THE GALACTIC ENVIRONMENT AND ITS CONNECTION TO THE ISM

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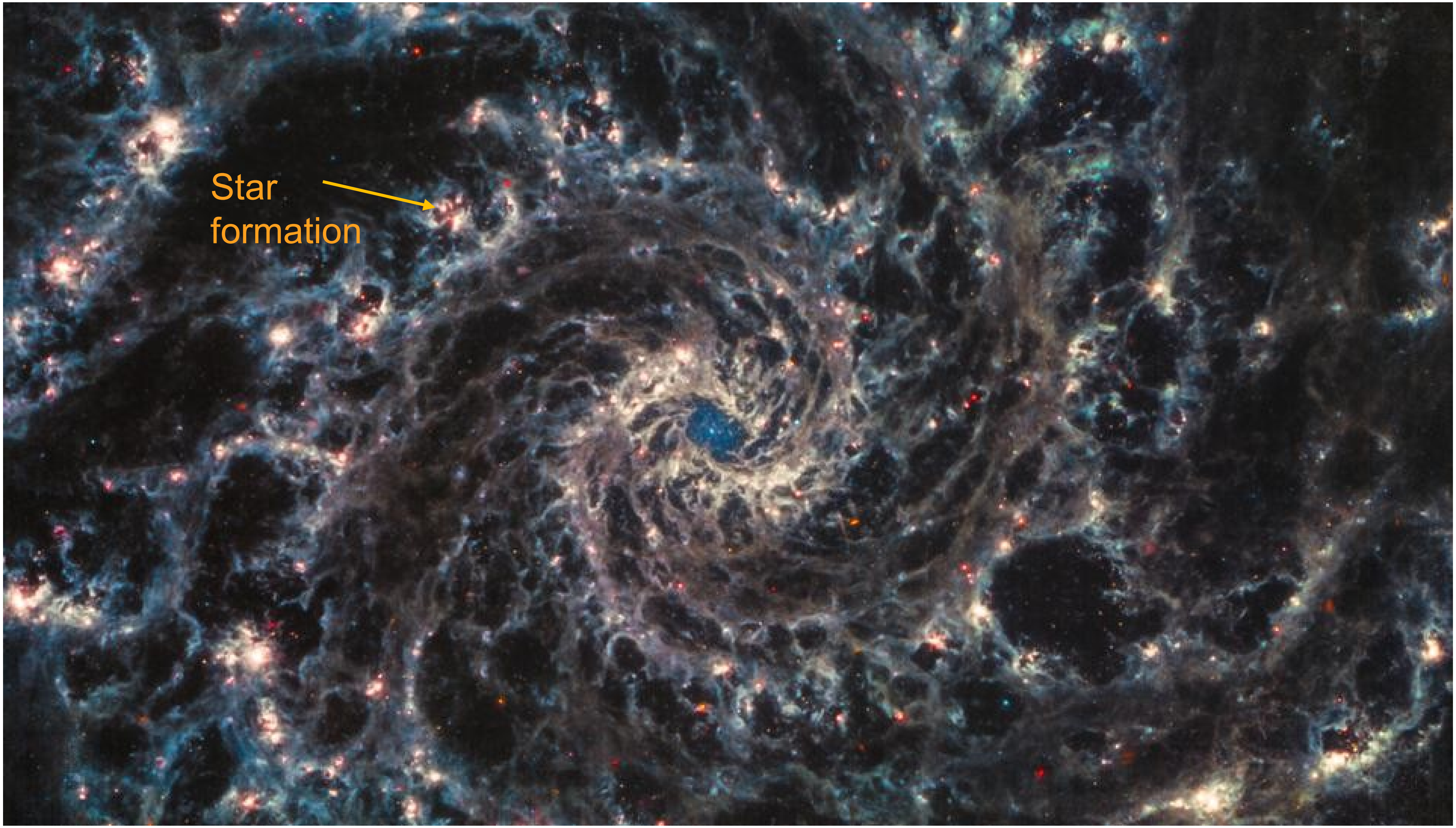
Outline

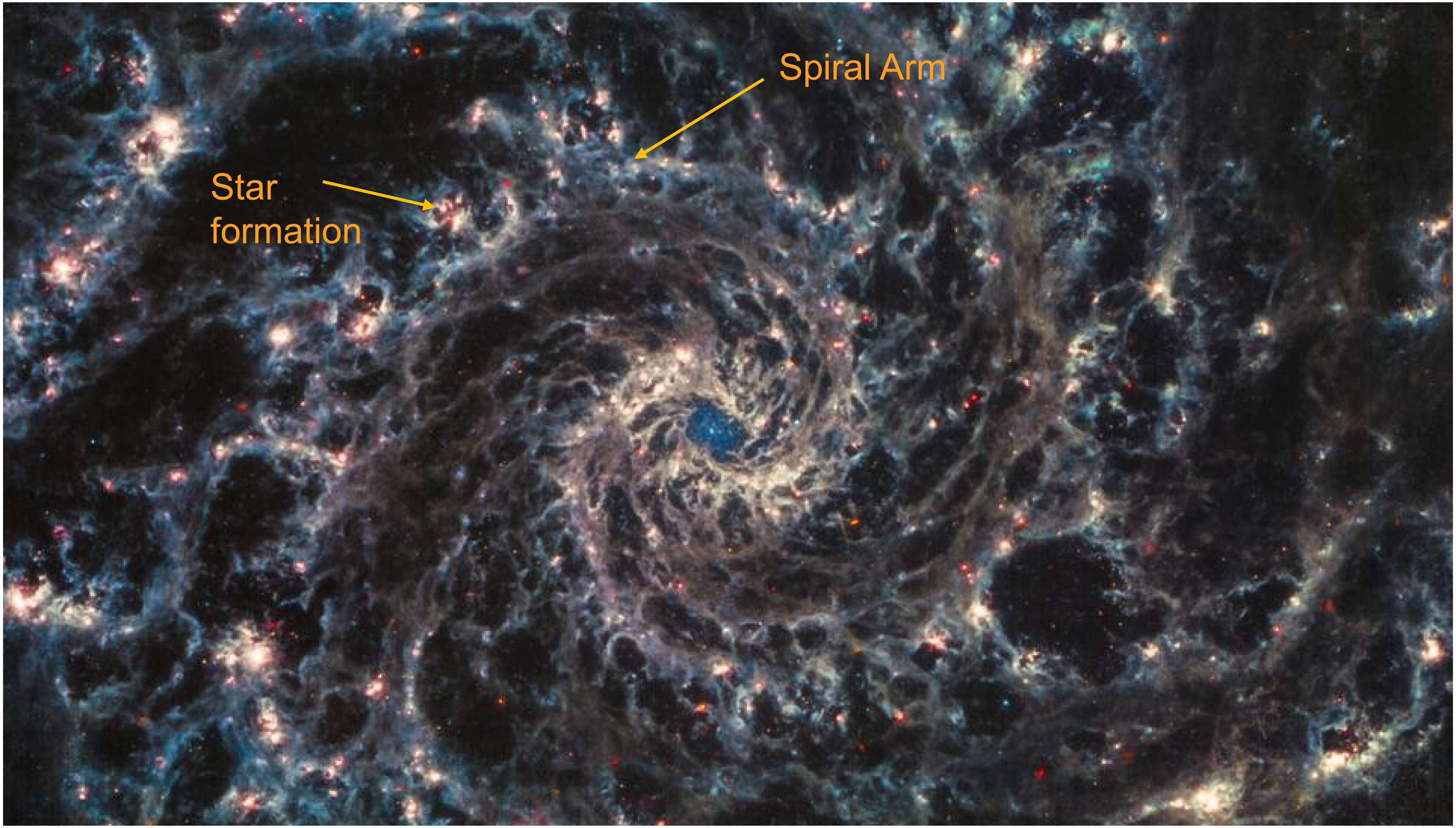
1. An Illustrative Example
2. Environments in the Milky Way
3. Forming Molecular clouds
4. Connecting the scales with filaments

Motivation

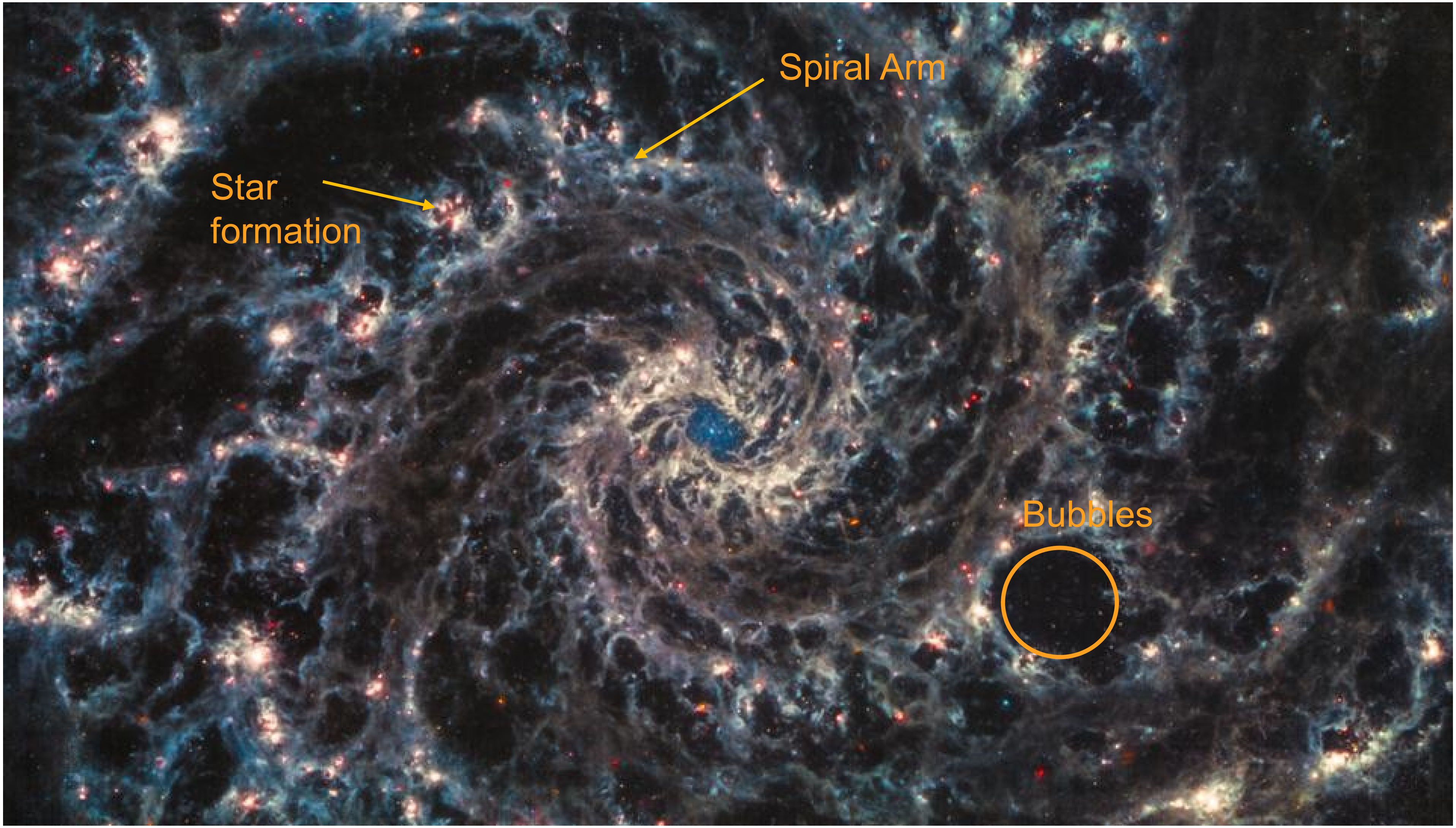
An example



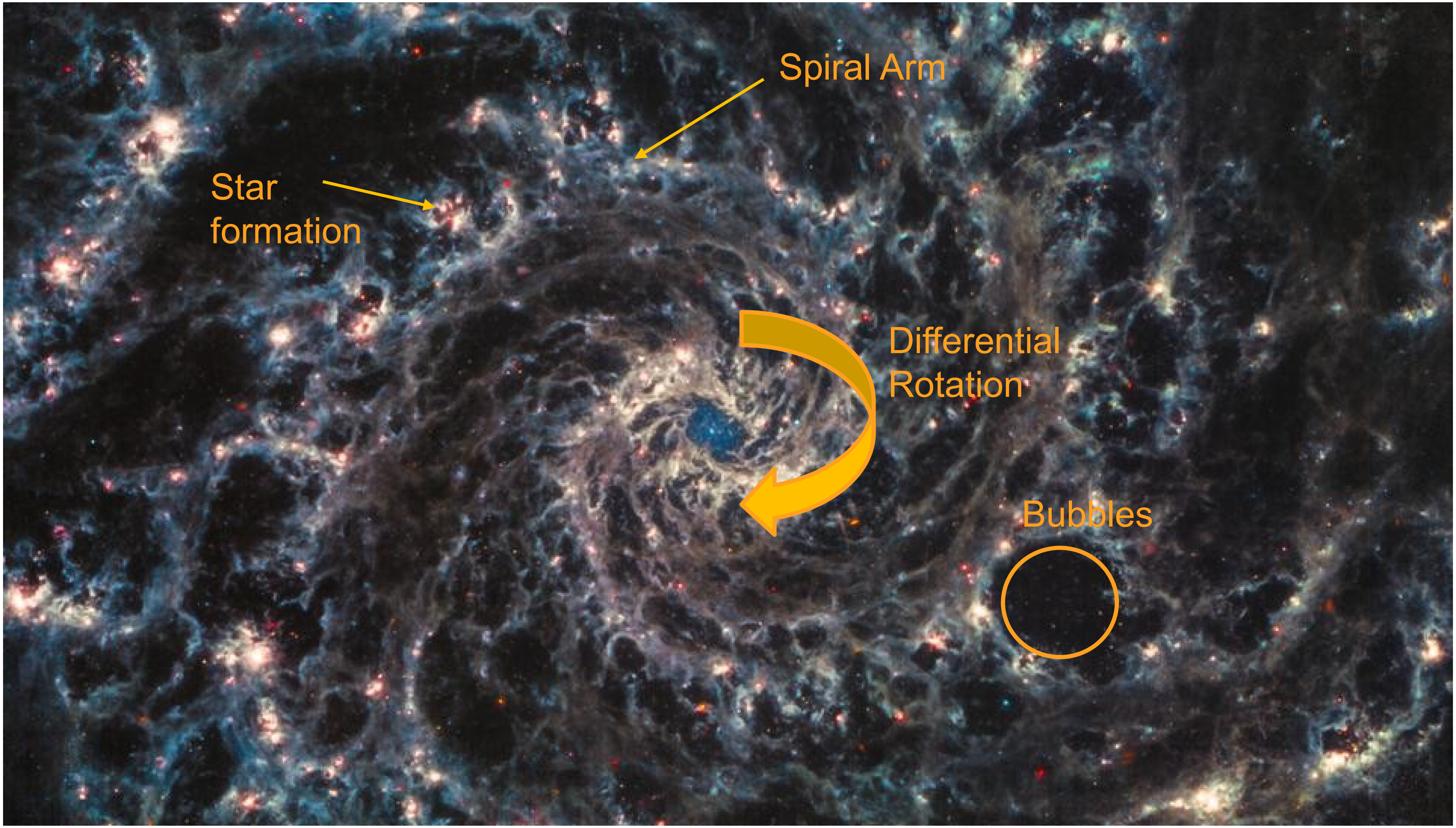
An example



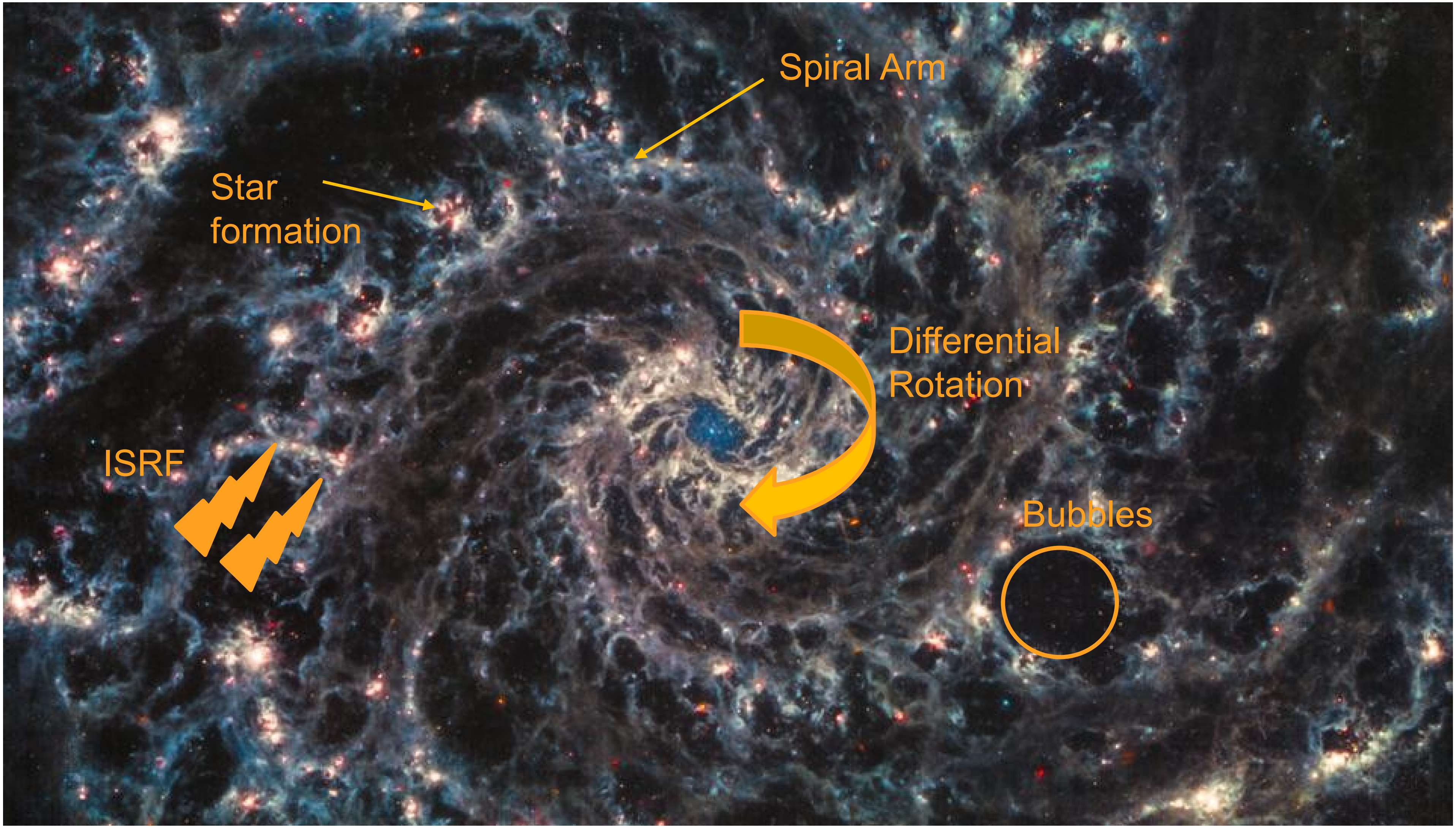
An example



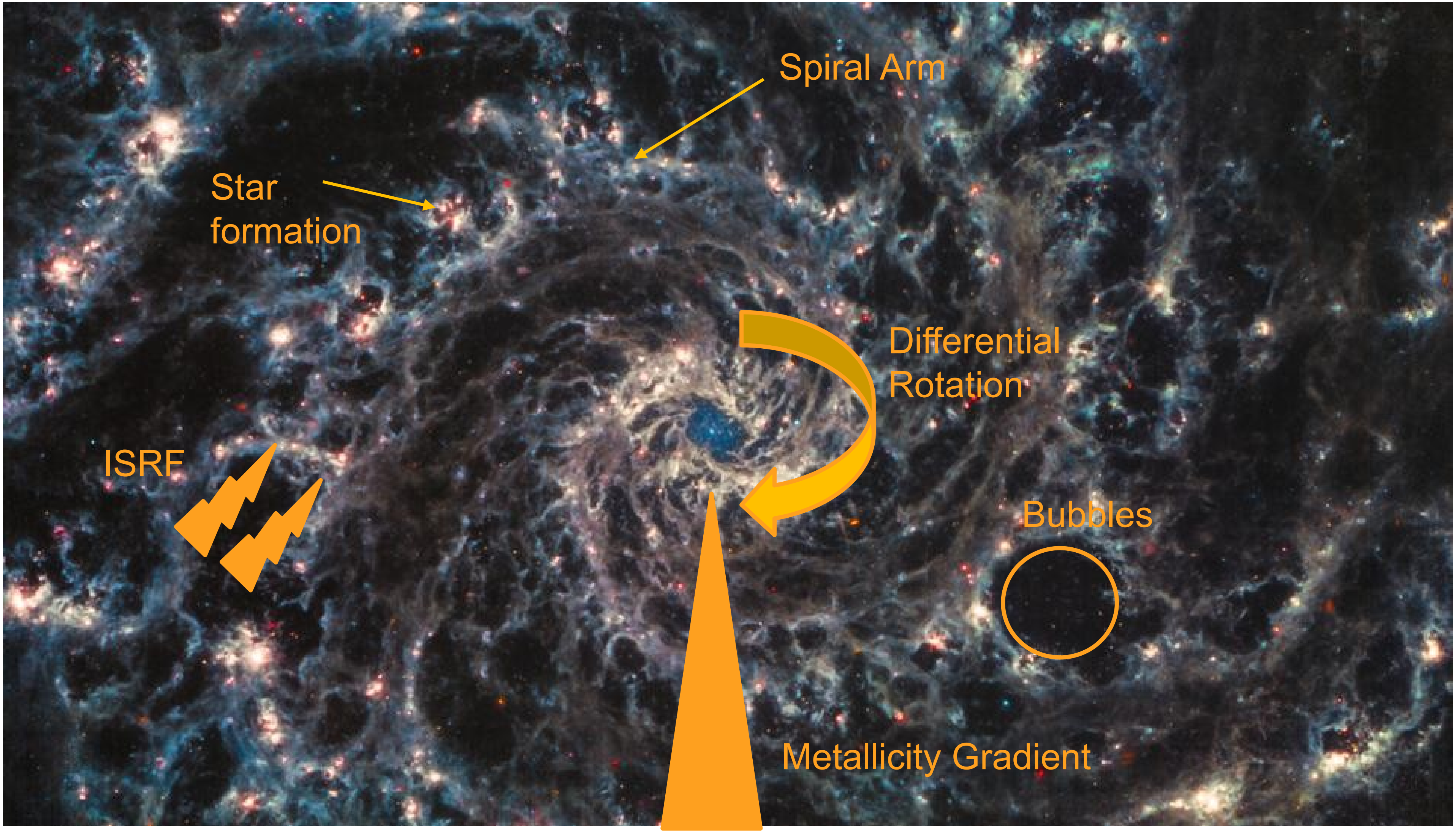
An example



An example

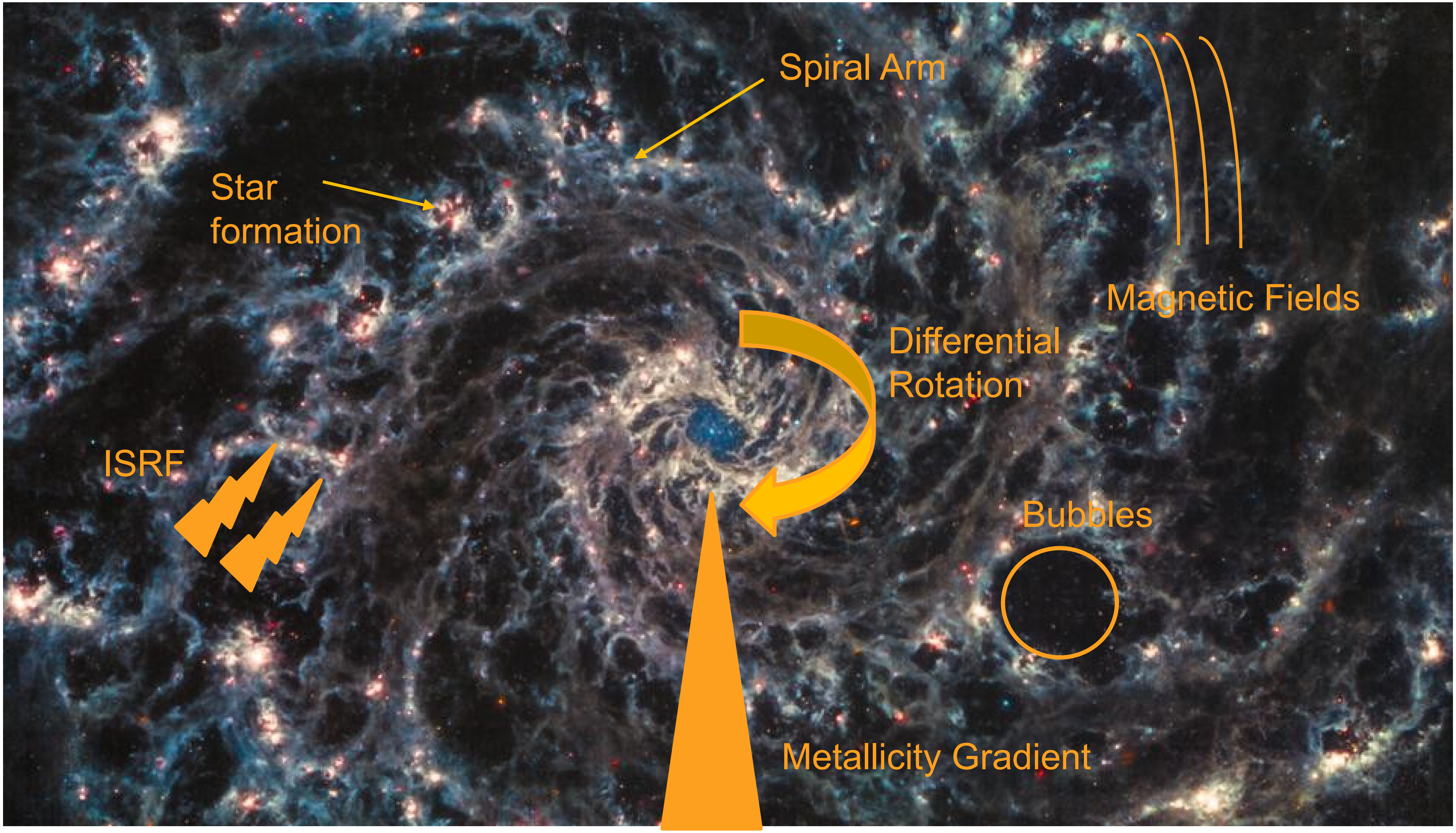

Spiral Arm
Star formation
Differential Rotation
ISRF
Bubbles

An example



Spiral Arm
Star formation
Differential Rotation
ISRF
Bubbles
Metallicity Gradient

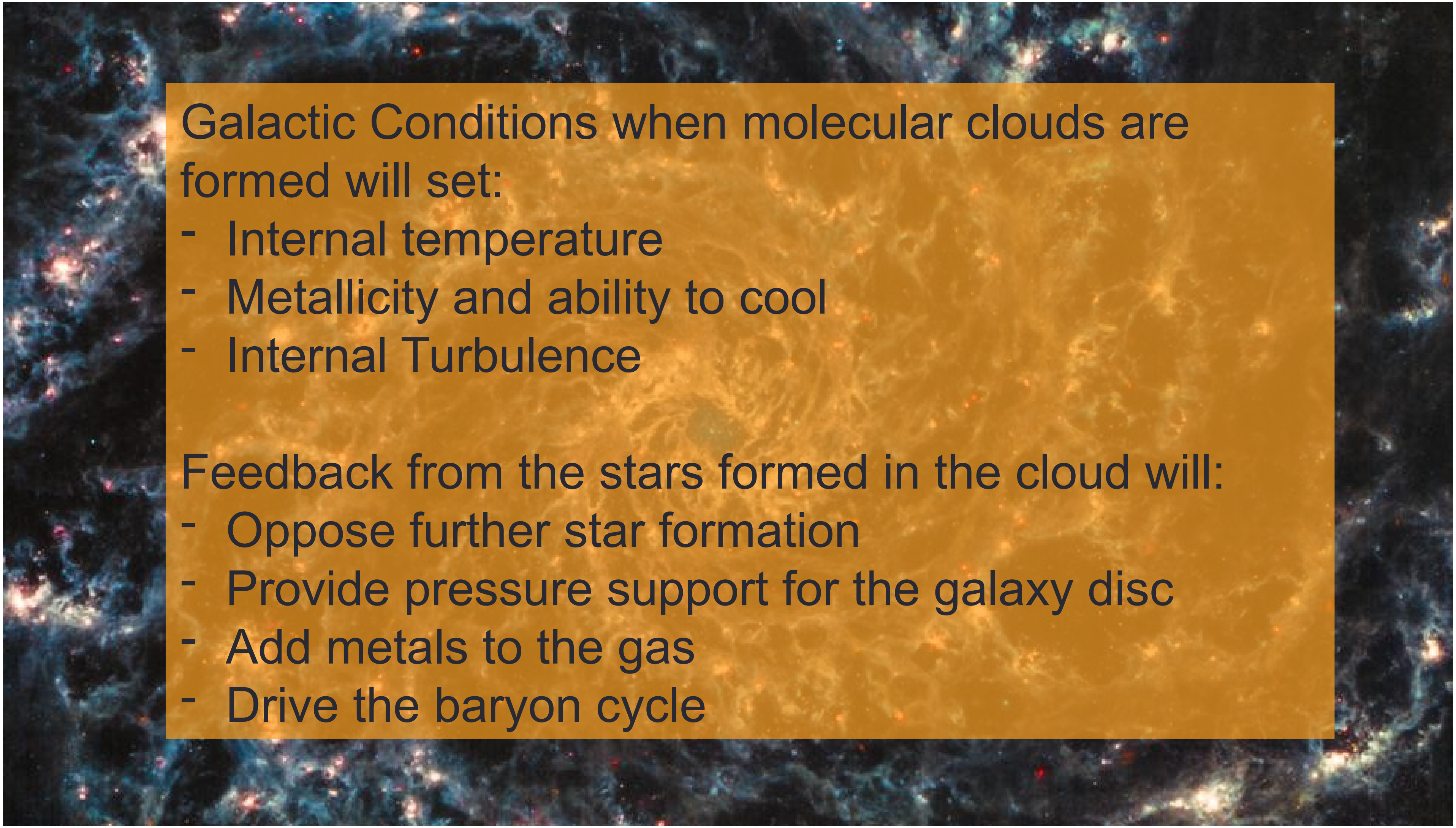
An example


Spiral Arm
Star formation
Magnetic Fields
Differential Rotation
ISRF
Bubbles
Metallicity Gradient

Aims of this lecture

- To investigate how different galactic environments affect the ISM and star formation.
- For details of how feedback from stars affect their surrounding see lecture by Melanie Chevance.
- For more on star formation within clouds see the lecture by Steffanie Walsch.

An example



Galactic Conditions when molecular clouds are formed will set:

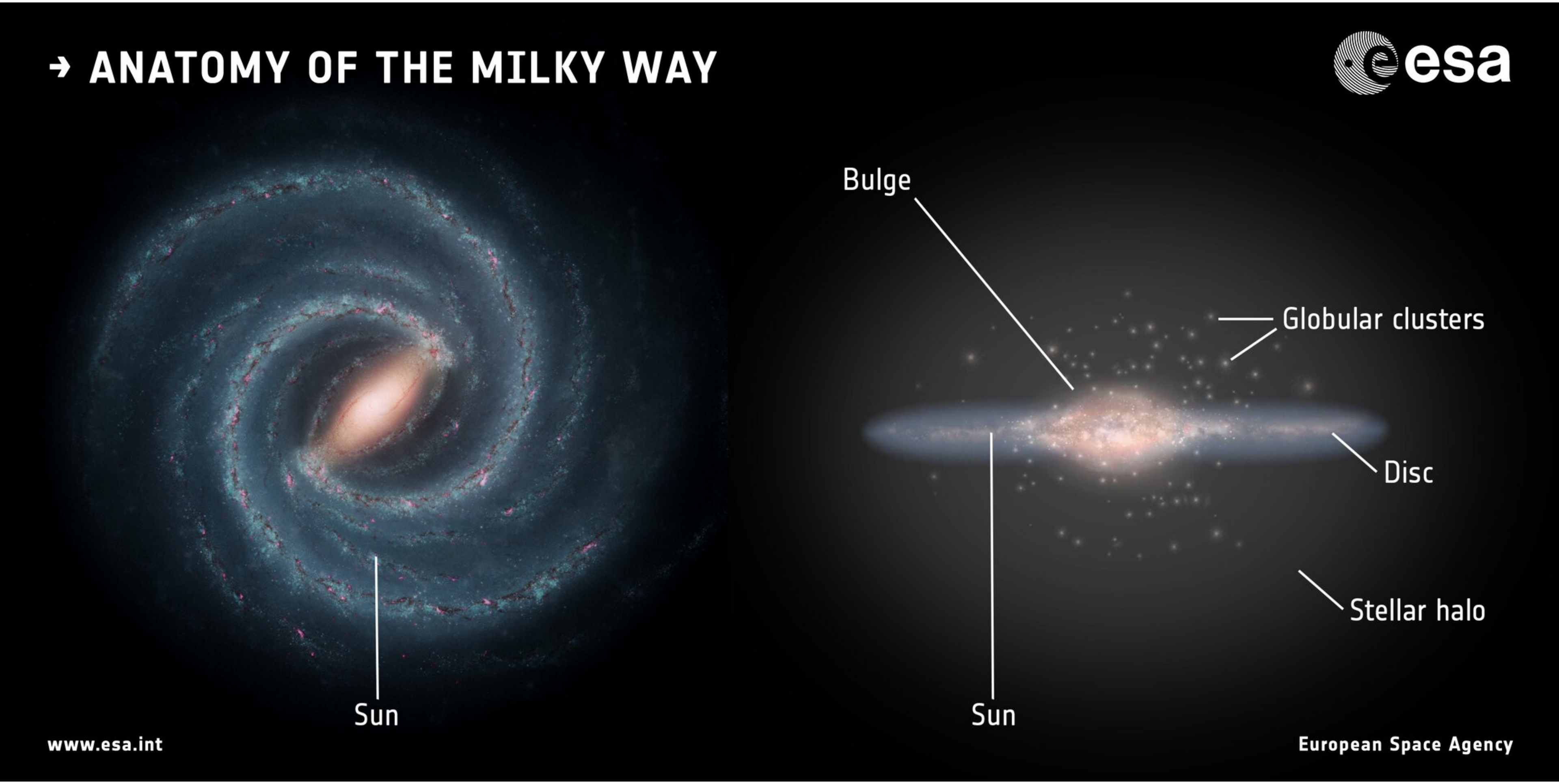
- Internal temperature
- Metallicity and ability to cool
- Internal Turbulence

Feedback from the stars formed in the cloud will:

- Oppose further star formation
- Provide pressure support for the galaxy disc
- Add metals to the gas
- Drive the baryon cycle

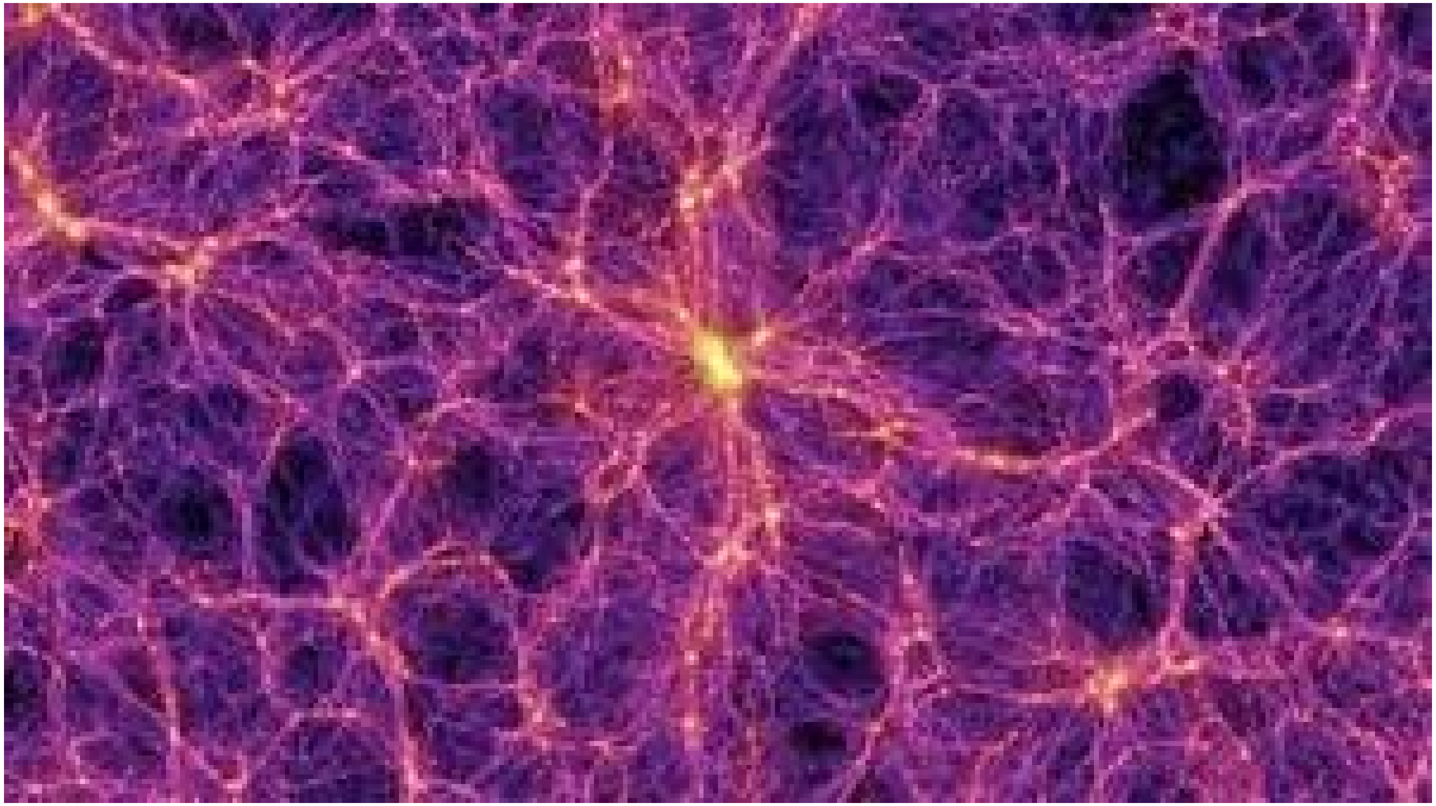
Environments in the Milky Way

Schematic of our galaxy



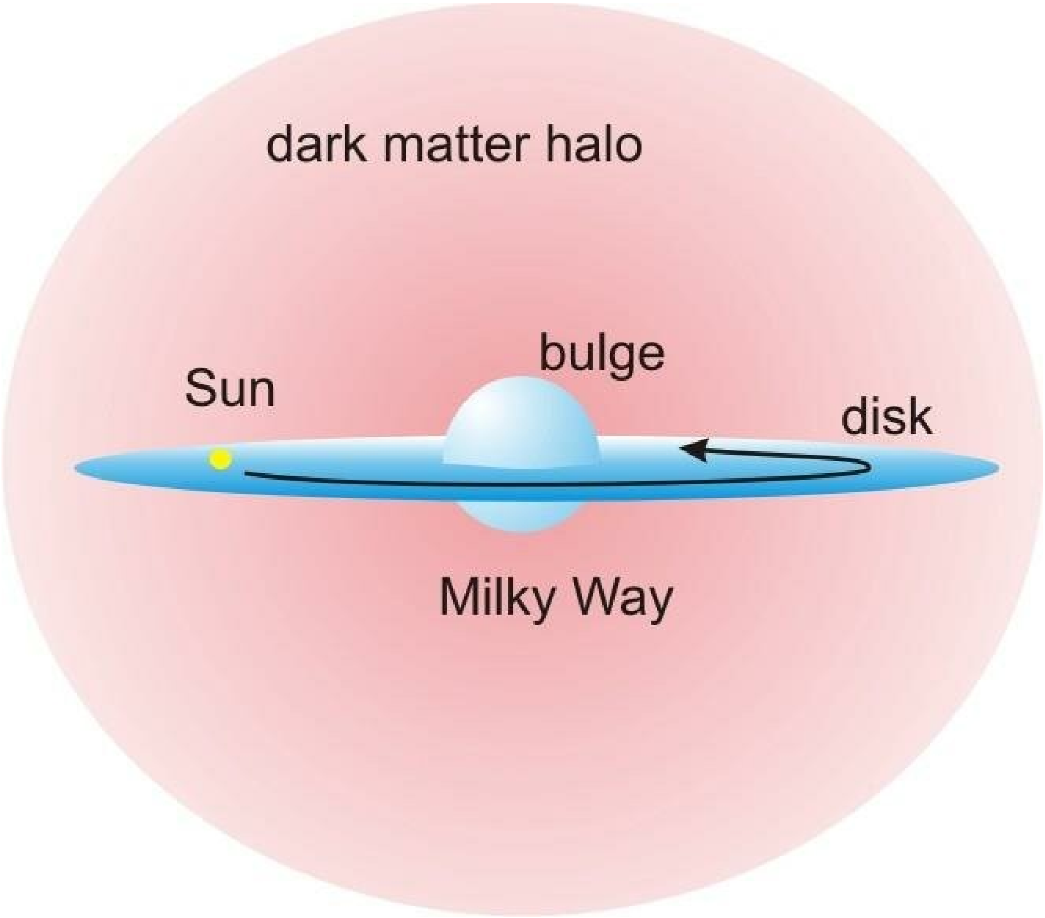
For this lecture we will focus on the Milky Way

The cosmic web



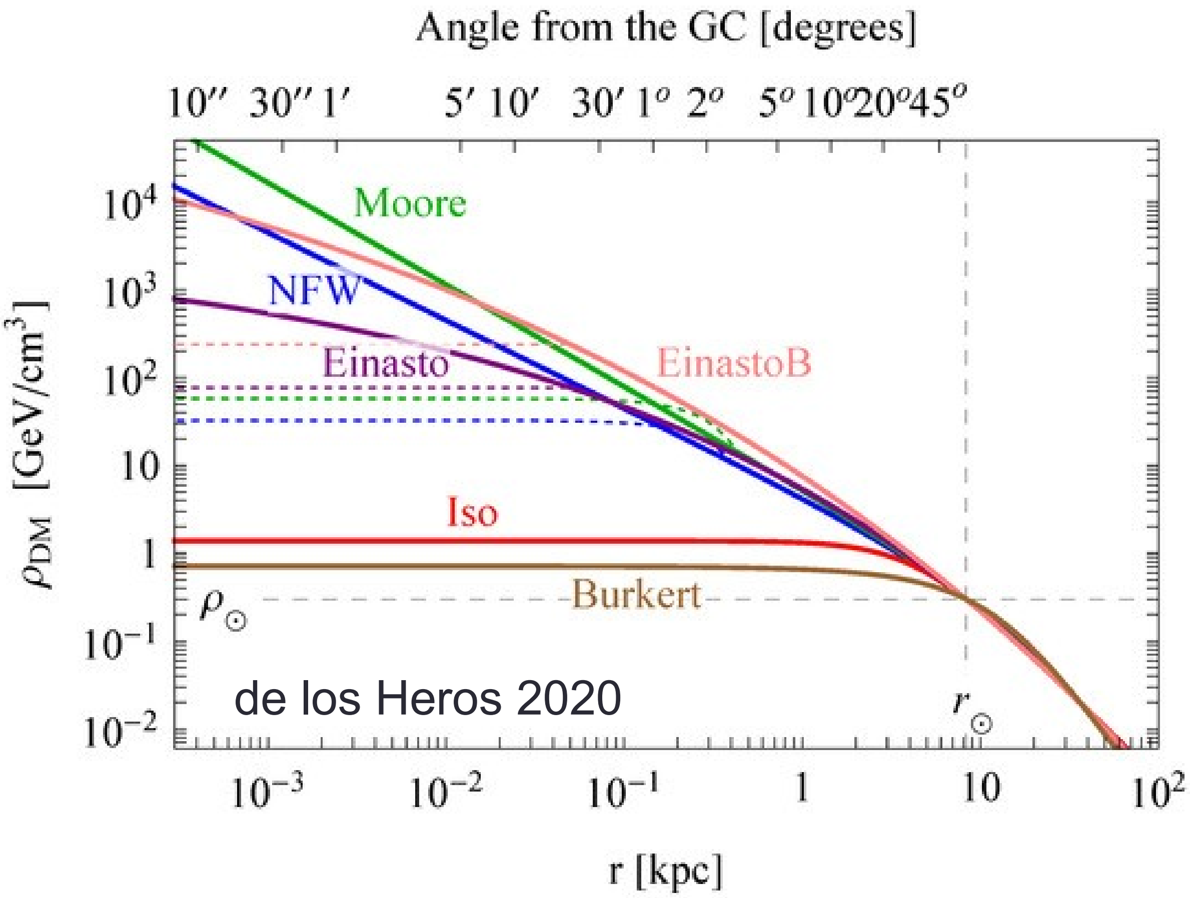
Credit: Virgo consortium

Dark matter halo



Controls the potential well in which the gas sits

Dark matter halo



de los Heros 2020

NFW profile

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

General profile

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^{\gamma} \cdot \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

Recent Gaia results suggest more complex structure

- sub-structure
- galaxy history matters

Bulge

Old stars at the centre of the galaxy.
With a quasi-spherical distribution.

- Classical bulge
  - no star formation
  - old Pop II stars
  - random orbits due to collisions

- Pseudo-bulge
  - ordered rotation
  - correlated with spiral arms
  - can have star formation

$$\rho_b = \frac{\rho_{b0}}{(1 + a/a_0)^{\alpha}} \exp\left[-(a/a_{\mathrm{cut}})^2\right]$$

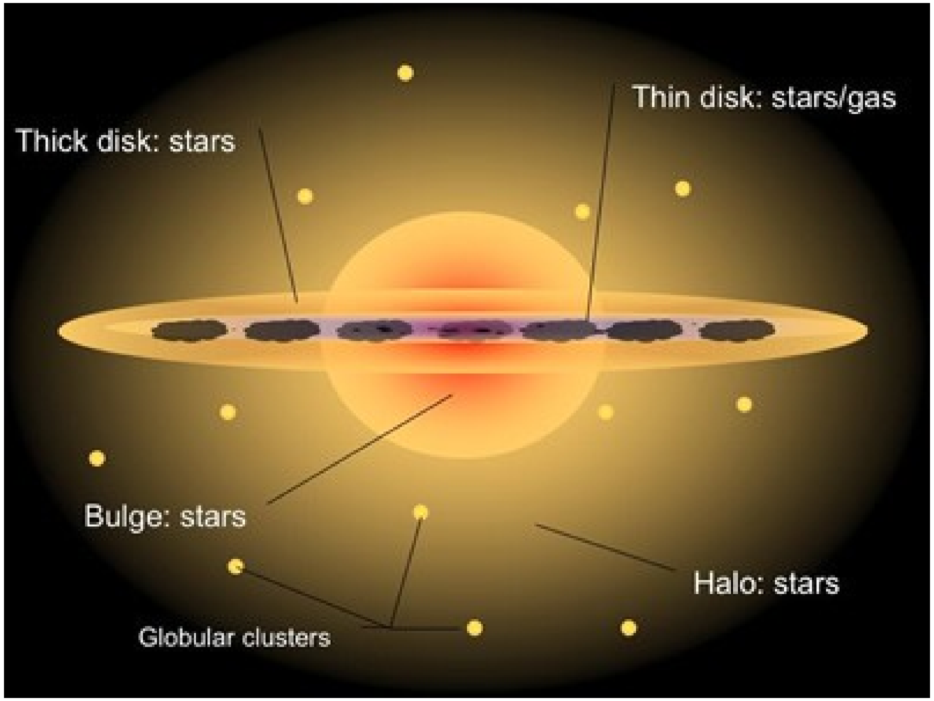
where

$$a = \sqrt{x^2 + y^2 + \frac{z^2}{q_b^2}},$$

Mc Millan 2017

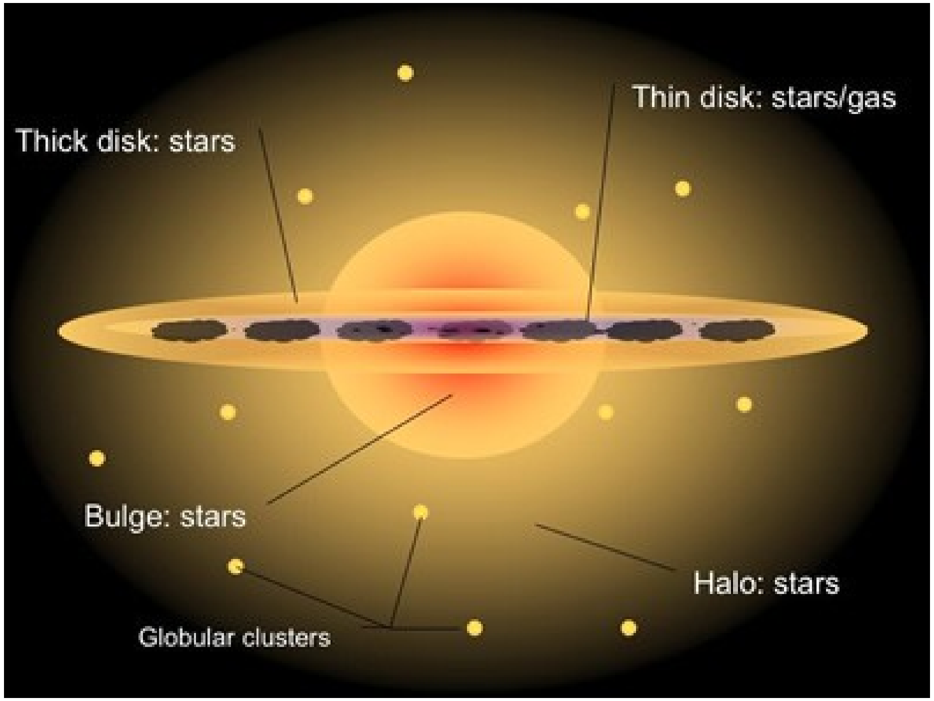
Thick disc

- Contains about 10% of stellar mass
- Scale height ~ 1kpc
- Stars older 10 Gyr and more metal poor
- Kinematically and chemically distinct from the thin disc



Thin disc

- About 85% of the stars
- Scale height of 300-400 pc
- Multiple age populations, all younger than the thick disc
- Thin disc formed ~9 Gyr ago



$$\rho_d = \frac{\Sigma_1}{2z_1}\exp\left(-\frac{|z|}{z_1} - \frac{R}{R_{d1}}\right) + \frac{\Sigma_2}{2z_2}\exp\left(-\frac{|z|}{z_2} - \frac{R}{R_{d2}}\right), \qquad (3)$$

where $R = \sqrt{x^2 + y^2}$ is the cylindrical radius, $\Sigma_1 = 896 M_\odot\,\mathrm{kpc}^{-2}$, $R_{d1} = 2.5\,\mathrm{kpc}$, $z_1 = 0.3\,\mathrm{kpc}$, $\Sigma_2 = 183 M_\odot\,\mathrm{kpc}^{-2}$, $R_{d2} = 3.02\,\mathrm{kpc}$, and $z_2 = 0.9\,\mathrm{kpc}$.

Gilmore & Reid 1983

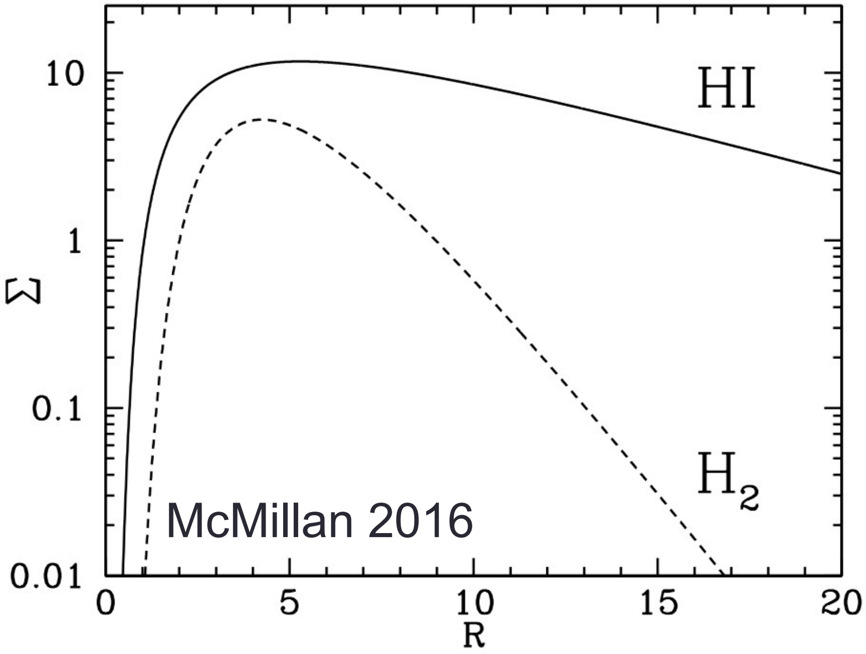
Gas discs

$$\rho_{\mathrm{d}}(R,z) = \frac{\Sigma_0}{4z_{\mathrm{d}}} \exp\left(-\frac{R_{\mathrm{m}}}{R} - \frac{R}{R_{\mathrm{d}}}\right) \operatorname{sech}^2(z/2z_{\mathrm{d}}),$$

Disc	R_{d}	R_{m} (kpc)	z_{d}	Σ_0 ($\mathrm{M}_\odot\,\mathrm{pc}^{-2}$)	$\Sigma_\odot$	M ($\mathrm{M}_\odot$)
H I	7	4	0.085	53.1	10	1.1×10^{10}
H_2	1.5	12	0.045	2180	2	1.2×10^{9}

Sum of these potentials causes the gas to follow a disc distribution.

- Thicker HI disc with scale height ~100 pc
- Thinner H_2 disc with scale height ~50 pc
- Imparts a maximum size on the vertical extent of clouds



McMillan 2016

Toomre stability

Stability of gas in a disc is determined by the Toomre criteria

In differentially rotating disc the dispersion of perturbations is

$$\omega^2 = \kappa^2 - 2\pi G\Sigma|k| + k^2 v_{\mathrm{s}}\,,$$

where the epicyclic frequency (the frequency at which a radially displaced fluid parcel will oscillate) is

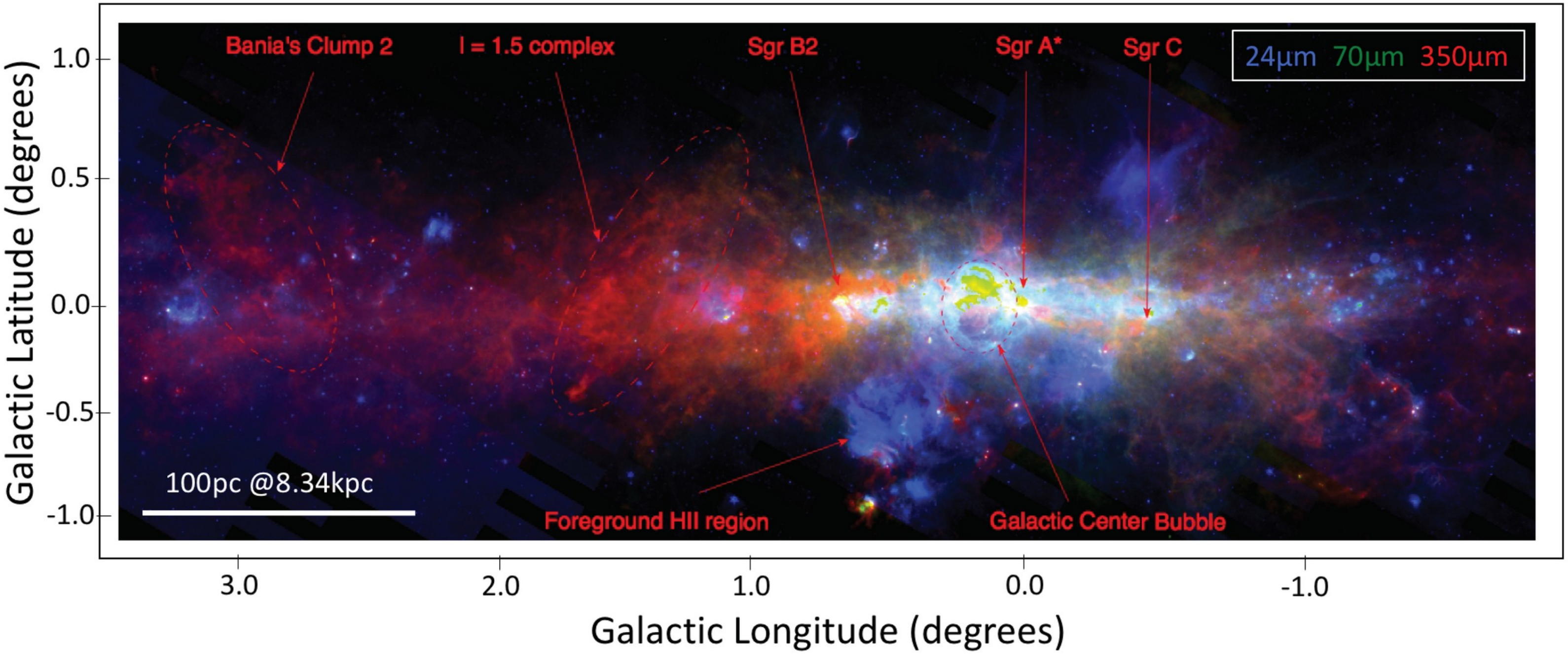
$$\kappa = \sqrt{R\frac{d\Omega^2}{dR} + 4\Omega^2}\,,$$

For a perturbation $f_1(\mathbf{r},\mathbf{v},t) = g(\mathbf{v})e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}\,,$ id $\omega^2<0$ then perturbation grows

This implies that for stability $Q_{\mathrm{gas}} \equiv \frac{\kappa v_{\mathrm{s}}}{\pi G\Sigma} > 1\,,$

In the solar neighbourhood Q~1 – **moderately stable** but this is a self-fulfilling prophecy

Galactic Centre



Contains SgrA* but also the **Central Molecular Zone**

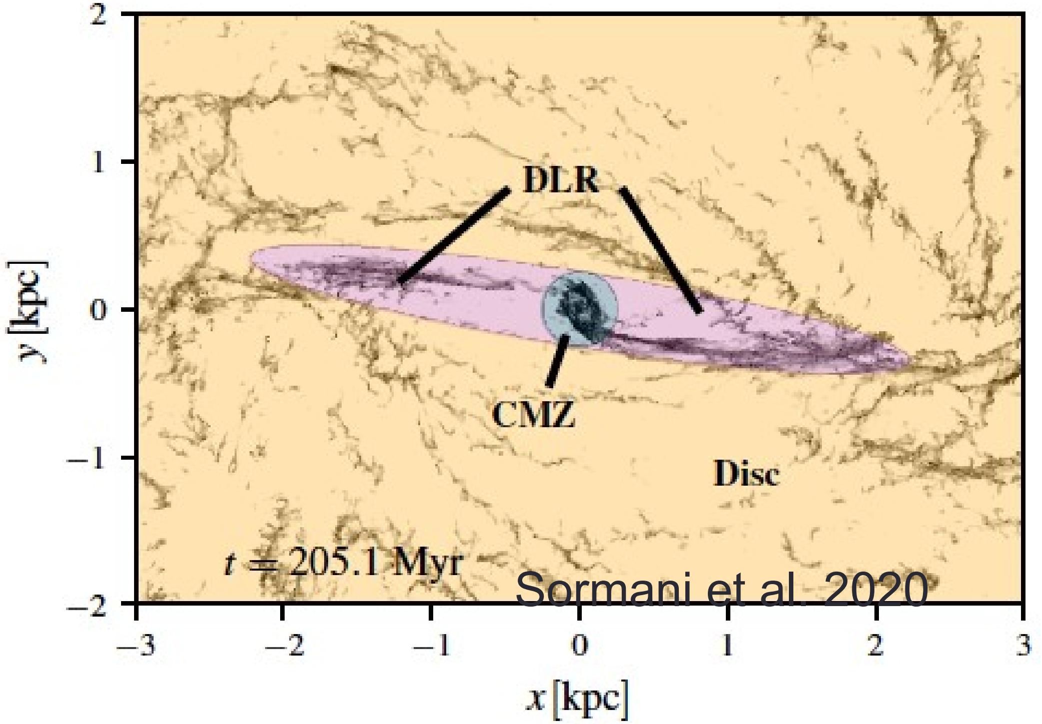
- 5% of total molecular gas reservoir within 600 pc of centre
- Surface density 100 times higher than disc similar to ULIRGS ($n>10^4$ cm^{-3})
- Warm gas 70-100K in GMCs
- Highly turbulent, line widths (10-100 km/s)
- Higher (~100*) UV field and cosmic ray ionization rate

CMZ

- Most star formation at R>100 pc

- Rate 0.1 Msol/yr roughly constant over 5 Myr – variation expected from other galaxies.

- Much lower than expected purely from density.



Sormani et al. 2020

Star formation scenarios:-

- conveyer belt – star formation triggered at pericentre
- popcorn – star formation everywhere
- pearls on a string - down stream from the apocentre at contact with the dust lane

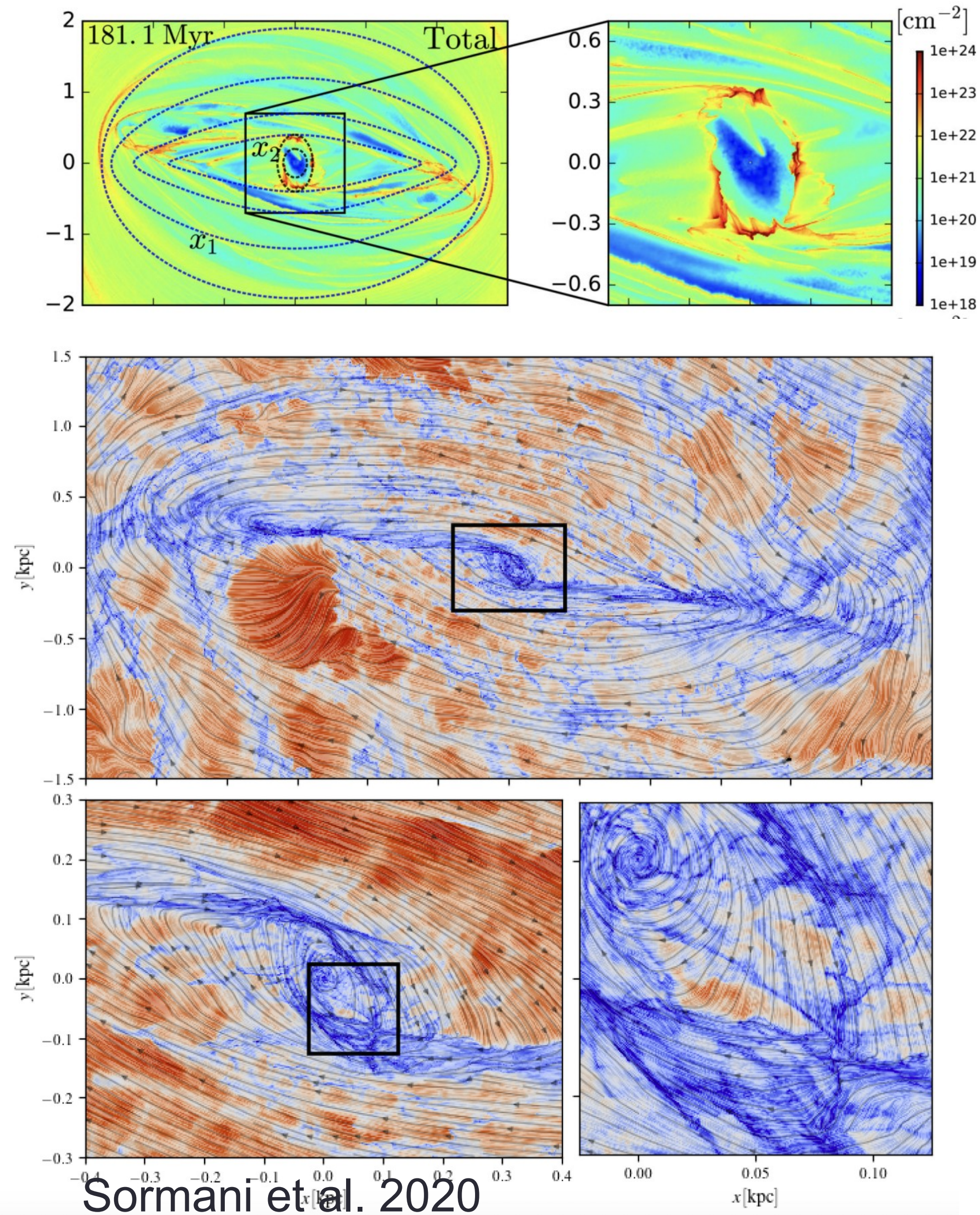
Bar

Emergent behaviour of differentially rotating stars and gas in spiral galaxy.

- x1 orbits align with bar and material drifts inwards
- X2 orbits perpendicular

- Gas transfers through large scale shock

Feeds gas onto the galactic centre ~ 0.8 - 3 Msol/yr



Sormani et al. 2020

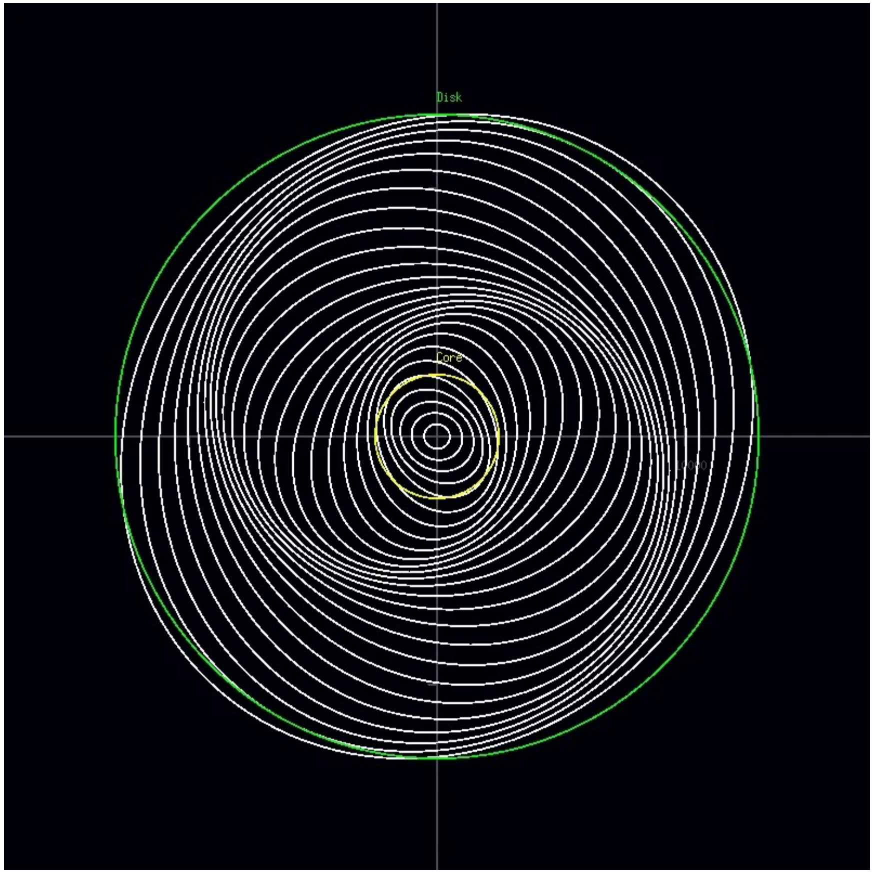
Spiral Arms – grand design

Density wave theory
(Lin & Shu 1964)

Elliptical orbits that turn at different speeds.

Stars and Gas build up where orbits overlap.

Potential of the over-density causes nearby gas to fall into the gravity well.



Spiral Arms - flocculent

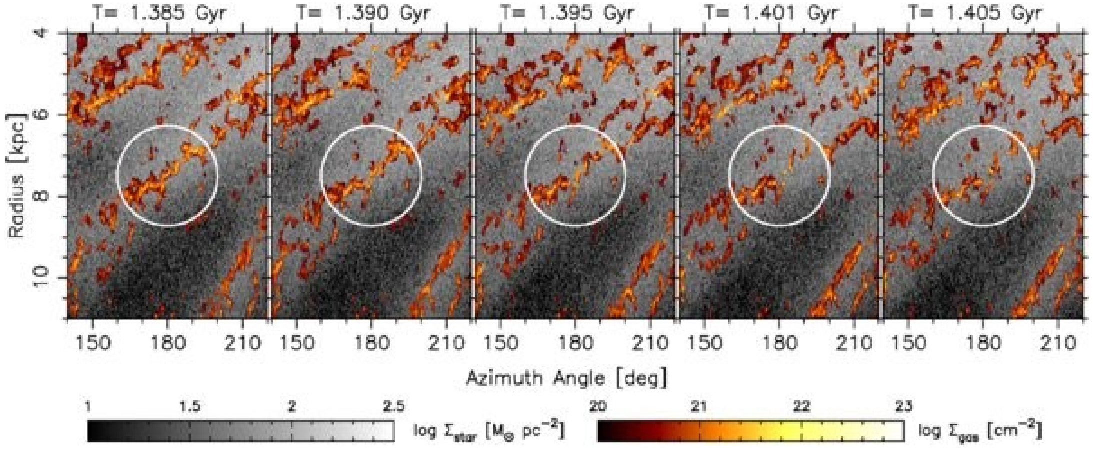
NGC 2841- NASA

Patchy (flaky) discontinuous spiral arms

Self- propagating model

- Star forming regions stretched by differential rotation
- Non-linear evolution, bars are not fixed in time. Less well defined potential.

Many galaxies not clearly in either class – combination of both

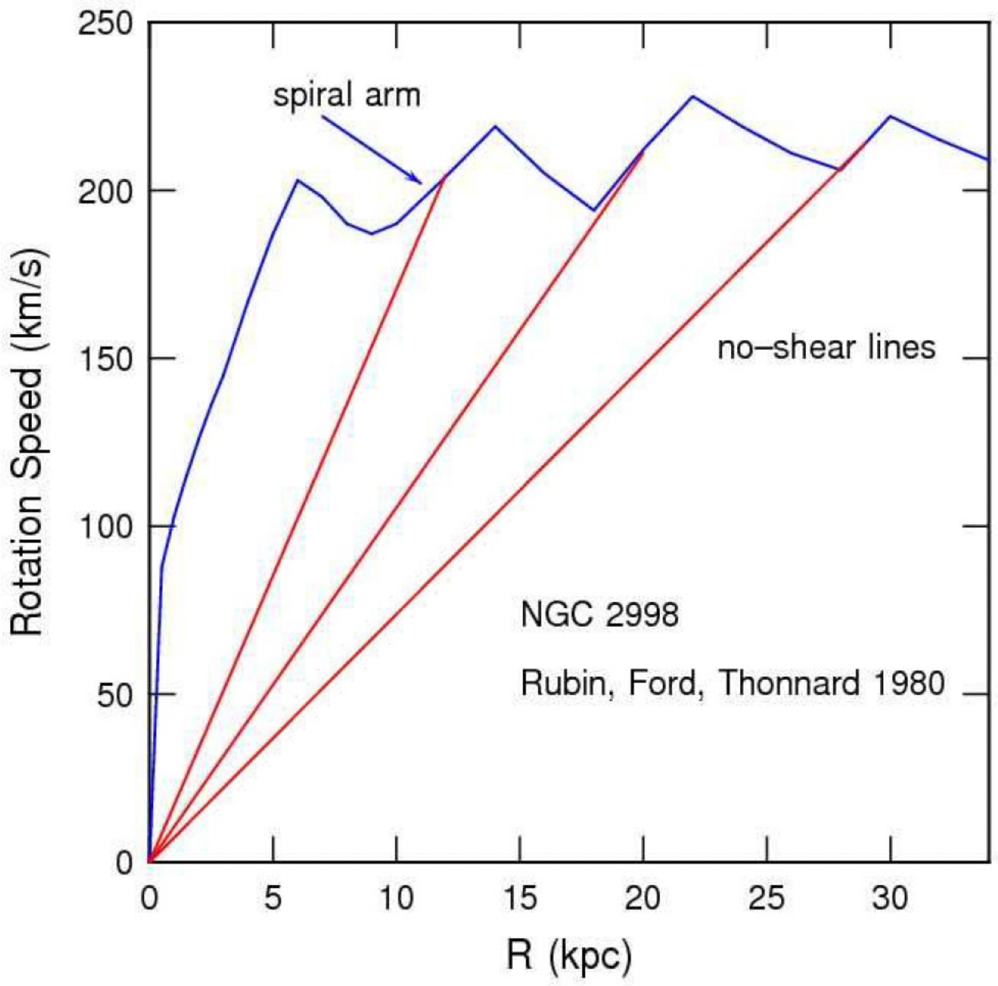


Wada 2011

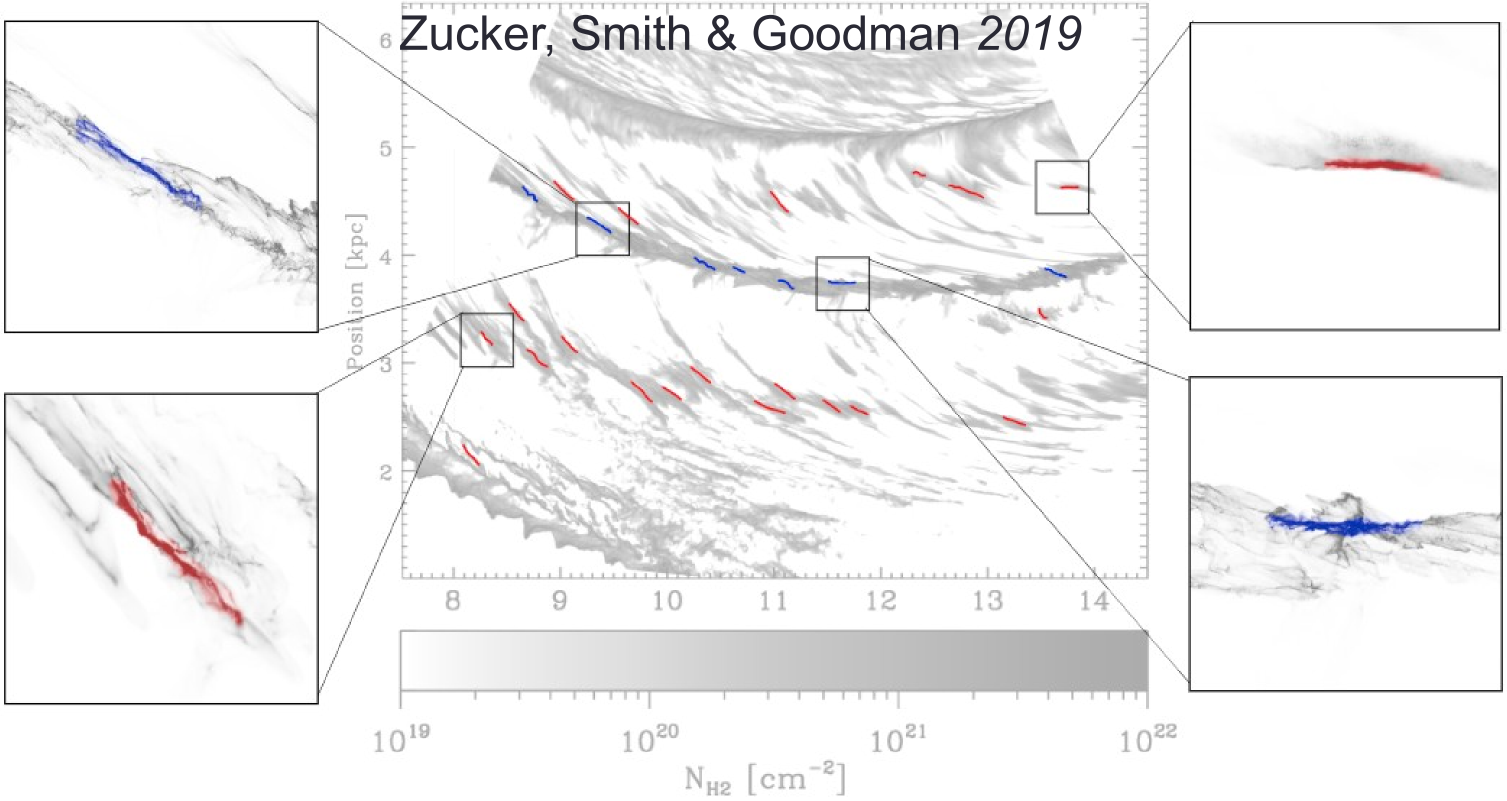
Shear

Spiral Arms have low shear and therefore low tidal forces.

Gas will move faster as it enters arm and more slowly when it leaves.



Giant Molecular Filaments and Bones



Zucker, Smith & Goodman *2019*

- Identified giant filamentary structures from Smith et al. 2014 without self-gravity

- Predict maximum of 1 observationally identified giant molecular filament per kpc squared.

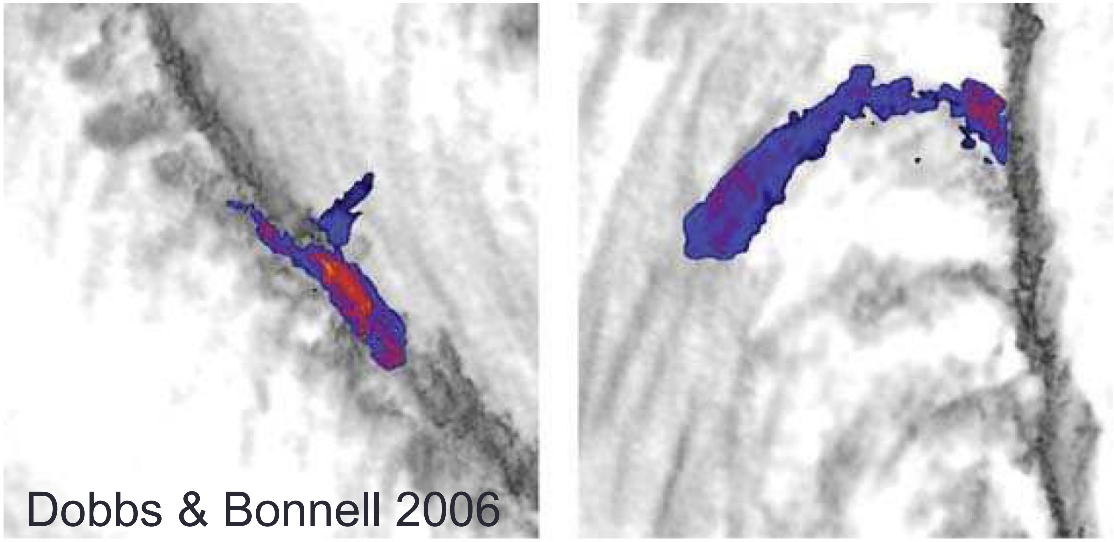
Spiral Arms – feathers and spurs


Wada & Koda 2004

Created by wiggle instability in isothermal simulations

- Kelvin Helmholtz instability
- Amplified by repeated shock passages

Created by the shearing of gas as it leaves the spiral arm on different orbits.

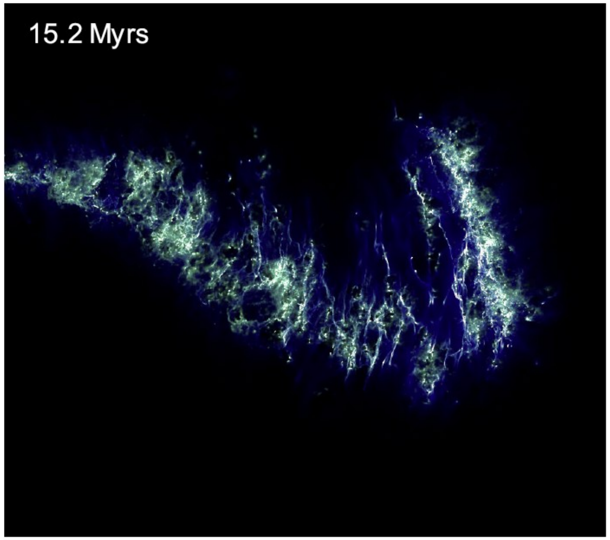

Dobbs & Bonnell 2006

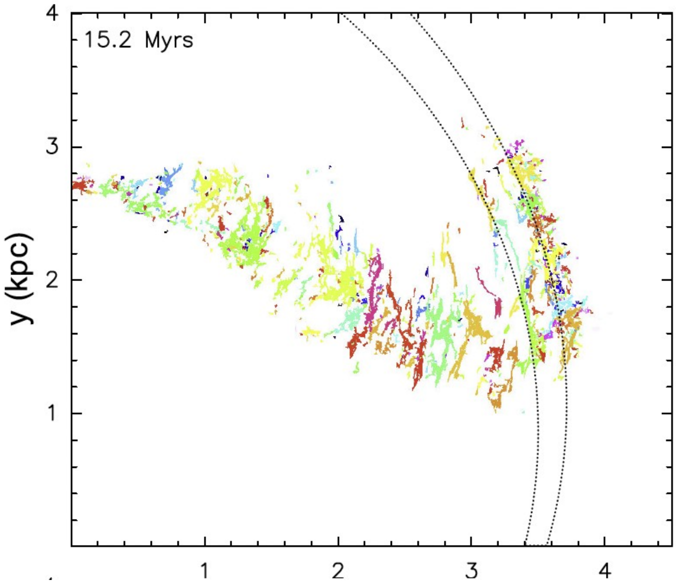
Inter-arm regions

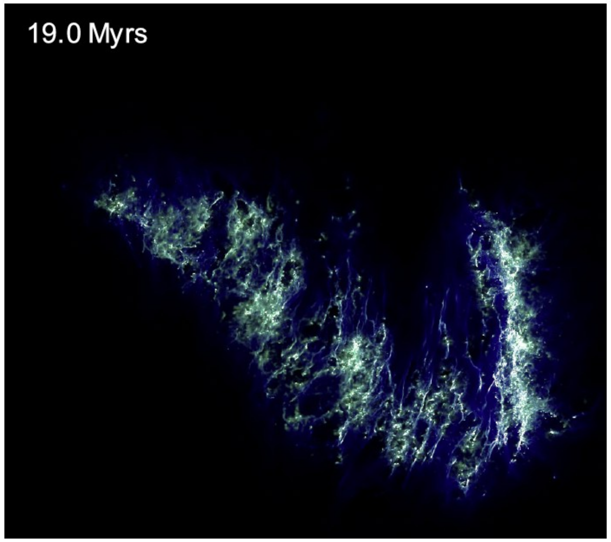
Lower density high shear environments.

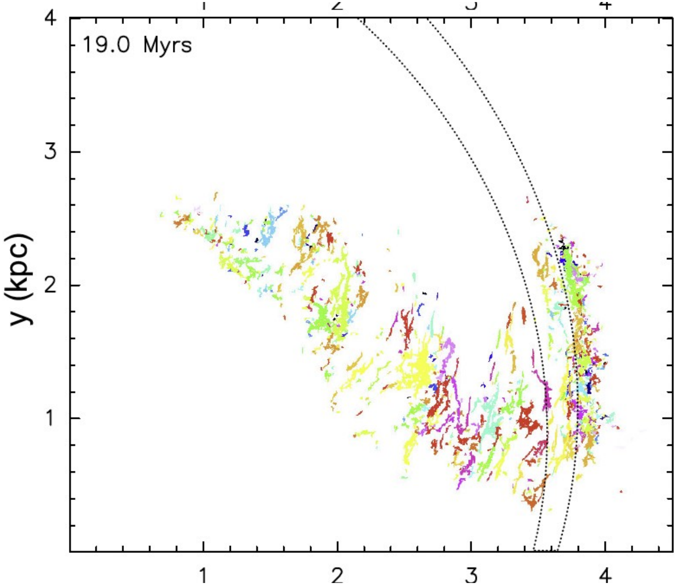
Gas will move through between spiral arm passages.

Simulations suggest most gas is unbound.



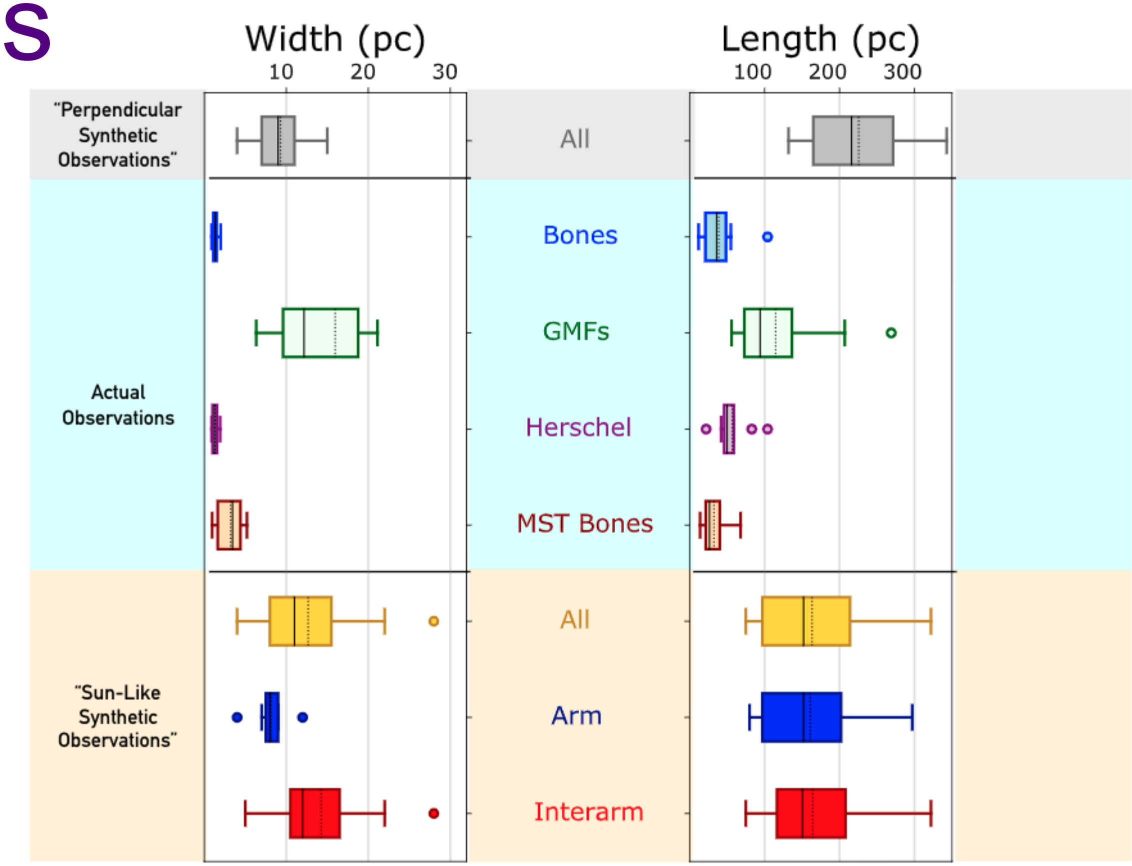


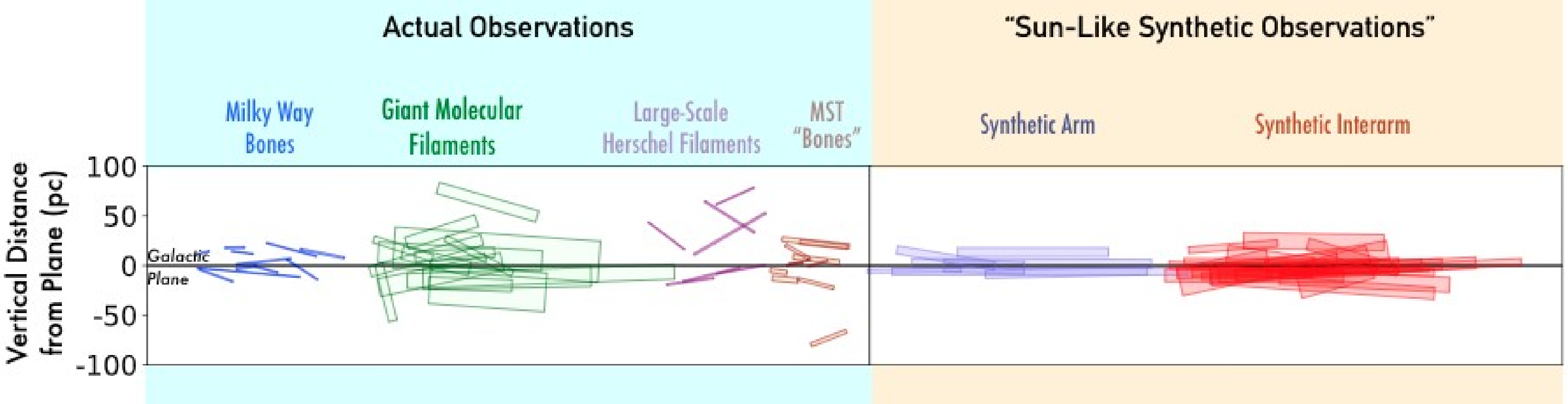




GMFs and Bones

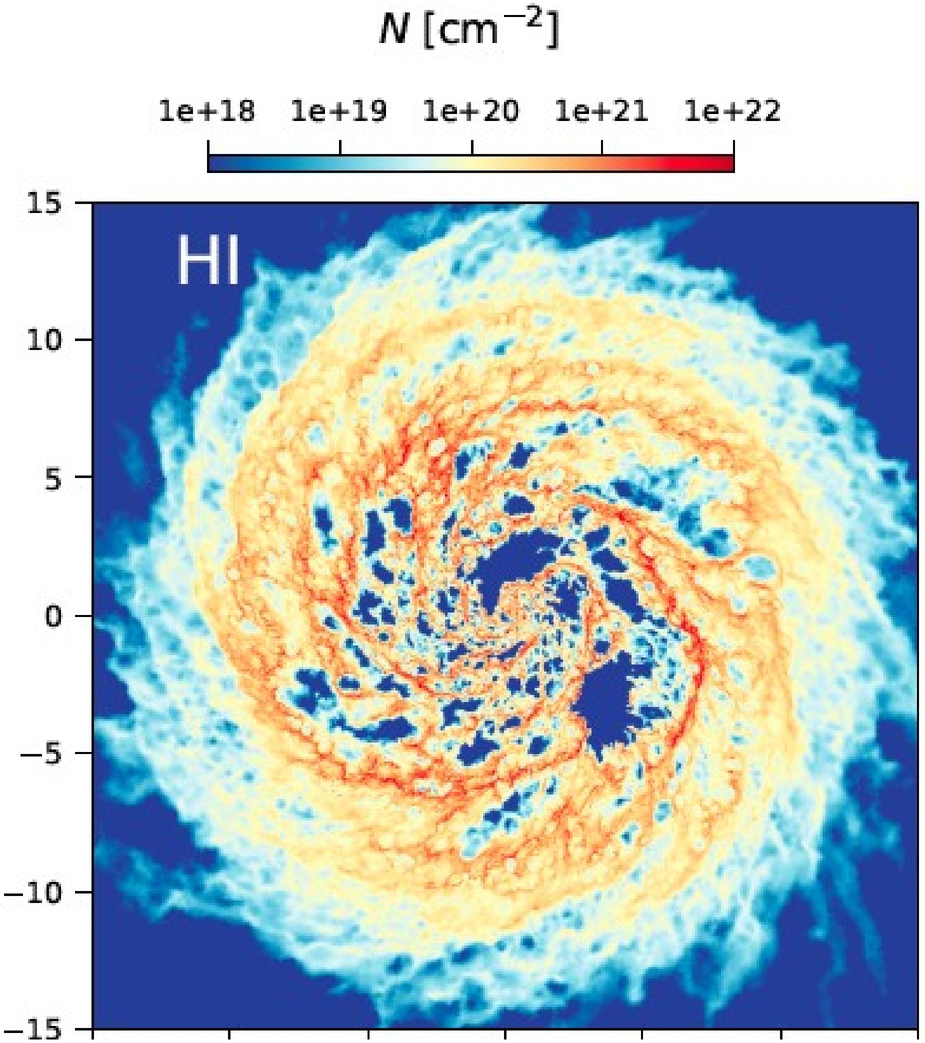
- Good match to Giant Molecular Filament properties of *Ragan+14, Abreu-Vicente+16* –**probably unbound**
- Positions are more consistent with "Bones" e.g. *Goodman+14*
- But, Bones require additional physics e.g self-gravity



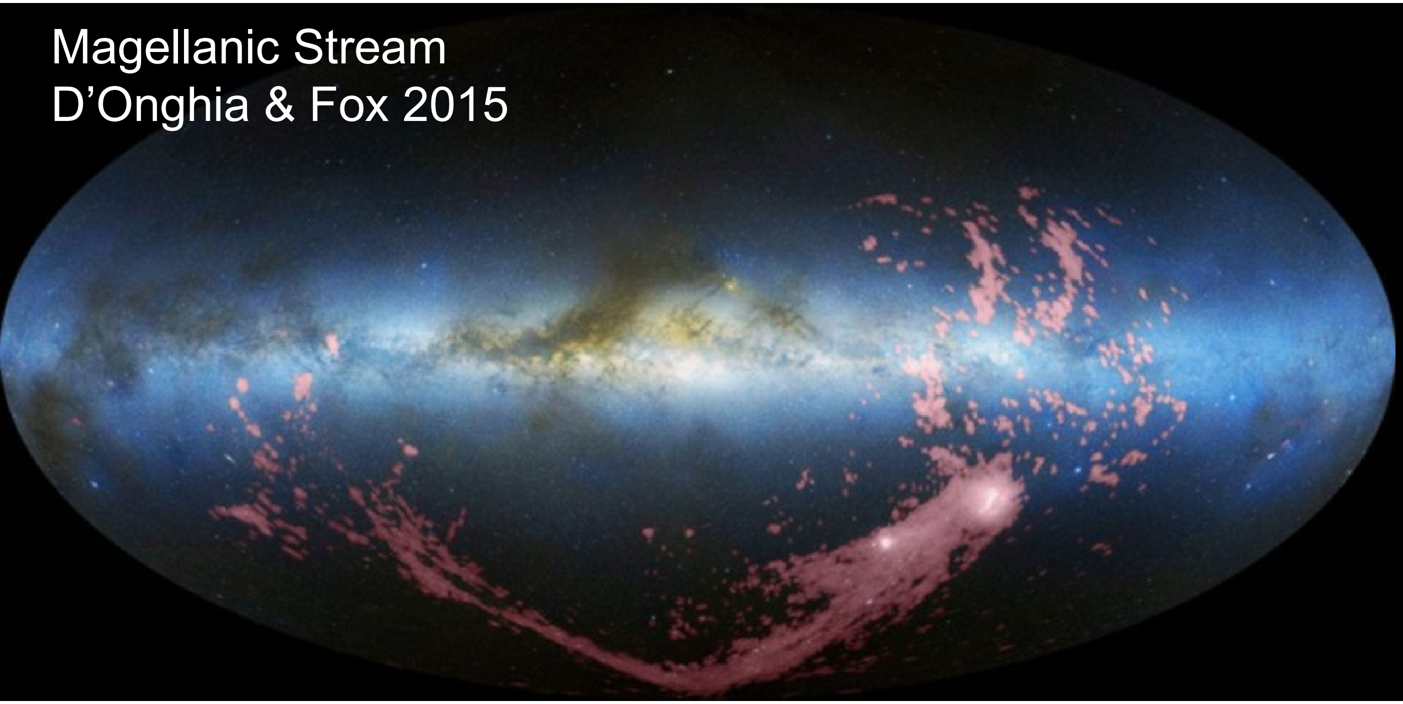


Outer galaxy

- Low density environment
- Little cold molecular gas
- Low metallicity
- Low interstellar radiation field



Tidal Streams



Magellanic Stream
D’Onghia & Fox 2015

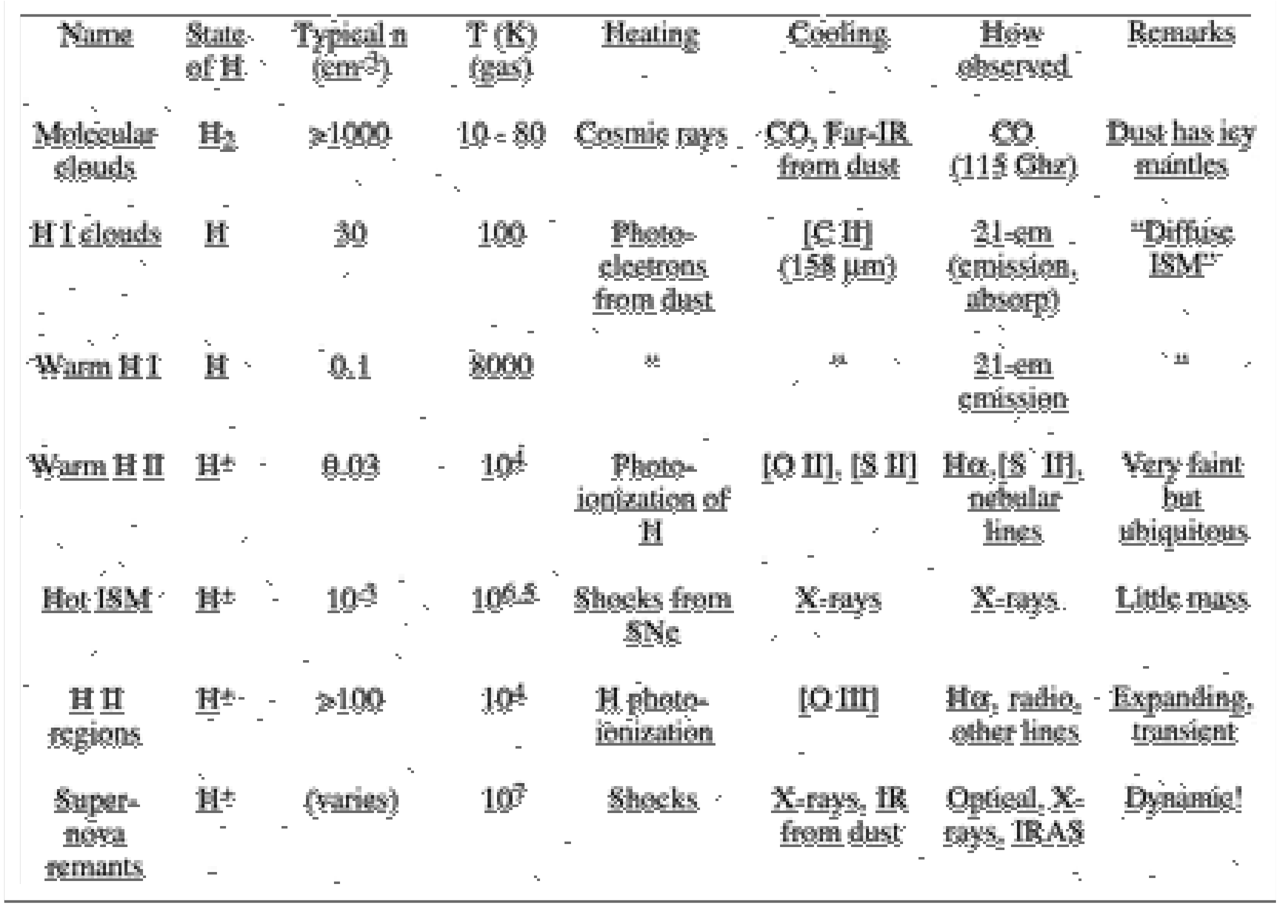
Stellar Streams

- Can be both gaseous and stellar
- Magellanic stream most important high velocity cloud
- Feeds fresh gas into the galactic corona

Forming Molecular Clouds in the Galaxy

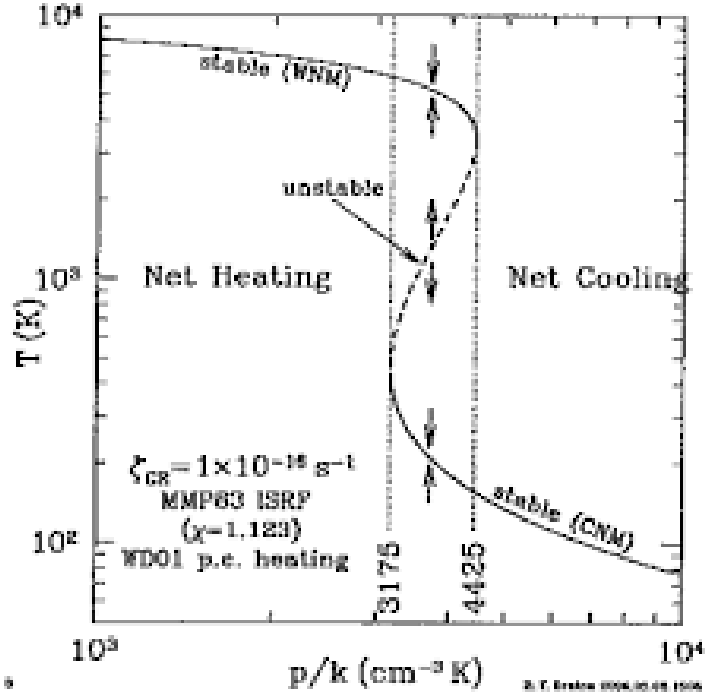
The Interstellar Medium

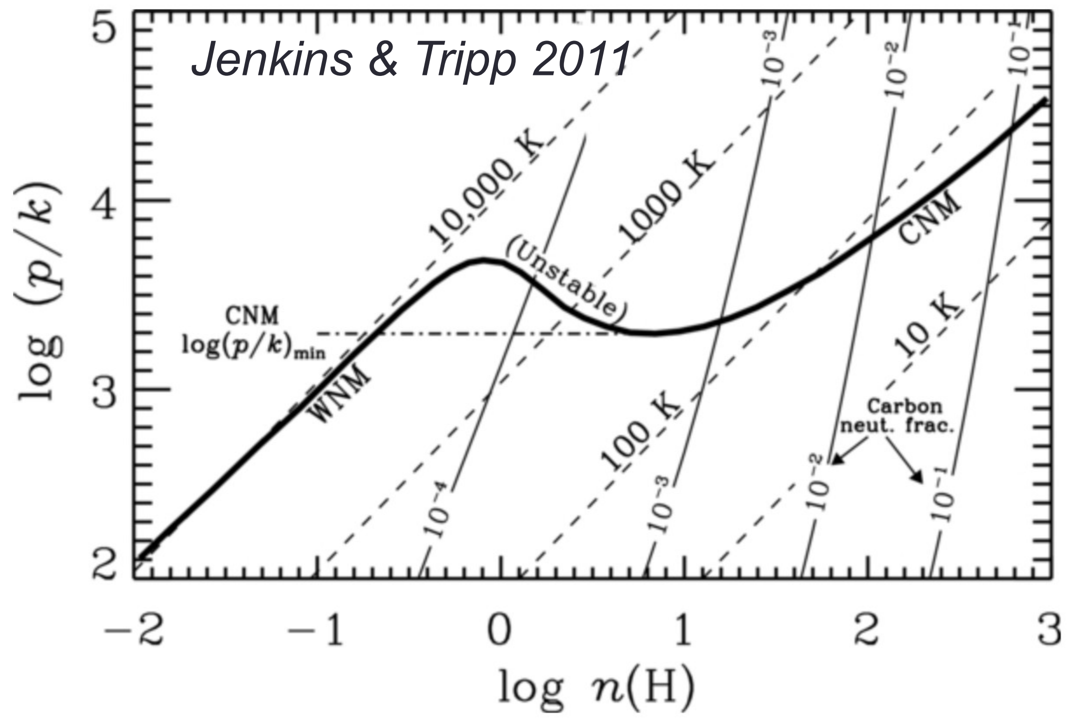
At least 5 thermal phases



Name	State of H	Typical n (cm^{-3})	T (K) (gas)	Heating	Cooling	How observed	Remarks
Molecular clouds	H_2	≥ 1000	10 - 80	Cosmic rays	CO, Far-IR from dust	CO (115 Ghz)	Dust has icy mantles
H I clouds	H	30	100	Photo-electrons from dust	[C II] (158 μm)	21-cm (emission, absorp)	"Diffuse ISM"
Warm H I	H	0.1	8000	"	"	21-cm emission	"
Warm H II	H^+	0.03	10^4	Photo-ionization of H	[O II], [S II]	Hα, [S II], nebular lines	Very faint but ubiquitous
Hot ISM	H^+	10^{-3}	$10^{6.5}$	Shocks from SNe	X-rays	X-rays	Little mass
H II regions	H^+	≥ 100	10^4	H photo-ionization	[O III]	Hα, radio, other lines	Expanding, transient
Super-nova remnants	H^+	(varies)	10^7	Shocks	X-rays, IR from dust	Optical, X-rays, IRAS	Dynamic!

Thermal instability





Huge drop in temperatures at n~1 cm^{-3} **Thermal Instability**

Heating: Photo-electric heating from hot stars, cosmic rays.

Cooling: Atomic fine structure emission lines.

Size of thermal instability

For gas to be isobaric it must be able to maintain pressure equilibrium

$$L_{iso} = c_s \, t_{cool}$$

At T = 100 K then

c_s = 1 km/s   cooling rate Λ_{C+} = 1.1 e-27 erg cm^3 s^{-1}

t_{cool} = 3/2 nkT / Λn^2

= 0.6 n^{-1} Myr.

Cooling is rapid

L_{iso} = 0.6 n^{-1} pc

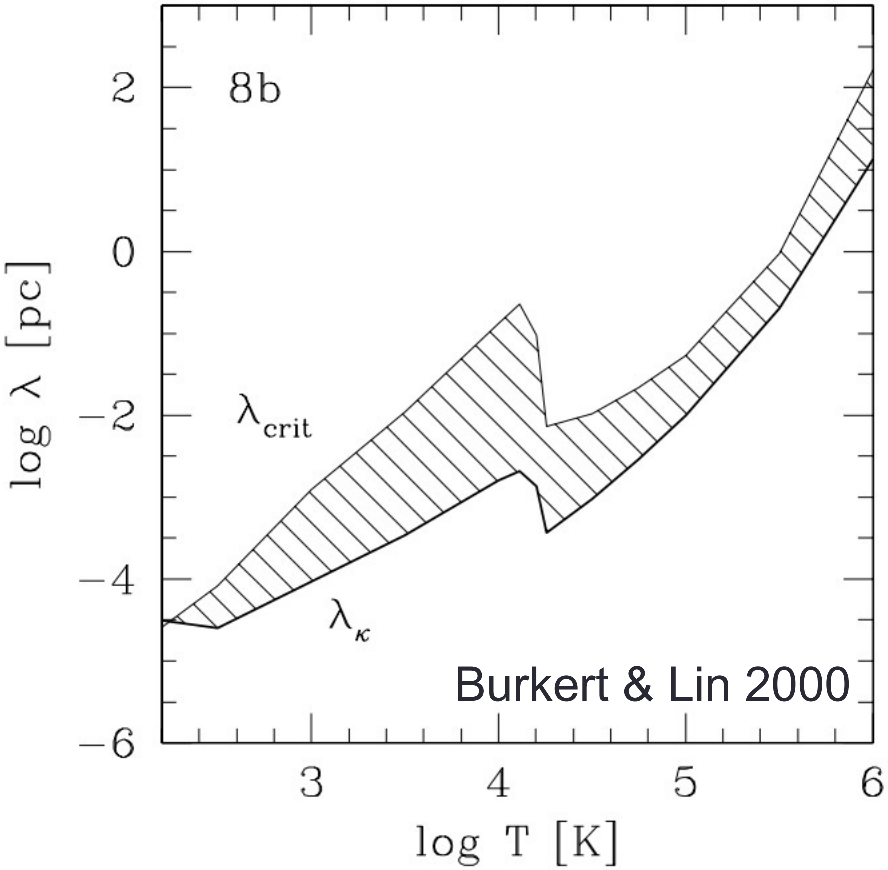
Small size scale shows not the sole driver of molecular cloud formation

Size of thermal instability

Size scale in reality depends

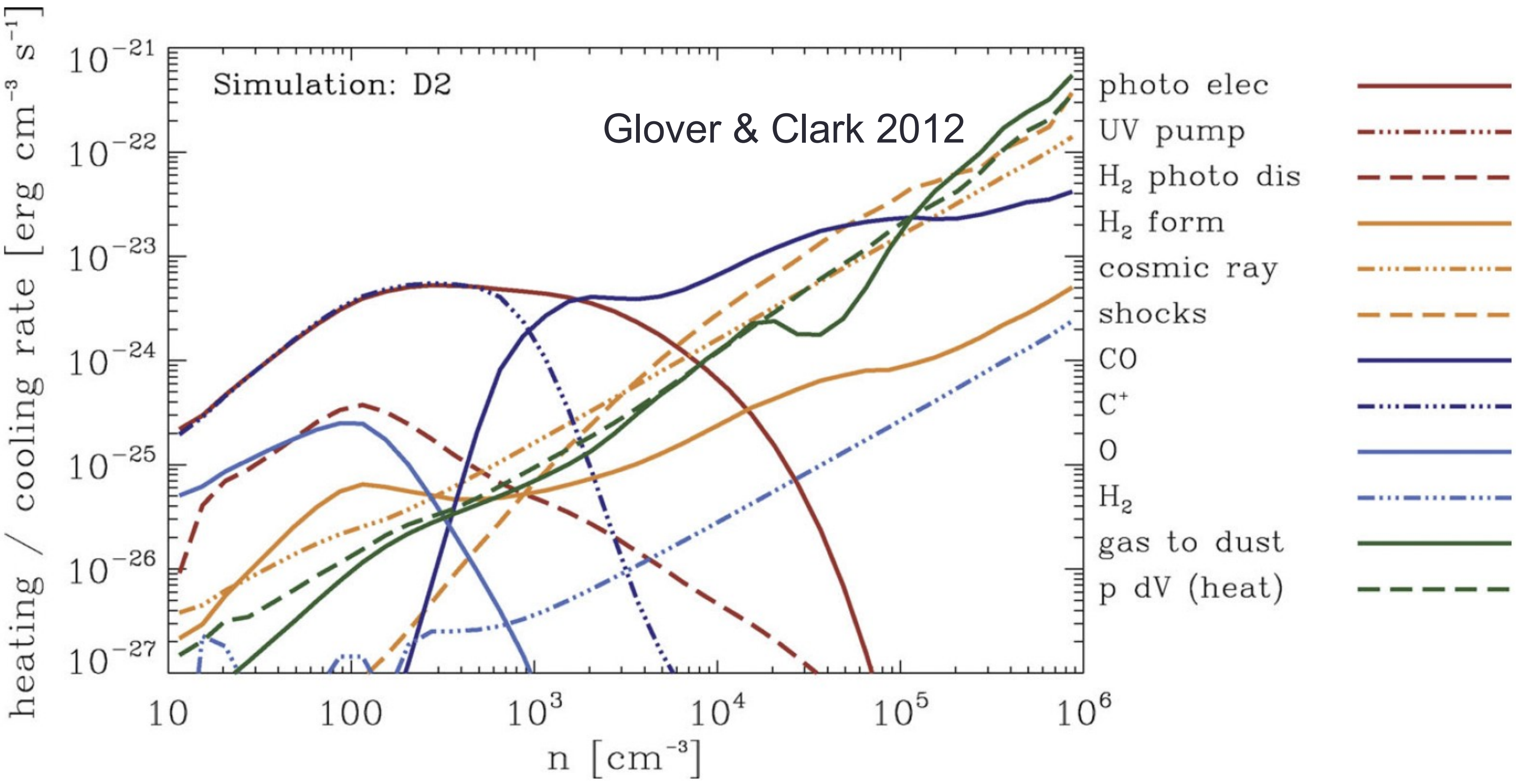
- On the heating and cooling balance
- Initial temperature
- Initial perturbation

e.g. 0.01 overdensity can grow nonlinearly in shaded region on right



Burkert & Lin 2000

Heating and Cooling for dense gas

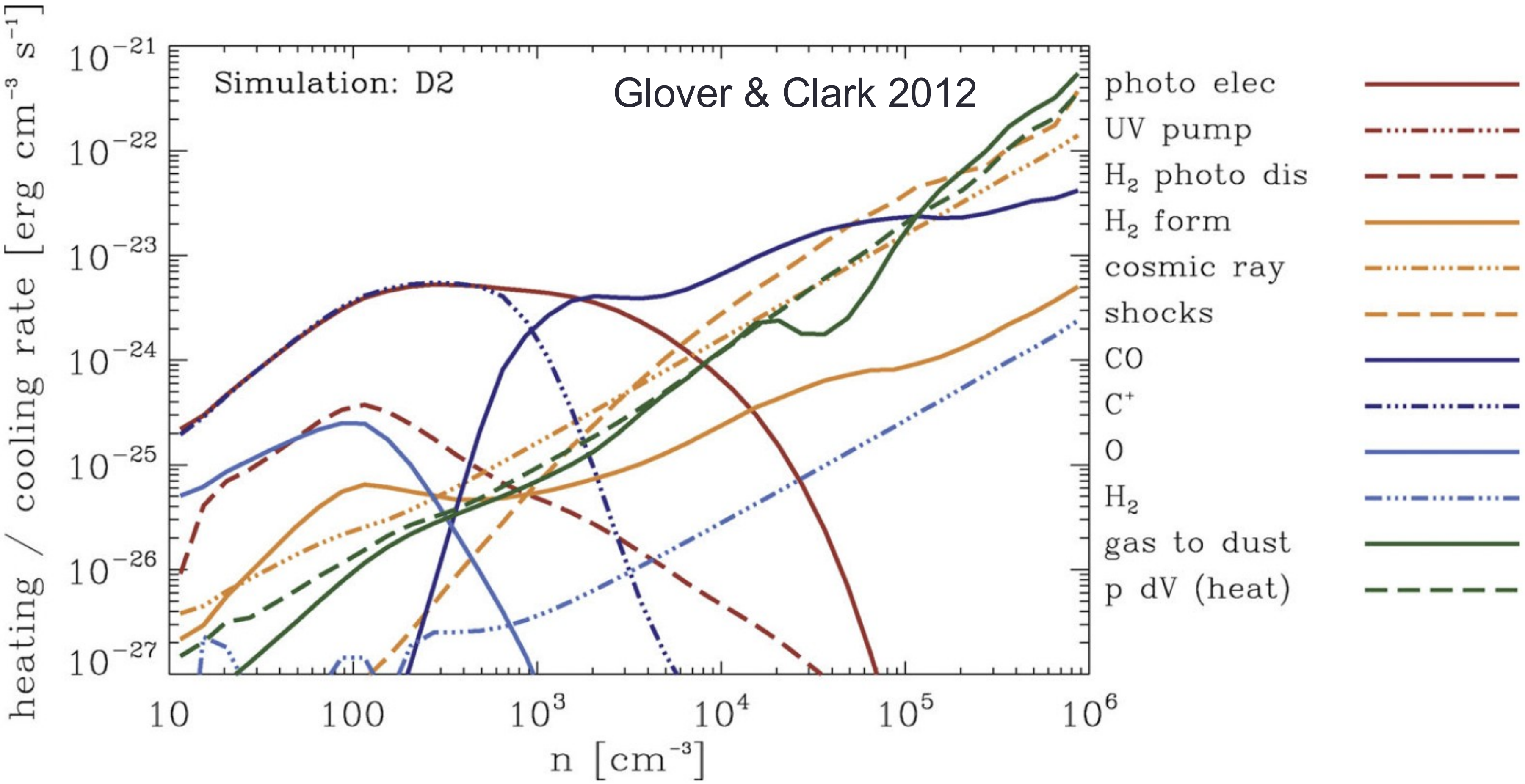


Glover & Clark 2012

Major coolant at - low density = atomic lines

- int densities = molecular lines
- high densities = dust

Heating and Cooling for dense gas



Most cooling processes are dependent on **metallicity** and **dust-to-gas ratio**

Jeans Instability

Characteristic mass and radius of a gravitationally unstable cloud supported by thermal pressure

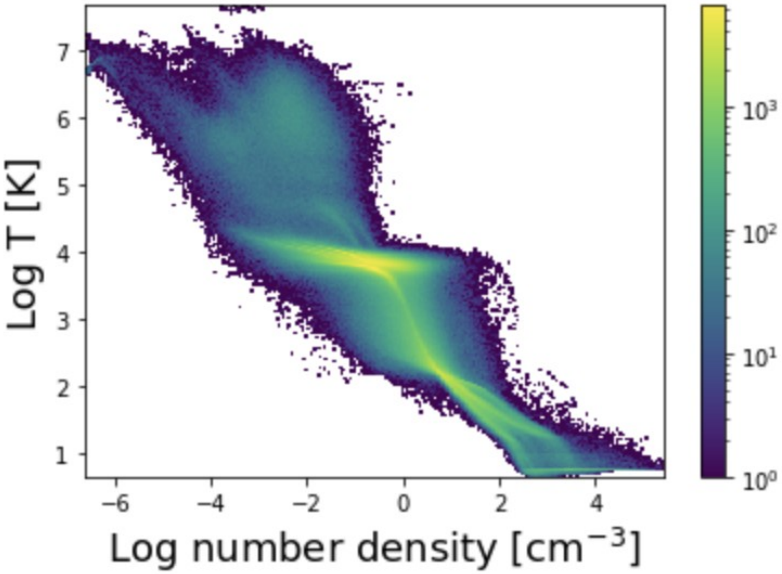
$$m_\mathrm{J} = \left(\frac{4\pi\rho}{3}\right)^{-1/2} \left(\frac{5}{2}\frac{kT}{G\mu}\right)^{3/2}$$

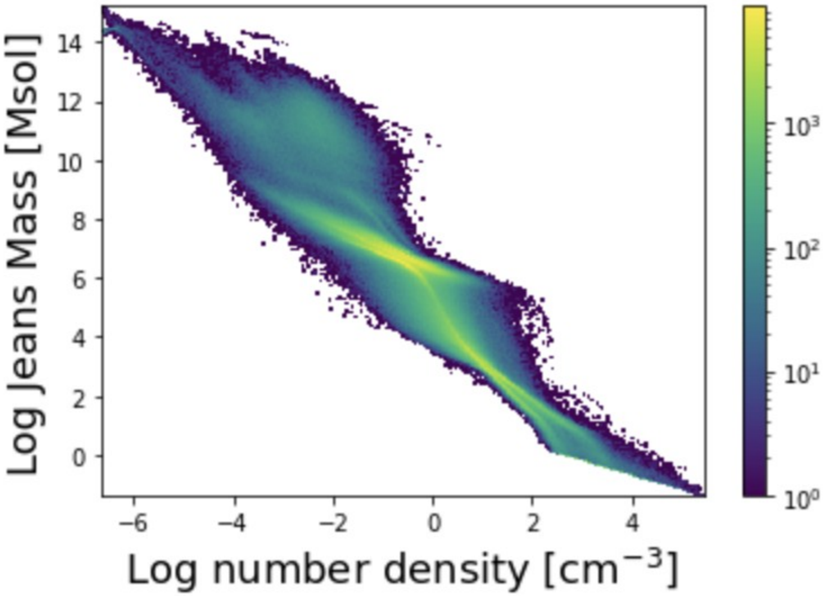
$$r_\mathrm{J} = \left(\frac{4\pi\rho}{3}\right)^{-1/2} \left(\frac{5}{2}\frac{kT}{G\mu}\right)^{1/2}$$

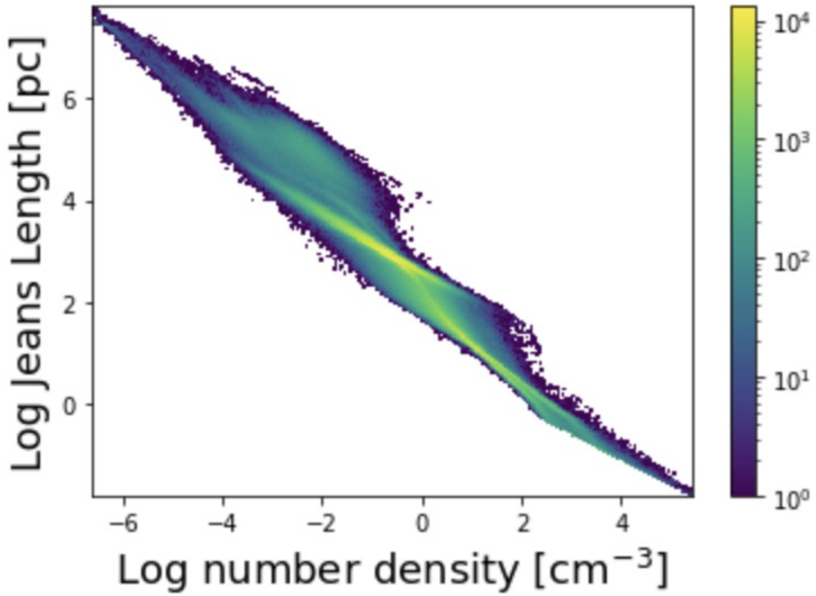
This will collapse on the freefall timescale

$$t_\mathrm{ff} = \left(\frac{3\pi}{32\,G\rho}\right)^{1/2} .$$

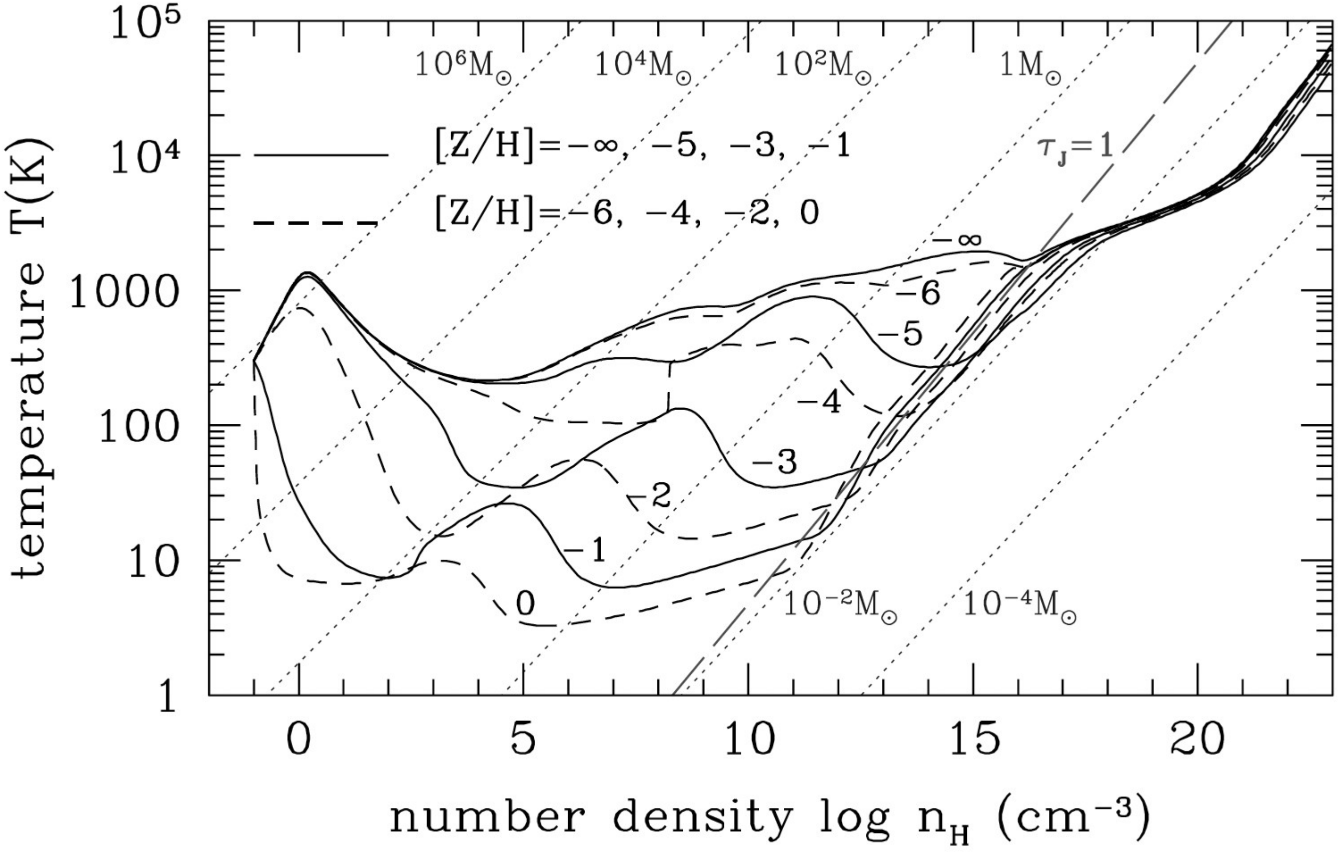
Jeans Instability



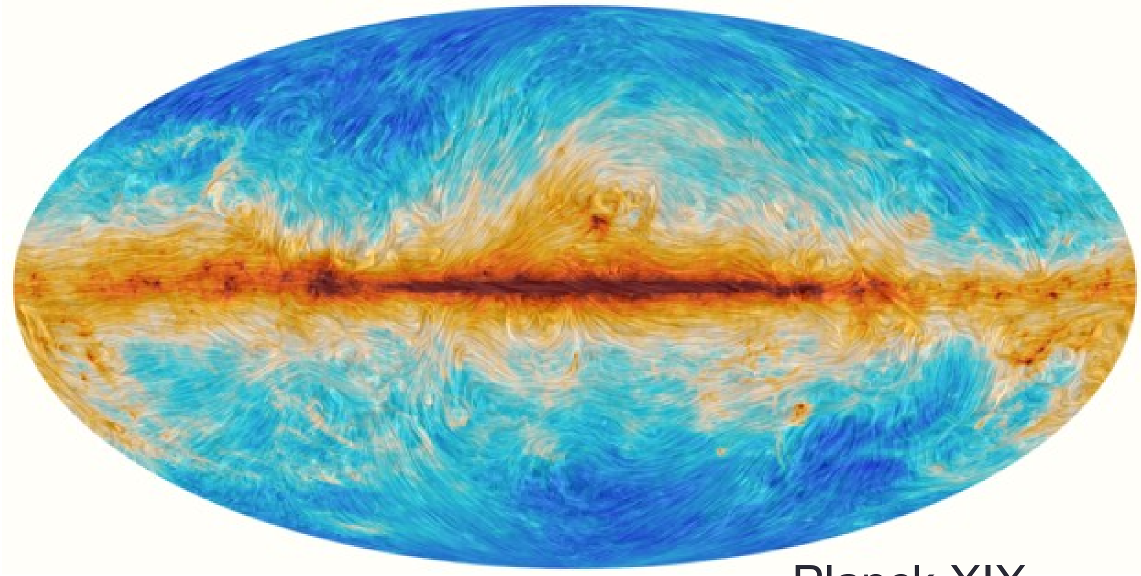




Temperature with metallicity



Magnetic Fields – large scale



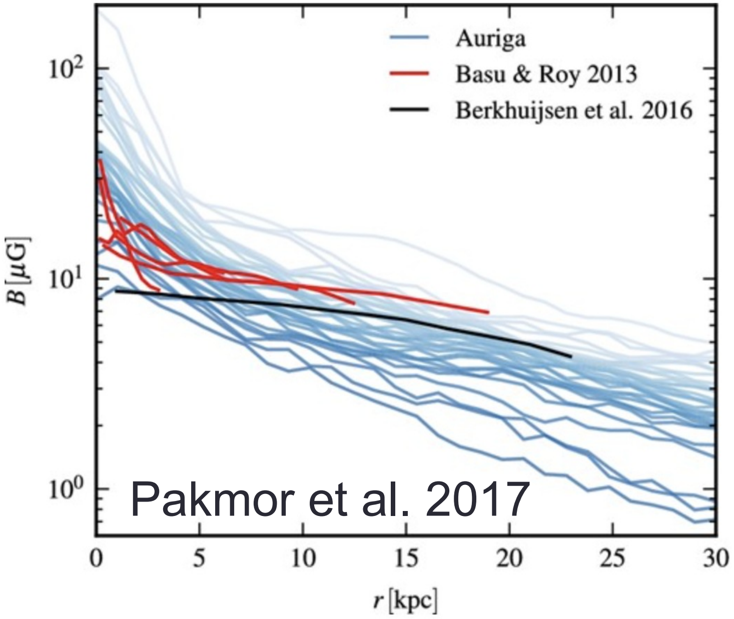
Planck XIX

Often trace the alignment of the spiral arms – generally parallel to vector of the density field.

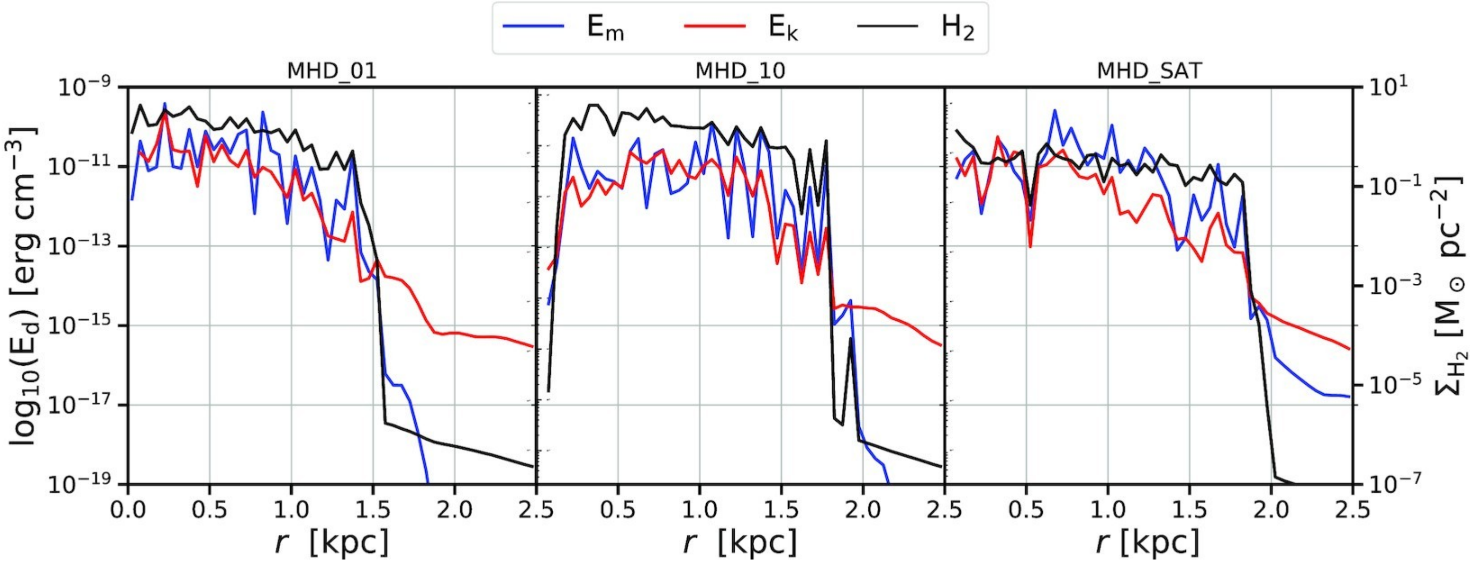
Magnetic fields

Varies throughout the galaxy radially, highest at the galactic centre.

In energy equipartition with the kinetic energy of the gas.

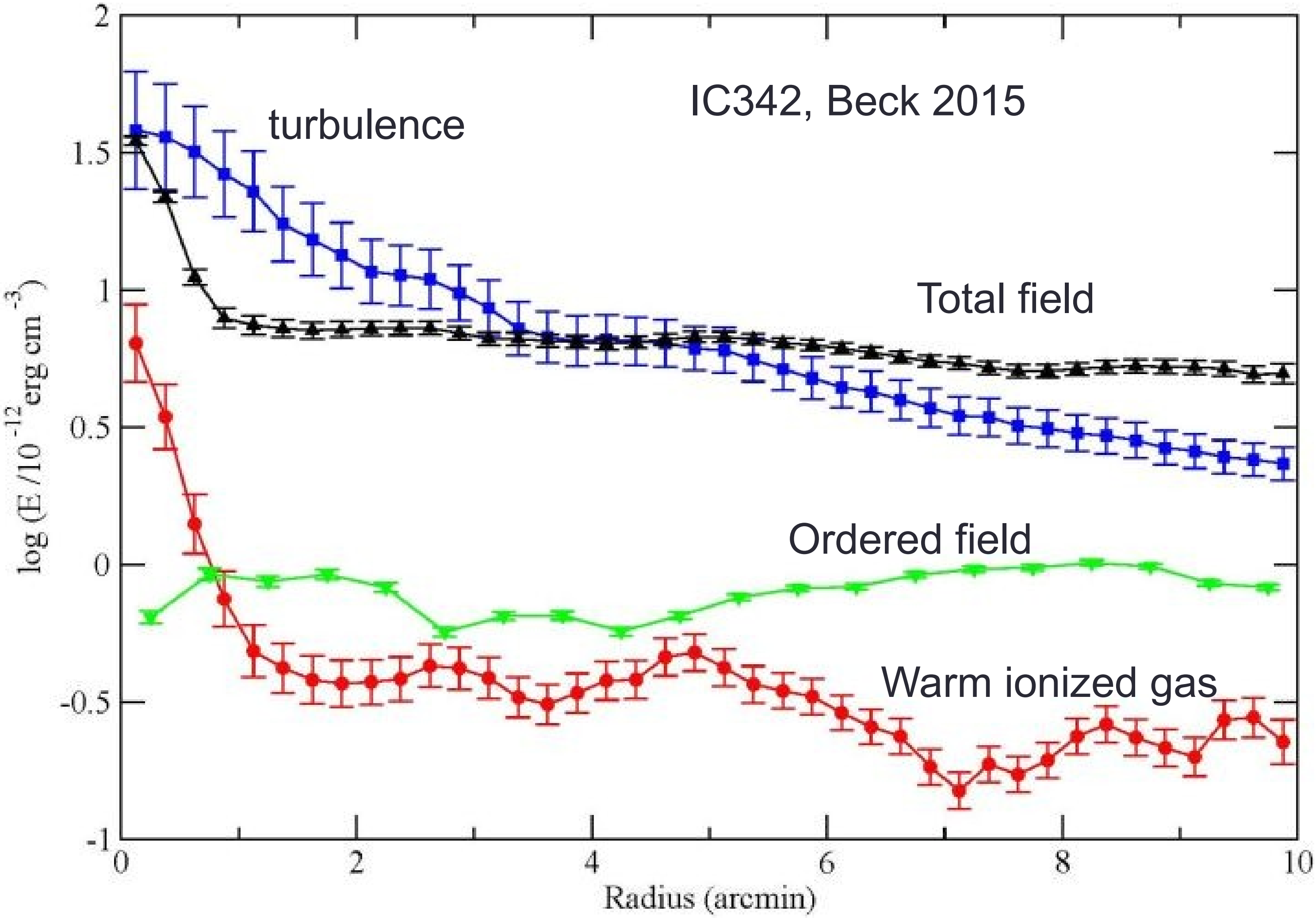


Pakmor et al. 2017

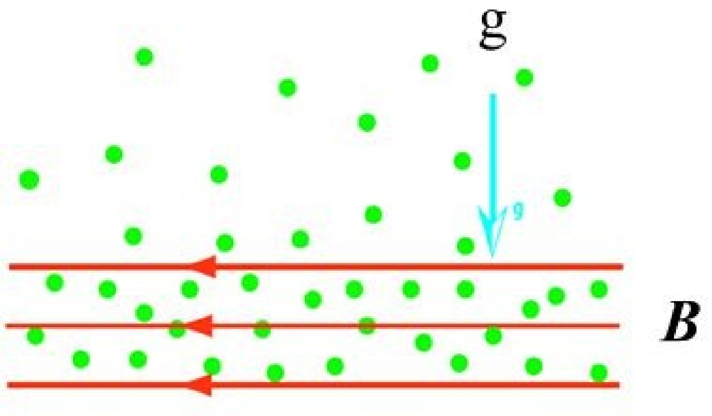


Whitworth et al. 2022

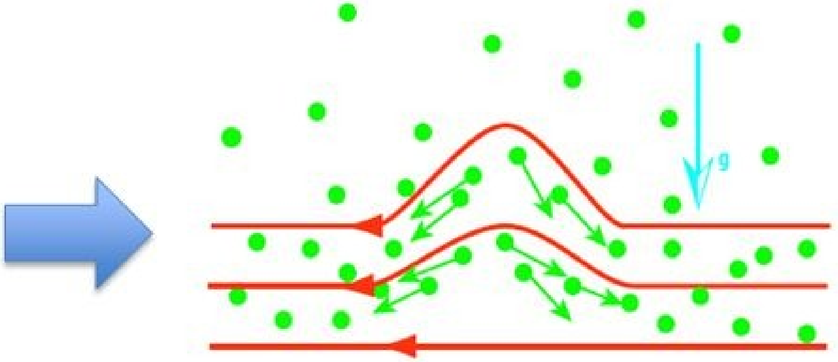
Energy density



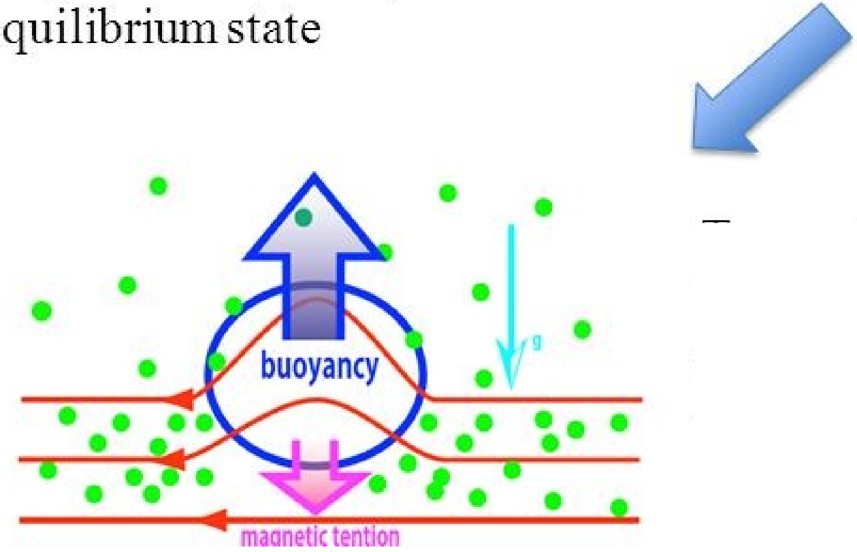
Parker Instability

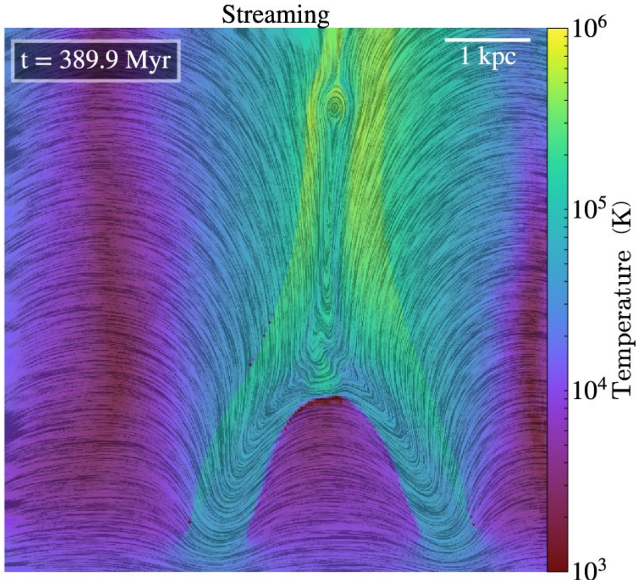


Magnetic field lift-up from equilibrium state



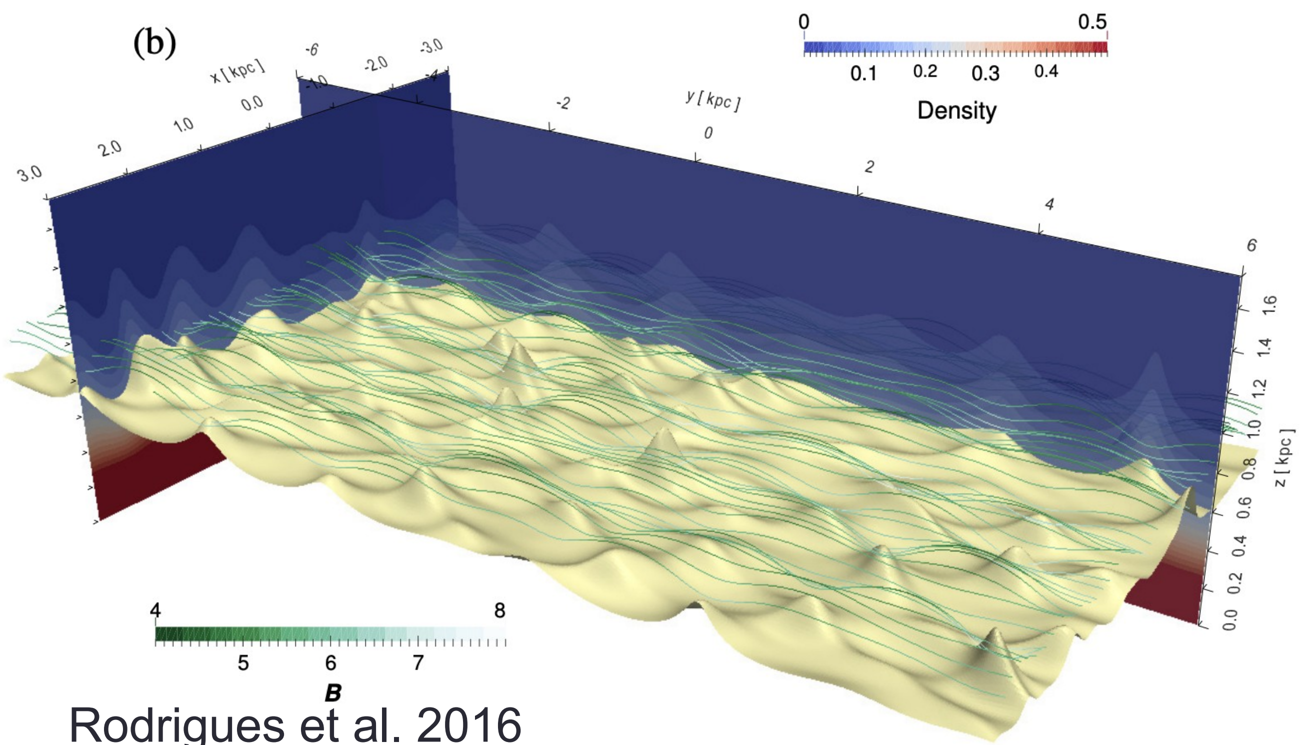
Plasma falls down along bending magnetic field lines





Credit: Y Mizuno

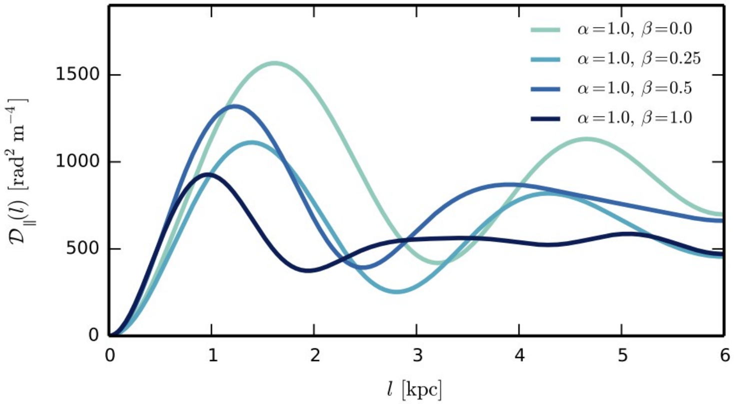
Parker Instability



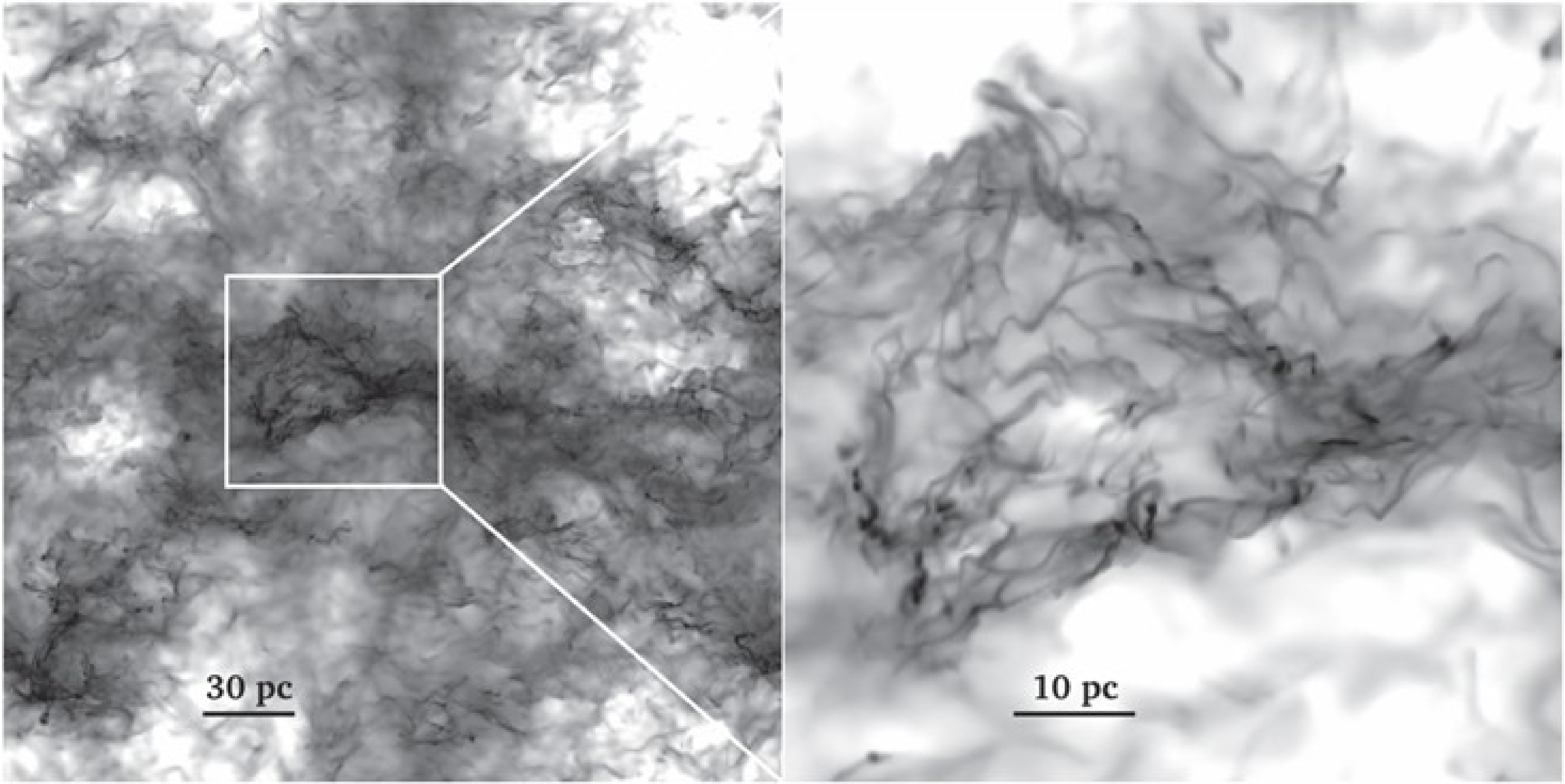
Creates large scale over-densities in the disc

Rodrigues et al. 2016

Structure function shows this is on size scale of several kpc



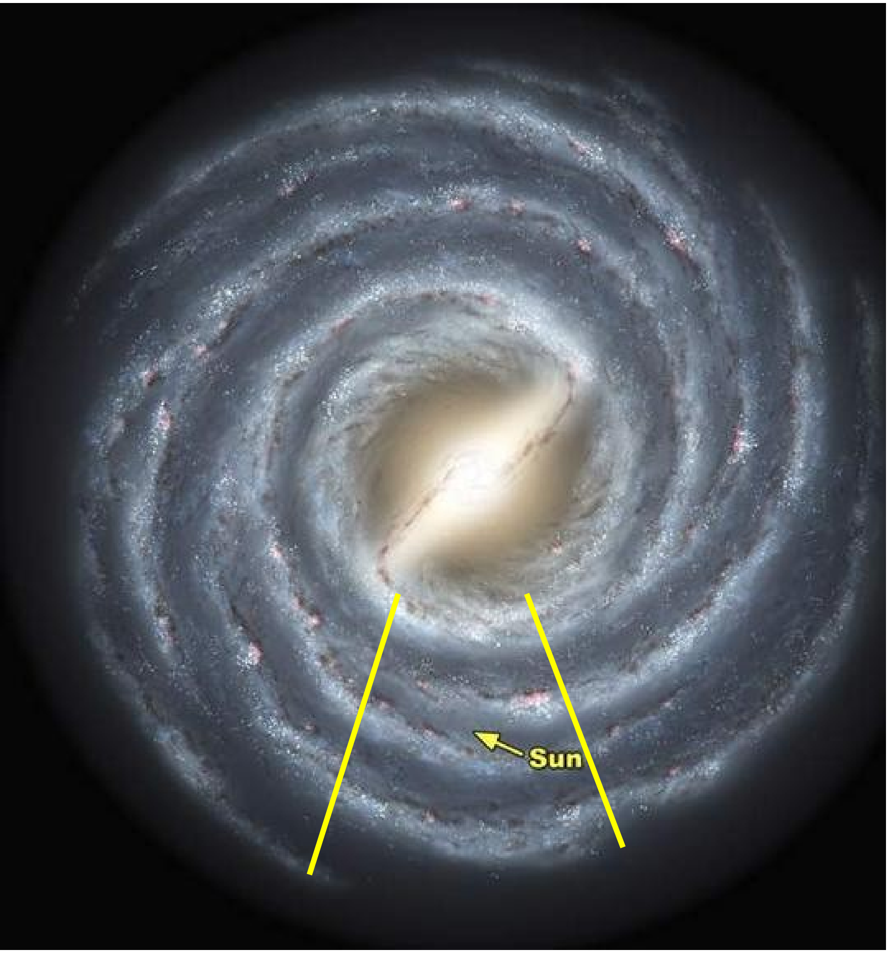
Forming clouds – super bubbles

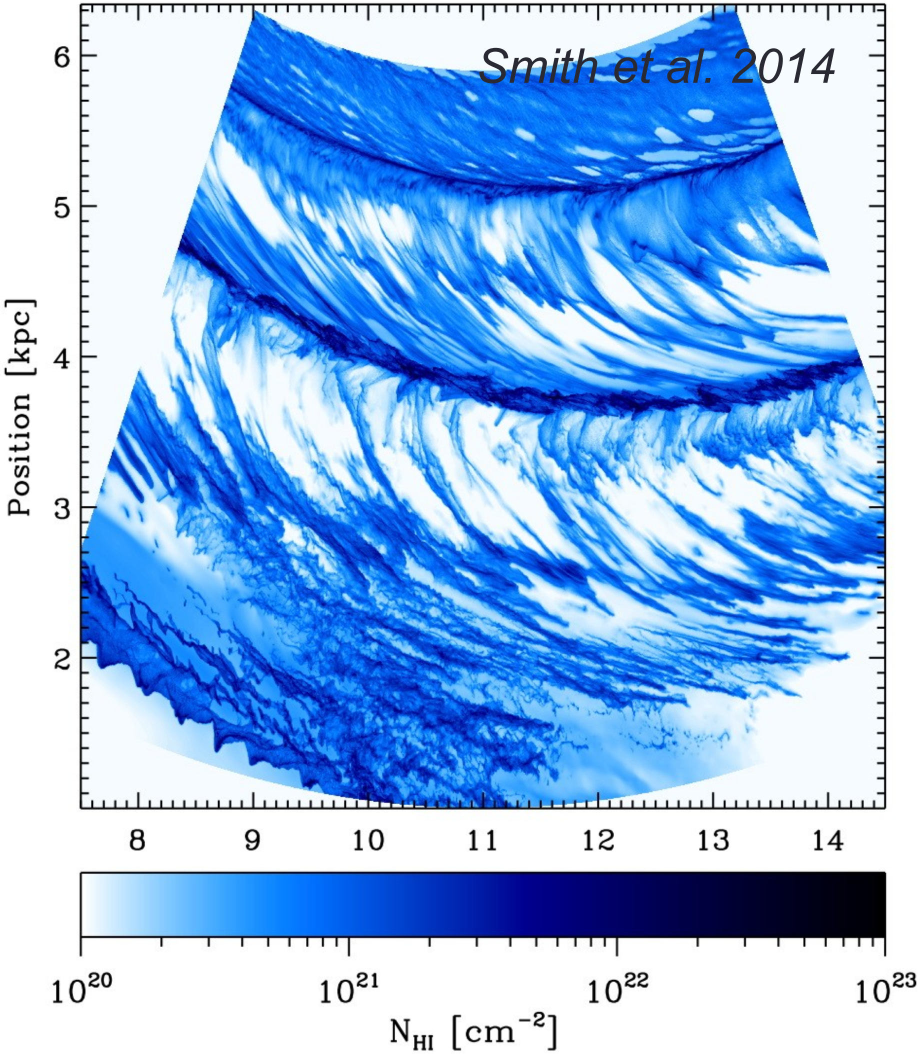


Padoan et al. 2016

For more details on turbulence in the ISM see later lectures.

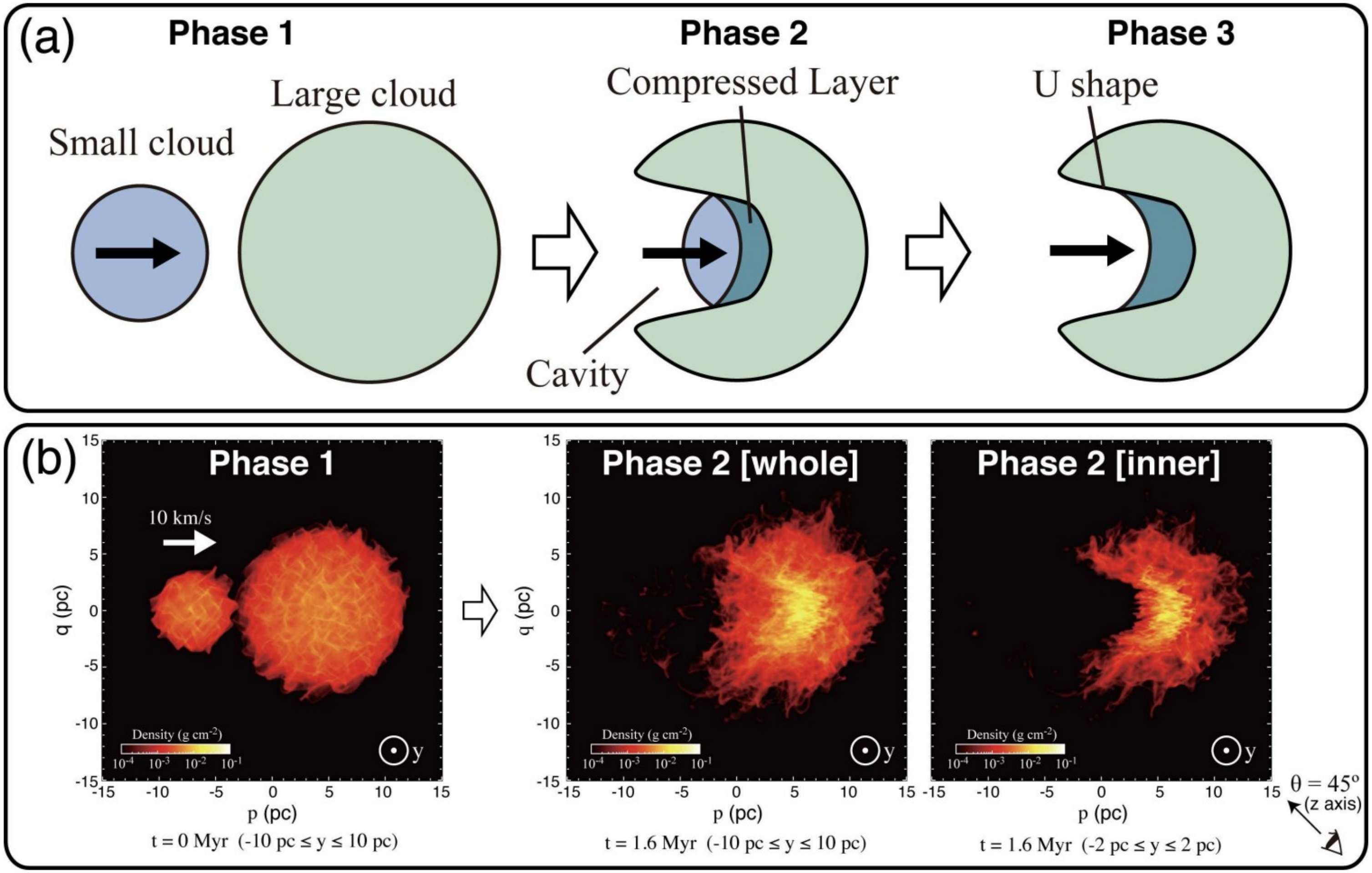
Forming clouds – spiral arms





Gas concentrates in spiral arms where it is compressed.

Forming clouds – collisions



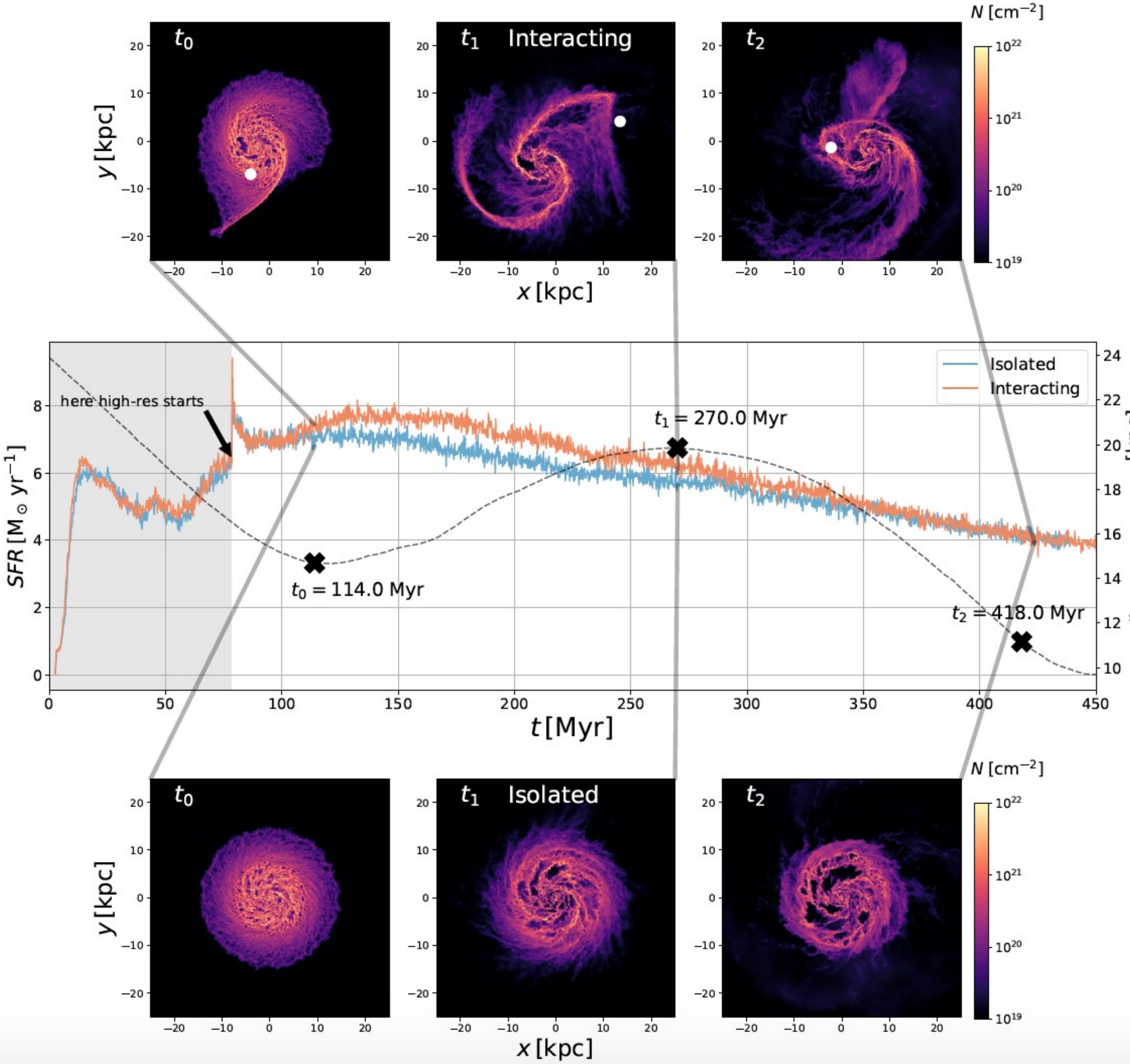
t = 0 Myr (-10 pc ≤ y ≤ 10 pc)

t = 1.6 Myr (-10 pc ≤ y ≤ 10 pc)

t = 1.6 Myr (-2 pc ≤ y ≤ 2 pc)

Fukui et al. 2020

The ISM in an M51 model

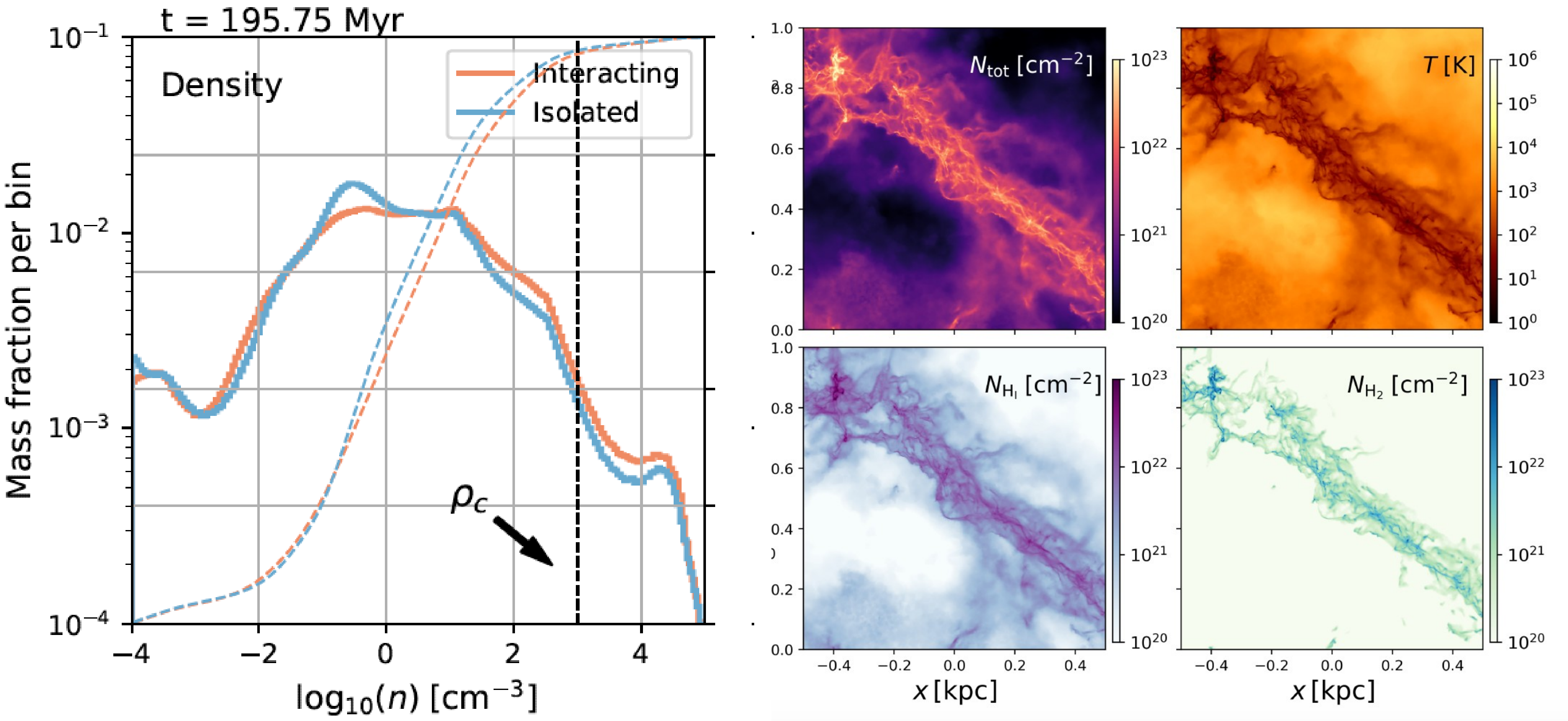


Close encounter with a perturber (but no gas transfer).

Very little global enhancement in star formation.

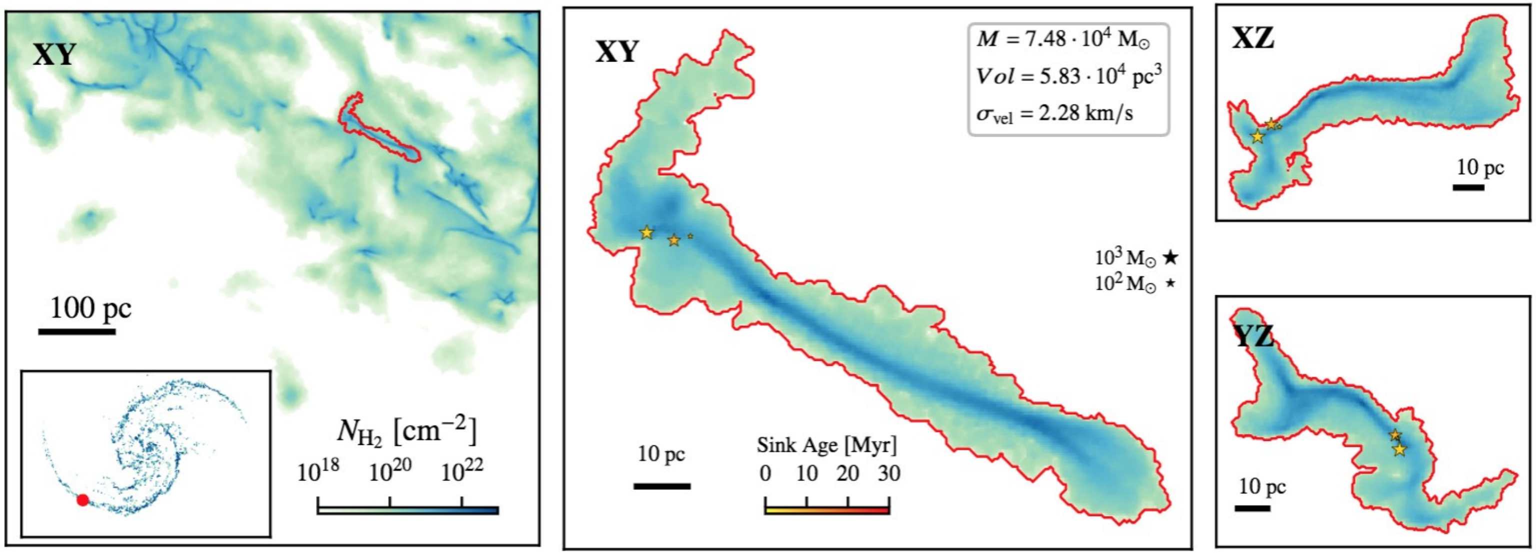
Tress, Smith et al. 2020

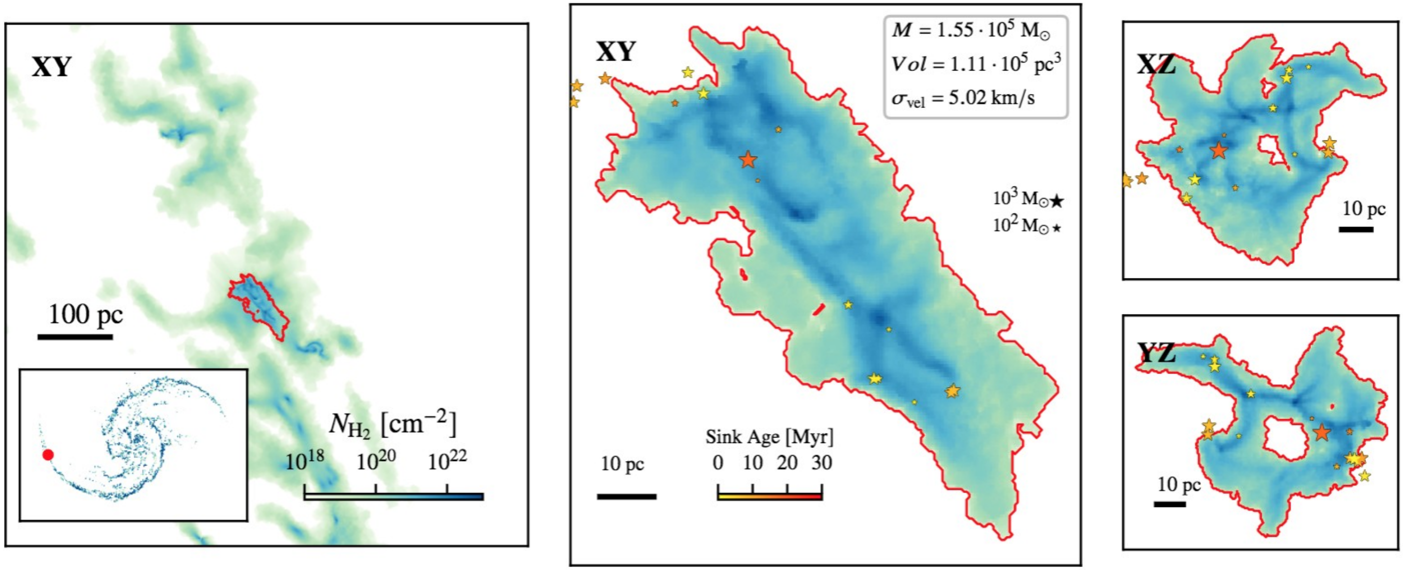
The ISM in an M51 model



PDF used for SIGAME_v3 (Simulator of Galaxy Millimeter/submillimeter Emission) *Olsen et al. 2021.*

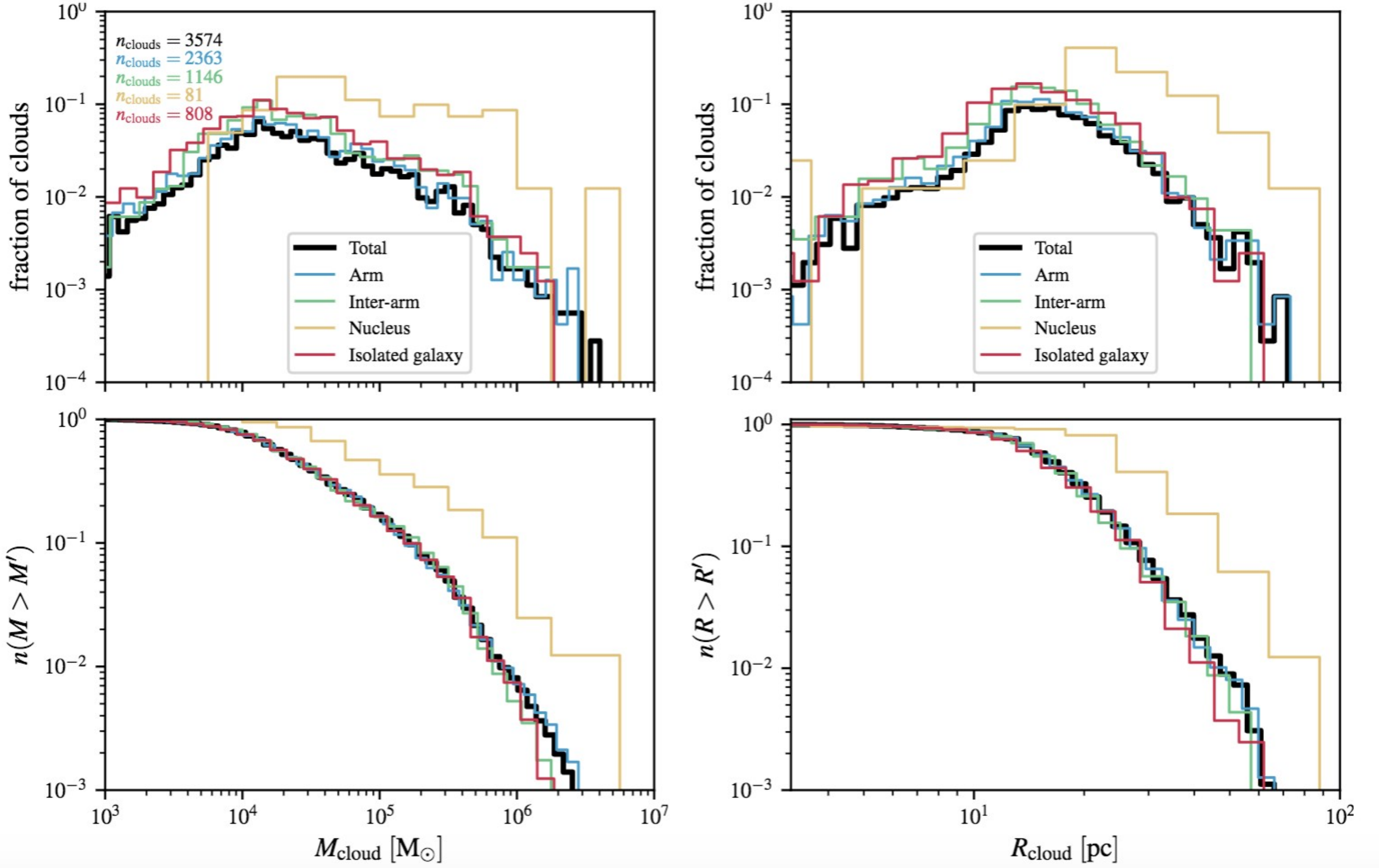
Identifying Molecular Clouds





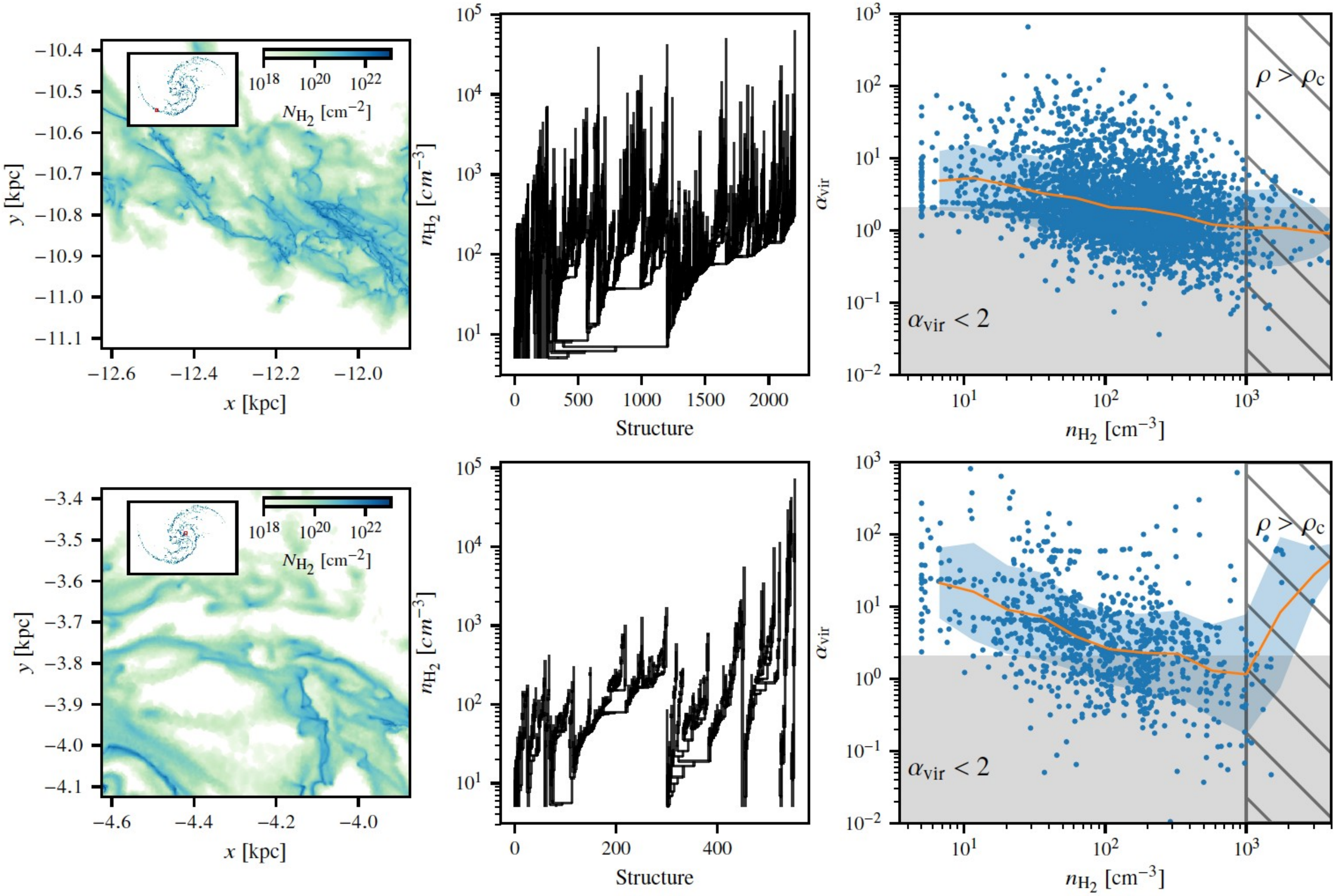
Systematically identify clouds in H_2 using the SCIMES tool and dendrograms to make galaxy catalogue
Tress+2021

Cloud Mass with environment

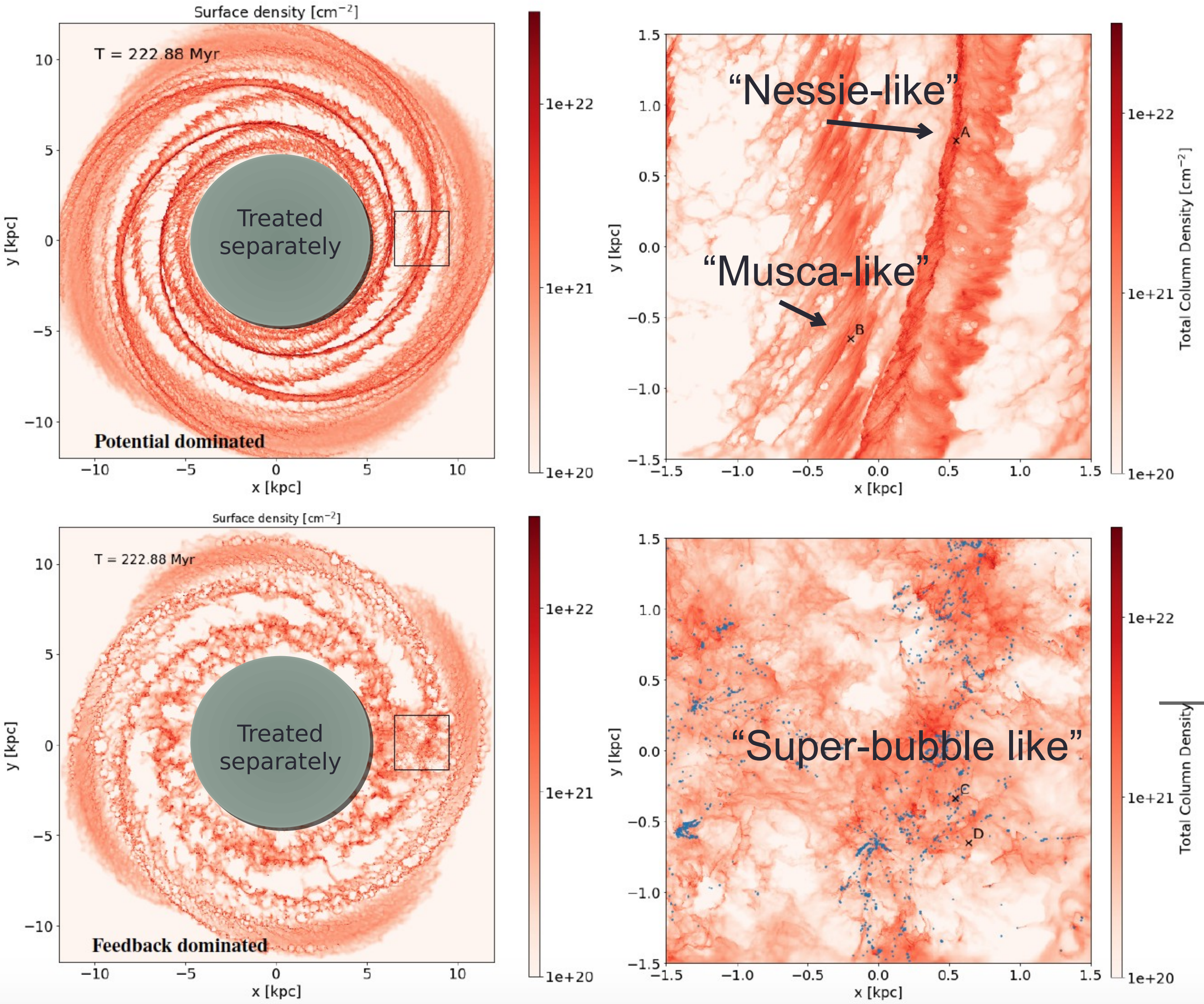


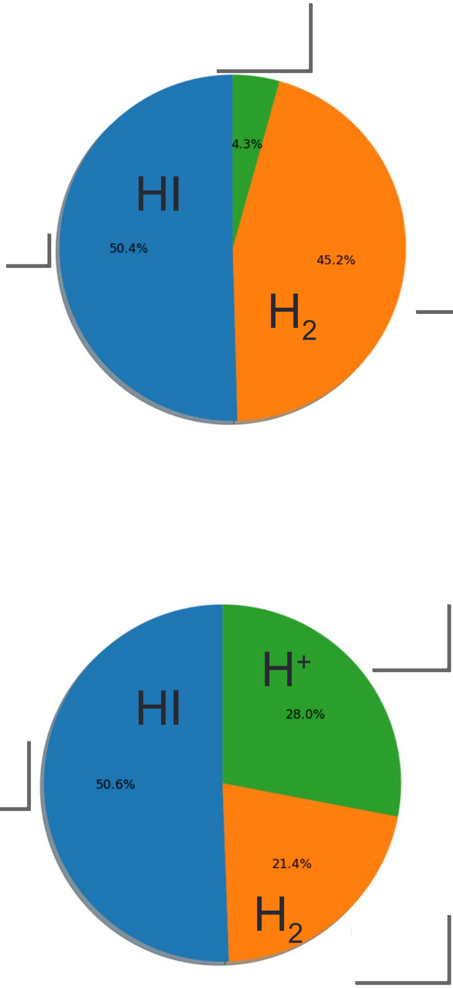
Little variation of Cloud Mass distribution in the disc – but substantial increase at the nucleus.

Scales of Gravitational Binding



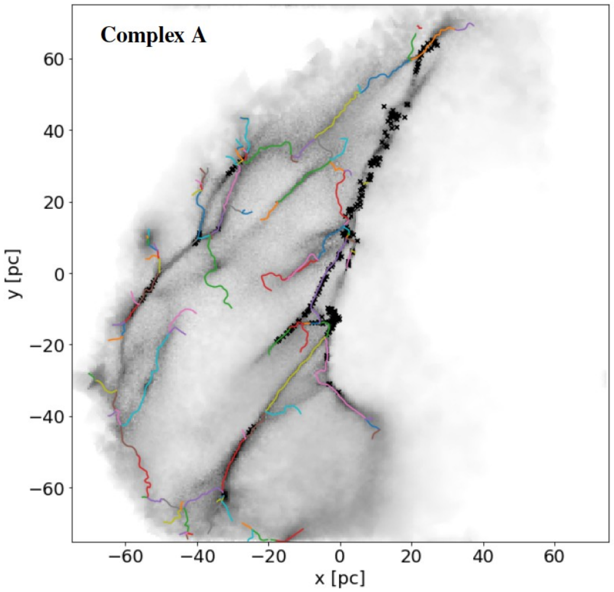
The Cloud Factory simulations

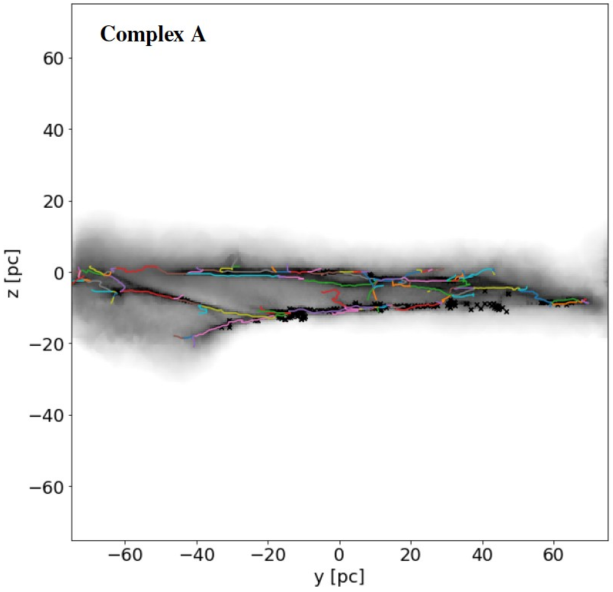


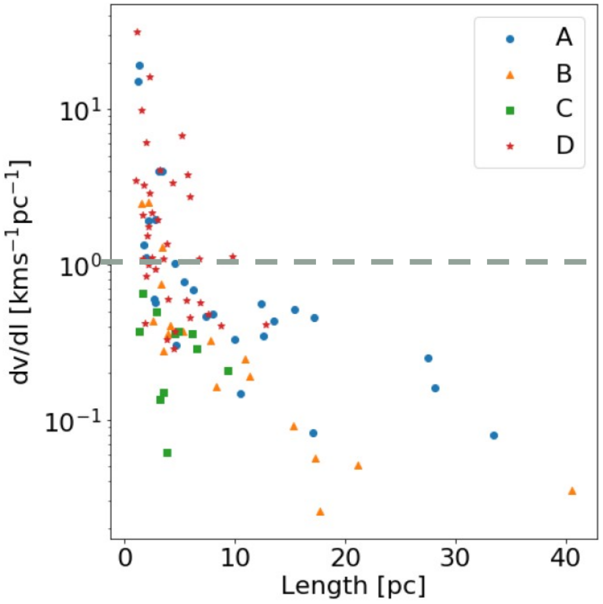


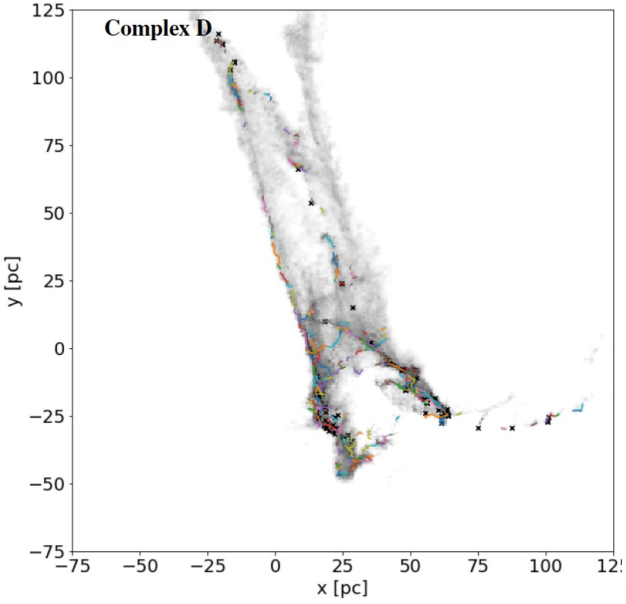
Smith et al. 2020

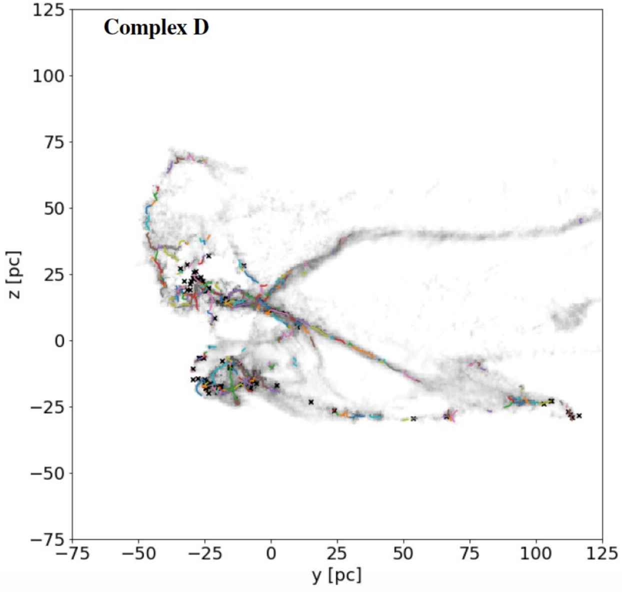
Different environment – different substructure





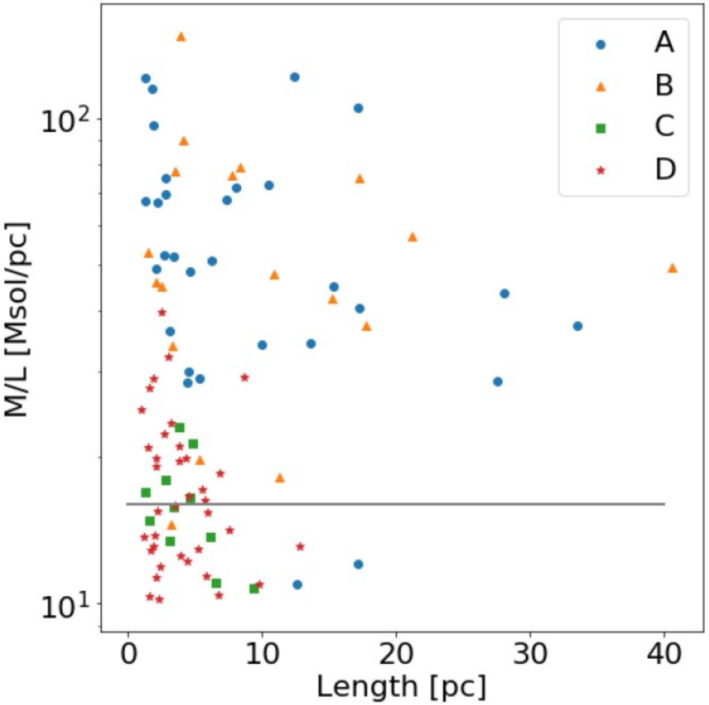


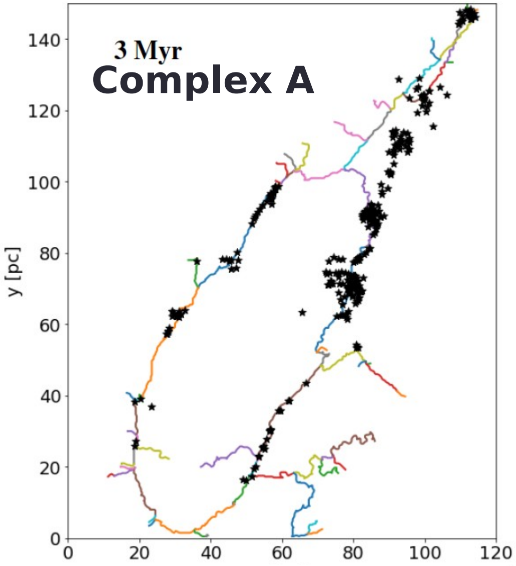


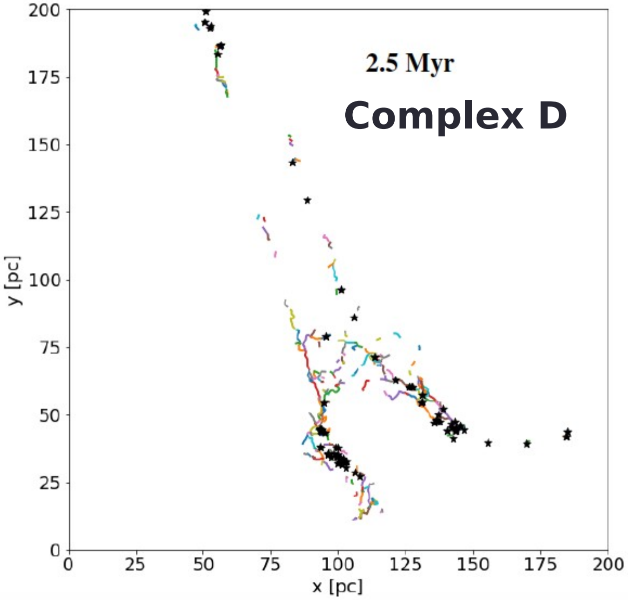


- Filaments **longer** in potential dominated regions.
- Long filaments are **coherent**.

Different environment – different fragmentation



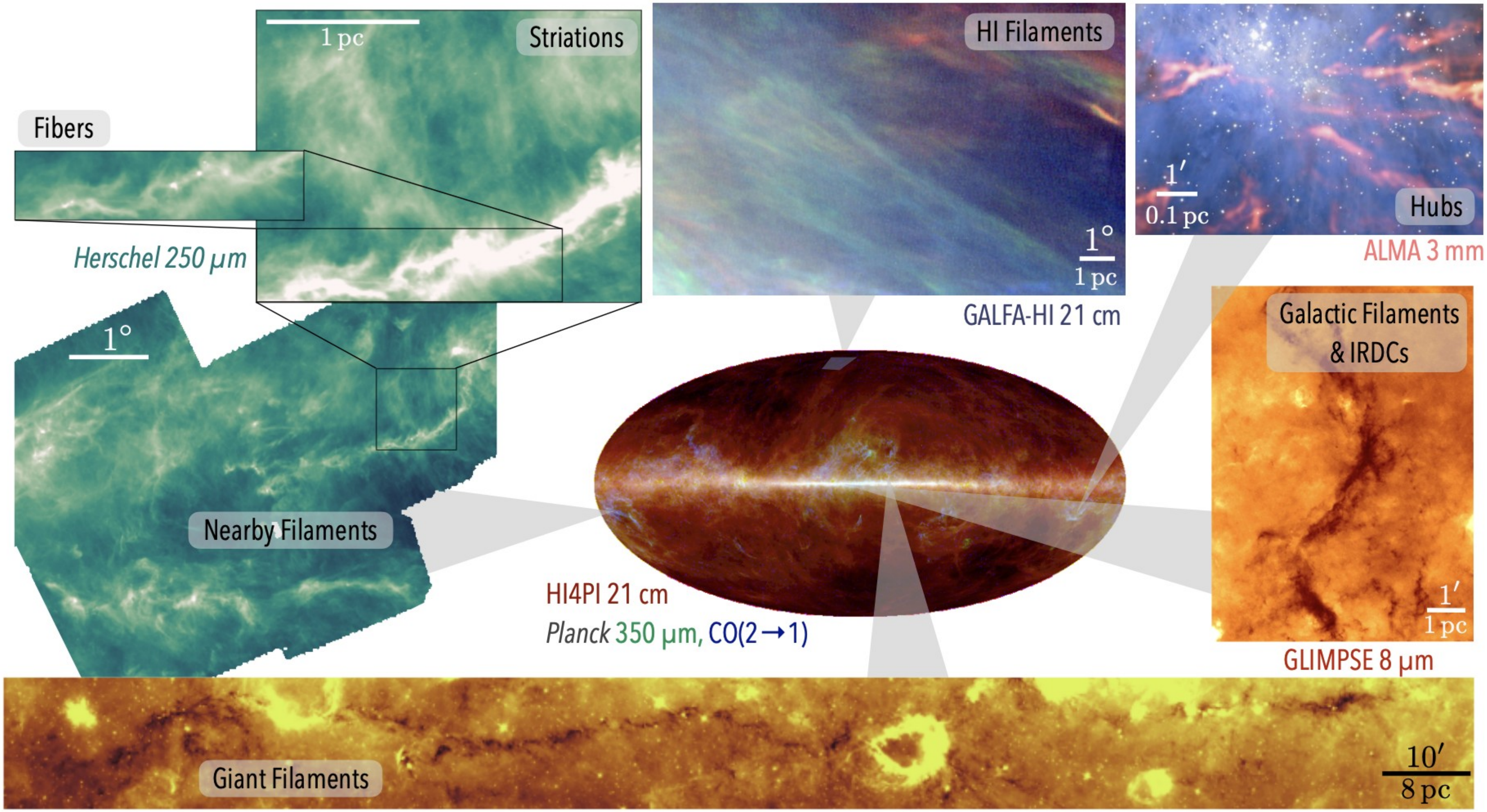




- Feedback dominated clouds are **less susceptible to filament fragmentation.**
- Star formation is **more distributed and sequential**.
- Do these stellar associations persist? E.g. Beccari+20, Kounkel19

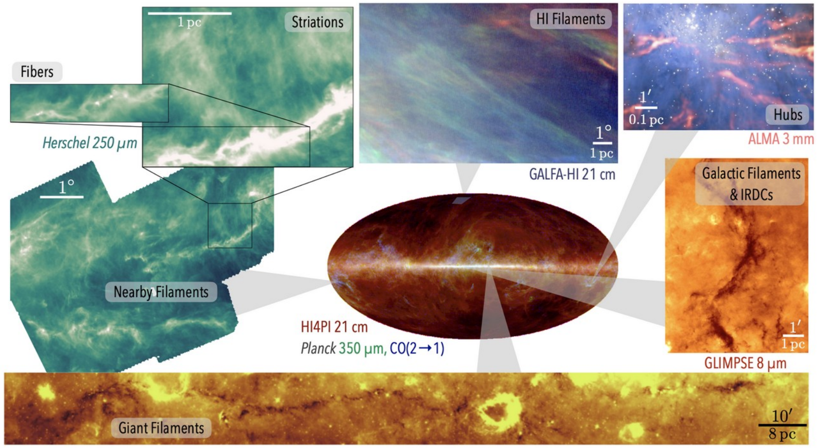
Connecting scales

Filaments


1 pc
Striations
Fibers
Herschel 250 µm
1°
Nearby Filaments
HI Filaments
1°
1 pc
GALFA-HI 21 cm
1′
0.1 pc
Hubs
ALMA 3 mm
Galactic Filaments
& IRDCs
1′
1 pc
GLIMPSE 8 µm
HI4PI 21 cm
Planck 350 µm, CO(2→1)
Giant Filaments
10′
8 pc

Meta-analysis

- 49 observational works
- **22,803** filaments
- Inhomogeneous with some multiple entries
- Incomplete, only < 5% include both velocities and B-fields

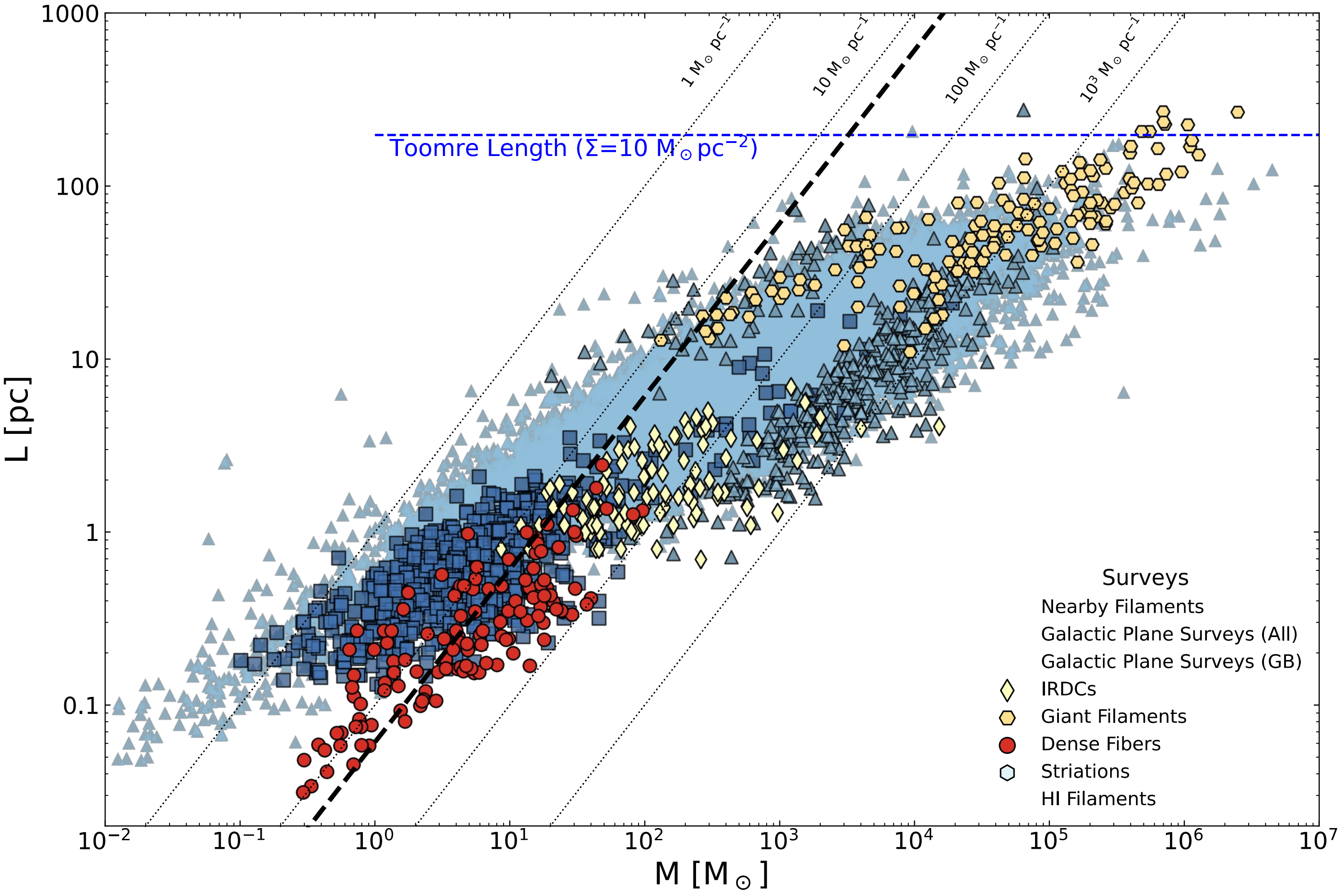


A large **community effort**:

- **Nearby Filaments***: Arzoumanian et al. (2013, 2019); Palmeirim et al. (2013); Nagahama et al.(1998); Kainulainen et al. (2016); Hacar et al. (2016a); Chung et al. (2021).*
- **Galactic Plane Surveys***: Schisano et al. (2020); Li et al. (2016); Wang et al. (2016); Mattern et al. (2018a); Xiong et al. (2019).*
- **IRDCs***: Schneider et al. (2010); Hennemann et al. (2012); Kainulainen and Tan (2013); Peretto et al. (2014); Lu et al. (2014); Beuther et al. (2015); Pillai et al. (2015); Chen et al. (2019); Busquet et al. (2016); Santos et al. (2016); Treviño-Morales et al. (2019); Leurini et al. (2019); Arzoumanian et al. (2021, 2022).*
- **Giant Filaments***: Contreras et al. (2013); Ragan et al. (2014); Zucker et al. (2018); Zhang et al. (2019); Colombo et al. (2021)*
- **Dense fibers***: Hacar and Tafalla (2011); Hacar et al. (2013, 2016b, 2017b); Hacar et al. (2018); Lee et al. (2014); Tafalla and Hacar (2015);Seo et al. (2015); Dhabal et al. (2019); Eswaraiah et al. (2021); Schmiedeke et al. (2021); Dhabal et al. (2018); Li et al. (2021b). Striations: Chapman et al. (2011); Panopoulou et al. (2016).*
- **HI Filaments***: Clark et al. (2014), Putman et al.*

Special thanks to D. Arzoumanian, E. Schisano, M.E. Putman, & E.Y. Chung

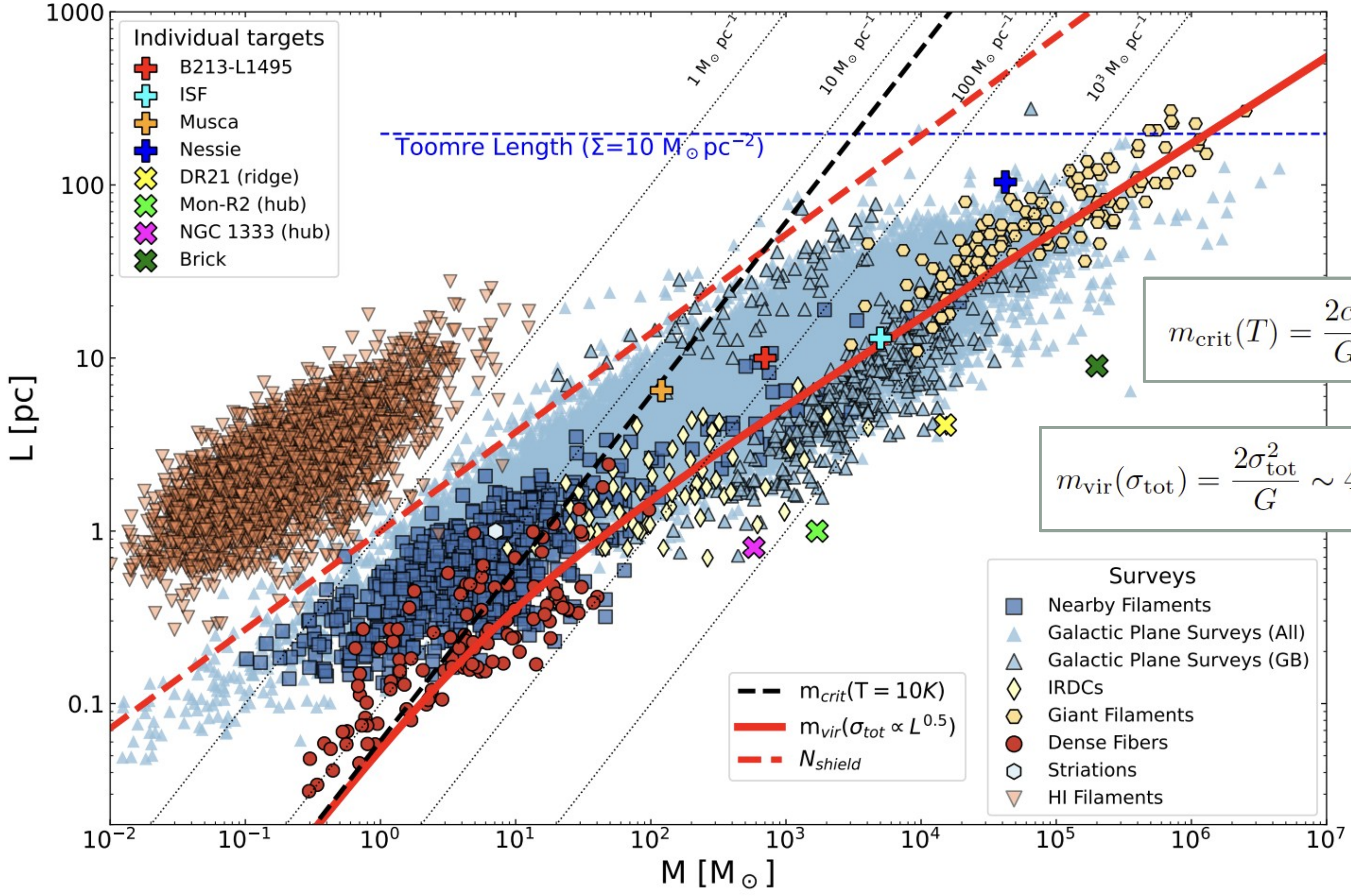
Mass and Length



- **Common scaling relation** across multiple orders of magnitude, $\mathbf{L} \propto \mathbf{M}^{0.5}$

Stability

Hydrostatic isothermal cylinders gravitational stability characterised by a **line mass** $m = \frac{M}{L}$

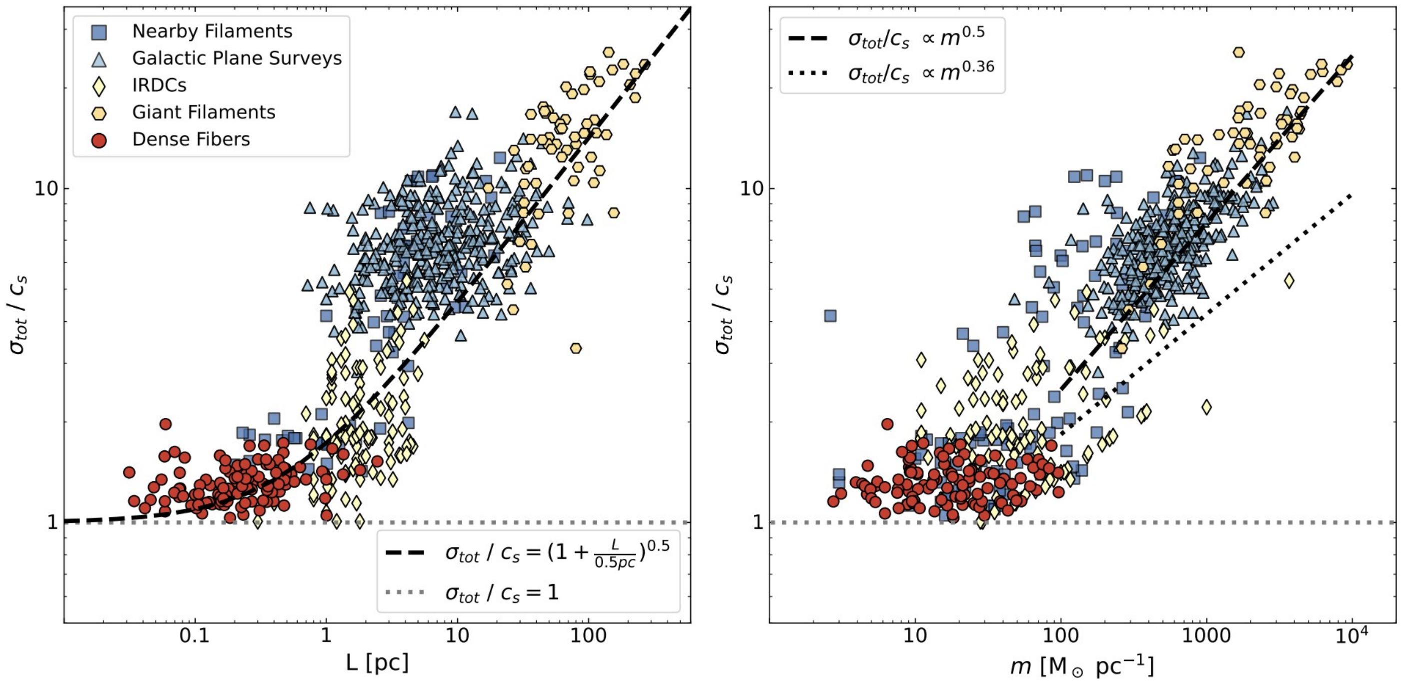


$$m_{\mathrm{crit}}(T) = \frac{2c_{\mathrm{s}}^2}{G} \sim 16.6 \left(\frac{T}{10\,\mathrm{K}}\right) \mathrm{M_\odot\,pc^{-1}}$$

$$m_{\mathrm{vir}}(\sigma_{\mathrm{tot}}) = \frac{2\sigma_{\mathrm{tot}}^2}{G} \sim 465 \left(\frac{\sigma_{\mathrm{tot}}}{1\,\mathrm{km\,s^{-1}}}\right)^2 \mathrm{M_\odot\,pc^{-1}}$$

e.g. Stodólkiewicz 1963; Ostriker 1964, Nakamura et al. 1993, Fischera and Martin 2012a

Velocity dispersion



Fibers have velocity dispersions close to the **sonic speed**, while giant filaments are **highly supersonic**.

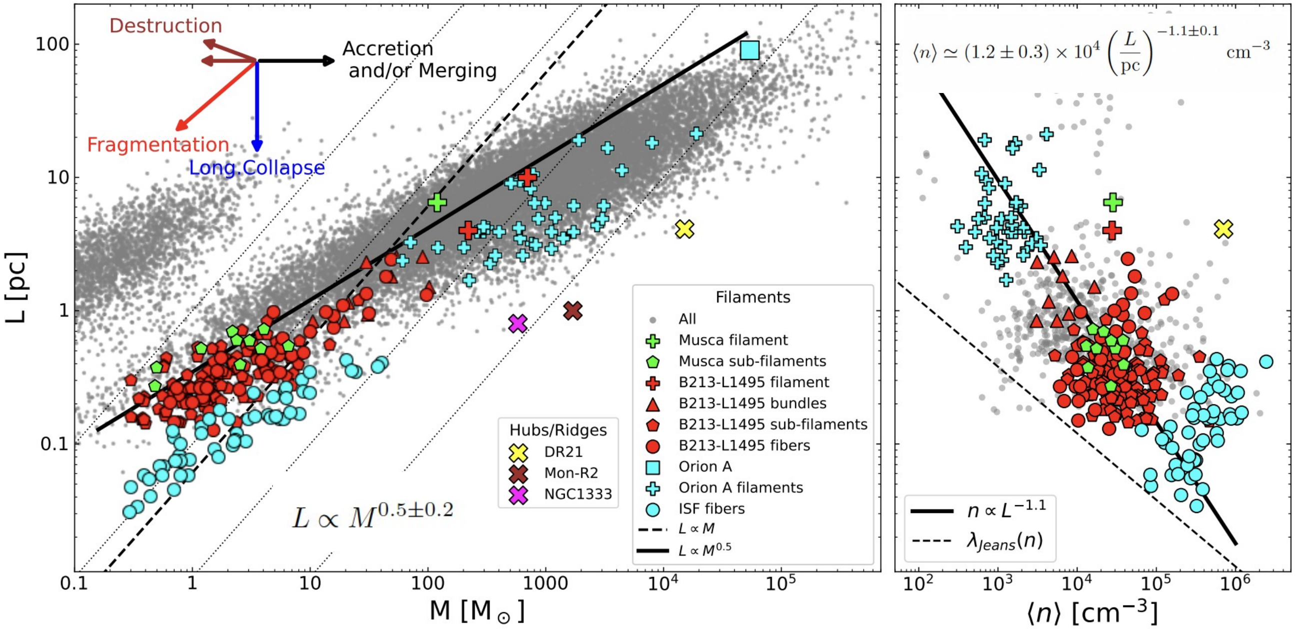
$$\frac{\sigma_{\rm tot}}{c_{\rm s}} = \left(1 + \frac{L}{0.5\,{\rm pc}}\right)^{0.5}$$

Non-thermal contribution increases with both length and line mass.

$$\sigma_{\rm tot}/c_{\rm s} \propto m^{0.5}$$

e.g. Hacar and Tafalla 2011, Arzoumanian et al. 2013, Wang et al. 2016, Mattern et al. 2018a

Filament Hierarchy



Observed filaments are self-similar networks of nested structure.

- Large scale filaments appear thermally supercritical but resolve into smaller (trans-) critical structures**. What does a line mass mean in this context?**

- **Mean** gas density increases with decreasing length.

- Ridges and hubs **depart** from mass-length and density-length correlations.

e.g. Schneider et al. 2011, Schisano et al. 2014, Henshaw et al. 2014, Chen et al. 2019, Shimajiri et al. 2019

Widths

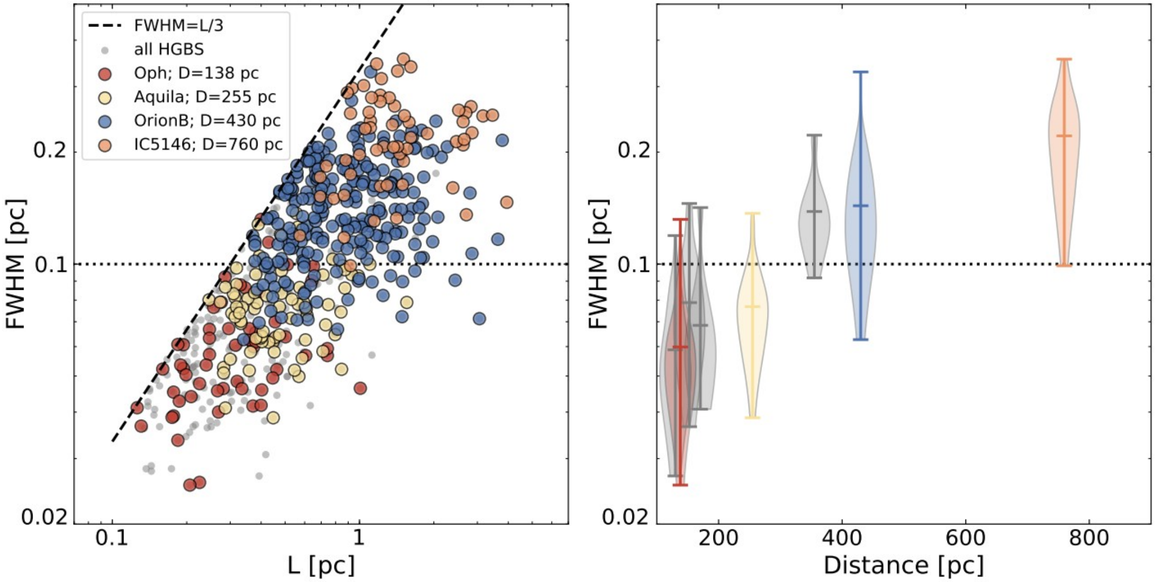
Herschel found a narrow distribution of widths in nearby clouds ~0.1 pc

However, **variation** in width is expected due to varying physics

A constant width does not fit all filament families, is not seen in all tracers, and varies along individual filaments.

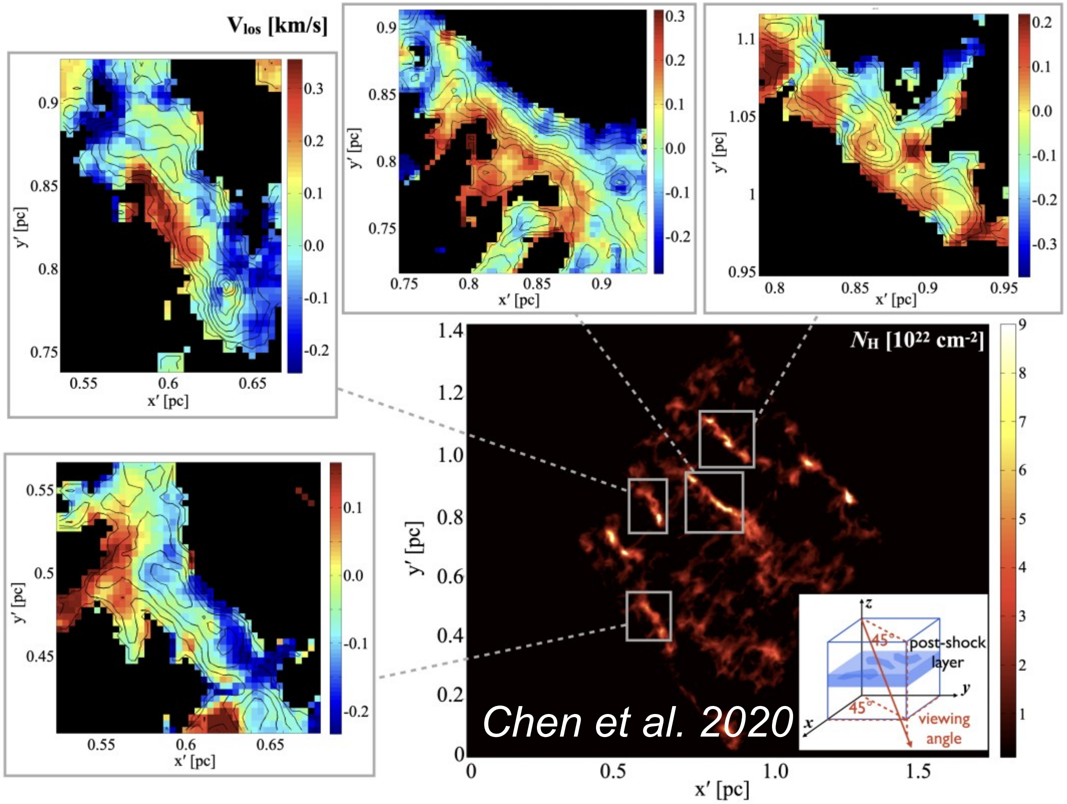
Re-analysing Herschel filaments with **updated distance estimates**:

- Linear correlation between length and width.
- Increasing width with distance (see also Hi-GAL)



e.g.: Arzoumanian et al. 2011, Hennebelle and André 2013, Heitsch 2013a, Smith et al. 2014b, Seifried and Walch 2015, Federrath 2016, Panopoulou et al. 2017, Suri et al. 2019, Panopoulou et al. 2021

The Role of Environment



Chen et al. 2020

External pressure confinement may suggest **dynamical or transient** filaments.

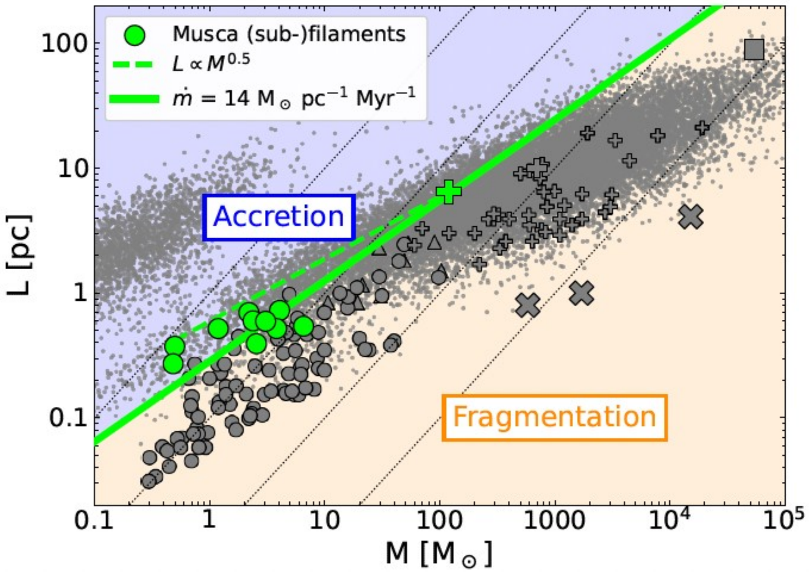
Massive filaments embedded in **higher column density** medium.

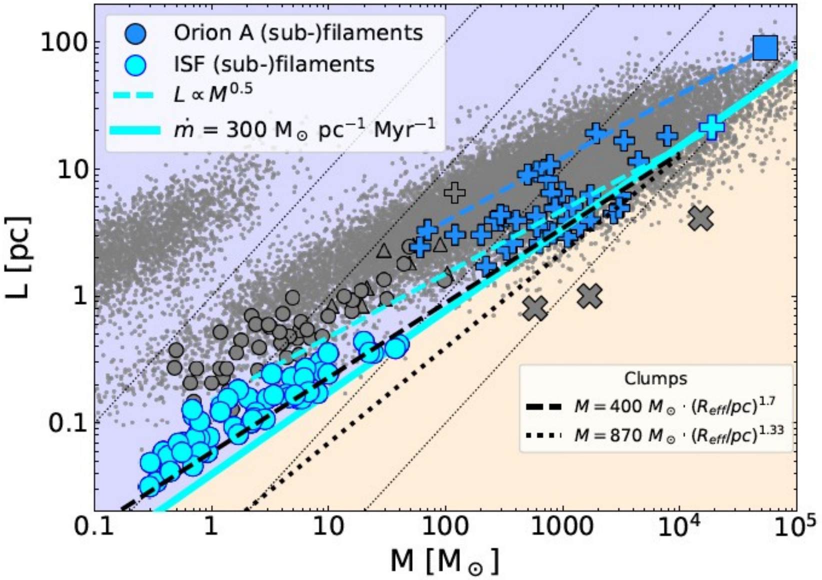
Simulations and observations see perpendicular velocity gradients indicative of **accretion onto** filaments.

Accretion may drive **turbulence**, but this is unlikely to be supportive.

e.g. Heitsch 2013b, Fischera and Martin 2012a, Kirk et al. 2013, Shimajiri et al. 2019, Klessen and Hennebelle 2010, Heigl et al. 2020, Seifried and Walch 2015,Clarke et al. 2017

Timescales & Normalisation





$$\tau_{\text{acc}} = \frac{M/L}{\dot{m}} \qquad \tau_{\text{frag}} \simeq 0.5 \cdot \left(\frac{L}{\text{pc}}\right)^{0.55}$$

Both accretion and fragmentation occur simultaneously.

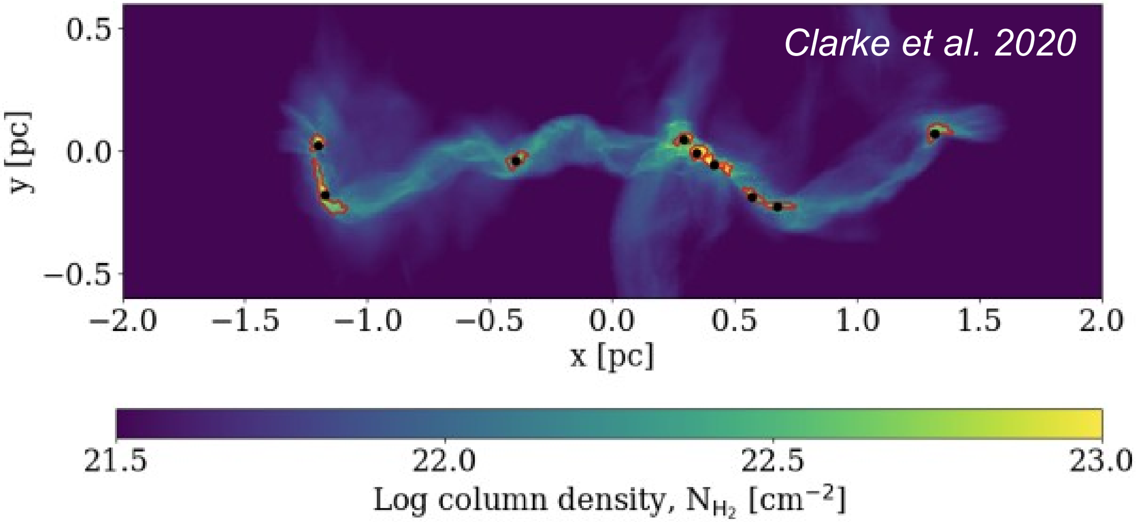
The rate of accretion sets the **normalisation** in the M-L space.

Hub systems tentatively formed above accretion rates of 500 $M_{\odot}pc^{-1}Myr^{-1}$

Fragmentation

Hydrostatic filaments fragment under gravity if perturbations exceed

$\lambda_{\rm crit} = 3.93 \cdot R_{\rm flat}$ with fastest growing mode $\lambda_{\rm max} \sim 2 \times \lambda_{\rm crit}$



Median fragmentation spacing similar to the observed width, but **rarely evenly spaced**.

Spacing may be **hierarchical** – small chains consistent with Jeans fragmentation, embedded in clumps determined by large scale gravitationally unstable modes.

e.g. Nagasawa 1987, Larson 1985, Inutsuka and Miyama 1992, 1997, Kainulainen et al. 2017, Clarke et al. 2017, 2019, Beuther et al. 2021, Zhang et al. 2020

Revisiting Larson's Relations

Larson

1) $\sigma_{tot} \propto L^{0.5}$

2) $M \propto L^{1.9}$

3) $n \propto L^{-1.1}$

Constant column density

Filaments

1) $\sigma_{tot} \propto L^{0.5}$

2) $M \propto L^{2}$

3) $n \propto L^{-1.1}$

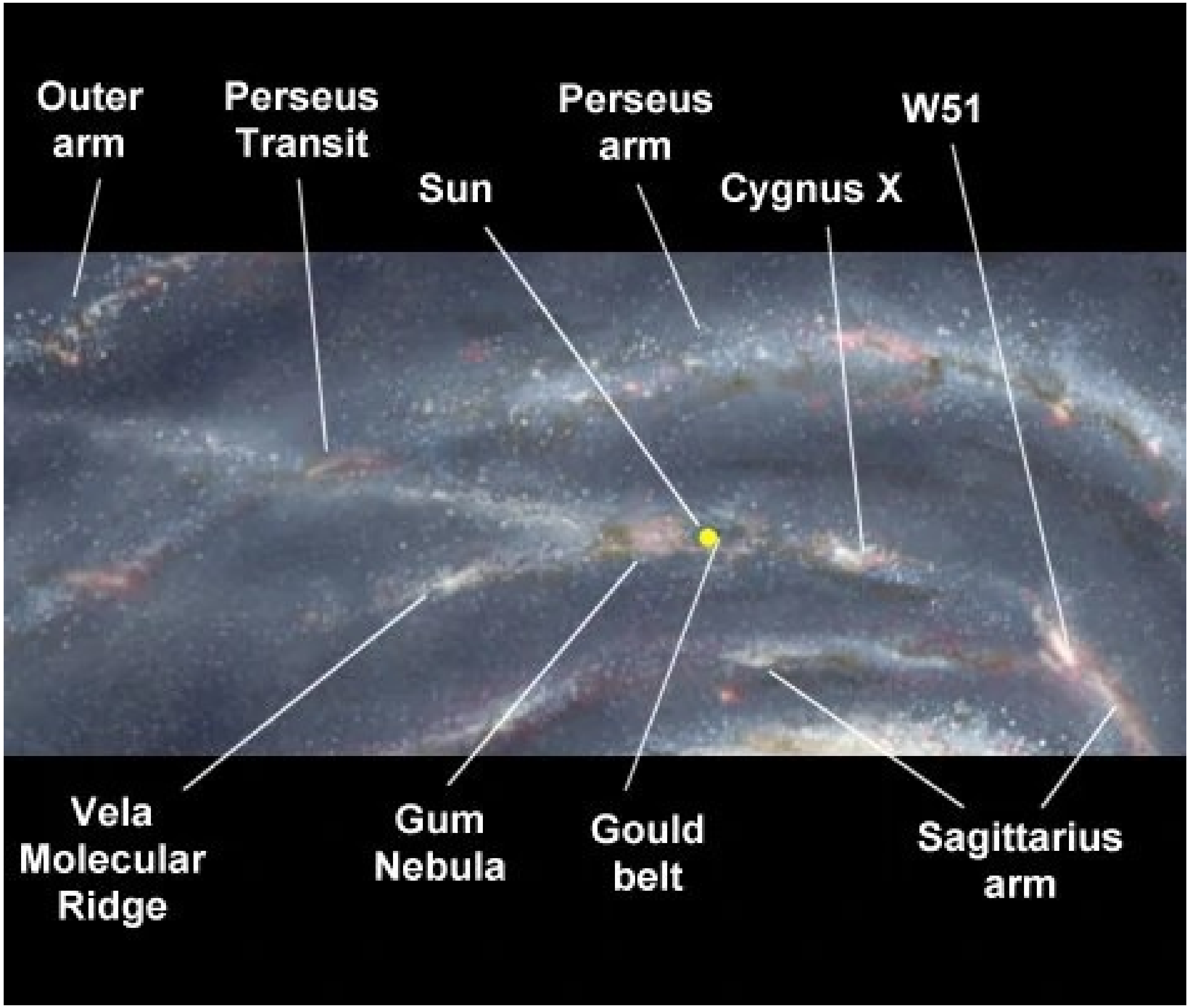
4) $FWHM \propto L^{\gamma}$

Varying column density

(1) + (2) implies energy balance in the **radial direction only**

Our back yard

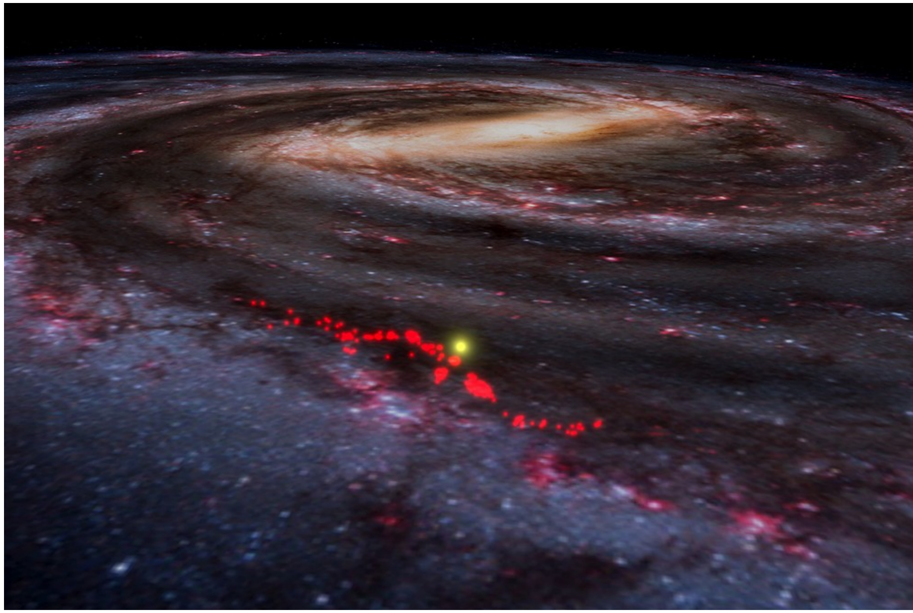
Our local environment

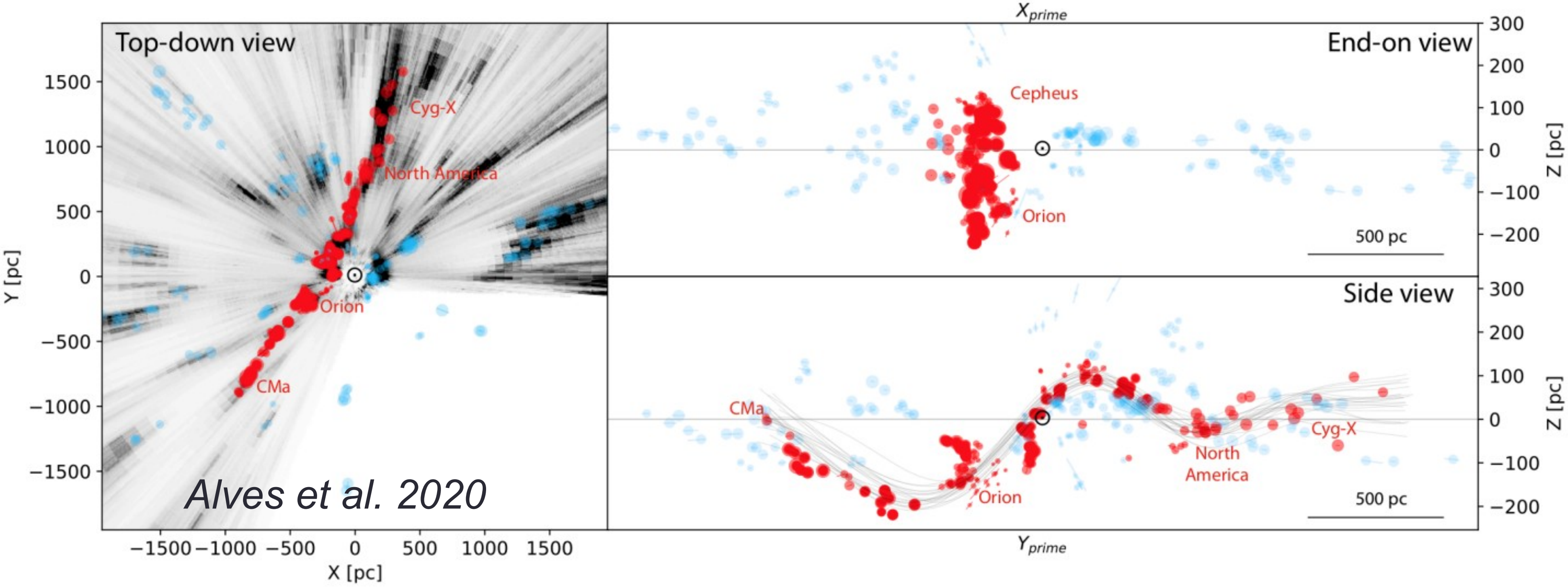


Radcliffe Wave

Local star formation regions seem to be connected.

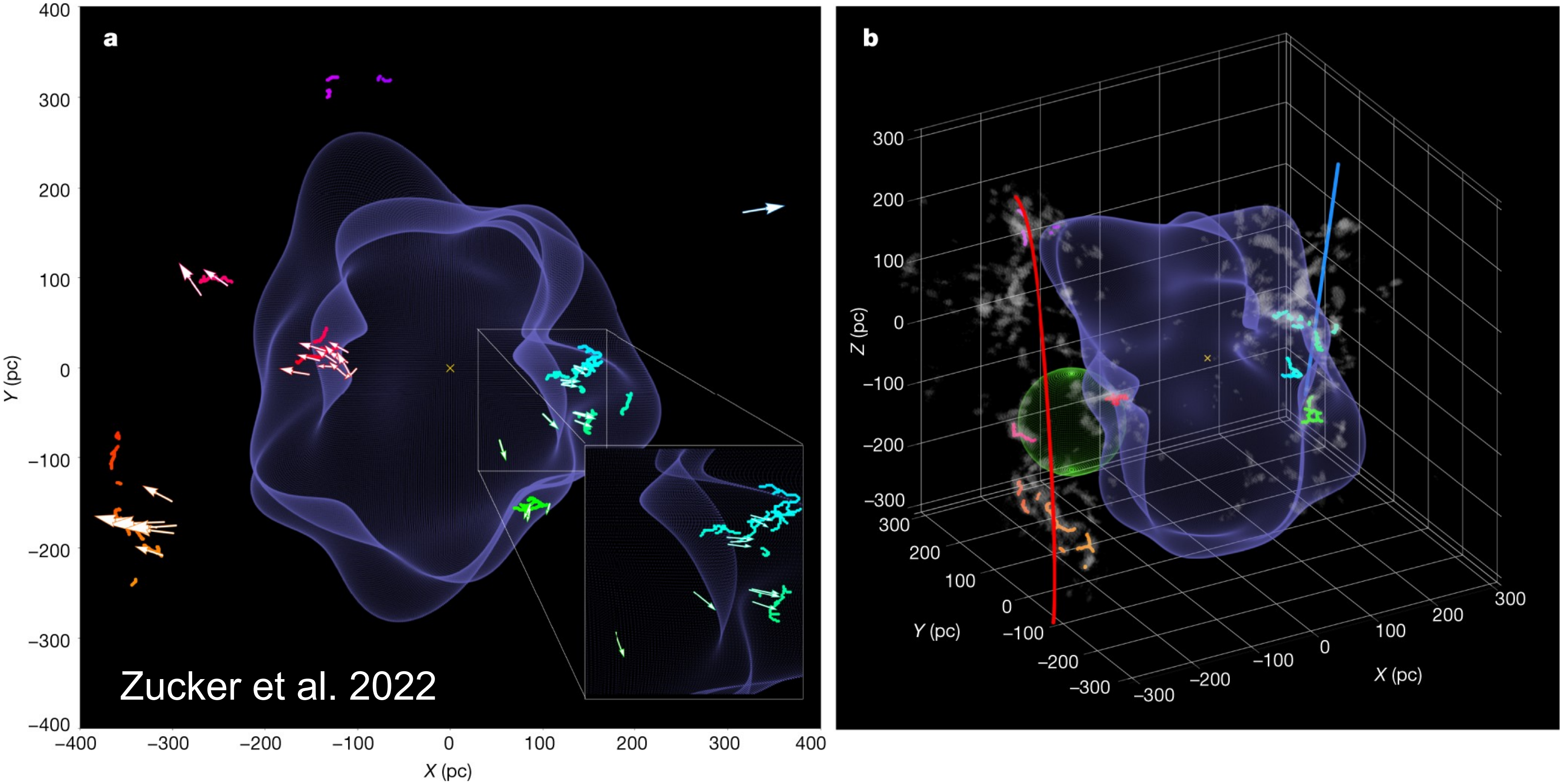
New 3D view of our local gas environment.





Alves et al. 2020

Local Bubble



Zucker et al. 2022

We are at the centre of the Local Bubble.

Nearby cloud appear to be on the rim of the bubble and are experiencing compression.

Summary

1. An Illustrative Example
2. Environments in the Milky Way
3. Forming Molecular clouds
4. Connecting the scales with filaments