Molecular Clouds and Star Formation

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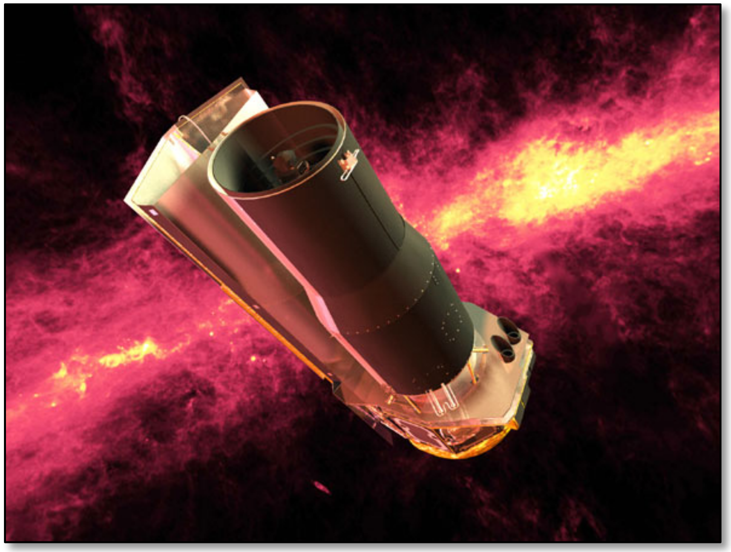
Conseil national de recherches Canada

Hubble image of M51 (NASA/ESA)

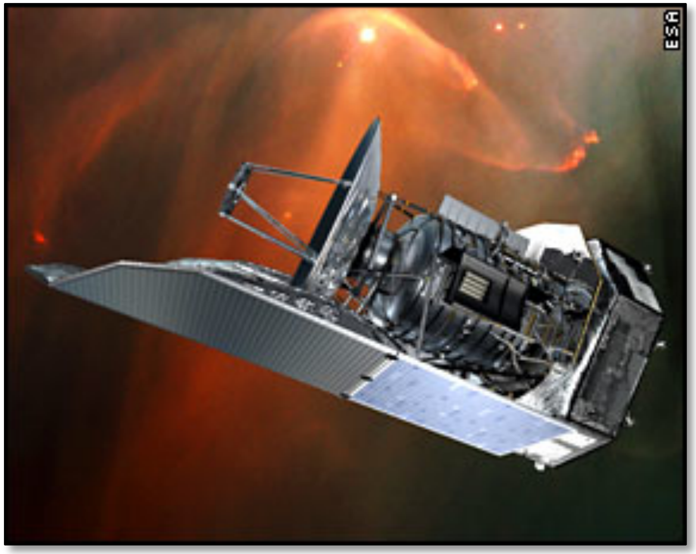
Five Star Formation Regimes

- **Local (Low-mass) Star Formation**
    - <0.5 kpc; *Taurus, Orion, Ophiuchus*
- **High-mass Star Formation**
    - 0.5-6 kpc; *W3/4/5, Cygnus, Carina*
- **Galactic Plane**
    - 6-30 kpc; outer galaxy (*IRDCs*), inner galaxy (*CMZ, Galactic Center*)
- **Nearby Galaxies**
    - 50 kpc – 15 Mpc; Local Group (*LMC, SMC, M31, M33, and dwarf galaxies*), Clusters (*Virgo, Coma*)
- **High-redshift (*z* > 1) Galaxies**
    - LIRGs & ULIRGs, SMGs, etc.

Tracing Star Formation with Wide-field Mapping



Spitzer Space Telescope



Herschel Space Observatory

Dust emission traces mass in clouds very well:

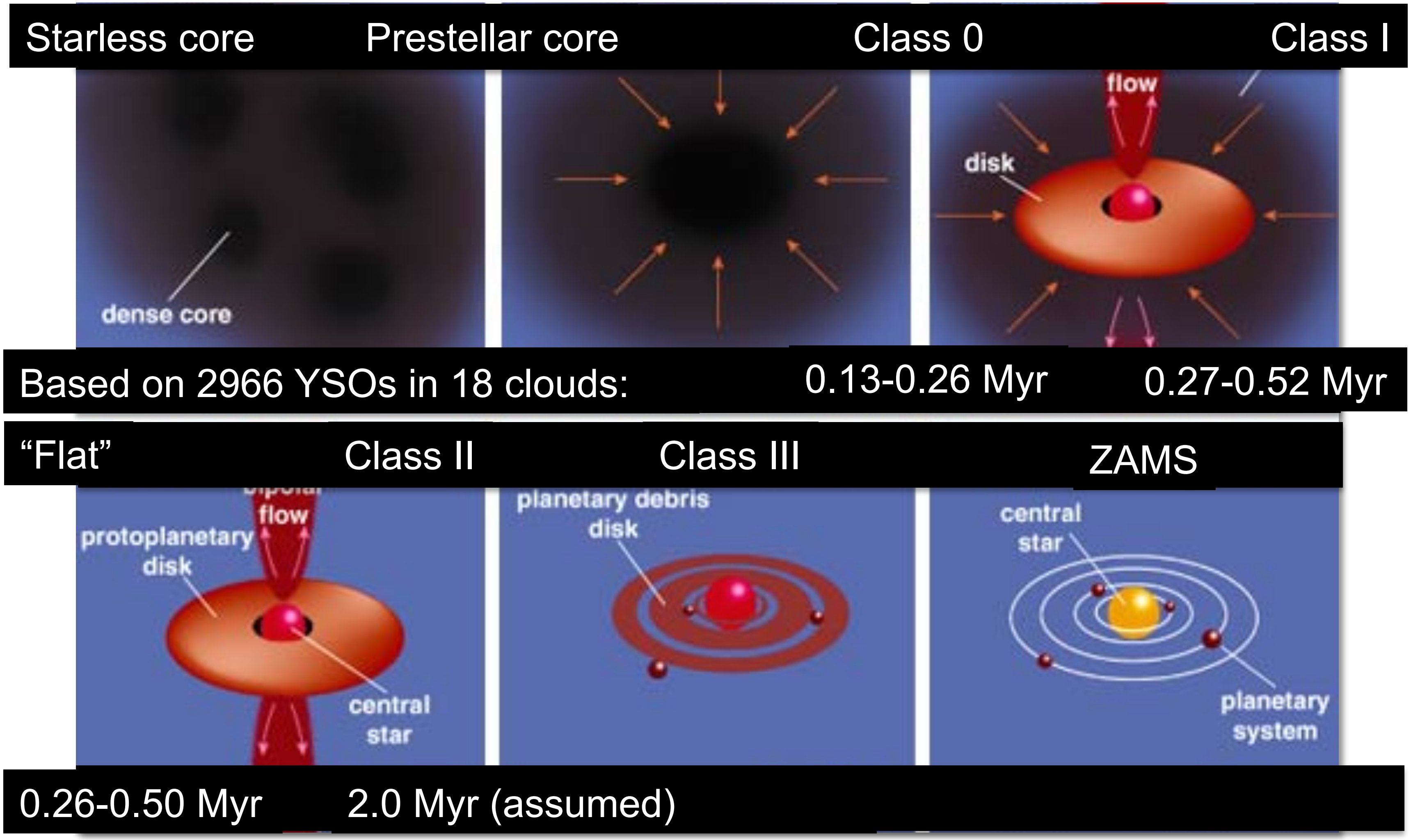
- **Spitzer** (3.6 – 8 μm, 24 – 160 μm) traced Class 0/I, II, III pops.
- **Herschel** (70 μm – 500 μm) traced cores + filaments, T_{dust} + $N(H_2)$

Surveys of Five Star Formation Regimes

- **Local (Low-mass) Star Formation**
  - <0.5 kpc; *c2d+GBS*, *H-GBS*
- **High-mass Star Formation**
  - 0.5-6 kpc; *Orion, W3/4/5, Cygnus, Carina*; *HOBYS*
- **Galactic Plane**
  - 6-30 kpc; *GLIMPSE-360*; *Hi-GAL, PCC*
- **Nearby Galaxies**
  - 50 kpc – 15 Mpc; *SINGS*; *KINGFISH*
- **High-redshift ($z > 1$) Galaxies**
  - *S-GOODS*, *H-ATLAS*

Spitzer survey
Herschel survey

Low-mass Star Formation ($M_\star < 8\ M_\odot$)



Starless core   Prestellar core   Class 0   Class I

Based on 2966 YSOs in 18 clouds: 0.13-0.26 Myr   0.27-0.52 Myr

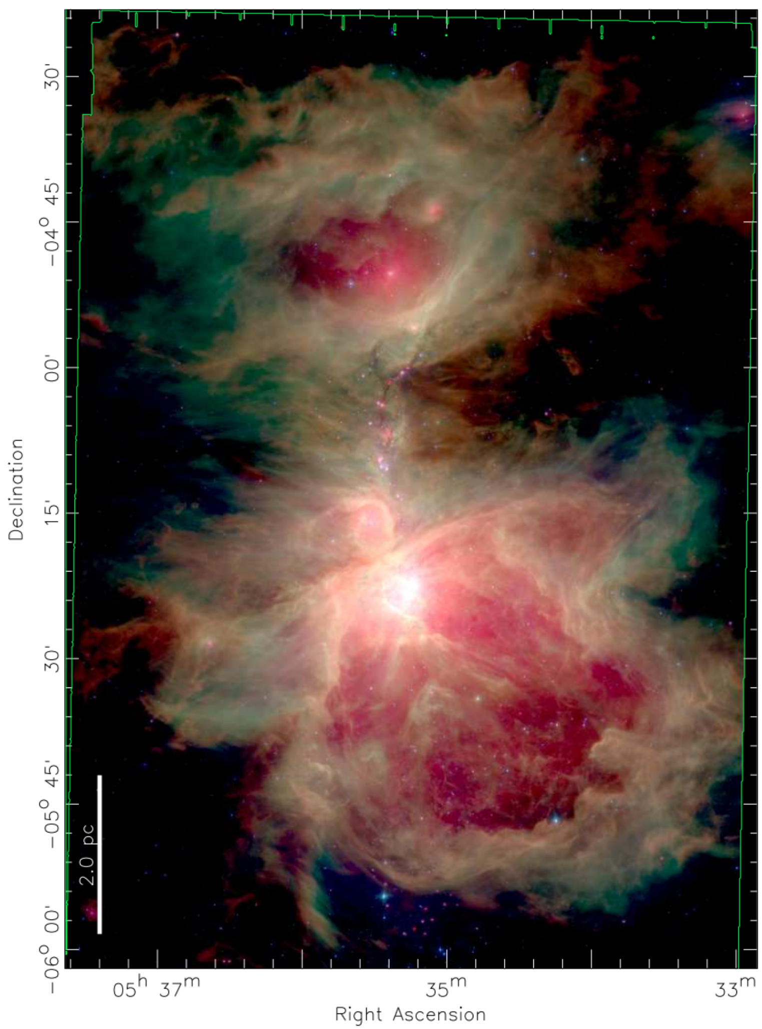
“Flat”   Class II   Class III   ZAMS

0.26-0.50 Myr   2.0 Myr (assumed)

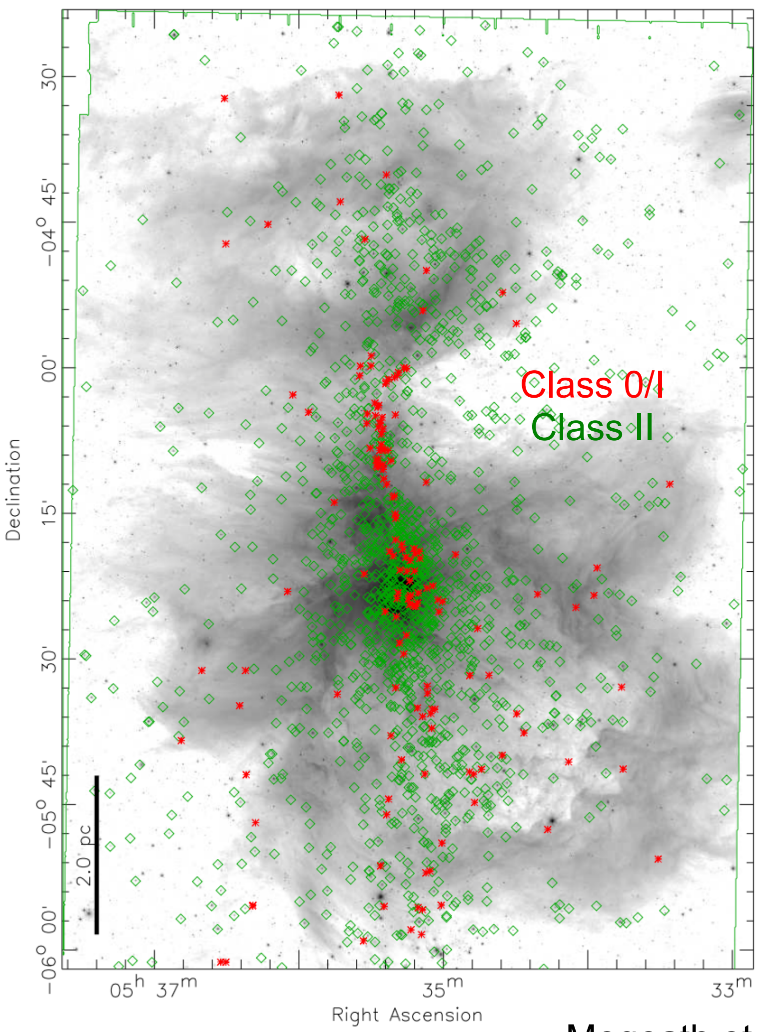
c2d+S-GBS+submm data

Greene (2001); Dunham et al. (2015)

Spitzer Observations: Orion (A)



Spitzer 4.5, 5.8, + 24 μm image of northern Orion A



Megeath et al. (2006)

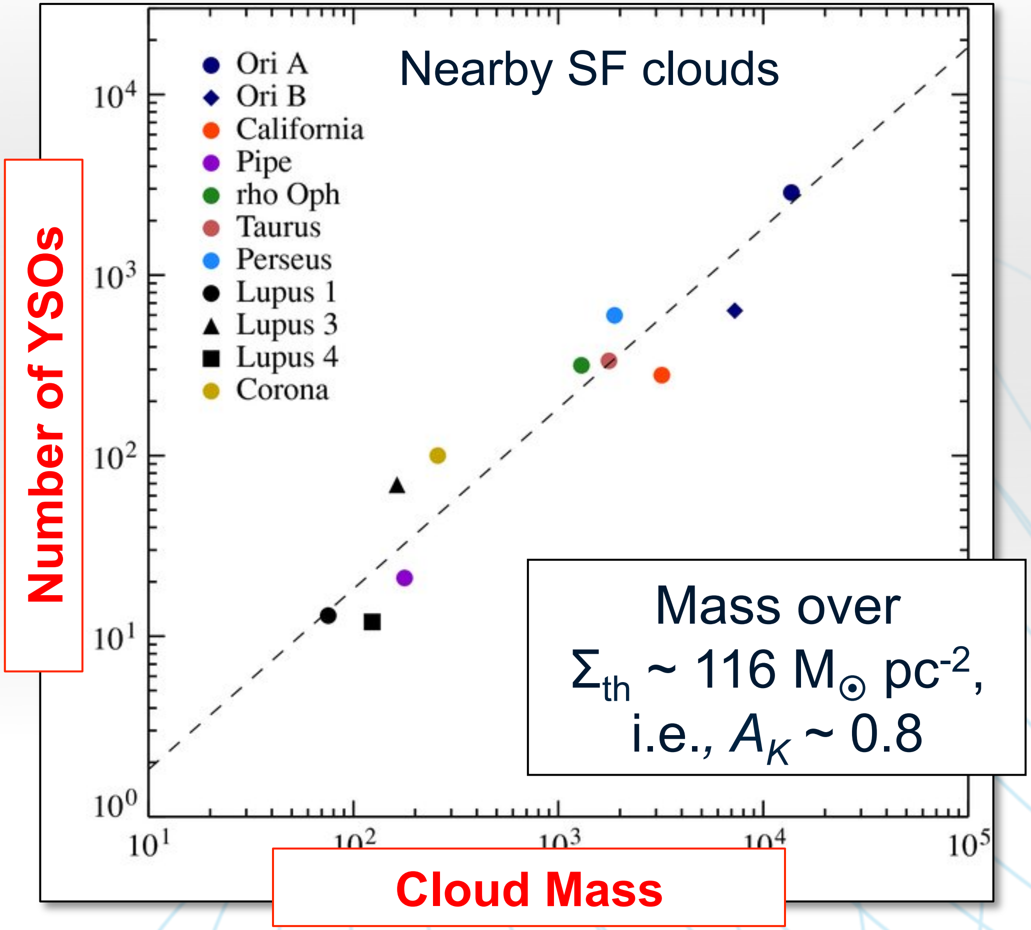
Stars form out of dense molecular gas

- Lada, Lombardi & Alves (2010) find a ***linear*** scaling between *N*(YSO) and the (H_2) mass of a cloud over a surface density threshold of ~116 $M_\odot$ pc^{-2}

- Interestingly, this threshold corresponds to a number density of ~10^4 cm^{-3}

- SFR ($M_\odot$ yr^{-1}) =

  $4.6 \pm 2.4 \times 10^{-8}\, M_{0.8}$ ($M_\odot$)

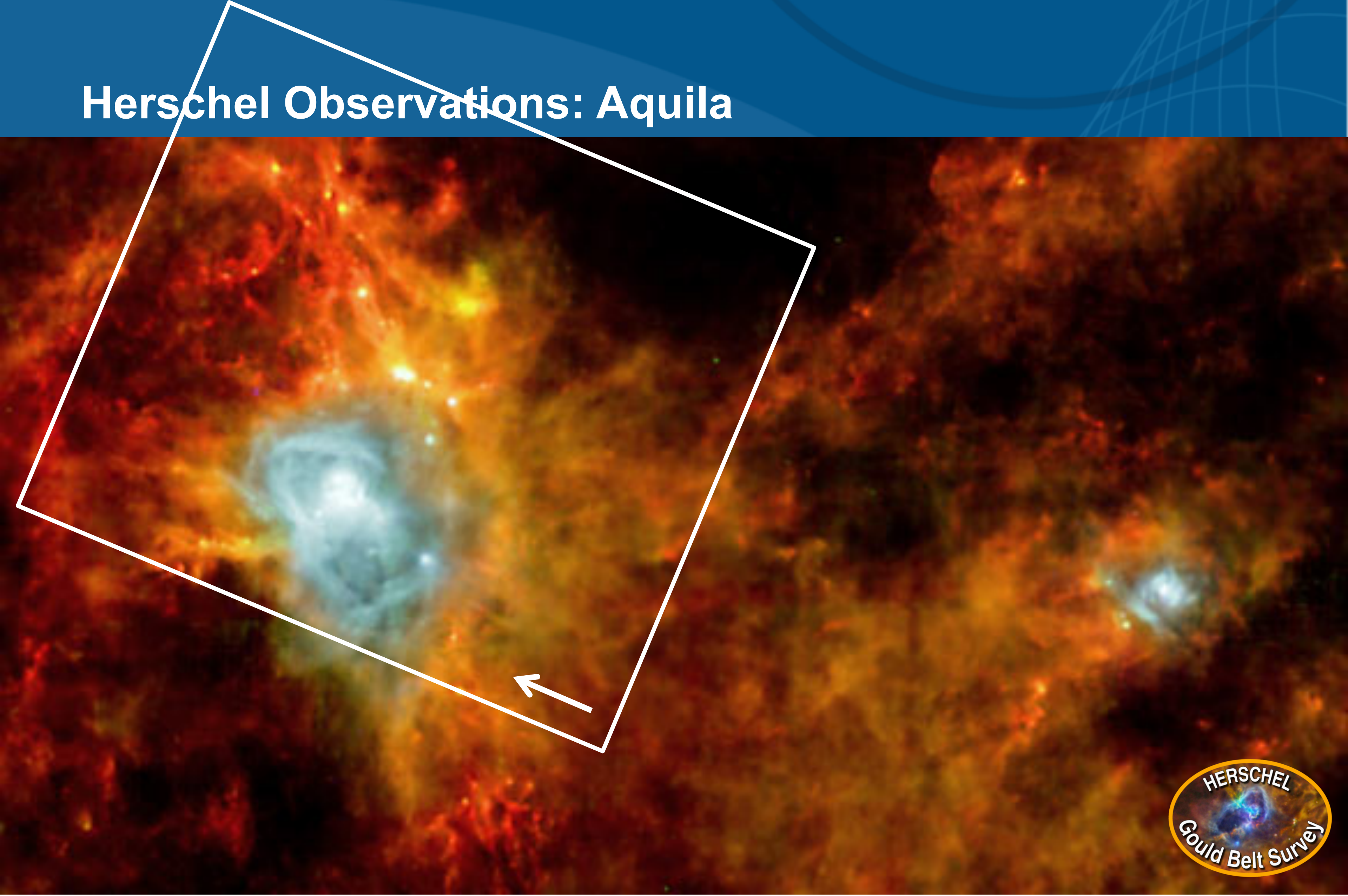


Nearby SF clouds

Mass over Σ_{th} ~ 116 $M_\odot$ pc^{-2}, i.e., A_K ~ 0.8

Lada, Lombardi & Alves (2010); see also Lada et al. (2012)

Herschel Observations: Aquila



Herschel 70, 160, 500 µm image of Aquila Rift

Könyves et al. (2010, 2015); Bontemps et al. (2010)

Threshold originates from cylinder fragmentation

- Core formation occurs primarily due to ***fragmentation of parent filaments***

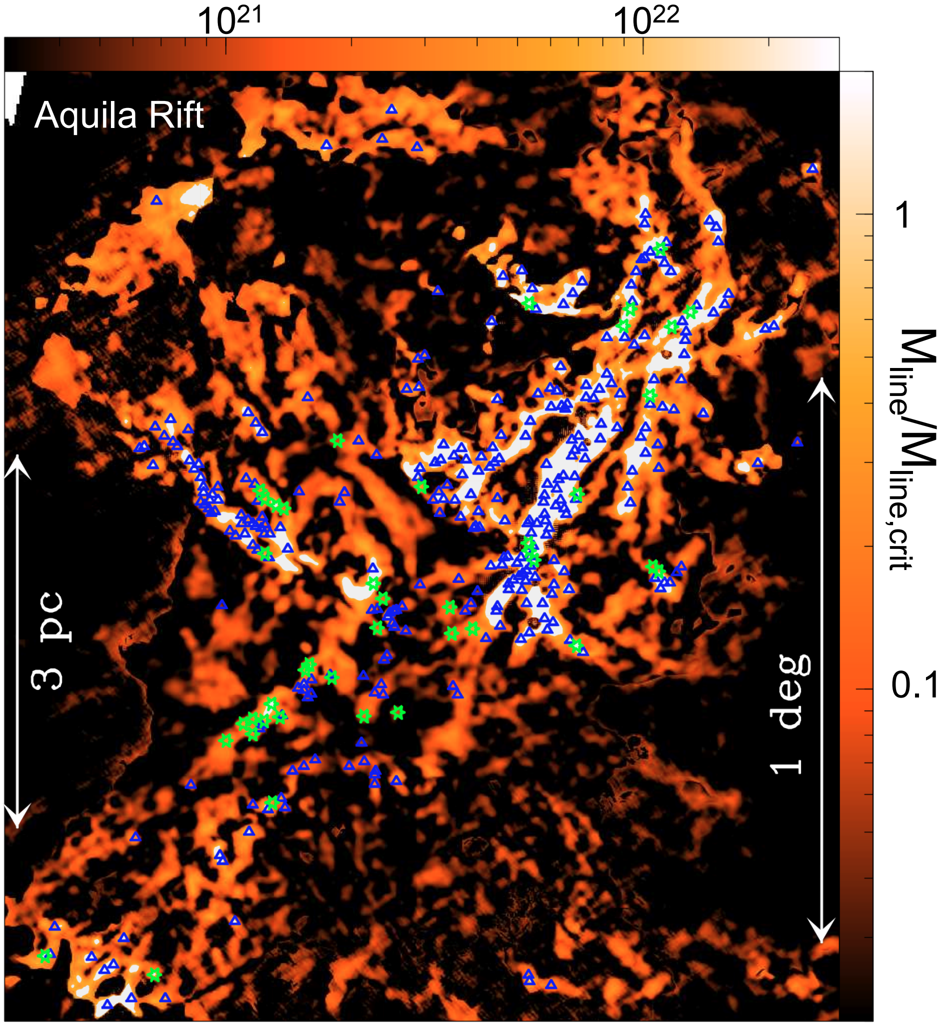
- **mass per unit length** M_{line} of an isothermal cylinder (see Ostriker 1964; Inutsuka & Miyama 1997)

- such cylinders *unstable* if:

$$\mathbf{M_{line} > M_{line,\,crit} = 2c_s^2/G}$$

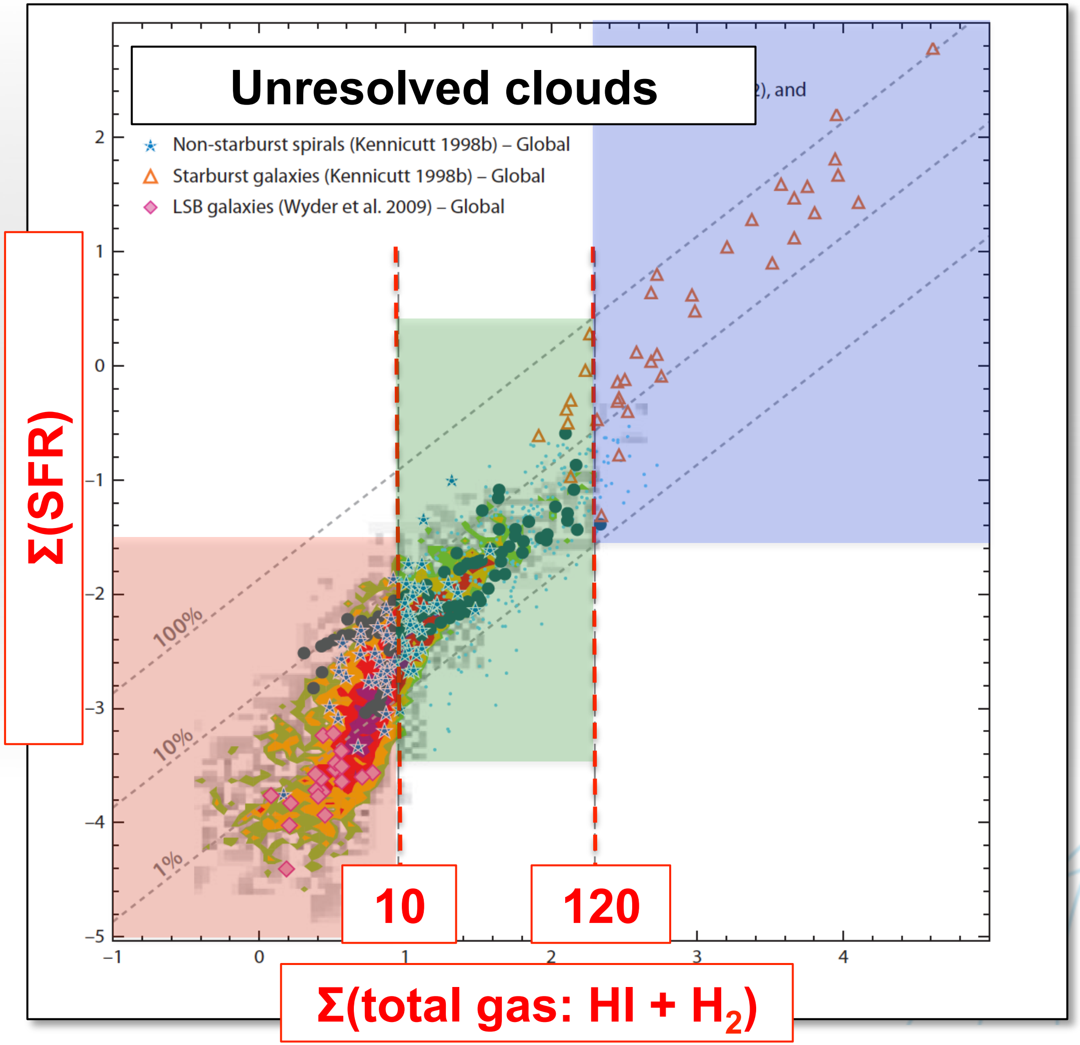
$$\sim 16\ M_\odot\ pc^{-1}\ \text{at}\ 10\ K$$

- if $M_{line} \sim 16\ M_\odot\ pc^{-1}$, $W = 0.1$ pc, then $\boldsymbol{\Sigma_o = 160\ M_\odot\ pc^{-2}}$



André et al. (2010); Könyves et al. (2015)

Interpretation of the K-S scaling relation

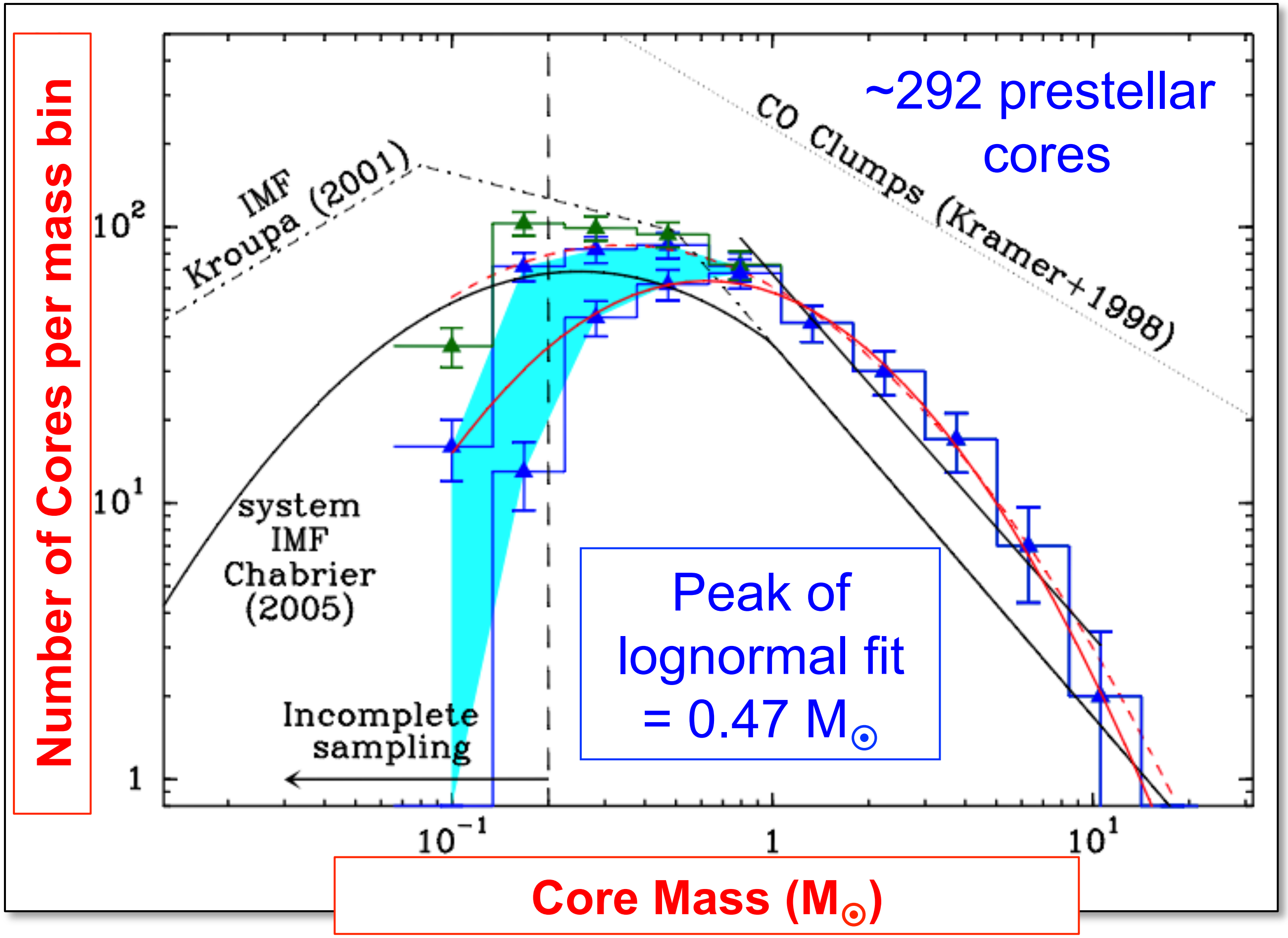


- **Σ(gas) < 10 M$_\odot$ pc^{-2}** : gas is **atomic**, little but some H$_2$ / dense gas
- **Σ(gas) ≈ 10-120 M$_\odot$ pc^{-2}** : gas is **atomic + molecular**, latter are discrete clouds of constant column density
- **Σ(gas) > 120 M$_\odot$ pc^{-2}** : gas is **molecular**, little atomic gas

- is ***dense filament fragmentation*** the universal process defining the onset of star formation in galaxies?

Bigiel et al. (2008); Kennicutt & Evans (ARAA; 2012); see also Schruba et al. (2011)

Filaments also define the Core Mass Function (IMF?)



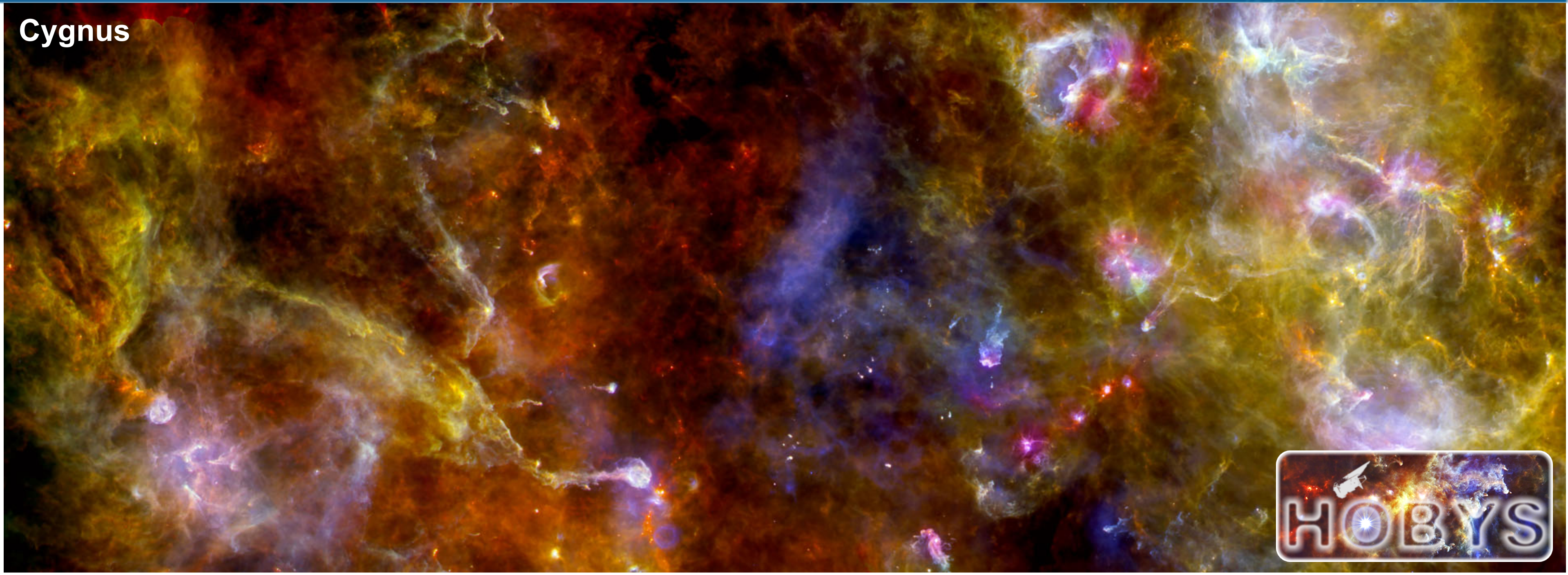
~292 prestellar cores

Peak of lognormal fit = 0.47 $M_\odot$

André et al. (2014; PPIV) Könyves et al. (2015)

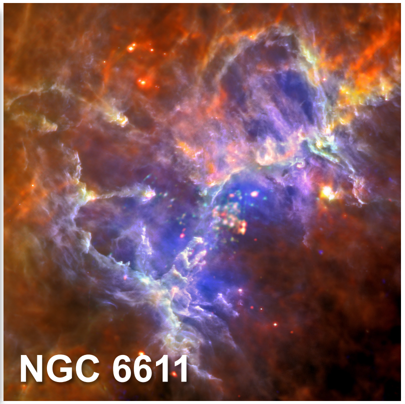
- shape of CMF very similar to IMF ($\varepsilon \approx 0.3\text{-}0.4$)
- slope of high-mass end **$\alpha \approx -1.33 \pm 0.06$** and Salpeter = **-1.35**

High-mass Star Formation with HOBYS


Cygnus

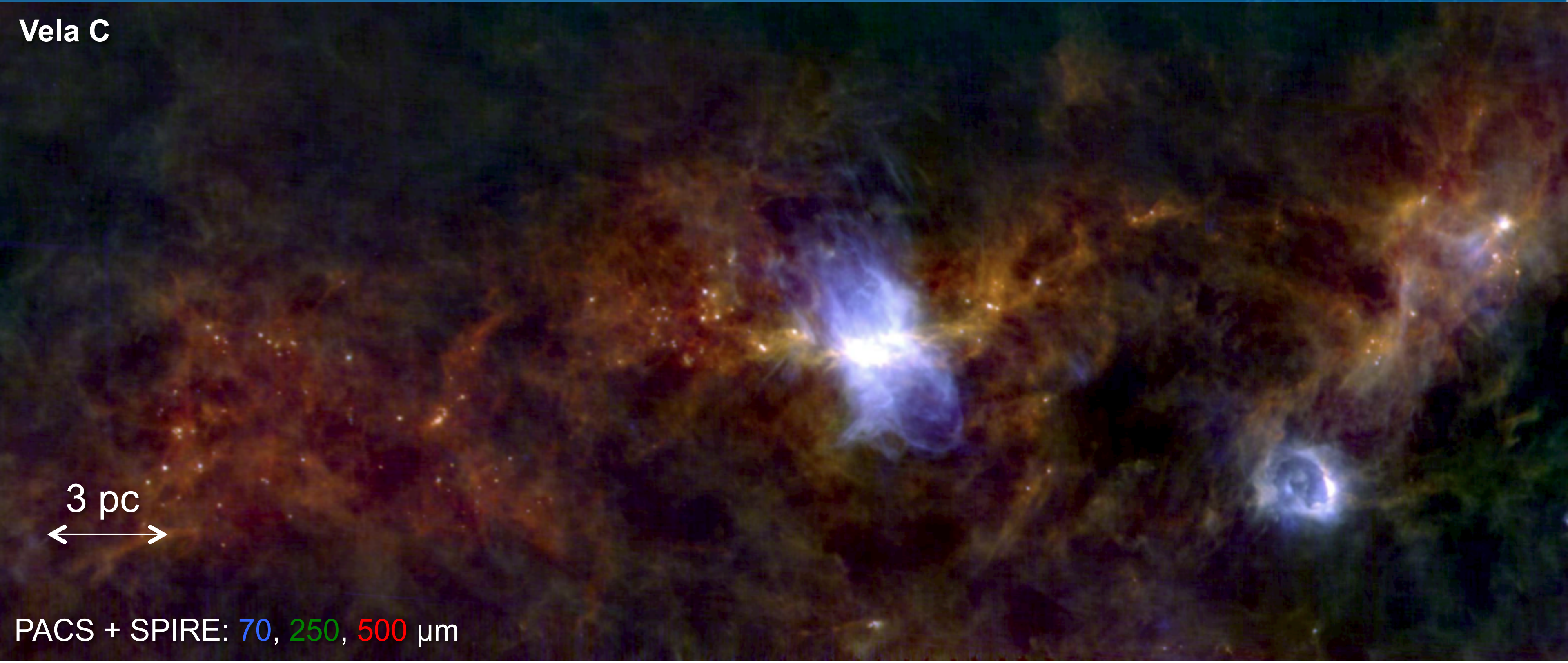

Carina


Rosette


NGC 6611


NGC 7538

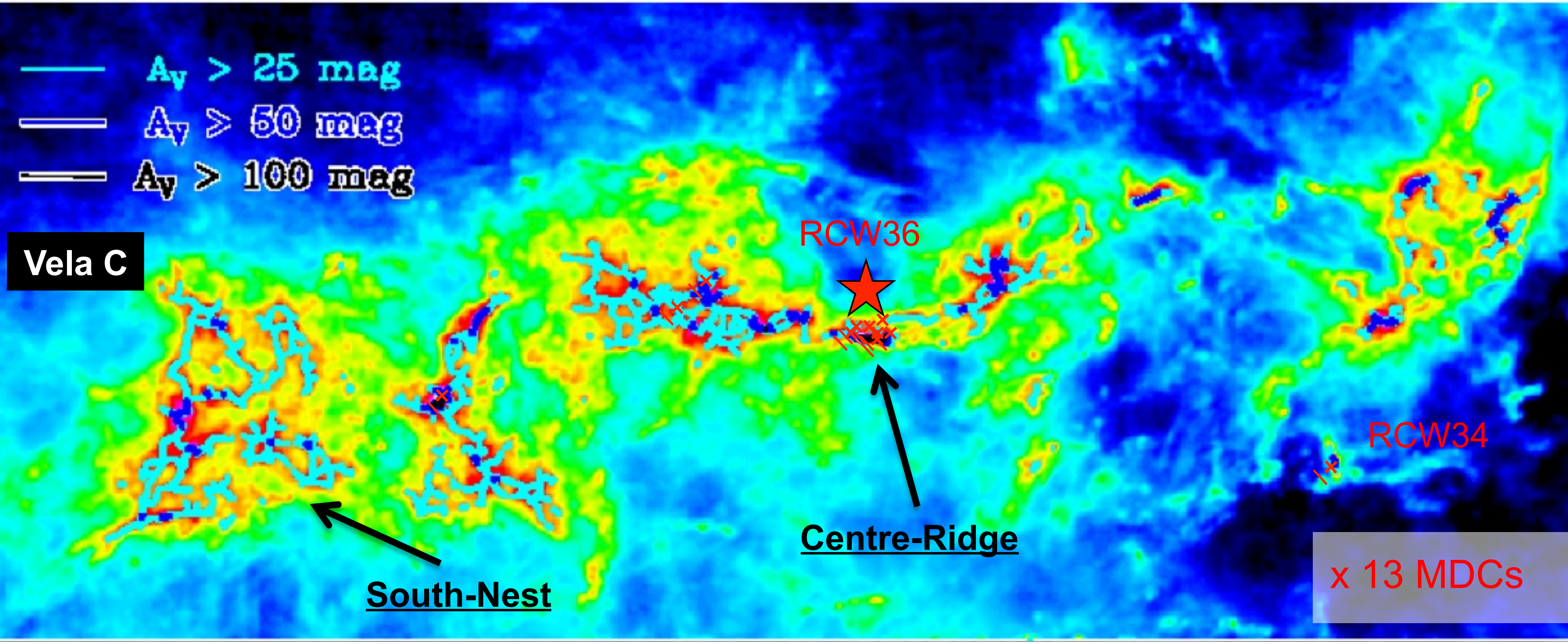
High-mass Star Formation and Ridges



- What is the connection between filaments and high-mass star formation?

Hill et al. (2011)

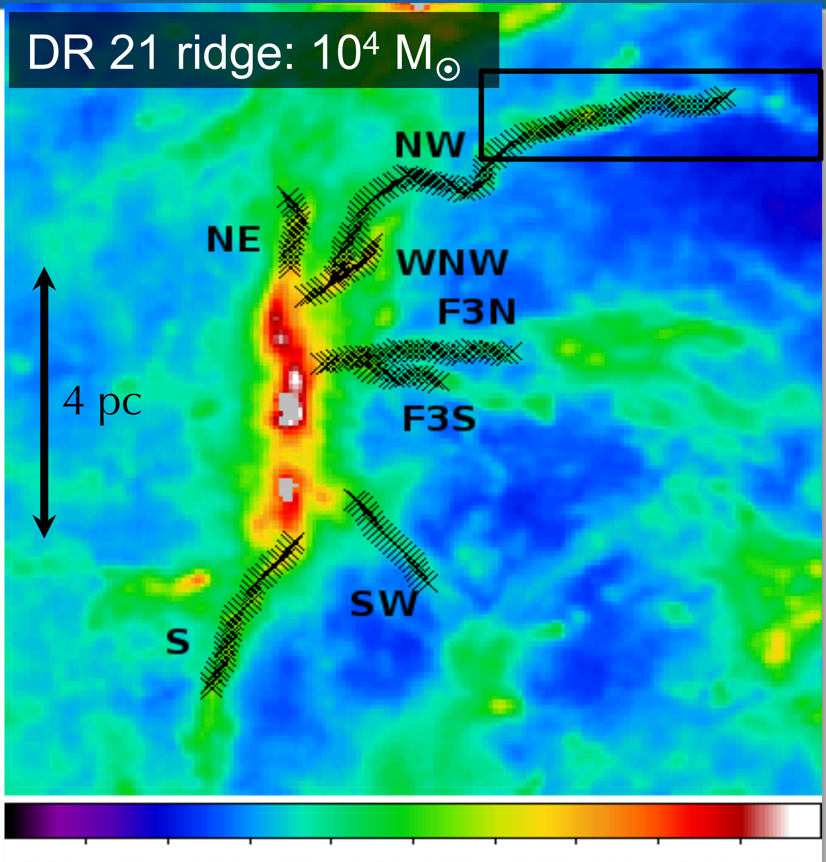
High-mass Star Formation and Ridges



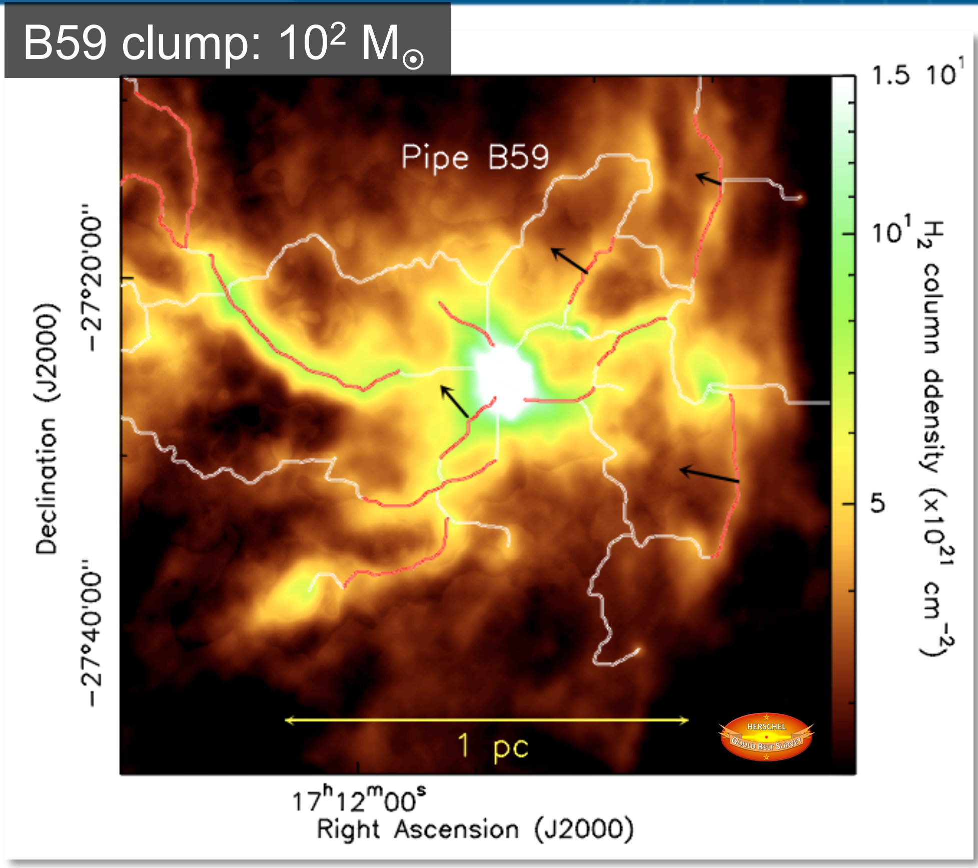
- disorganized networks ('nests') and dominating 'ridges' show relative importance of turbulence vs. gravity
- high-mass stars only found in '**ridges**' ; filaments of $A_V > 100$

Hill et al. (2011); Minier et al. (2012)

High-mass Star Formation and Ridges



DR 21 ridge: $10^4\ M_\odot$

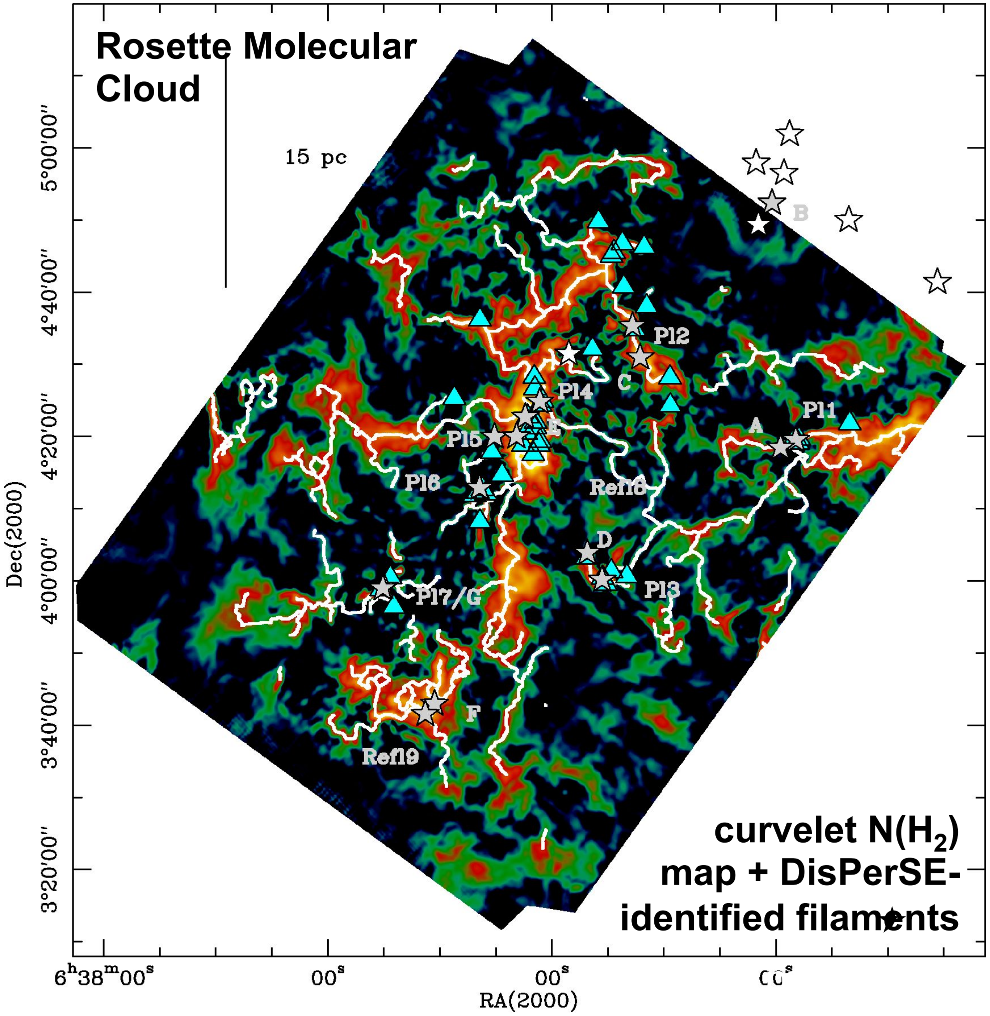


B59 clump: $10^2\ M_\odot$

- ridges formed and fed by filament merging
- sub-filaments also surround (feed?) dominant clump in Pipe Nebula

Hennemann et al. (2012), Schneider et al. (2010), Peretto et al. (2012)

Ridges and Filament Intersections


Rosette Molecular Cloud

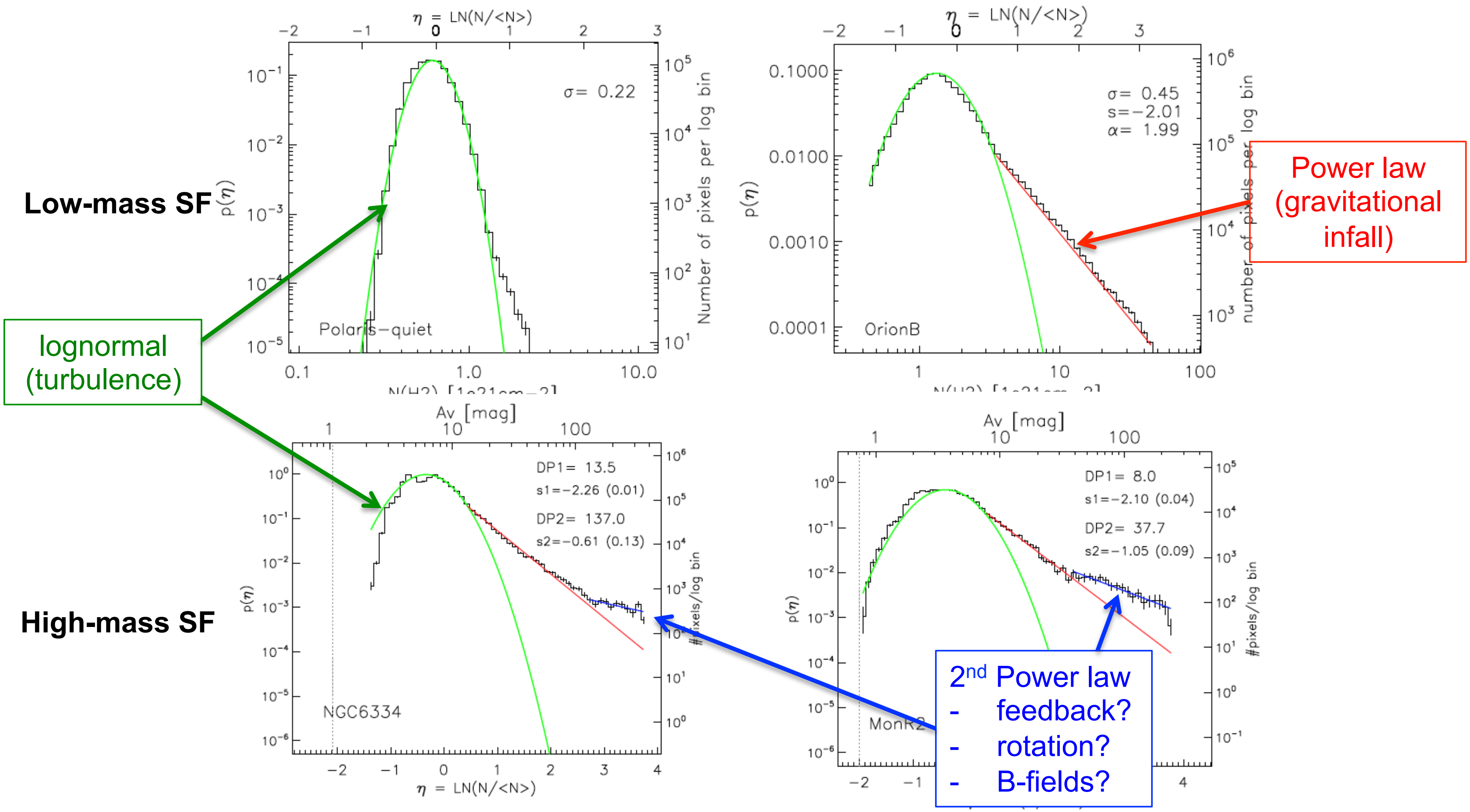
curvelet N(H_2) map + DisPerSE-identified filaments

Schneider et al. (2012)

- massive clumps and IR clusters found at **filament intersections**
- mass flow into intersected regions: more clustered star formation?

Schneider et al. (2012)

Herschel $N(H_2)$ Probability Density Functions



Low-mass SF

High-mass SF

lognormal
(turbulence)

Power law
(gravitational
infall)

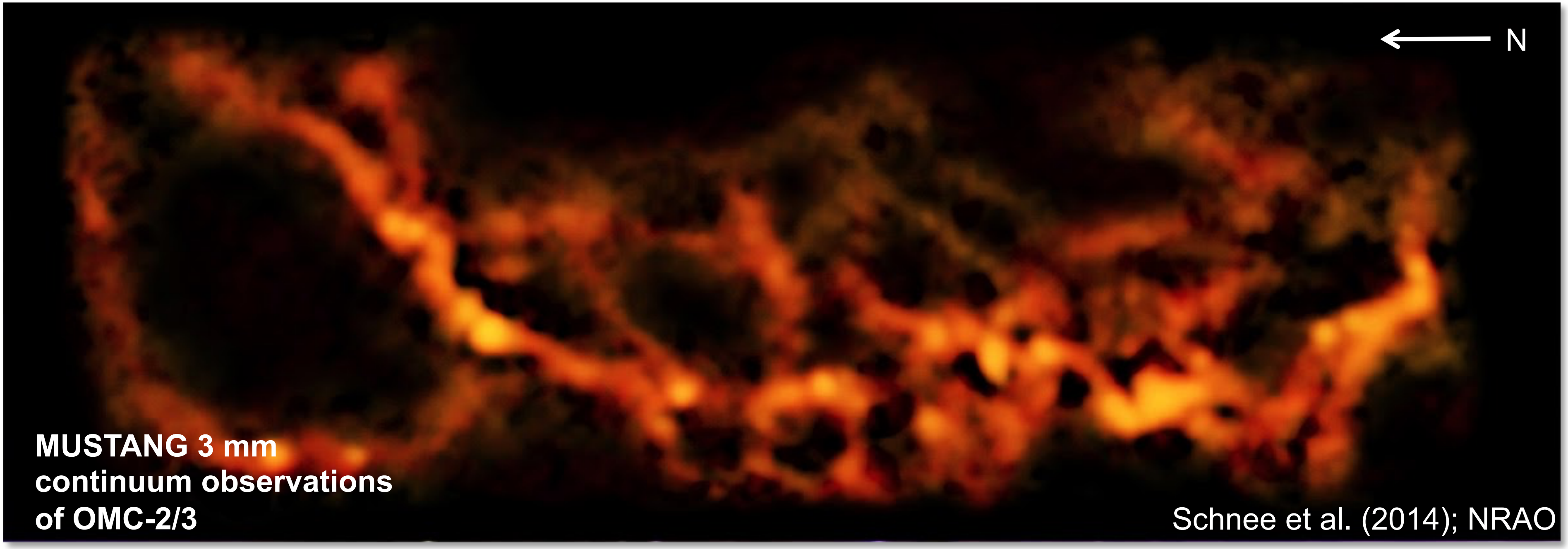
2^{nd} Power law
- feedback?
- rotation?
- B-fields?

Schneider et al. (2013; 2015); also Russeil et al. (2013), Rivera-Ingraham et al. (2015)

What the GBT can do

- high-frequency (HF) instrumentation at GBT can enable key insights into high-mass SF via **wide-field observations**

What the GBT can do: MUSTANG-2

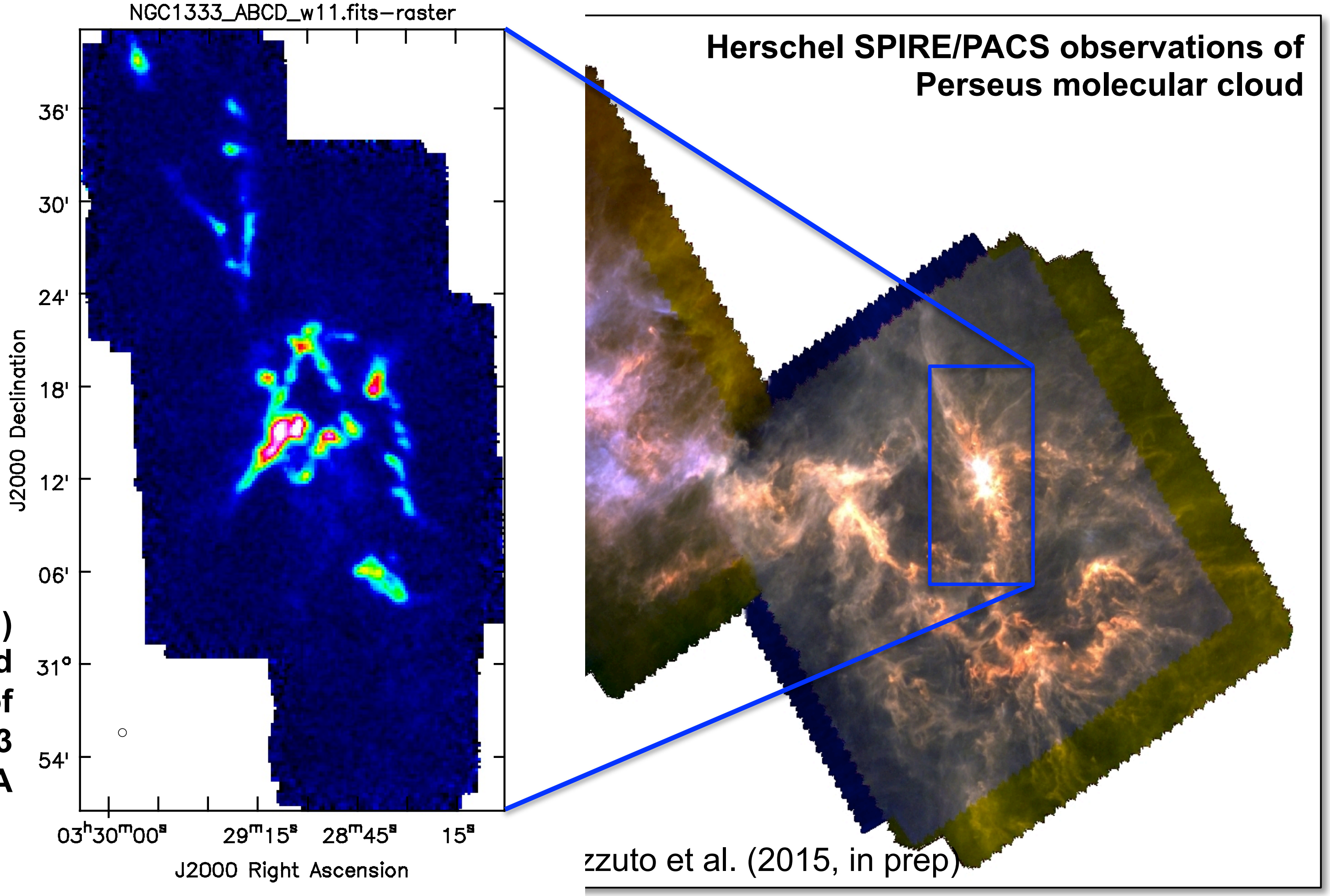


MUSTANG 3 mm continuum observations of OMC-2/3

Schnee et al. (2014); NRAO

- provide key high-resolution observations of ***ridges***, clarifying their column density structure at ~9” FWHM
- combine data with those from Herschel *et al.* to find **dust opacity**, **temperature**, **free-free contributions**

What the GBT can do: KFPA



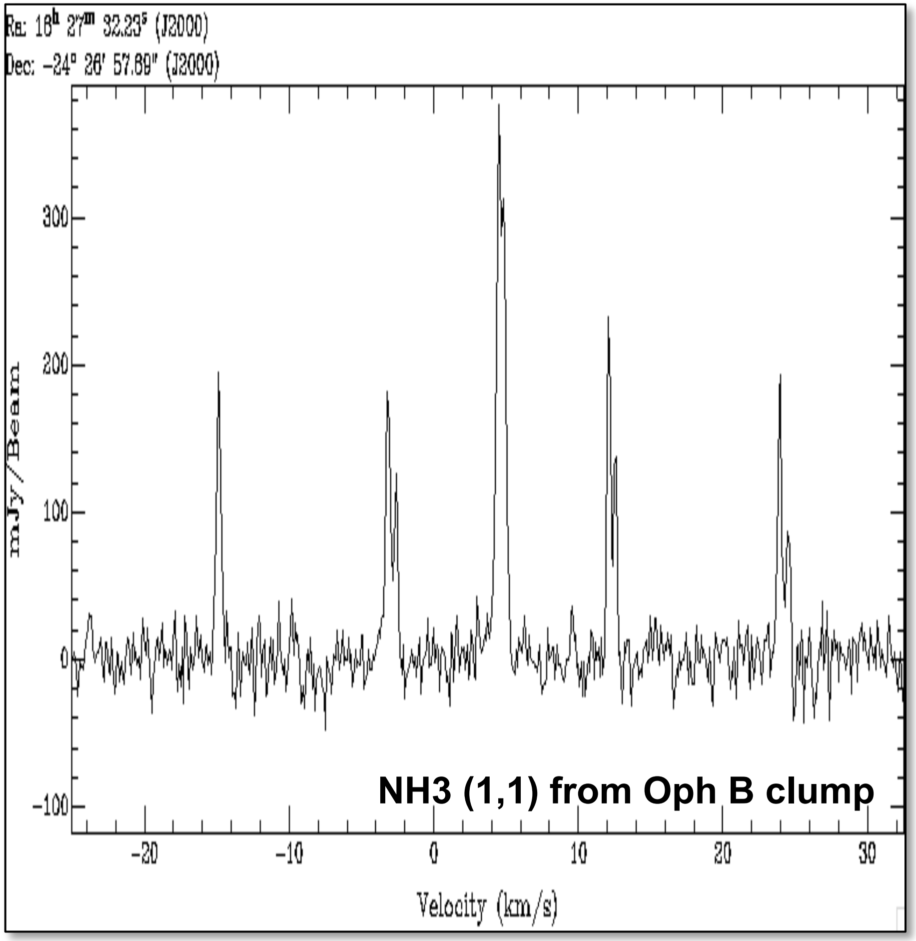
Herschel SPIRE/PACS observations of Perseus molecular cloud

zzuto et al. (2015, in prep)

NH_3 (1,1) integrated intensity of NGC 1333 with KFPA

GAS (2015), in prep

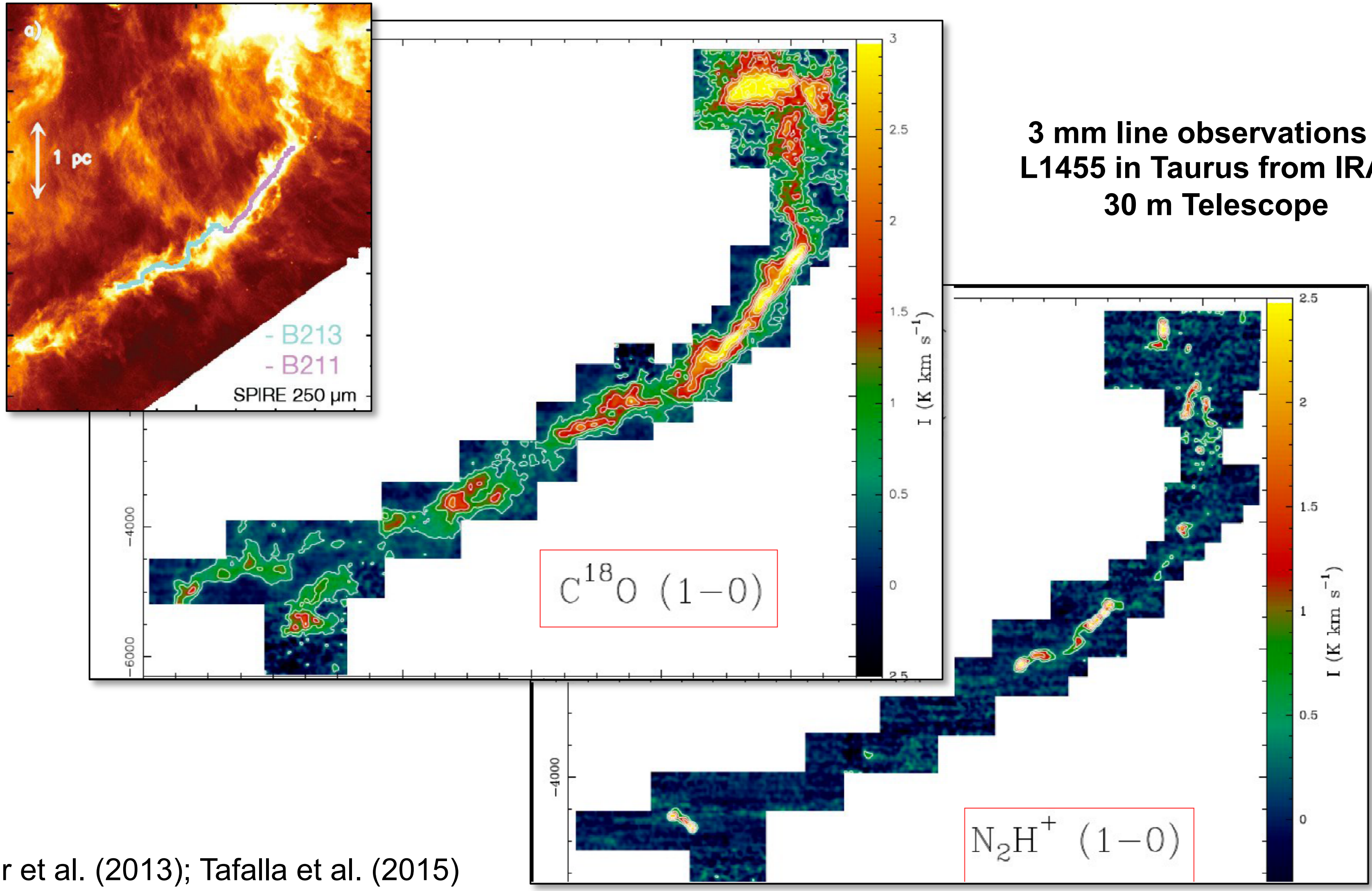
What the GBT can do: KFPA



Friesen et al. (2008)

- NH_3 rotational-vibrational emission traces dense gas, n_{crit} [$NH_3(1,1)$] ~ 10^{3-4} cm^{-3}
- Can probe:
  - **ridge dynamics**, role of turbulence in formation
  - **gas kinematics**, flows from ridges to clusters, explore filament intersections
  - **LOS gas temperatures**, explore external heating
  - **abundances**, cf. accurate column densities

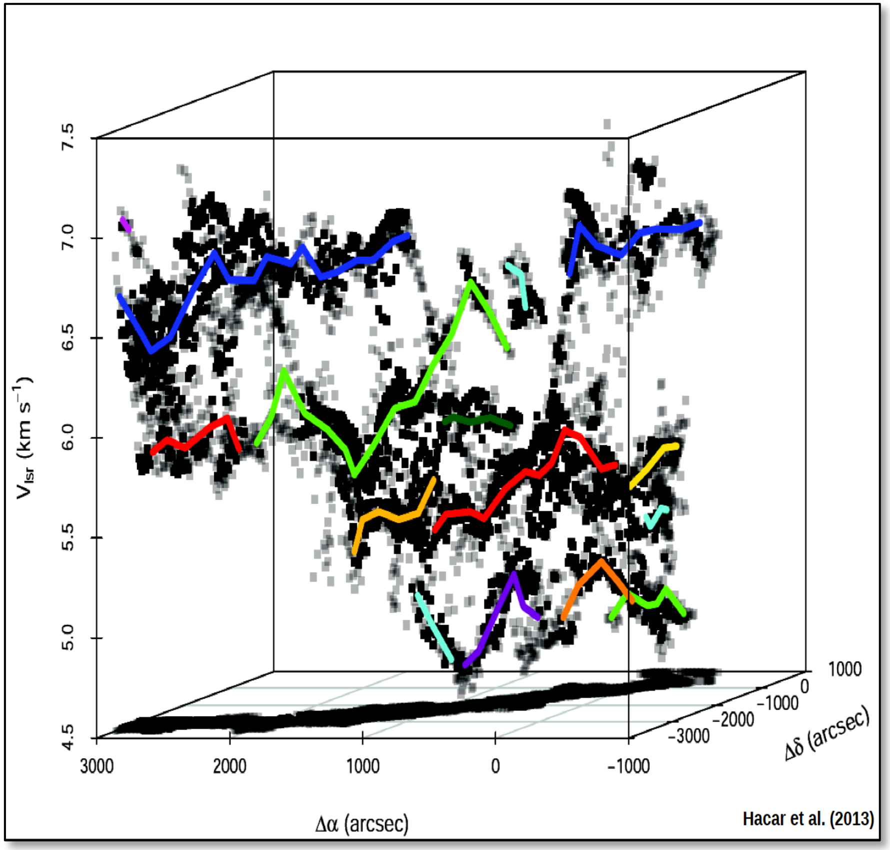
What the GBT can do: ARGUS



3 mm line observations of L1455 in Taurus from IRAM 30 m Telescope

Hacar et al. (2013); Tafalla et al. (2015)

What the GBT can do: ARGUS



Filament fibres?

- N_2H^+ rotational lines trace well denser gas:
  n_{crit} [N_2H^+ (1-0)] ~ 10^5 cm^{-3}
- can probe:
  - ridge dynamics,
  - gas kinematics,
  - abundances
  - (not temperature)

  at **~9” FWHM resolution**
- NH_2D (1,1) can probe locations where NH_3/N_2H^+ lines are optically thick

Hacar et al. (2013); Tafalla et al. (2015)

Summary

- Recent surveys have revealed the YSO populations and column density substructures of molecular clouds in many star formation regimes

- GBT's HF instruments will enable key insights into how filaments/ridges relate to star formation, by providing high-resolution observations of
  - 3 mm cont. (**MUSTANG-2**): dust opacity, free-free
  - NH_3 lines (**KFPA**): filament/ridge kinematics, dynamics
  - N_2H^+ (1-0), NH_2D (1,1) (**ARGUS**) lines: densest ridges

- High-mass star forming regions within 3 kpc are ripe for GBT wide-field observations

Thanks to:

Philippe André, Vera Könyves, Arabindo Roy, Doris Arzoumanian, Derek Ward-Thompson and the Herschel Gould Belt Survey Team;

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Thank you

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