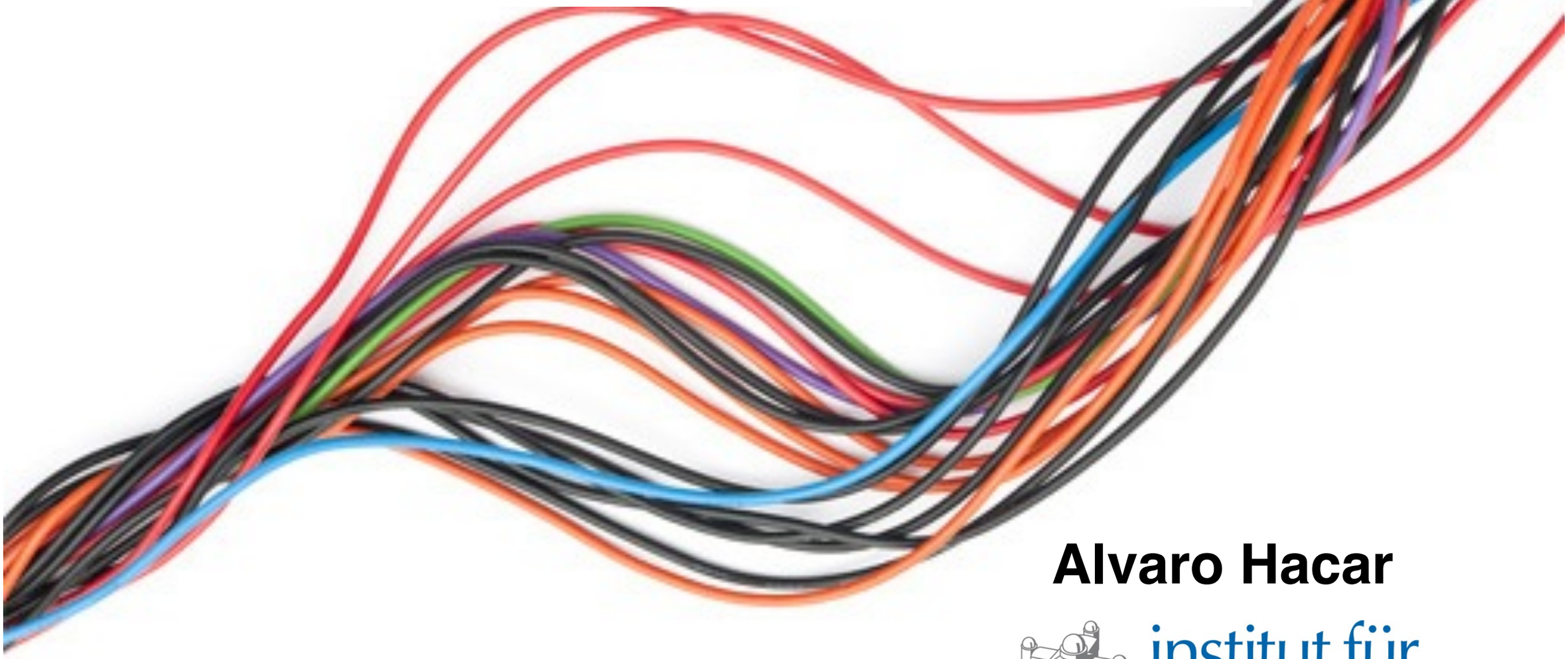
Understanding the internal substructure of Herschel filaments



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Star Formation across Space and Time
Noordwijk, Nov. 11-14th, 2014

Science before Herschel…

- Filaments directly involved in the SF-process (since Barnard 1907)
- Filaments present in all SF-clouds (e.g. Loren 1981, Bally+1987)
- Most of the cores/YSOs found in filaments (Hartmann+ 2002)
- Cores formed from the gravitational fragmentation of filaments (Schneider & Elmegreen 1979)
- CMF slope similar to IMF (Motte+1998)
- CMF shape mimics IMF with SFE ~ 30% (Alves+ 2007)
- A_V~7-8^{mag} as column density threshold (Johnstone+2004)
- Striations correlated to magnetic fields (Goldsmith+2008, Heyer +2008)
- ….

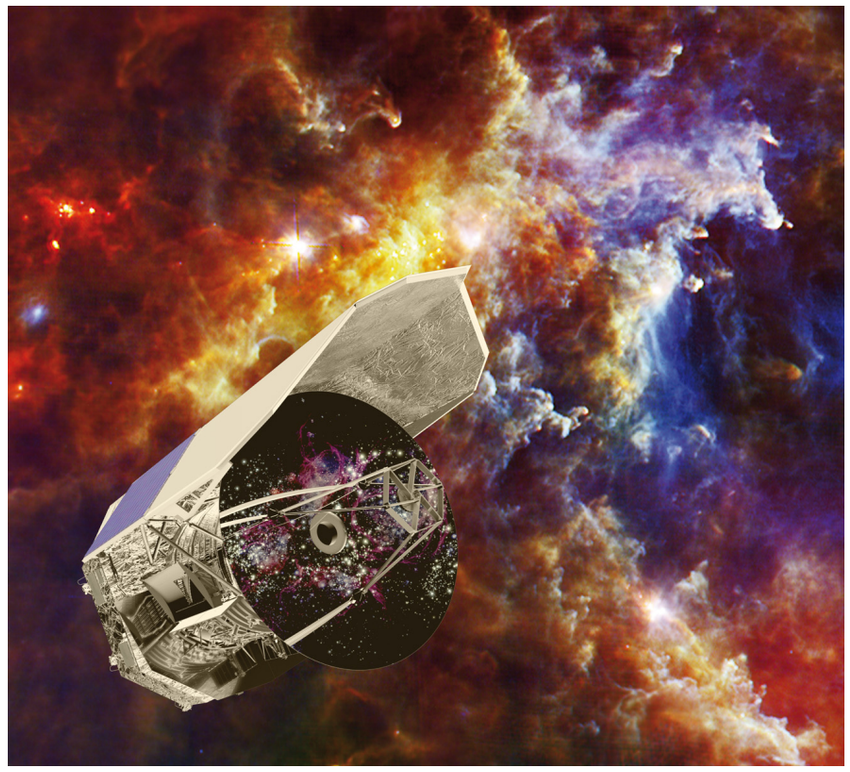
The Herschel Era

Unprecedented results:

- Precise masses and col. densities (>> molecular observations)
- (Effective) dust temperature measurements
- Systematic and Statistical studies in multiple clouds
  (e.g. Gould Belt survey)
- Access to the detailed substructure of clouds at large scales

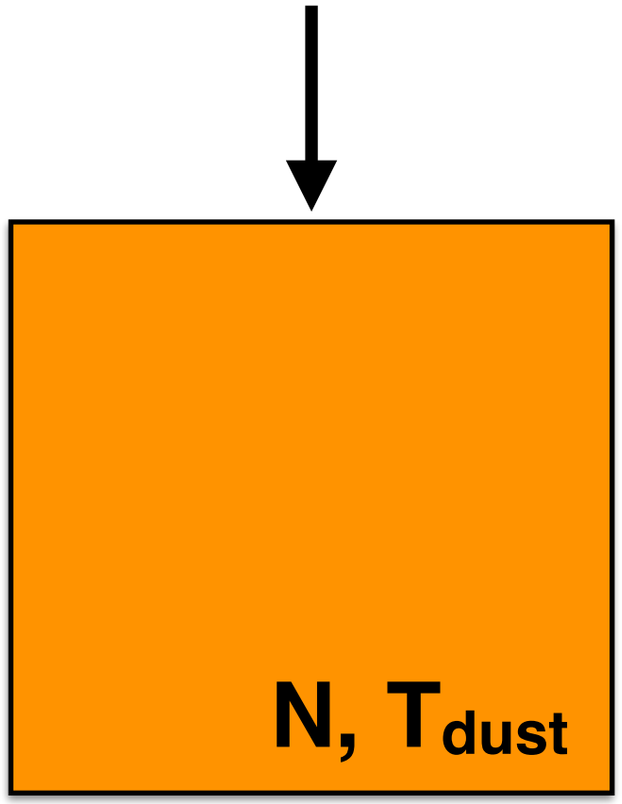
New Herschel observations (e.g. >> ISO):

- Sensitivity
- Spectral coverage
- Dynamical range
- Large scale maps
- Resolution (~18 arcsec)



Pixel information: Herschel vs Molecular lines

FIR-Herschel



Integrated emission

Precise measurement of the total Column density

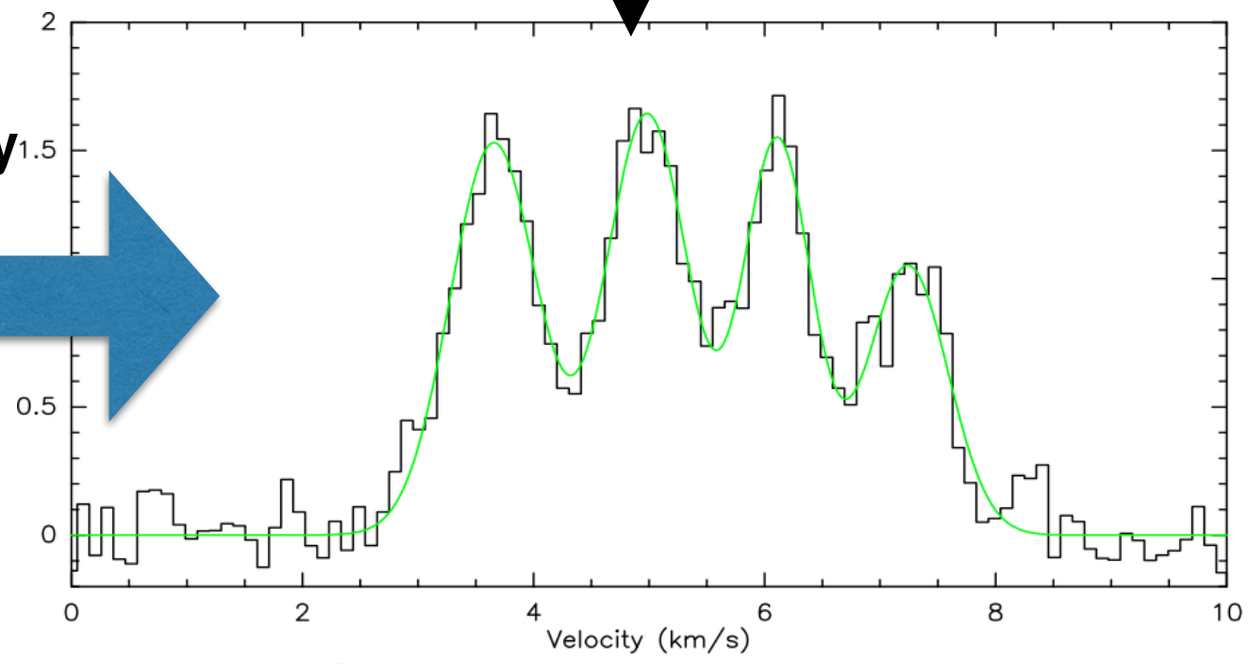
Pixel information: Herschel vs Molecular lines

FIR-Herschel

mm-Molecular lines

Complementary Information

N, T_{dust}



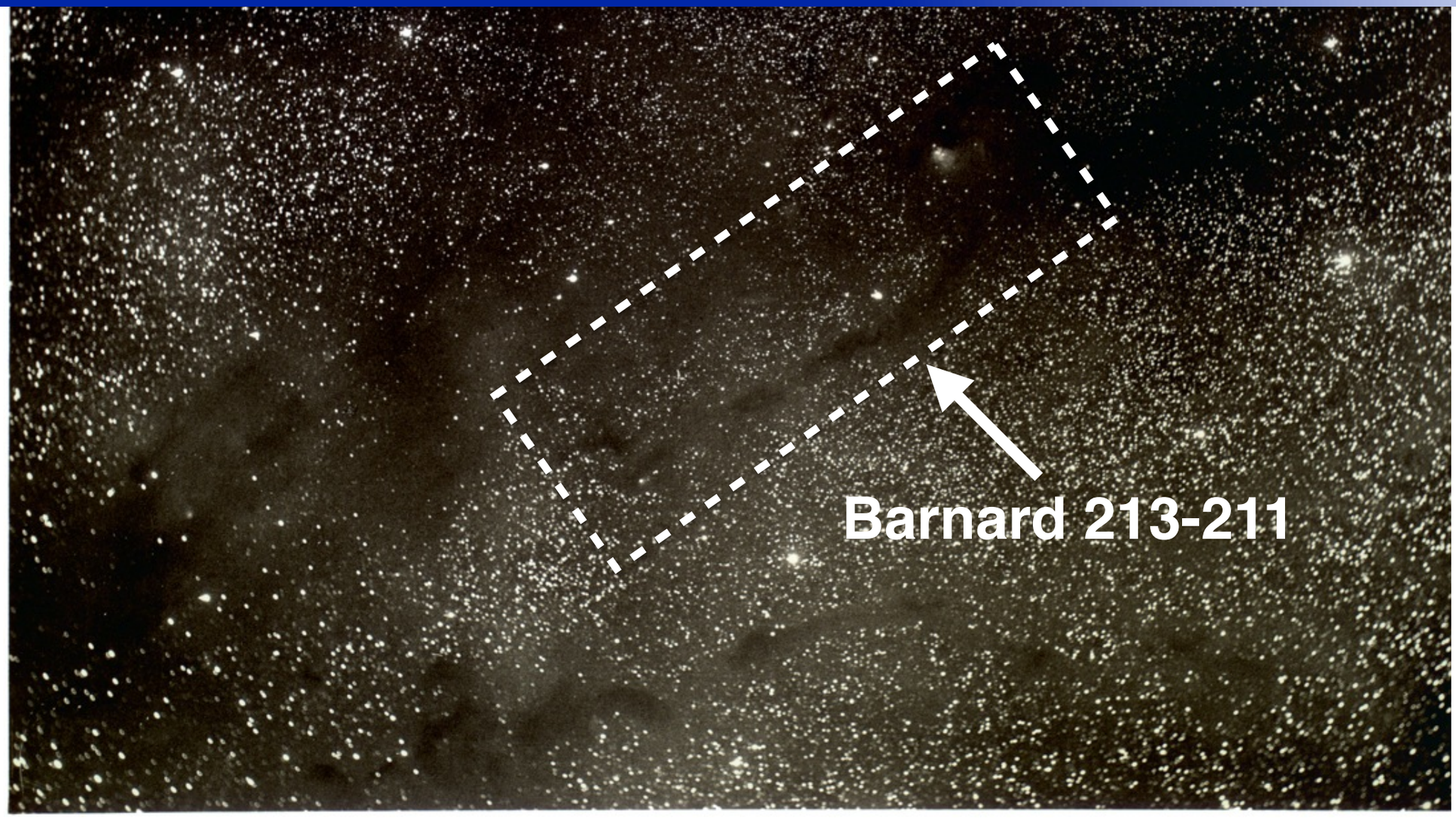
Integrated emission

Spectral resolution (detailed Kinematic information)

Precise measurement of the total Column density

Helps to disentangle superposed structures

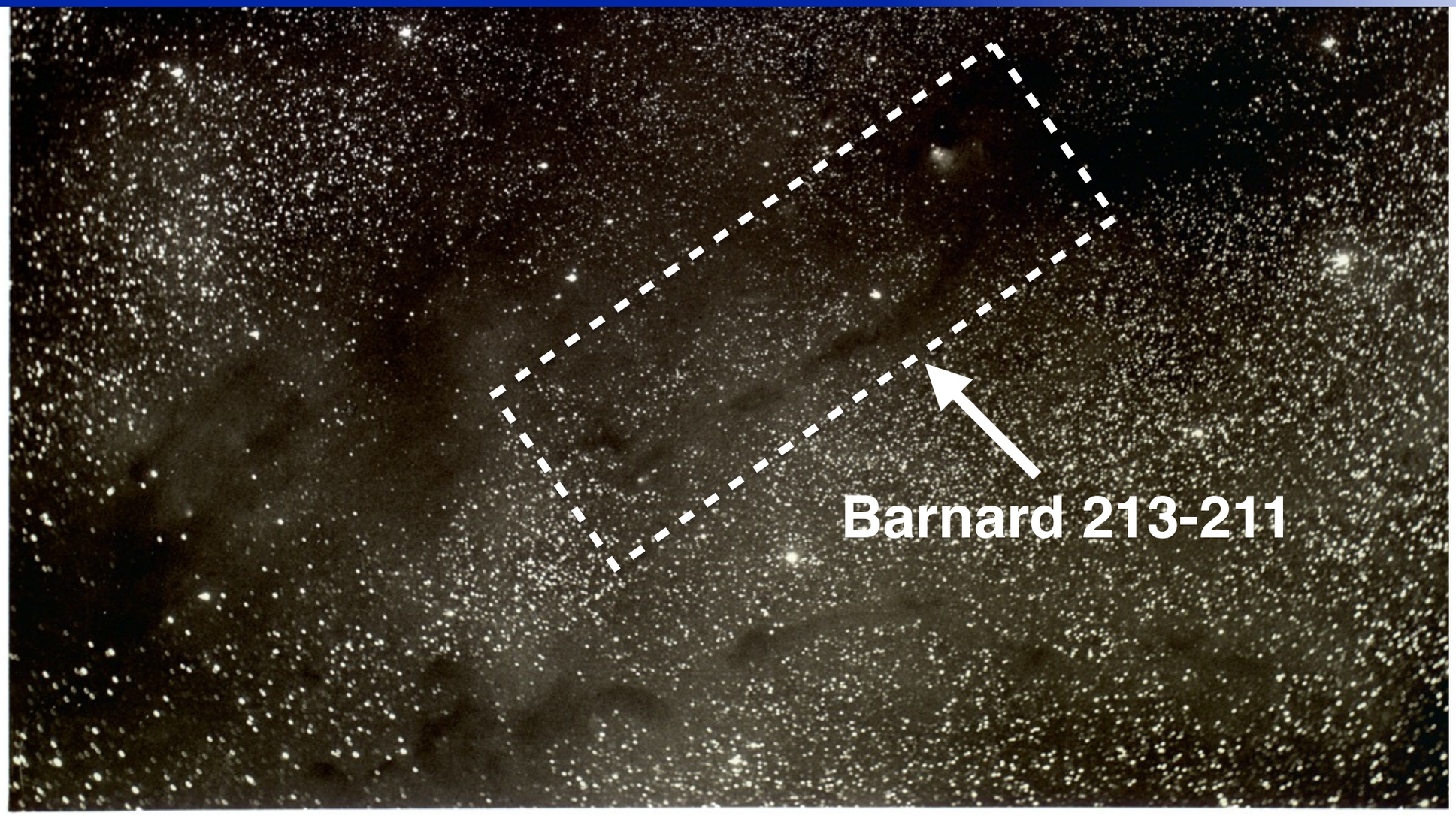
The B213-L1495 filament



"Among the most surprising things in connection with these nebula-filled holes are the vacant lanes (**filaments**) that so frequently run from them for great distances. These lanes undoubtedly have had something to do with the formation of the holes (**cores**) and with the nebula (**YSOs**) in them."

Barnard 1907

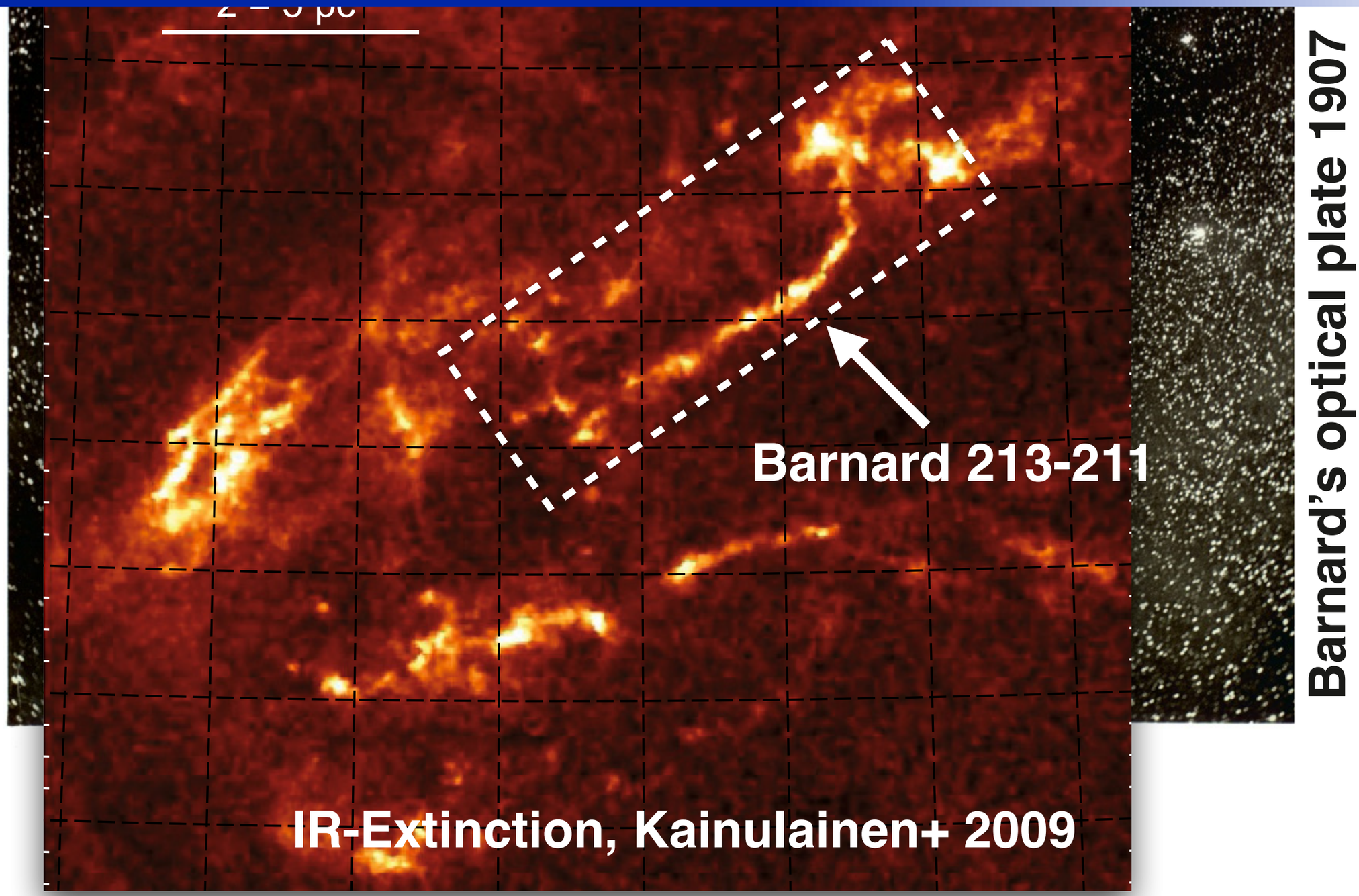
The B213-L1495 filament



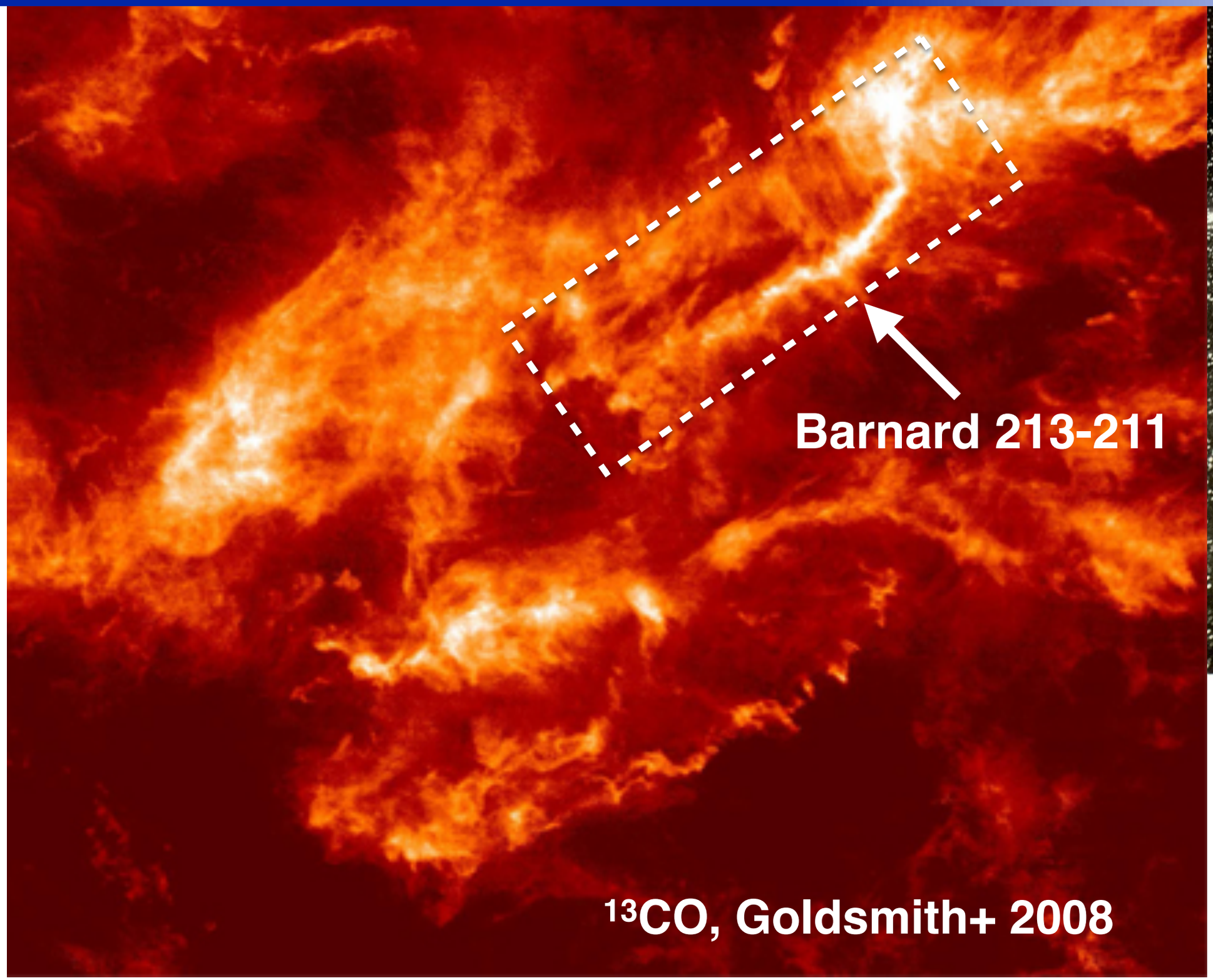
- Since its discovery, studied as prototypical filament in nearby MCs
- B213-L1495 = active star-forming filament in Taurus (D=140pc)

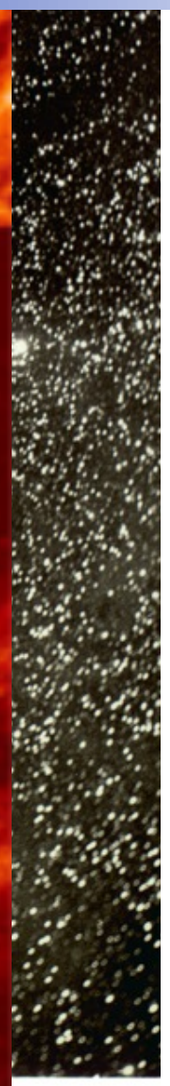
  ~ 40 YSOs + 20 cores, L ~ 10pc & M ~ 700 $M_\odot$

The B213-L1495 filament



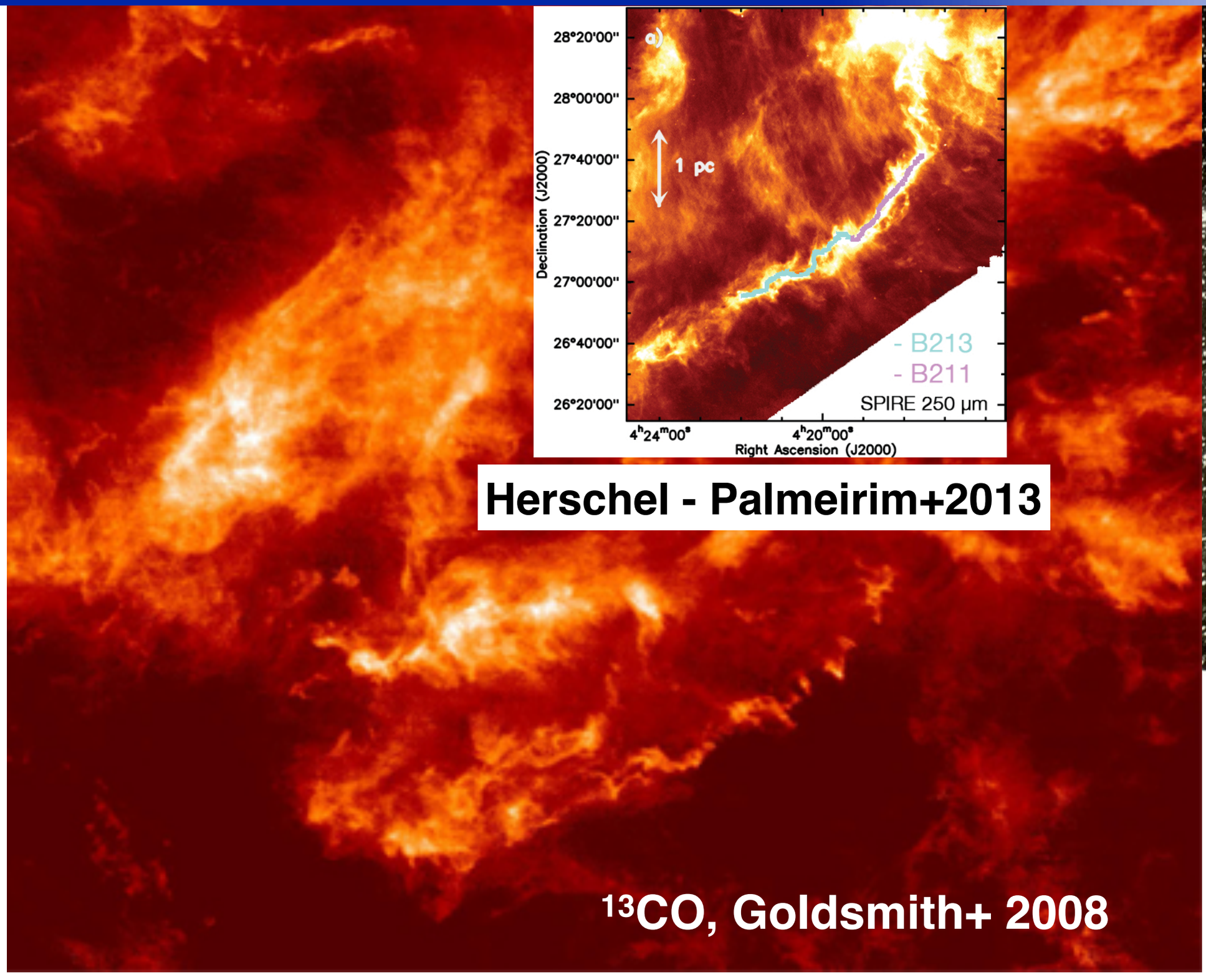
The B213-L1495 filament





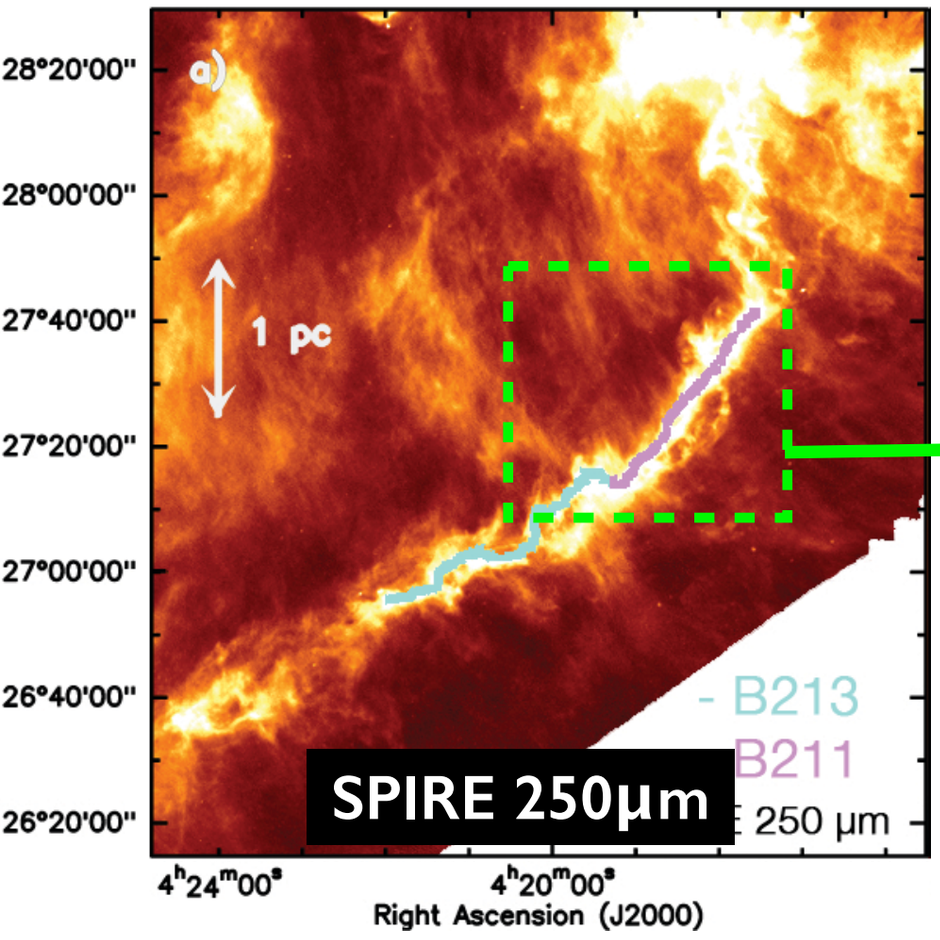
Barnard's optical plate 1907

The B213-L1495 filament

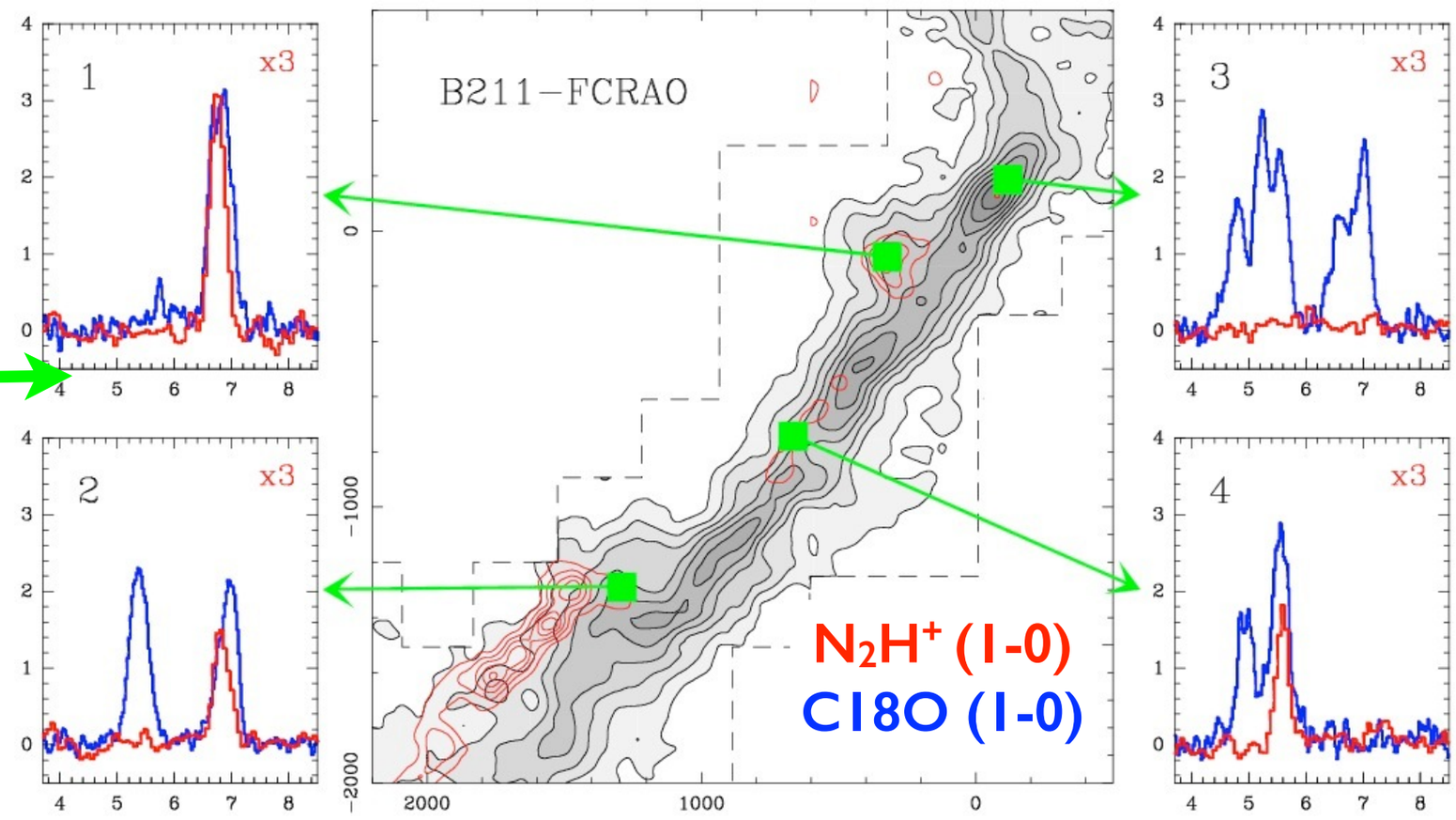


Kinematic complexity within B213-L1495

Herschel vs Molecular Lines



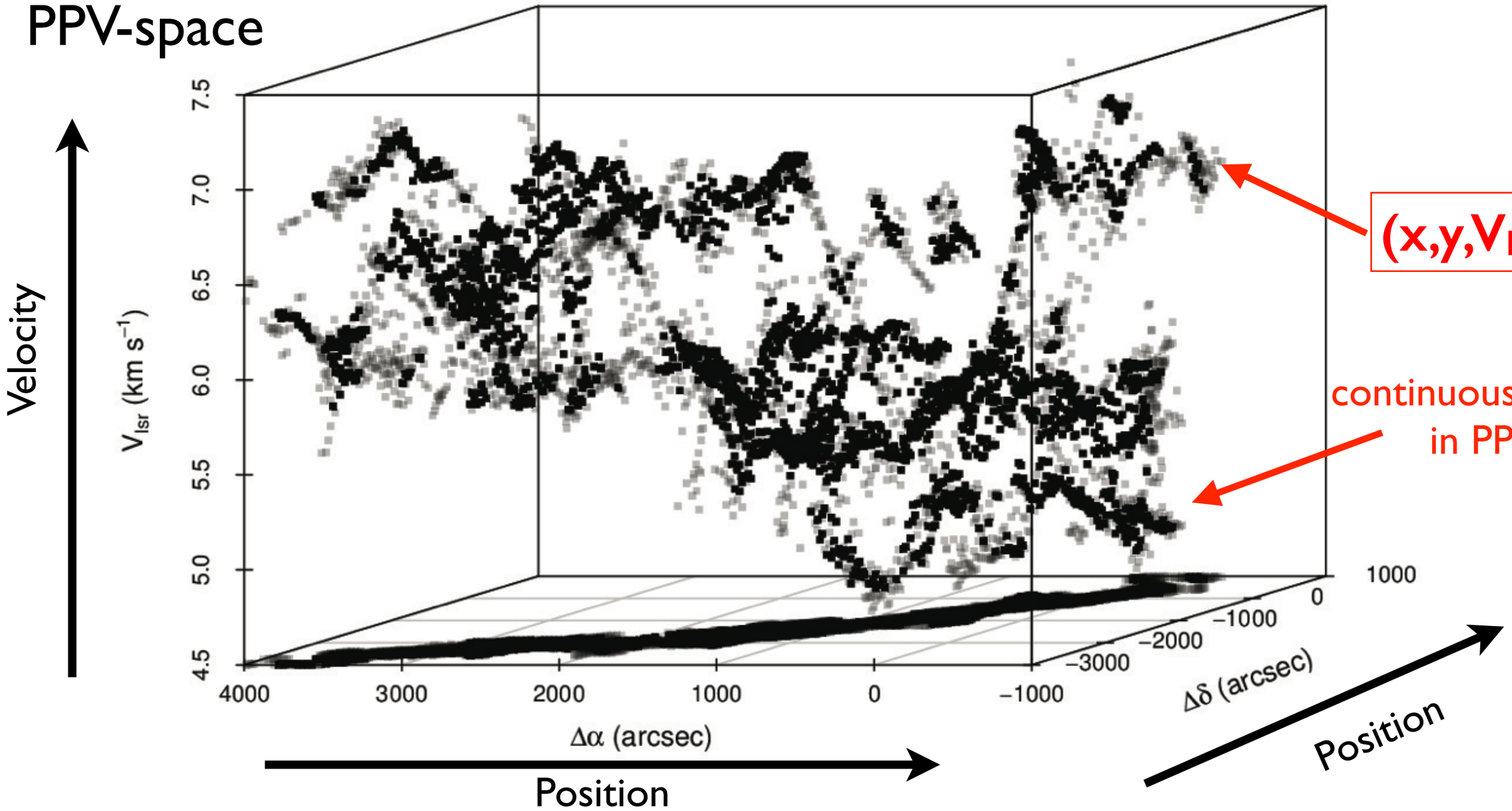
Palmeirim+ 2013



Hacar+ 2013

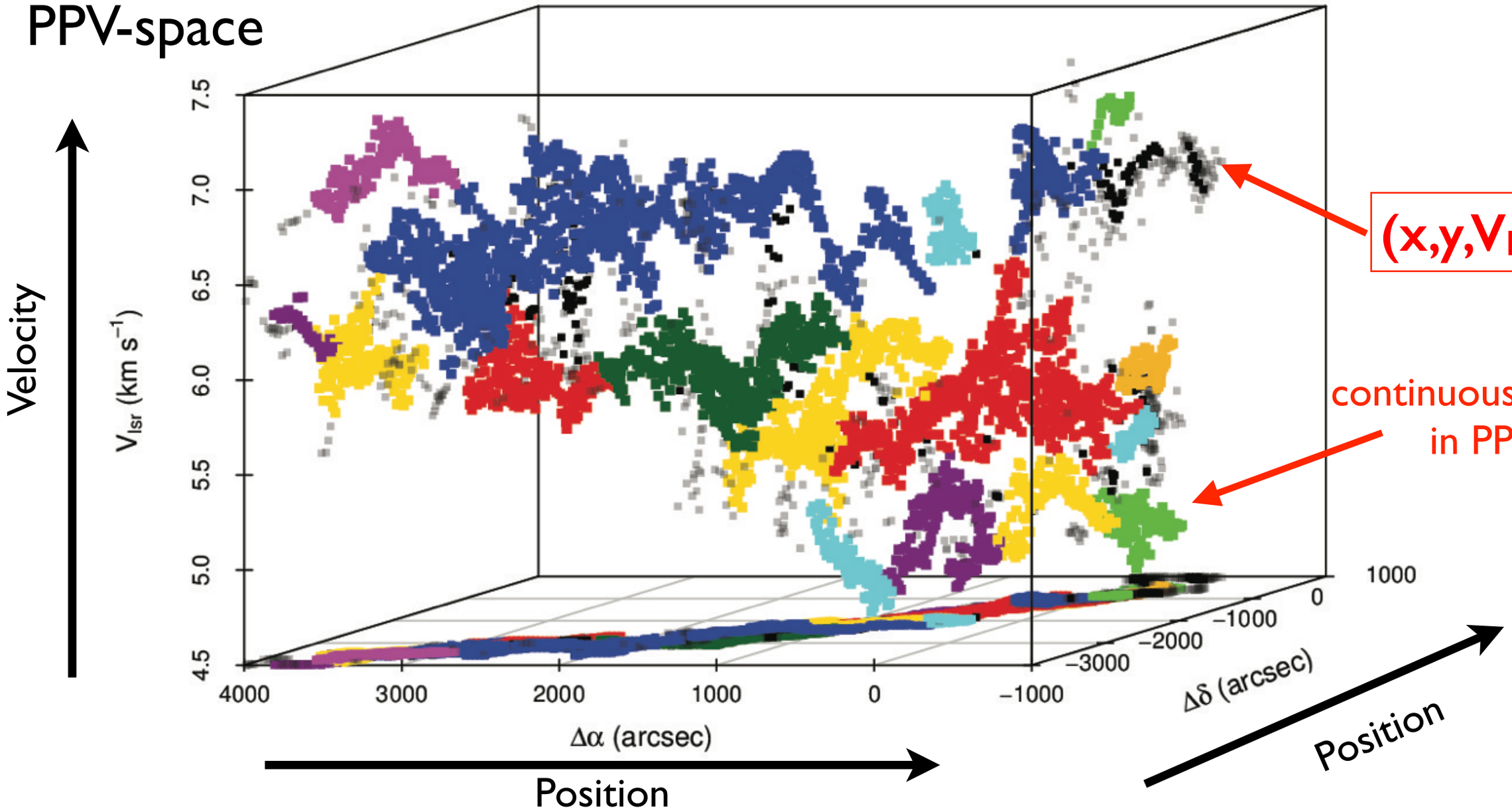
- Geometrically simple structures in Herschel (i.e. continuum) present a complex kinematic structure when observed in mm-lines

Velocity coherent substructure



- Multiple velocity-coherent structures found within B213
- All continuous in PPV space, presenting smooth velocity gradients
- Reconstruction using Friends-In-Velocity (FIVE, Hacar+ 2013)

Velocity coherent substructure



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Velocity coherent substructure

PPV-

Velocity

V_{lsr} (km s^{-1})

,V_{lsr})

ous struct.
PPV

Properties:

- 35 structures
- Aspect ratio > 3 - 4 → Filamentary
- Length ~ 0.6 pc
- M_{lin} ~ 15 $M_\odot$ pc^{-1} → equilibrium
- σ_{NT} and $\sigma(V_{lsr})$ ~ Cs → (tran-)sonic

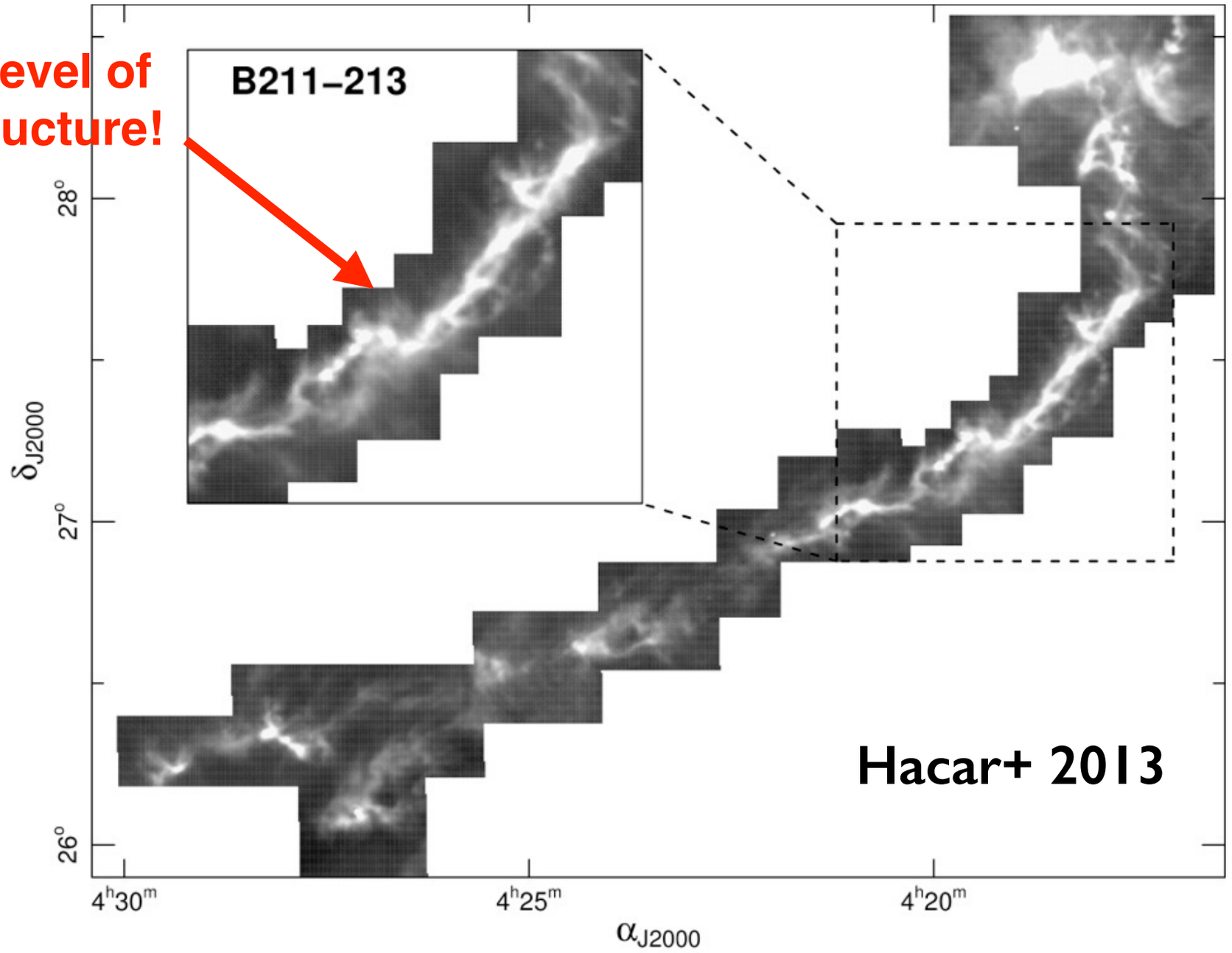
⇒ 35 velocity coherent filaments

(see also Hacar & Tafalla 2011)

- Mu
- All
- Reconstruction using Friends-in-Velocity (FIVE, Hacar+ 2013)

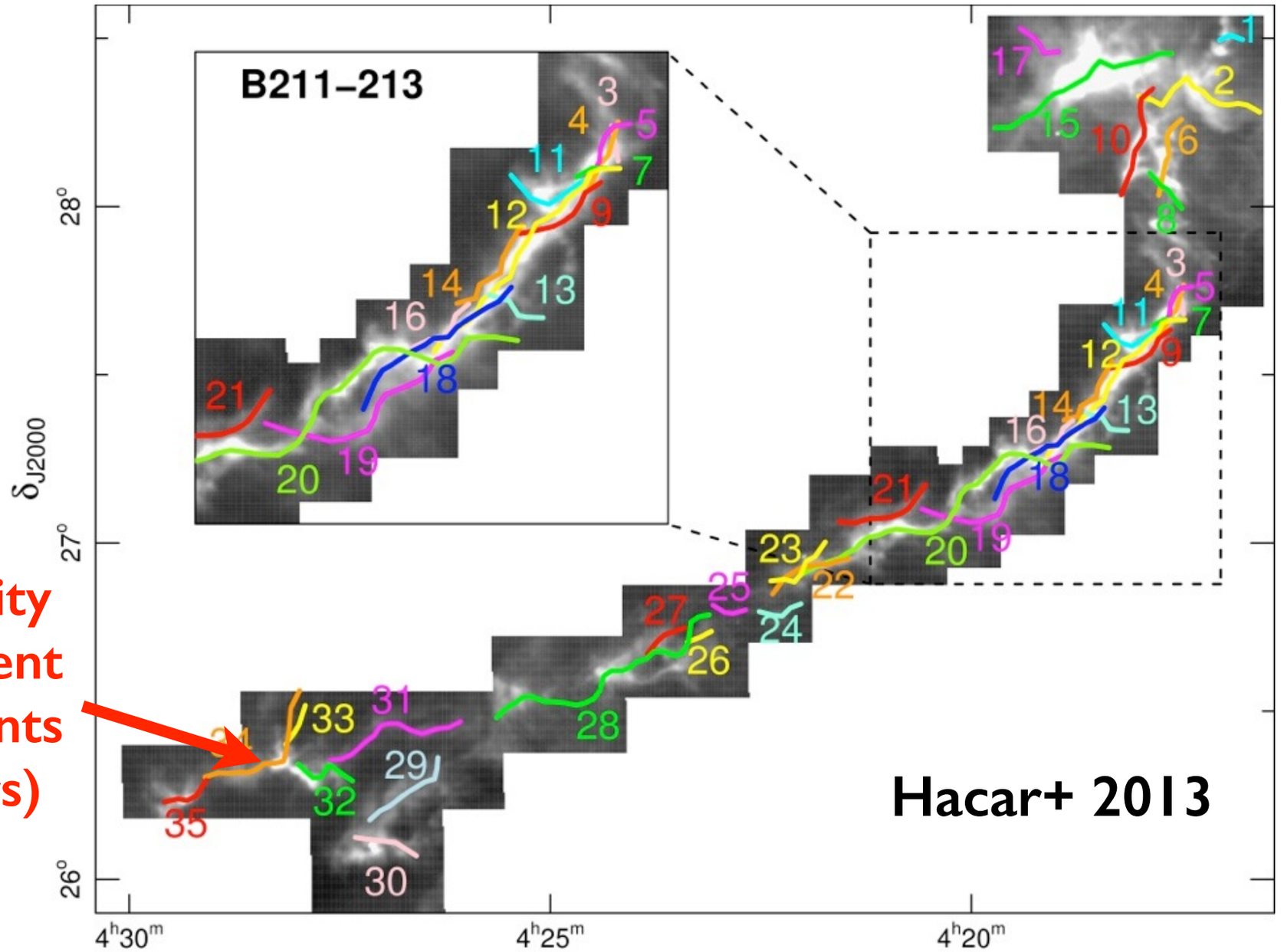
Filaments within filaments

High level of substructure!



Background: Herschel SPIRE Archive Image
Gould Belt Project (PI: P. Andre)
see also Palmeirim+ 2013

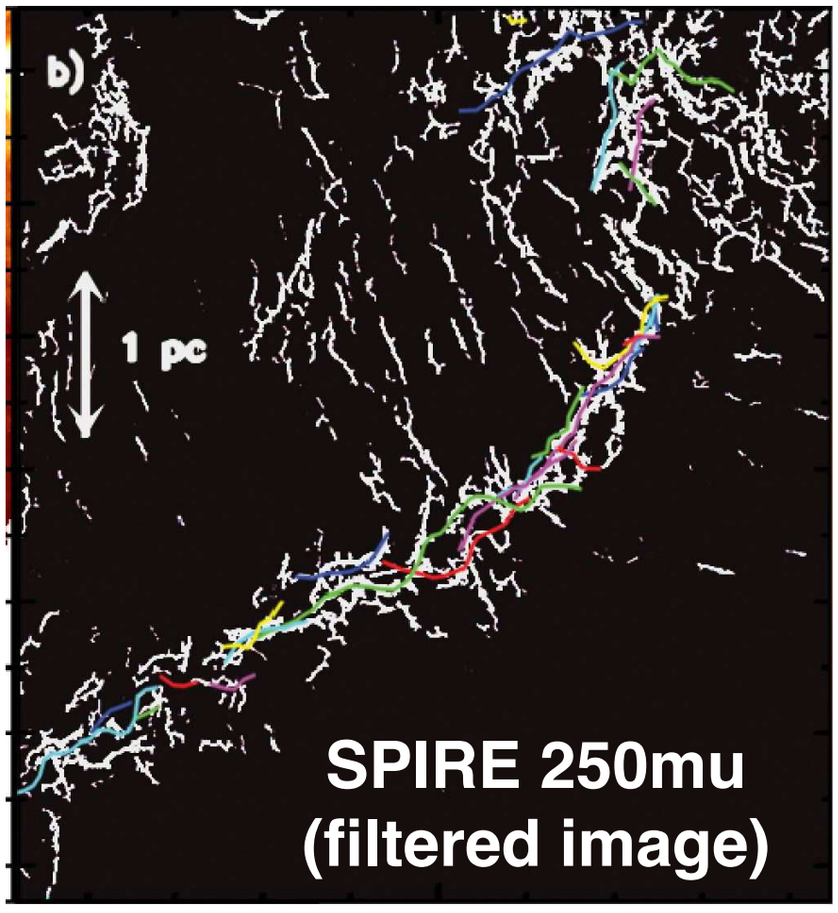
Filaments within filaments



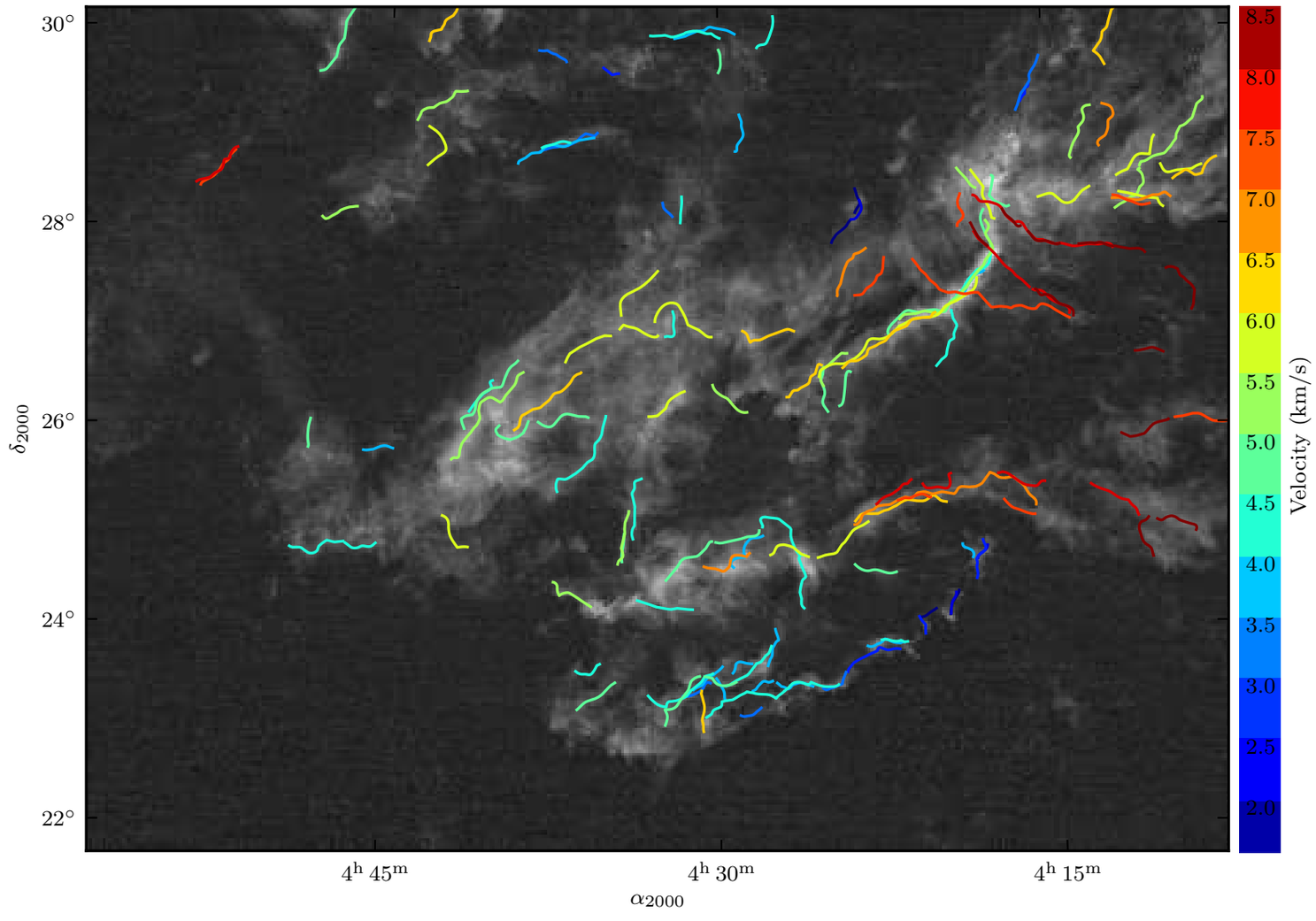
- B213 = 35 velocity-coherent filaments (**fibers**) forming a **bundle**
- Apparently supercritical filament but actually a collection of (sub-)critical fibers
- **Explains substructure of the Herschel column density maps!!**

Fibers in Taurus: new observations

André et al PPVI

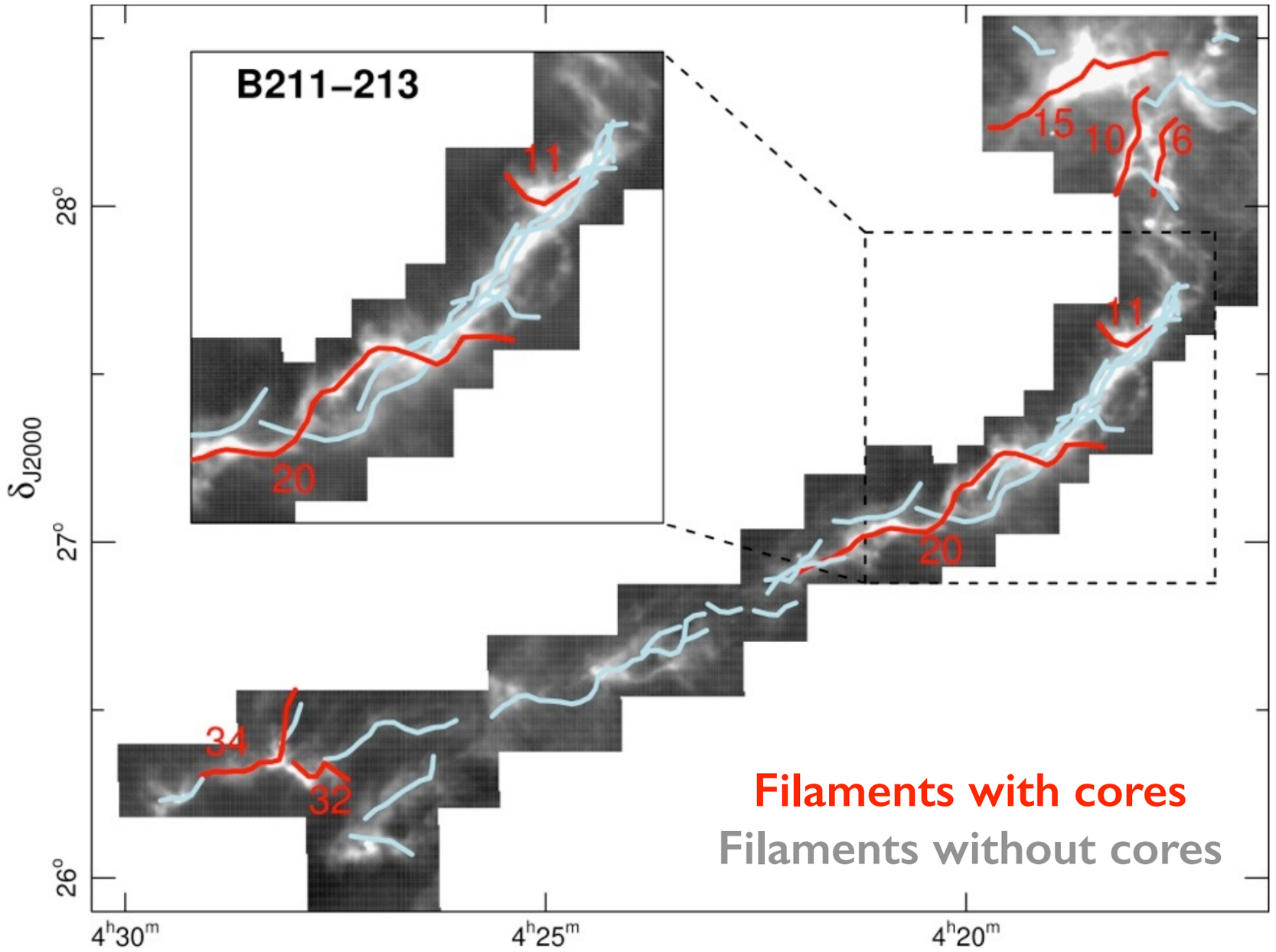


Panopoulou+ 2014



- B213 fibers confirmed in Herschel maps (André+2014)
- >100 filaments in Taurus (Panoupoulou+2014)
- Additional (tran-)sonic fibers identified in Perseus, IC5146, Oph…

Fertile vs. Sterile fibers



- Cores formed inside these ~0.5pc length, (tran-)sonic fibers
- But only few **fertile** fibers form cores (~1/4; high SFE) → $M_{lin} \gtrsim M_{Ost}$
- While most of them remain sterile (~3/4; SFE ~ 0) → $M_{lin} \lesssim M_{Ost}$

Monolithic vs composed filaments

What theory predicts:

- Critical mass per unit length (Stodolkievitz 1963, Ostriker 1964)

$$M_{crit} = 2Cs^2/G \sim 16\ M_\odot\ pc^{-1} @\ 10\ K$$

- Filament fragmentation (e.g. Inutsuka & Miyama 1997)
  - If $M_{lin} \sim M_{crit}$ (critical) $\Longrightarrow$ fragmentation into cores
  - If $M_{lin} >> M_{crit}$ (supercritical) $\Longrightarrow$ collapse into a spindle (without fragmenting!)

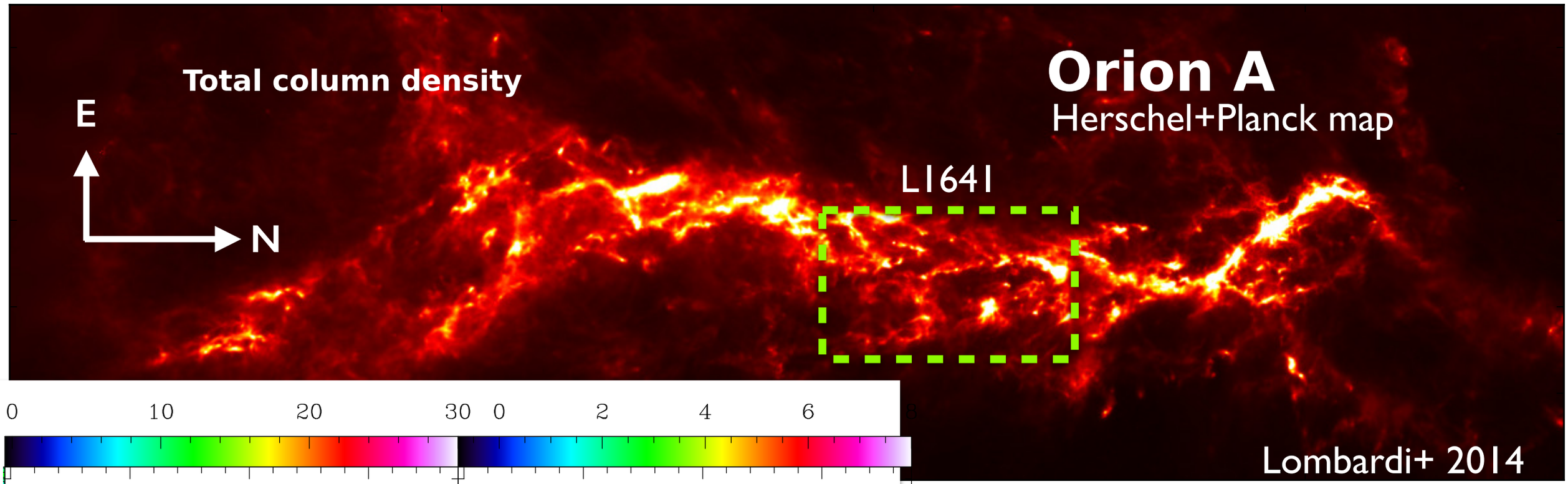
What Herschel observations have found:

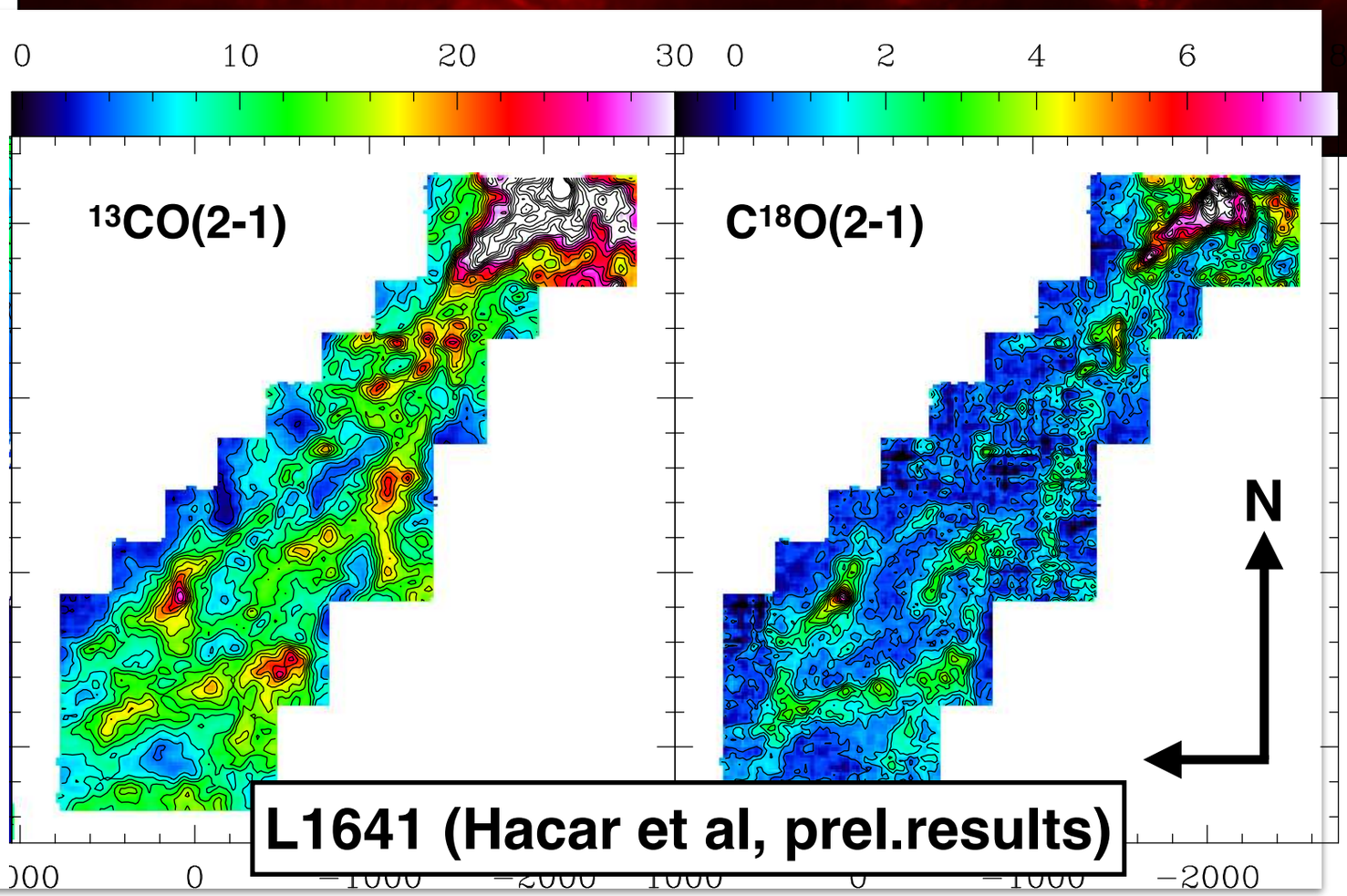
- Cores are found in supercritical filaments!!
  (e.g. B213-L1495, $M_{lin} = 54\ M_\odot\ pc^{-1} >> M_{crit}$, Palmeirim+2013)

Solution:

- Composed filaments (= bundles of fibers)
  present large-scale stability while allowing local fragmentation

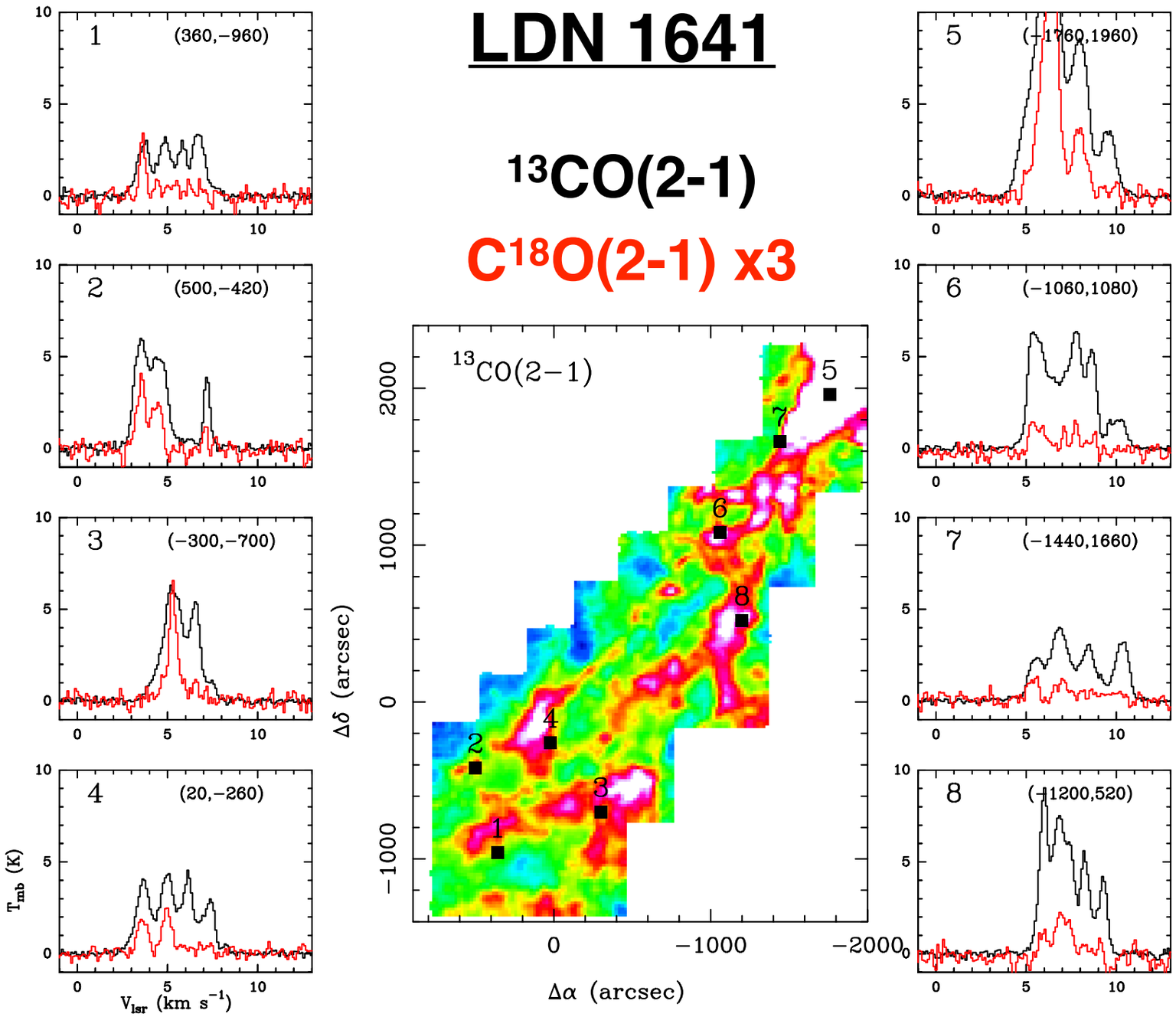
Fibers & massive SF filaments





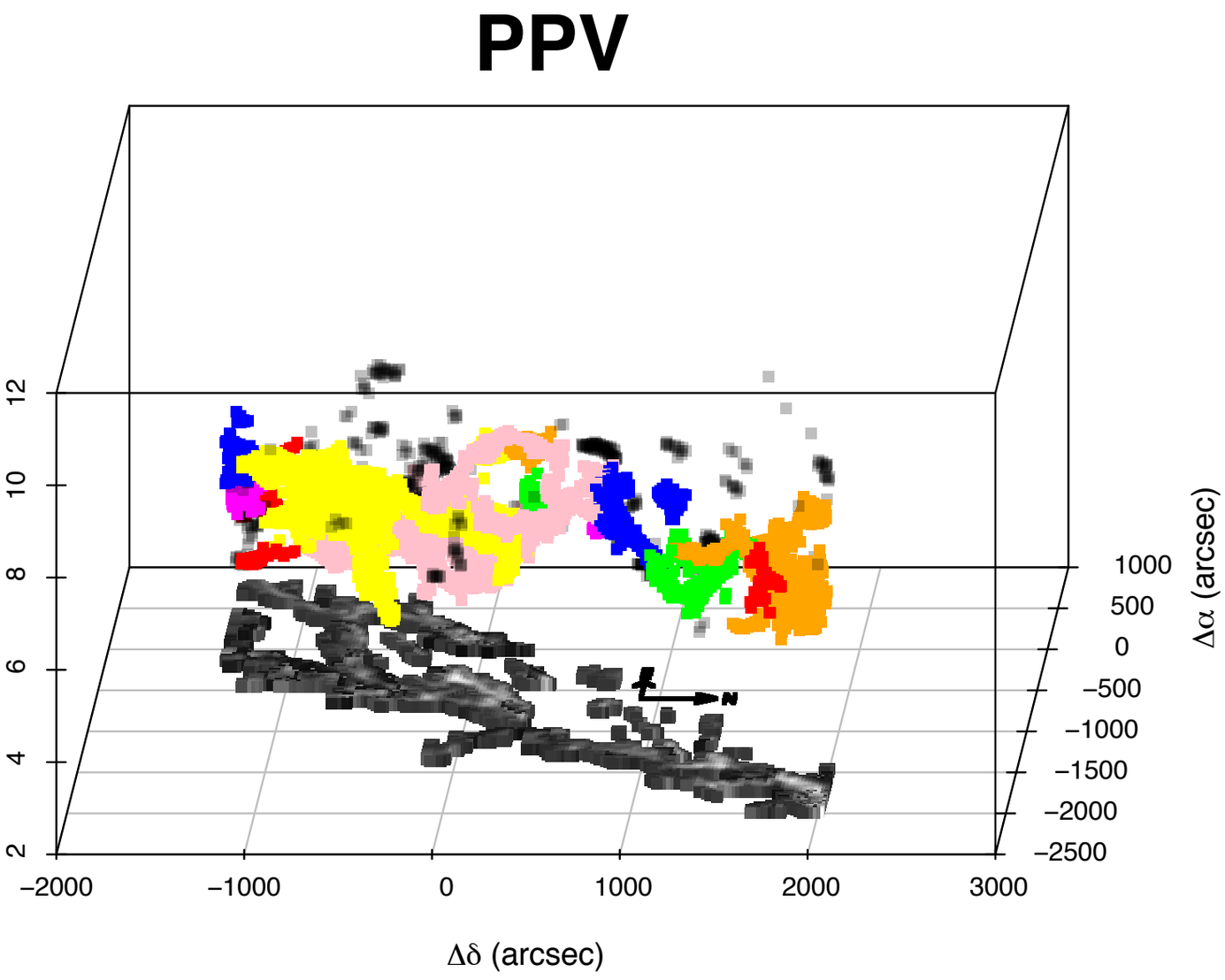
- Tangled filaments also found in massive regions like Orion
- Previous evidences found by Nagahama+1998(Ori A) & Li+2013(OMC2-3)
- Open bundles in nearby clouds: directly observed in Herschel

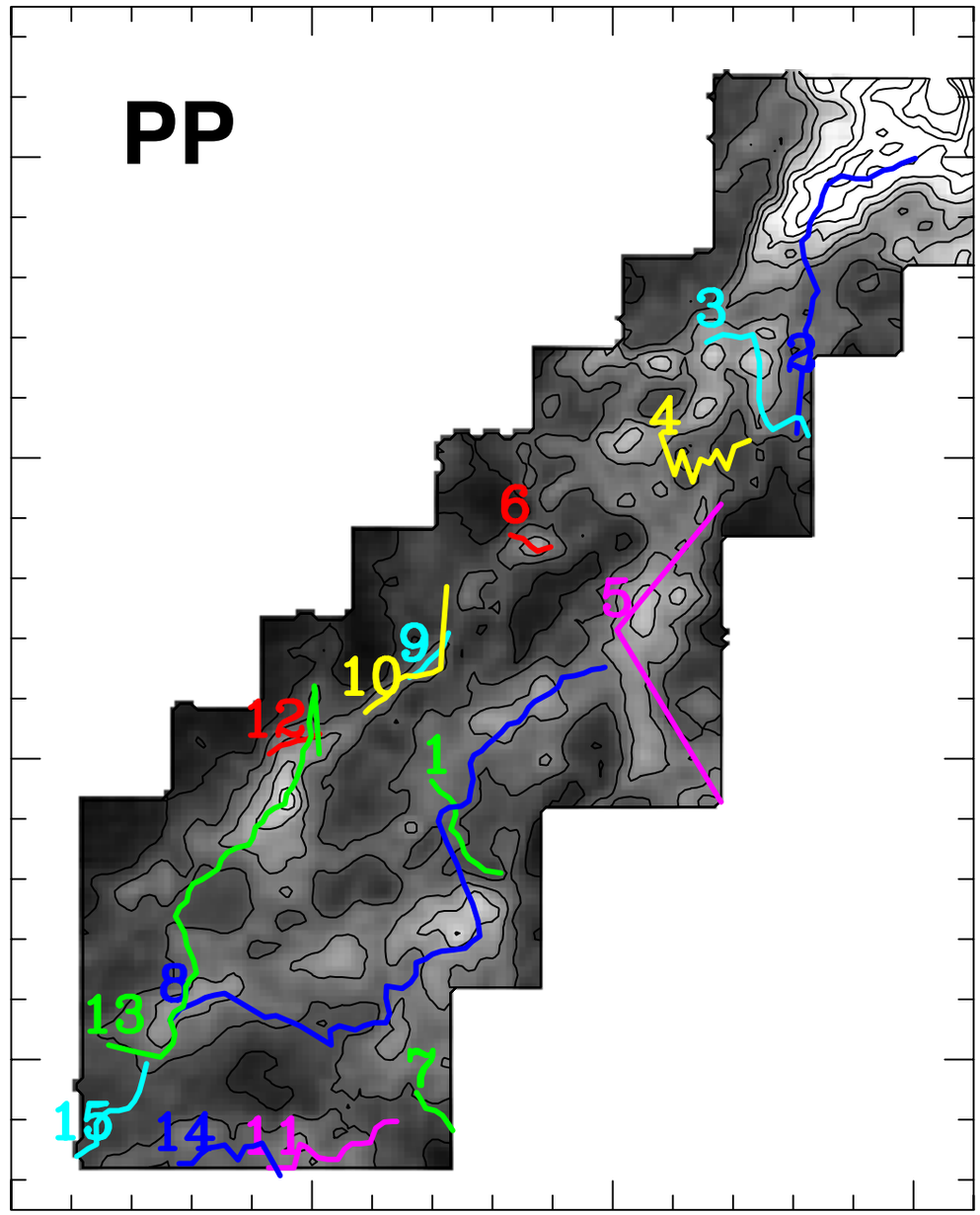
Complex bundles



- Line multiplicity in >80% of the ^{13}CO spectra
- Individual components with different intensities, densities, chemistry…

L1641: (ultra-)preliminary results

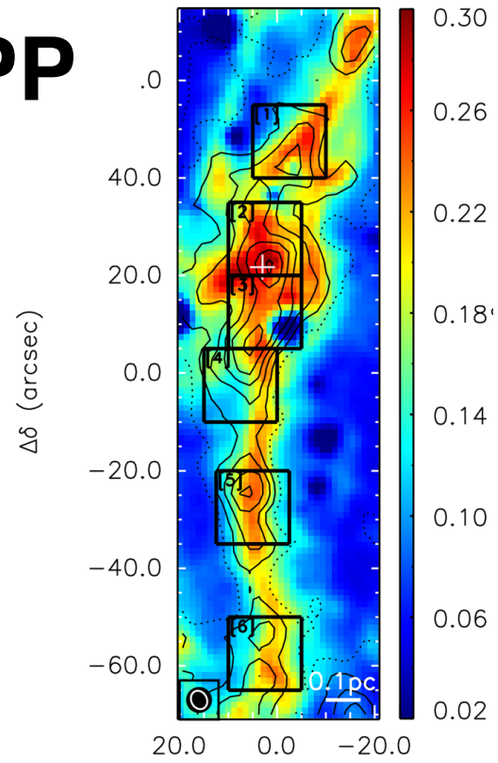




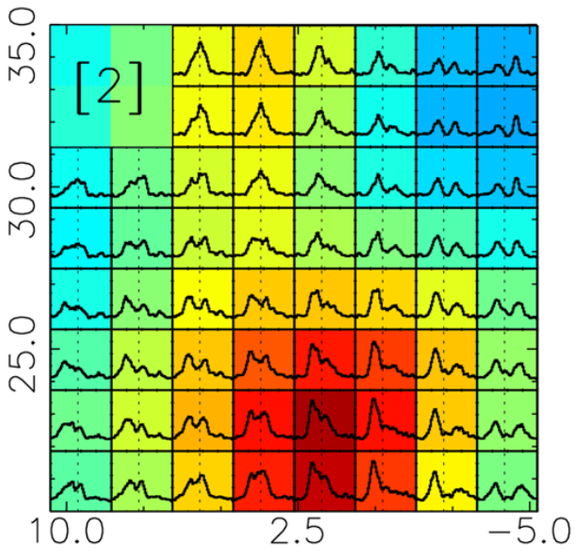
- >15 transonic fibers identified in L1641
- L1641 = Complex Bundle
- Important: Multi-tracer analysis required !!

IRDC as bundles of fibers

PP

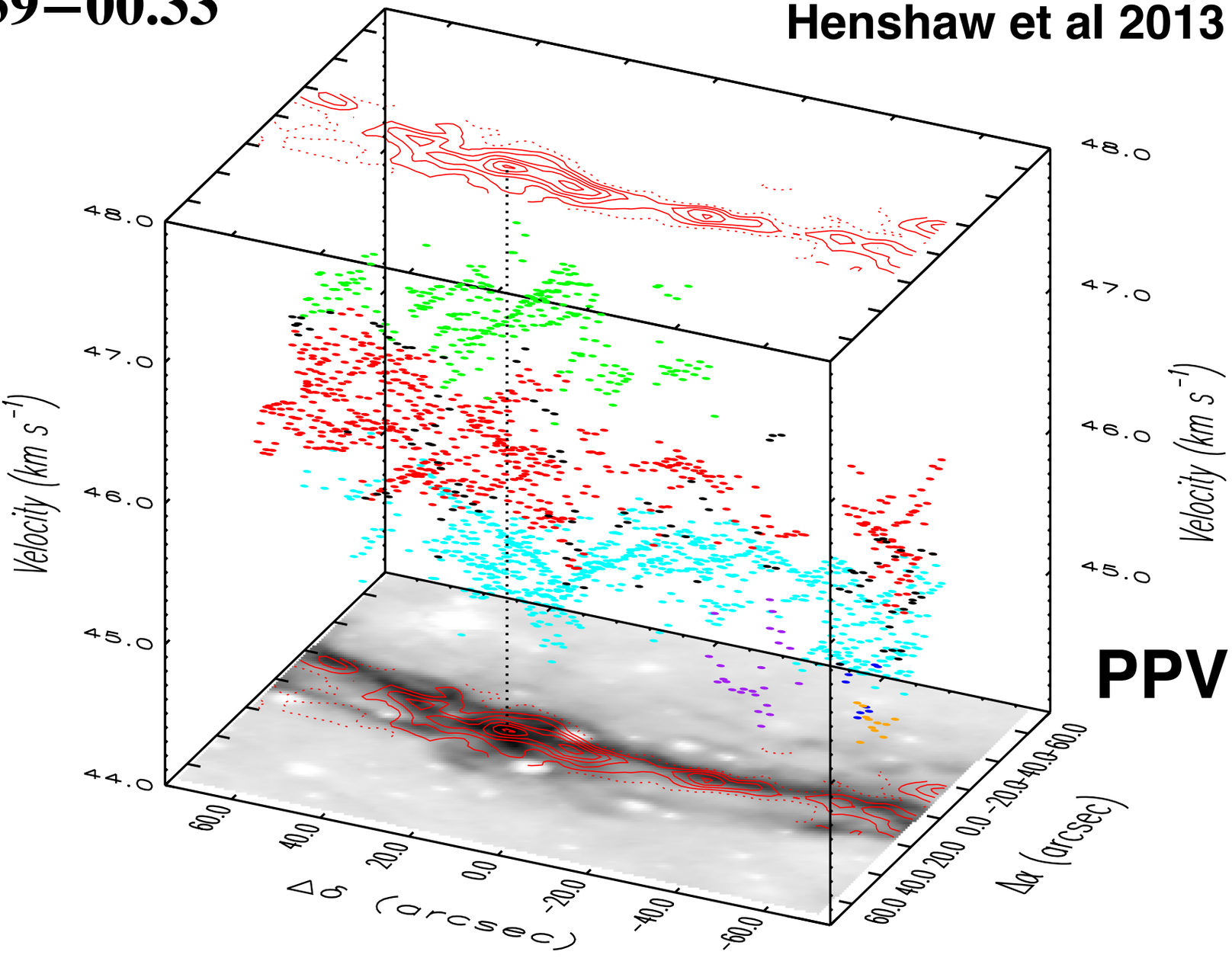


representative spectra



G035.39−00.33

Henshaw et al 2013

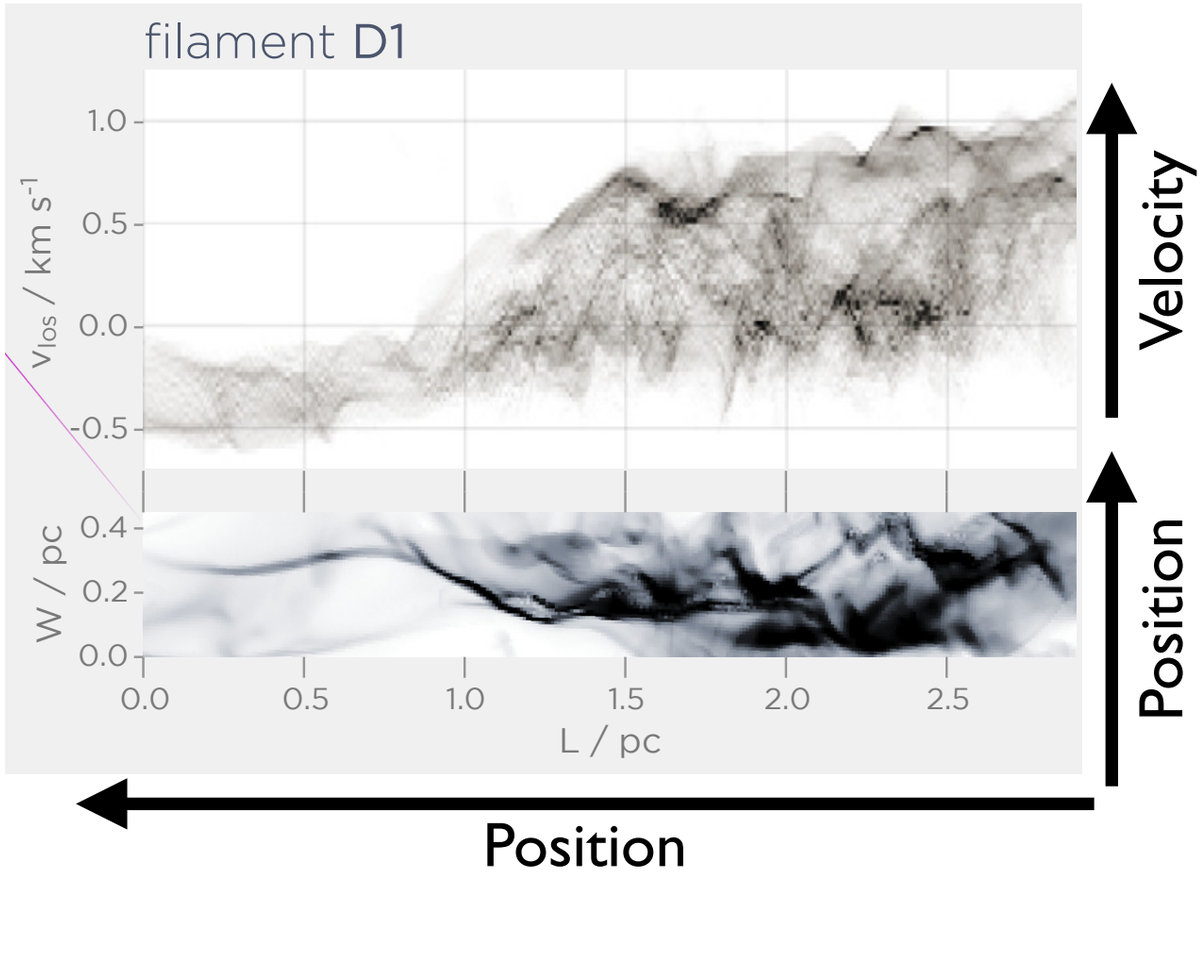


PPV

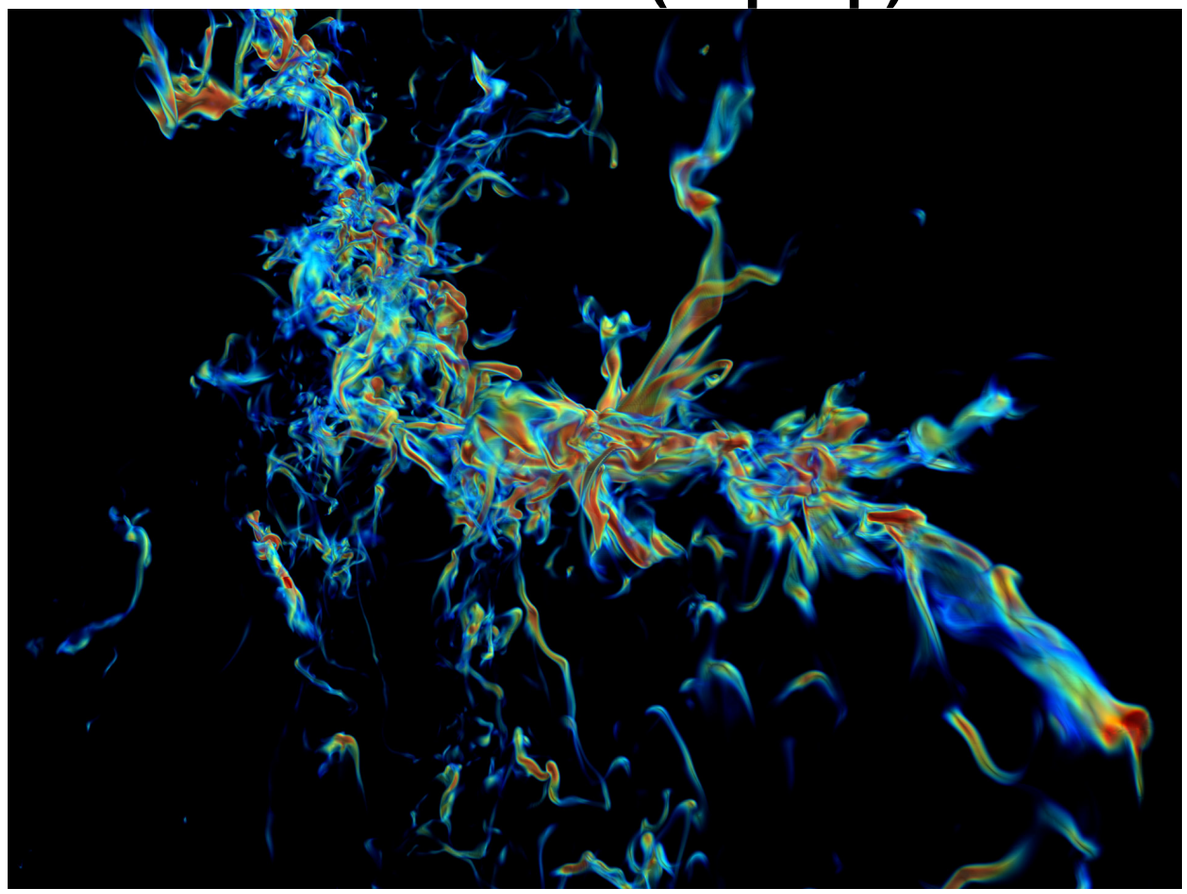
- Strong similarities between local and distant clouds
- Multiplicity + complex velocity structure

Bundles: recent simulations

Moeckel & Burkert 2014



Klein et al (in prep)



- Reproduced by hydro-simulations (Moeckel & Burkert 2014, Smith 2014)
- Although also in models including B (Klein et al)
- Fibers are present in all kind of simulations:

<u>filaments are not “monolithic objects” but complex bundles of fibers</u>

Conclusions

- Kinematic information key to understand the internal substructure of Herschel maps

- Fibers ⇒ fundamental building blocks
  - Present in all kind of environments
  - Sonic-like structures naturally created as part of the turbulent cascade
  - Cores & Stars are formed from the fragmentation of only those gravitationally unstable (i.e. fertile) fibers
- Large scale, complex filaments = Bundles of fibers