Molecular clouds & filaments

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MARIE CURIE ACTIONS

April 2007 - Gainesville, FL

Hans’ wonders of star formation

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Session topics at this meeting:

1. Molecular clouds and filaments
2. Low mass star formation
3. High mass star formation
4. Jets and outflows
5. Triggering and feedback from massive stars
6. Multiple systems
7. Clusters
8. Galactic context
9. The initial mass function (IMF)

Molecular clouds and filaments

This talk will be:

- Observationally (Milky Way) driven and definitely biased / incomplete.

I will discuss:

- Definition(s) of molecular clouds
- Challenges in understanding cloud formation
- Cloud substructure & interpreting molecular gas tracers
- Ubiquity of filamentary morphology

Molecular clouds

The term "cloud" refers to a structure in the ISM separated from its surroundings by the rapid change of some property, such as pressure, surface density or chemical state.

… The molecular cloud boundary is usually defined by the detection, above some threshold, of emission from the lower rotational transitions of CO. Alternatively, a certain level of extinction of background stars is often used.

Kennicutt & Evans (2012, ARAA)

CO surveys of Galactic plane

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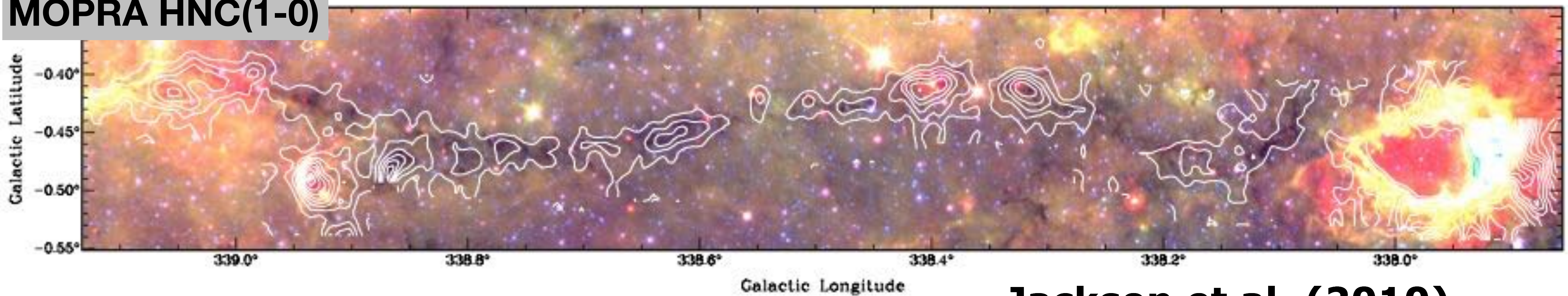
- **Colombia/CfA** - ^{12}CO(1-0) - Dame+2001 (mixed) / **USMB**, θ = 45”, 1 km s^{-1} - Clemens+1986
- **Galactic Ring Survey GRS / FCRAO** - ^{13}CO(1-0) - Jackson+2006
    - 18° < ℓ < 55.7°, | b | < 1°, θ = 47”, 0.21 km s^{-1}
- **EXFC** - ^{12}CO, ^{13}CO (1-0) - Brunt+(in prep.) - outer Galaxy [used in Roman-Duval+2016]
    - 55° < ℓ < 100°, -1.4° < b < 1.9° & 135° < ℓ < 195°, -3.6° < b < 5.6°, θ = 48”, 0.13 km s^{-1}
- **THRUMMS / MOPRA** - ^{12}CO, ^{13}CO (1-0) - Barnes+2015
    - 300° < ℓ < 360°, | b | < 0.5°, θ = 72”, 0.3 km s^{-1}
- **MOPRA CO survey** - ^{12}CO, ^{13}CO, C^{18}O (1-0) - Burton+2013
    - 305° < ℓ < 345°, | b | < 0.5°, θ = 35”, 0.1 km s^{-1}
- **FOREST / FUGIN -** ^{12}CO, ^{13}CO, C^{18}O (1-0) - Umemoto+2017
    - 10° < ℓ < 50° and 198° < ℓ < 236°, | b | < 1°, θ = 20”, 1.3 km s^{-1}
- **SEDIGISM / APEX** - ^{13}CO, C^{18}O (2-1) - Schuller+2017
    - -60° < ℓ < 18°, | b | < 0.5°, θ = 28”, 0.1 km s^{-1}
- **COHRS / JCMT** - ^{12}CO (3-2) - Dempsey+2013
    - 10° < ℓ < 55°, | b | < 0.5°, θ = 16”, 1 km s^{-1}
- **CHIMPS / JCMT** - ^{13}CO, C^{18}O (3-2) - Rigby+2016
    - 27.5° < ℓ < 46.3°, | b | < 0.5°, θ = 15”, 0.5 km s^{-1}

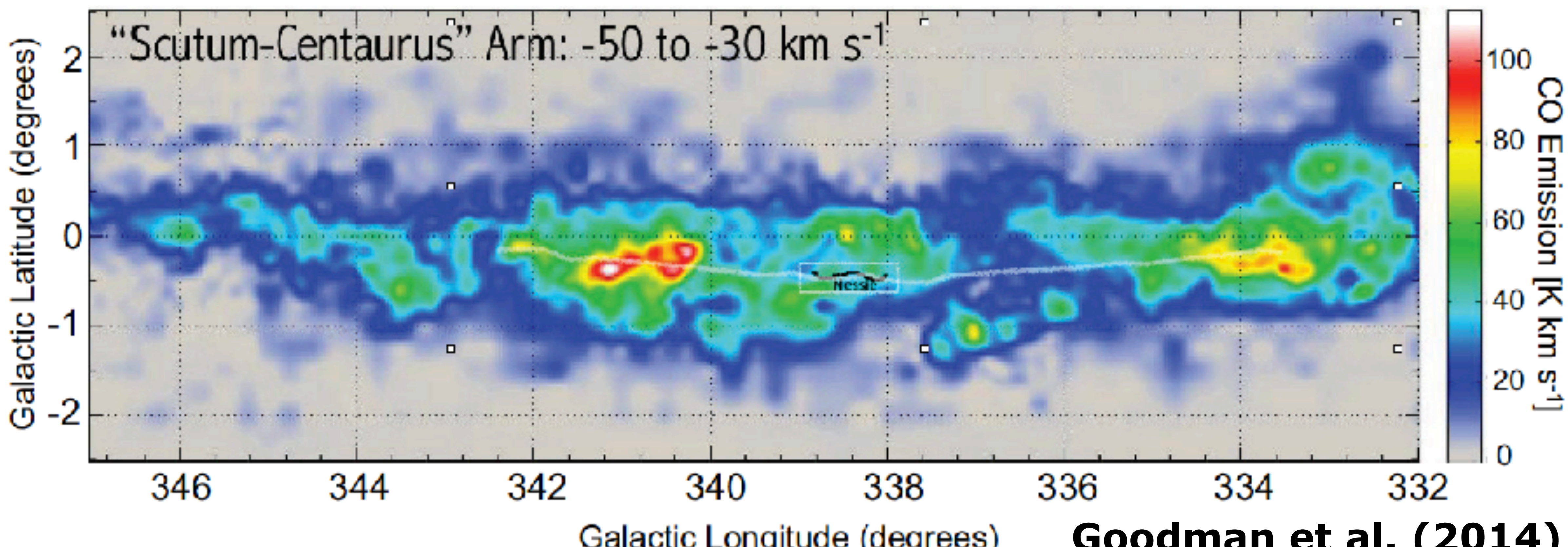
In progress:
CHIMPS2 - ^{12}CO, ^{13}CO & C^{18}O
(PI: Toby Moore)
extending in to ℓ = -5° &
outer galaxy 198° < ℓ < 235°

Close up of the Milky Way’s spiral arms

Nessie IRDC
MOPRA HNC(1-0)



Jackson et al. (2010)

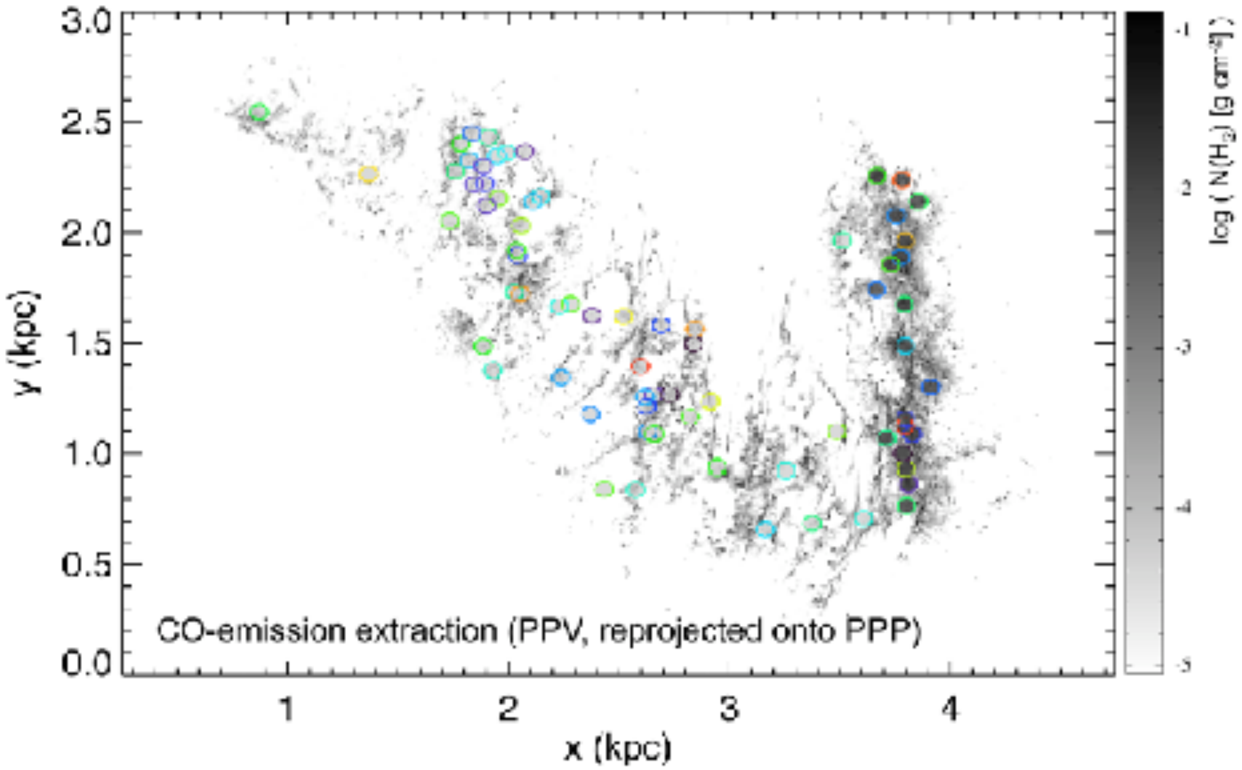


Goodman et al. (2014)

Ragan et al. (2014), Abreu-Vicente et al (2016),
Zucker et al (2015), Wang et al. (2016), Li et al. (2016)

Giant filaments are everywhere!

Duarte-Cabral & Dobbs (2016)



Giant molecular filaments (GMFs)

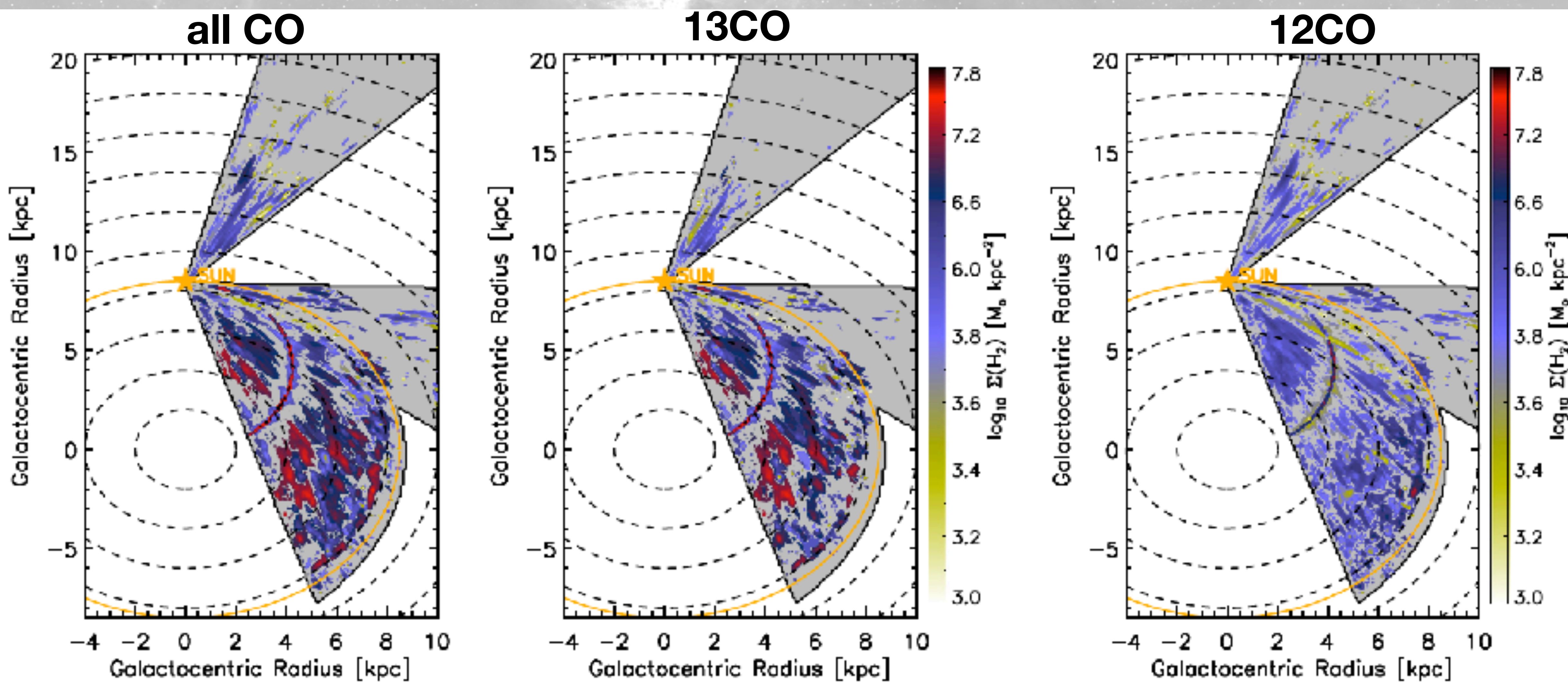
100pc scale, velocity coherent

Mix of arm-related and inter-arm structures

Arm-related structures have higher fraction of gas at high density (Ragan et al. 2014)

Ragan et al. (2014), Ragan & Henshaw (in prep)

What does CO trace?



Roman-Duval et al. (2016)

- Only 14% of molecular gas mass traced by ^{12}CO is part of ^{13}CO emission boundaries
- There is a significant *diffuse molecular* component of the ISM

	^{12}CO 1-0	^{13}CO 1-0	CS 2-1	$\Sigma_v(H_2)$ ($M_\odot$ pc^{-2} (km s^{-1})$^{-1}$)
Diffuse	Detected	Undetected	Undetected	<10
Dense	Detected	Detected	Undetected	>10
Very dense	Detected	Detected	Detected	>20

Molecular clouds

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The term “cloud” refers to a structure in the ISM separated from its surroundings by the rapid change of some property, such as pressure, surface density or chemical state.

… The molecular cloud boundary is usually defined by the detection, above some threshold, of emission from the lower rotational transitions of CO. Alternatively, a certain level of extinction of background stars is often used.

Kennicutt & Evans (2012, ARAA)

“The concept of ‘clouds’ may be misleading.”
- Neal Evans, 2018

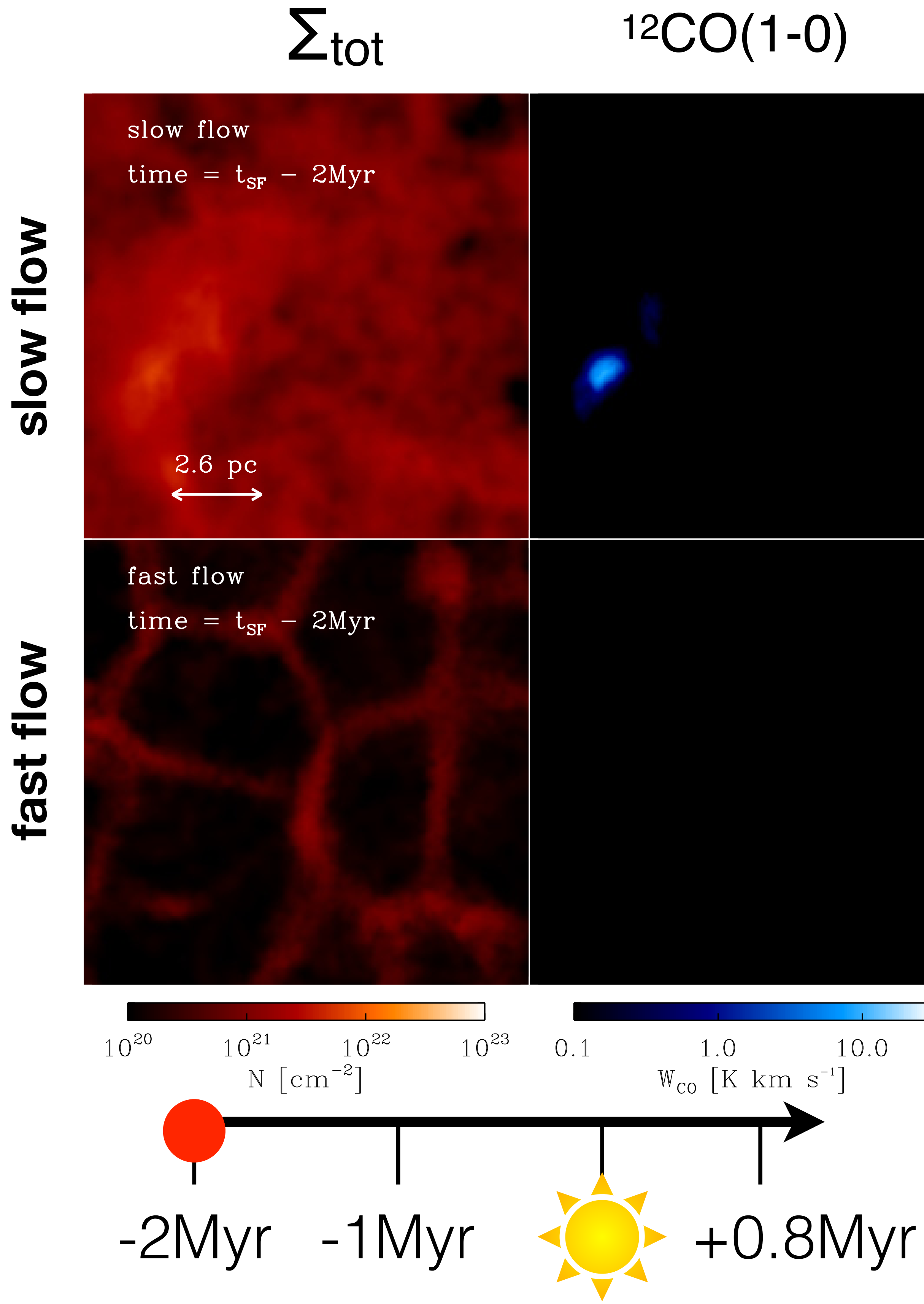
“They’re a mess.”
- Ian Bonnell, last Friday

CO: benefits and limitations

- CO is the most commonly used tracer of molecular gas because it emits strongly and is easy to observe
- Dynamic range of column density that CO can effectively trace is very limited
    - At low N_{H2}, CO needs shielding from photodissociation and minimum density for excitation (doesn’t need to be bound)
    - Upper limit to N_{H2} range set by saturation, freeze out, which happens at modest column densities
- Abundance ratios / conversion factors are variable! (Bolatto et al. 2013)

Kennicutt & Evans (2012)
see also Glover & Clark (2011), Bolatto et al. (2013)

Observational time sequence of cloud formation

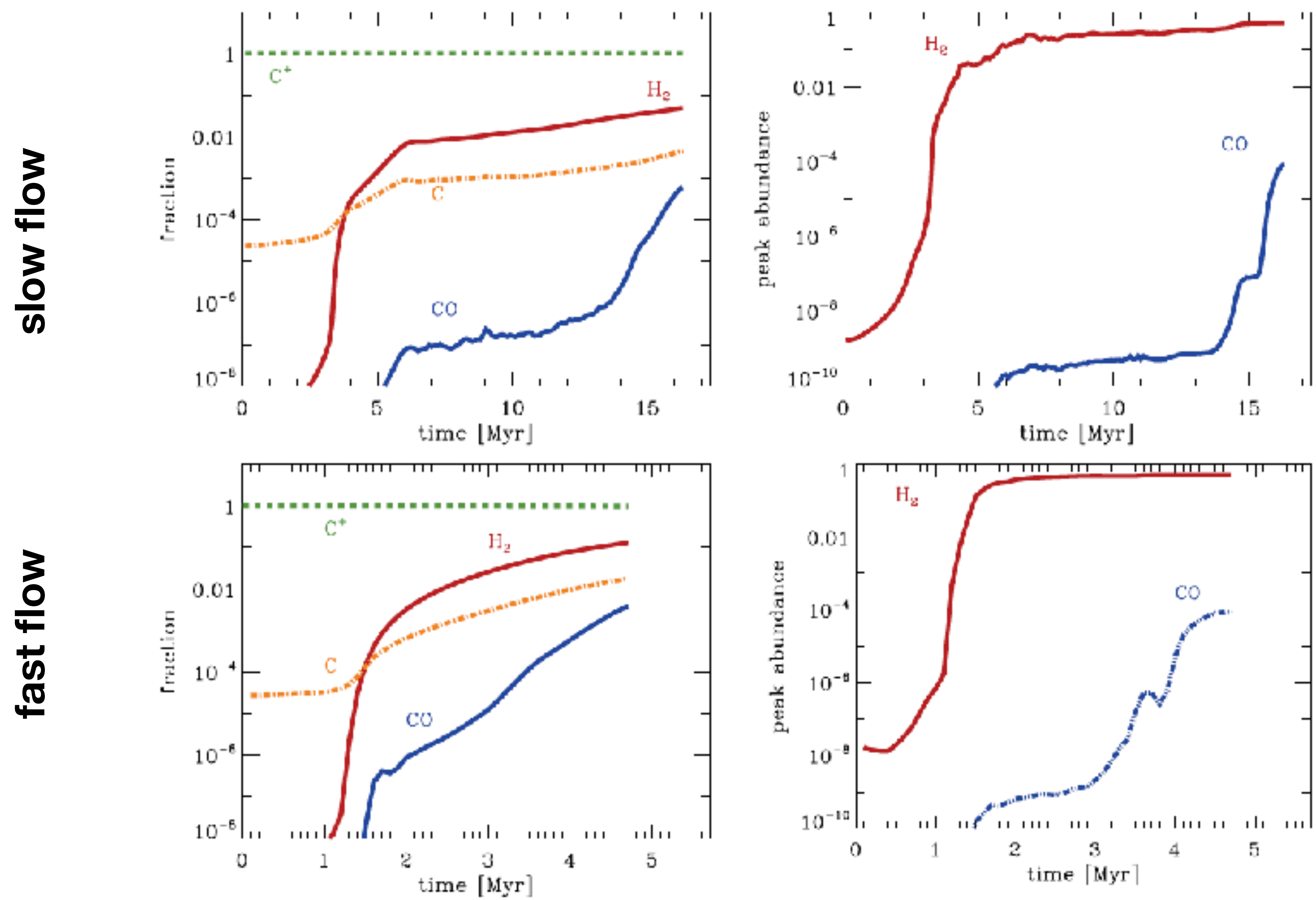


- Colliding atomic flow simulations
  - “slow" (6.8 km s^{-1})
  - “fast” (13.6 km s^{-1})
- Formation of CO
  - 2 Myr before SF (both)
- Formation of H_2
  - 10 Myr before SF
  - 3 Myr before SF

Clark et al (2012), see also Pringle et al. (2001), Heitsch et al. (2006), Hosokowa & Inutsuka (2007), Dobbs et al. (2008, 2012)

Observational time sequence of cloud formation

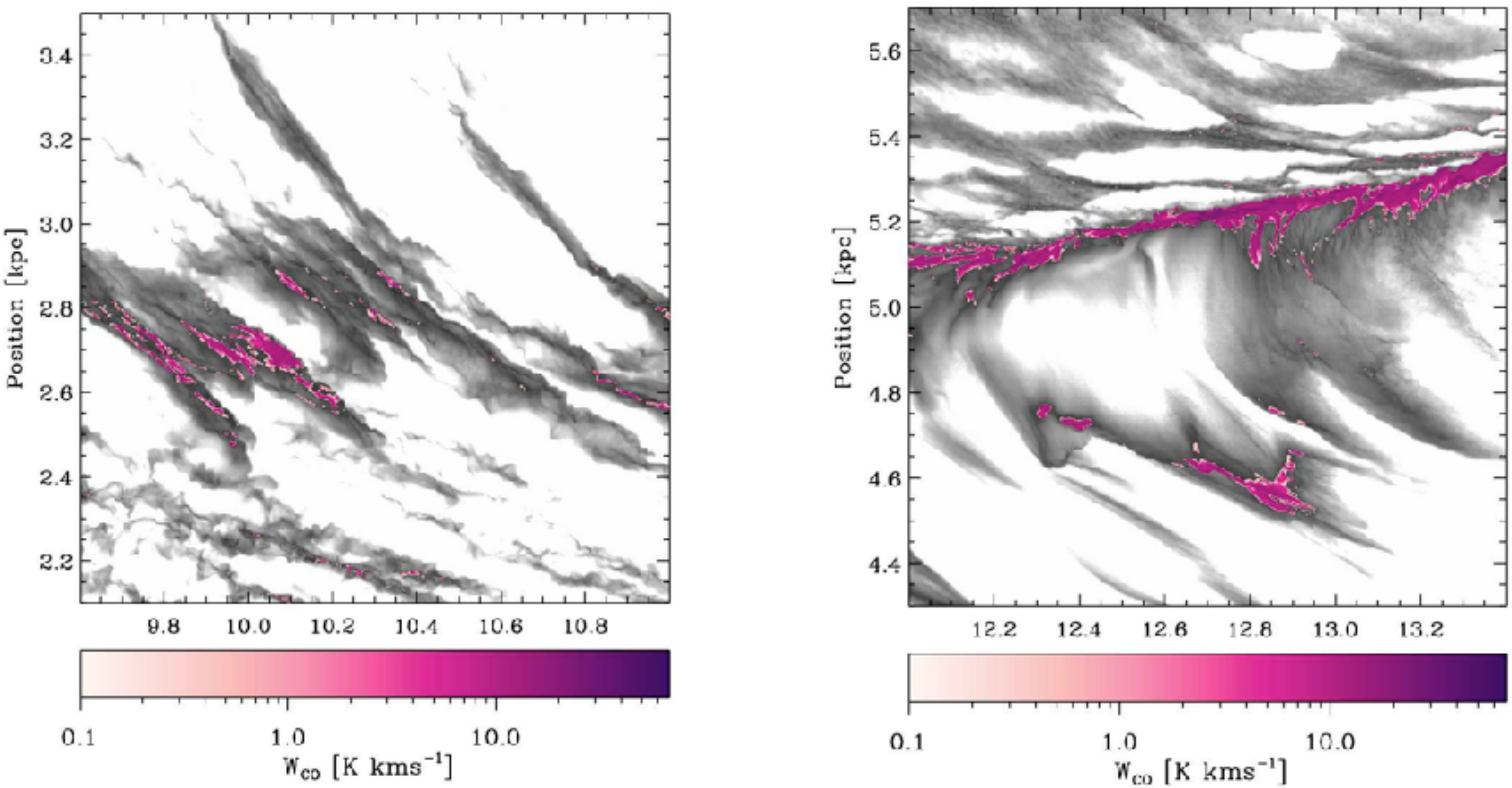
- H_2 forms quickly, regardless of flow speed
- Cloud assembly is mostly "CO-dark"



Clark et al (2012)

CO-dark H_2

- Galaxy scale simulations predict high fraction (> 40%) of CO-dark gas, greater proportion in the inter-arm regions

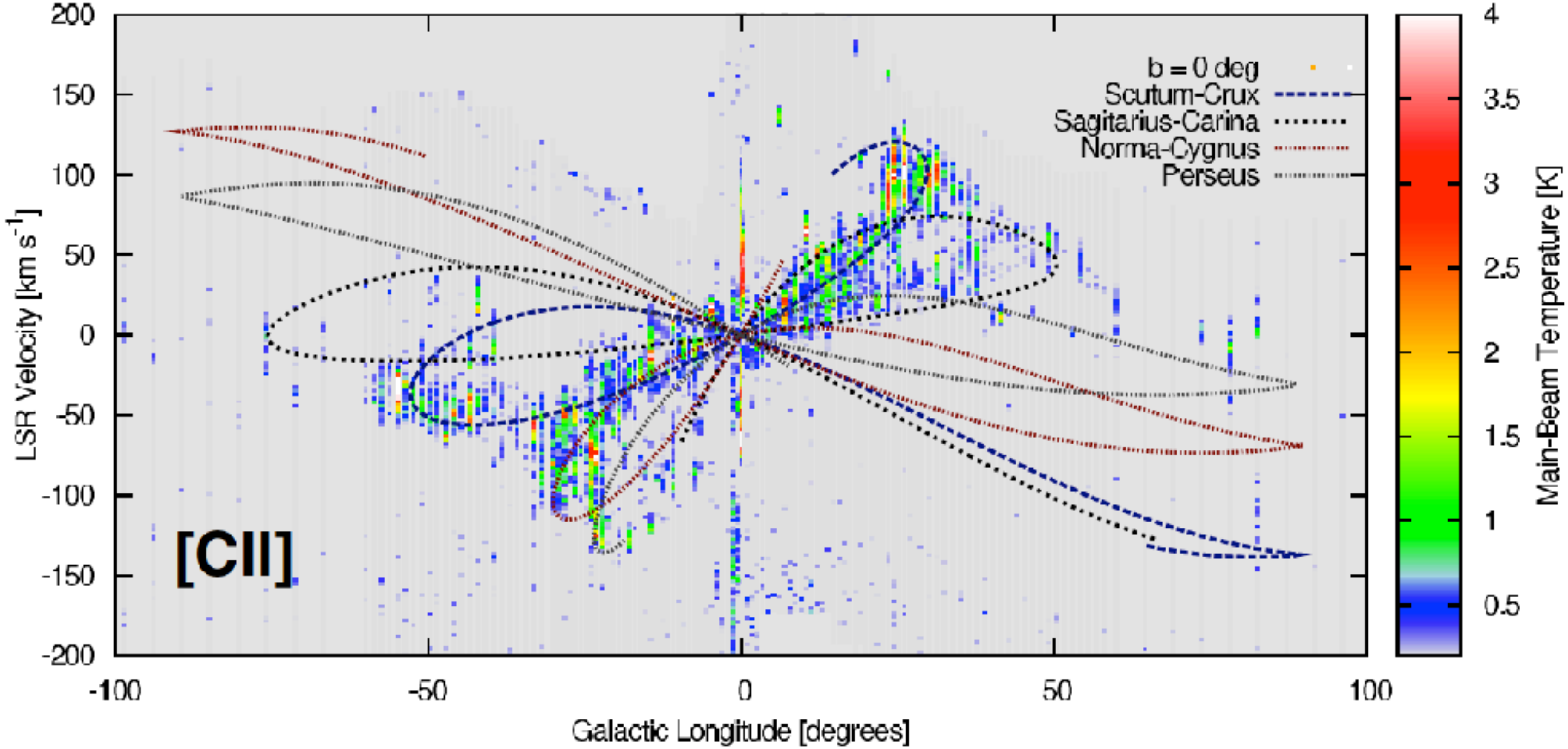


Grey: H_2 column density
Pink: W_{CO}

Smith et al. (2014)

Got C^+?

- C^+ is present in ionised, neutral atomic and molecular medium
- [CII] emission budget: PDRs (47%), CO-dark H_2 (28%), cold atomic gas (21%) and ionised gas (4%)



Pineda et al. (**2013**, 2014), Langer et al. (2014), Goldsmith et al. (2015)

Looking ahead (and beyond CO emission)

- Can [CII] emission trace cloud formation?
  - Simulations show this can be challenging. (Paul Clark's talk)
- Do we know what we're doing when interpreting [CII] emission?
  - It's complicated. (Jürgen Stutzki's talk)
- Are there other ways to trace CO-dark gas?
  - OH absorption (Rugel et al. 2018, THOR)
  - Try CO *absorption* studies! (Jin Koda's talk)

Molecular cloud structure

The structure of molecular clouds is complex, leading to considerable nomenclatural chaos.

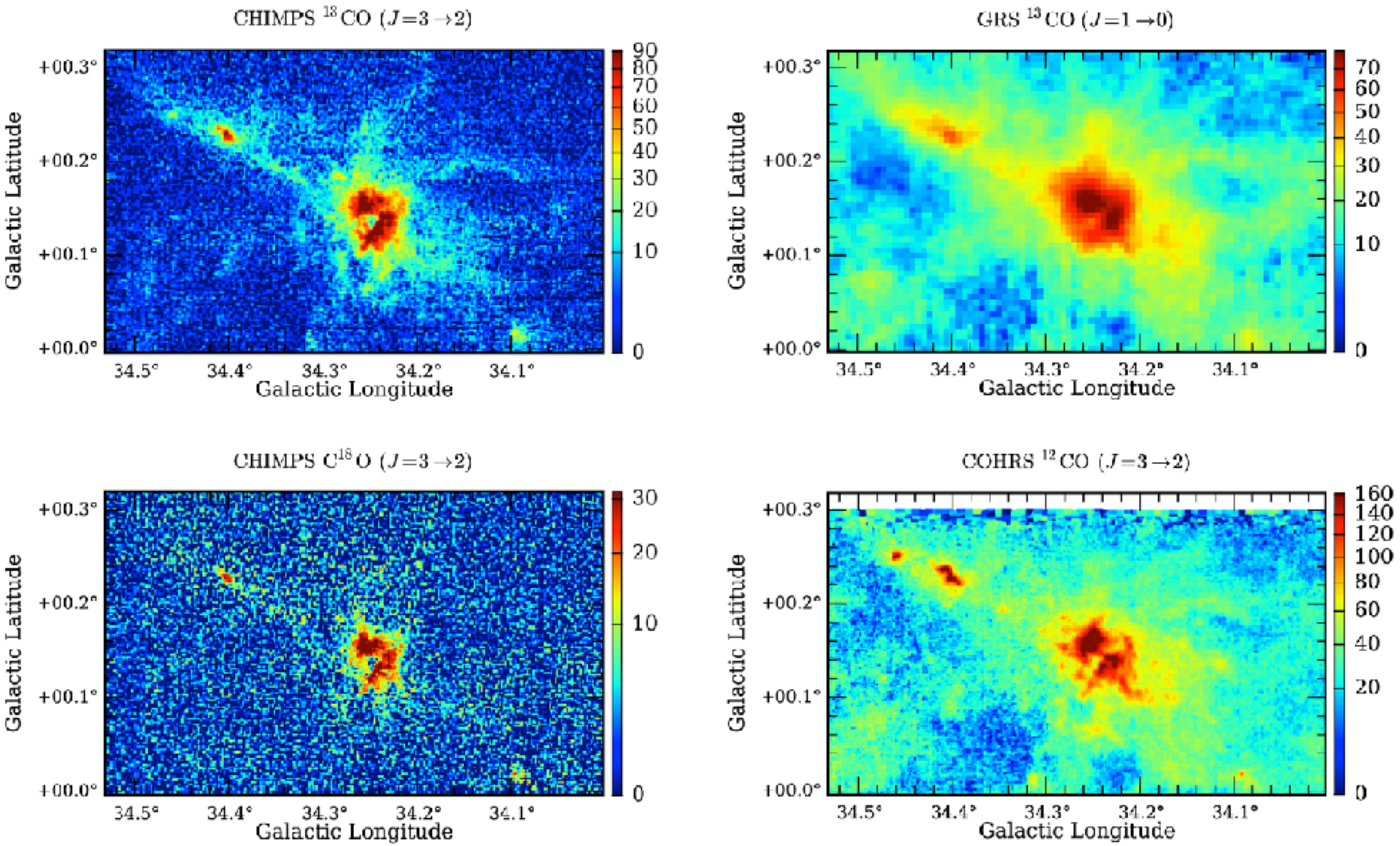
Kennicutt & Evans (2012, ARAA)

… our operational definitions for the remainder of the talk.

Bergin & Tafalla (2007, ARAA)

	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent ($km\ s^{-1}$)	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

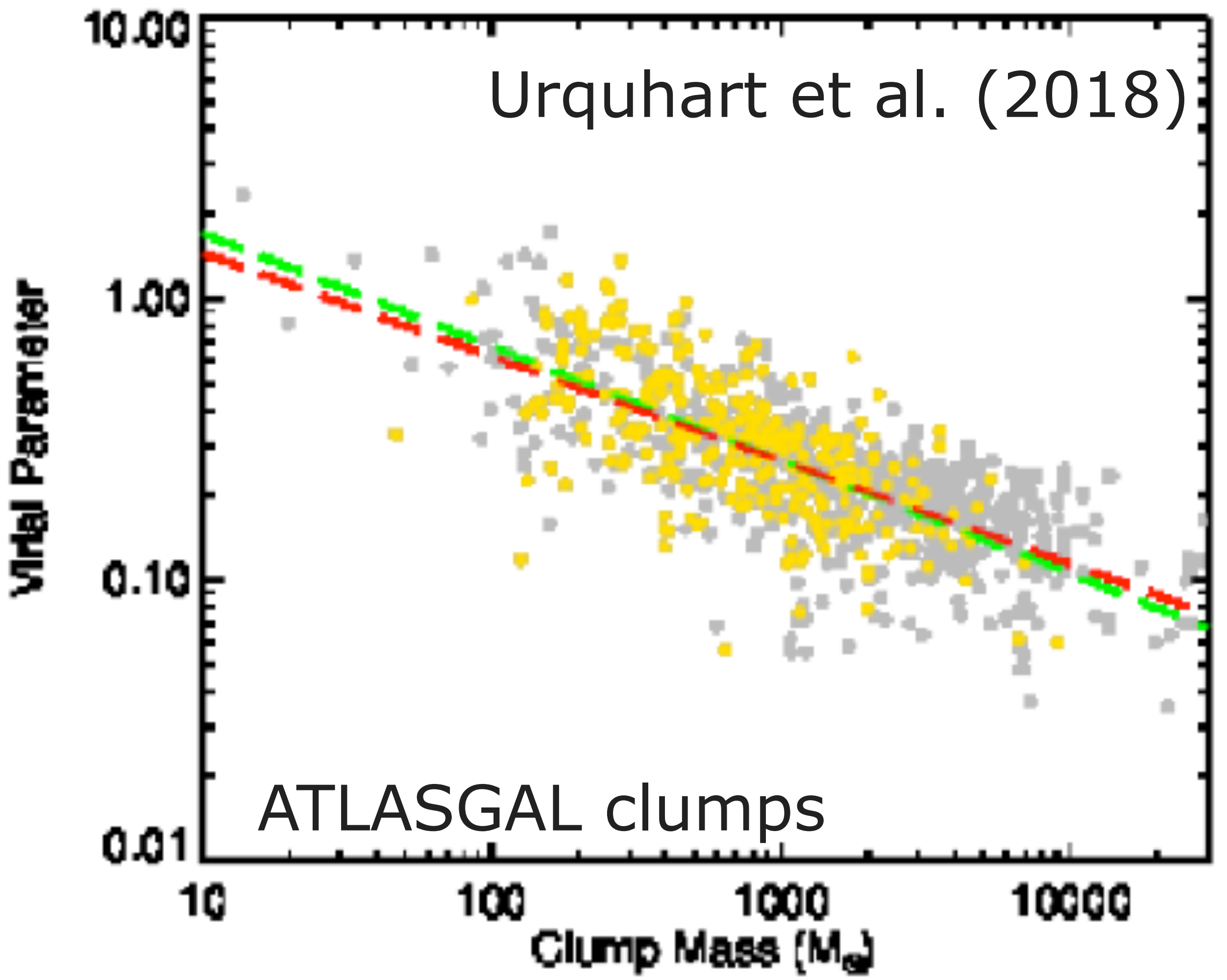
Boundaries are tracer-dependent



Rigby et al. (2016)

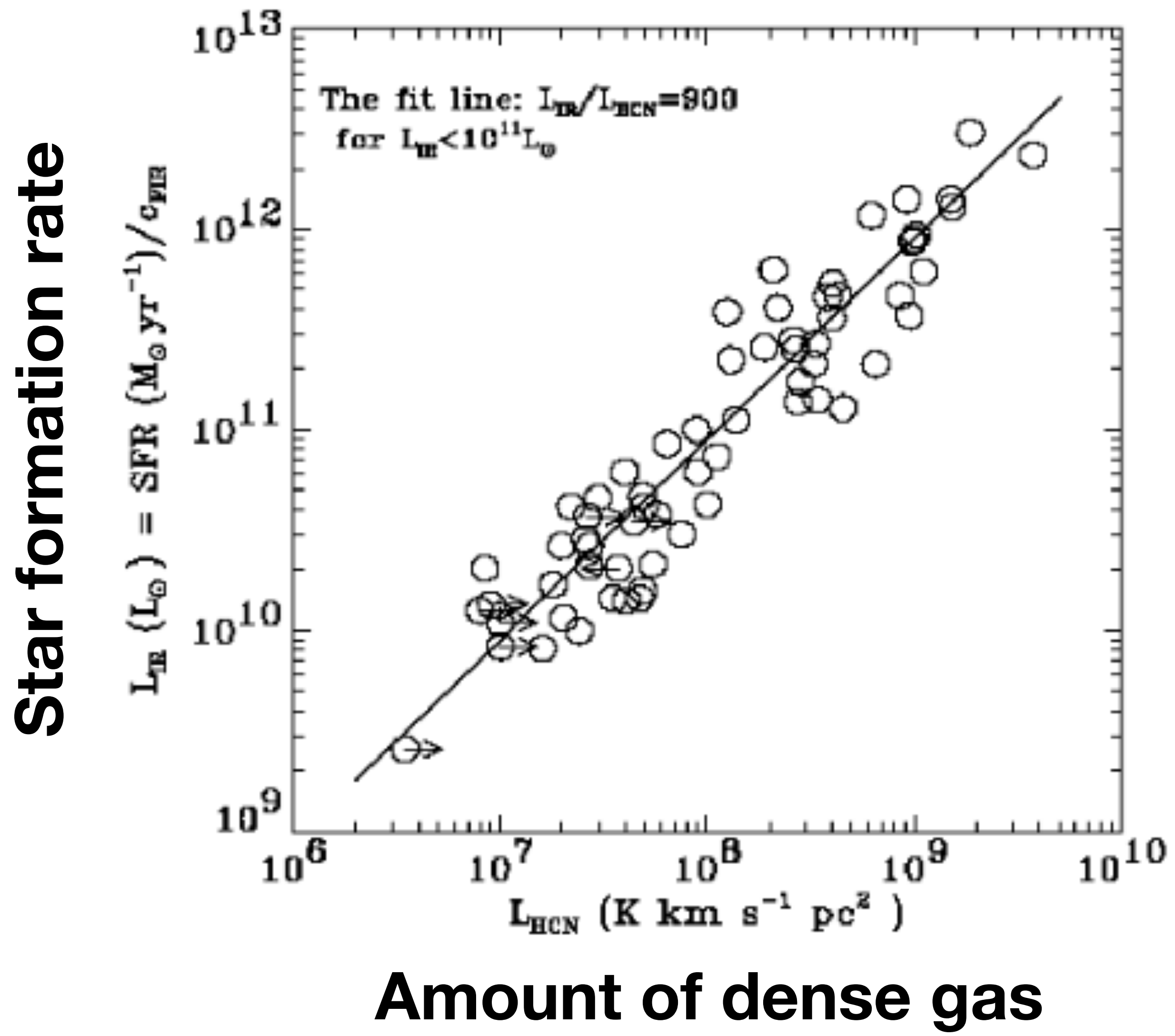
Rethinking the importance of "cloud" boundaries

- Molecular clouds are gravitationally unbound (Dobbs et al. 2011 and many more…)
- If clouds are unbound, then they aren't collapsing
  - … then how relevant can t_{ff}, ε_{ff} really be?
- Some local regions *within* denser parts of cloud (i.e. the clumps) do become bound* and form stars



* *how* this occurs is a question I'll let experts answer later in the session!

Tracing "dense" gas, clumps



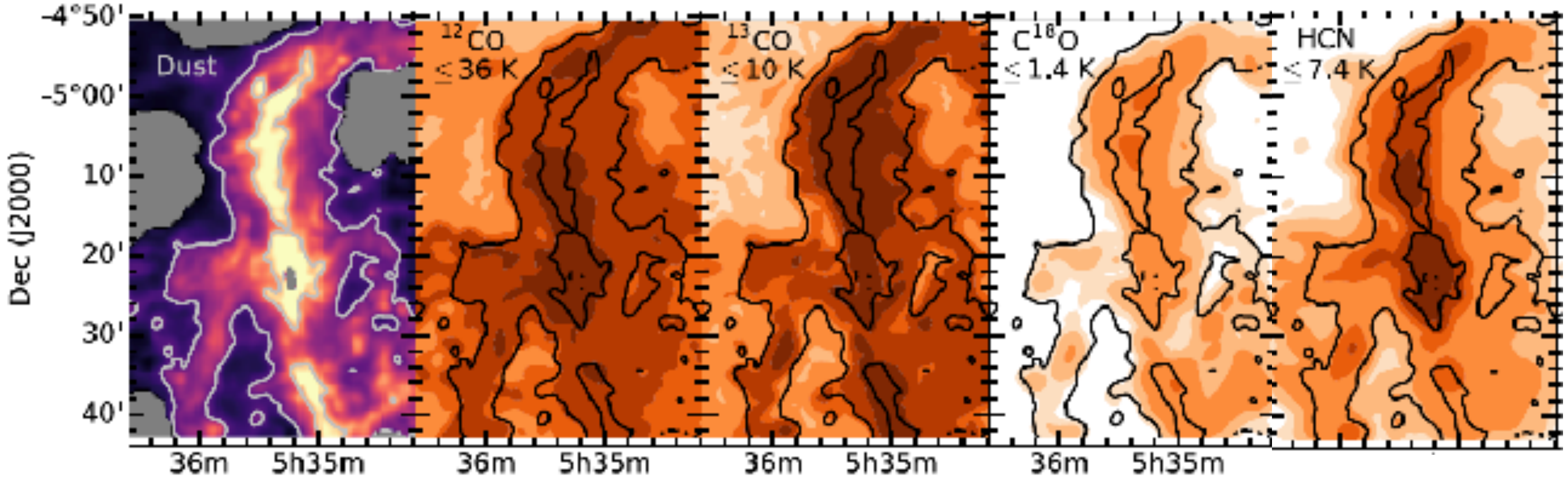
Gao & Solomon (2004)

see also Wu et al (2005, 2010),
Pety et al. (2016), Kauffmann et al. (2017)

- Star formation better correlates with "dense" gas tracers, e.g. HCN
- BUT Galactic studies reveal that a significant fraction of HCN line flux comes from low densities
  - *Example*: **Orion B** 38% HCN (1-0) from Av < 6; conversion to mass depends on G_o Pety et al. (2016)

Take away

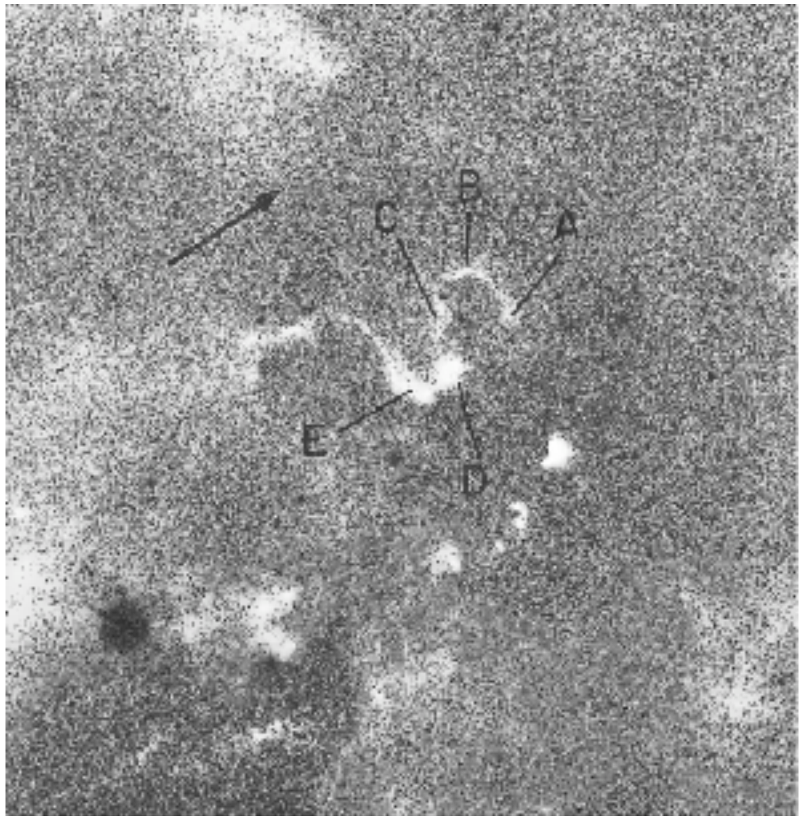
- Gravity doesn't care about chemistry or detection thresholds.
- If you're interested in gravitationally bound entities, the boundary of CO emission could be misleading.
- Tracers like HCN get us *closer* to isolating the "bound" bits of clouds (a.k.a. clumps), BUT we still need to quantify how much line flux is coming from outside of clumps.



Orion A; Kauffmann et al. (2017)

Filaments

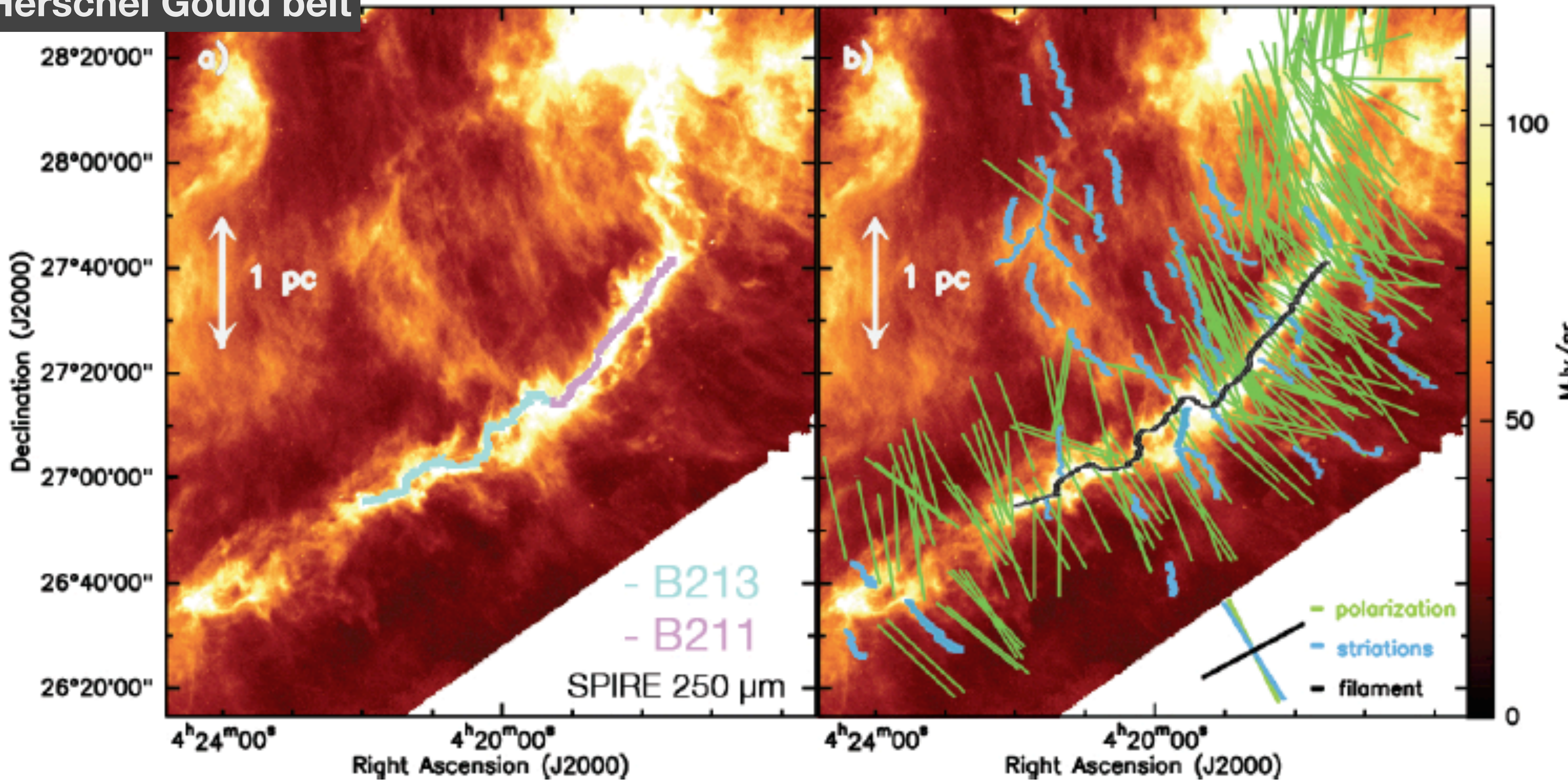
- "Filamentary" is the most common descriptor of molecular cloud morphology
- A filament is the most beneficial geometry for local gravitational collapse to occur before global collapse. (Pon et al. 2011, Heitsch et al. 2013)



Schneider & Elmegreen (1979)
'A catalog of dark globular filaments'

Filament networks: low mass

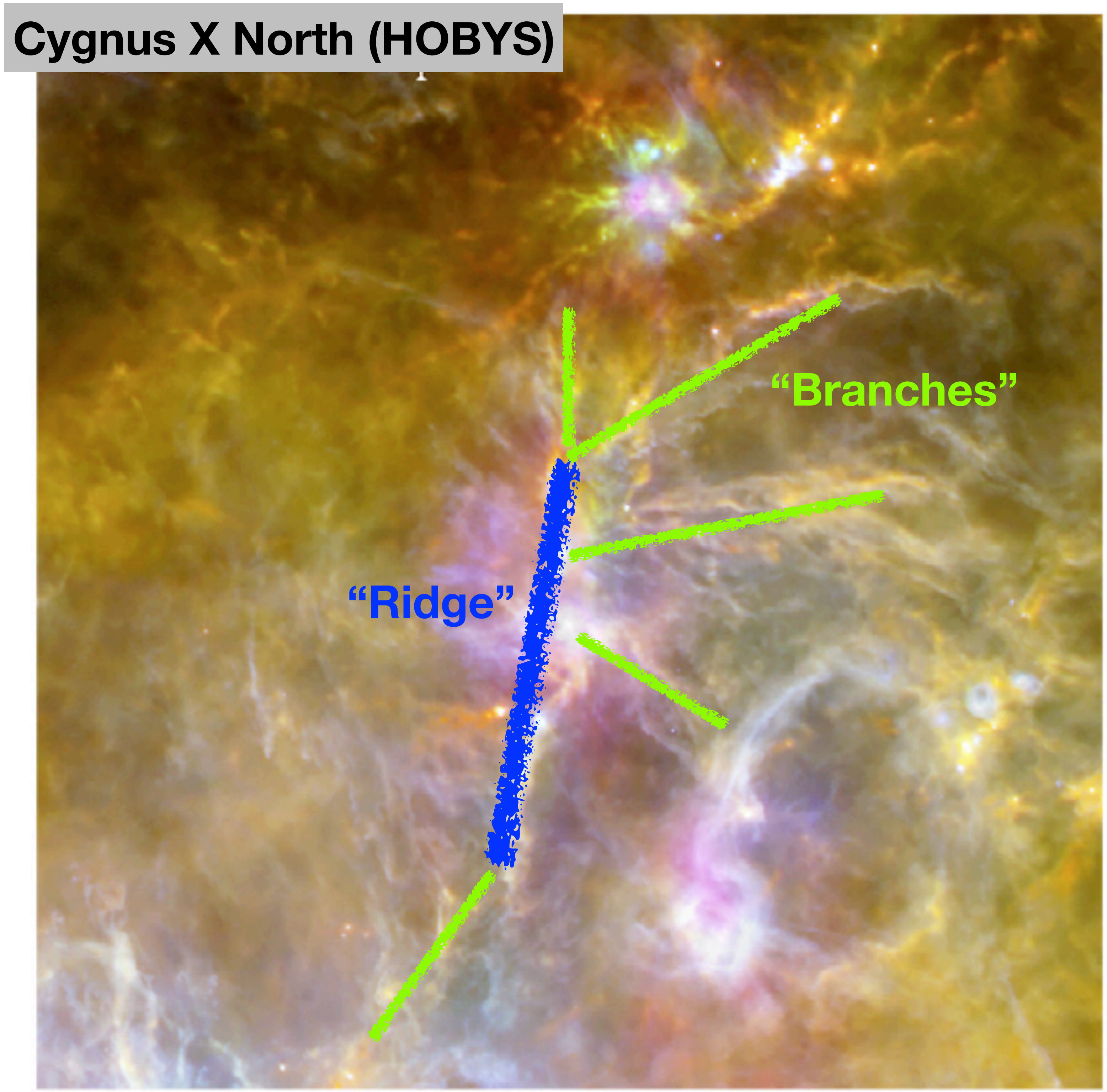
Taurus B211/3
Herschel Gould belt



"Striations" are channels for accretion onto main filament. Alignment with polarisation vectors suggestive of important role of magnetic fields.

Palmeirim et al. (2013)

Filament networks: high mass



Hennemann et al. (2012)

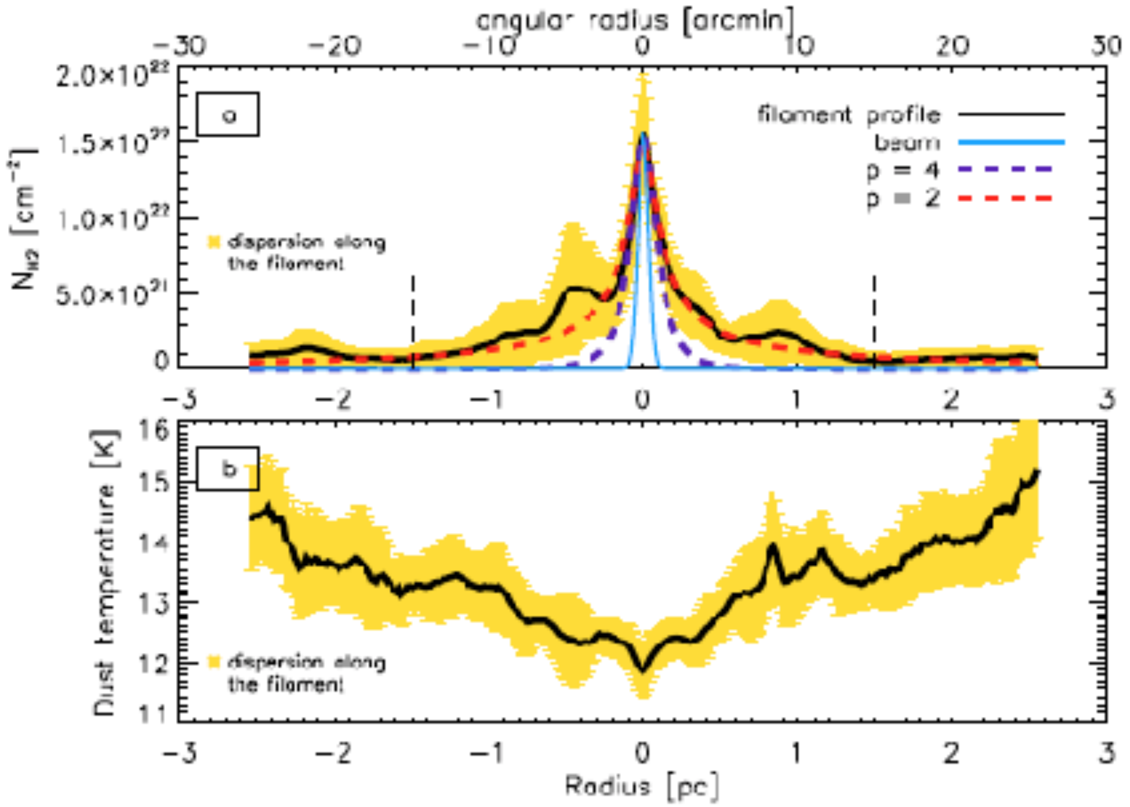
Herschel enables us to investigate substructure more completely

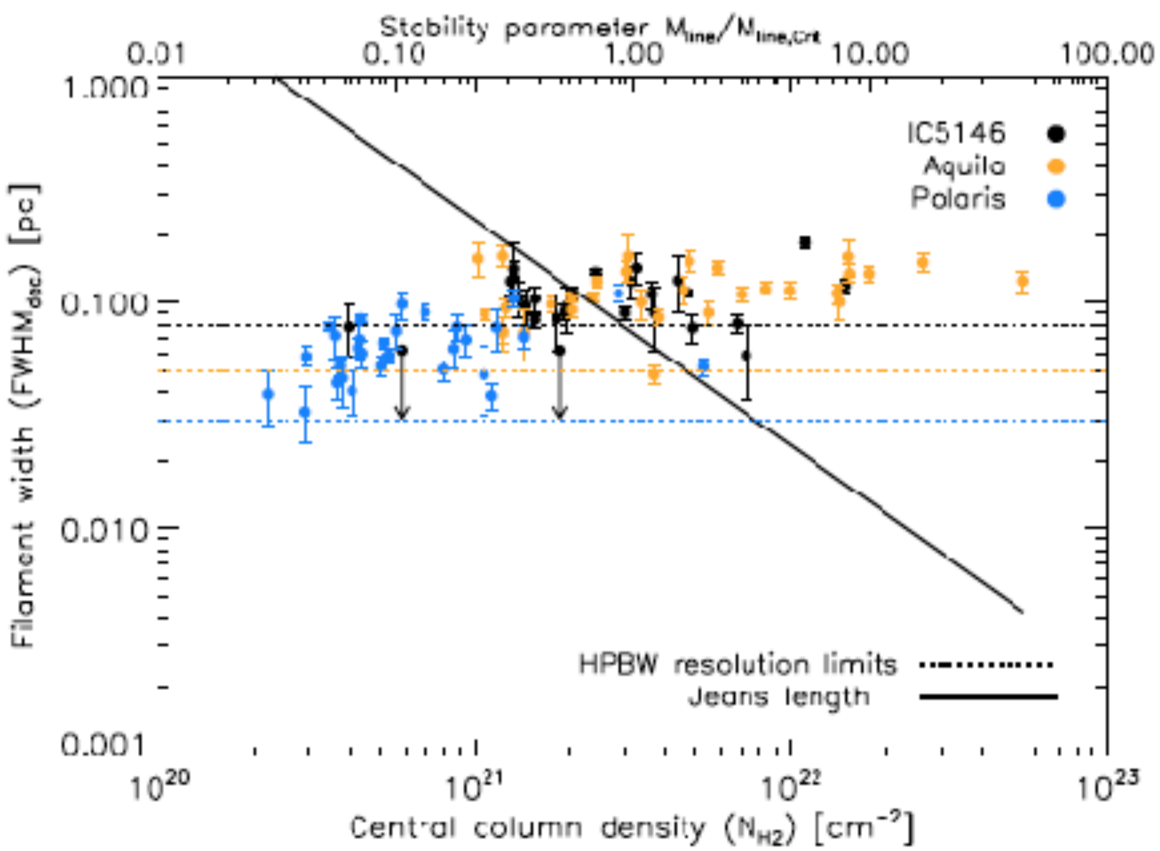
Filament networks are a common feature of young star forming regions

Branches appear gravitationally unstable (in contrast with "striations" in low-mass regions, e.g. Taurus)

see also Schneider et al. (2012), Kirk et al. (2016)

Filament structure

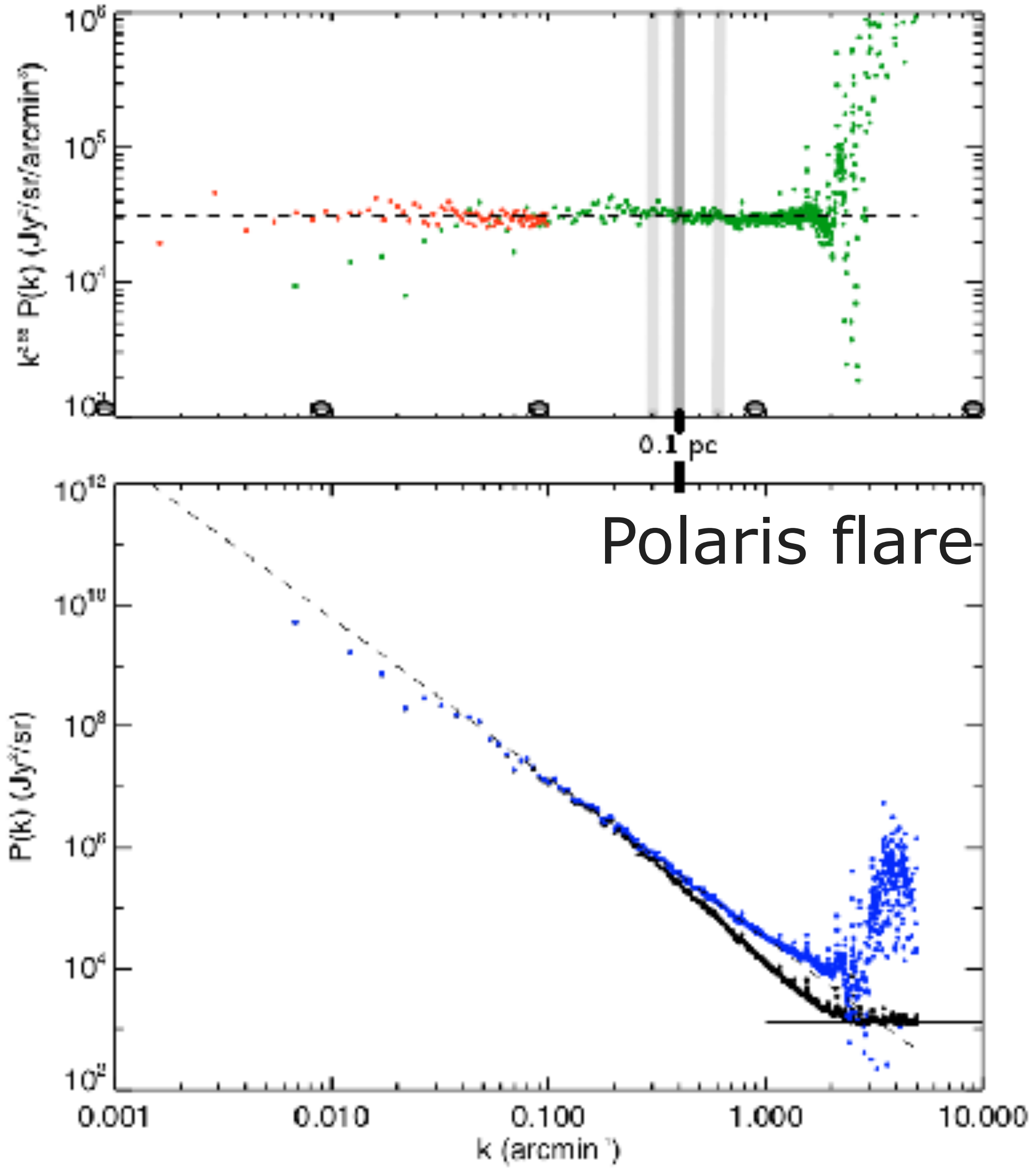




Characteristic width of 0.10 ± 0.03pc in IC5146, within a factor of 2 of sonic scale. Arzoumanian et al. (2011)

Filament structure

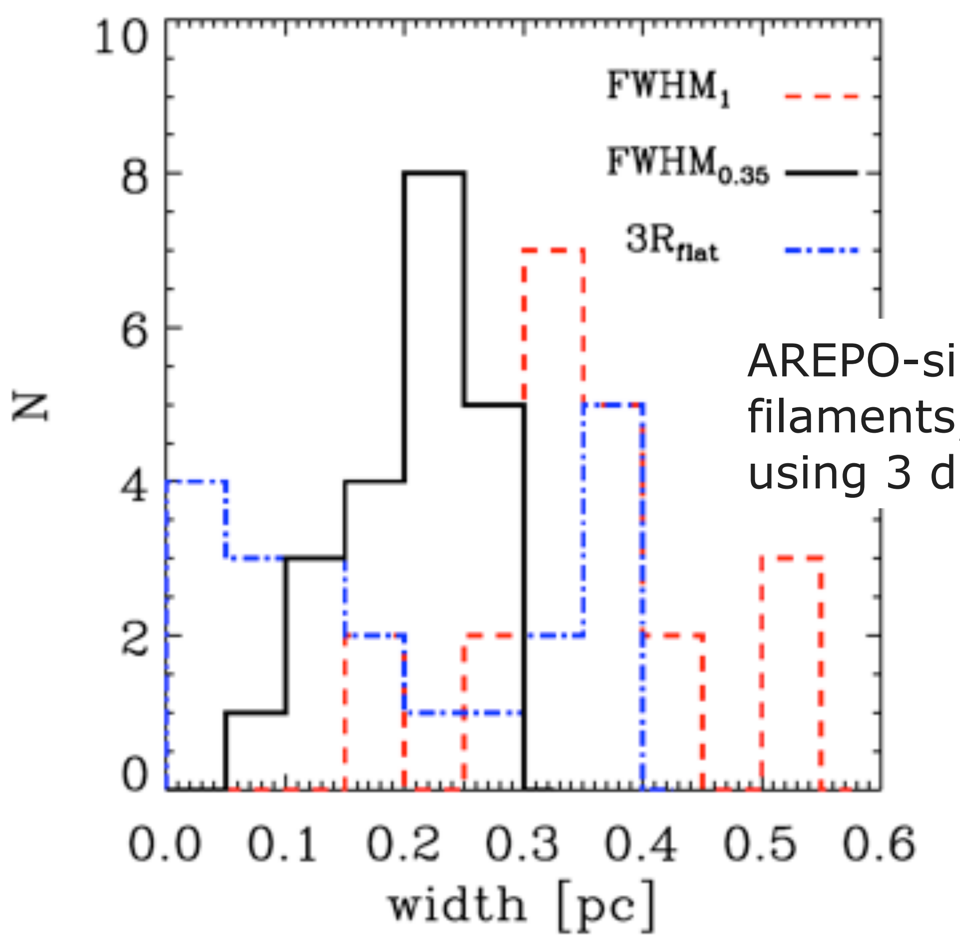
The power spectrum shows no features — at 0.1pc or anywhere!



Miville-Deschênes et al. (2010)

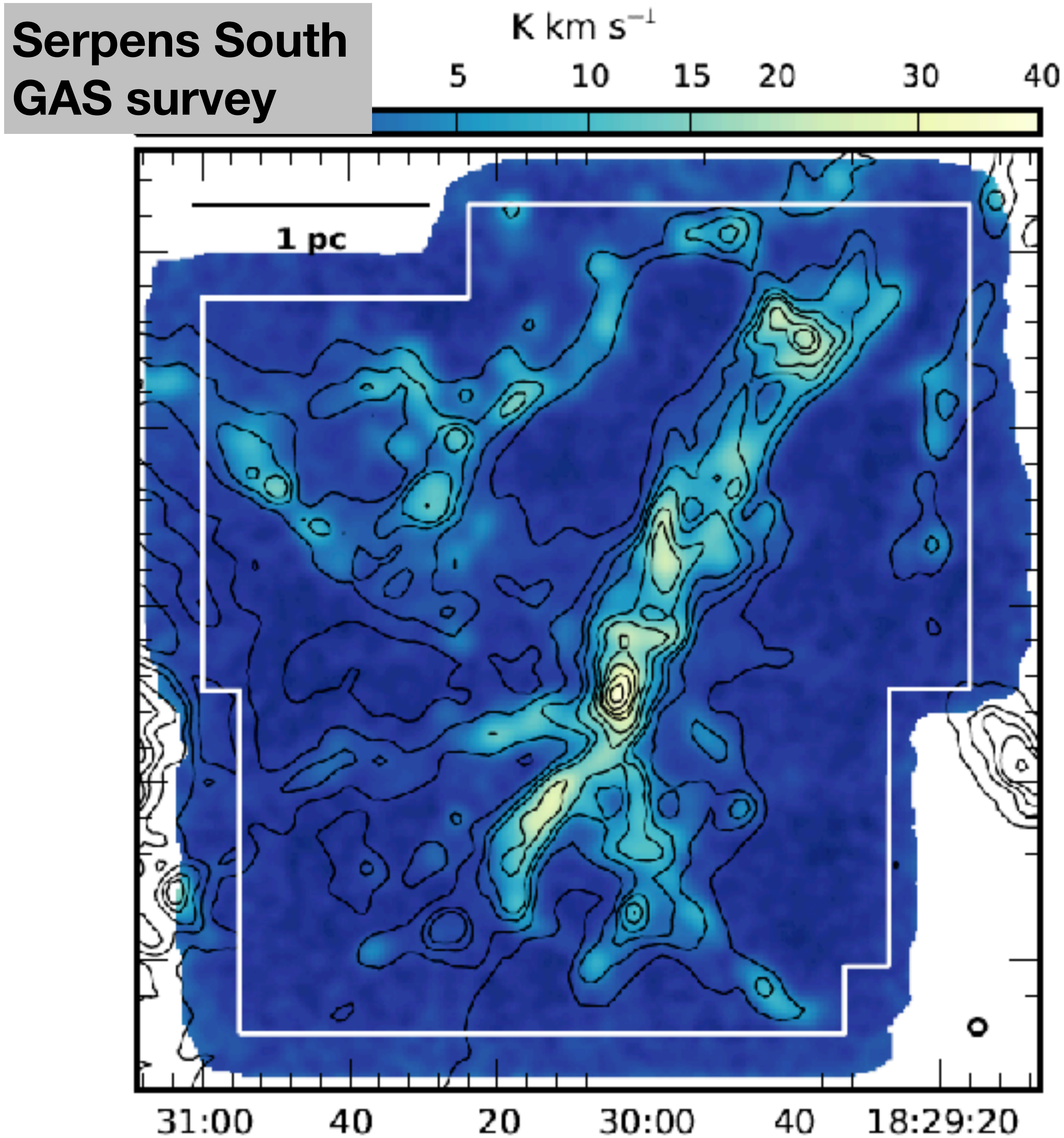
Width measurement technique is biased (Panopoulou et al. 2017)

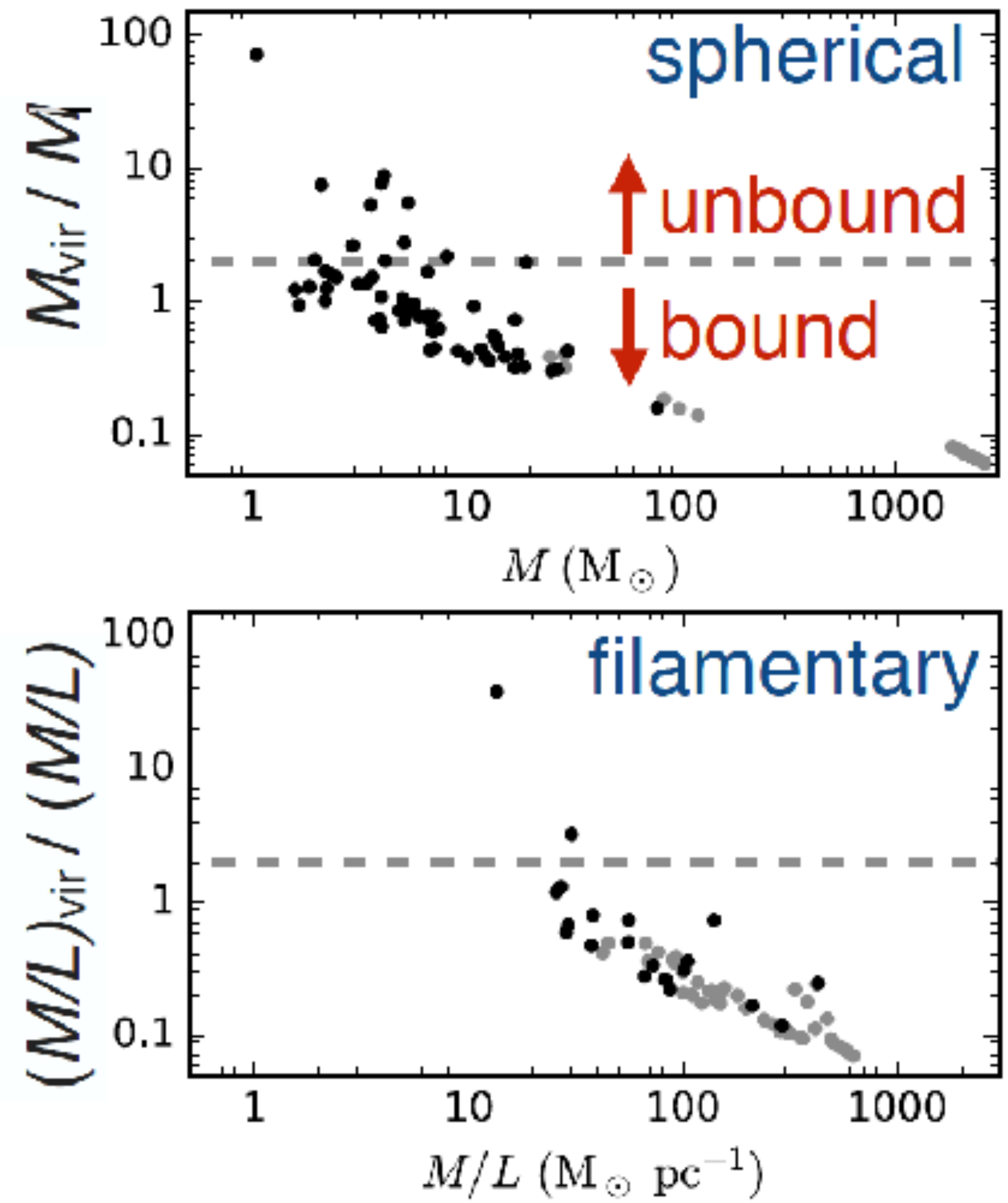
- Sampling a power-law distribution with uncertainties results in a peaked distribution.
- Restricted fitting range results in narrow fit (Smith et al. 2014)



AREPO-simulated filaments, extracted using 3 different methods

Filament stability





Friesen et al. (2016)

Filament dissection

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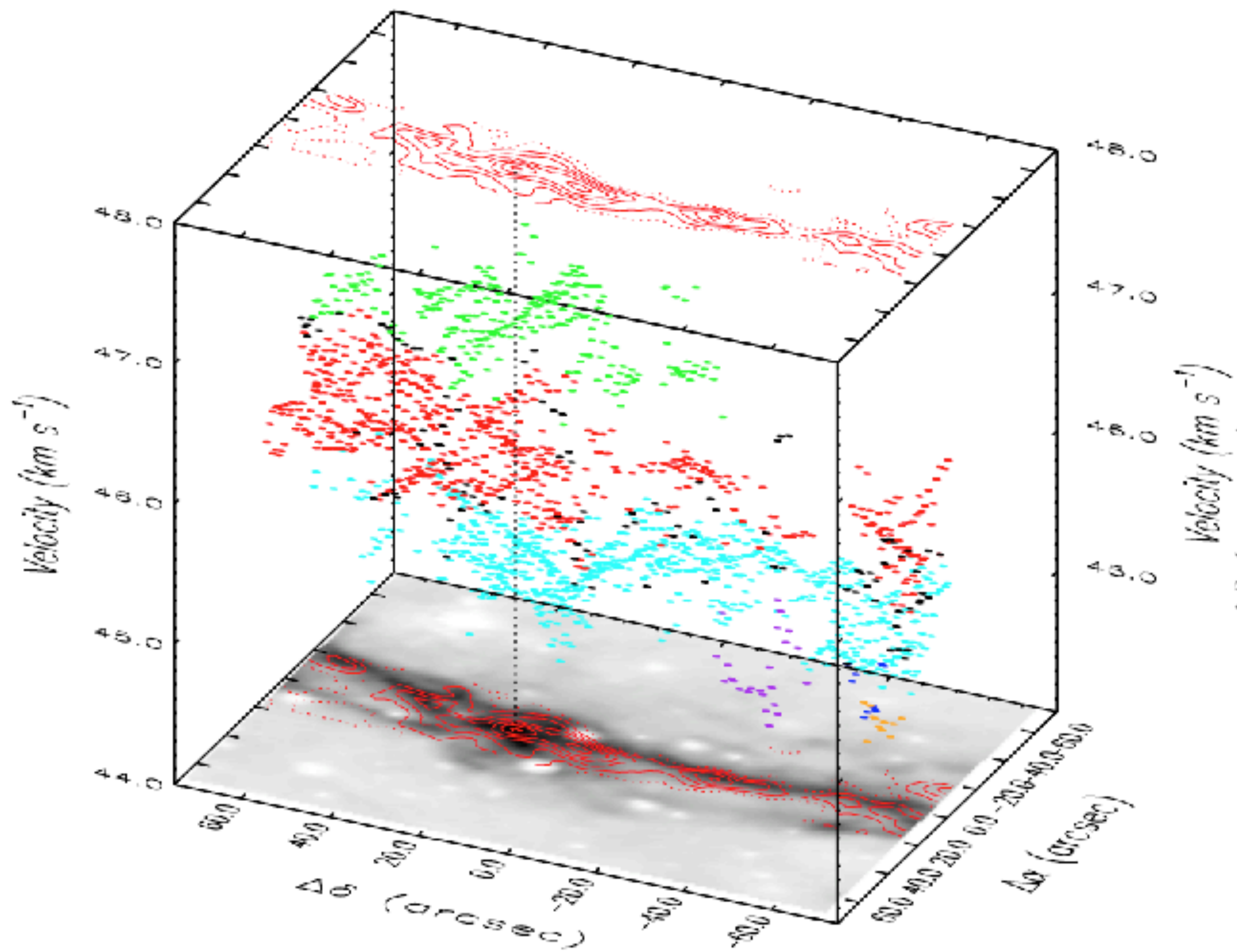
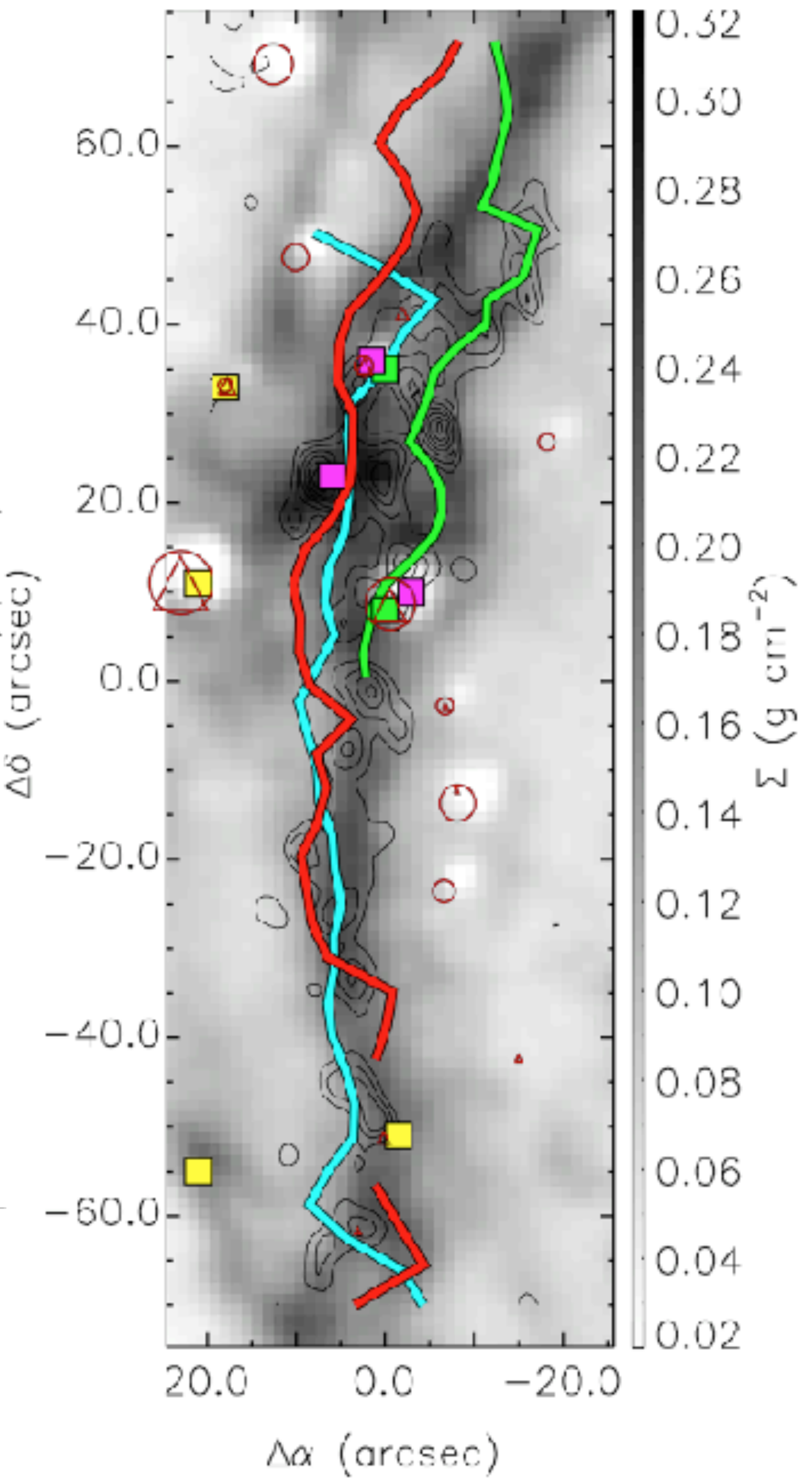
G035 - IRAM 30m + PdBI



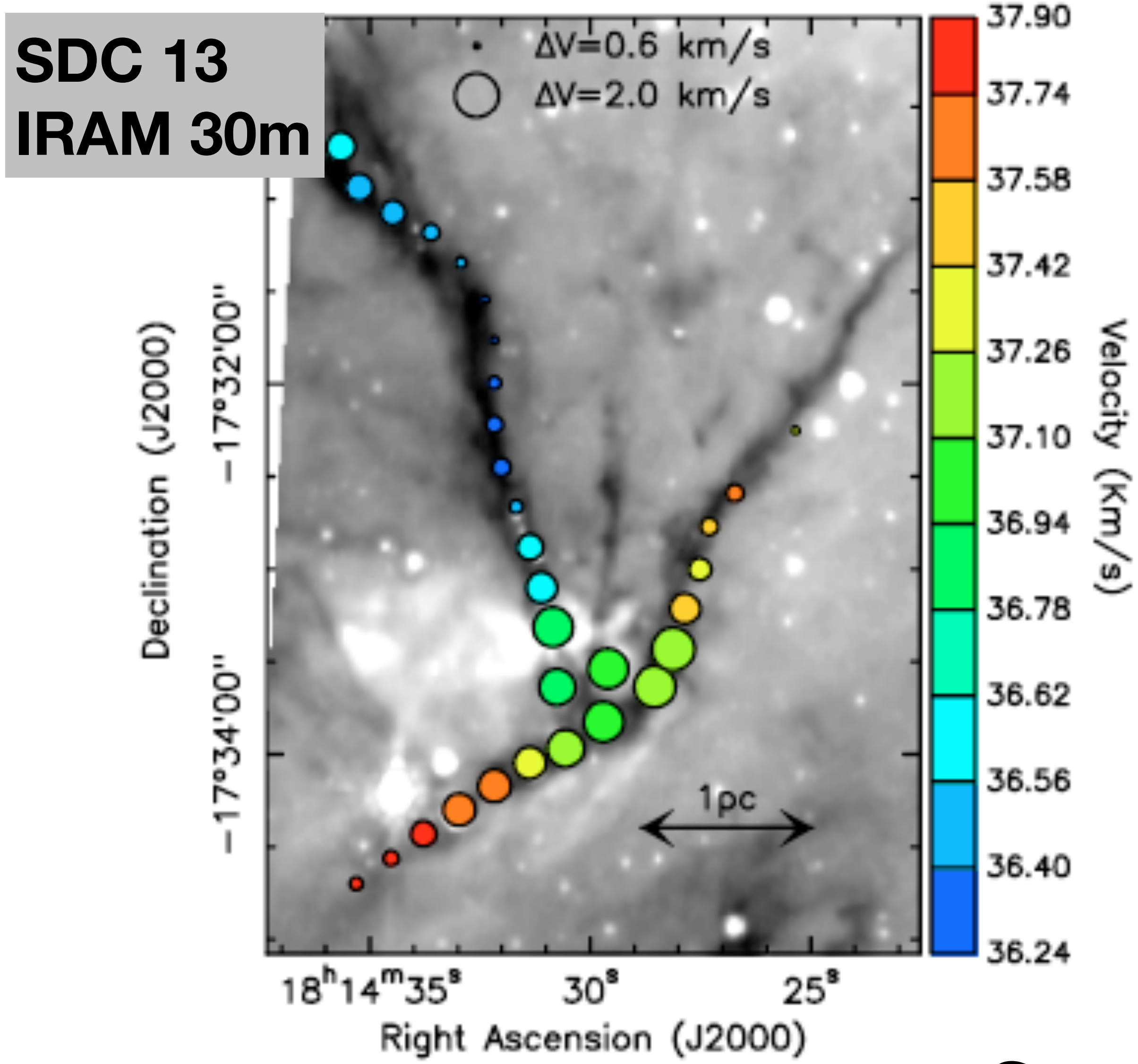


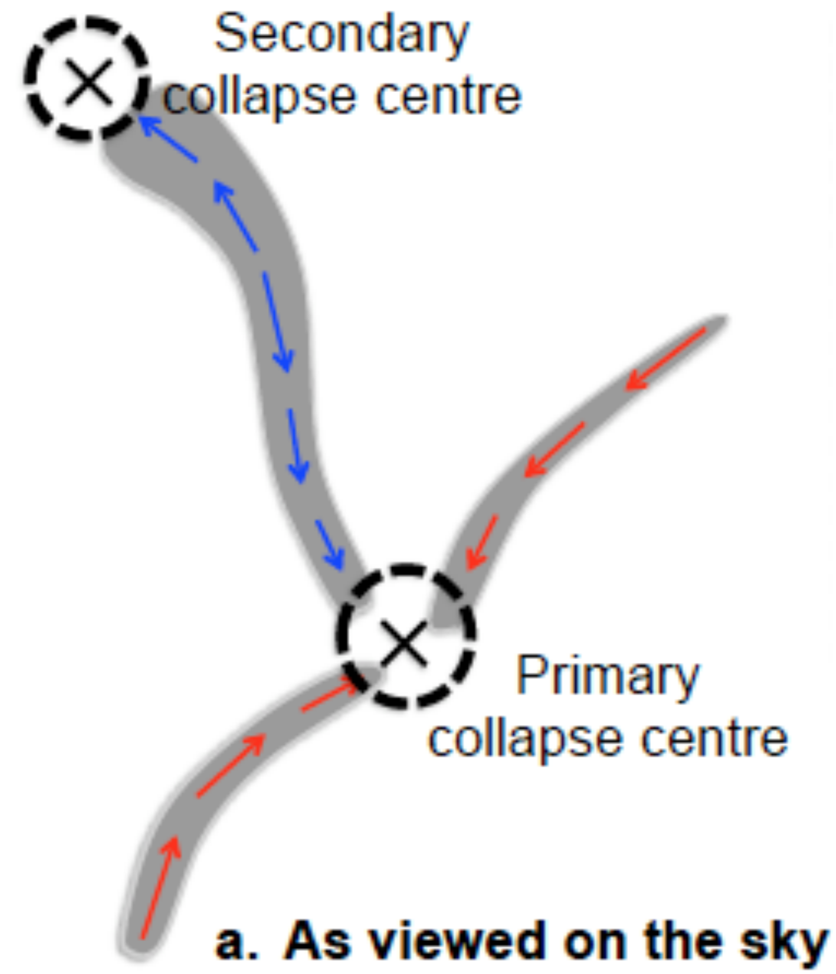
Henshaw et al. (2014, 2016a)

see also Hacar et al. (2013, 2016), Mattern et al. (2018)

Gas motion along filaments

- Longitudinal collapse in IRDCs, centred on "hubs"





Peretto et al. (2014)
see also Kirk et al. (2013),
Williams et al. (2018),
Yuan et al. (2018)

- Gas motion along filament toward hub, promotes pure Jeans fragmentation along length (Bonnell et al 2008)
- Is this where the influence of filaments ends?

Summary

Molecular clouds

Observational boundaries ≠ gravitational boundedness

Filaments

Ubiquitous morphology sets stage for observed patterns in fragmentation and young cluster morphology