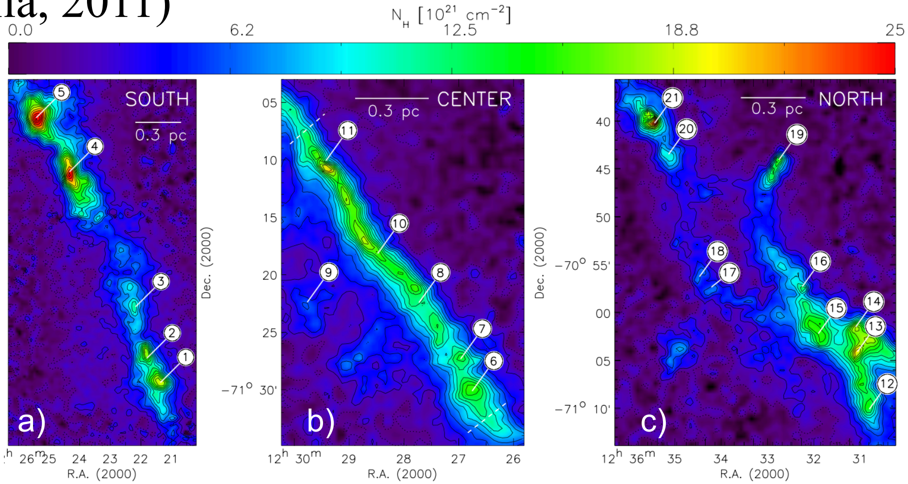


Collapsing filament $M_{lin} > M_{lin}^{crit} \sim \mathbf{c^2_s}$ [$\boldsymbol{\sigma}^2$ if presence of no-thermal motions] (Ostriker+1964

Triggers a (isothermal) fragmentation → constant λ_M = 5-6 x $FWHM_{cyl}$) (Fishera & Martin 2012)

Local motions toward sources (Hacar & Tafalla, 2011)



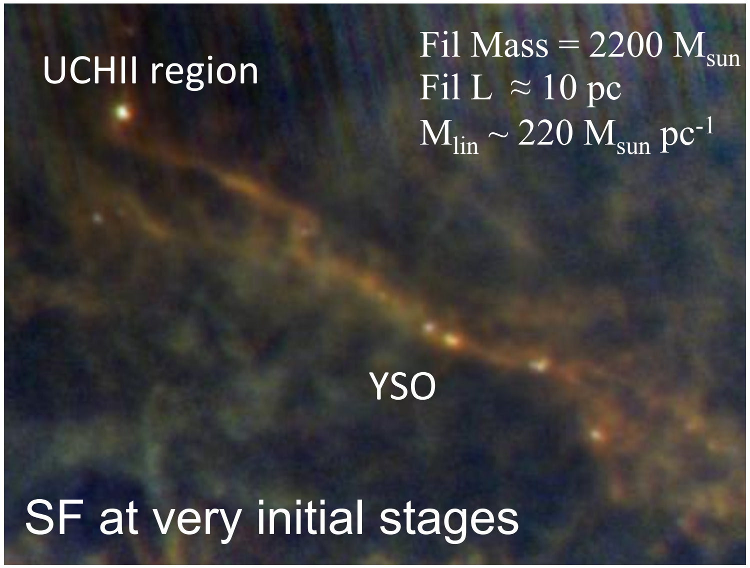


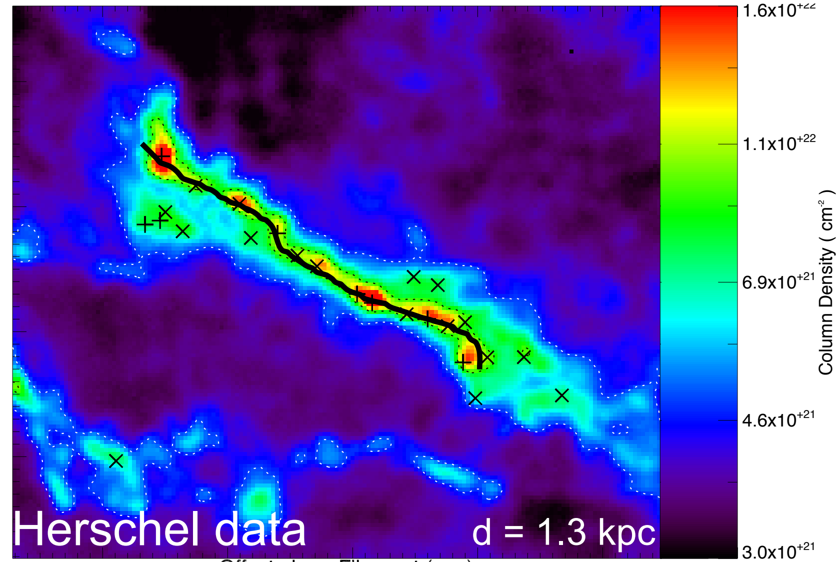
21 fragments with mass M ~ 0.3-7 M_{sun}
Expected Fragmentation length λ_M ~ 0.35-0.44 pc

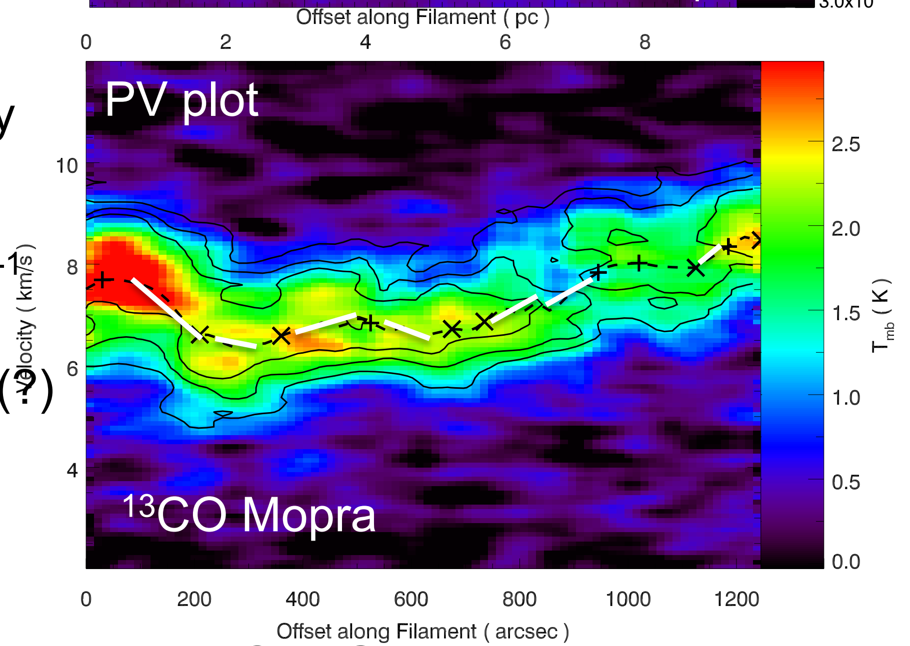
Kainulainen, 2016
Measured fragmentation separation ~0.4

Very Good agreement with Thermal fragmentation

Isolated linear filaments as laboratory test







Enlarged version of Taurus filament
2 times longer and 4 times higher density

Forming a B star in northern part

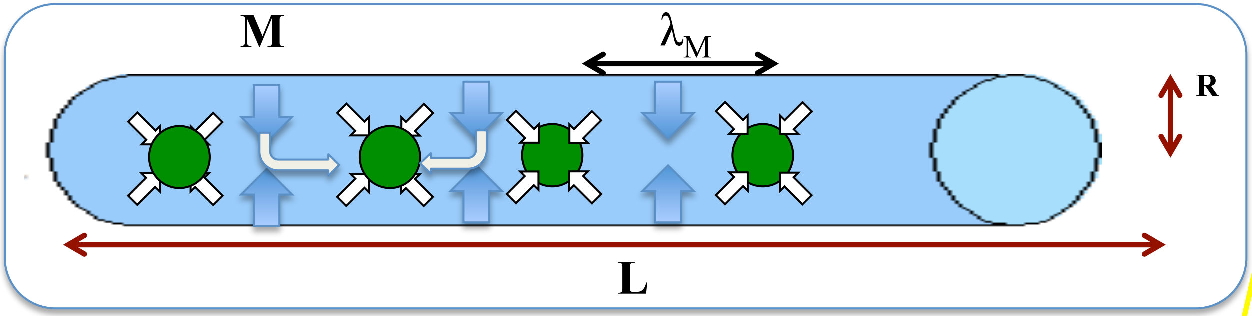
Large scale velocity gradient ~ 0.4 km s^{-1} pc^{-1} over the entire structure.
Collapse: observed longitudinal, radially(?)

Hosting constant λ_M fragmentation

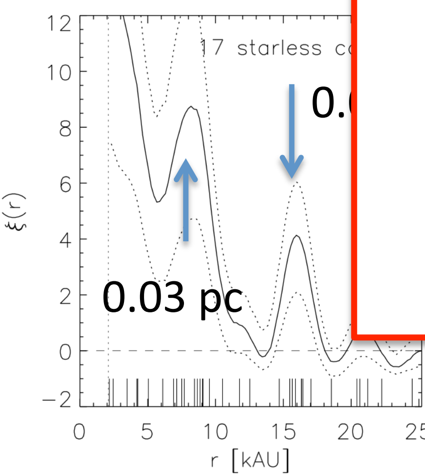
Signs of velocity gradients near sources (acceleration ?)

PI. Schisano 2018.1.01691.S ALMA ACA Observation ongoing

Fragmentation Modes in Filaments



In supercritical filaments with M > > M crit
fragmentation

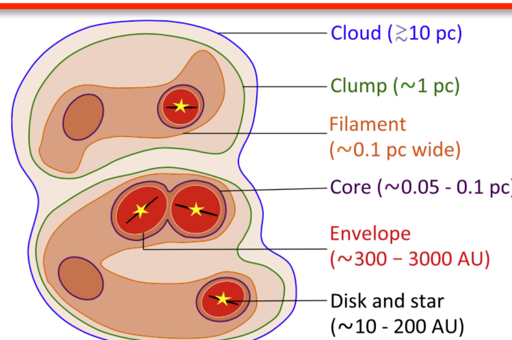


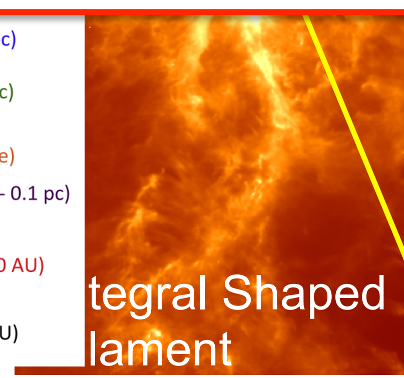
Unpredicted from any existing gravitational fragmentation.

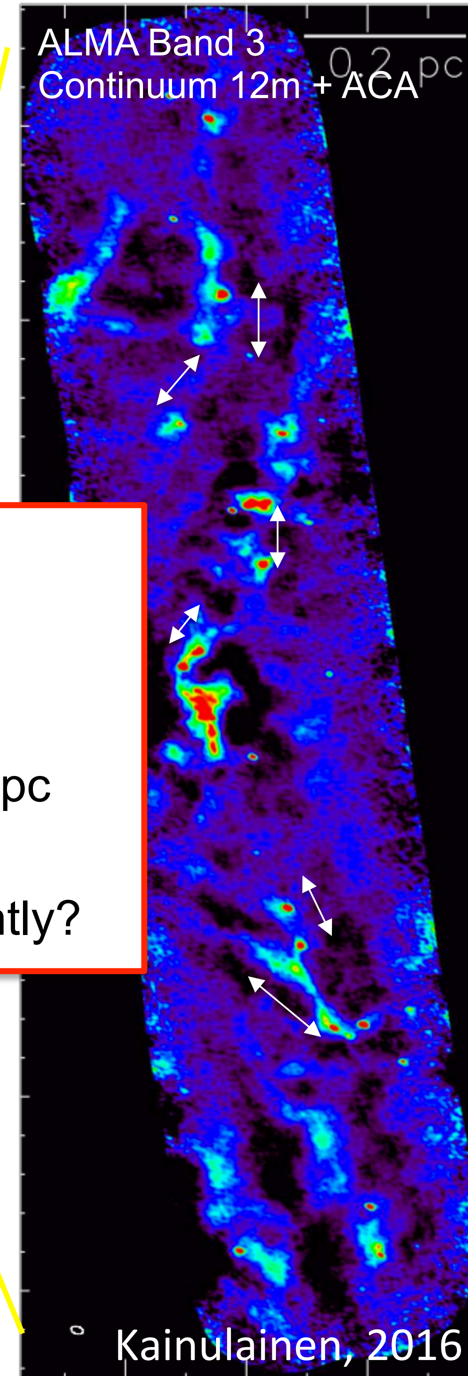
Jeans Fragmentation ~ 0.05 pc
Filament Gravitational Fragmentation ~0.2 pc

Does SuperCritical filaments behave differently?

2 modes: Hierarchical fragmentation, scale dependent.

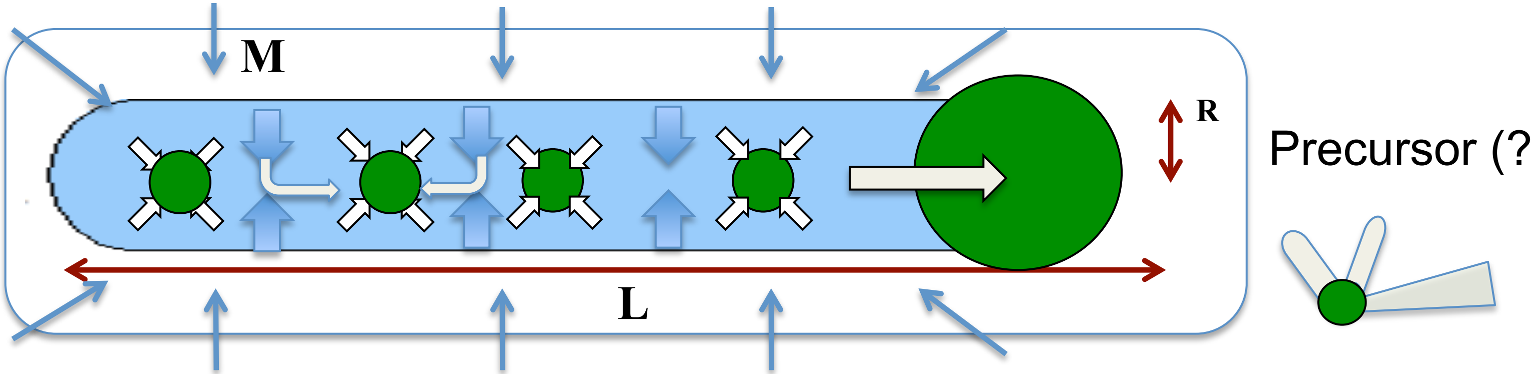






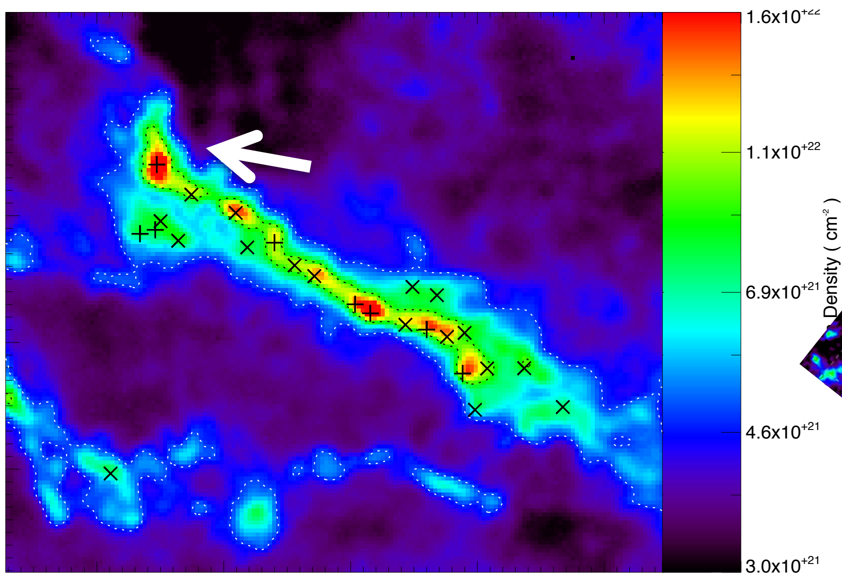
Gravitational Focusing

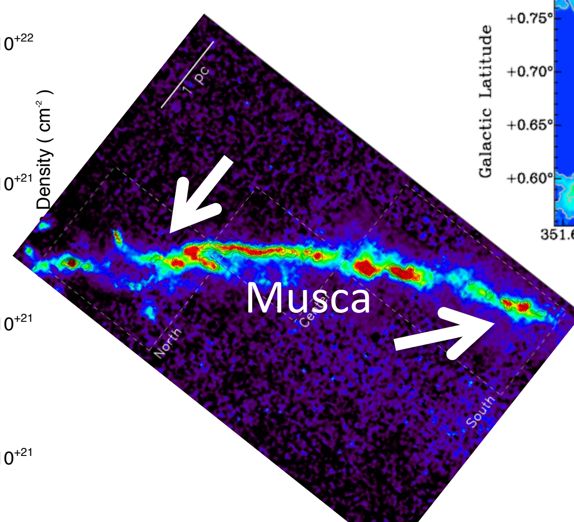
SF at very initial stages

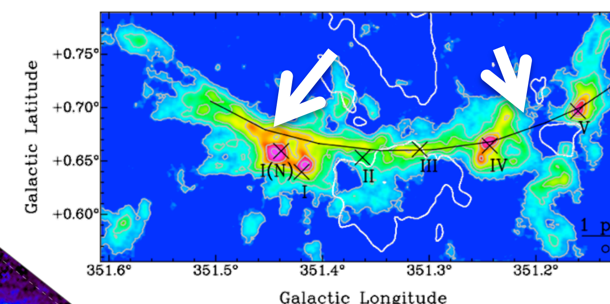


Unstable, accreting filaments induce "Gravitational focusing" at one edge
Observed in several cases.

(Burket & Hartmann, 2004,Heitsch+ 2013)



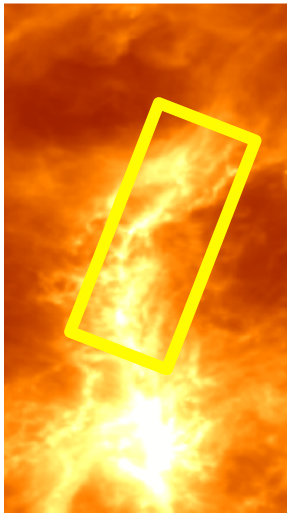


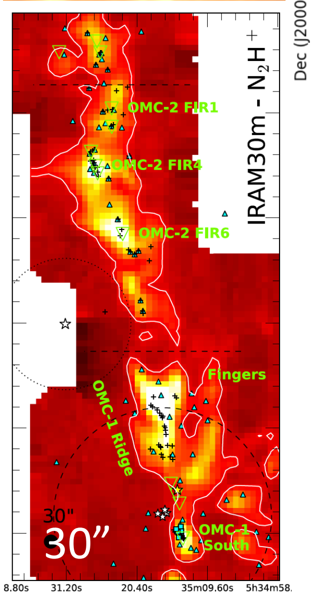


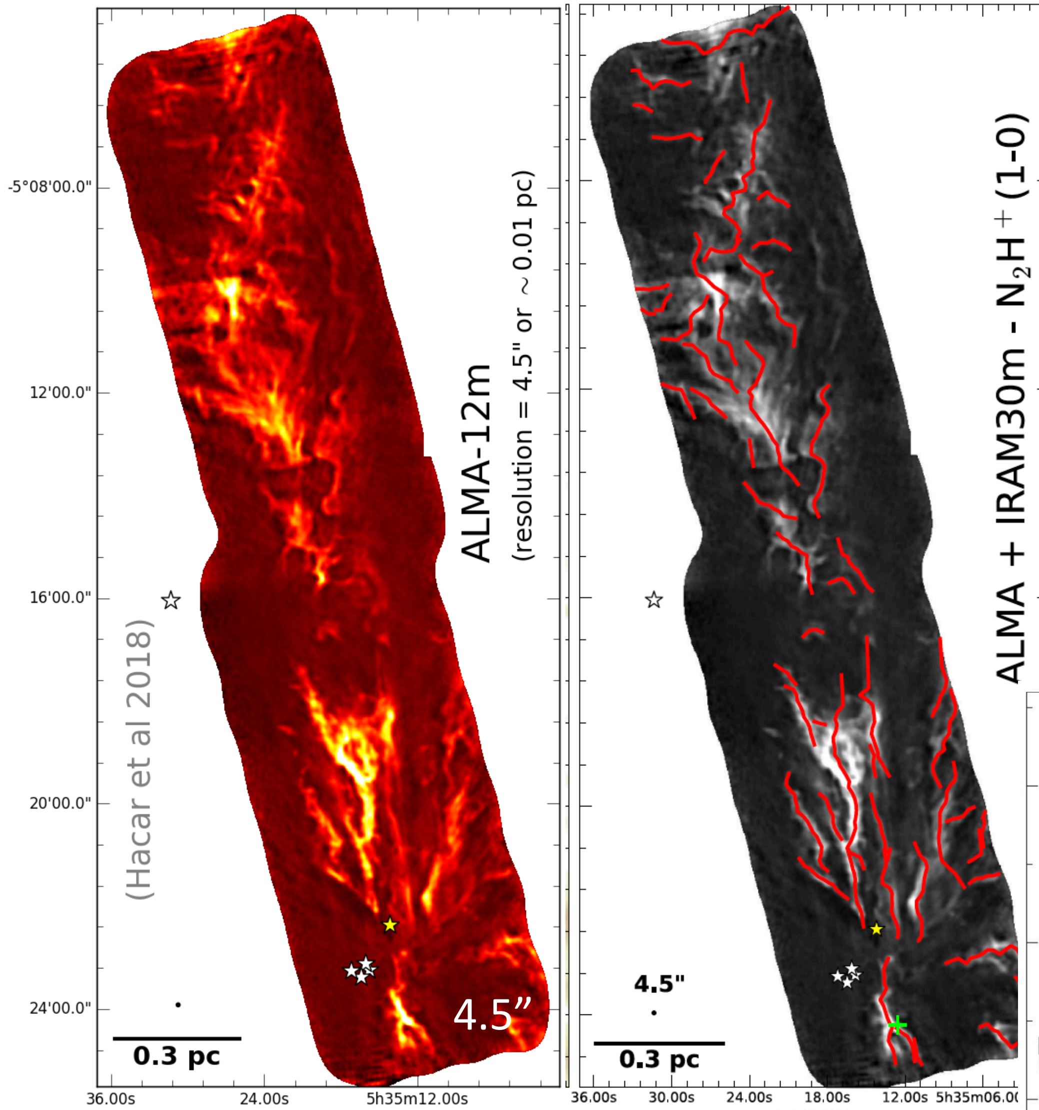
Zeinikel+ 2013

Filament Substructures

Northern region of Integral Shape Filament







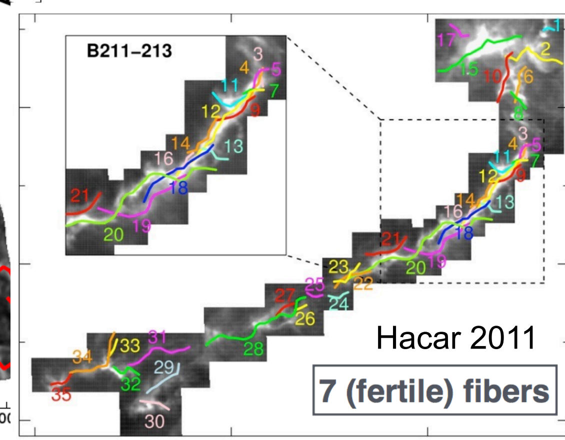
Hacar et al 2018

Monolithic structure in dust continuum reveal a very complex substructure

Large number of subfilaments - Fibers

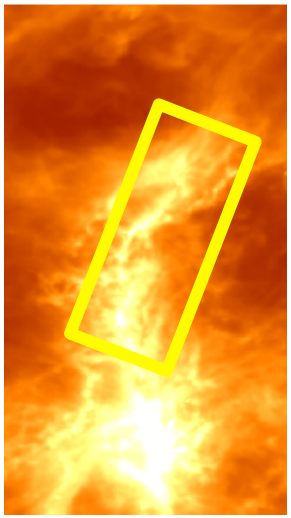
~55 fibers hosting most of the detected cores

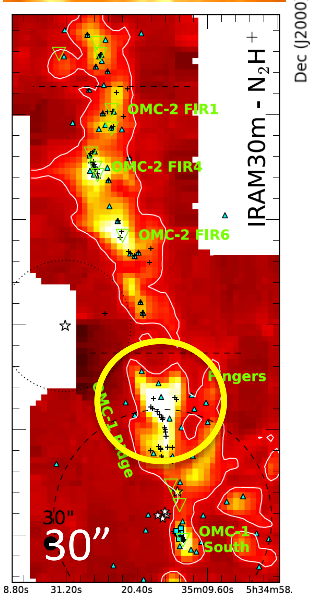
#Orion >> #Taurs

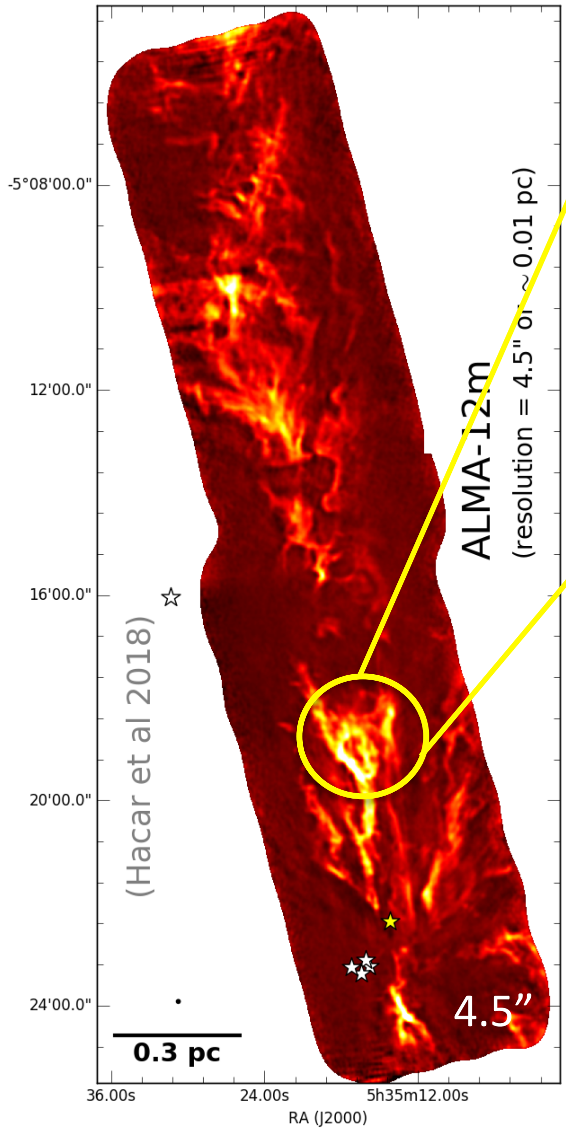


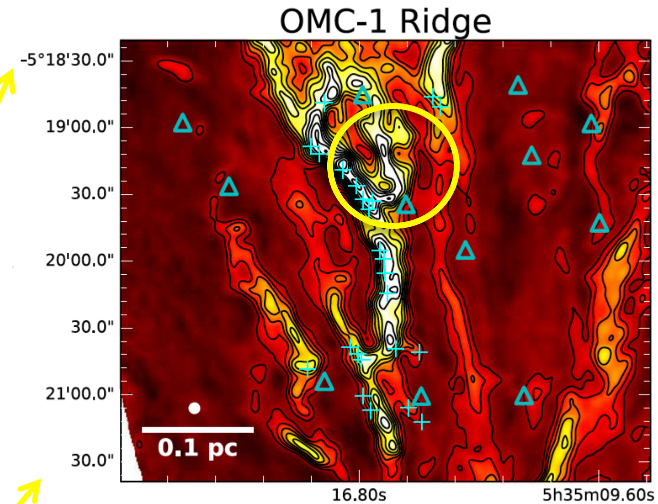
Filament Substructures

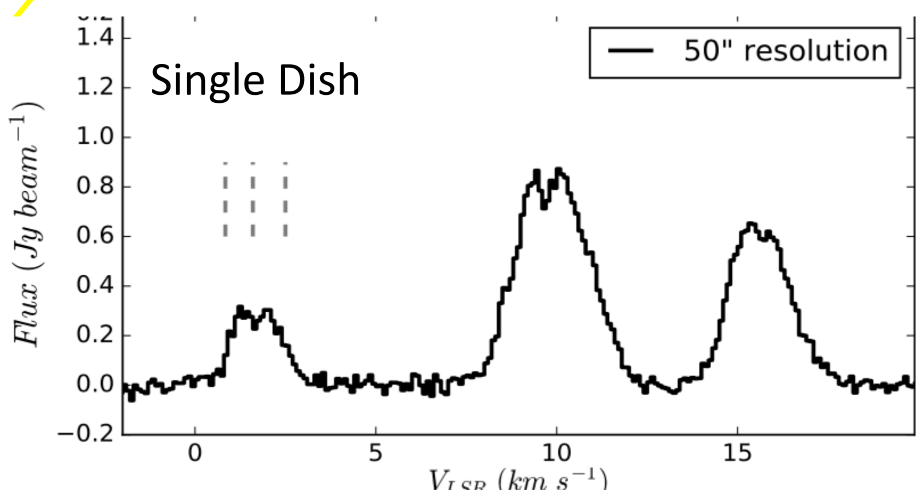
Northern region of Integral Shape Filament









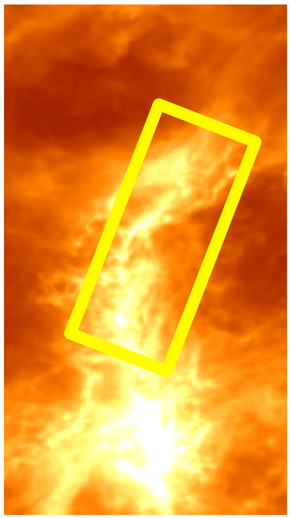


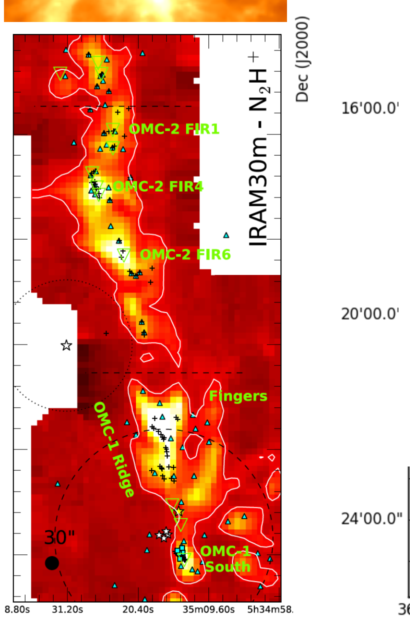
Multiple components with sonic width

Hacar, 2018+

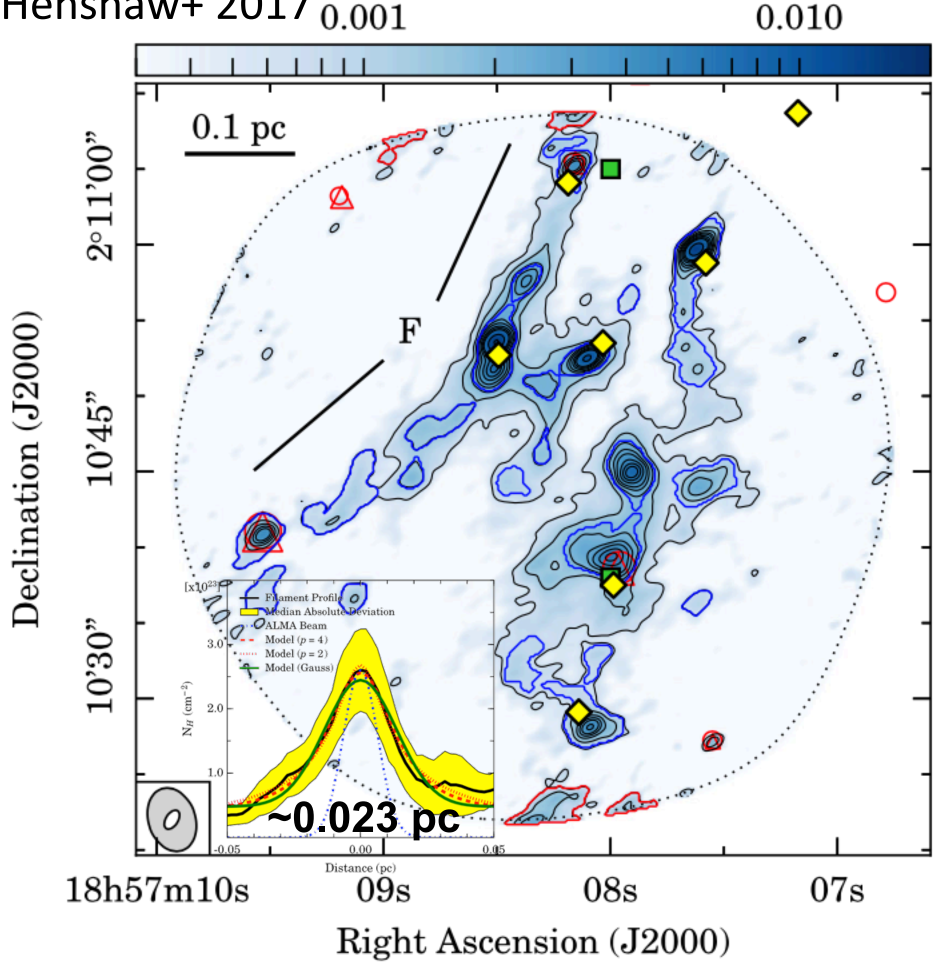
Filament Substructures

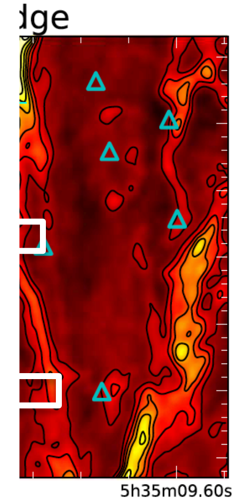
Northern region o

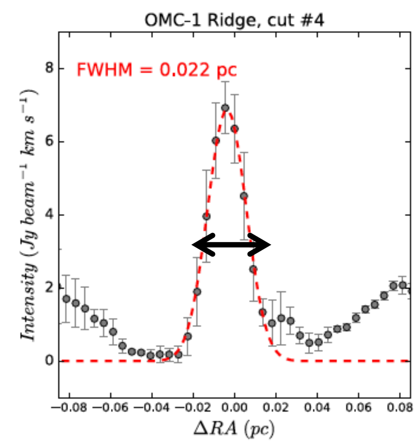




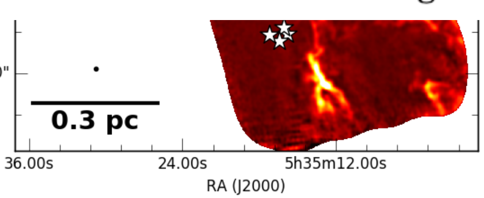
Henshaw+ 2017







0.035 pc << 0.1 pc

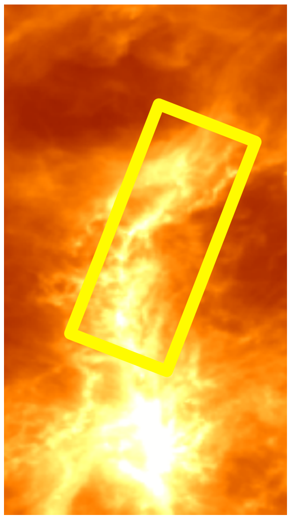


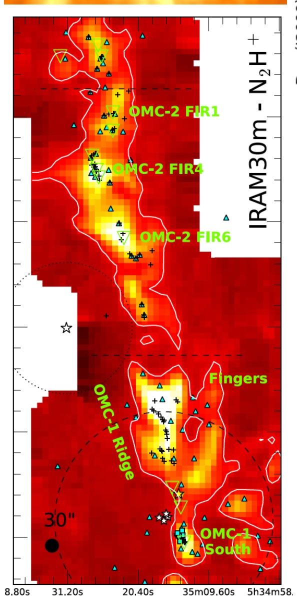
Herschel Gould Belt → Universal width 0.1 pc

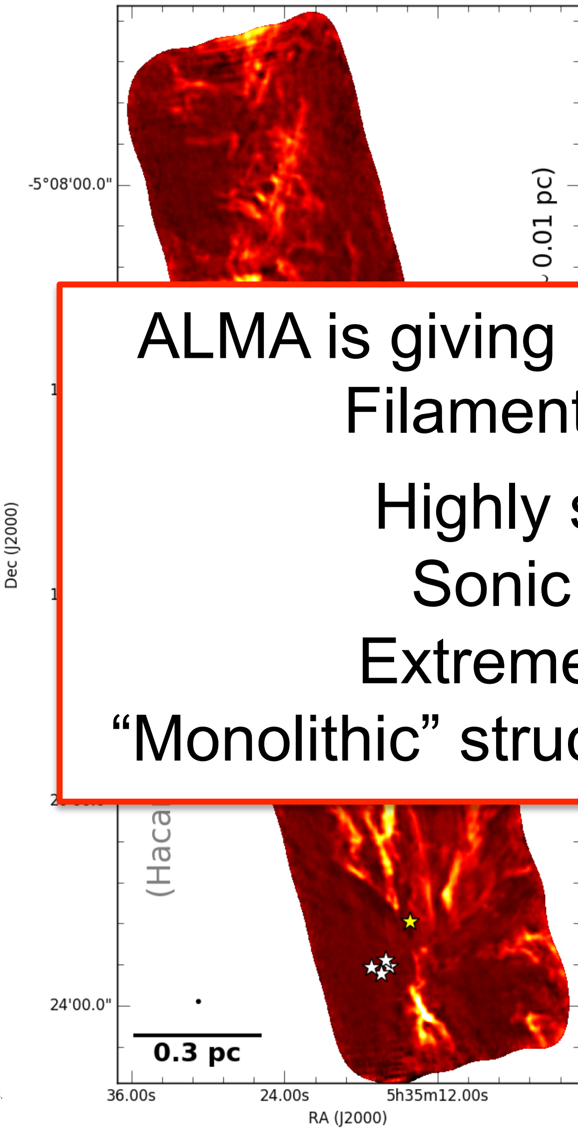
High spatial resolution → smaller widths

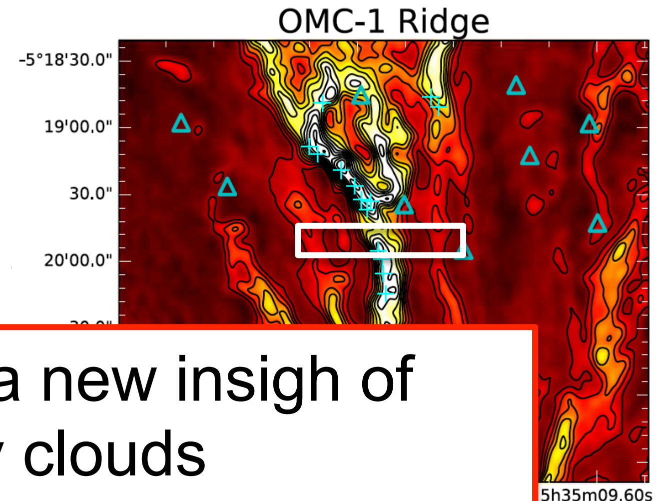
Filament Substructures

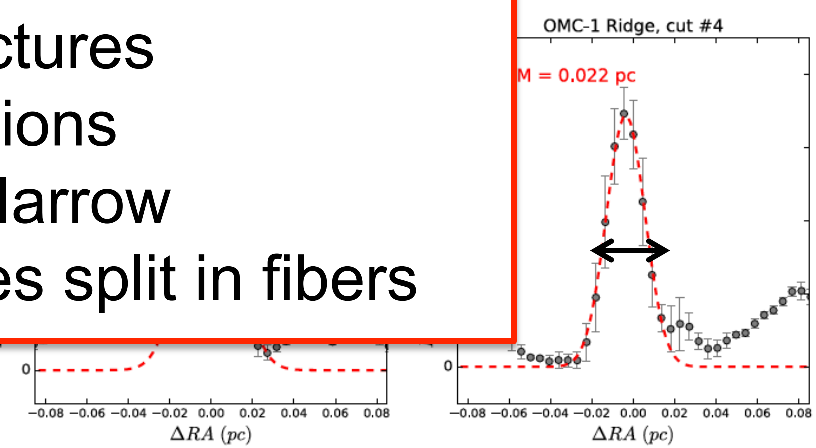
Northern region of Integral Shape Filament











ALMA is giving us a new insigh of Filamentary clouds

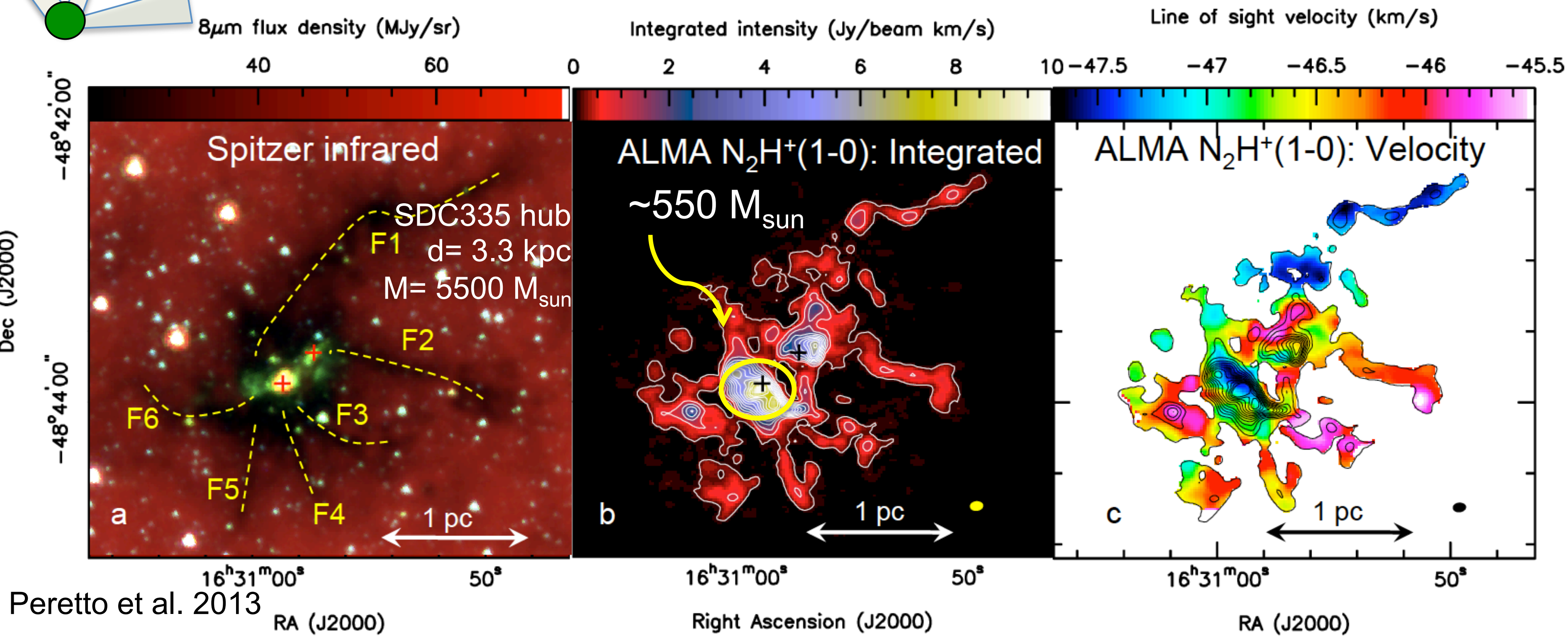
Highly structures
Sonic motions
Extremely Narrow
“Monolithic” structures split in fibers

Mean Width of Fibers ~ 0.035 pc << 0.1 pc

Herschel Gould Belt → Universal width 0.1 pc

High spatial resolution → smaller widths

Hub-filaments systems



Peretto et al. 2013

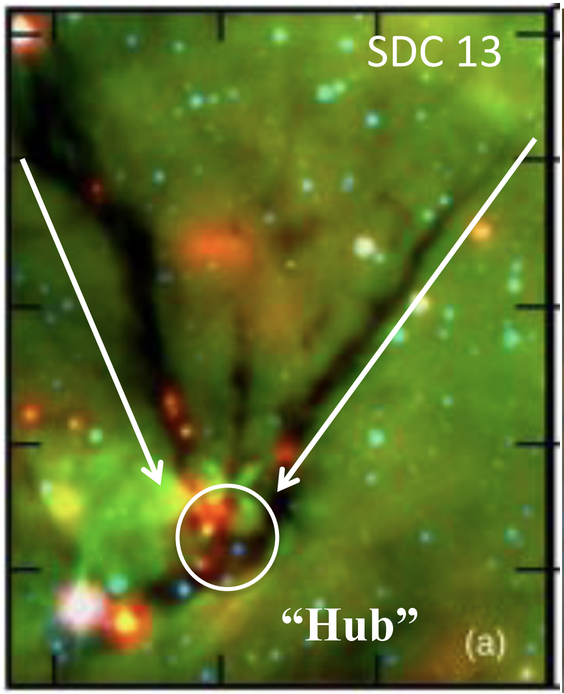
500 Msun protostellar clump in rapid collapse - Infall velocities ~0.7 km/s

Important consequences:

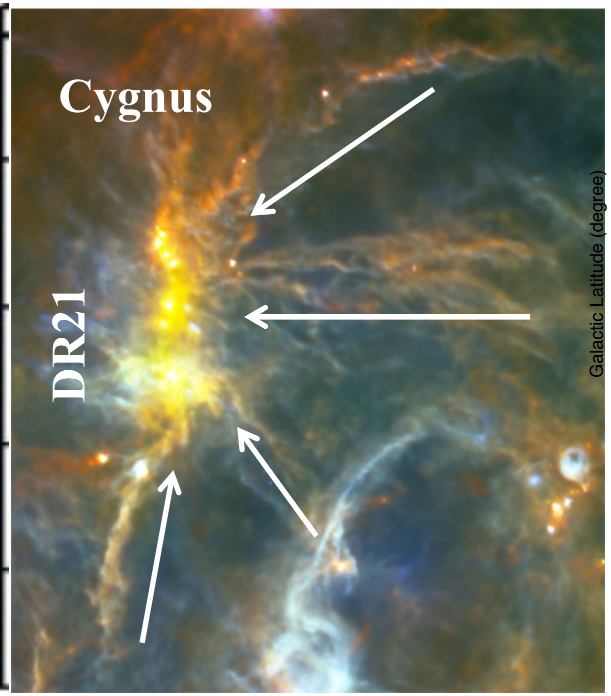
MC generally assumed self-gravitating, close to Virial equilibrium
Possibly not all clouds are in equilibrium, but they are in Global Collapse

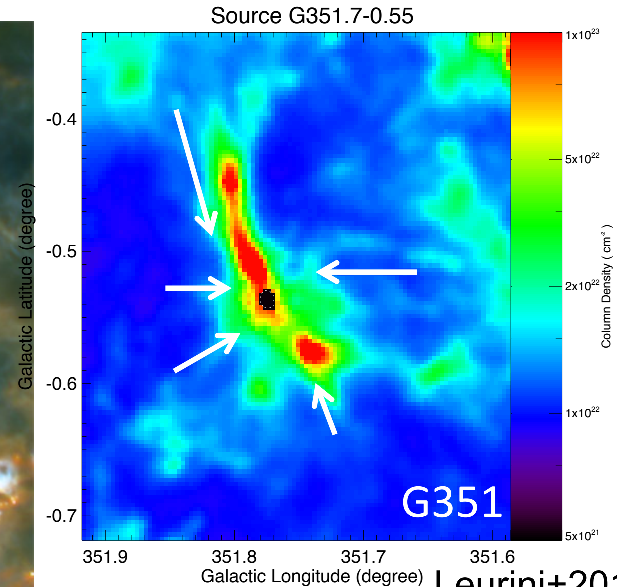
Hub-filaments systems / subfilament network

Peretto+ 2013, Williams, 2017



Schneider+ 2010





Leurini+2019

Observed with ALMA
PI Leurini 2015.1.00601

Intersecting filaments are the preferential enviroment for massive star and cluster formation

Likely to collapse on pc scales gathering matter at their centre.

Multiple examples of clouds analyzed -

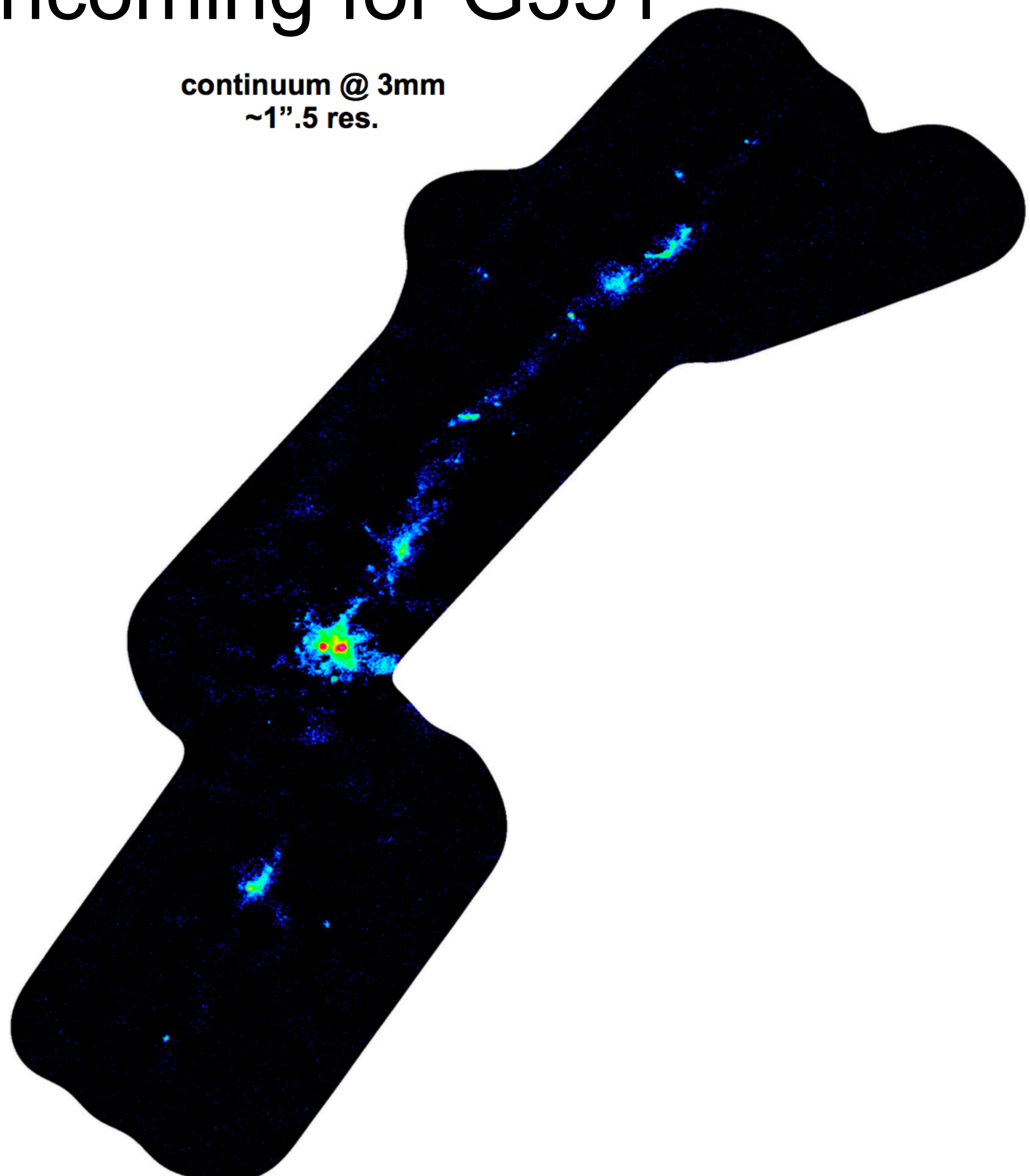
ALMA data incoming for G351

ALMA/ACA/TP observations

- 149 fields to cover the full main filament
- SiO, $H^{13}CO^+/HCO^+$, HNC, $H^{13}CN$ data (3mm) ⇒gas kinematics, outflows, large scale shocks
- 3mm continuum sensitive to ~solar masses ⇒ fragmentation

Leurini, in prep

Fragmentation,
Kinematics @ High spatial resolution
Star formation content.



Slide Courtesy of Leurini

Summary

ISM is a dynamic environment fundamental for the Galaxy.

The processes driving the continuous interchange of gas between ISM and stars can be studied in detail in the Galactic environment.

Key question are linked to the formation of molecular clouds and how they evolve by forming stars

We have learnt a lot on these processes from single dish ground telescopes, but high spatial resolution and sensitivity offered by ALMA are rapidly influencing what we know about ISM.

(Lot of new exciting discoveries also on ISM chemical enrichment, not discussed here… ISM enriched with Salt, Sugar, precursors of amminoacids)

ALMA will help to extend our discoveries towards other galaxies, studying the molecular cloud components outside the Milky Way

ALMA observations are also opening new questions in the Galactic objects, such as how fragmentation proceed and the existence of substructures within the filaments .