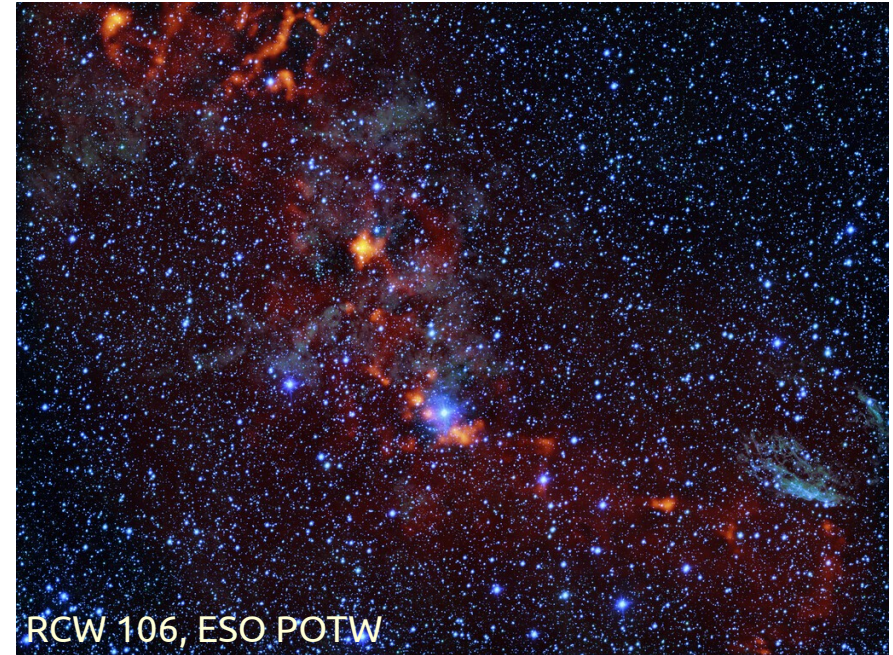
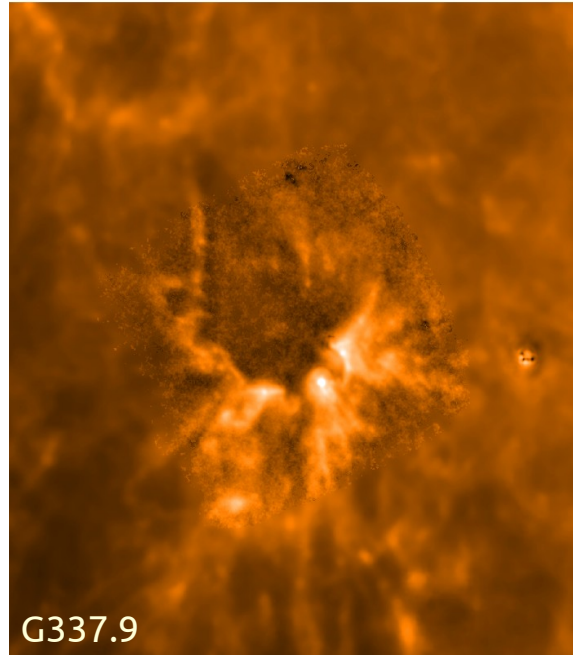
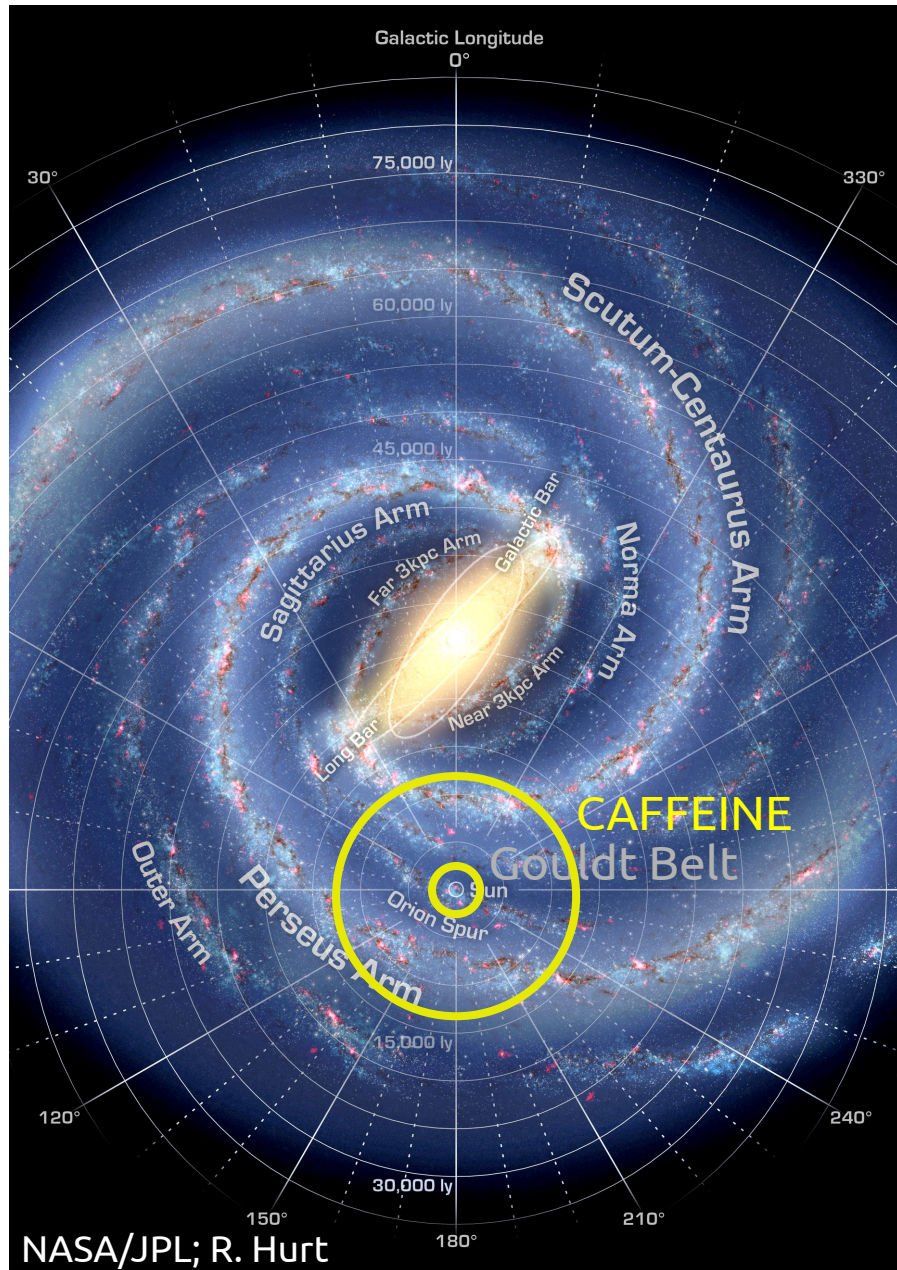


CAFFEINE: Understanding Star Formation Efficiency in Dense Gas

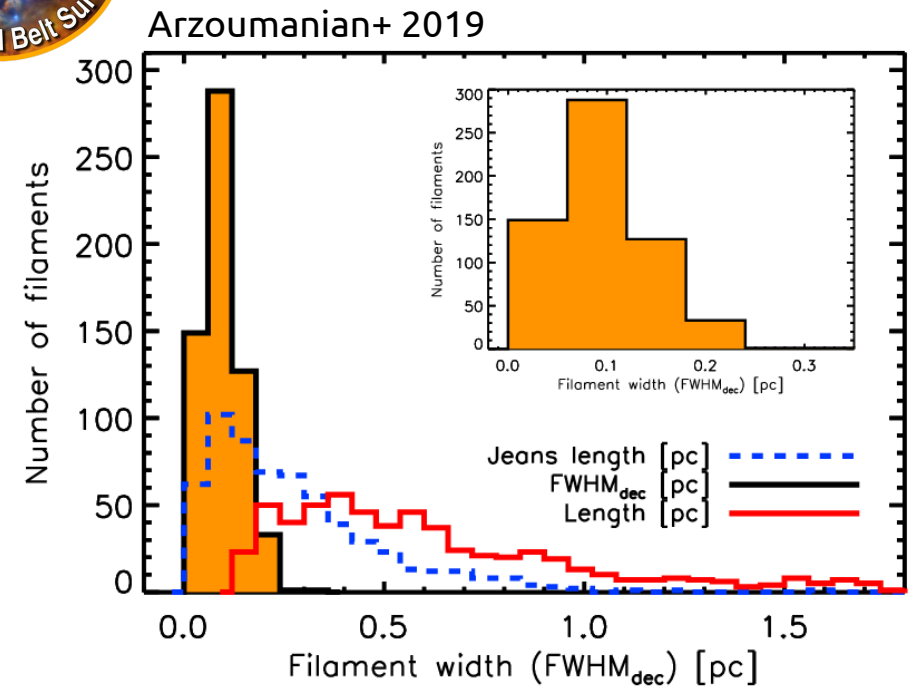
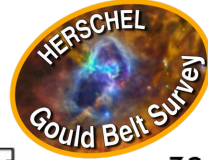
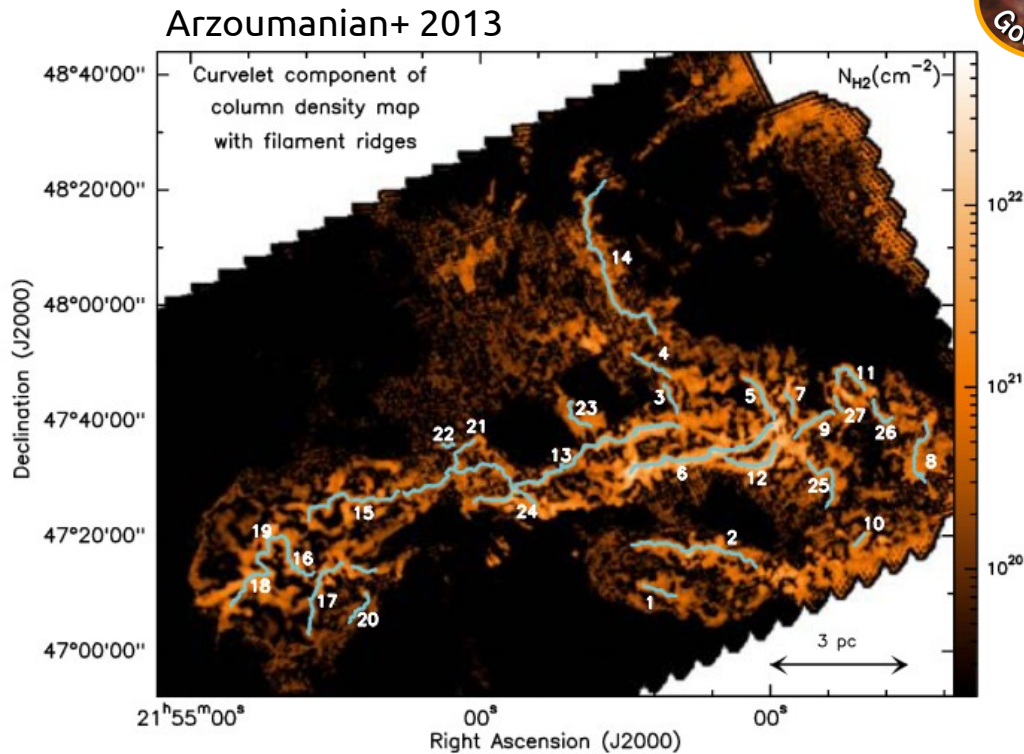
Michael Mattern (CEA Paris-Saclay, Lab. AIM),
Ph. André, A. Zavagno, D. Russeil, H. Roussel and the
CAFFEINE collaboration
(A&A, 2024, 688, A163)



Outlook



Star formation in filaments



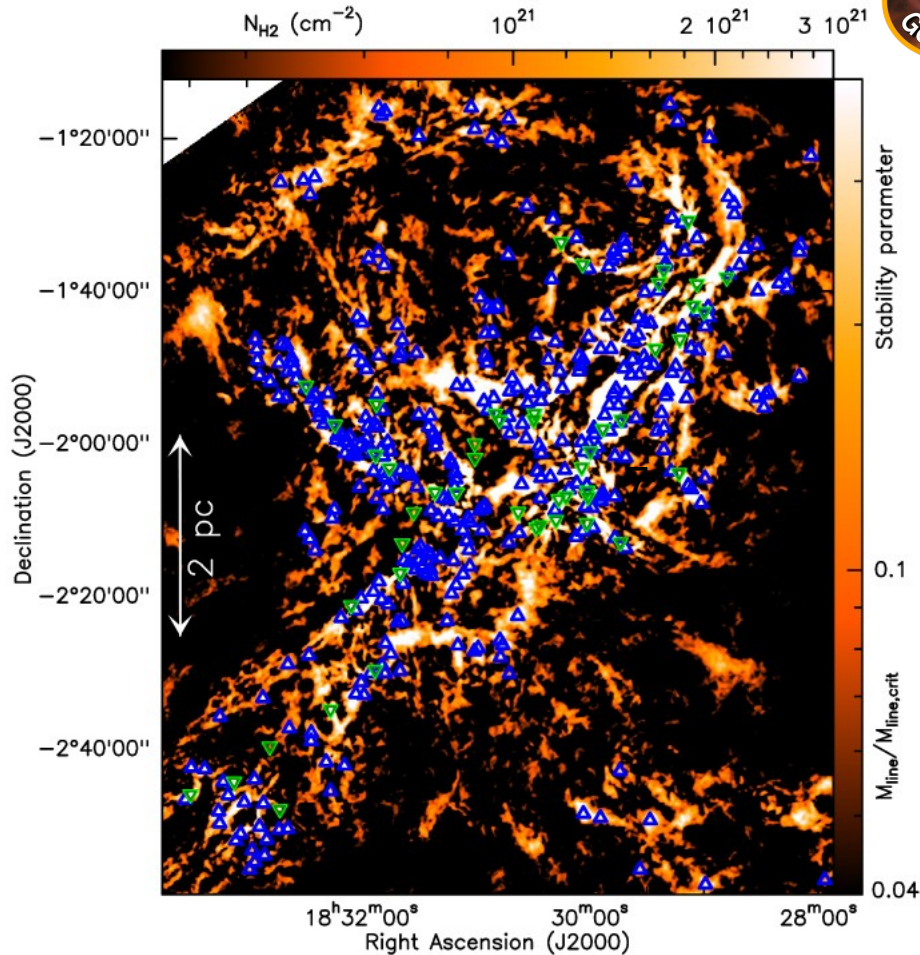
The cold interstellar medium is organized in filamentary structures and networks (e.g., Schneider & Elmegreen 1979; André+2010; Molinari+ 2010)

Filaments have a typical width of ~ 0.1 pc (Arzoumanian+ 2011, 2019; Palmeirim+2013; Koch & Rosolowsky 2015)

Some debate (cf. Panapoulou+ 2022), but tests support the result in GB clouds (cf. André+ 2022)

Star formation in filaments

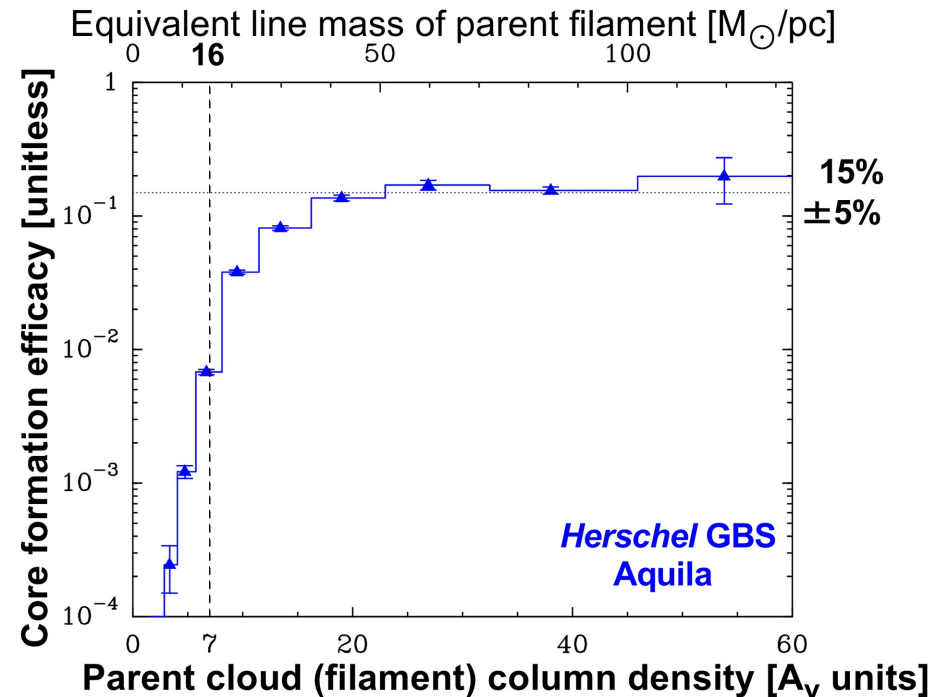
Könyves+ 2015



~75% of dense cores are associated with dense filaments
(Könyves+ 2015, 2020; Marsh+ 2016)

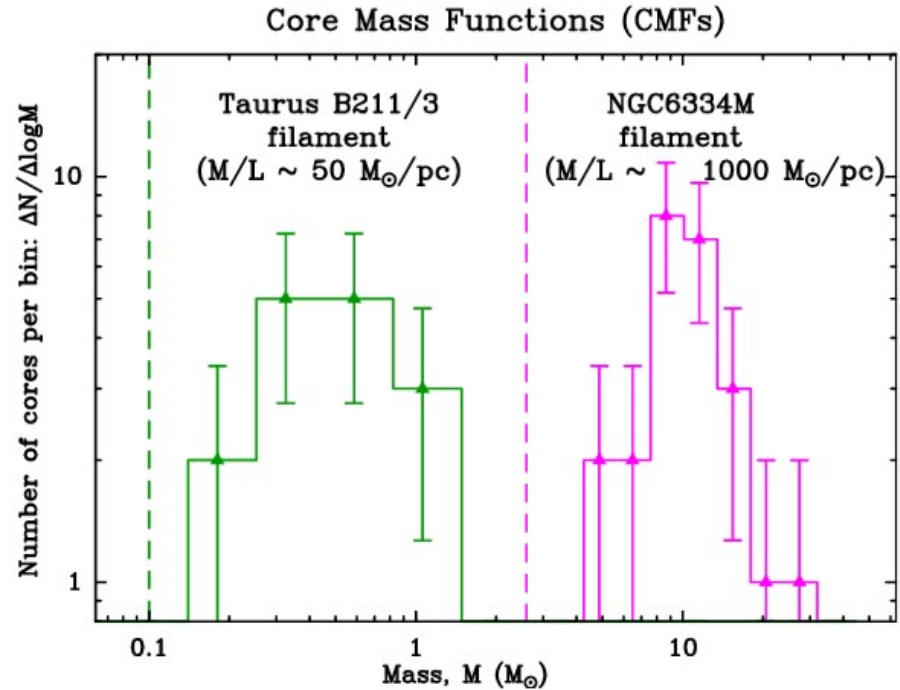
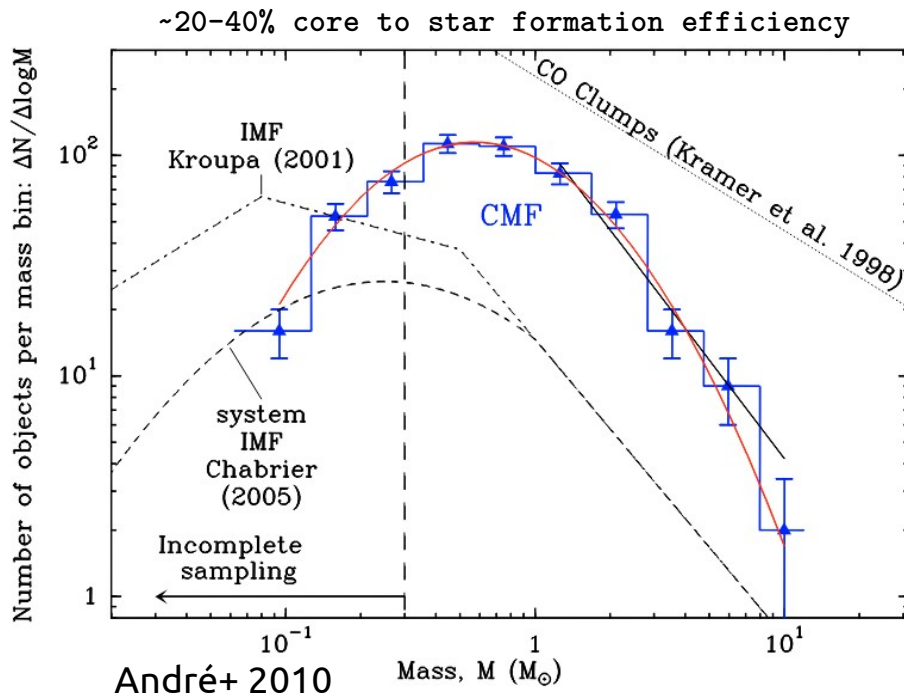
Könyves+ 2015

Core Formation Efficacy versus background A_V



The core formation efficacy quickly rises to ~15% for column densities above $N(\text{H}_2) \sim 8 \times 10^{21} \text{ cm}^{-2}$.

Filament Paradigm for Star Formation



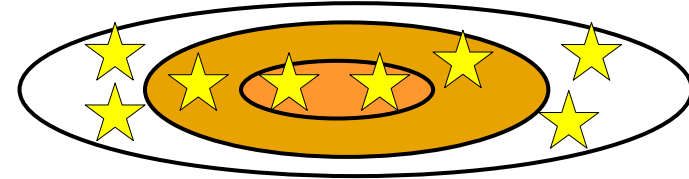
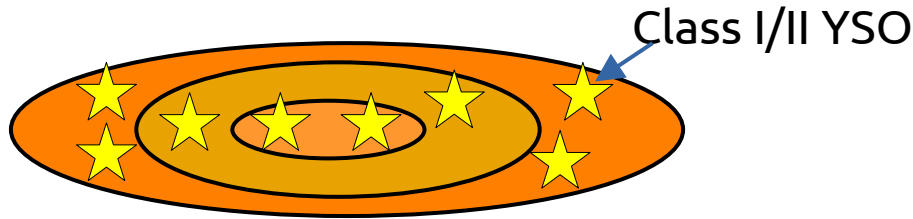
Adopted from Marsh+ 2016; Shimajiri+ 2019

- Large scale compression of the ISM in supersonic MHD flows create filaments
- Dense, thermally trans- or supercritical filaments fragment into prestellar cores

This scenario predicts: (André+2014)

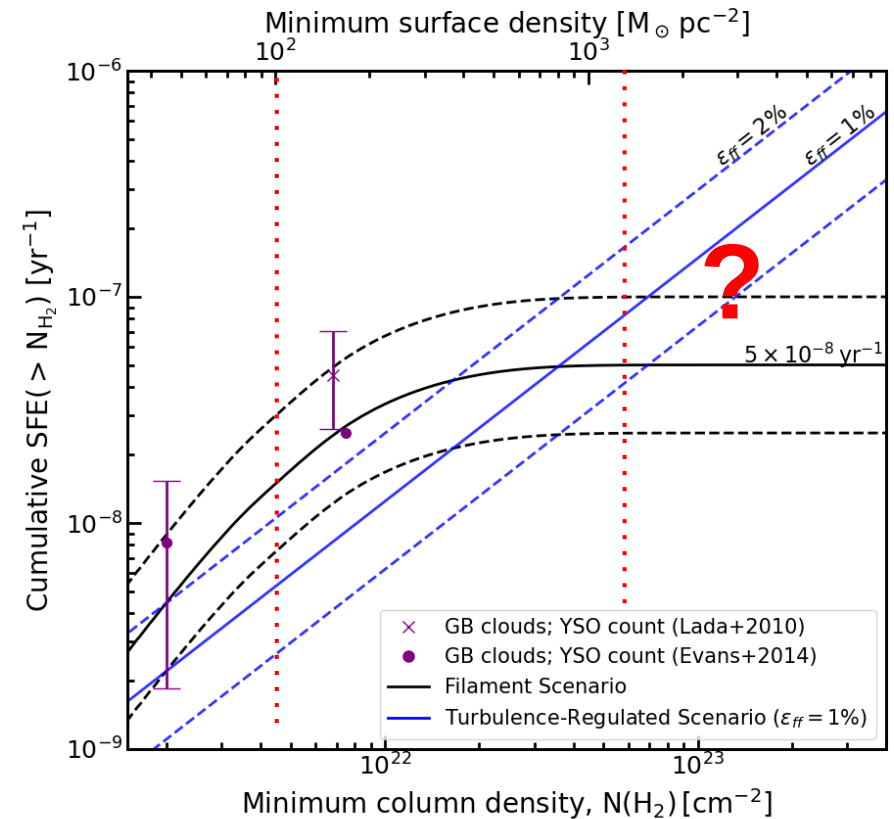
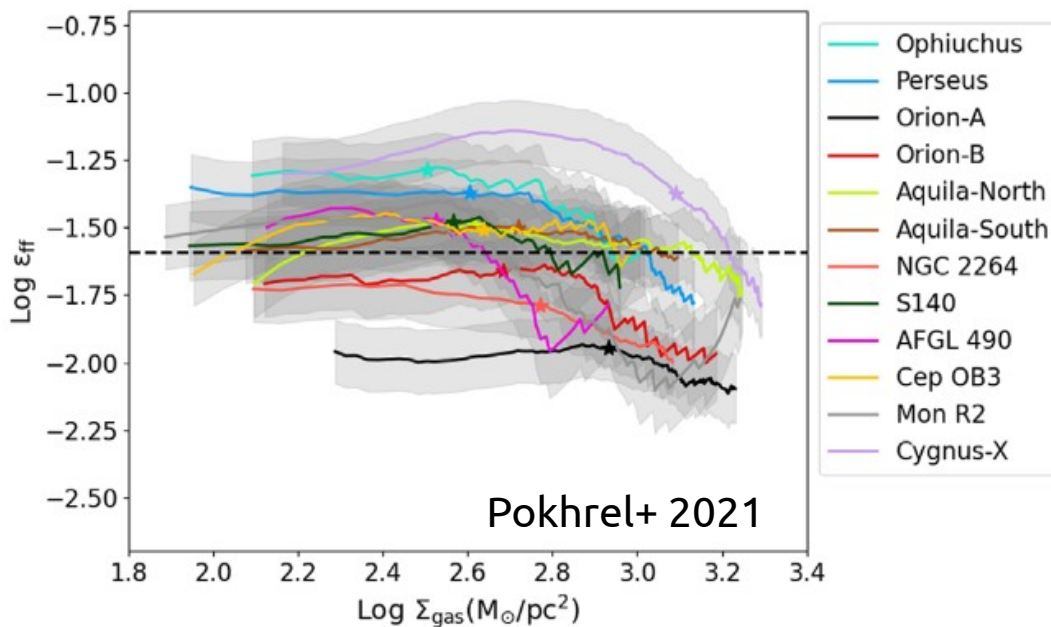
- Typical filament width of ~ 0.1 pc
- CMF is shifting with the line mass of the filament
- SFE is constant above a threshold

Star Formation Efficiencies



$$\text{SFE}(> N_{\text{H}_2}) = \frac{\text{SFR}(> N_{\text{H}_2})}{M_{\text{cloud}}(> N_{\text{H}_2})}$$

$$\epsilon_{\text{ff}} = \text{SFR} / (M_{\text{gas}} / t_{\text{ff}}) \text{ (e.g. Krumholz+2007)}$$



CAFFEINE with ArTéMiS

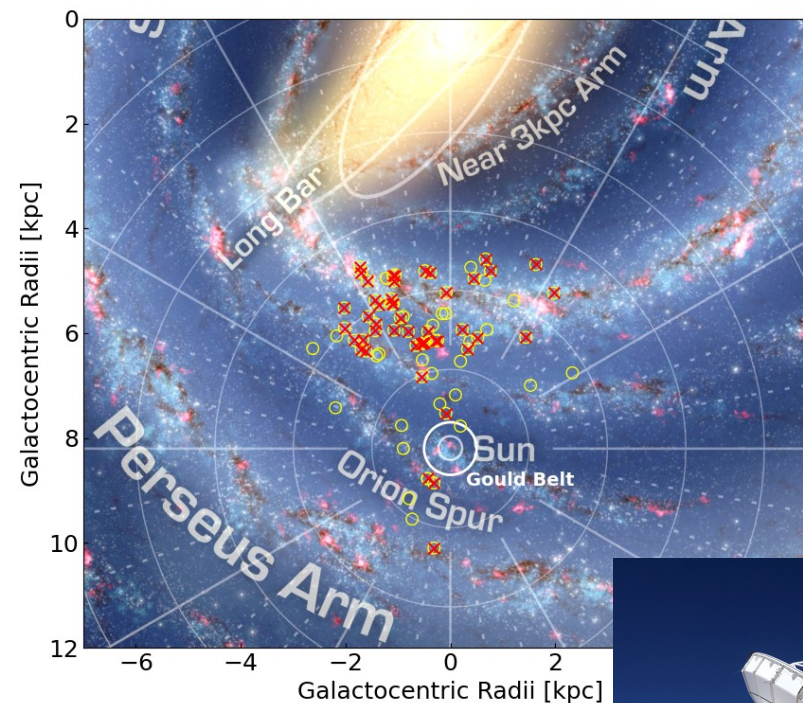
Core And Filament Formation and Evolution In Natal Environments

Goal:

- Target all regions of $A_V > 40$ mag ($N(\text{H}_2) > 4 \times 10^{22} \text{ cm}^{-2}$) within **3.0 kpc** from the Sun.
→ 80 regions, in total $\sim 5.5 \text{ deg}^2$
- produce column density maps with a **high spatial dynamic range** and **without saturation**
- Identify all filaments and cores and derive their properties

Observations:

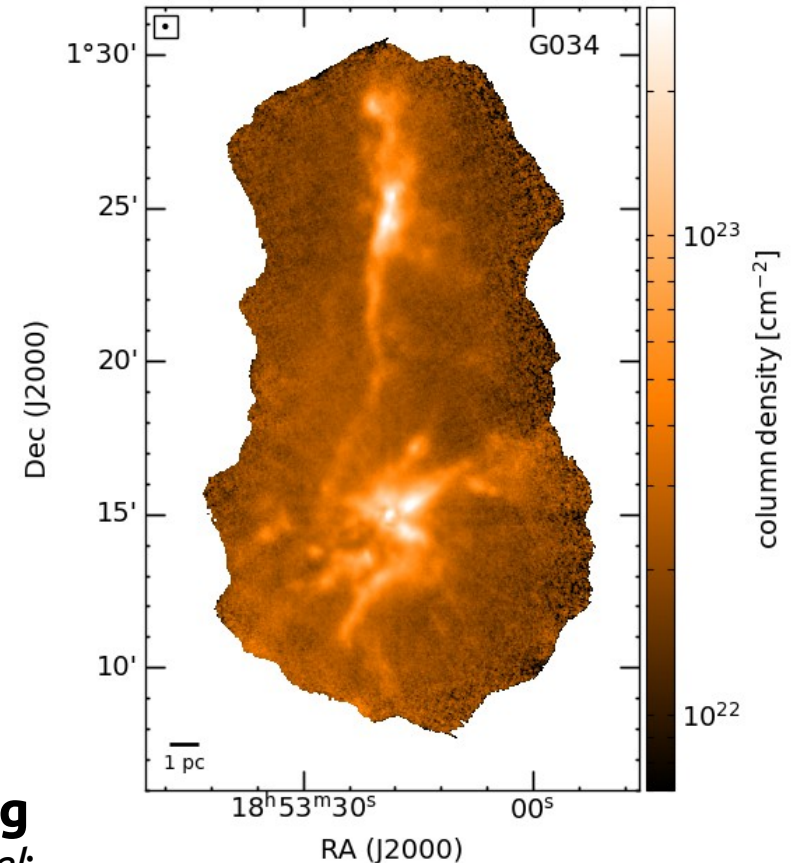
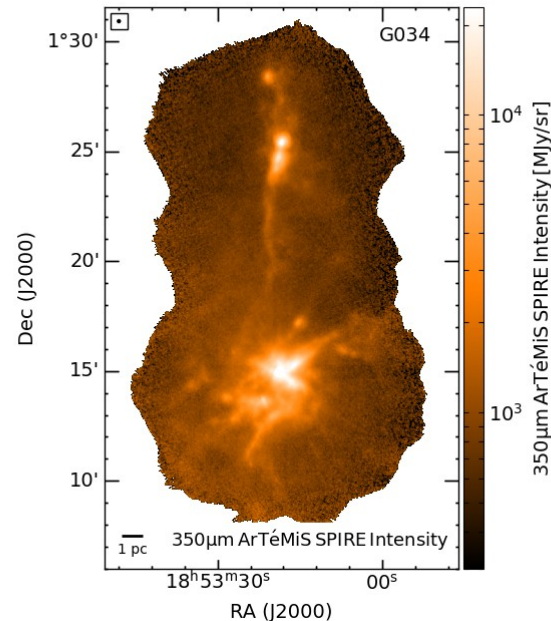
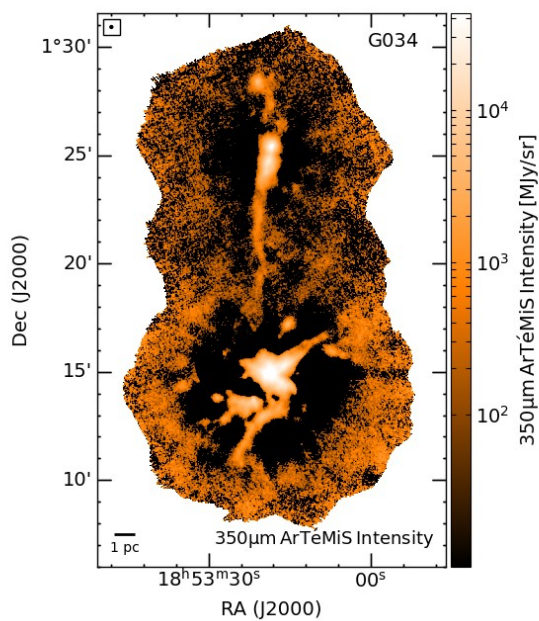
- **ArTéMiS** camera at APEX 12m telescope in Chile
- **Parallel imaging at 350 μm and 450 μm** continuum dust emission, **8''** and **10''** resolution (0.1 pc @3kpc)
- ESO large program 288h started August 2018
2/3 observed



<https://sites.google.com/view/caffeine-2024/home>



Combining Data



Recover large scales

combining data with *Herschel*/SPIRE 350 μm , 500 μm in UV plane:

- using MIRIAD (see Zavagno+ 2020)
- using *Scananmorphos* (Roussel 2013, 2018)

SED fitting

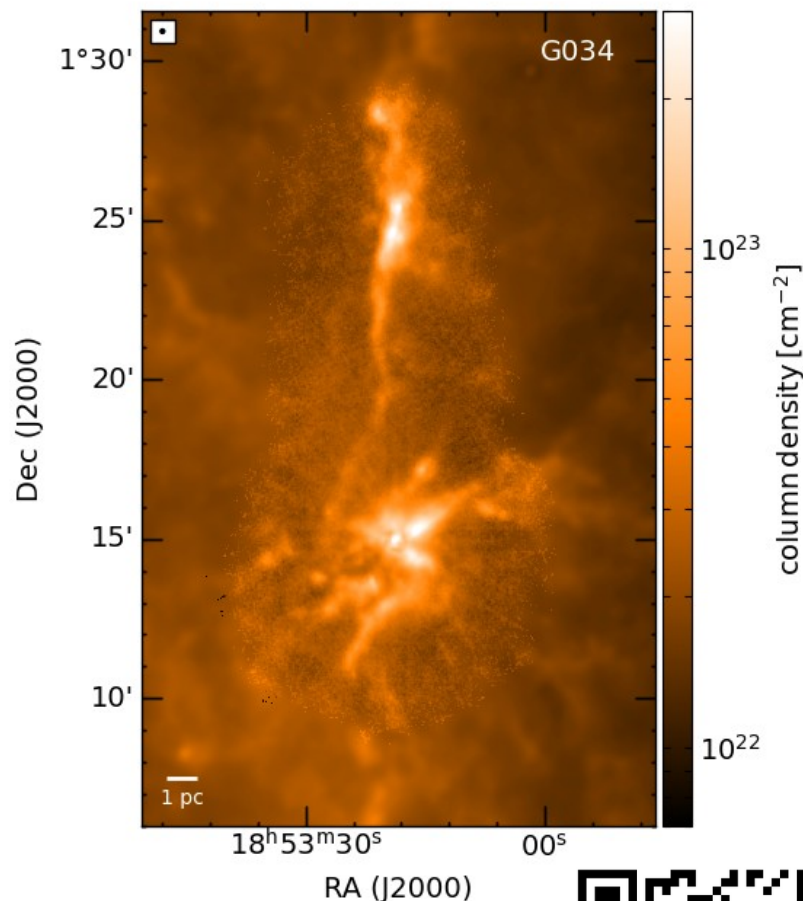
using *Herschel*:

PACS 70 μm , 160 μm , SPIRE 250 μm

Planck data for absolute calibration

See also Schuller+ 2021

High quality column density maps



Data products in
the ESO archive
~5 deg²



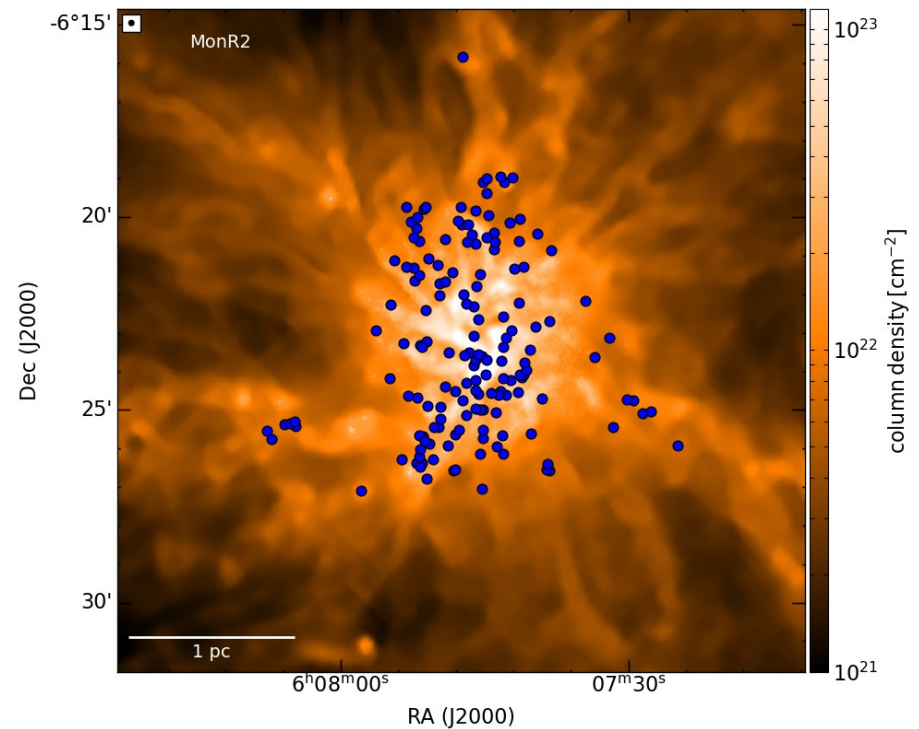
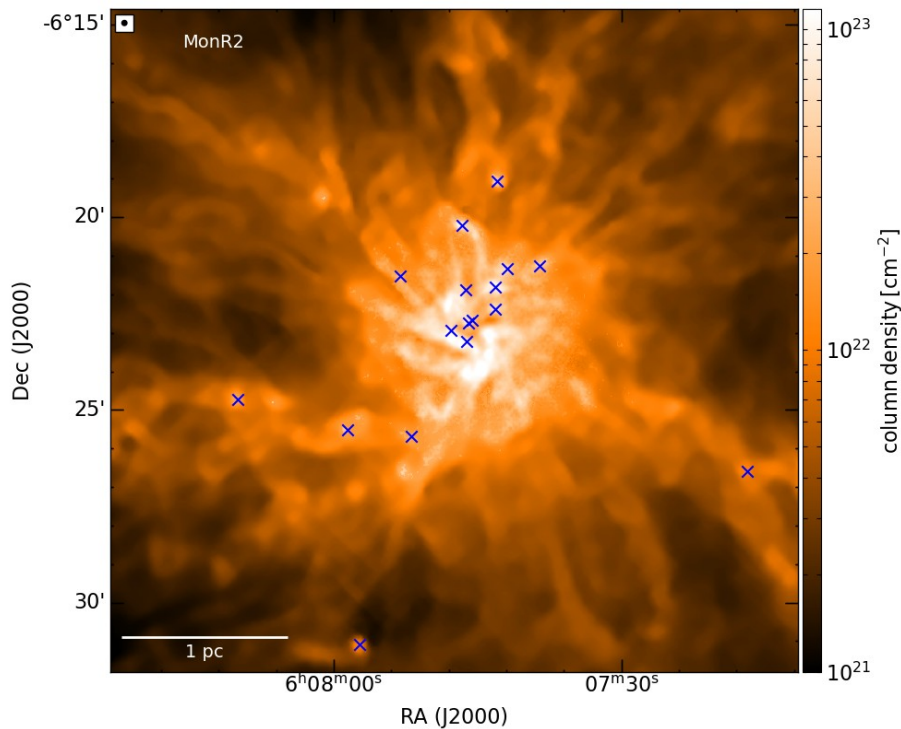
Preparing column density maps:

- **Multi-resolution** maps for all CAFFEINE targets
→ ArTéMiS combined/embedded in Herschel maps (cf. André+2016, Schuller+2021)
- **~4 times higher resolution** than default Hi-GAL column density maps (**8" vs. 36"**)
resolving **0.1 pc** scale up to **3 kpc** distance
- **Corrected for saturation** often affecting Herschel maps of massive star forming regions
- Line of sight contamination in the Galactic Plane is corrected with ¹³CO data from SEDIGISM, GRS, THRUMMS

Source selection for SFE study:

Area with $N(\text{H}_2) > 2 \times 10^{22} \text{ cm}^{-2}$ larger than 1 pc^2
→ 49 of 80 fields

Star Formation Rates



- Identifying Hi-GAL clumps associated with the cloud
- $\text{SFR}_{\text{clump}} = (5.6 \pm 1.4) \times 10^{-7} (M_{\text{clump}}/M_{\odot})^{0.74 \pm 0.03} M_{\odot} \text{yr}^{-1}$ (Elia+ 2022)
- $\text{SFR} = \sum \text{SFR}_{\text{clump}}$

- Identifying YSOs (Class I + II) from Spitzer catalogs and derive their masses.
- Mass distribution fitting
- $\text{SFR} = \frac{M_{\star}}{t_{\star}} \quad t_{\star} = 2.5 \text{ Myr}$
- (also see Russeil+ 2023)

Star Formation Efficiencies

Column density contours:

- From $7.1 \times 10^{21} \text{ cm}^{-2}$ to $2.2 \times 10^{23} \text{ cm}^{-2}$
- Spacing 0.15 dex

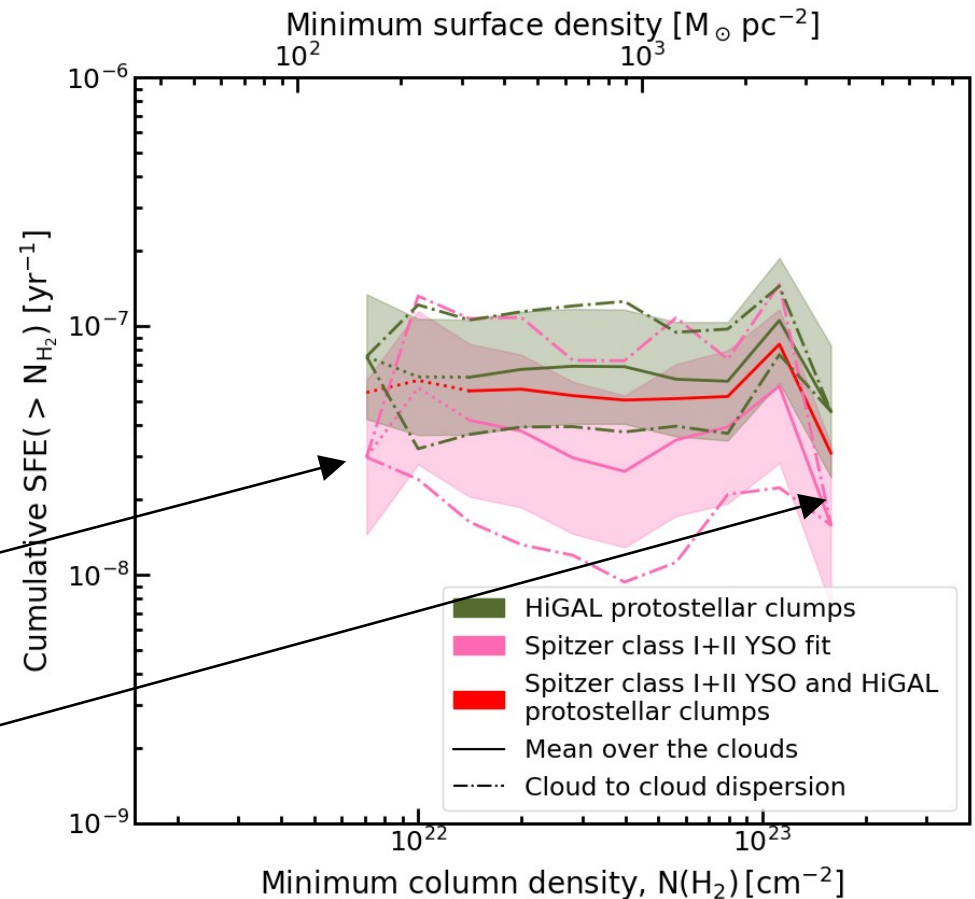
Weighted average SFE

Limitations:

- Closed contours/
line of sight contamination

- $N_{\text{obj}} > 5$

- $M_{\text{cloud}} \geq 2 \times \sum_i^{N_{\text{clumps}}} M_{\text{clump}}$



Broad agreement between the two methods

SFE essentially constant between 10^{22} cm^{-2} and 10^{23} cm^{-2}

Star Formation Efficiencies

SFR of Gould Belt clouds:

(André+2010, Megeath+2012, Dunham+2015, Lada+2017)

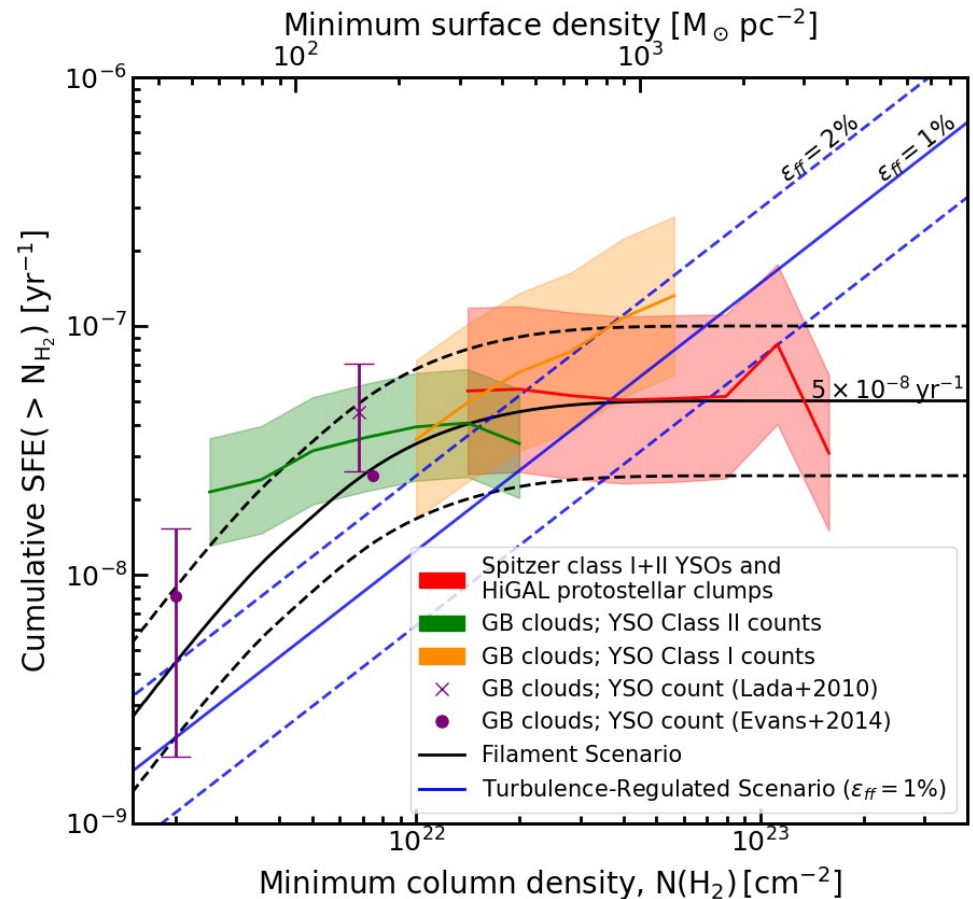
- Complete sample of YSOs for Class II $d < 0.3$ kpc \rightarrow 7 clouds
- $$\text{SFR}_{\text{Class II}} = \frac{N_{\text{Class II}} \times 0.5 M_{\odot}}{2.0 \text{ Myr}}$$
- Agreement with previous studies (Lada+2010, Evans+2014)

Better agreement with filament scenario

BUT...

- Complete sample of YSOs for Class I $d < 0.5$ kpc \rightarrow 12 clouds
- $$\text{SFR}_{\text{Class I}} = \frac{N_{\text{Class I}} \times 0.5 M_{\odot}}{0.5 \text{ Myr}}$$
- Agreement with previous studies (Pokhrel+2021)

Better agreement with turbulence regulated scenario



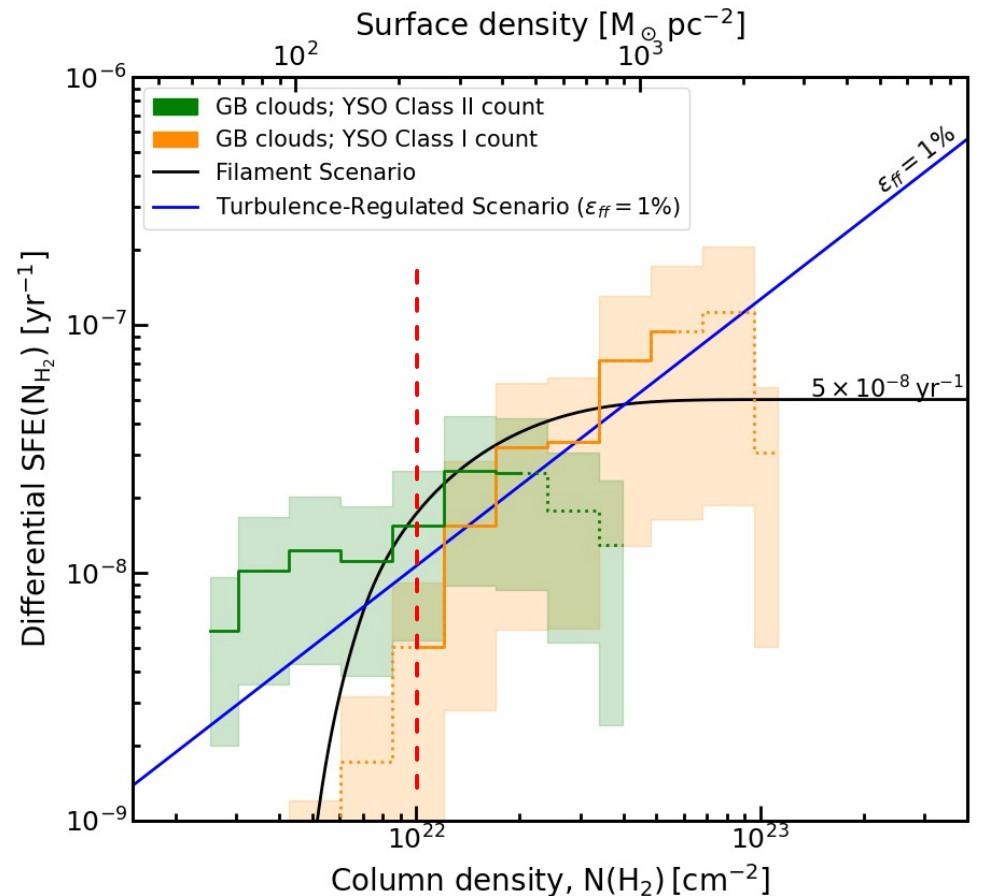
Star Formation Efficiencies

Differences between Class I and Class II estimates:

- Class I YSOs are younger
- Class I YSOs are more concentrated towards high column densities
- Class I evolution time is based on the Class II estimate

Possible explanations:

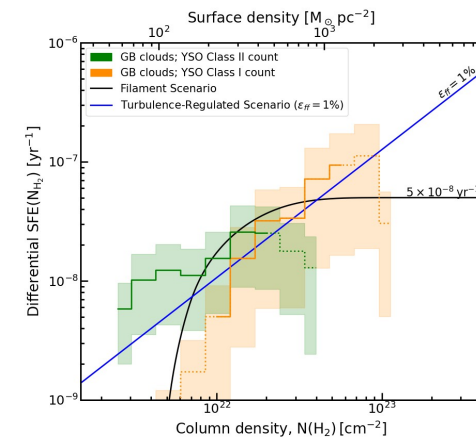
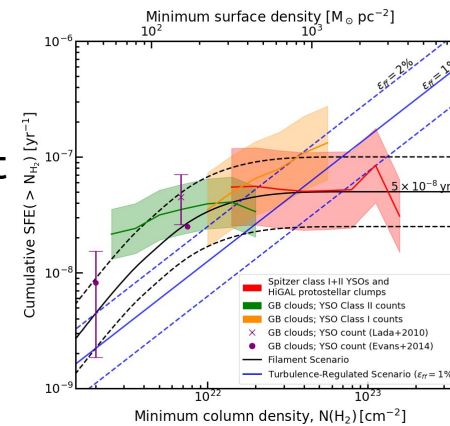
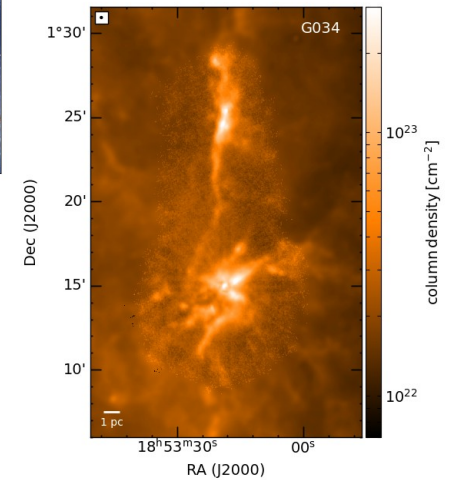
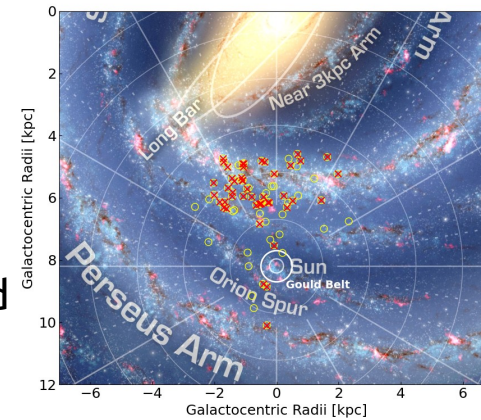
- YSOs decouple from their parent cloud and move from their birthplace.
- Star formation is episodic.



Star formation above column densities of $\sim 10^{22} \text{ cm}^{-2}$ (e.g., Onishi+2001, Johnstone+2004, Lada+2010)

Summary

- CAFFEINE survey observed 80 dense molecular clouds within 3 kpc from the Sun at 350 μm and 450 μm
- Created **unsaturated** multi-resolution (8"-18") maps, **~4 times higher resolution** than standard Herschel column density maps
- The average star formation efficiency is **essentially constant between 10^{22} cm^{-2} and 10^{23} cm^{-2}** with **SFE $\sim 5 \times 10^{-8} \text{ yr}^{-1}$**
- In nearby clouds, Class I YSOs are concentrated at column densities above **$\sim 10^{22} \text{ cm}^{-2}$** , suggesting a **star formation threshold**
- The observations are in **better agreement with the filament paradigm** than the turbulence regulated scenario.
- CAFFEINE provides large scale calibration for filament studies with JWST



Thank You!



Special thanks to the
ESO and APEX staff!



A. Lundgren