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Early Stages of Massive Star Formation

ISOSS 22164+6003
(Distance = 6 kpc
L=20 000 L_{sun})

Deep NIR CAHA
Image +
Herschel/PACS
70, 100, 160 µm

Soul of High-Mass Star Formation, Puerto Varas, Chile, March 2015

Massive Star Formation – Fundamental Questions

- How gets enough mass assembled ? - Molecular Filaments (e.g. Ragan + 14)
- Do massive prestellar cores exist? - Kinematic Structure (e.g. Tan+ 13)
- How to prevent fragmentation ? - Magnetized cores (e.g. Commercon+ 11)
- How to cross the accretion barrier? - Flashlight effect (e.g. Kuiper+ 10,11)
- Which feedback processes operate? - Winds vs. Ionization (e.g. Kuiper+15)

Massive Stars

Stars with masses larger than 8 M_{sun}

a) Massive enough to produce type II SN
b) Energetic enough to form HII regions
c) Luminous enough to drive massive molecular outflows and winds

LMC – 30 Doradus (HST image)

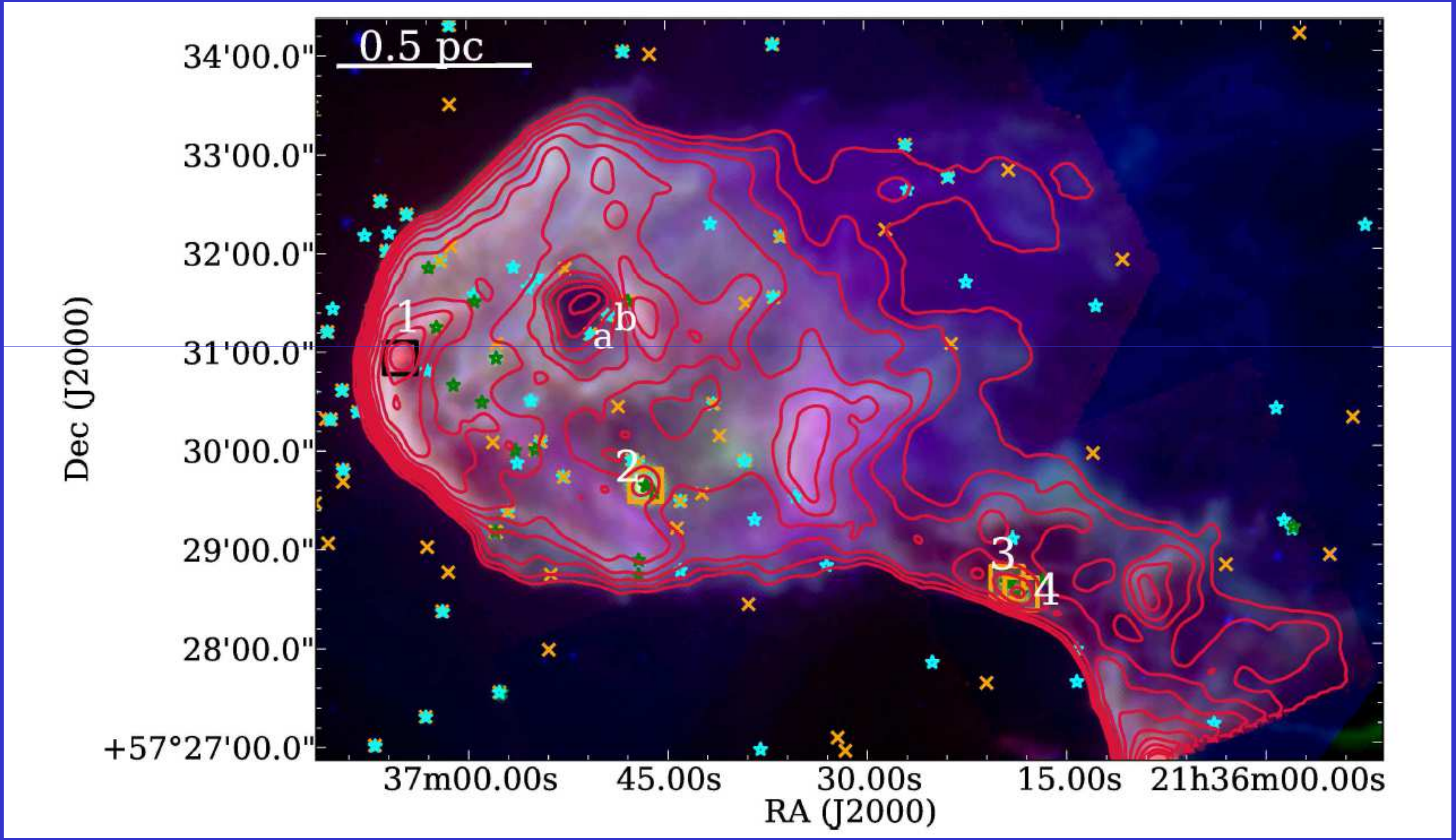
Large differences between „massive“ stars

8 -16 M_{sun}	Early B-type stars	B3V to B0V
16-32 M_{sun}	Late O-type stars	O9V to O6V
32-64 M_{sun}	Early O-type stars	O5V to O2V

12 stars in R 136, Arches, NGC 3603 with M > 150 M_{sun} (Crowther et al. 2010)
W49: Most massive star 100-200 M_{sun} (Wu et al. 2014)
HD 93129: A=120-127 M_{sun}, B=80 M_{sun}, Eta Carinae: 90-100 M_{sun}

The Fish-Eye – IC 1396 A Globule

Triggered star formation by HD 206 267
(Trapezium system, O6.5 star, 870 pc)



Spitzer 8 and 24 µm plus Herschel 70 µm

Sicilia-Aguilar et al. (2014)

The Great Barriers of Massive Star Formation

- How to form clumps/cores which are massive enough to form massive clusters/stars? Are they in virial equilibrium? Do they exist at all? (Core accretion vs. competitive accretion)
- How to avoid the fragmentation of such clumps?
- How to cross the radiation pressure barrier?

Fragmentation Barrier

Sub-condensations < # predicted by Jeans fragmentation

(e.g. Hennemann et al. 2009, Bontemps et al. 2010, Wang et al. 2014)

Jeans criterion (M, L, Local, Conditions)

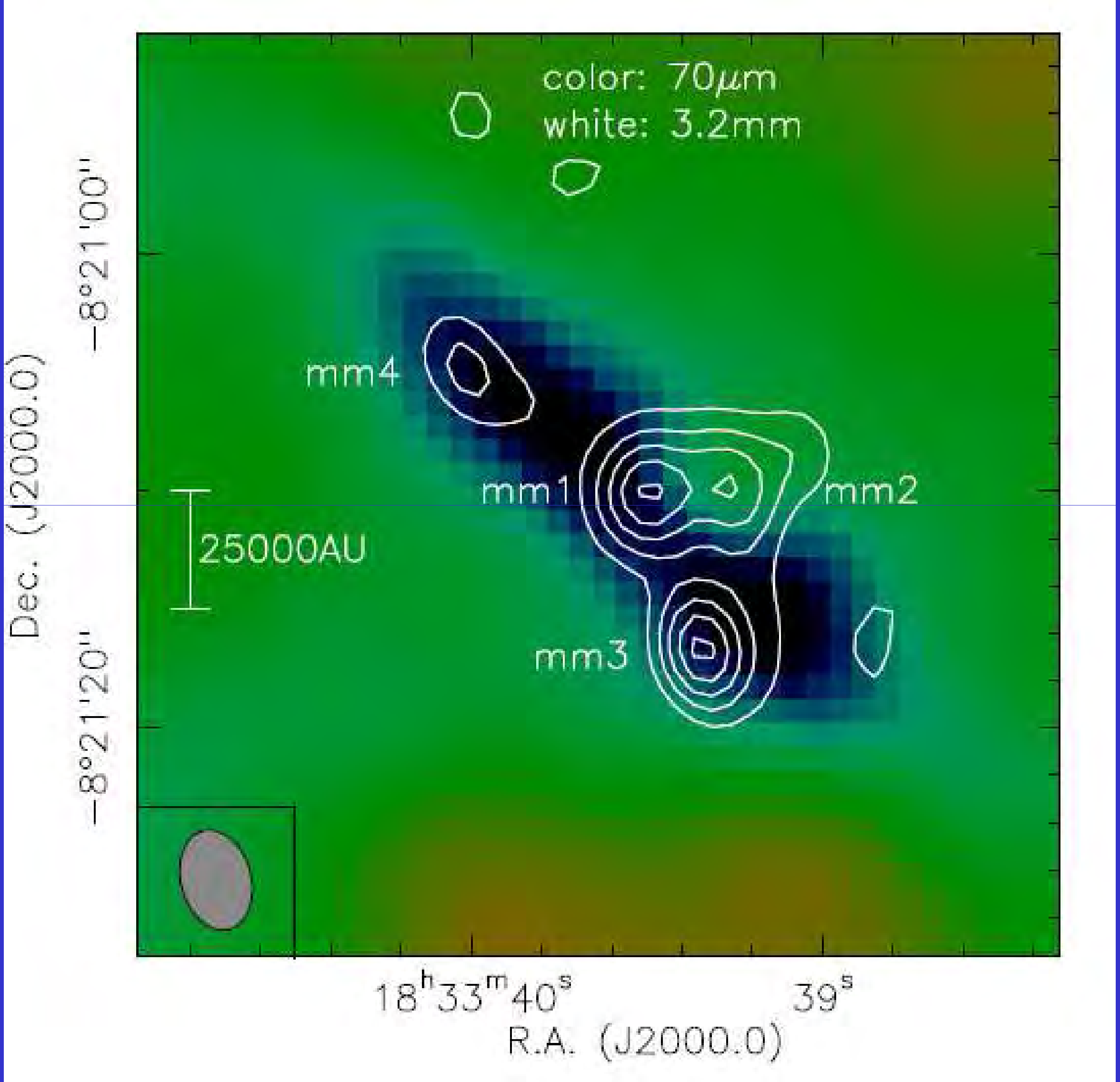
Going beyond Gravity

- Compressible turbulence **(Federrath et al. 2010)**
- Strong magnetic fields **(Hennebelle & Teyssier 2008)**
- Radiation feedback **(Krumholz et al. 2007, Krumholz & McKee 2008)**
- Combination of radiation feedback & magnetic fields

(e.g. Commercon et al. 2011, Myers et al. 2013)

Steeper density profiles : Less fragmentation (Palau et al. 14) –
Could be related to stronger magnetic fields

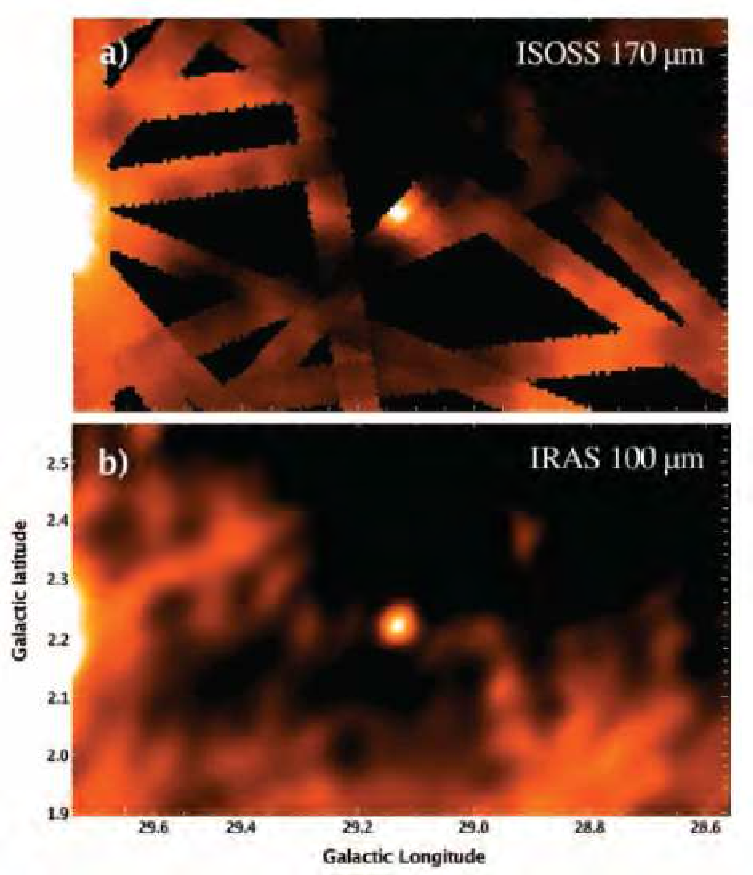
Observational Example for Fragmentation

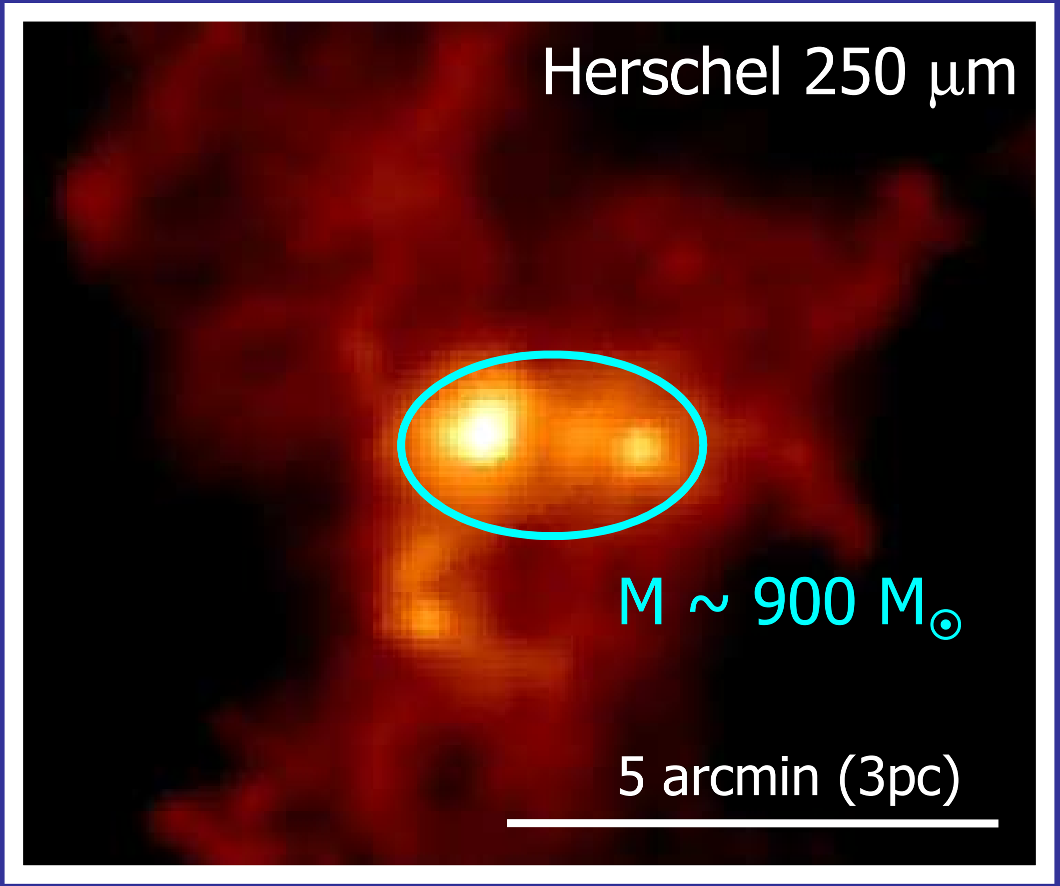


Beuther et al. 2013

IRDC 18310-4 (PdBI – resolution 3´´, D=4.9 kpc, 54-107 M_{sun})

Cold ISOSS Source J18364-0221

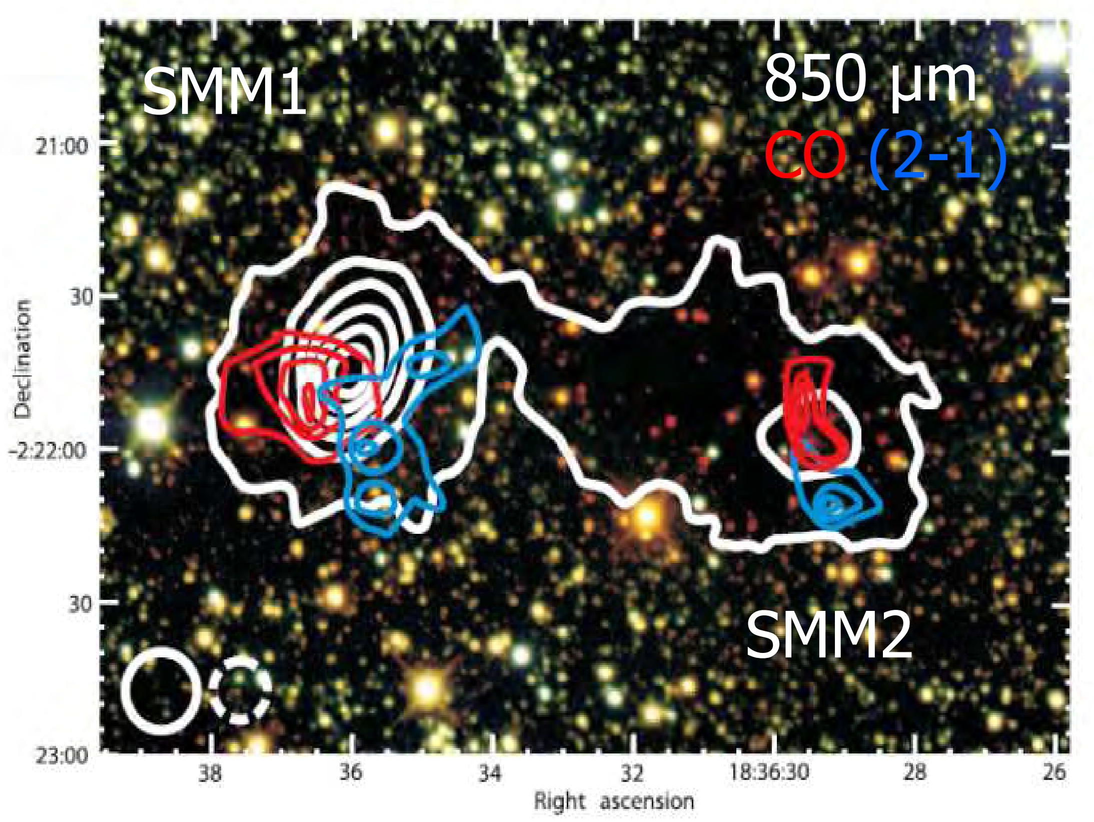


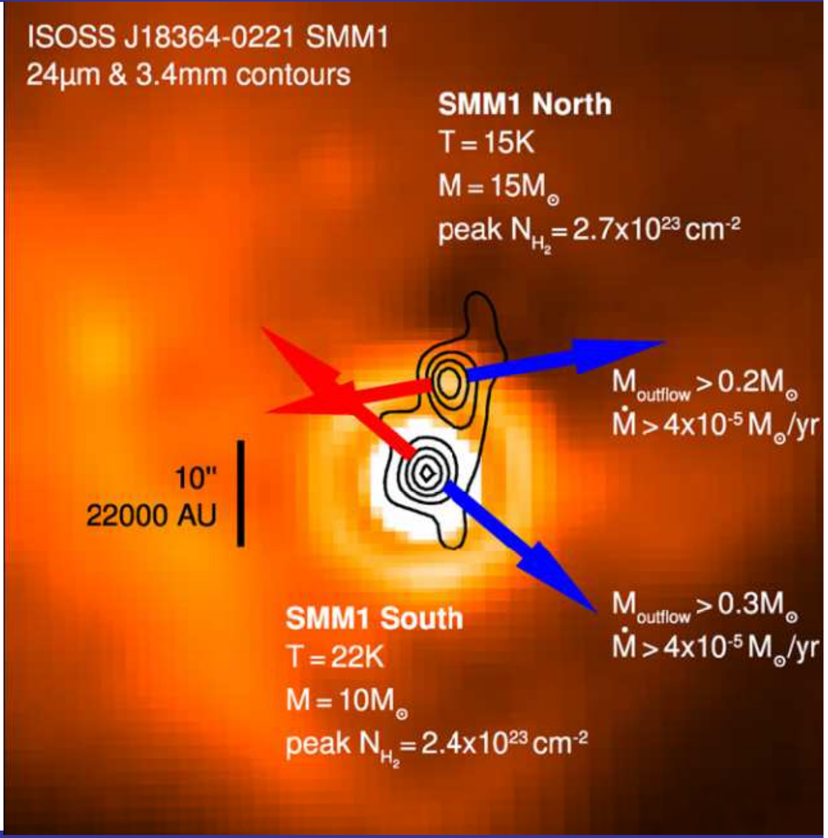


Krause (2003)
Birkmann et al. (2004)

3200 $M_\odot$ cloud complex
D = 2.2 kpc
$T(NH_3) = 11.6$ K

ISOSS J18364-0221N/S:
Two high-mass protostars with collimated outflows



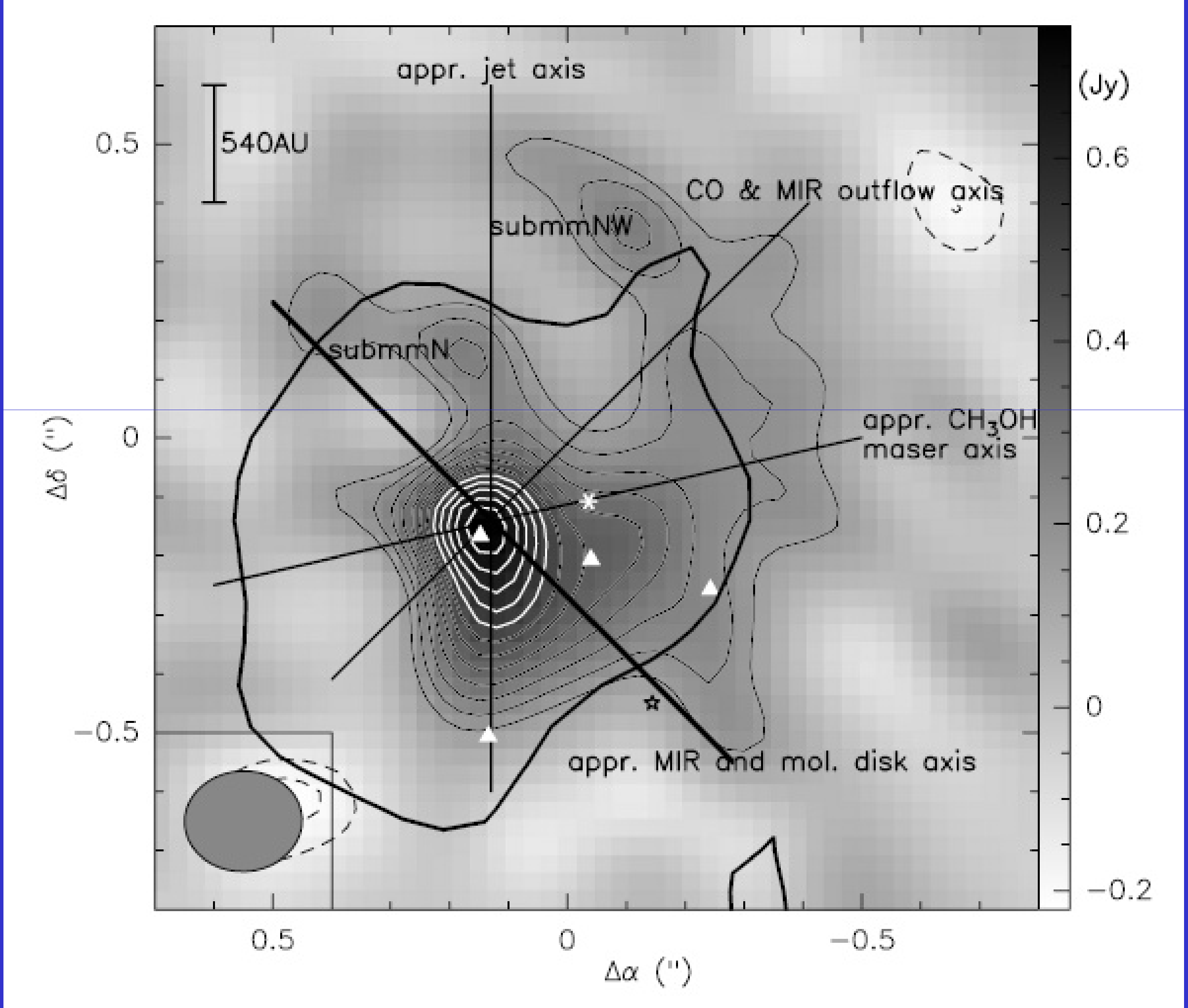


Birkmann et al. 2006

Hennemann et al. 2009

Disks and Fragmentation?

NGC 7538-IRS 1 at 0.2´´ resolution (500 AU) at the PdBI



Beuter, Linz
& Henning 2013

HCN (4-3) results in 1.8x10^{-3} M$_{sun}$/yr

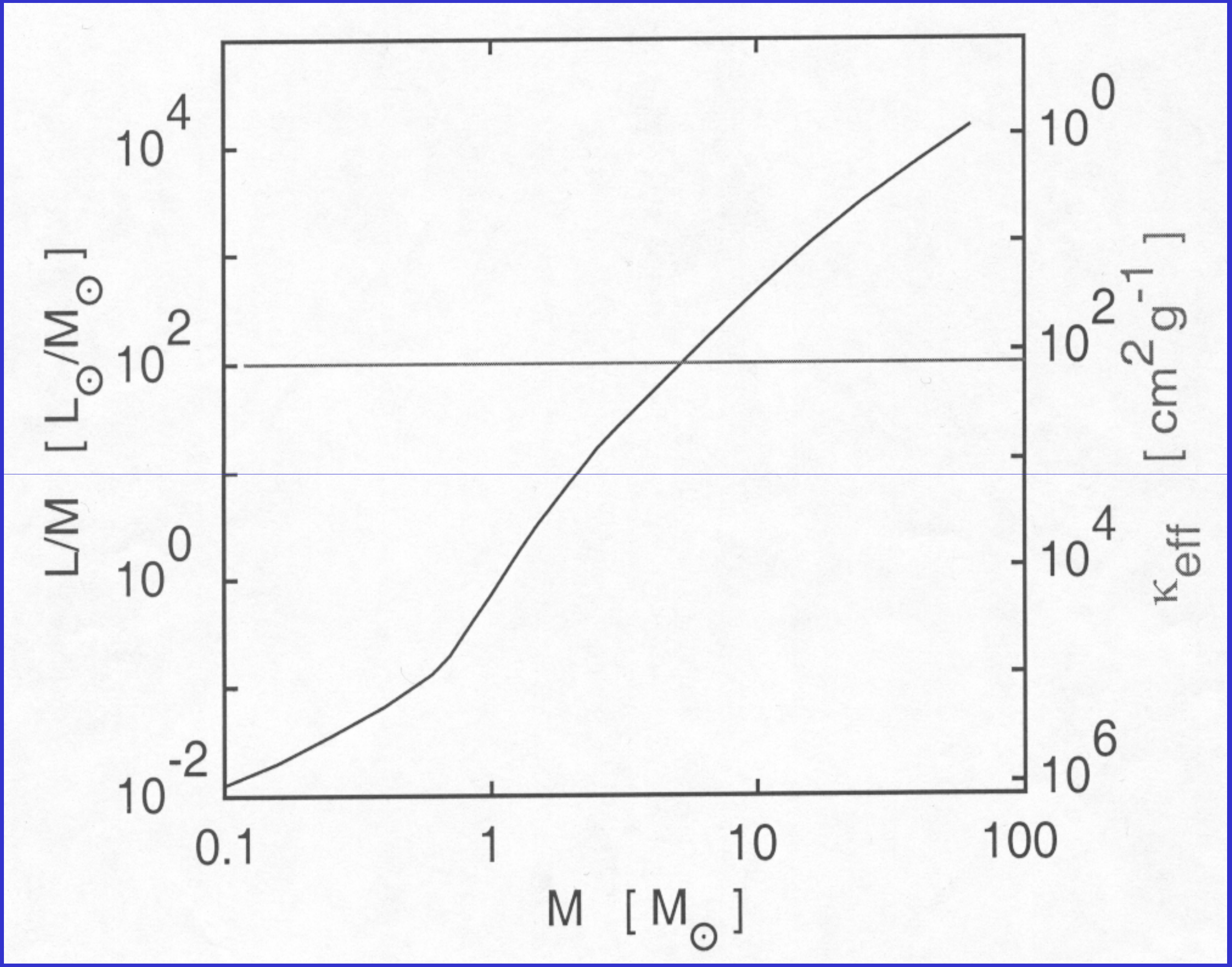
Accretion Limit - Spherical Symmetry

(Kahn 1974, Yorke & Krügel 1977, Wolfire & Cassinelli 1987)

Gravity
exceeds
radiative
acceleration

$$\frac{GM}{r^2} > \frac{\kappa_{\mathrm{eff}} L}{4\pi r^2 c}$$

with $L = L_* + L_{\mathrm{acc}}$

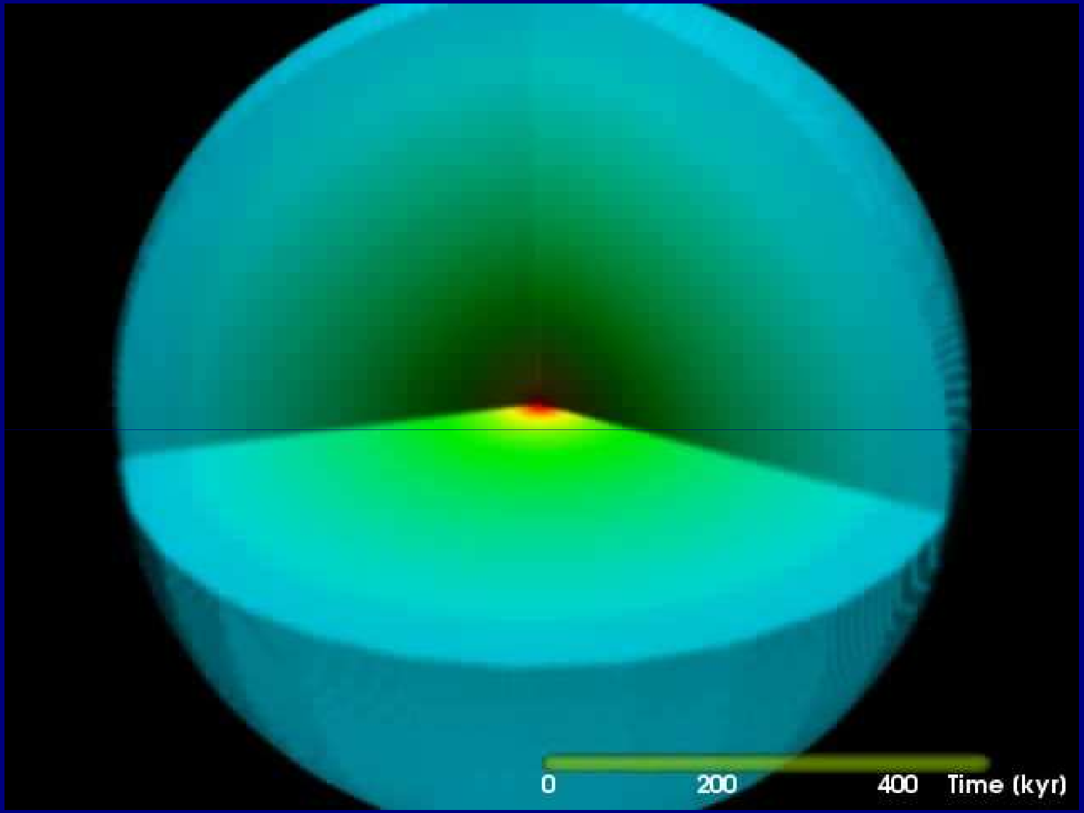


Flashlight effect:

Yorke & Sonnenhalter (2002)

$$\Rightarrow \kappa_{\mathrm{eff}} < 130\ \mathrm{cm^2 g^{-1}} \left[\frac{M}{10 M_\odot}\right]\left[\frac{L}{1000 L_\odot}\right]^{-1}$$

Breaking through the Radiation Barrier …



8-45 kyr:
Disk formation/growth

45-60 kyr:
Launch of bipolar outflow

860-940 kyr:
Radiation pressure blows away remnant disk

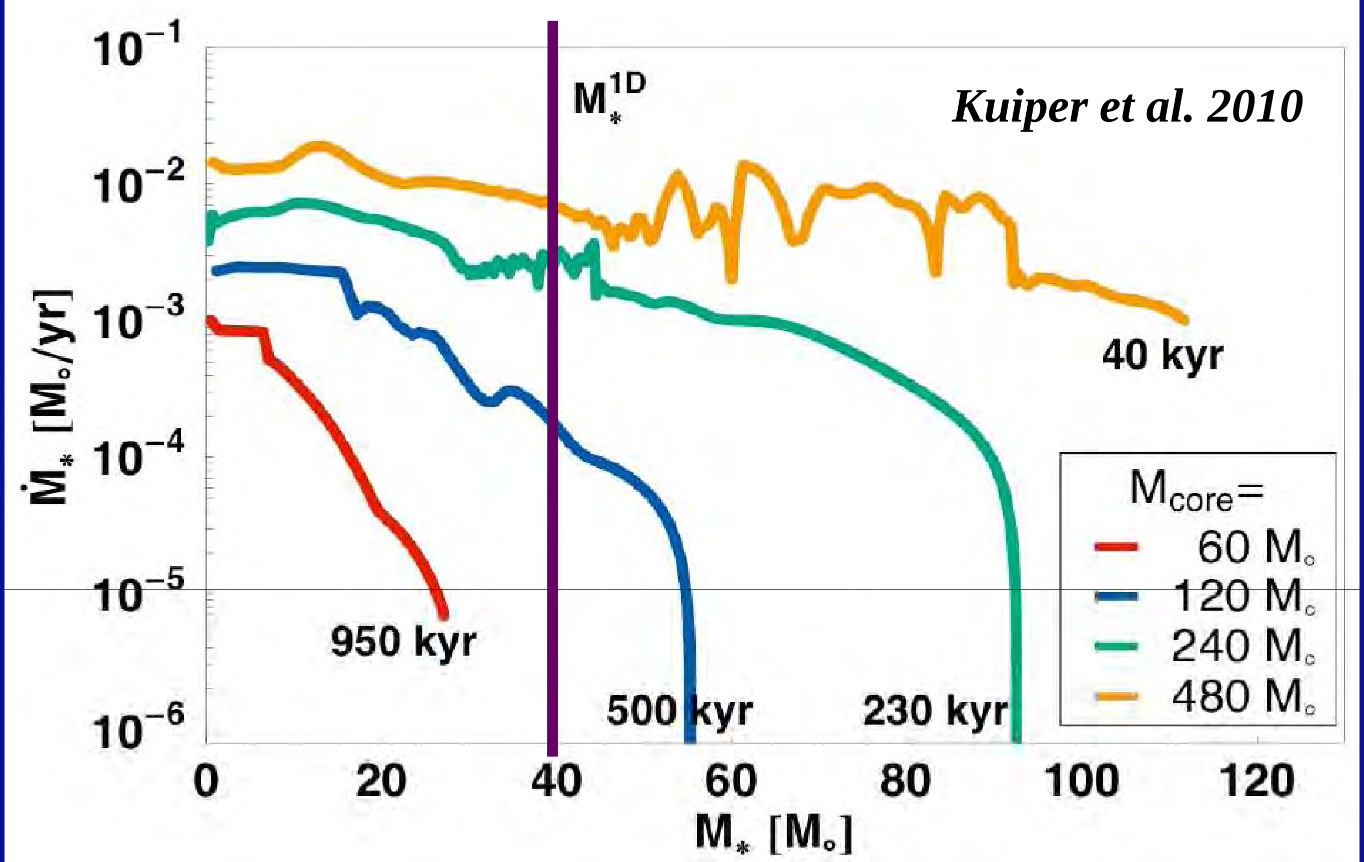
SFE: 47 %

Initial core mass = 60 M_{sun}

R_{core} = 0.1 pc, Density ~ r^{-2}
M_{core} = 60, 120, 240, and 480 M_{sun}

Kuiper et al. (2010, 2011, 2012)

Disk Accretion Solves the Pressure Problem …

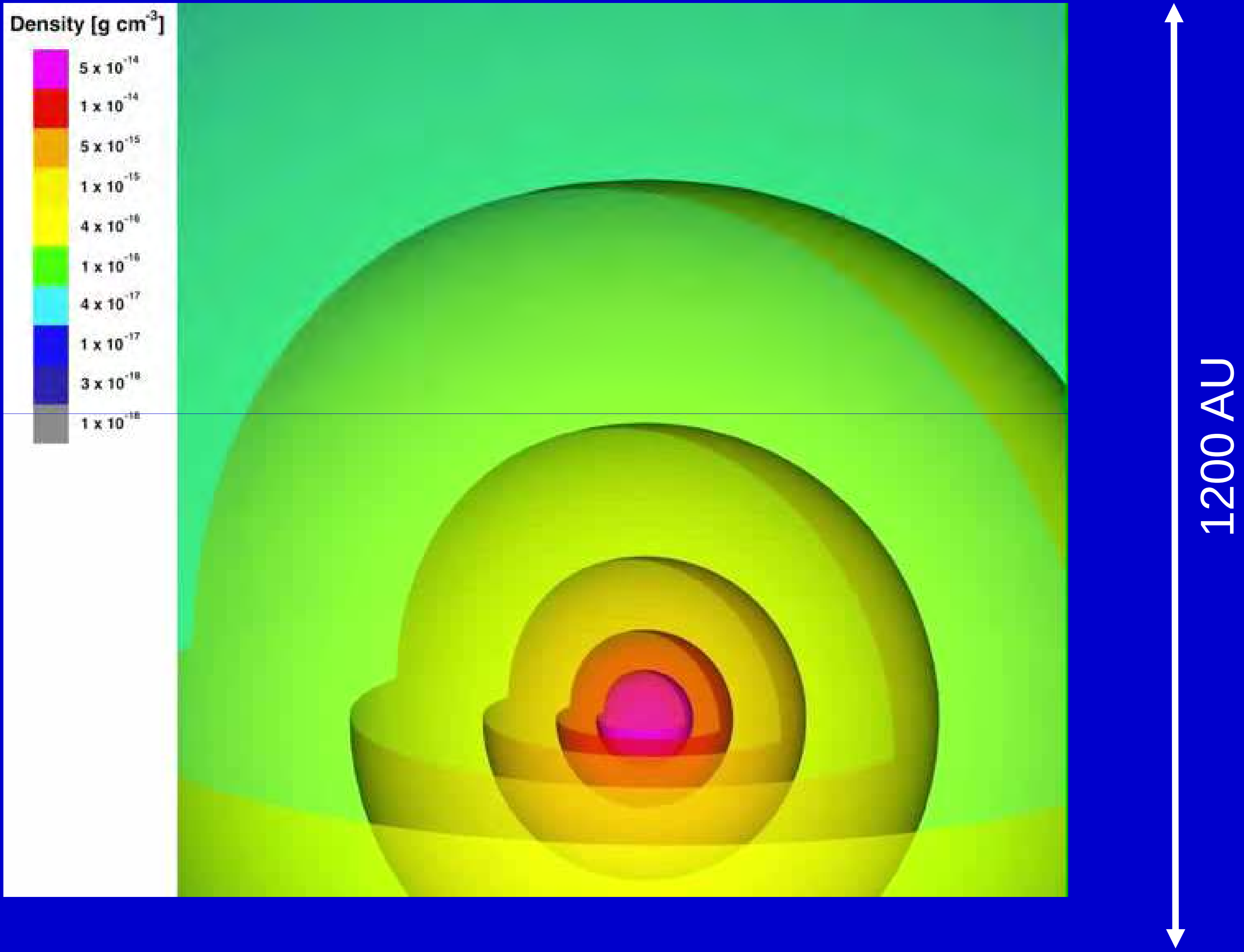


IRAS 20126+4104 (Cesaroni et al. 1997, 1999, 2005)
AFGL 490 (Schreyer et al. 2002, 2006)
AFGL 2591-VLA 3 (Wang et al. 2013)
S 140-IRS 1 (Hoare et al. 2013)
Mid-IR Interferometry (Kraus+ 2010, de Wit+, 2010, Follert +11, Boley+ 2013)

Talk by H. Beuther

Massive Star Formation

3D pre-stellar core collapse and massive accretion disk simulation

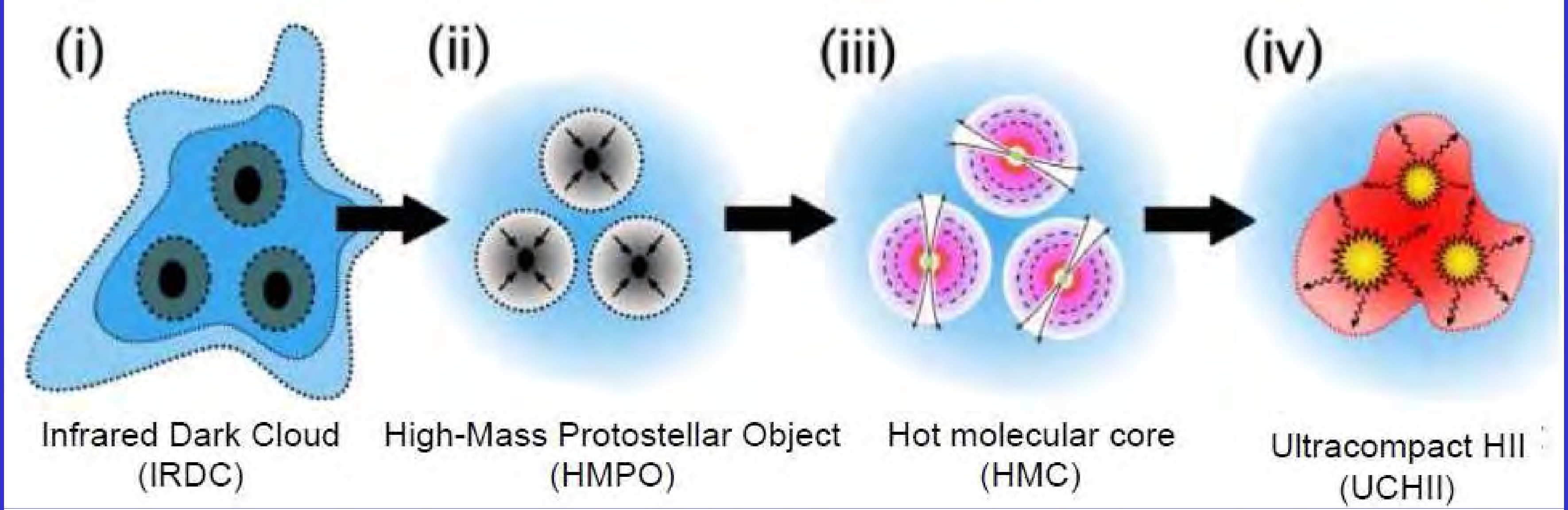


Inner region of a collapsing 120 M_{sun} pre-stellar core

Kuiper et al. (2011)

Search for the Earliest Stages

A Scheme is not Nature



Sketch - Courtesy C. Purcell

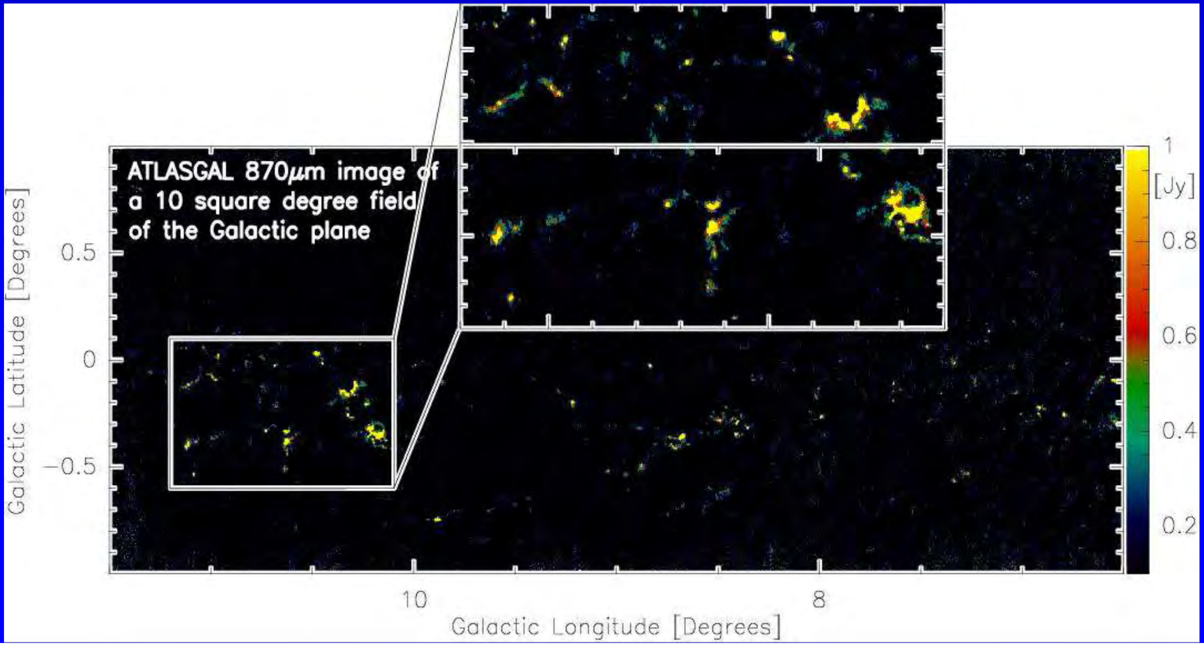
„There are known knowns, … there are known unknowns. But there are als unkonwn unknowns …“ Donald Rumsfeld - 2002

- **Known Knowns: T ↑ n(H_2) ↑**
- **Known Unknowns: Role of environment (W 43), Magnetic Field, Starless cores**
- **Unknown Unknowns: …..**

IRDCs are not an evolutionary stage (Protostars, Hot Cores, UC HII regions)
Massive and opaque IRDCs: Regions of massive SF

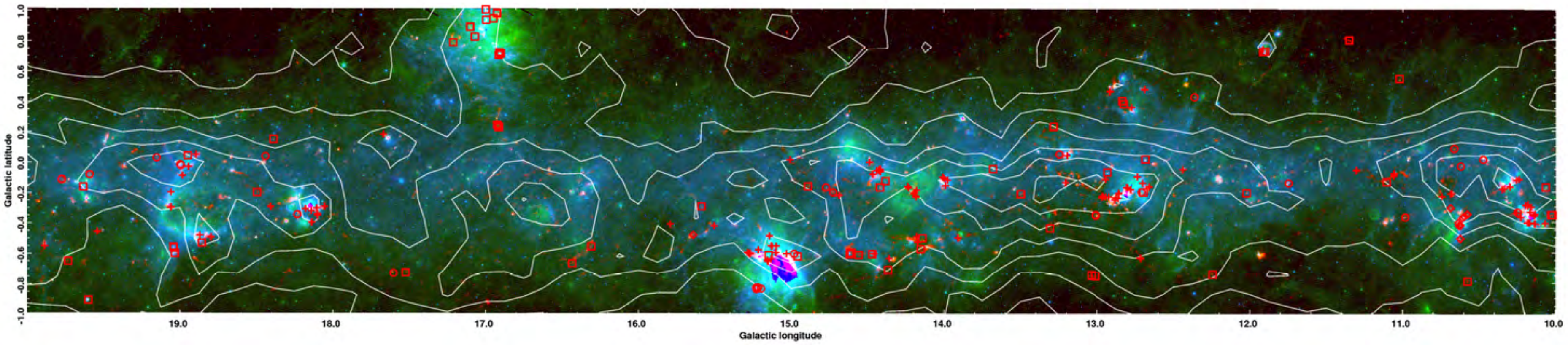
Earliest Stages of Massive Stars - Data Material

- Millimeter surveys around SF lighthouses
  (e.g., survey in the outer galaxy - Klein et al. 2005)
- MSX Dark Clouds (Carey et al. 2000, Sridharan et al. 2005, Simon et al. 2006, Rathborne et al. 2006, …)
- ISOSS Cold Cores (Krause et al. 2004, 170 microns)
- UKIDSS-GLIMPSE-MIPSGAL-ATLASGAL-BOLOCAM-HIGAL & MALT90 - SEDIGISM, …



Schuller et al. 2009 ATLASGAL

Global Star Formation in the Galaxy



Galactic plane l = 10°-20°, b = ± 1°

ATLASGAL: 993 clumps with $\Sigma \geq 10^{23}$ cm^{-2}
210 clumps or ~ 25% are starless down to 24µm
3 regions massive enough to form 40 M_{sun} star
Lifetime (6±5) x 10^4 yr

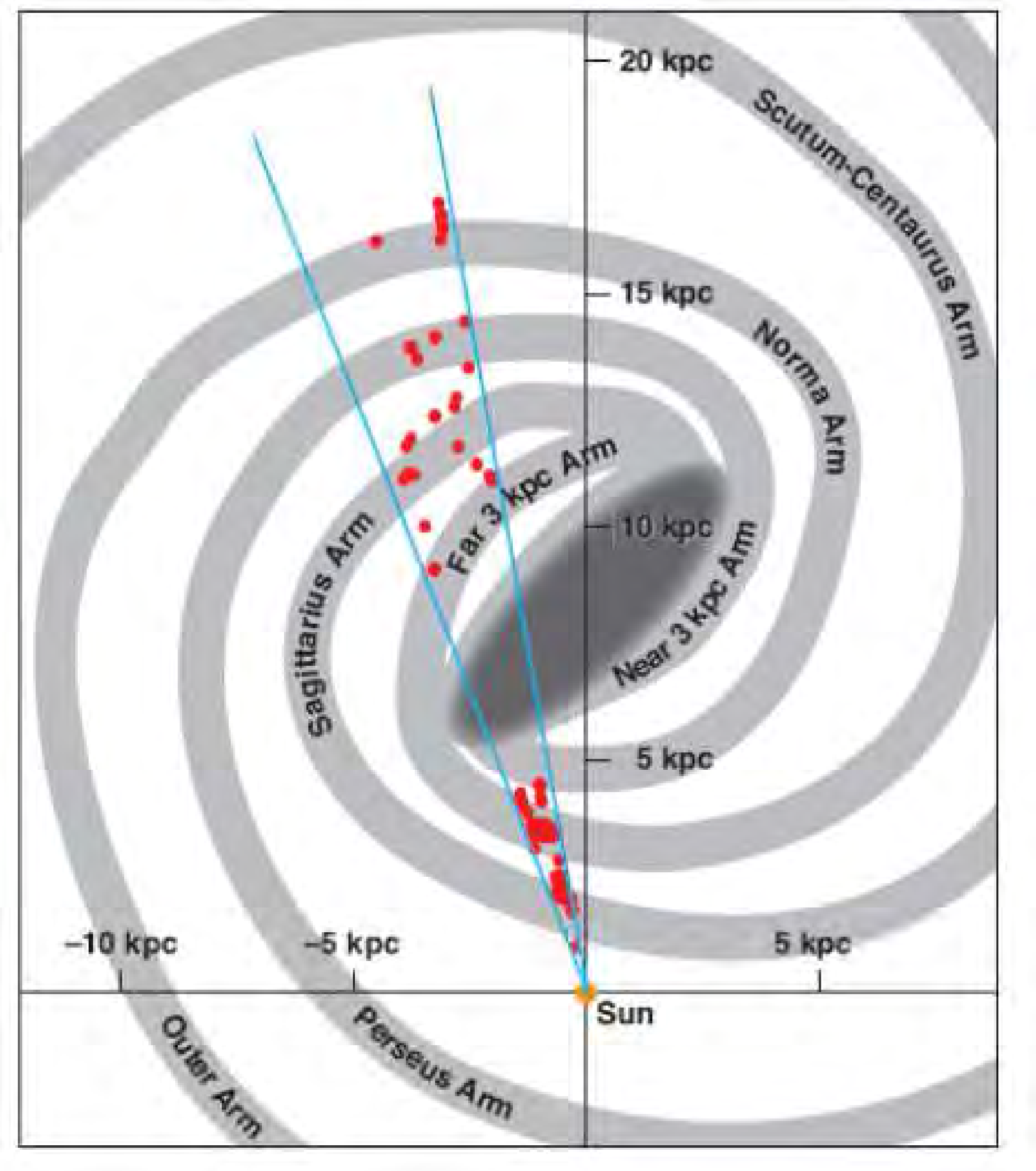
Blue: GLIMPSE 8µm
Green: MIPSGAL 24µm
Red: ATLASGAL 870µm
Contours: CO from Dame et al. (2001)

Tackenberg, Beuther, Henning
& ATLASGAL consortium,
2012, A&A 540, A113.

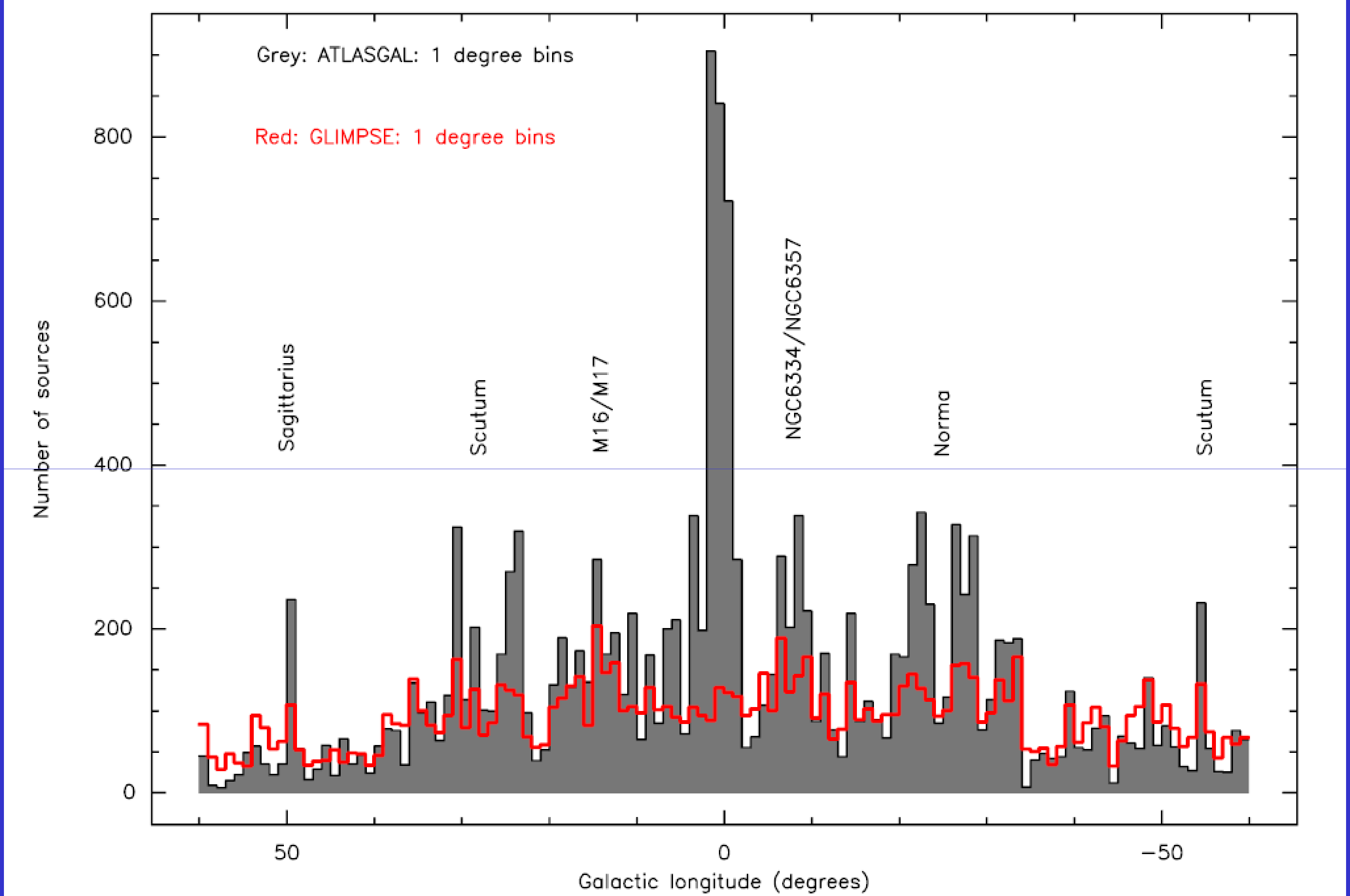
How many massive starless clumps at near distances?

115 starless clumps
at near distances

14 massive enough to
form stars more massive
than 20 M_{sun}



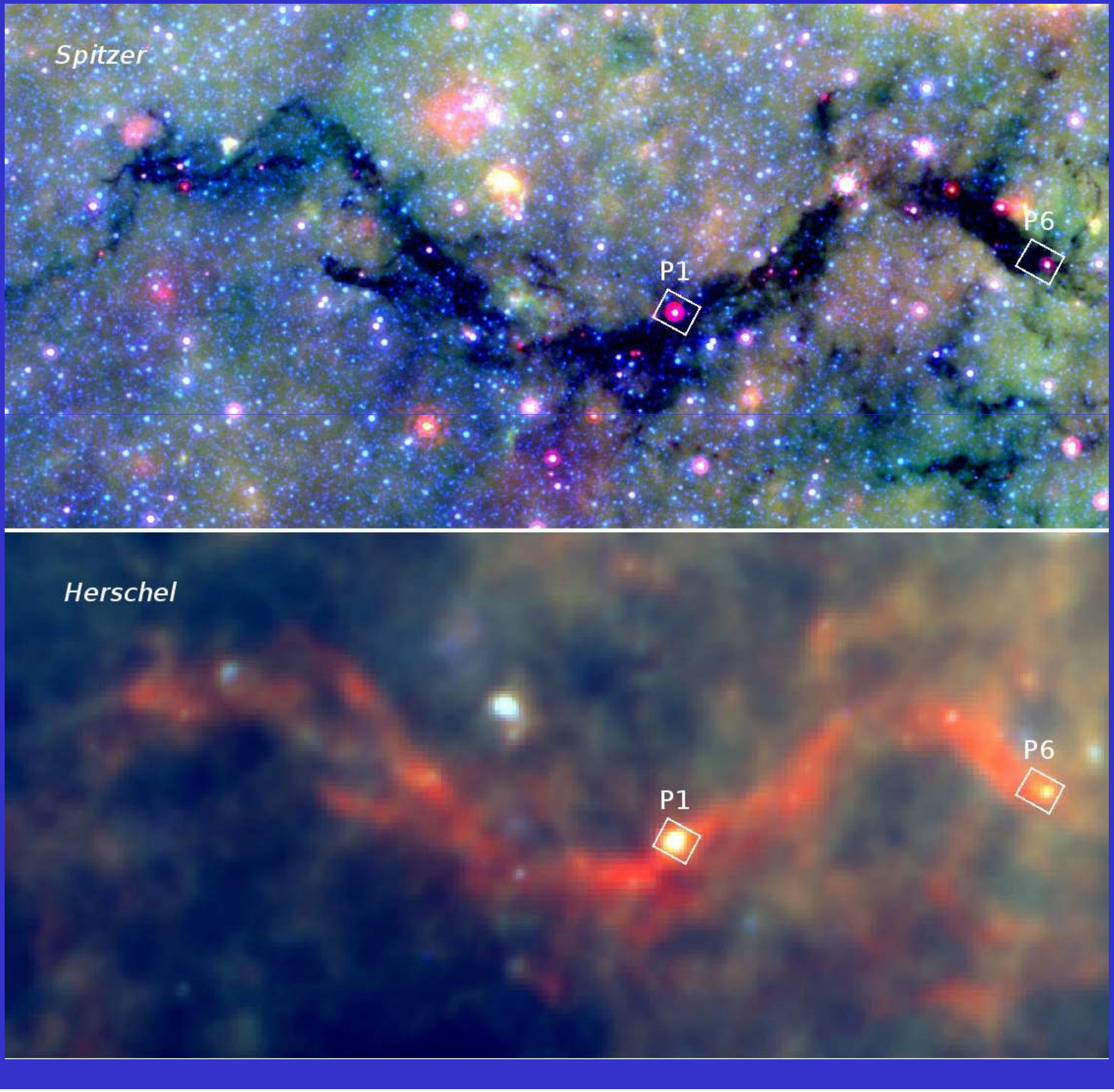
Global Star Formation in the Galaxy



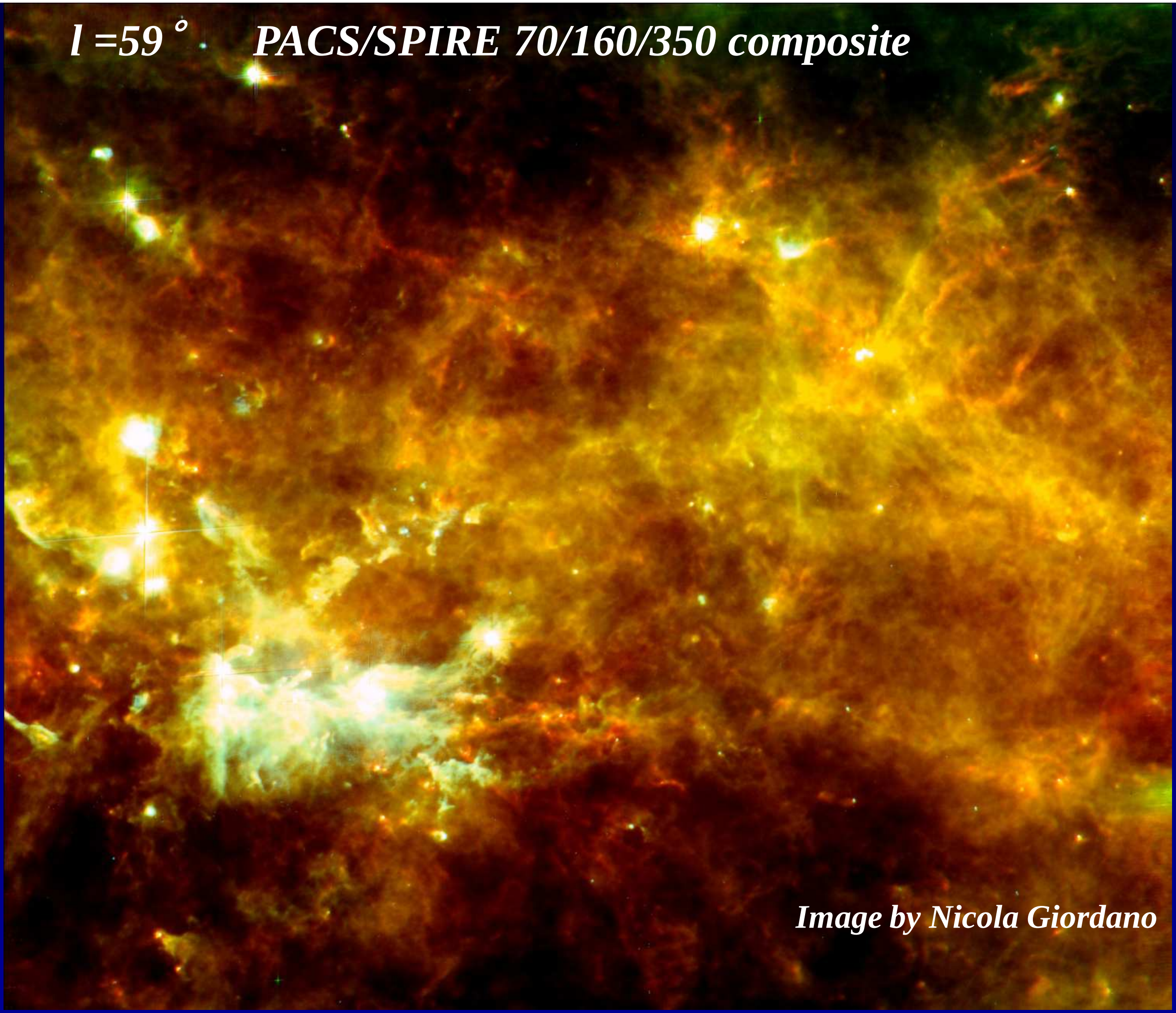
- Scale height in submm clumps: 46 pc (Beuther et al. 2012)
- Scale height in YSOs from GLIMPSE: 80 pc (Robitaille et al. 2008)

From Spitzer to Herschel to ALMA

The Promise of Infrared-Dark Clouds



2x2 deg



- Compact dust condensations preferentially found in filaments
- Compact sources in regions with higher column density (A_V ~ 1 mag)
- Cluster formation at junctions of filaments (e.g. Rosette - Schneider et al. 2012)

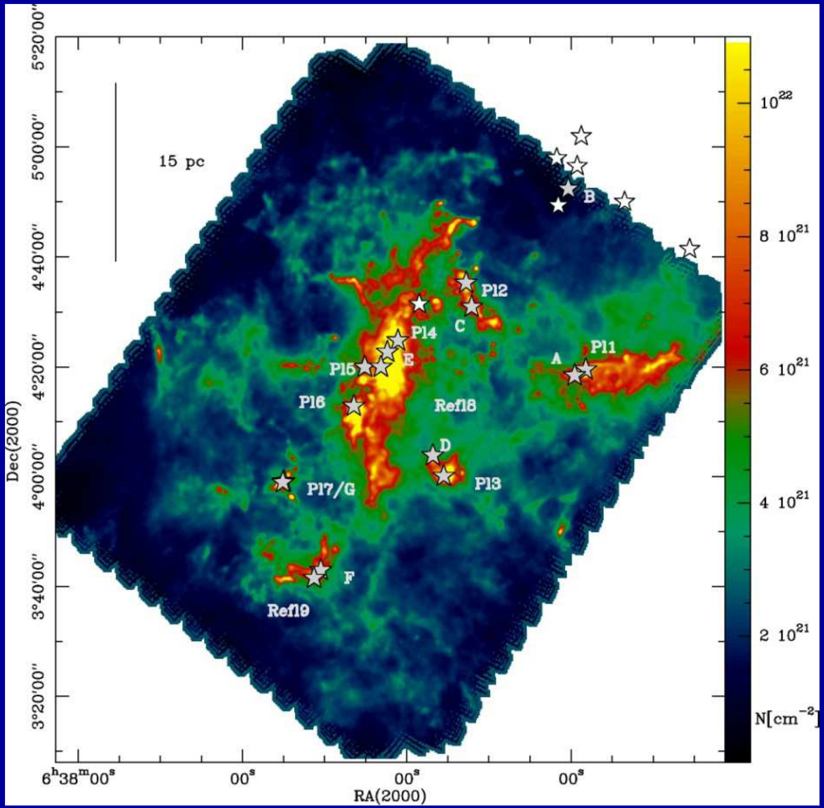
Herschel Imaging of High-Mass SF Regions

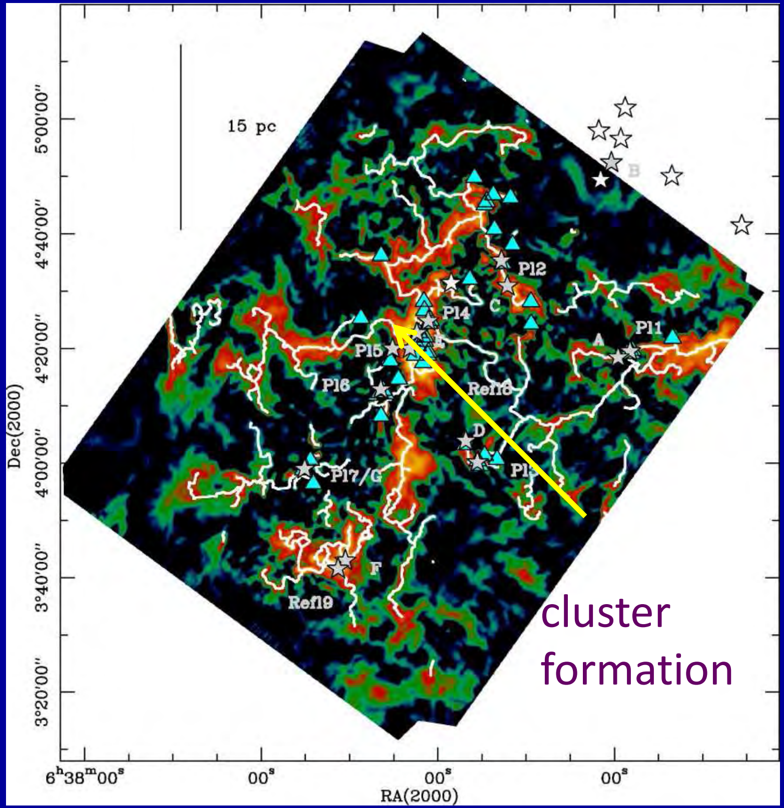
Merging of filaments into *ridges* and *hubs* to form OB-cluster
(high mass input rate)

Schneider et al. 2010, 2012; Hennemann et al. 2012; Nguyen-Luong et al. 2011; Hill et al. 2011, 2012

Rosette **Column density map**

Filaments on curvelet image



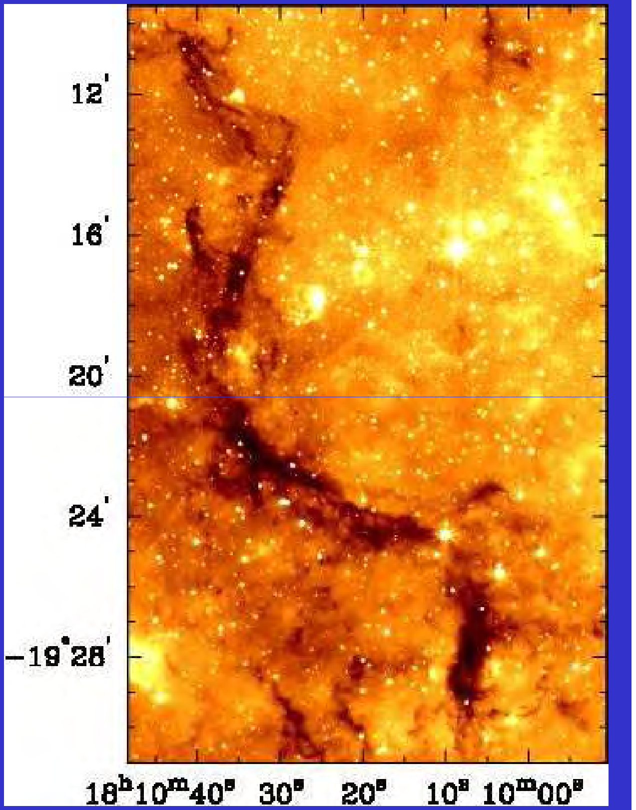


cluster formation

Schneider et al. 2012

Bringing a Snake to Chile – G 011.11-0.12

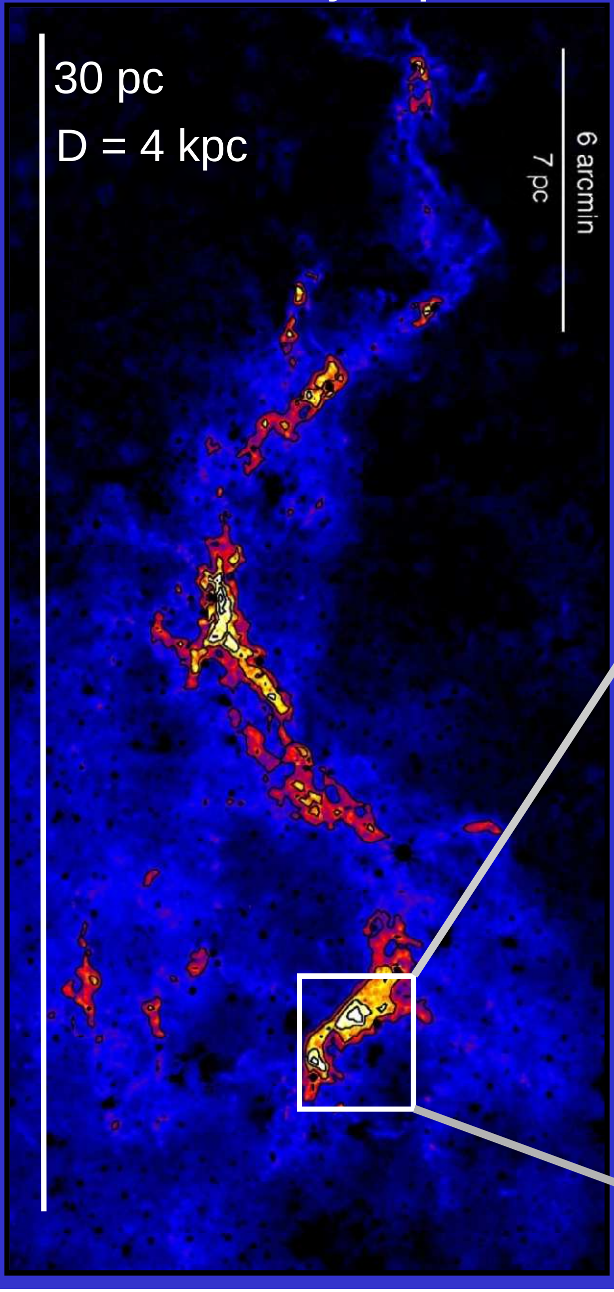
- Total mass of 2000-3000 M_{sun}
- Length of about 20 pc (Distance 3.6 kpc)
- Sub-regions observed in SCUBA maps (P1, P2, P6 and P7 – Johnstone ea. 2003) contain several 100 M_{sun}
- Temperatures very low throughout filament (about 12 K – Pillai ea. 2006)
- Column density reaches up to 10^{23} cm^{-2} (Carey ea. 1998, Johnstone ea. 2003)



5´´ = 18.000 AU

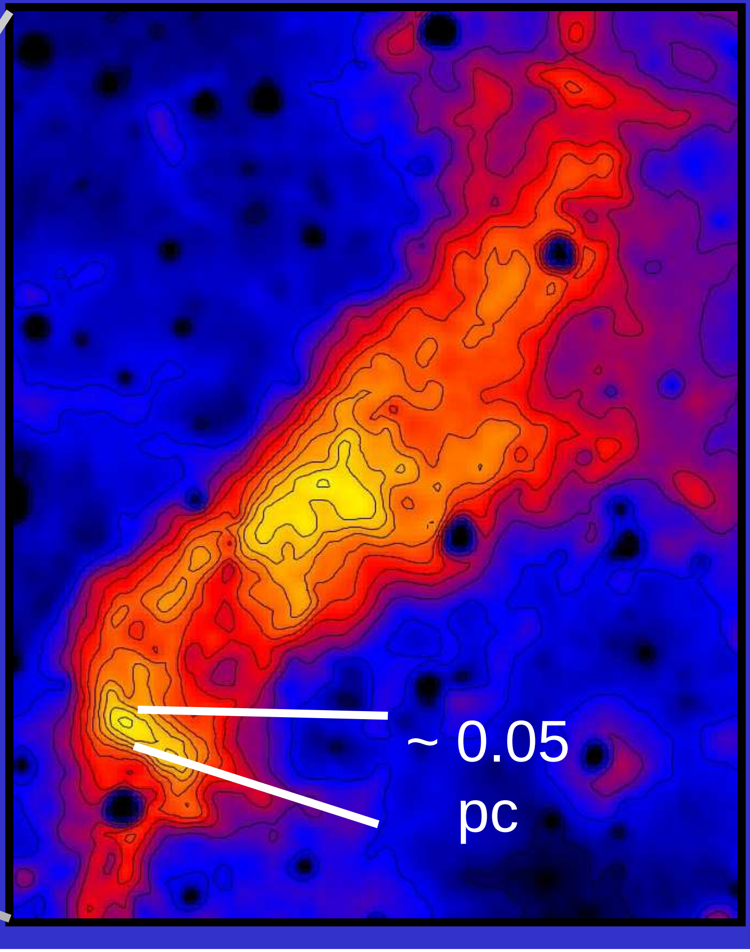
Hidden Mass Reservoir of Molecular Clouds

Column density map of G11

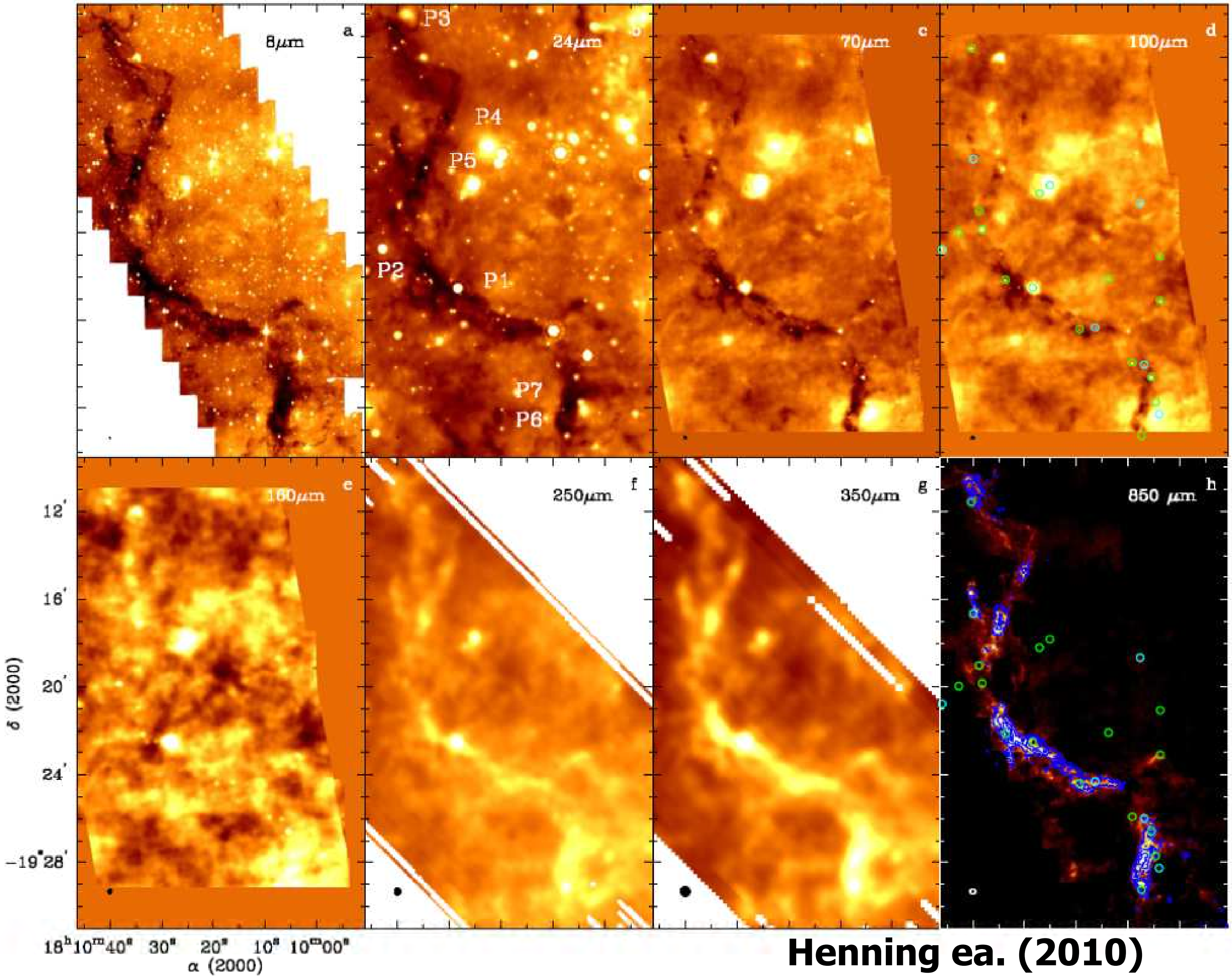


H**igh-dynamic-range** dust extinction mapping (Kainulainen ea. 13, Kainulainen & Tan 13): UKIDSS + Spitzer (2”, 1 - 100x10^{21} cm^{-2}); Filaments are not isolated: Heitsch 2012

10x more mass as probed by submm emission

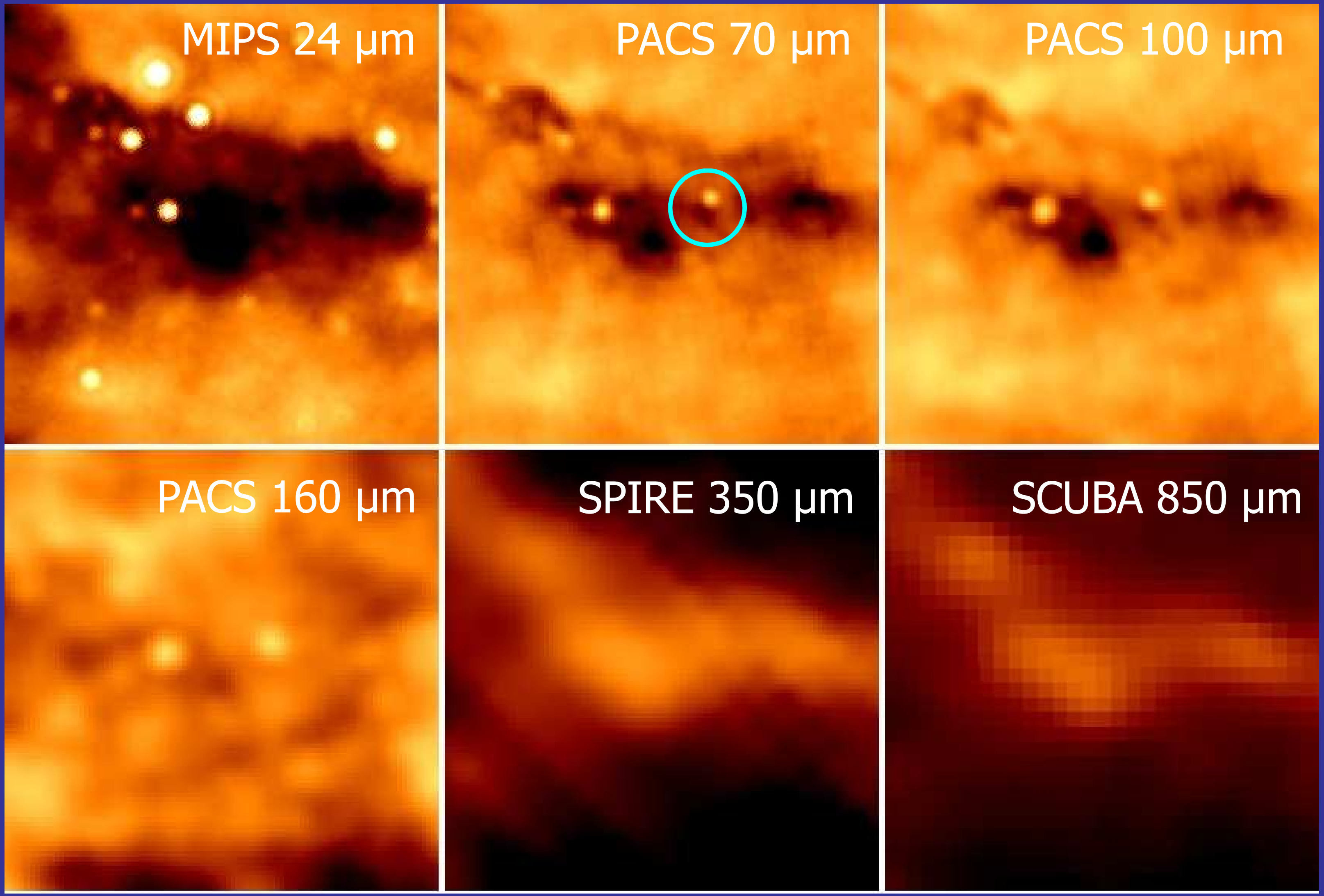


IRDC G11.11: The " Snake" as seen by Herschel

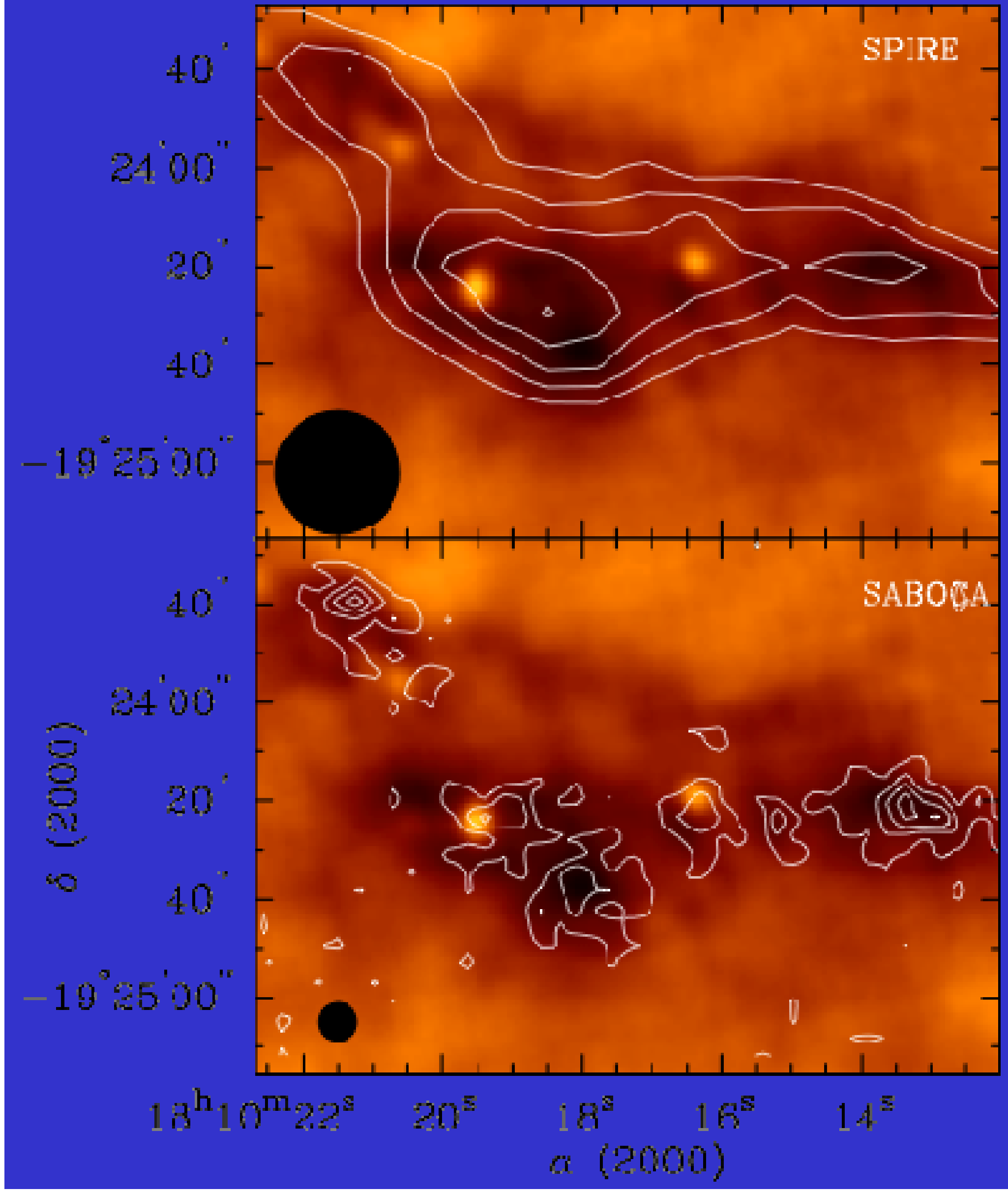


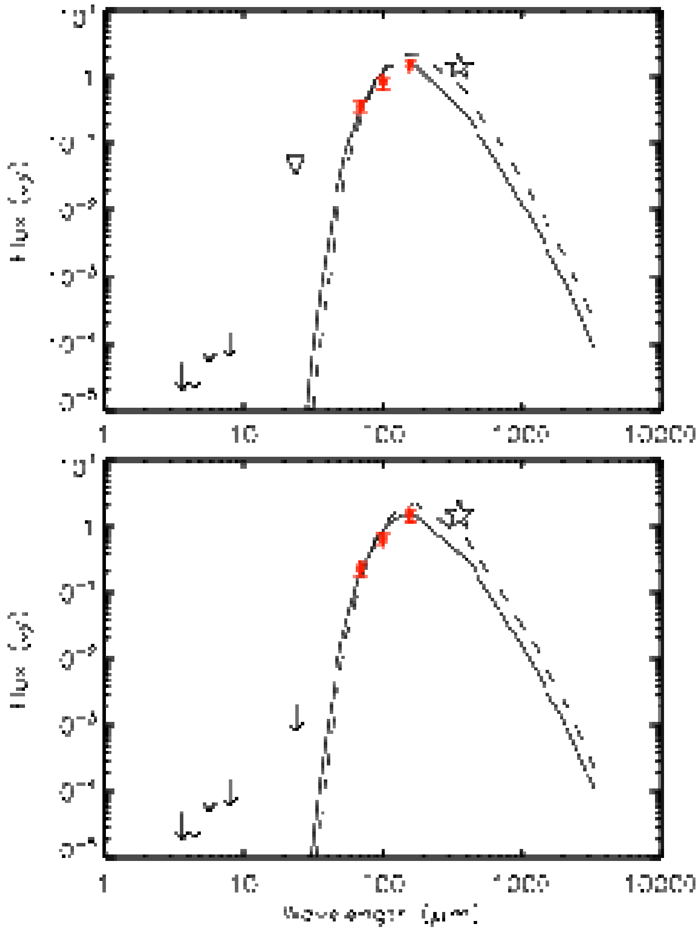
Henning ea. (2010)

Embedded protostars in the IRDC G11.11-0.12



SABOCA Follow-up Observations

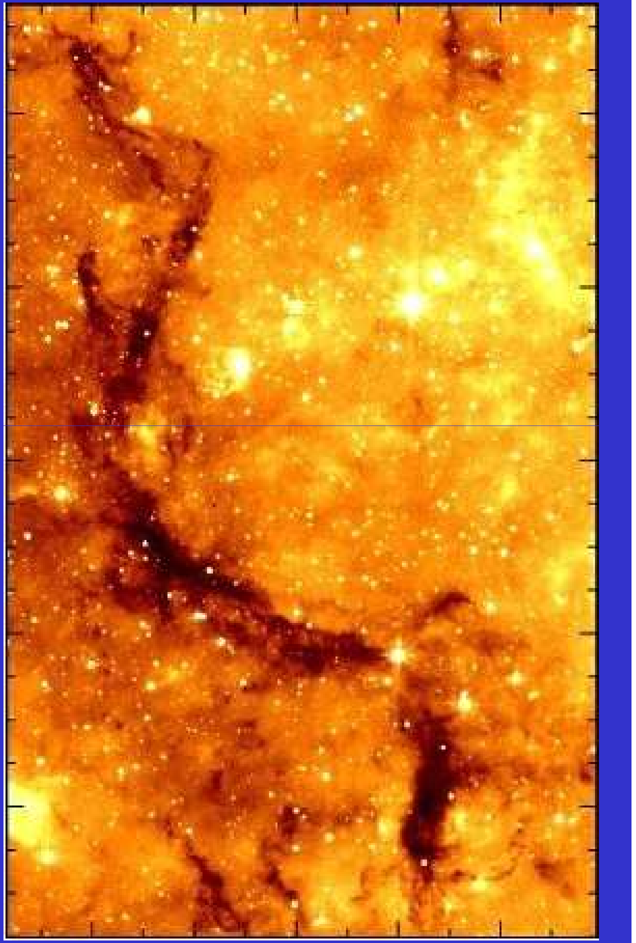




Ragan, Henning & Beuther (2013)

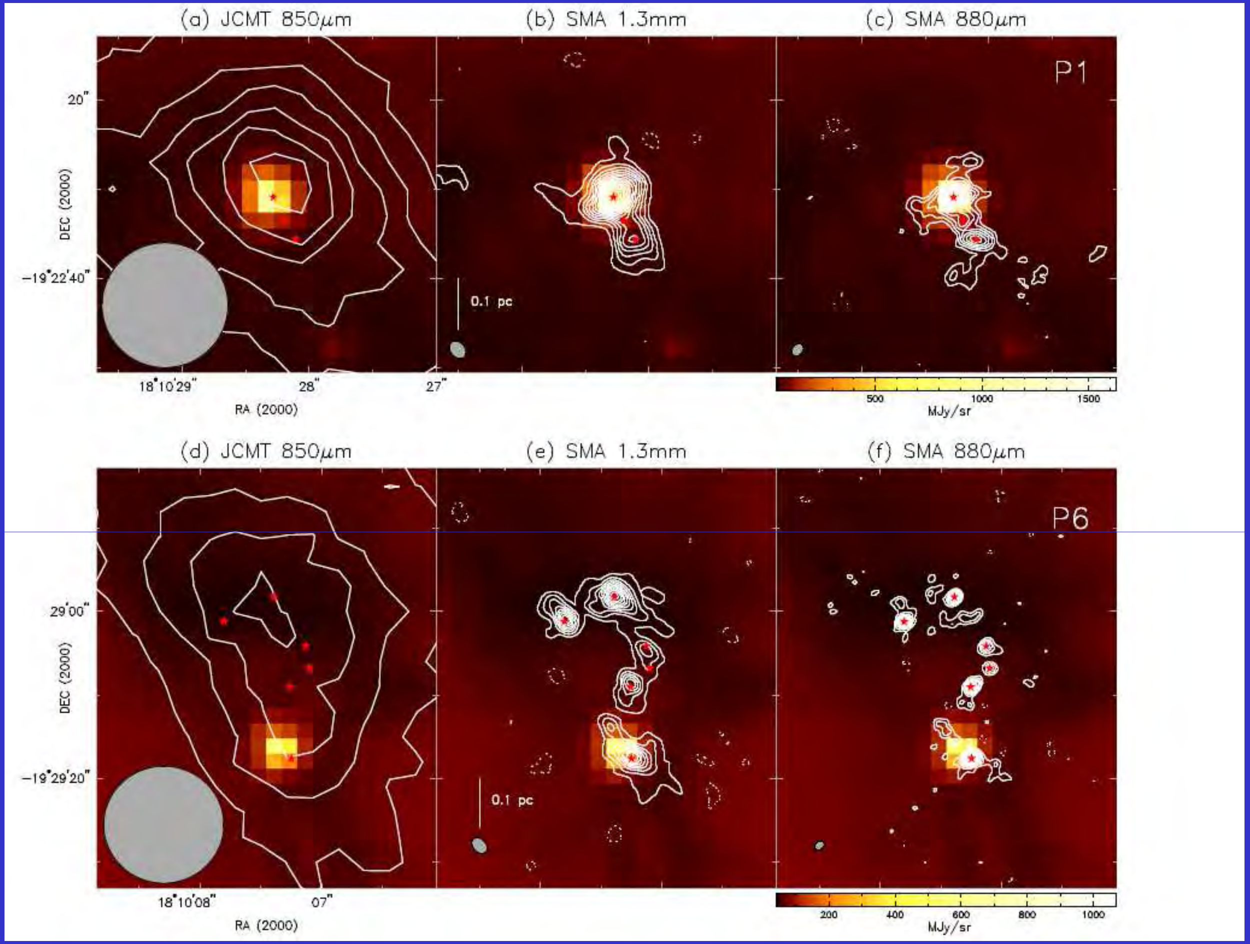
What do we find in the snake?

- 18 cores in the filament detected in all PACS bands + 20 cores detected only in two PACS bands
- Cores with/without 24 micron counterparts
- Average: 24 M_{sun}, 22 K, 96 L_{sun}
- Mean core separation 0.9 pc
- 3 cores with masses above 40 M_{sun} (P1 = 240 M_{sun}, P6 = 82 M_{sun})
- Few objects associated with bright emission to the north and west of the filament



5´´ = 18.000 AU

Hierarchical Fragmentation



240 M_{sun}

82 M_{sun}

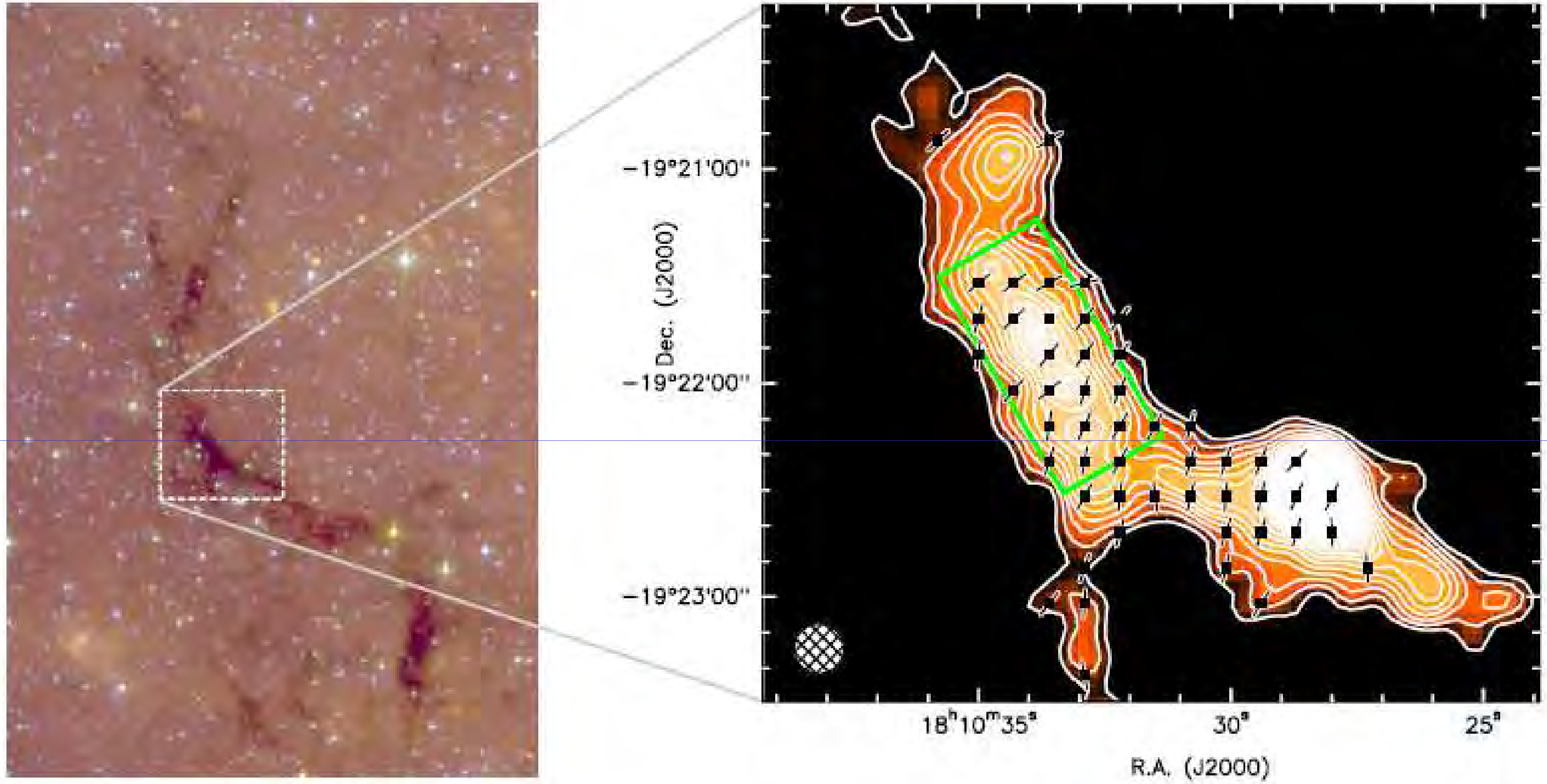
Wang et al. 2014

- From clumps (1 pc), to cores (0.1 pc) to condensations (0.01 pc)
- Scales and masses consistent with turbulent cylindrical fragmentation:

$$M/L_{crit} = 2\ \sigma^2/G$$

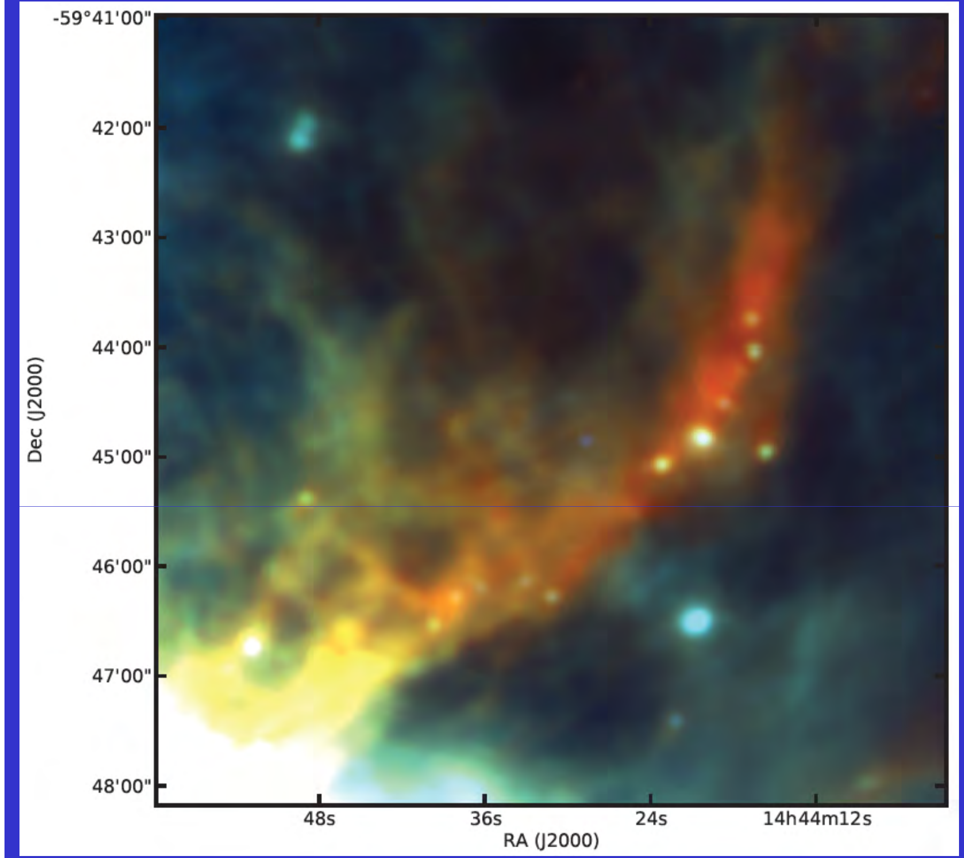
- Evidence for massive SF in P1 (Strong SiO flow, Type II methanol maser)

Magnetic Field Measurement

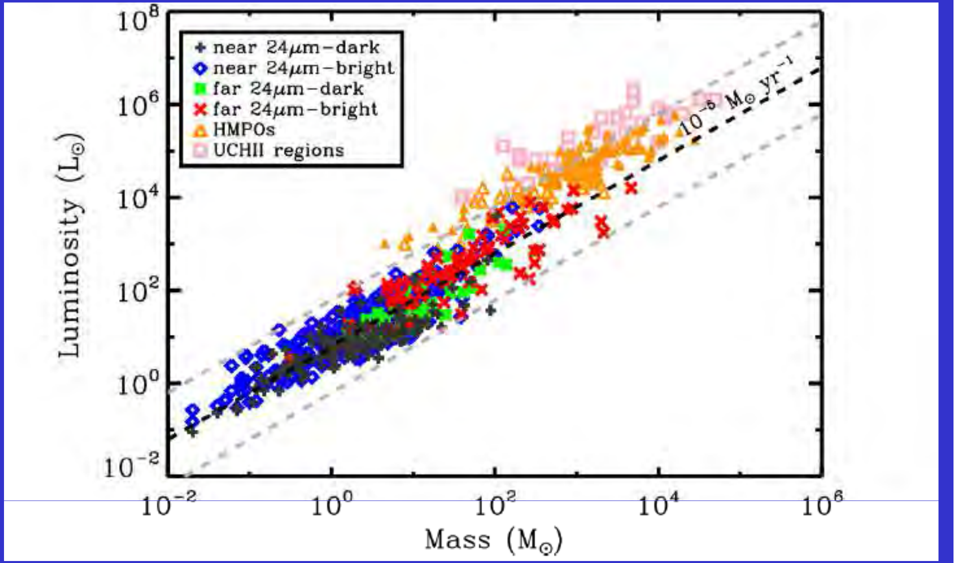


Pillai et al. (2015): $(M/\Phi)/(M/\Phi)_{cr} \leq 2$: Magnetic fields are dynamically important

EPoS – Infrared Dark Clouds



IRDC 316.72+0.07
70/100/160 micron image



- 496 cores in 45 high-mass SF regions (PACS/SPIRE)
- 34% lack counterparts at 24 µm
- 10% of total cloud mass is in cores
- 300 cand. cores – dark until 100 µm

(Ragan, Henning, Krause et al.
2012, A&A, 747, 43)

Do Massive Starless Cores/Clumps exist?

- Very high extinction – Embedded sources difficult to exclude
- They should form stars ….
- Close to virial equlibrium in *Core Accretion Model*

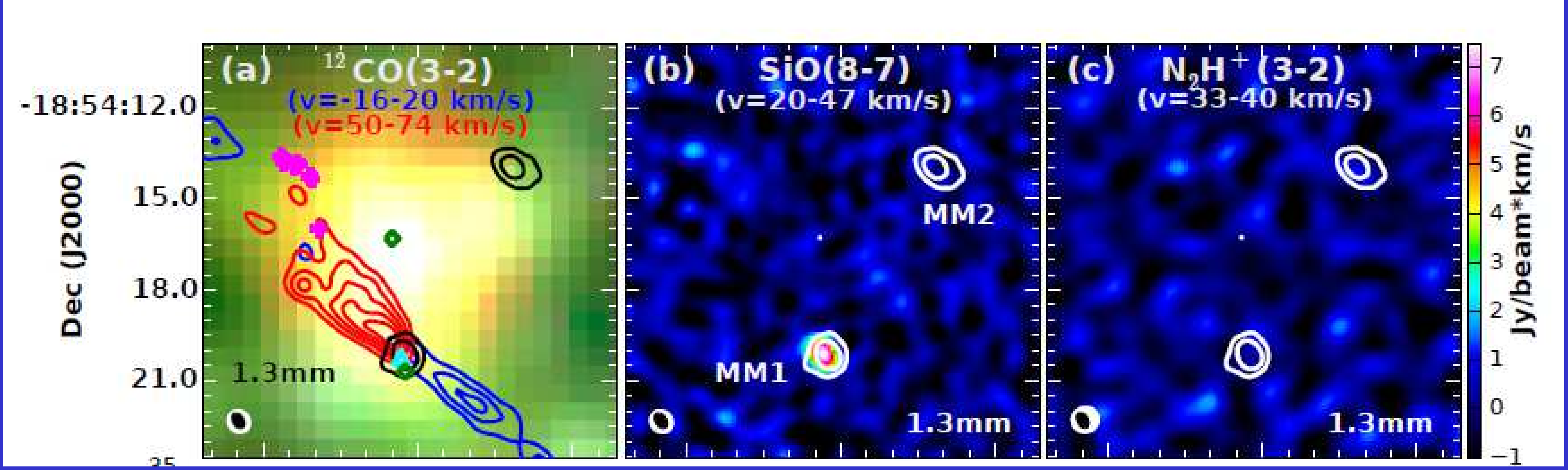
  (McKee & Tan 2002, 2003)
- Rare if they exist at all

  Short timescales (e.g. Russeil et al. 2010, Tackenberg et al. 2012)

Candidates: 2 massive cores (subvirial) – 16 and 63 M_{sun} (Tan et al. 2013)

G 11.92-0.61-MM2: M=30 M_{sun} within 1000 AU, L=5-7 L_{sun}

(Cyganowski et al. 2014)

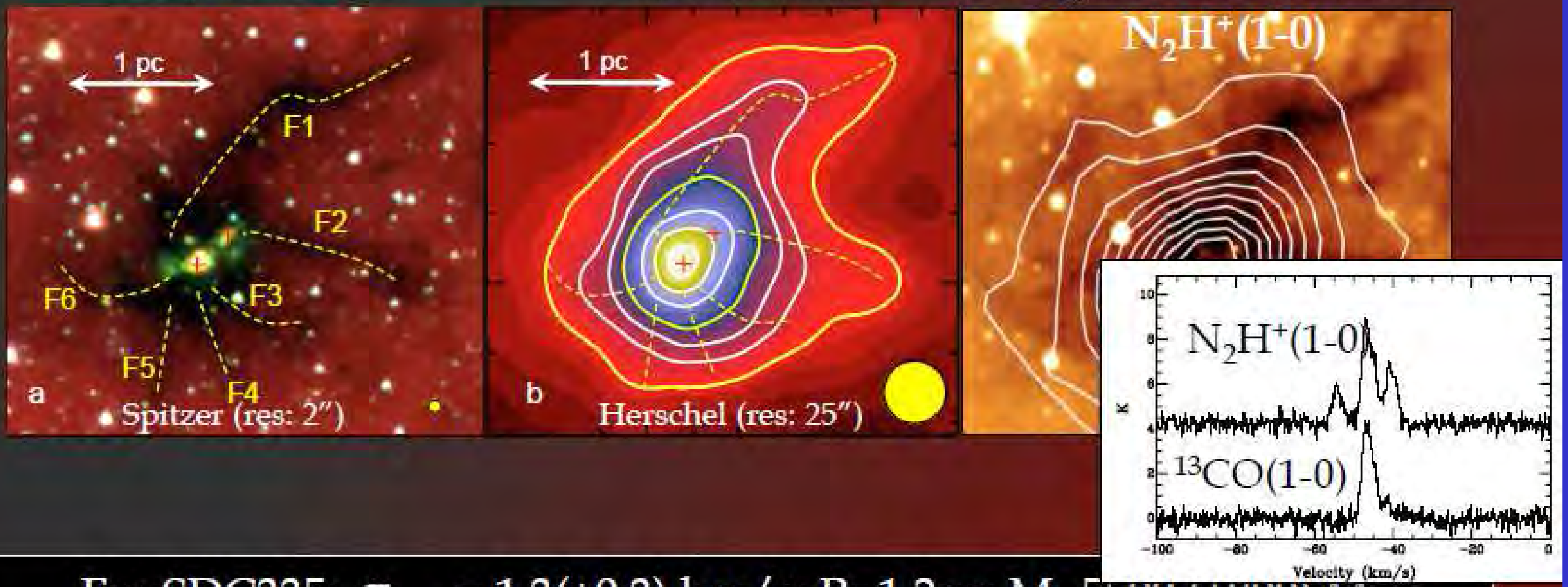


Kinematics of Star-Forming Regions: SDC 335

Virial balance: U+2T=0 where U=gravitational energy and T=kinetic energy

$\alpha_{vir} = 2T/U = 5\,\sigma_{turb} R/(GM)$ => $\alpha_{vir} < 1$: *cloud is collapsing*

Dust extinction — Dust emission — Integrated line emission

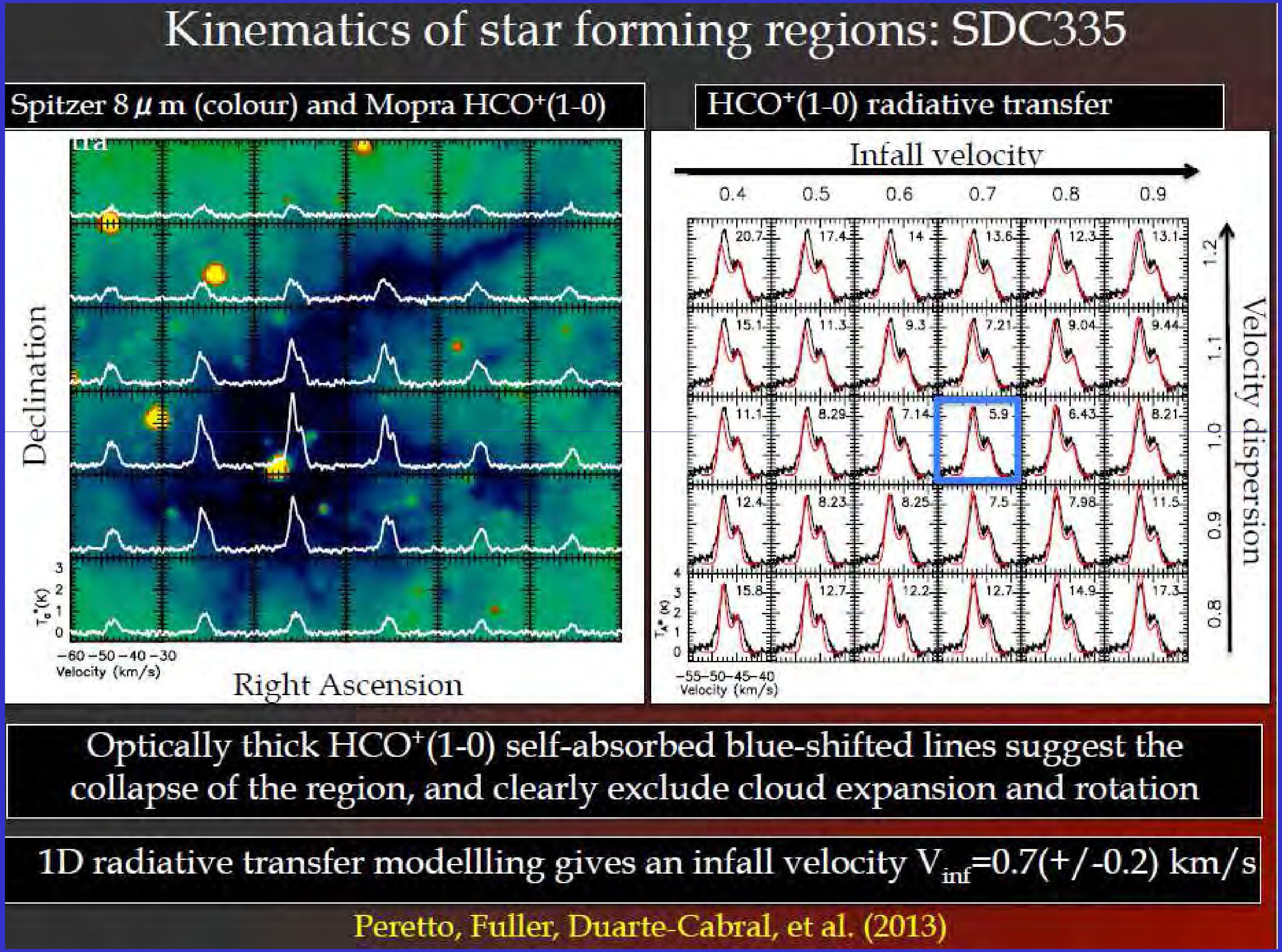


For SDC335: σ_{turb}= 1.3(±0.3) km/s; R=1.2pc; M=5500 (±800) M_{sun}

$\Rightarrow \alpha_{vir} = 0.4(^{+0.4}_{-0.2}) < 1$ => *SDC335 must be collapsing*

Peretto, Fuller, Duarte Cabral, et al. (2013)

SDC 335 – Infall Signatures



Kinematics of star forming regions: SDC335

Spitzer 8 μm (colour) and Mopra HCO⁺(1-0)

HCO⁺(1-0) radiative transfer

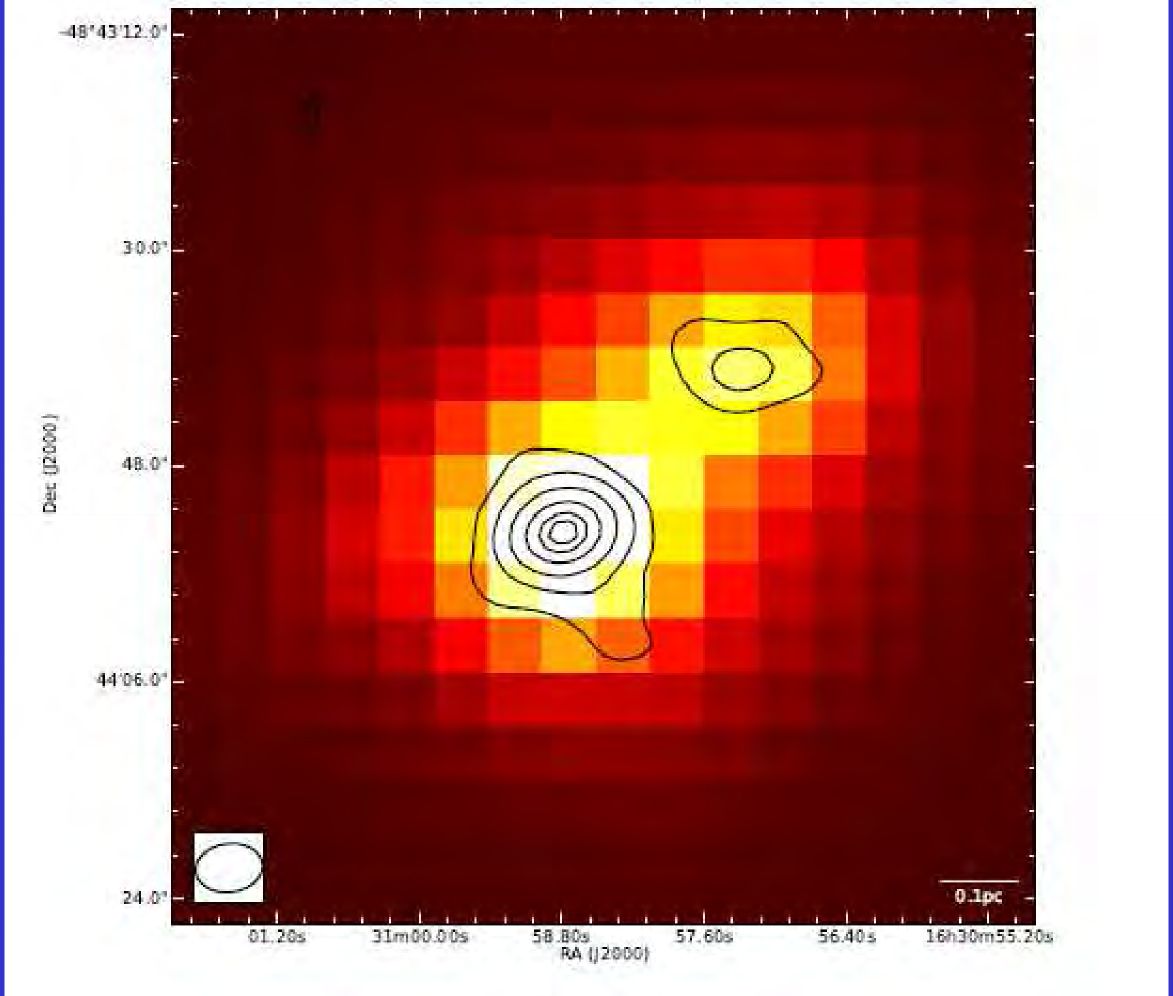
Optically thick HCO⁺(1-0) self-absorbed blue-shifted lines suggest the collapse of the region, and clearly exclude cloud expansion and rotation

1D radiative transfer modellling gives an infall velocity V_{inf}=0.7(+/-0.2) km/s

Peretto, Fuller, Duarte-Cabral, et al. (2013)

Infall Rate of $2.5\times10^{-3}\ M_{sun}$/yr

SDC 335 – MM1 & MM2

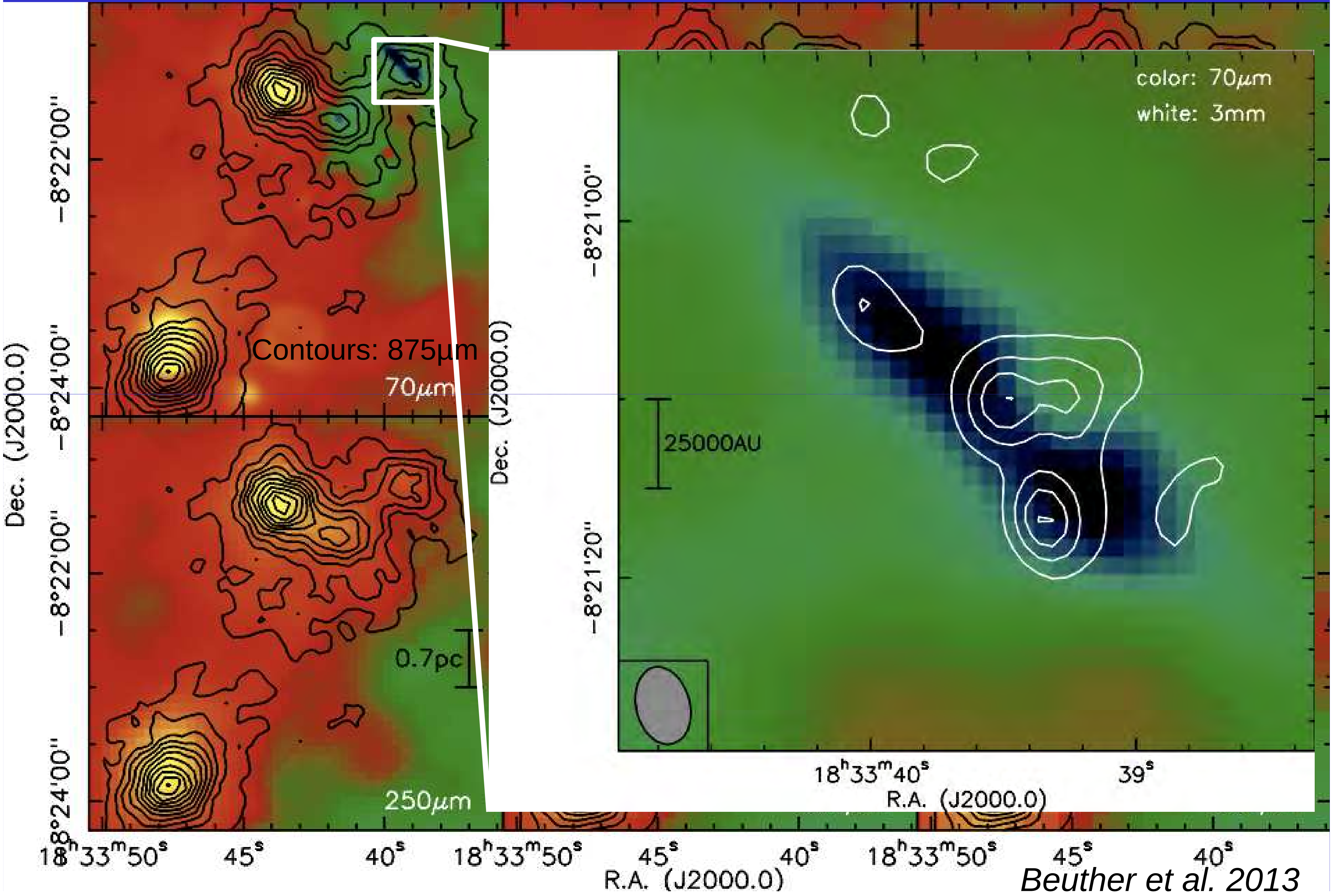


PACS 160 µm image
ALMA 3.2 mm contour lines

Peretto et al. (2013)
Avison et al. (2015)

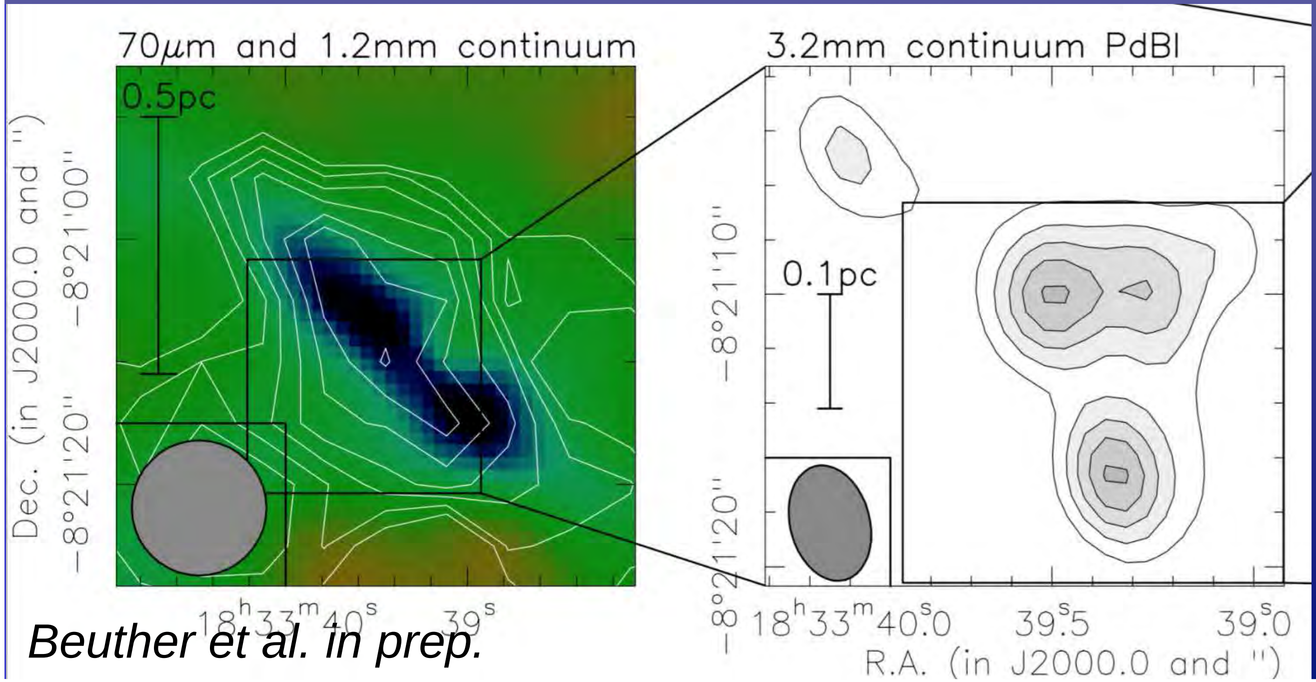
Masses: 500 M_{sun} & 50 M_{sun} (separation 0.32 pc), Stellar activity

Hierarchical Fragmentation: An Example



Beuther et al. 2013

Hierarchical fragmentation



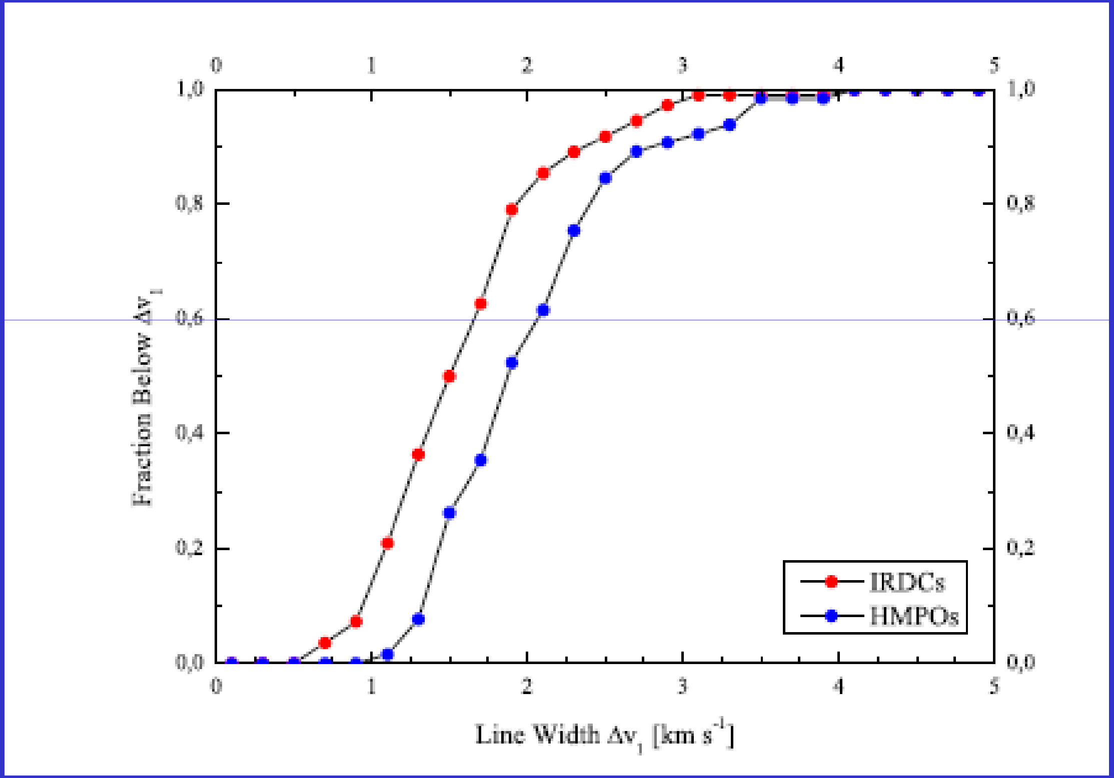
Beuther et al. in prep.

Turbulence in Massive Filaments

Molecular Tracers: CS, NH_3, N_2H^+, NH_2D, N_2D^+

Larger scales (1 pc): FWHM - 2-3 km/s

(e.g. Shridaran et al. 2005, Pillai et al. 2006, Dunham et al. 2011, Wienen et al. 2012, Bihr et al. 2015)

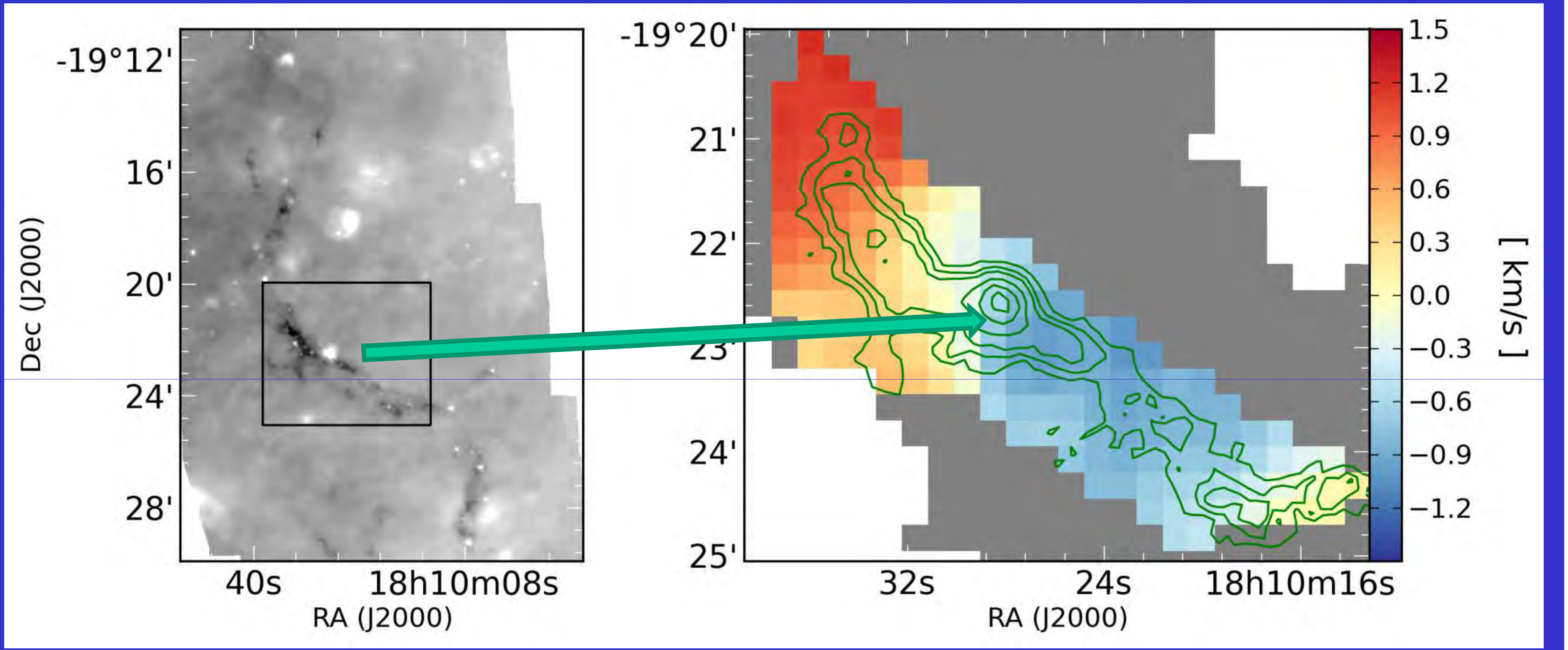


Chira et al. 2013

Cores without SF:: FWHM 0.2-1 km/s

(e.g. Beuther et al. 2009, 2015; Pillai et al. 2012, Tan et al. 2013, Ragan et al. 2015)

G11.11-0.12 - Searching for Flows …



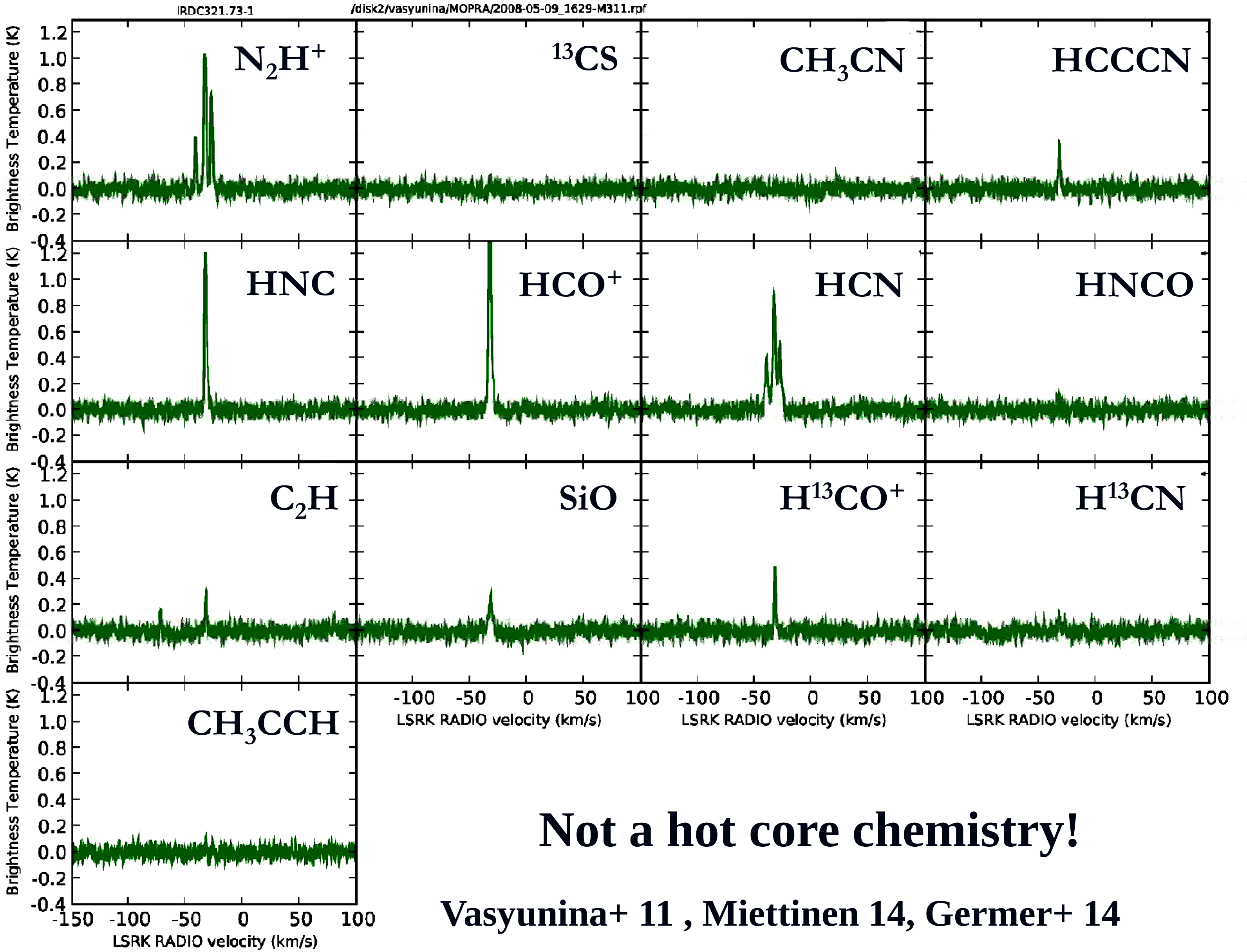
Herschel/PACS 70 μm

Mopra N_2H^+ Line Analysis

Henning et al. (2010)

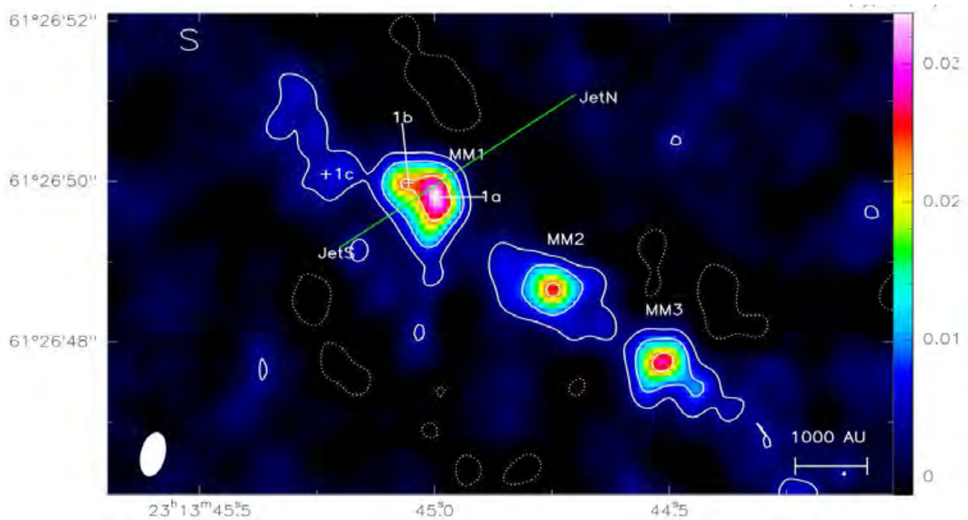
Tackenberg , Beuther, Henning et al. (2014)

The molecular content of the IRDCs



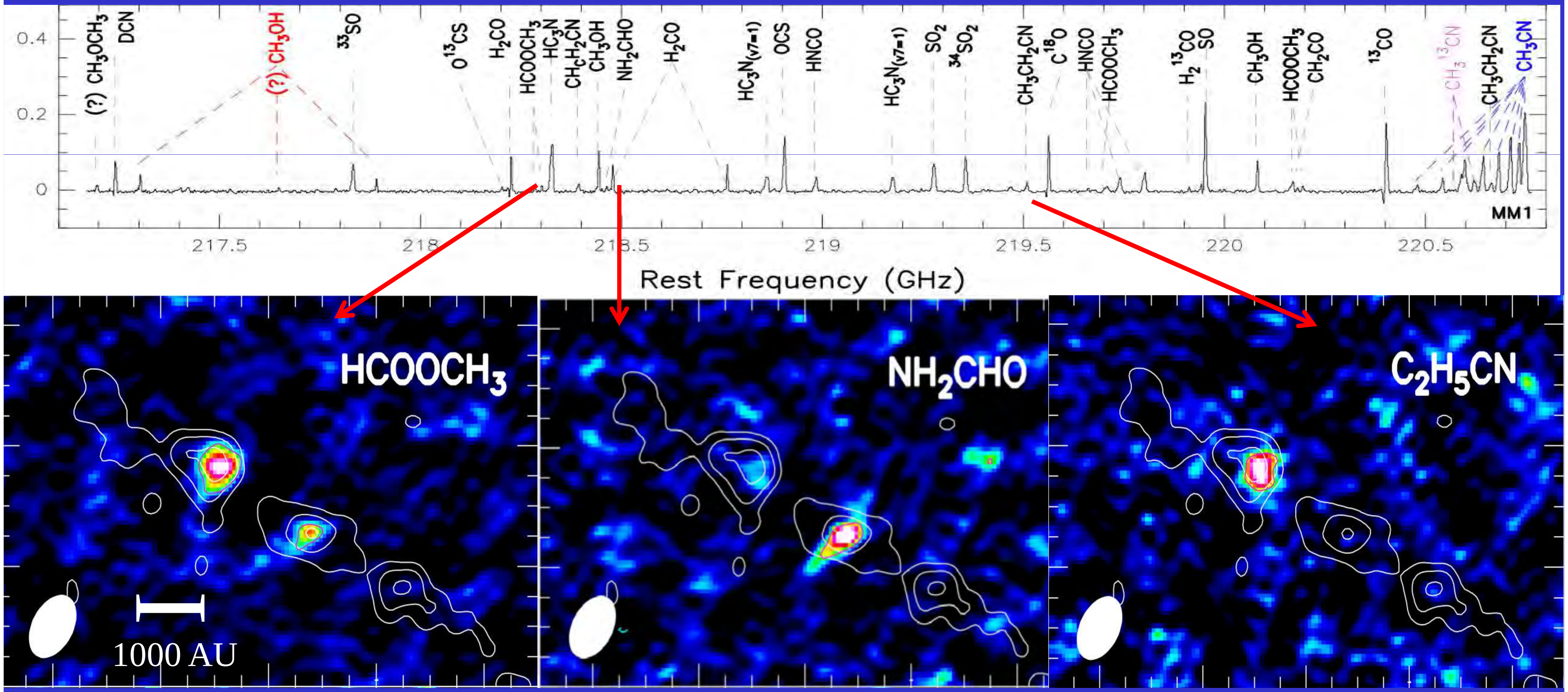
Not a hot core chemistry!

Vasyunina+ 11 , Miettinen 14, Germer+ 14



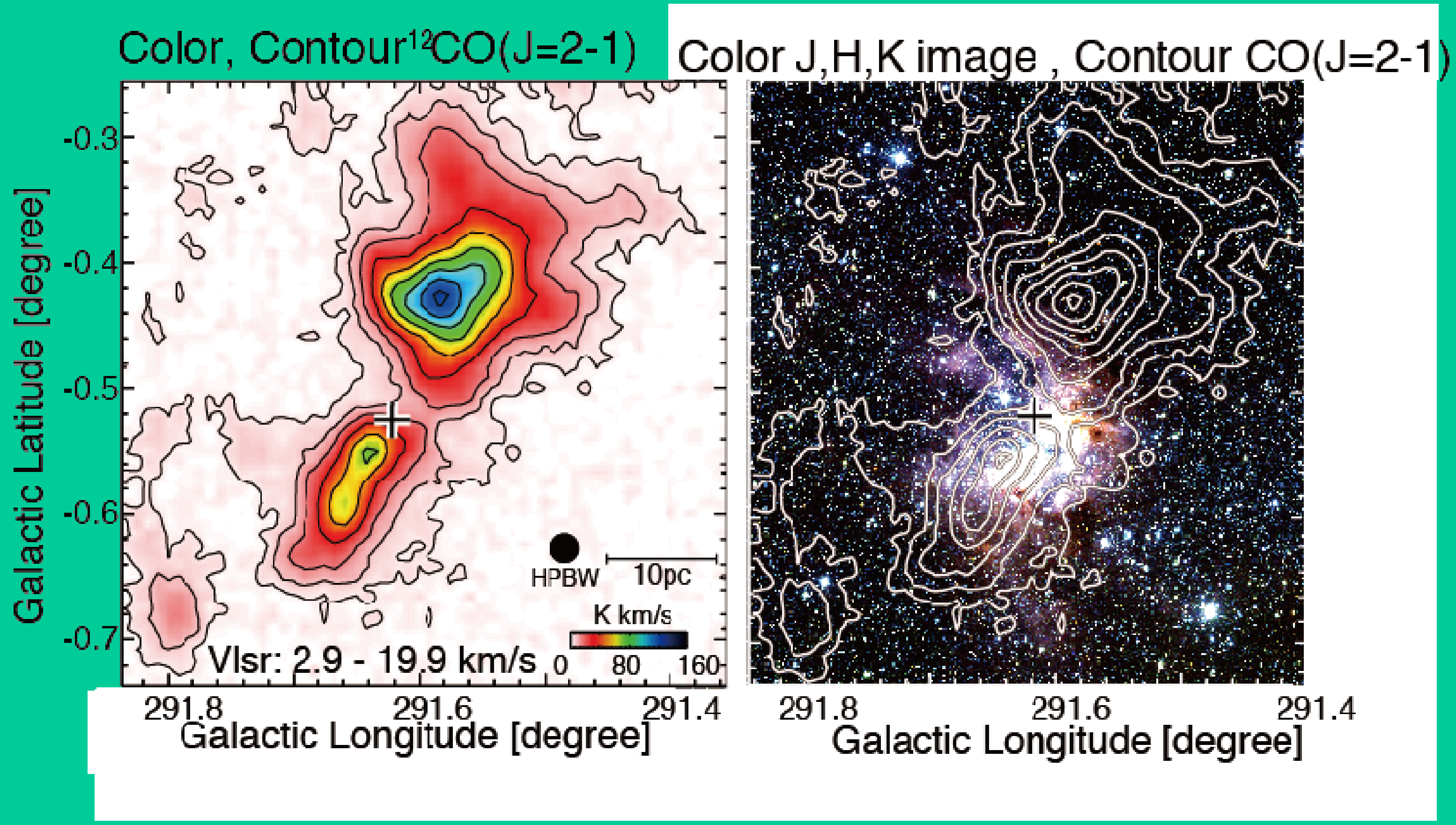
NGC 7538 S @ 2.7 kpc @ PdBI (Feng et al. sub)

Chemical Diversity



Converging Flows

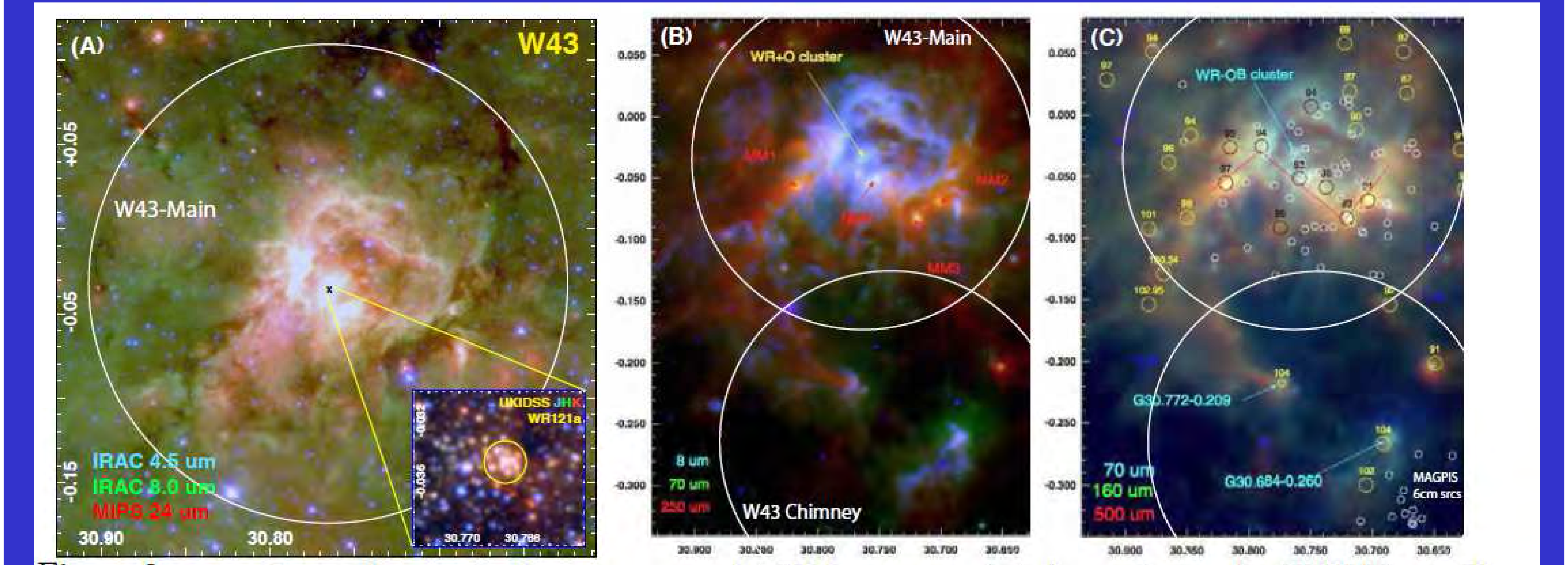
Formation of filaments remains an open problem
„Converging flows“ (e.g. Hennebelle 2013)



High-Velocity collision of two molecular clouds – NGC 3603

Fukui et al. (2013)

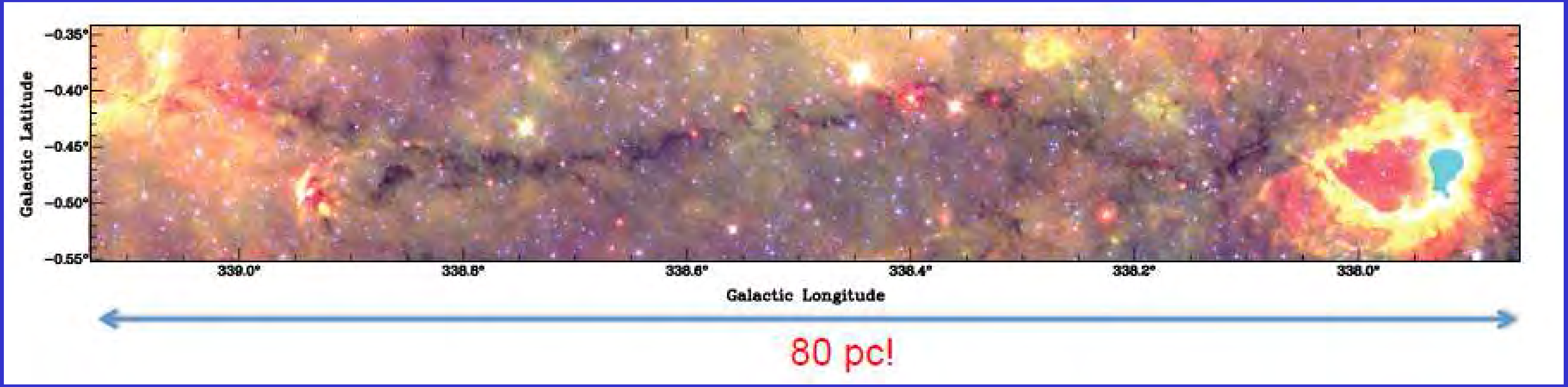
W 43 – The Galactic Powerhouse



(see Bally et al. 2010)

- Giant HII region powered by OB/WR stellar cluster
- GMC with 10^6 M_{sun} and 10^6 L_{sun} IR luminosity
- Population of clumps and embedded protostars

Discovery of Giant Molecular Filaments



Nessie: Jackson et al. (2010), Goodman et al. (2015): 80-160-430 pc
Galactic plane feature along the Scutum-Centaurus Arm

G 18.93-0.03 – 54pc, 4.7x10^4 M$_{sun}$ Tackenberg et al. 2013, Ragan et al. 2014

G 32.02+0.06 (80 pc, 2x10^5 M$_{sun}$ – Battersby & Bally 2012)
G 51.69-52.24 (500 pc, 1x10^5 M$_{sun}$ – Li et al. 2013)

Conclusions

- Scenarios for solving the fragmentation and radiation pressure puzzles
- Large-scale NIR/FIR/submm surveys available: Detection of embedded cold and massive cores with no NIR/MIR counterparts – Starless cores?
- Superb spatial resolution, spectral coverage, and sensitivity of HERSCHEL has opened a new window to study the formation of high-mass stars – ALMA is delivering first results
- Clumps/Cores embedded in filamentary structures
- Observational evidence for hierarchical fragmentation