An overview of modern star formation research

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Outline

01

Introduction

What is star formation and its place in Astronomy

02

Techniques

How we do star formation research

03

Open questions

Major questions in the field and how we are answering them

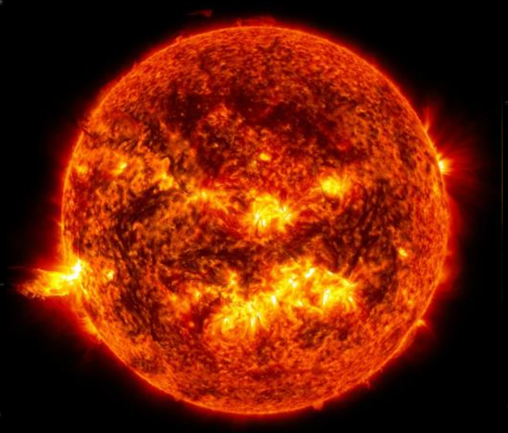
01
What is star formation, and why is it important?

(Protostar & Planets VII reviews – Pineda, Clarke et al. 2023)

Star formation at its basics

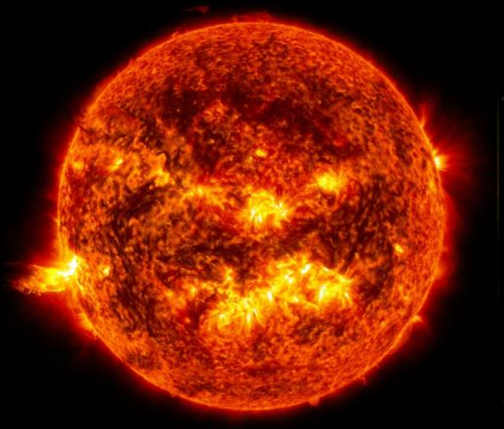
Credit: ESA

Credit: NASA



Star formation at its basics

Size –	20 kpc - 10^{21} m
Density –	1 cm^{-3} - 10^{-24} g cm^{-3}
Timescale –	100 Myr - 10^{15} s



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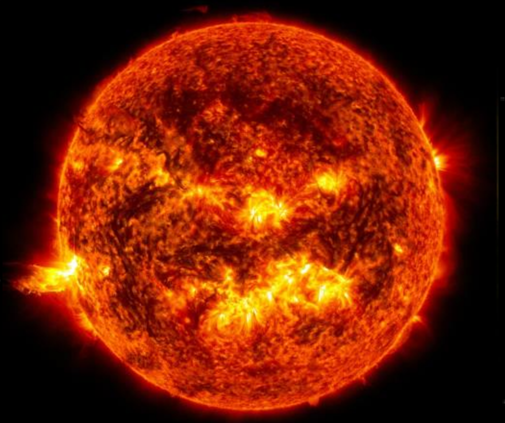
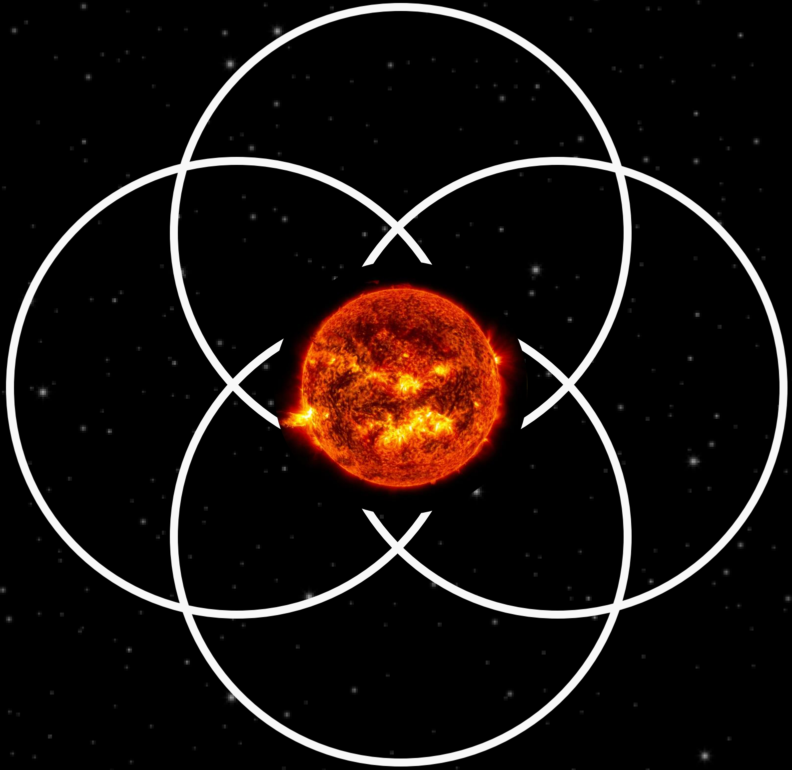
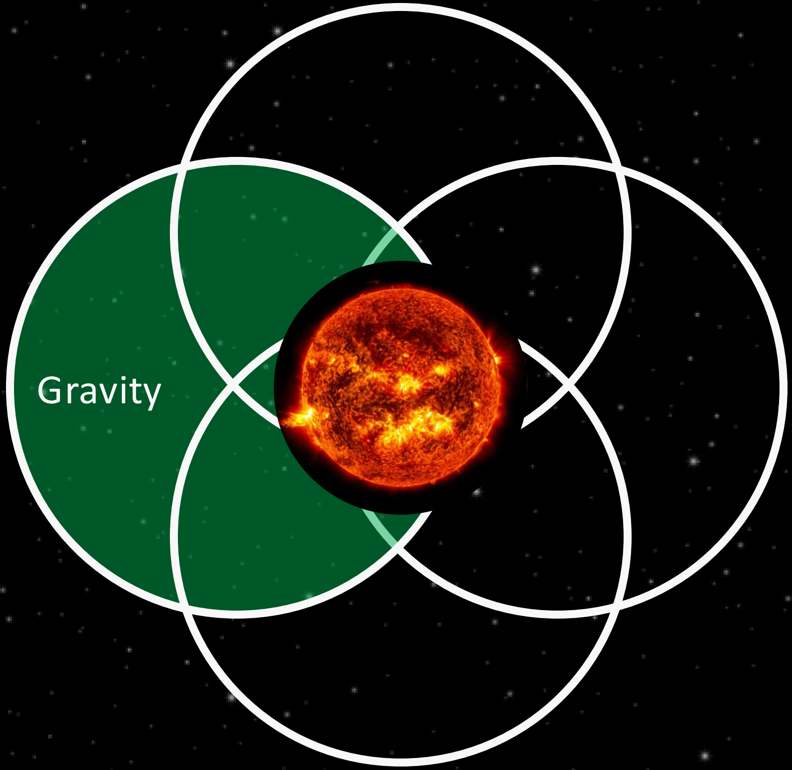


Size – 1 $R_\odot$ - 10^9 m
Density – 10^{24} cm^{-3} - 1 g cm^{-3}
Timescale – 100 s

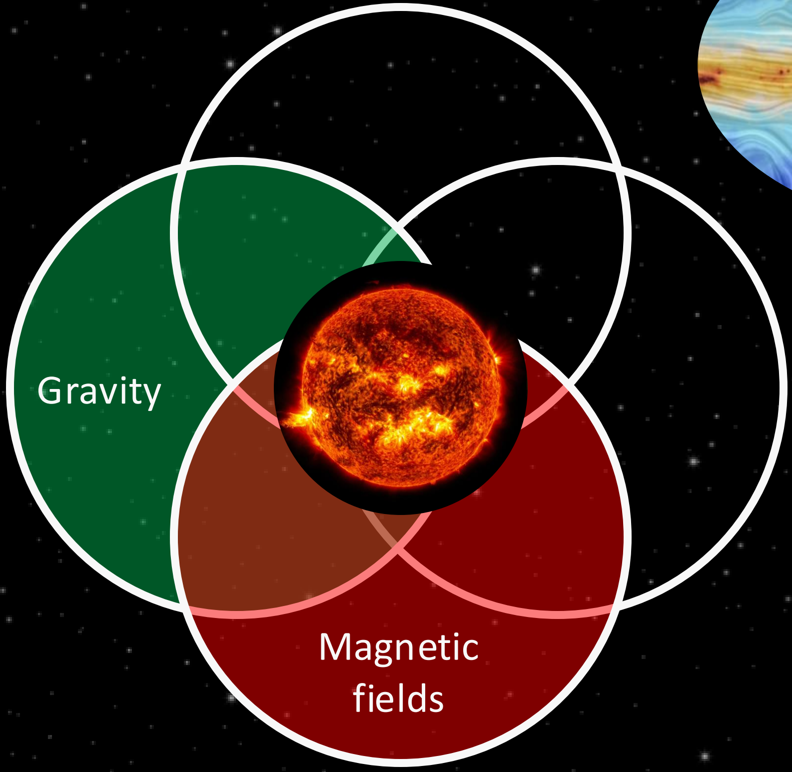
The physics at play



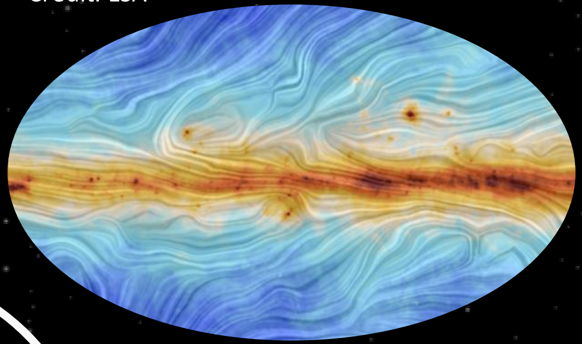
The physics at play



The physics at play



Credit: ESA

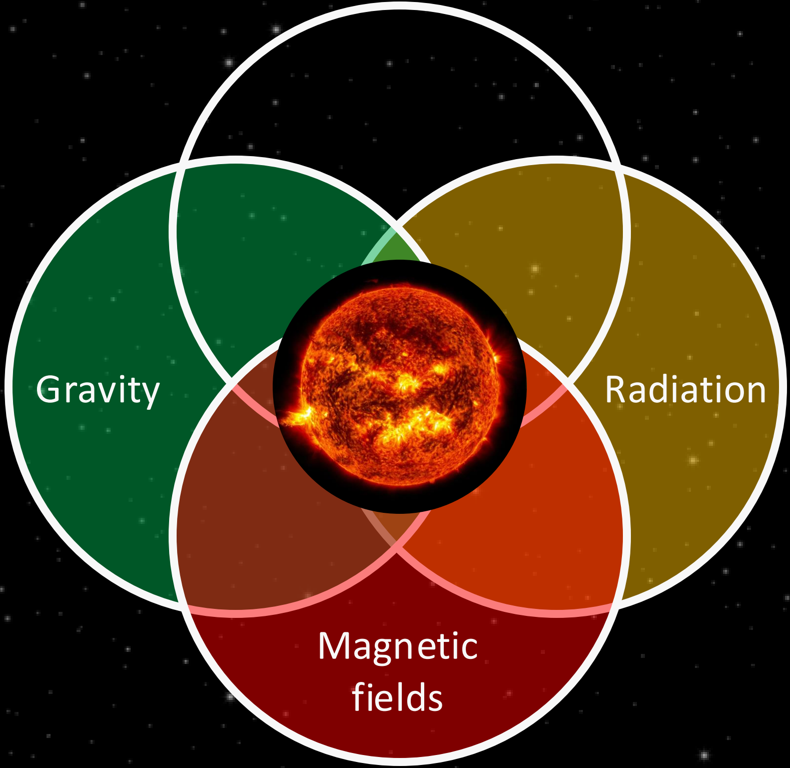


Lorentz force acts against compression in an anisotropic manner.

The physics at play

Credit: NASA/Hubble

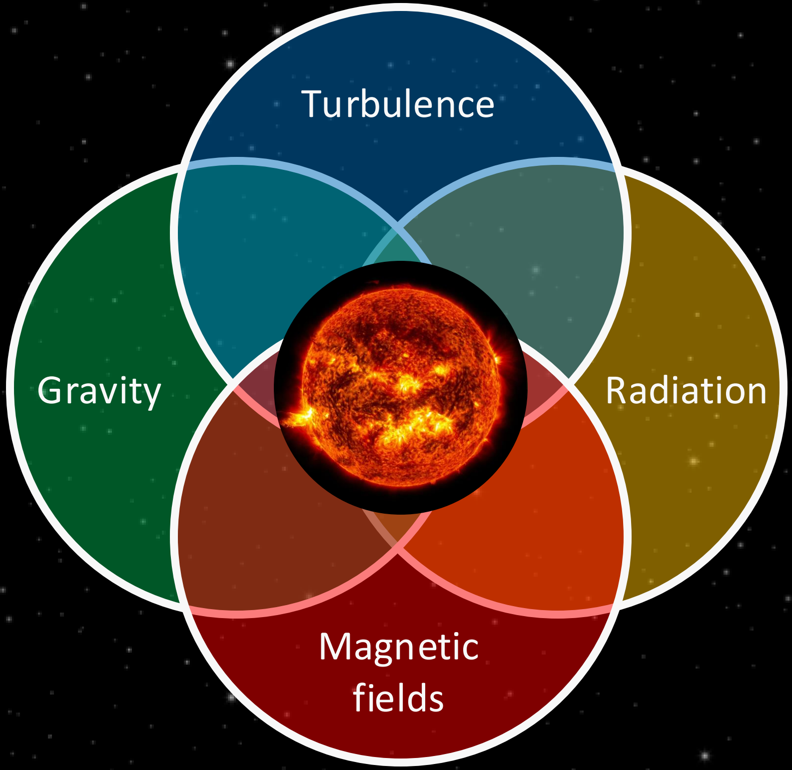
UV/X-rays apply radiation pressure on gas, and heats the gas to >10,000 K



Credit: NASA/CXC/SAO

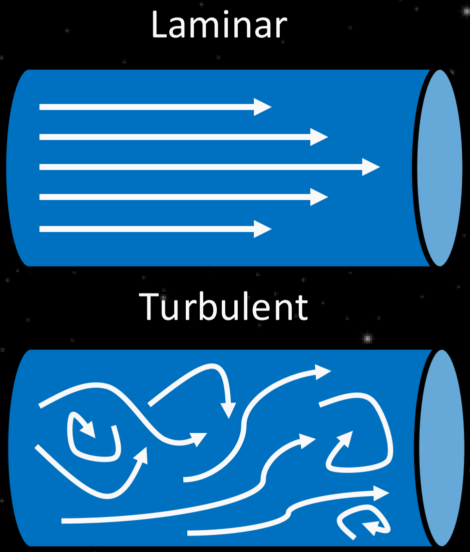
Cosmic rays (relativistic protons and electrons) collide and heat the gas as well.

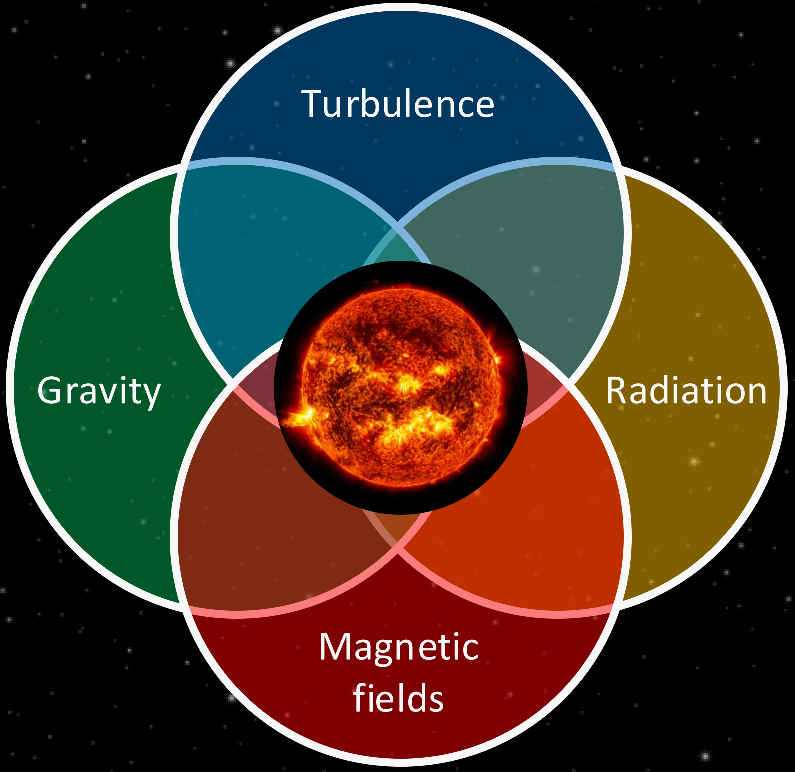
The physics at play



Non-ordered motions across multiple spatial scales.

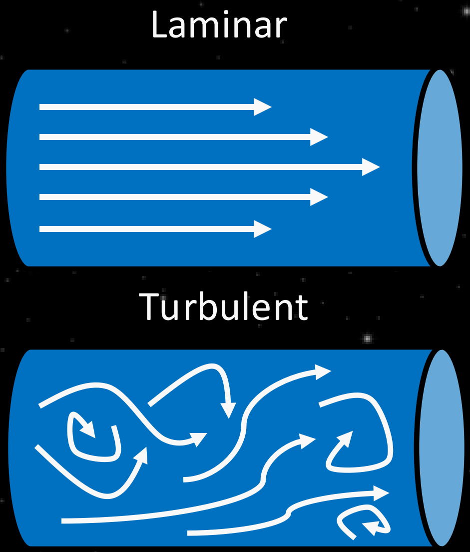
The physics at play

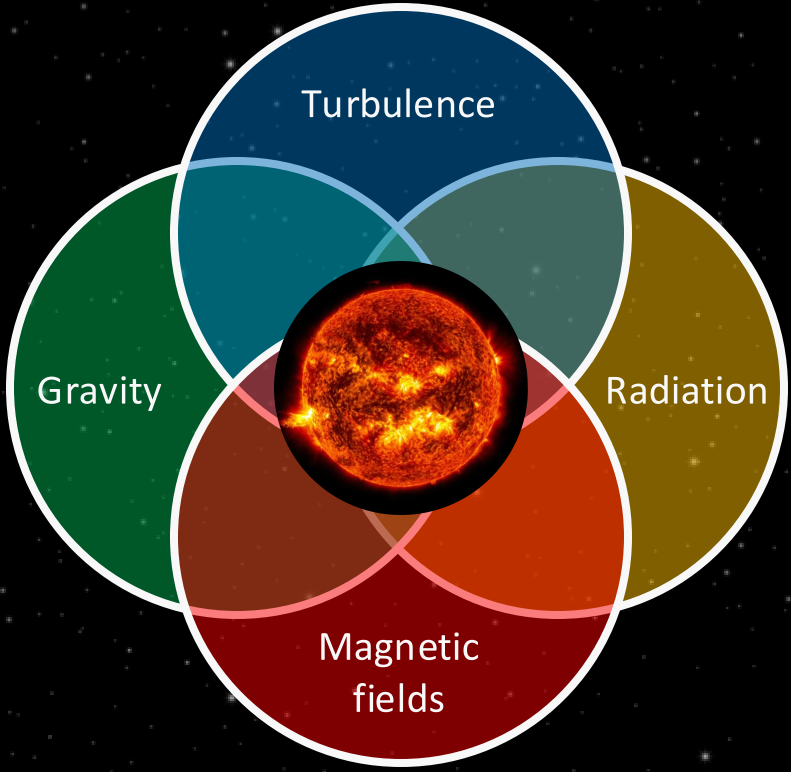




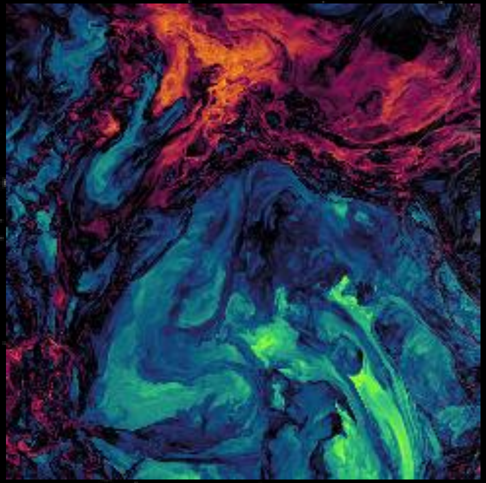
Non-ordered motions across multiple spatial scales.

The physics at play





Credit: Beattie et al. (2025)

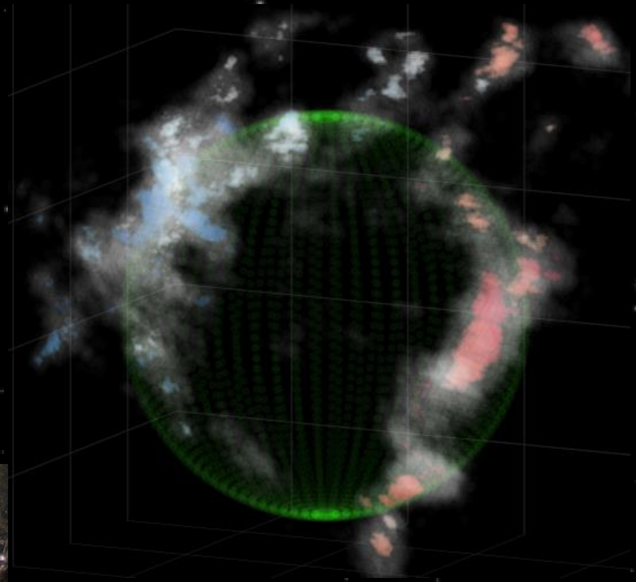


Non-ordered motions across multiple spatial scales.

From large-scales to stars

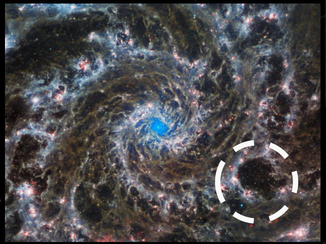
Credit: J. Schmidt, J. Lee, PHANGS-JWST

From large-scales to stars



Credit: Bialy et al. (2023)

Galaxies

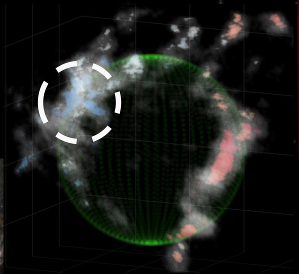


Credit: J. Schmidt, J. Lee, PHANGS-JWST

From large-scales to stars

Credit: Stutz & Kainulainen (2015)

Clouds



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From large-scales to stars

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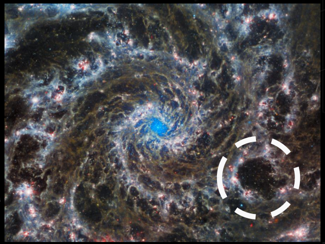

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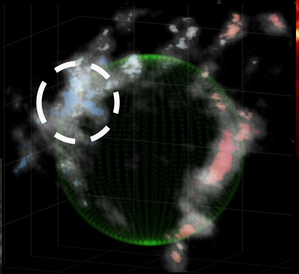
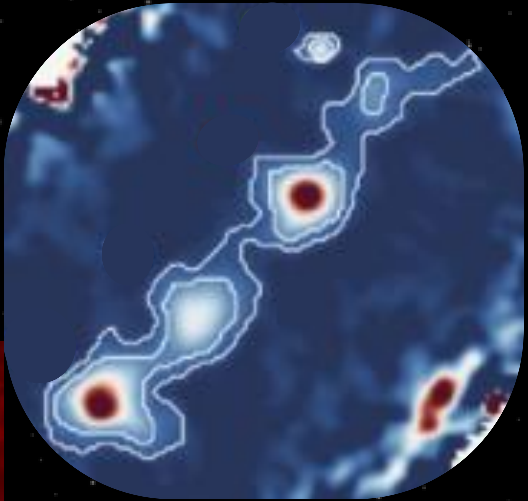


Credit: Bialy et al. (2023)

Filaments

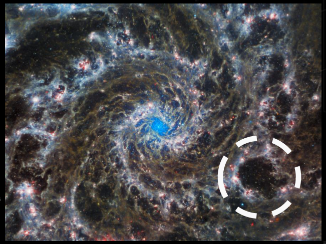
Credit: Stutz & Kainulainen (2015)



Credit: Lee et al. (2020)

From large-scales to stars

Galaxies



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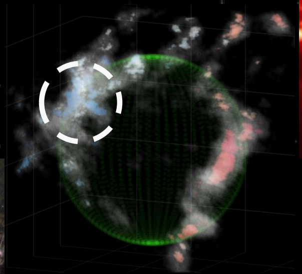
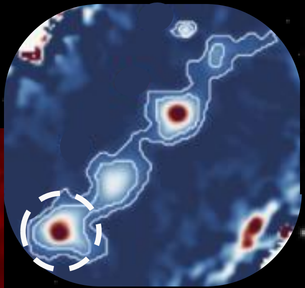


Credit: Bialy et al. (2023)

Filaments

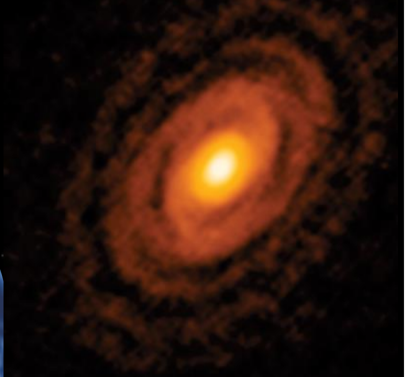
Credit: Stutz & Kainulainen (2015)

Cores



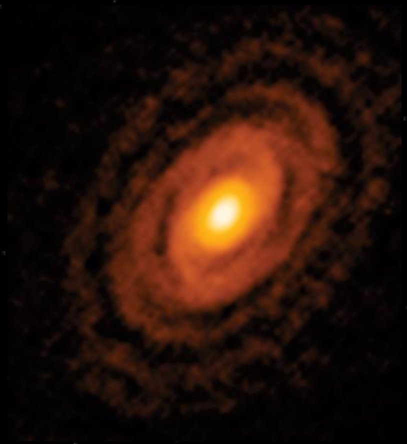
Credit: Lee et al. (2020)

Disks



Credit: Andrews et al. (2018)

Star formation in Astronomy



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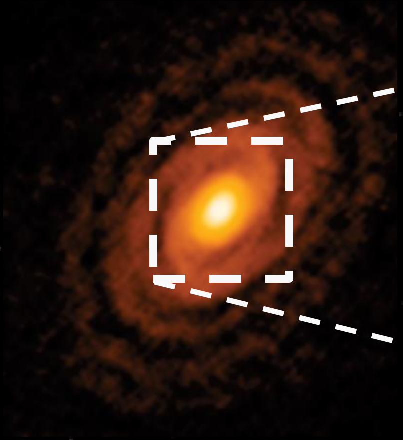

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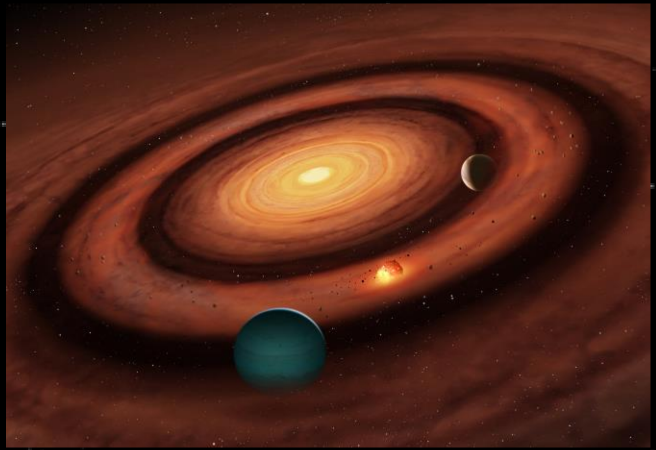
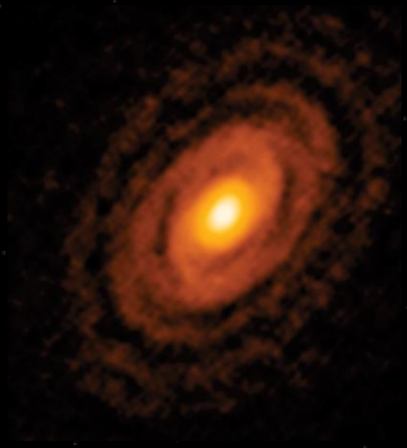


Credit: RAS, Mark A. Garlick

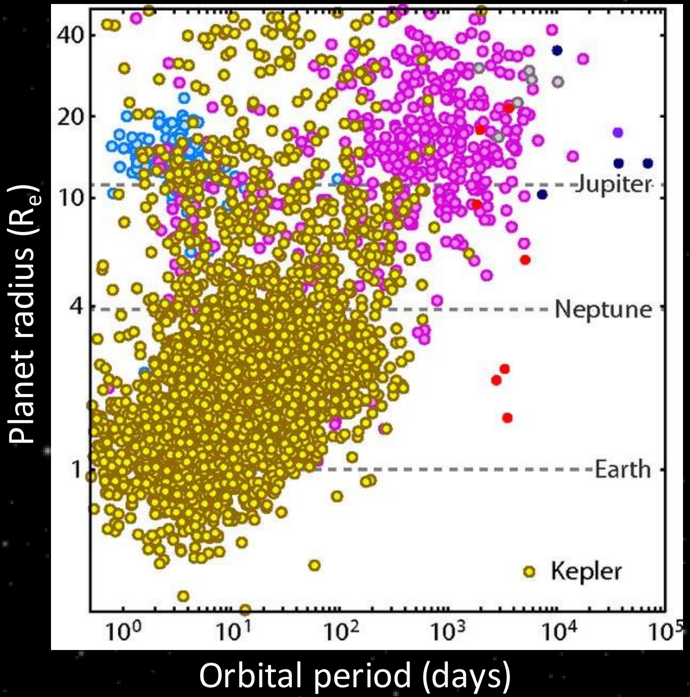
Planet formation takes place during star formation! Thus the two are intrinsically bound together and one can't understand planet formation without star formation.

Star formation in Astronomy



Credit: Andrews et al. (2018)

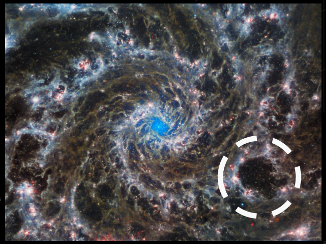
Credit: Seager & Bains (2015)



Understanding star formation helps understand the diversity of exoplanets.

Star formation in Astronomy

Galaxies



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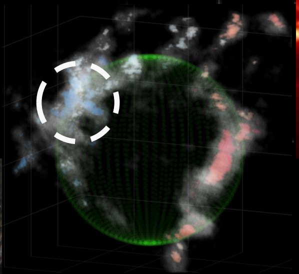
Clouds



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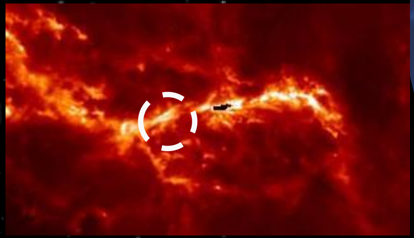
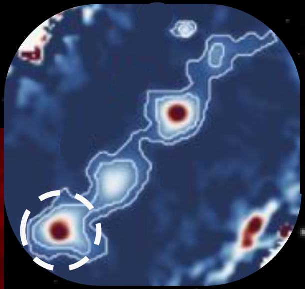


Credit: Stutz & Kainulainen (2015)

Cores



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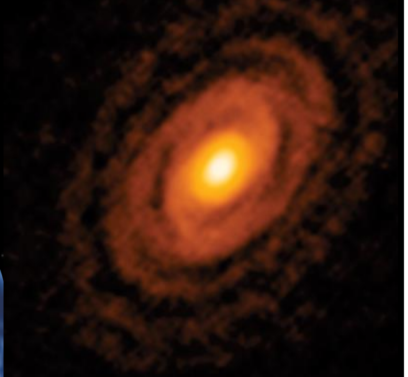

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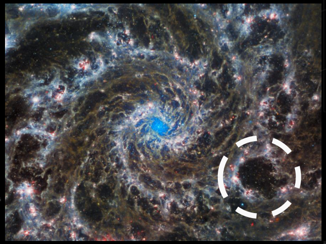
Star formation in Astronomy

Galaxies



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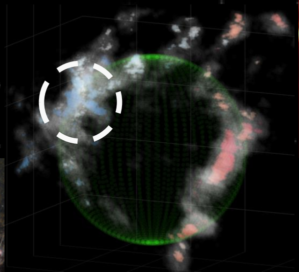

Credit: Bialy et al. (2023)

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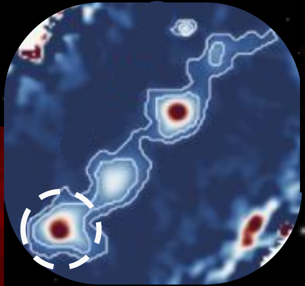

Credit: Lee et al. (2020)

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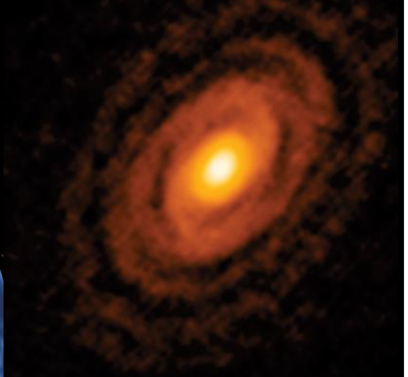


Credit: Andrews et al. (2018)

Stellar feedback events by forming and young stars inject >10^{37} J of energy into the host galaxy

Star formation in Astronomy

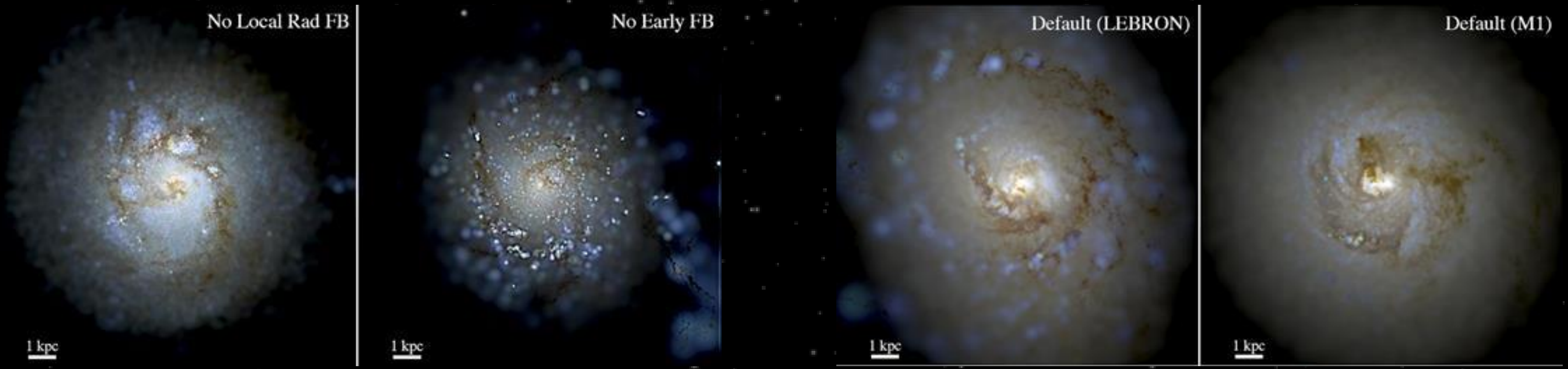
Galaxies without feedback

Without stellar feedback from young stars galaxies lack structures like spirals, and are too massive and compact compared to observed galaxies.

Star formation in Astronomy

Galaxies without feedback

Galaxies with feedback



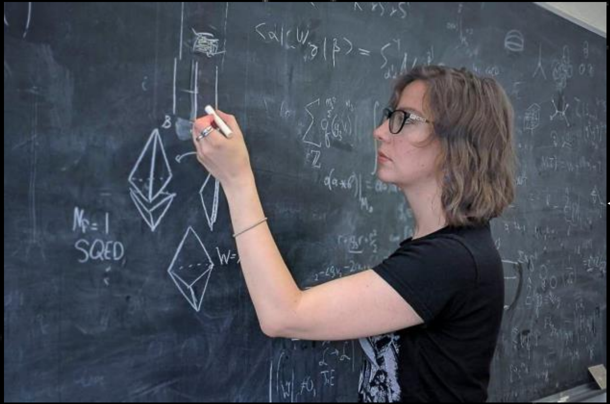
Credit: Hopkins et al. (2020)

Small-scale star formation is essential for realistic galaxy structure and morphology.

02
How do we research star formation?

Theory and observations

Theory



Credit: Stanford

Observations

Credit: Greenwich Observatory

Theory in star formation

Theory in star formation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

Conservation of mass

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}\boldsymbol{V} - \boldsymbol{B}\boldsymbol{B} + P^{*}\boldsymbol{I}) = 0$$

Conservation of momentum

$$\frac{\partial e}{\partial t} + \nabla \cdot ([e + P^{*}]\boldsymbol{V} - \boldsymbol{B}[\boldsymbol{B} \cdot \boldsymbol{V}]) = 0$$

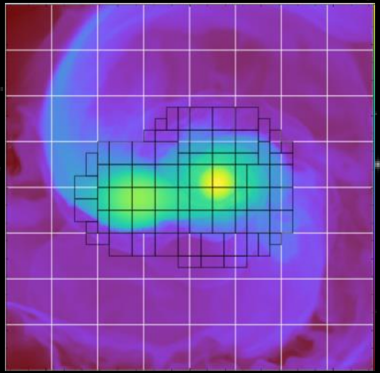
Conservation of energy

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0$$

Maxwell-Faraday

Theory in star formation

Adaptive Mesh Refinement (AMR)

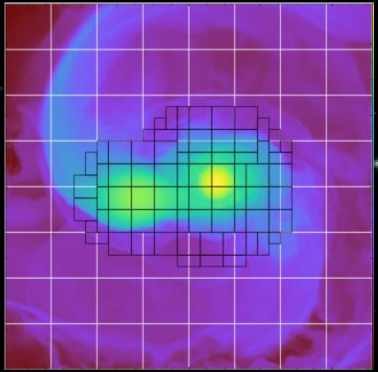


Credit: AMReX-Astro

Eulerian

Theory in star formation

Adaptive Mesh Refinement (AMR)



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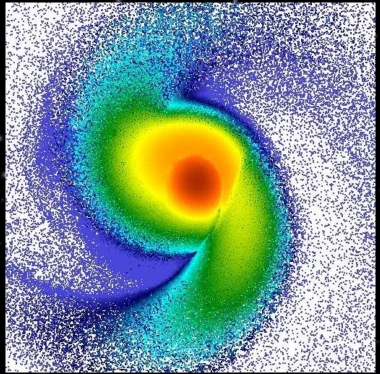
Eulerian

Smoothed Particle Hydrodynamics (SPH)

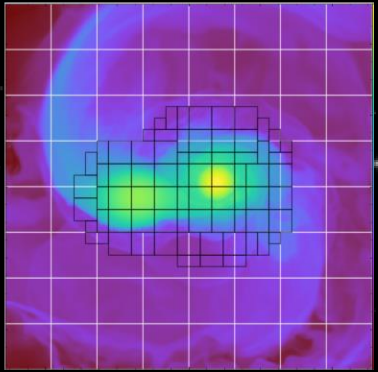


Credit: Diehl et al. (2008)

Lagrangian

Theory in star formation

Adaptive Mesh Refinement (AMR)



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Eulerian

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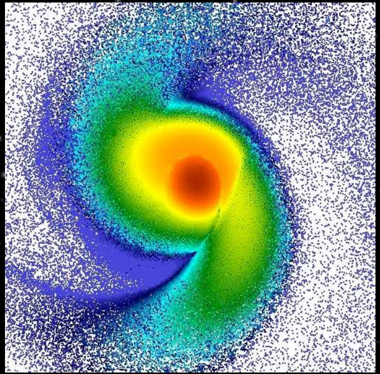
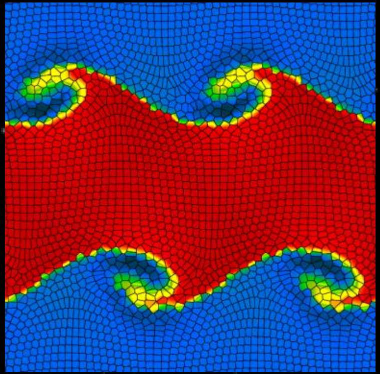


Credit: Diehl et al. (2008)

Lagrangian

Moving-Mesh

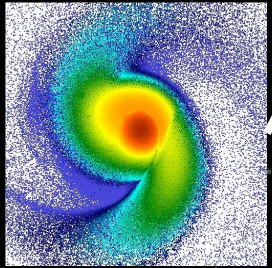


Credit: AREPO

Quasi-Lagrangian

Theory in star formation

Star cluster formation in a turbulent cloud

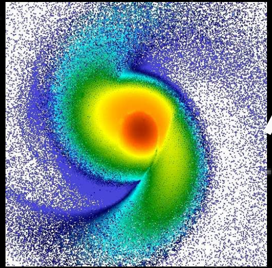


Credit: Diehl et al. (2008)

Gadget, PHANTOM, GANDALF

Theory in star formation

Star cluster formation in a turbulent cloud



Credit: Diehl et al. (2008)

Gadget, PHANTOM, GANDALF

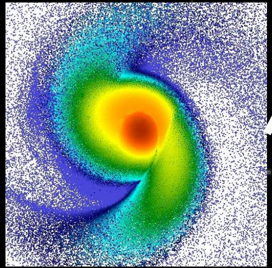
Build initial conditions relevant to the science question at hand.

Important to note that these are normally highly idealised forms of reality, and unfortunately do have an important on the results.

Theory in star formation

Star cluster formation in a turbulent cloud

Credit:UzK



Credit: Diehl et al. (2008)

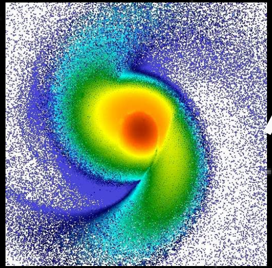
Gadget, PHANTOM, GANDALF

Theory in star formation

Star cluster formation in a turbulent cloud

Credit:UzK

Credit: Bates et al. (2009)

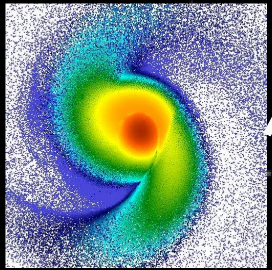


Credit: Diehl et al. (2008)

$10^4 – 10^6$ CPU hour simulations producing large datasets (>1TB) containing millions of fluid elements over 100s of timesteps.

Theory in star formation

Star cluster formation in a turbulent cloud



Credit: Diehl et al. (2008)

Credit:UzK

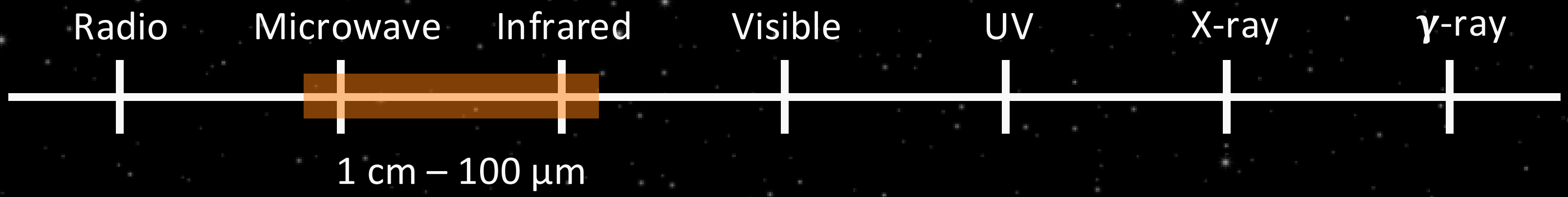
Credit: Bates et al. (2009)

Find/Construct a quantity relevant to the science question which is sensitive to physical parameters. Bonus – Can be observed!

Observations in star formation

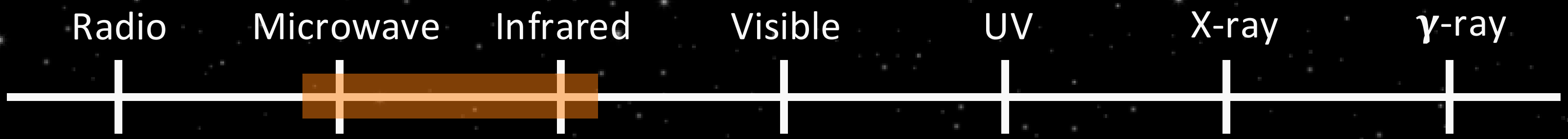
Radio | Microwave | Infrared | Visible | UV | X-ray | γ-ray

Observations in star formation



Main wavelength range to study the dense gas and dust for star formation due to low temperatures.

Observations in star formation



1 cm – 100 µm

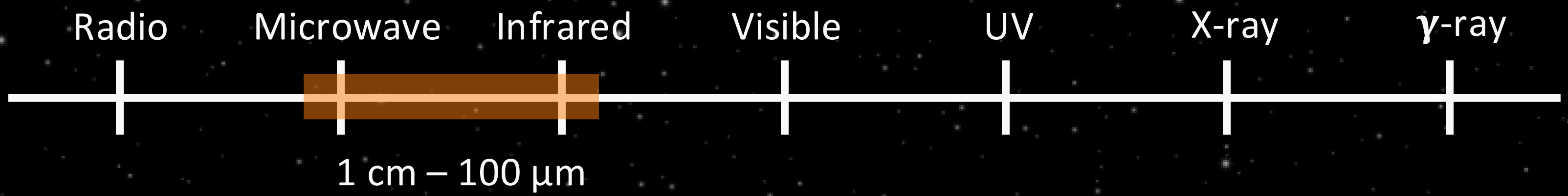
Main wavelength range to study the dense gas and dust for star formation due to low temperatures.

Earth-based mm/sub-mm

Credit: IRAM

Credit: ALMA

Observations in star formation



Main wavelength range to study the dense gas and dust for star formation due to low temperatures.

Earth-based mm/sub-mm

Credit: IRAM

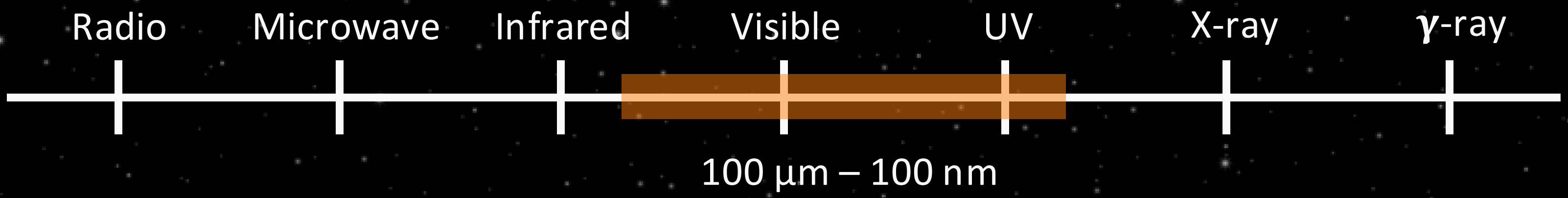
Credit: ALMA

Space & Airborne Far-Infrared

Credit: ESA/Herschel

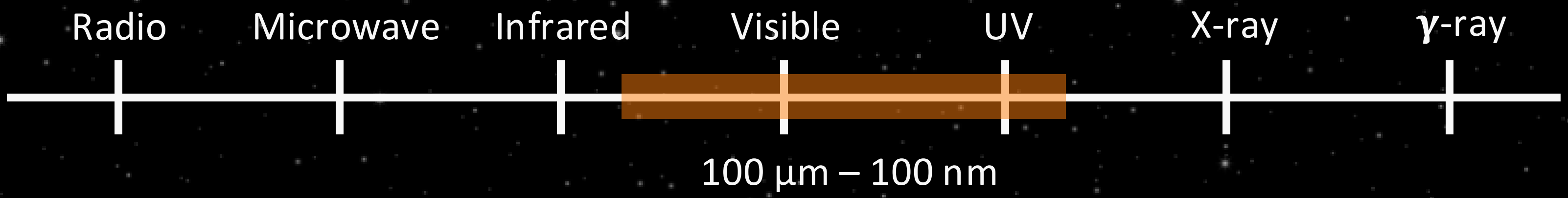
Credit: NASA/SOFIA

Observations in star formation



Feedback from outflows & HII regions dominate this wavelength range – Hot ionised gas

Observations in star formation



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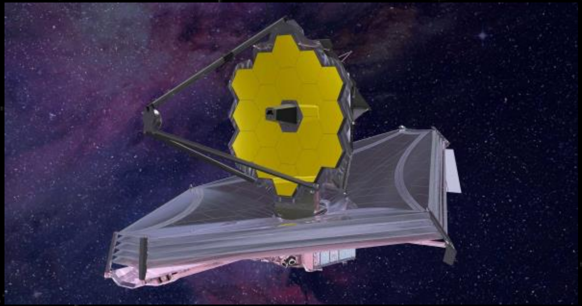
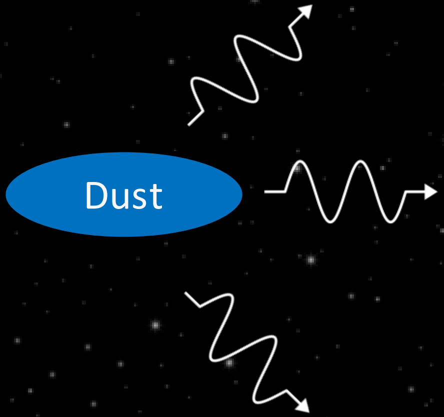


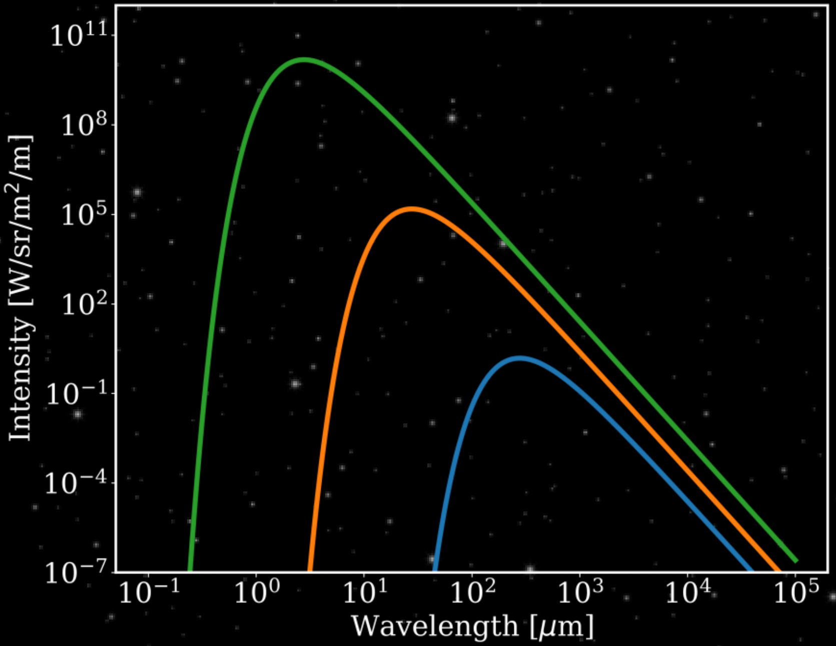
Credit: ESA/JWST

Credit: ESO/VLT

Credit: NASA/Hubble

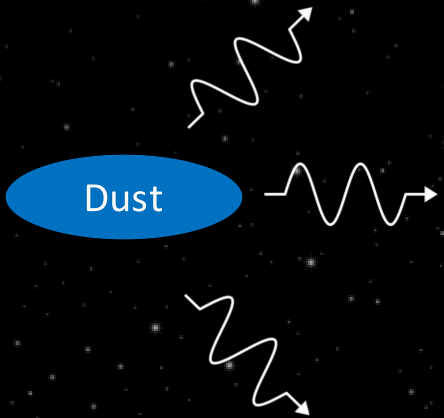
Observations in star formation - continuum

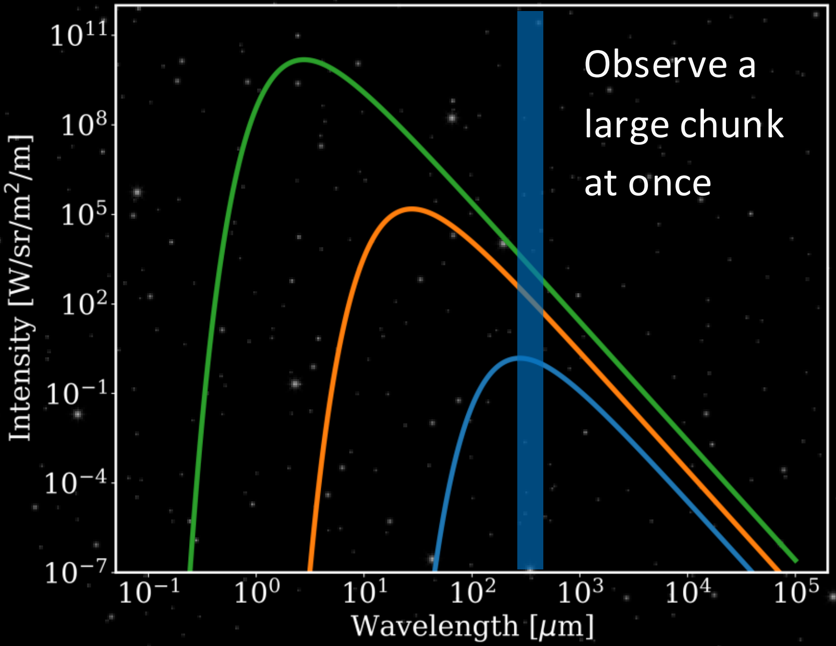




Dust emits as a blackbody – i.e. simultaneously across a wide wavelength range

Observations in star formation - continuum





Dust emits as a blackbody – i.e. simultaneously across a wide wavelength range

Observations in star formation - continuum

Credit:ESA/Herschel

Credit:ESA/Herschel

Observations in star formation - continuum

Credit:ESA/Herschel

Credit:ESA/Herschel

Dust is thought to trace gas well - An unbiased tracer of **mass** of the system

Observations in star formation - continuum

Credit:ESA/Herschel

Credit:ESA/Herschel

Dust is thought to trace gas well - An unbiased tracer of **mass** of the system

Multi-wavelength observations provide good **temperature** estimates

Observations in star formation - continuum

Credit:ESA/Herschel

Credit:ESA/Herschel

Dust is thought to trace gas well - An unbiased tracer of **mass** of the system

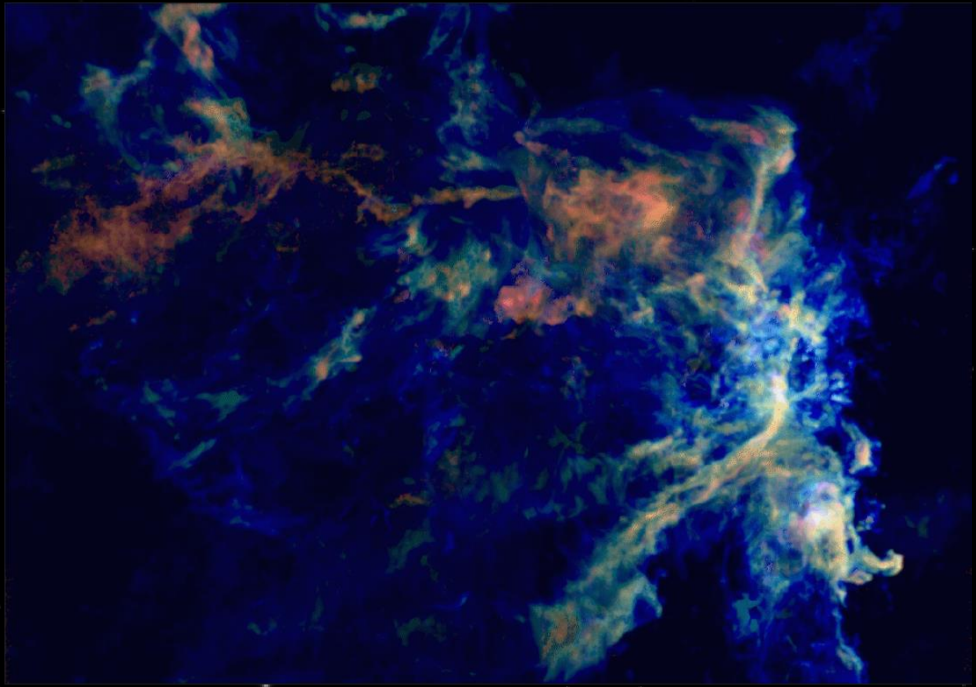
Multi-wavelength observations provide good **temperature** estimates

Including polarisation provides access to the morphology of the **magnetic field**

Observations in star formation - molecules

Credit: Orion B project

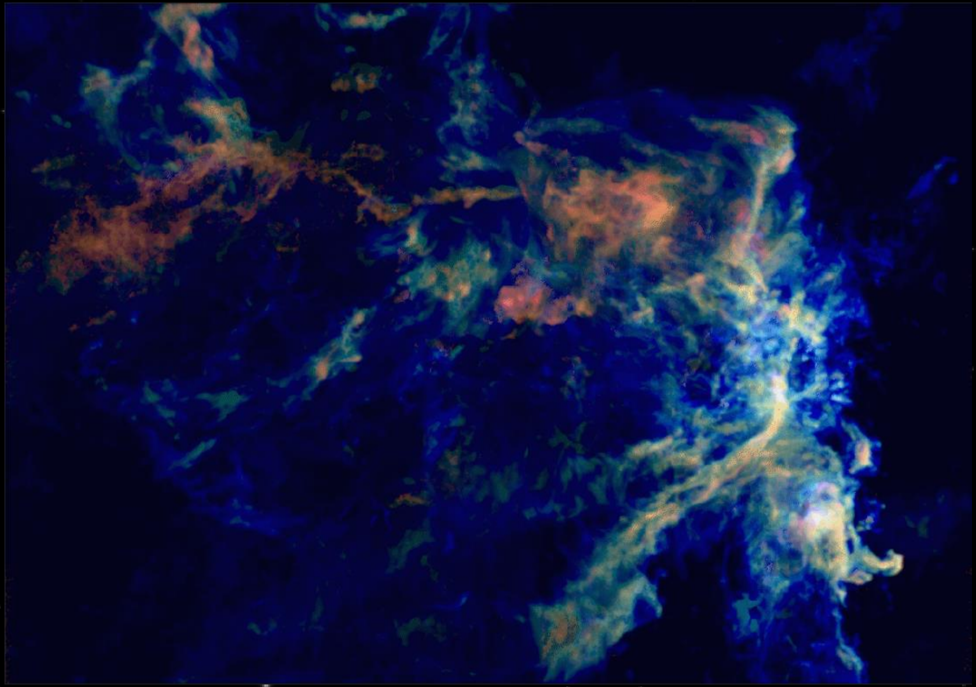
Observations in star formation - molecules



Credit: Orion B project

Use Doppler shifts to determine kinematic structure of clouds – **opens the third dimension up**

Observations in star formation - molecules

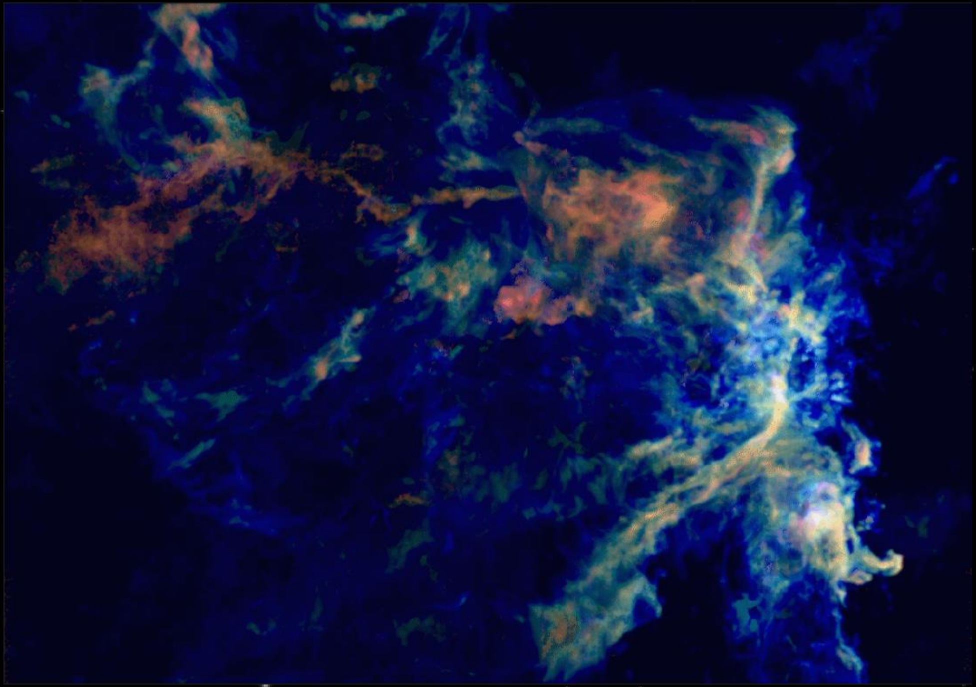


Credit: Orion B project

Use Doppler shifts to determine kinematic structure of clouds – **opens the third dimension up**

Different molecules trace different gas – **disentangle different structures/densities**

Observations in star formation - molecules



Credit: Orion B project

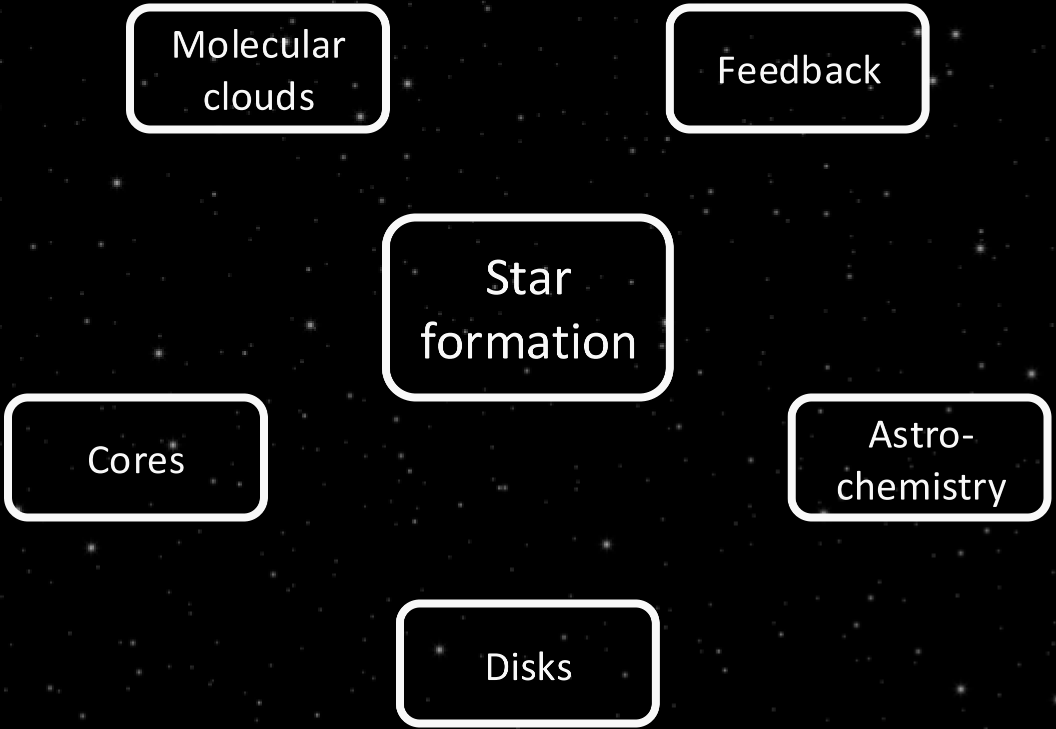
Use Doppler shifts to determine kinematic structure of clouds – **opens the third dimension up**

Different molecules trace different gas – **disentangle different structures/densities**

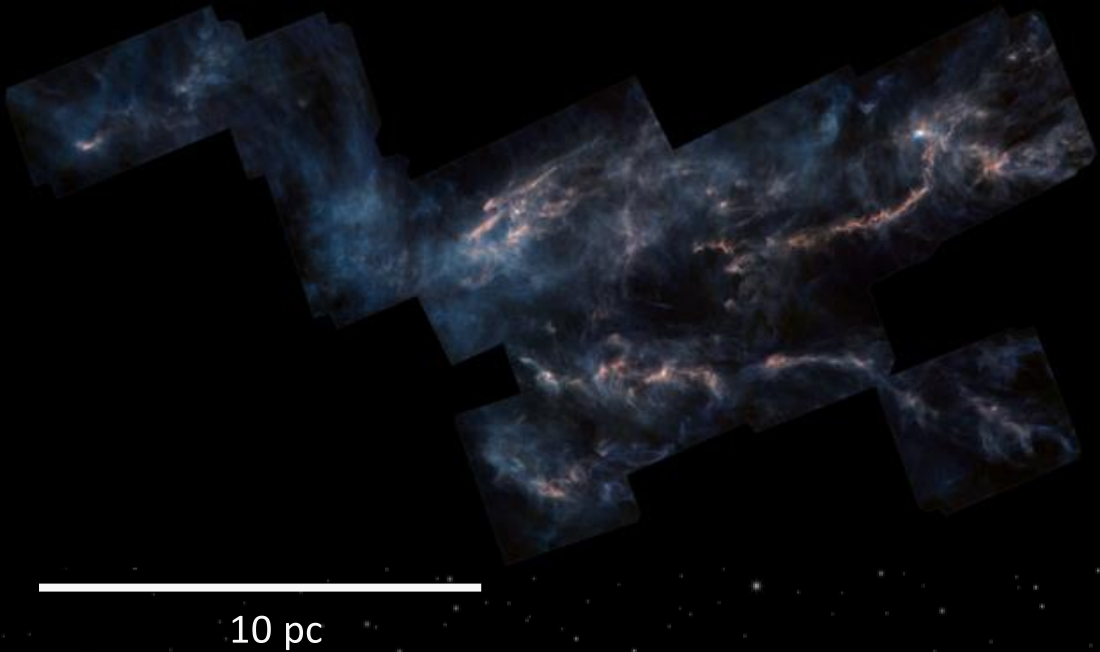
Relative abundances of molecules provide **density/temperature/history information**

03

Major open questions and how we’re addressing them


Molecular clouds
Feedback
Star formation
Cores
Astro-chemistry
Disks

Credit: ESA/Herschel



Molecular clouds

Star formation

Cores

Fee

Formation

How do we convert diffuse gas into parsec-scale molecular gas? Does this depend on environment in the galaxy?

Evolution

Molecular clouds

Fee

Star formation

Cores

Formation

How do we convert diffuse gas into parsec-scale molecular gas? Does this depend on environment in the galaxy?

Evolution

Are clouds in quasi-equilibrium? Collapsing? Long-lived? Short-lived? What causes them to stop forming stars?

Molecular clouds

Fee

Star formation

Cores

The Astrophysical Journal, 925:196 (14pp), 2022 February 1 https://doi.org/10.3847/1538-4357/ac3b58

Gravity versus Magnetic Fields in Forming Molecular Clouds

Juan C. Ibáñez-Mejía[1,6], Mordecai-Mark Mac Low[2,3], and Ralf S. Klessen[4,5]
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[2] Dept. of Astrophysics, American Museum of Natural History, 79th St. at Central Park West, New York, NY 10024, USA; mordecai@amnh.org
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Received 2021 August 5; revised 2021 November 16; accepted 2021 November 17; published 2022 February 4

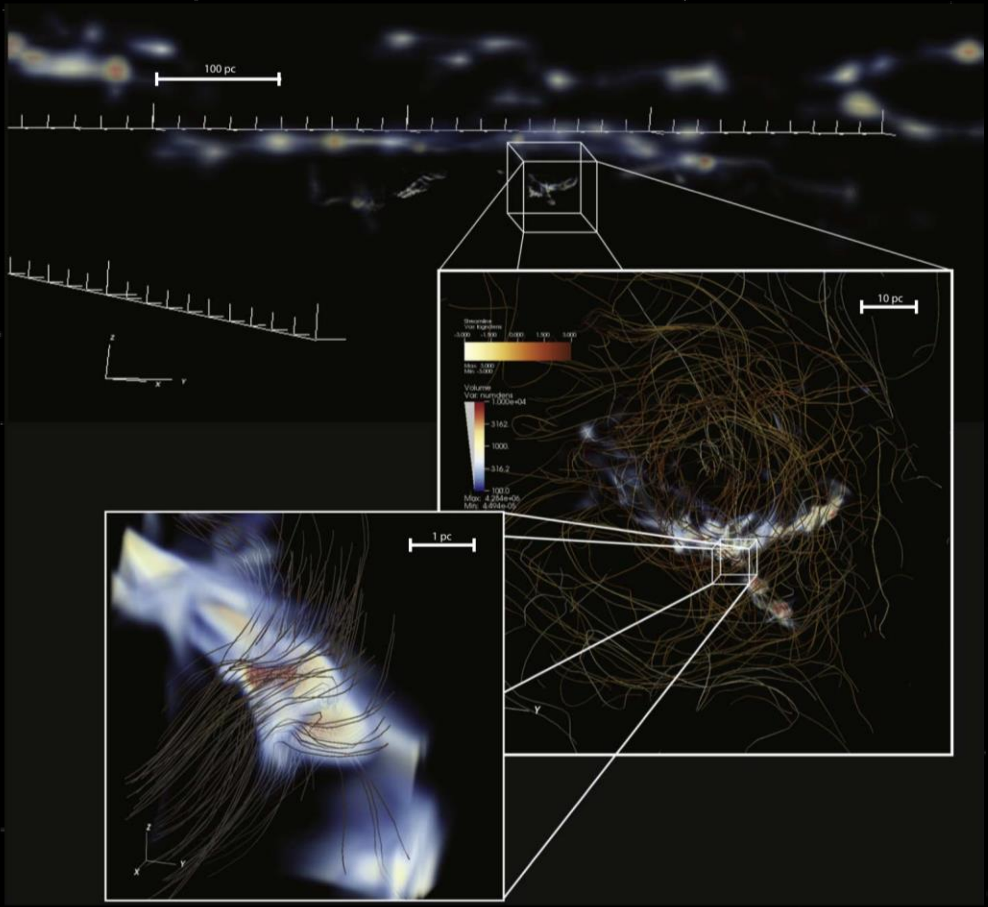
Galactic plane

↓

Molecular cloud

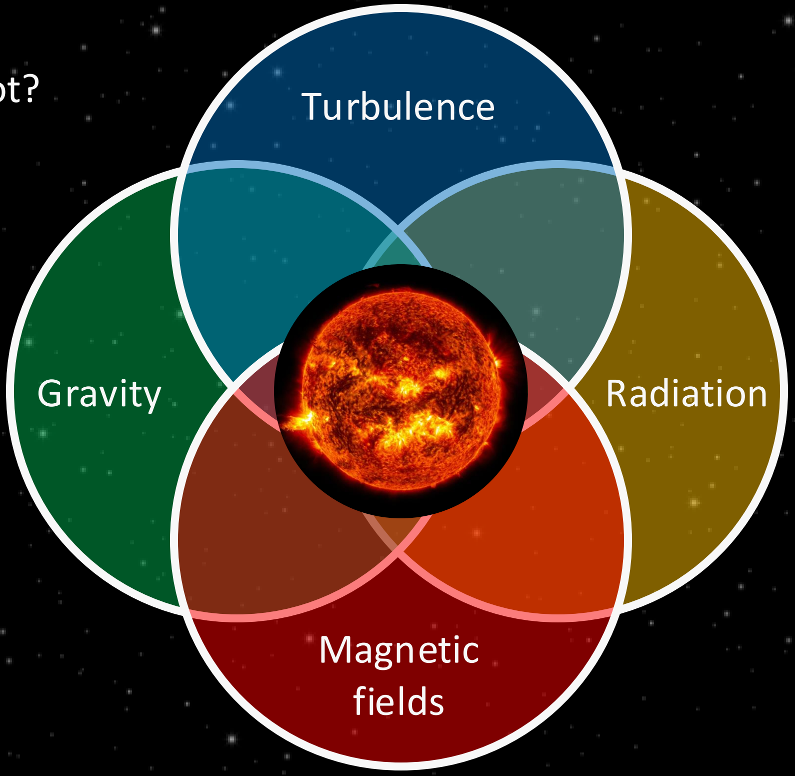
↓

Dense filament



AMR simulation of a chunk of the galactic plane with zoom-ins of clouds down to 0.06 pc

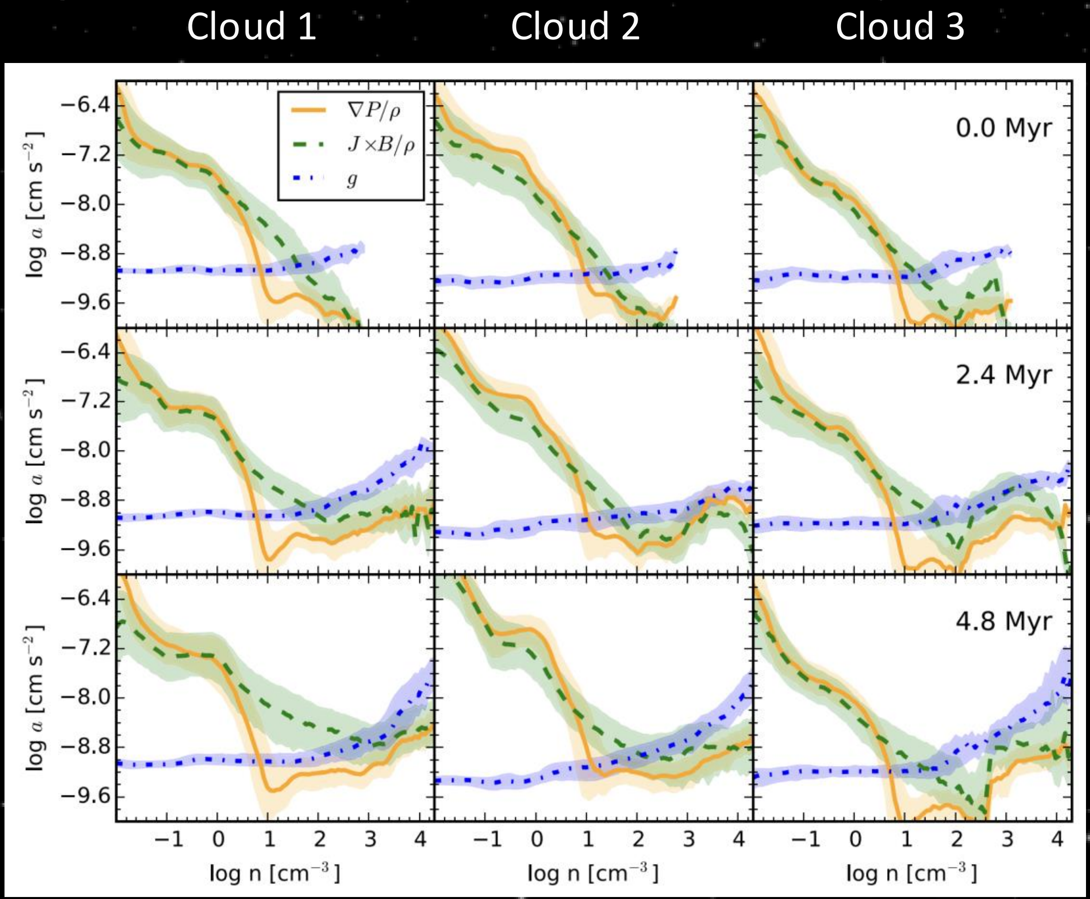
Are the clouds in some form of equilibrium of not?



Are the clouds in some form of equilibrium of not?

Look at the forces of the three components:

Thermal
Magnetic fields
Gravity

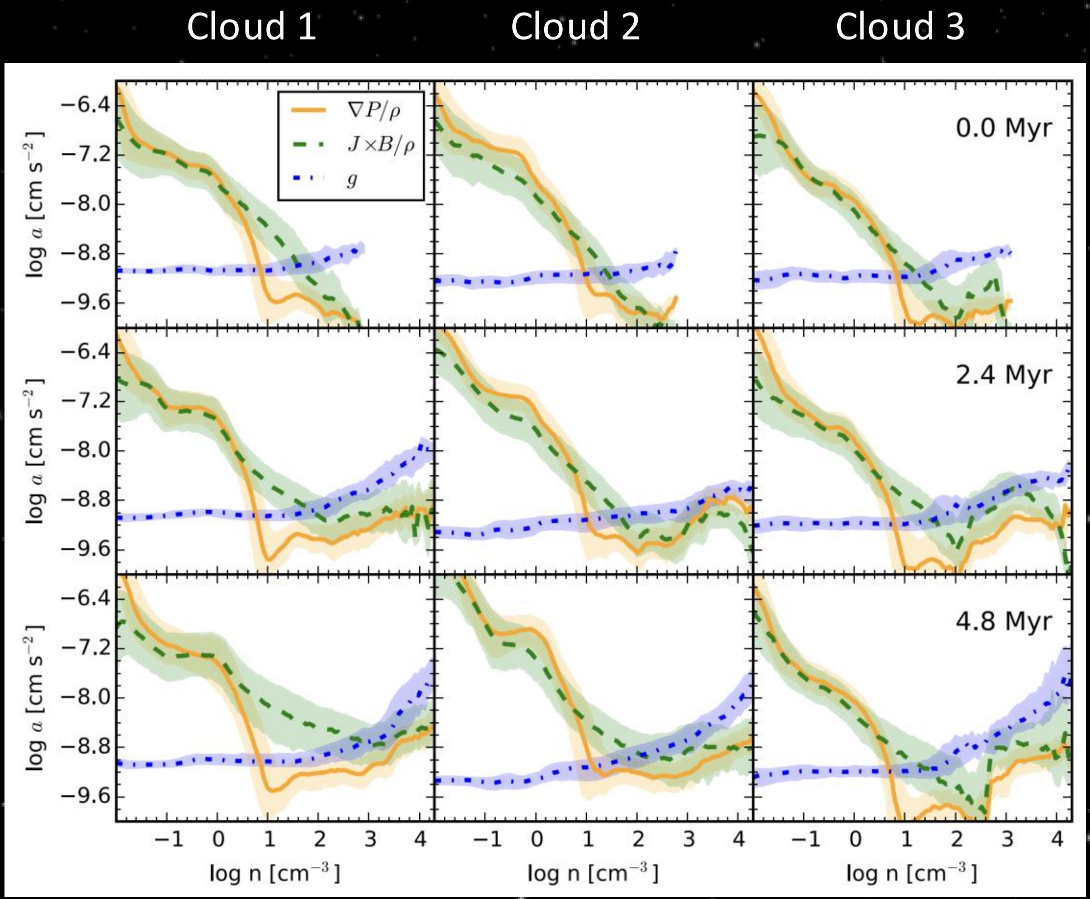


Are the clouds in some form of equilibrium of not?

Look at the forces of the three components:

Thermal
Magnetic fields
Gravity

Three regimes are seen:
Thermal+magnetic mix
Magnetic dominance
Gravity dominance



Formation

How do we convert diffuse gas into parsec-scale molecular gas? Does this depend on environment in the galaxy?

Evolution

Are clouds in quasi-equilibrium? Collapsing? Long-lived? Short-lived? What causes them to stop forming stars?

Molecular clouds

Star formation

Fee

Cores

Formation

How do we convert diffuse gas into parsec-scale molecular gas? Does this depend on environment in the galaxy?

Evolution

Clouds are highly dynamic with turbulence playing a major role. Magnetic fields act only at intermediate scales, while gravity dominate at higher densities, $n > 10^2\ cm^{-3}$

Molecular clouds

Fee

Star formation

Cores

Molecular clouds

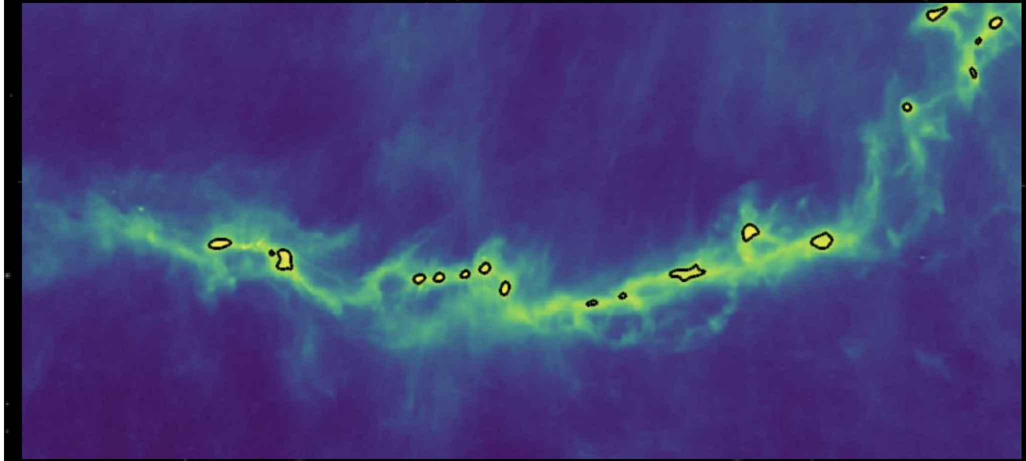
Fee

Star formation

Cores

Disks

1 pc



Credit: ESA/Herschel

Molecular clouds

Star formation

Filaments

Cores

How do filaments fragment into cores, and how does this impact core properties? Do cores keep accreting from the parent filament?

Disks

Multiplicity

Molecular clouds

Fee

Star formation

Filaments

How do filaments fragment into cores, and how does this impact core properties? Do cores keep accreting from the parent filament?

Cores

Disks

Multiplicity

What sets the number and masses of stars that form in a given core? Is this mostly driven by the cores or the larger environment

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **497,** 4390–4406 (2020) doi:10.1093/mnras/staa2298
Advance Access publication 2020 August 5

The hierarchical fragmentation of filaments and the role of sub-filaments

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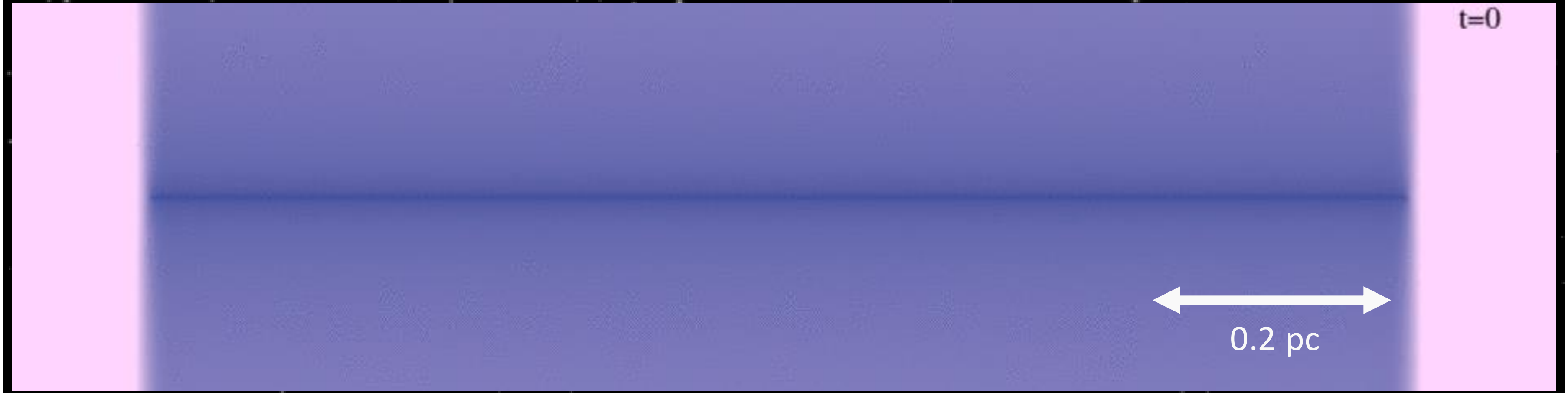
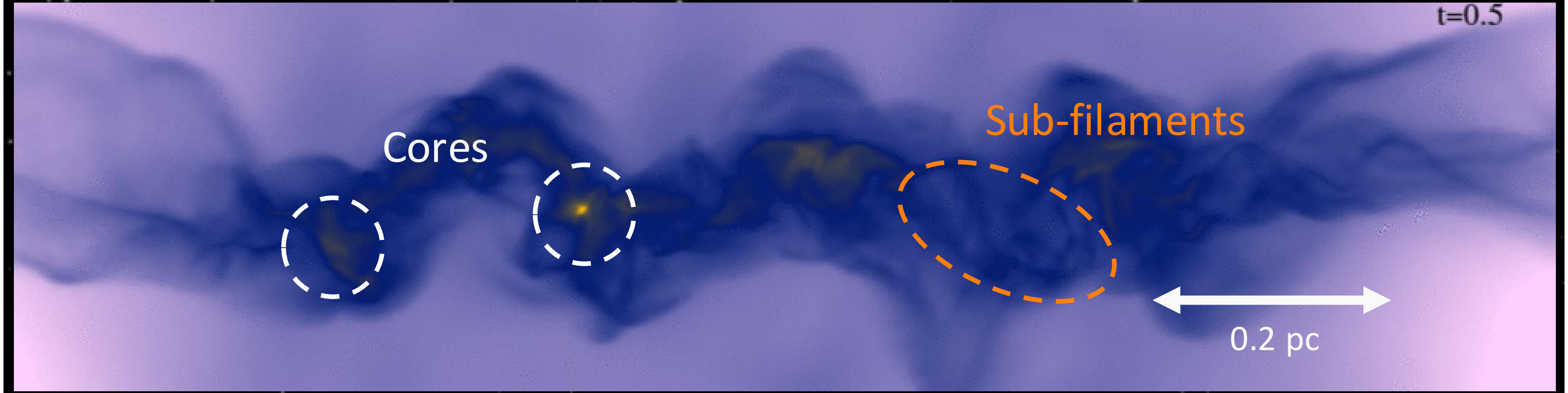
[1]*I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, D-50937 Köln, Germany*
[2]*Centre for Astrophysics Research, Department of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield Al10 9AB, UK*
[3]*Cologne Centre for Data and Simulation Science, University of Cologne, D-50937 Cologne, Germany*

Accepted 2020 July 29. Received 2020 July 28; in original form 2019 July 16



10x SPH simulations of individual filaments - 1 pc long

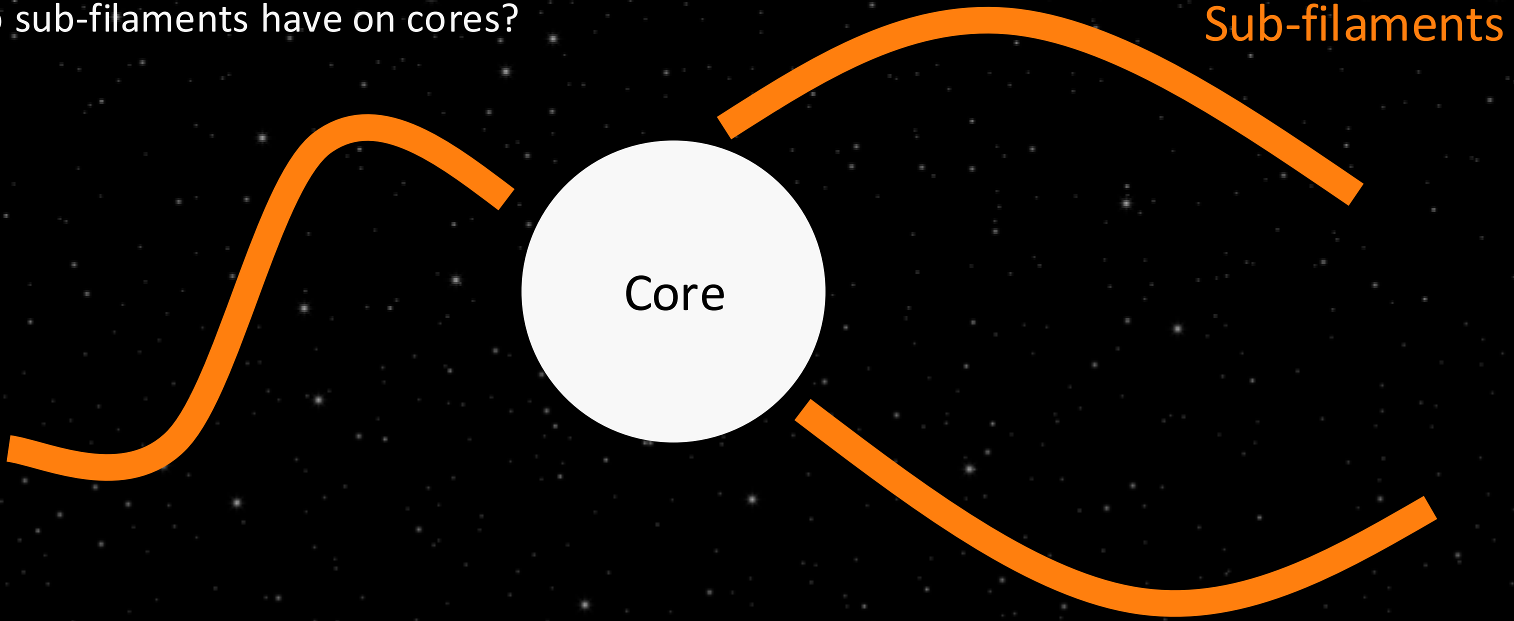


In each filament, cores and sub-filaments are formed simultaneously.

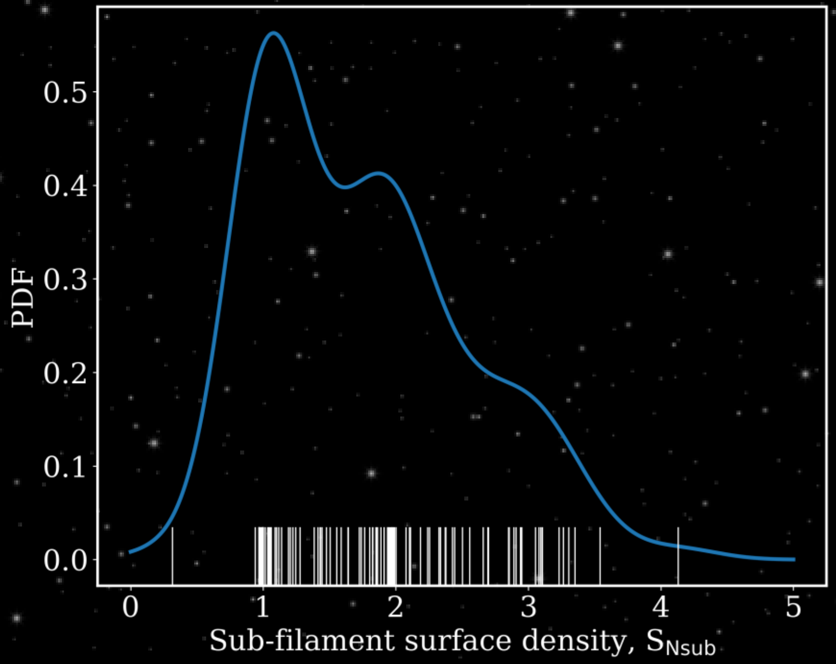
Both are initially formed due to turbulence in the filament, cores at locations with compressive flows, sub-filaments at locations with more vorticity.

How are the two structures connected? What impact do sub-filaments have on cores?

How are the two structures connected? What impact do sub-filaments have on cores?

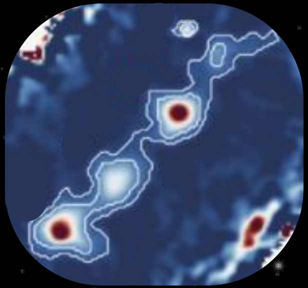


Counting the number of sub-filaments around cores, one can calculate a sub-filament surface density

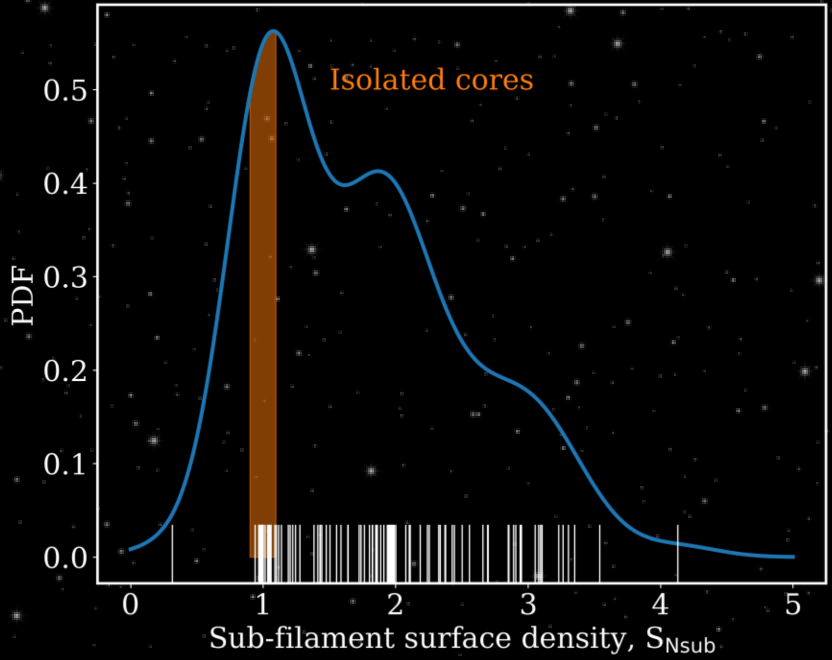


0.5
0.4
0.3
0.2
0.1
0.0
PDF
0
1
2
3
4
5
Sub-filament surface density, S_Nsub

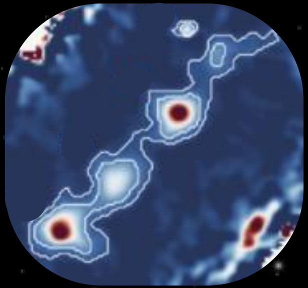
Single cores or small chains of cores are found to be "isolated"



Credit: Lee et al. (2020)



Single cores or small chains of cores are found to be “isolated”



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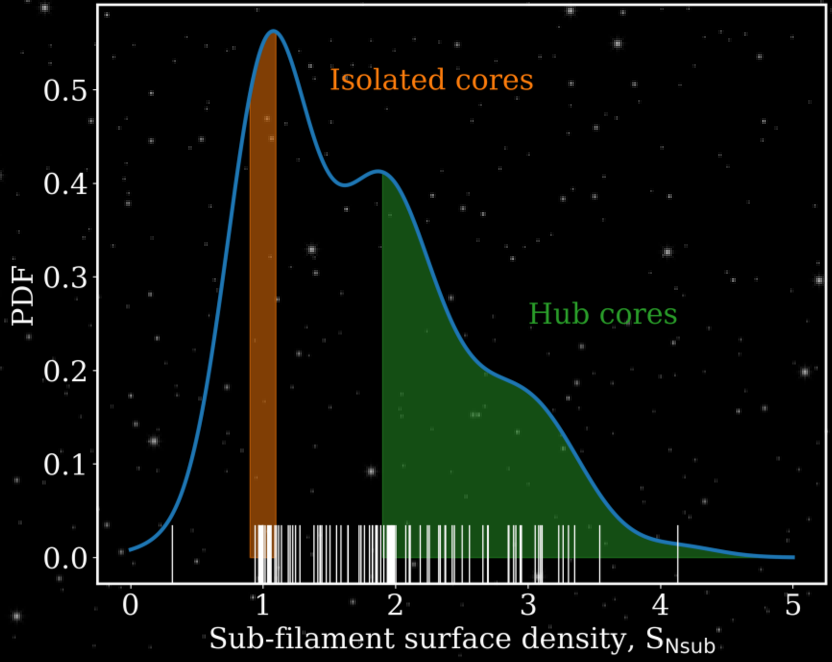
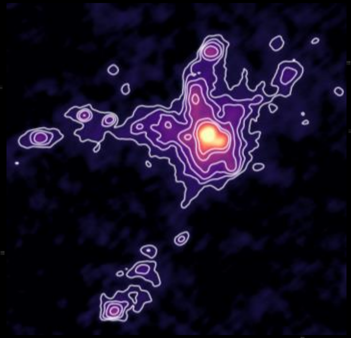
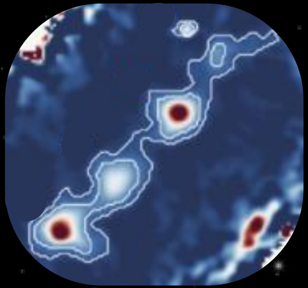


Small clusters of cores are often found in these “hubs”

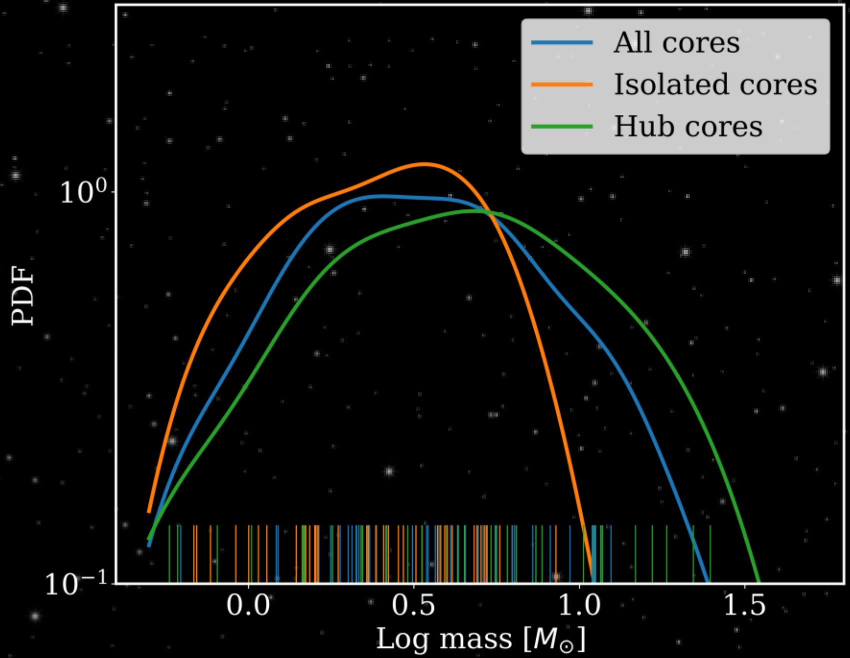


Clarke et al. (in prep.)

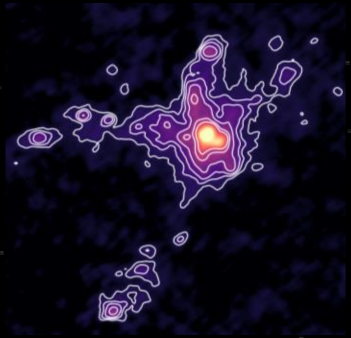
"Isolated" cores are typically only low-mass



Credit: Lee et al. (2020)



"Hub" cores are more massive, but with a wide range of masses



Clarke et al. (in prep.)

Molecular clouds

Fee

Filaments

Star formation

How do filaments fragment into cores, and how does this impact core properties? Do cores keep accreting from the parent filament?

Cores

Disks

Multiplicity

What sets the number and masses of stars that form in a given core? Is this mostly driven by the cores or the larger environment

Molecular clouds

Fee

Filaments

Star formation

Filament fragmentation is controlled by accretion-driven turbulence, with the connection between cores and sub-filaments affecting core properties

Cores

Disks

Multiplicity

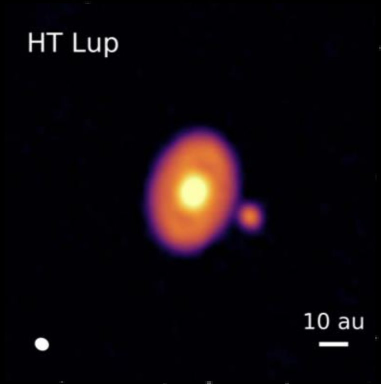
What sets the number and masses of stars that form in a given core? Is this mostly driven by the cores or the larger environment

Star formation

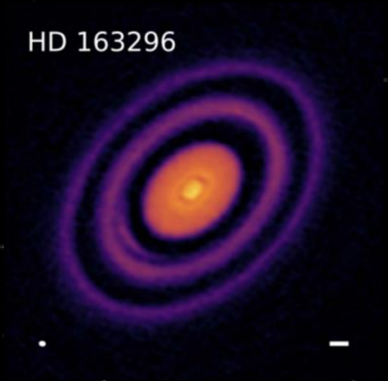
Cores

Astro-chemistry

Disks



Credit: Andrews et al. (2018)



Star formation

Cores

Astro-chemistry

Disks

Morphology

What determines a disk's mass and size? What causes the wide variety of sub-structures in disks and how is linked to planet formation?

Streamers

Star formation

Cores

Astro-chemistry

Disks

Morphology

What determines a disk's mass and size? What causes the wide variety of sub-structures in disks and how is linked to planet formation?

Streamers

Do disks accrete predominately via streamers? Or are they mostly chemical/density/temperature enhancements?

cular
ds

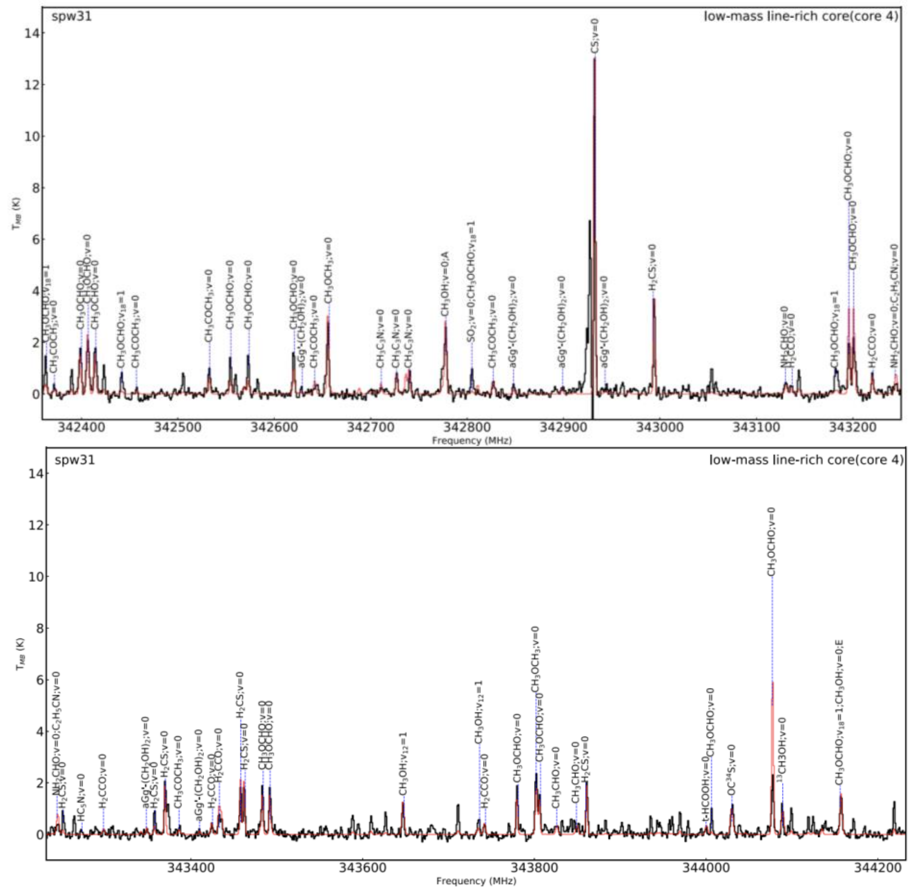
Feedback

Credit: Liu et al. (2023)

Star formation

Astro-chemistry

Disks



Star formation

Astro-chemistry

COMs

When do complex organic molecules form? What level of complexity of the molecules can be reached and at what scale?

Disks

Conditions

Feedback

ular
ds

Feedback

Star formation

Astro-chemistry

Disks

COMs

When do complex organic molecules form? What level of complexity of the molecules can be reached and at what scale?

Conditions

What can we tell about the physical conditions from the different molecules we observe? Are these universal or environment dependent?

cular
ds

40 pc

Credit:ESA/Herschel

Feedback

Star
formation

Astro-
chemistry

Dominance

Which feedback mechanism is the dominate mode of dispersal at each scale? Is this environment dependent?

Triggered star formation

cular ds

Feedback

Star formation

Astro-chemistry

cular
ds

Feedback

Star
formation

Astro-
chemistry

Dominance

Which feedback mechanism is the dominate mode of dispersal at each scale? Is this environment dependent?

Triggered star formation

Can feedback trigger new star formation to occur? Does it mostly just shift where star formation happens? Or does it have a purely damping effect?

Monthly Notices
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MNRAS **478,** 4799–4815 (2018)
Advance Access publication 2018 May 25

doi:10.1093/mnras/sty1315

The relative impact of photoionizing radiation and stellar winds on different environments

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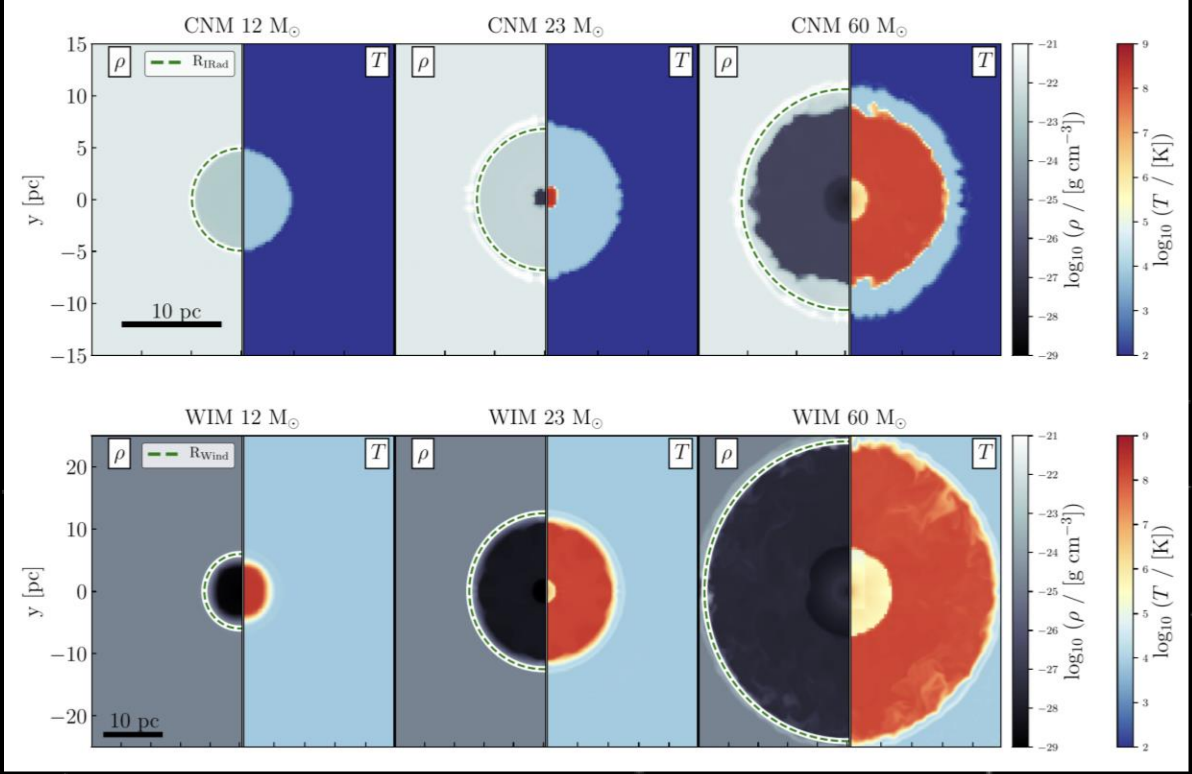
[1]*I. Physikalisches Institut, Universität zu Köln, Zülpicher-Strasse 77, 50937 Cologne, D-Germany*
[2]*Astronomický Ústav, Akademie vd Žcesky Republiky, BoŽcní II 1401, CZ-14131 Praha, Czech Republic*
[3]*Max-Planck-Insitut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741 Garching, Germany*

Accepted 2018 May 8. Received 2018 April 27; in original form 2017 October 20

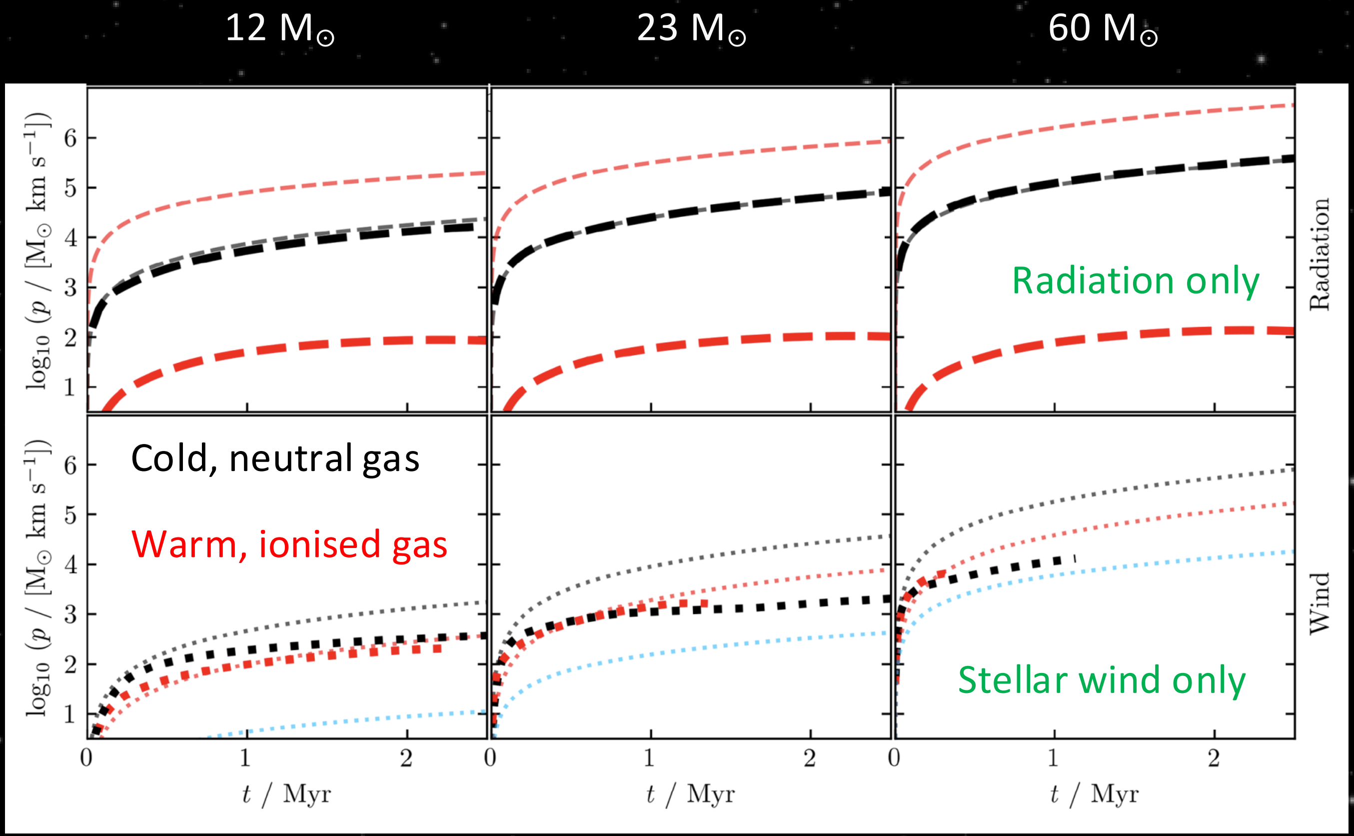
Cold neutral medium
(inside a molecular cloud)

Warm ionised medium
(outside a molecular cloud)



Radiation is imparts far less momentum in warm, ionised gas

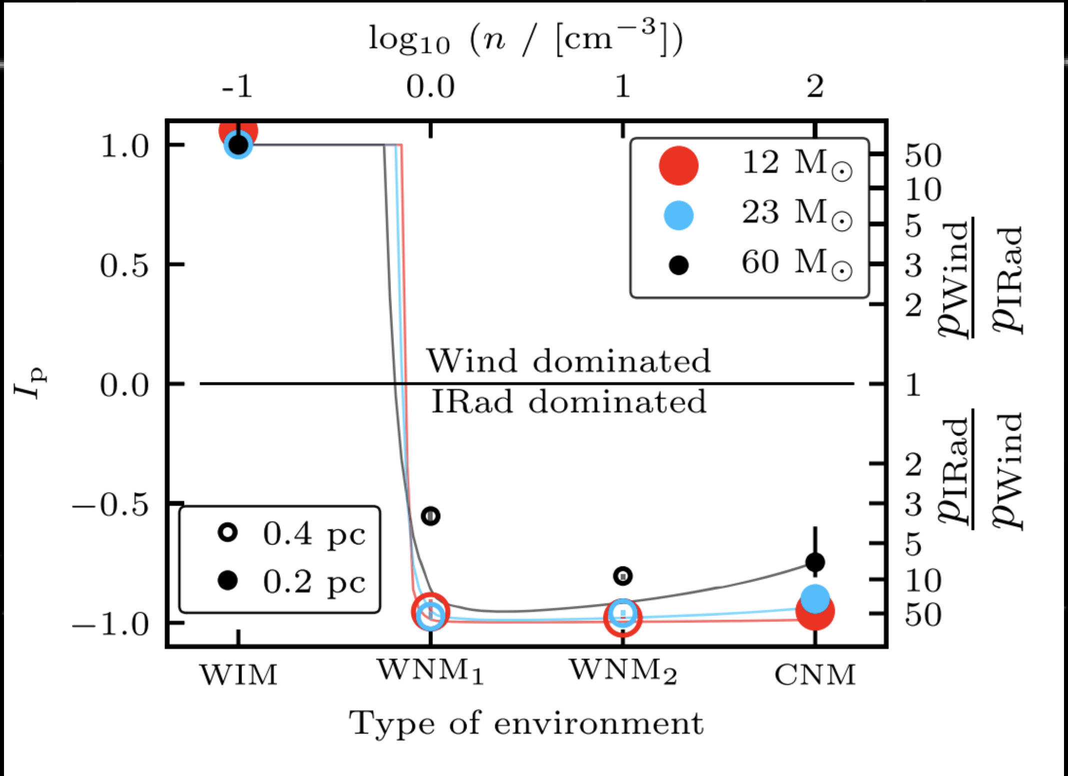
Wind imparted momentum is less sensitive to environment



Therefore, there is an environmental dependence on the importance of the feedback

In **neutral media,** radiation dominates the momentum injection

In **ionised media**, winds dominate instead



Dominance

Which feedback mechanism is the dominate mode of dispersal at each scale? Is this environment dependent?

Triggered star formation

Can feedback trigger new star formation to occur? Does it mostly just shift where star formation happens? Or does it have a purely damping effect?

cular
ds

Feedback

Star formation

Astro-
chemistry

Dominance

The coupling between feedback and its energy/momentum injection is environment dependent, as so dominance varies

Triggered star formation

Can feedback trigger new star formation to occur? Does it mostly just shift where star formation happens? Or does it have a purely damping effect?

cular
ds

Feedback

Star formation

Astro-
chemistry

Molecular clouds

Feedback

Star formation

Cores

Astro-chemistry

Disks

Conclusions

Star formation is an extremely complex problem due to the physics involved and the scales which need to be covered

We have a well established set of tools to tackle the issue, on both the theoretical side and the observational side

But there are still many, many major questions left to answer across the field

There are a lot of exciting theoretical results tackling these questions, with a lot more still to do.