Linking the formation of molecular clouds & high-mass stars

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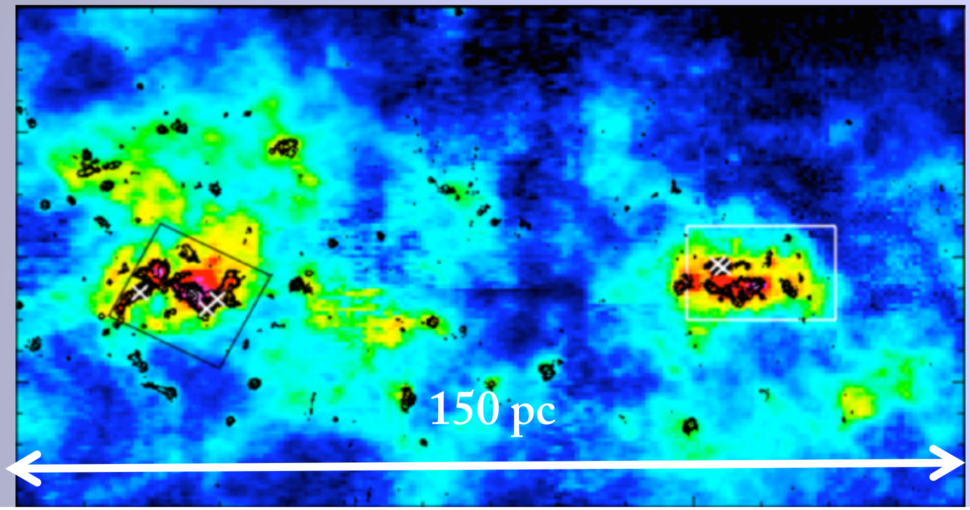
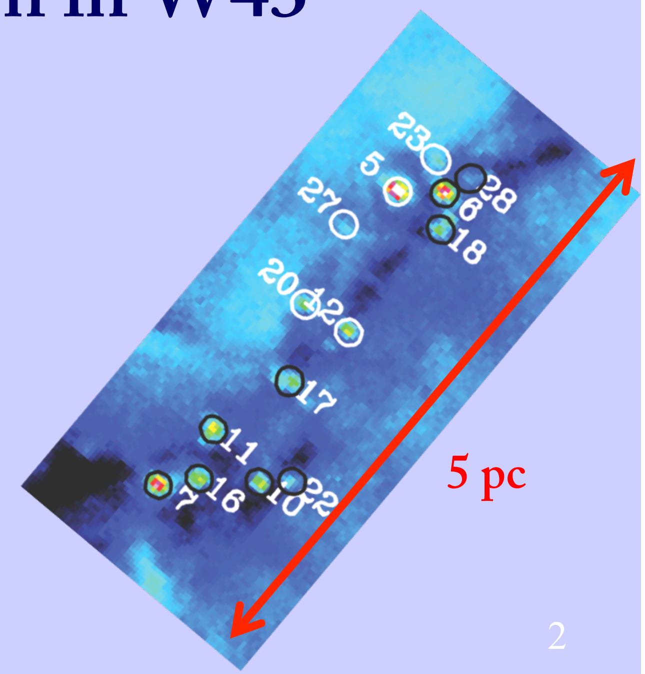
université PARIS DIDEROT PARIS 7

Linking the formation of molecular clouds & high-mass stars

1. Introduction to high-mass star formation
2. Star formation activity in one of the densest IRDCs
3. W43: An extreme molecular cloud complex
4. Imprints of molecular cloud formation in W43
5. Conclusions & Perspectives





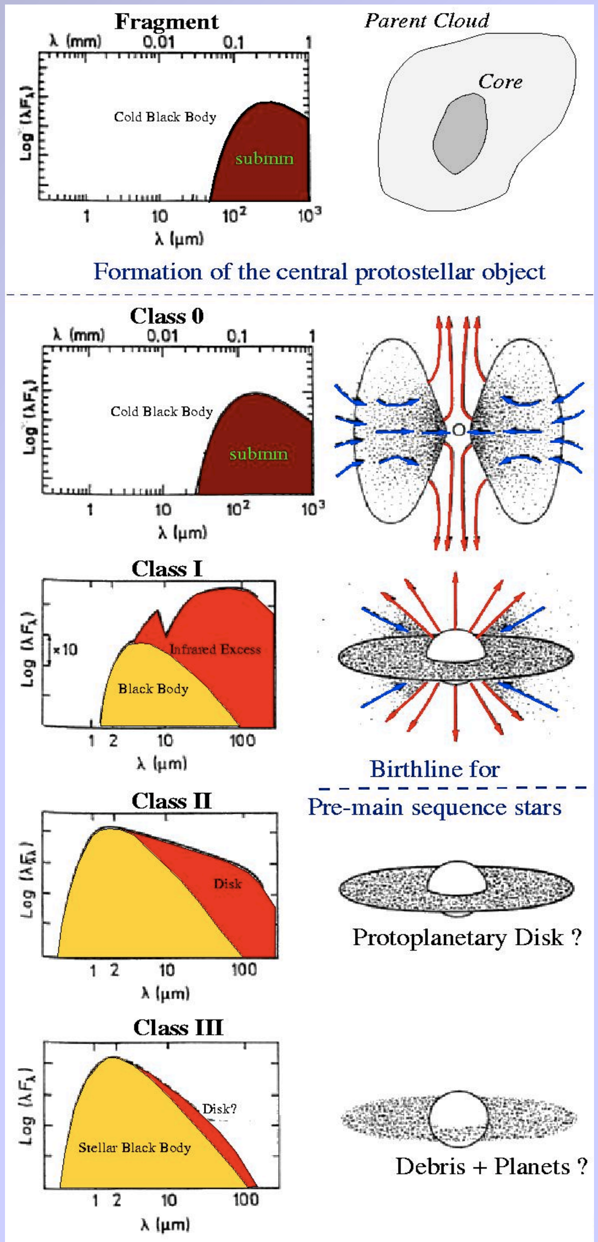
Low-mass star formation scenario

Pre-stellar core

Protostar

Pre Main Sequence Star

Main Sequence Star



Fragmentation into cores

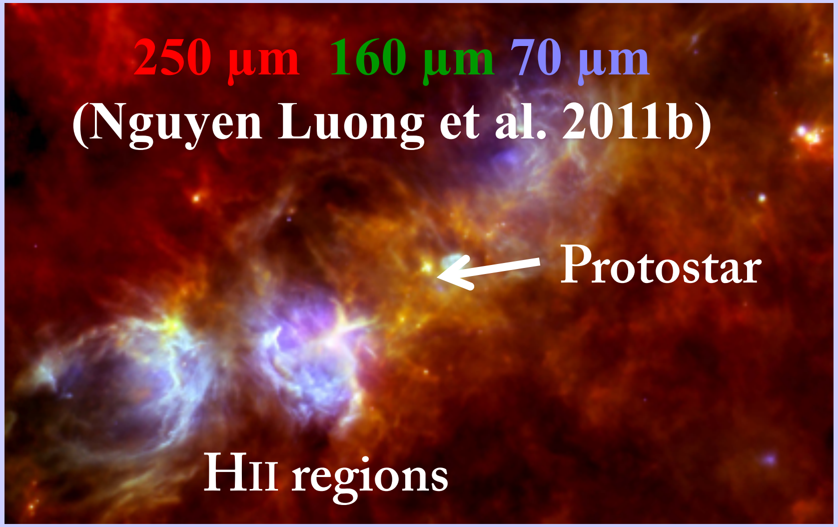
Gravitational collapse:
Protostellar accretion + Outflow

Planet formation

Lada et al. 87; André et al. 1994

The case of high-mass stars

Importances of high-mass stars (M~8-100 $M_\odot$, OB type)



- Dominant role in the galactic energy budget
- Source of turbulence & mixing in the ISM

Difficulties

- Rare event given the mass distribution of stars: 0.05 OB star / yr
- Short lifetimes (a few 10^6 yr)
- Further distance (nearest massive protostar at 400pc, low mass ones at 100pc)
- High dust extinction sites
- Development of HII regions

High-mass star formation scenario

Observed evolutionary phases:

IRDC or massive prestellar cores??? (e.g. Peretto & Fuller 2009)
IR-quiet/young protostars (e.g. Motte et al. 2007, Bontemps et al. 2010)
IR-bright/more evolved protostars: HMPOs (Beuther et al.2002) or RMS objects (Urquhart et al. 2011)…
HII regions (Churchwell 2002)

Proposed theories

A scaled-up version to low-mass stars: Powerful accretion (e.g. McKee & Tan 2003)
More dynamical processes: Competitive accretion (e.g. Bonnell et al. 2001), Coalescence (e.g. Bonnell & Bate 2006), Converging flows (e.g. Heitsch et al. 2008)

High-mass star formation scenario

Observational arguments against coalescence:

Strong outflow (Beuther et al.2002b)
Accelerating accretion (Davies et al.2011)

Observational arguments for dynamical processes:

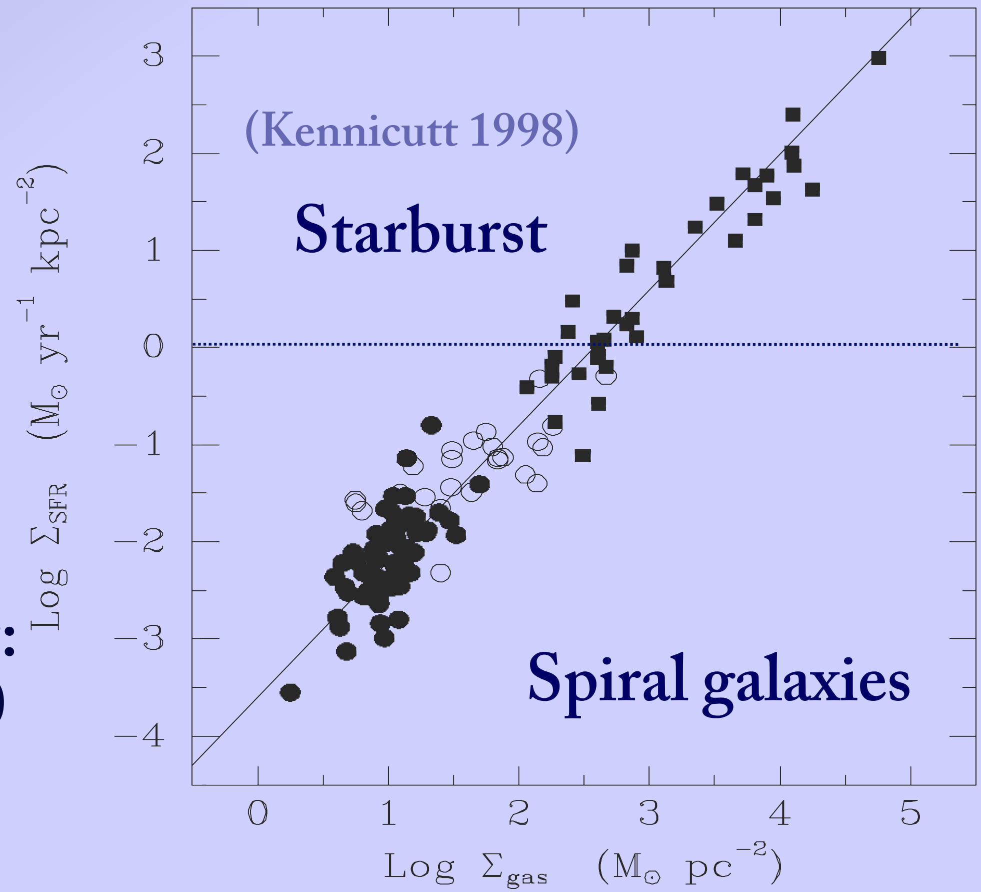
Short prestellar & protostellar lifetimes (Motte et al. 2007, Mottram et al. 2011)
Global infall & colliding flows (e.g. Schneider et al. 2010; Csengeri et al. 2011)

Star formation rate

$$\Sigma_{SFR} = A\Sigma_{gas}^{N}$$

SFR density ($M_{\odot} yr^{-1} kpc^{-2}$)

Gas density ($M_{\odot} pc^{-2}$)



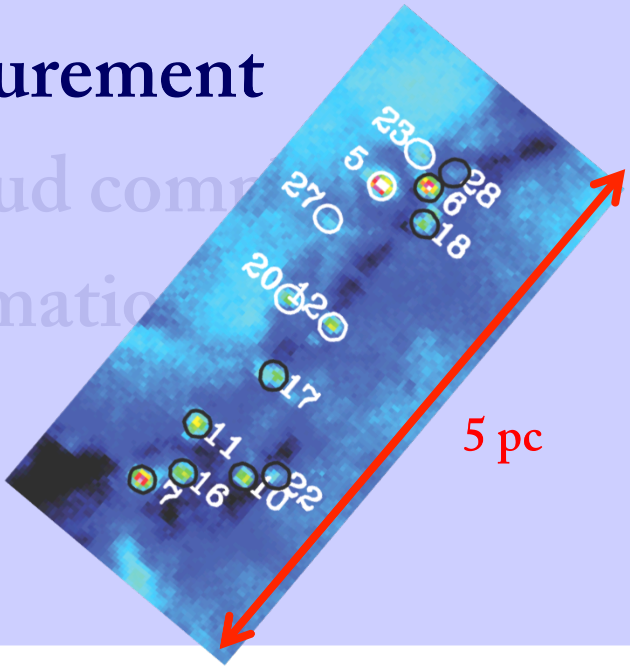
Starburst galaxies: $\log(\Sigma_{SFR}) > 0$
Normal spiral galaxies & Milky Way: $\log(\Sigma_{SFR}) < 0$

Extragalactic SFR measurements:
Indirect (OB star radiation), past star formation (Main sequence)

Galactic SFR measurements:
Direct (counting), present or past star formation (protostars or Pre-main sequence)

Linking the formation of molecular clouds & high-mass stars

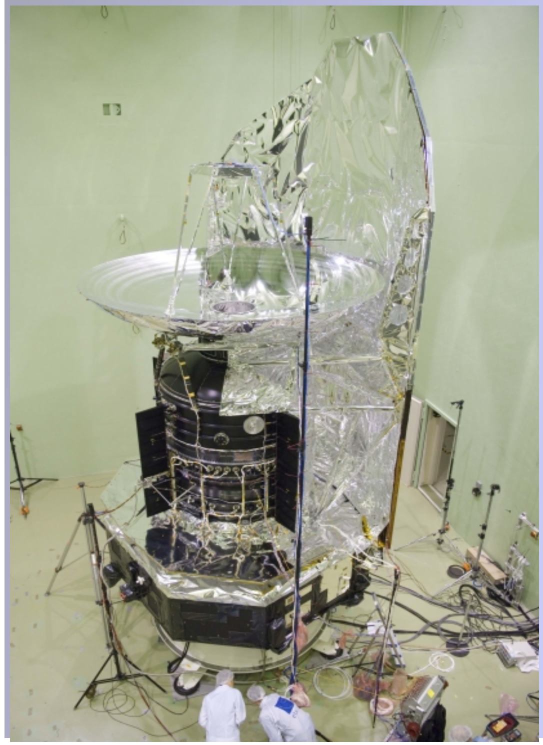
1. Introduction to high-mass star formation
2. Star formation activity in one of the densest IRDCs
   2.1 Herschel observations
   2.2 Massive dense core characterisation
   2.3 Star formation activity measurement
3. W43: An extreme molecular cloud comp
4. Imprints of molecular cloud formatio
5. Conclusions & Perspectives



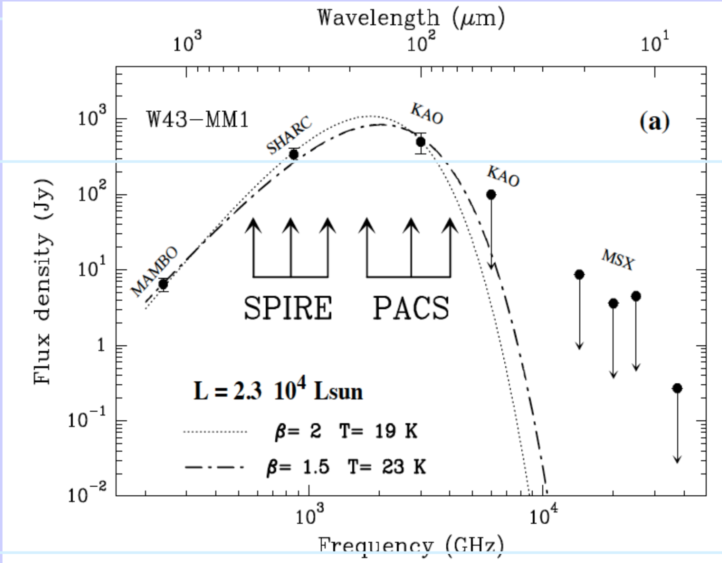
Herschel Space Observatory

Launched: 14 May, 2009
3.5 m telescope
3 instruments
Imaging instruments:
PACS & SPIRE
70 to 500 μm
Resolutions: 5-36”

Allows:
Complete mapping of molecular complex (fast scanning, large cameras)
Simultaneous characterisation of young stellar objects (submm wavelength, sensitivity)

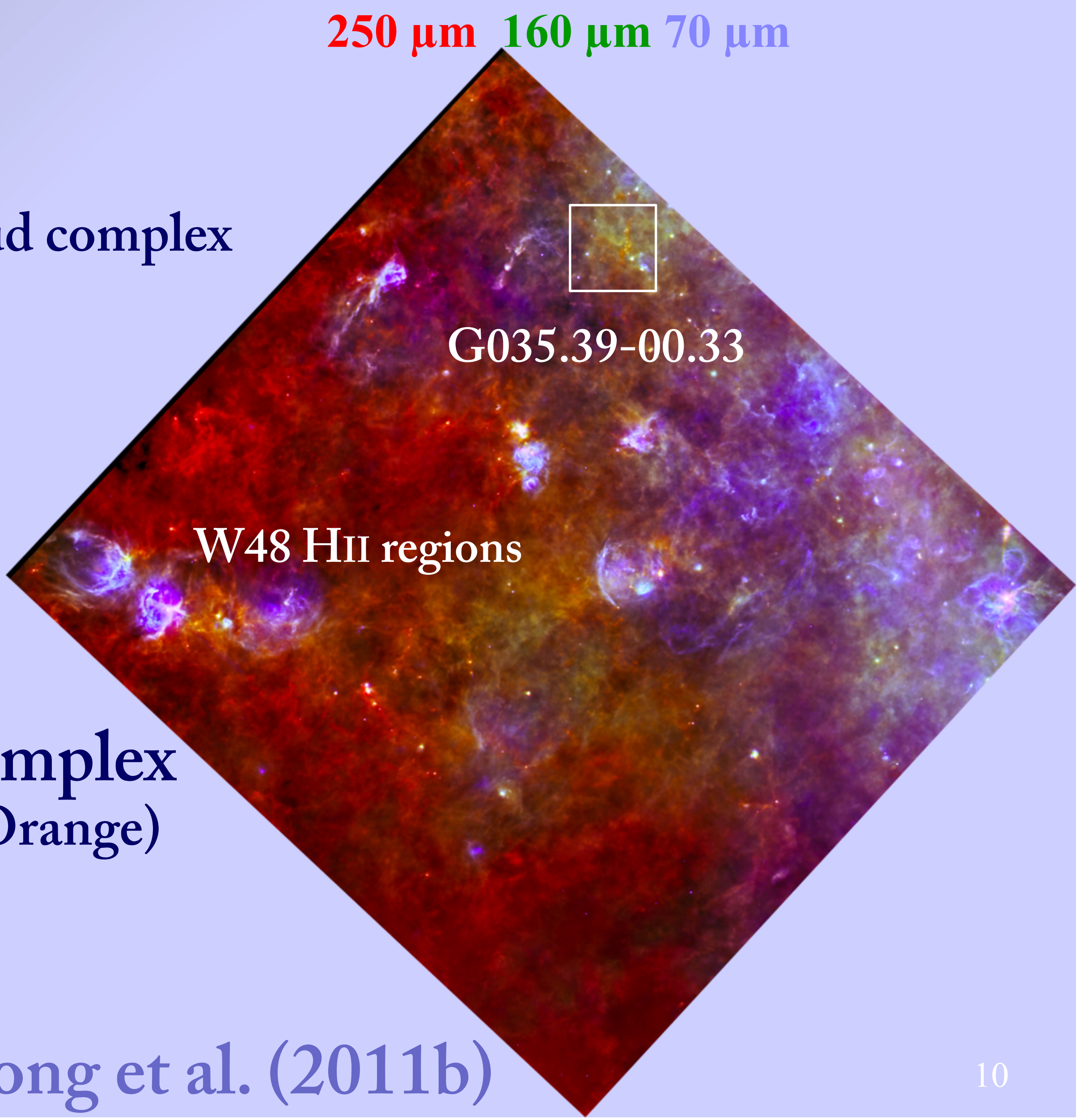


Star formation surveys:
Gould’s Belt survey (PI: P. André)
HOBYS survey (PI: F. Motte)
EPOS survey (PI: O. Kraus)
HiGal survey (PI: S. Molinari)



The Herschel imaging survey of OB Young Stellar Objects
(Motte et al. 2010)

My role:
Reduce SPIRE data
Analyse the W48 molecular cloud complex



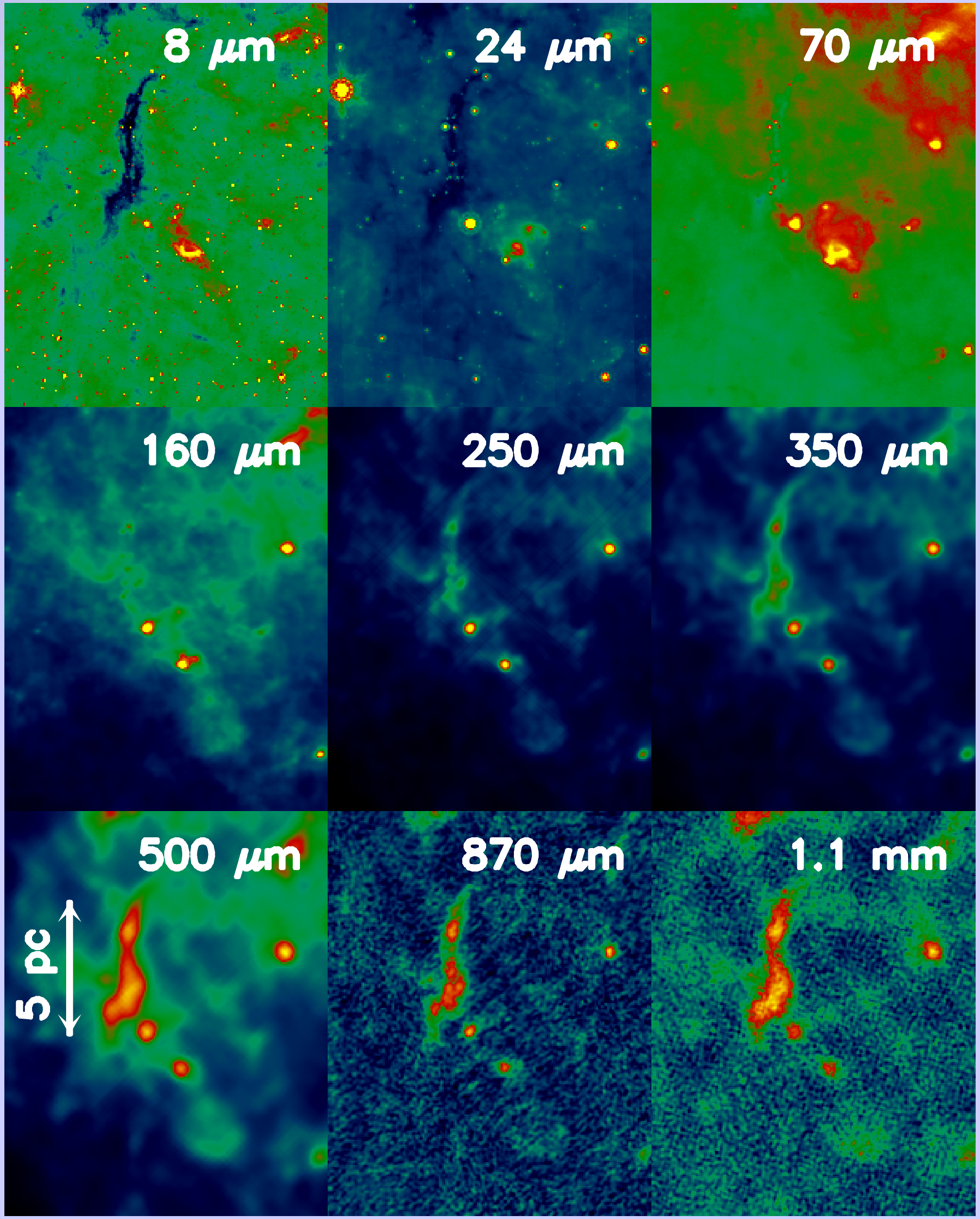
The W48 molecular cloud complex
Cold dust → Star formation site (Orange)
Hot dust → H II regions (Blue)

Nguyen-Luong et al. (2011b)

IRDC G035.39-00.33

Among the top 5% densest IRDCs in the entire Milky Way
(e.g. Peretto & Fuller 2009)

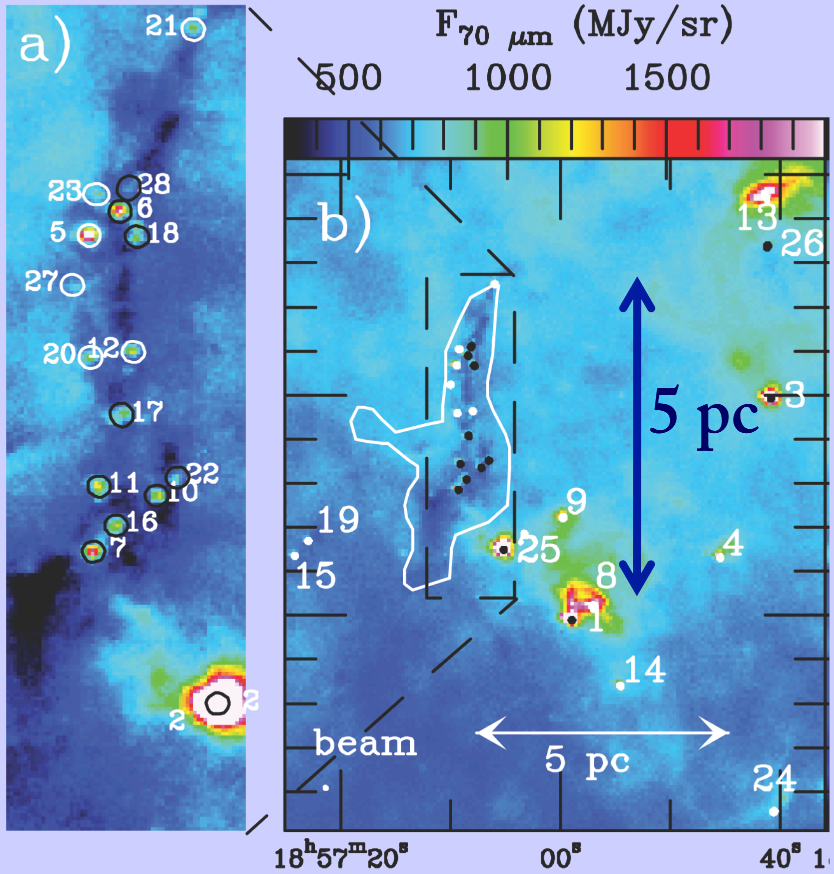
A ~ 8 pc^2
D ~ 3 kpc (Rygl et al. 2010)
AV > 30 mag over 8 pc^2
M ~ 5000 $M_\odot$



Nguyen-Luong et al. (2011b)

Census of massive dense cores

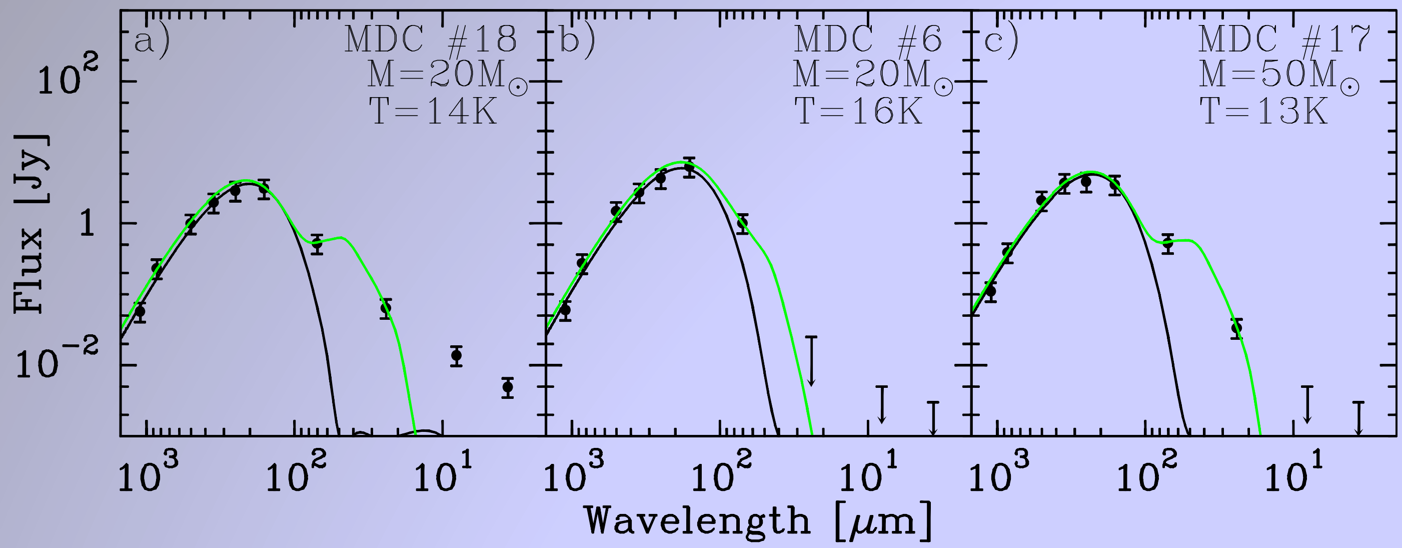
Use Getsources (Men'shchikov et al. 2012)
Detection at 3 wavelengths minimum
Measurement at all 9 wavelengths

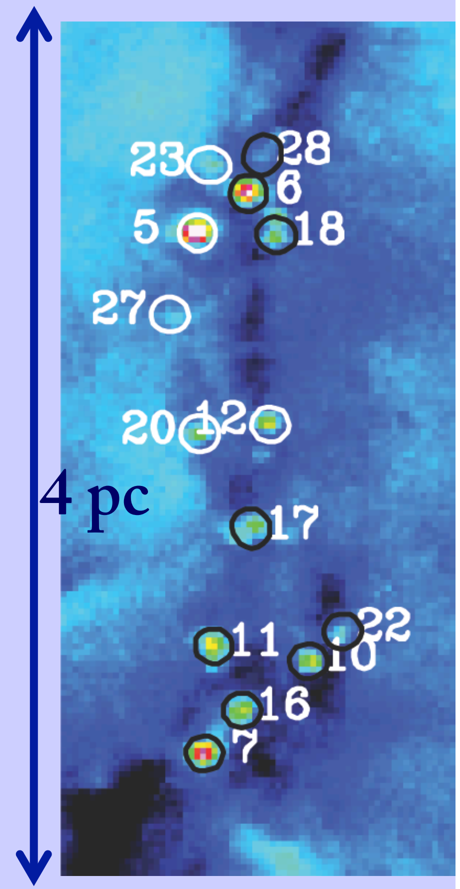


→28 dense cores (size ~0.1pc)
15 inside the IRDCs

Nguyen-Luong et al. (2011b)

Massive dense cores' physical properties





1 grey body fitting to 160 μm-1mm fluxes

13 IR-quiet Massive Dense Cores
Size ~ 0.1 pc, M> 20 $M_\odot$, n_{H2} > $2x10^5$ cm^{-3}
probably harbouring high-mass class 0 stars

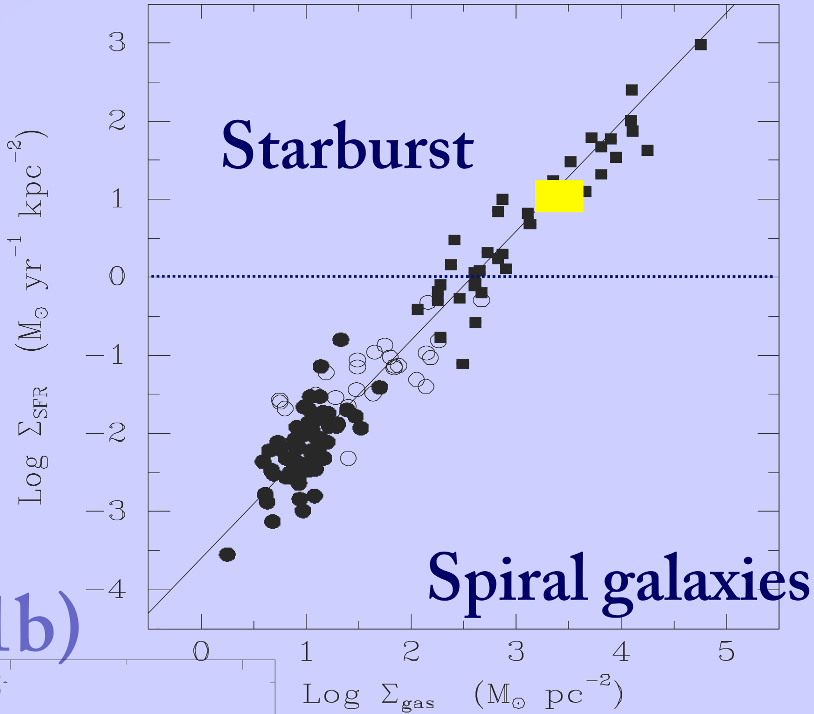
Nguyen-Luong et al. (2011b)

A burst of star formation in IRDC G035.39-00.33

Present SFR measurement from protostars count assuming their main sequence mass & a typical IMF

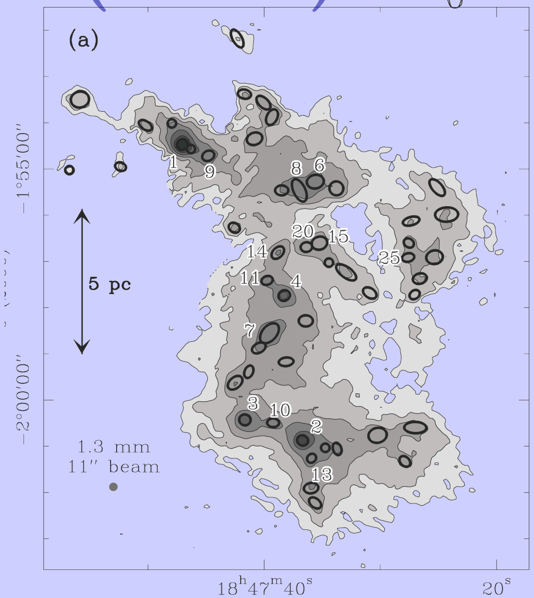
SFR ~ 400 $M_\odot$ Myr^{-1} over 8 pc^2
→SFR density ~ 50 $M_\odot$ $Myr^{-1} pc^{-2}$

A burst of (high-mass) star formation ? → Ministarburst



Nguyen-Luong et al. (2011b)

W43-Main ministarburst:
50 high-mass protostars
SFR ~1500 $M_\odot$ Myr^{-1} over 60 pc^2
SFR density ~ 25 $M_\odot$ $Myr^{-1} pc^{-2}$



(Motte et al. 2003)

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    3.1 Discovery of a new molecular complex
    3.2 Extreme star formation activity
    3.3 Location at the tip of the Bar
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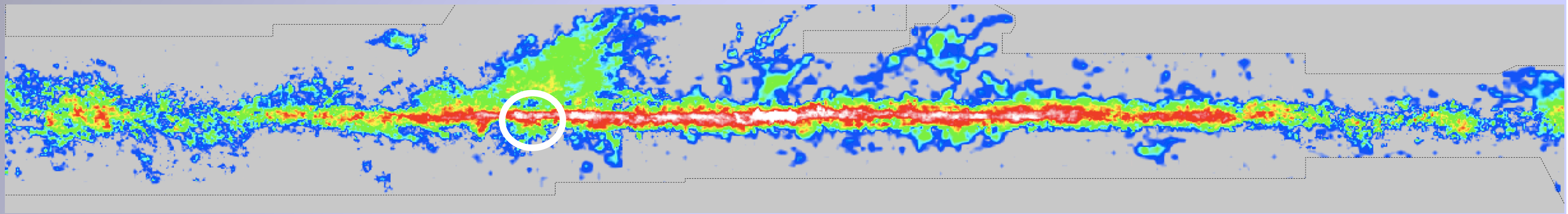
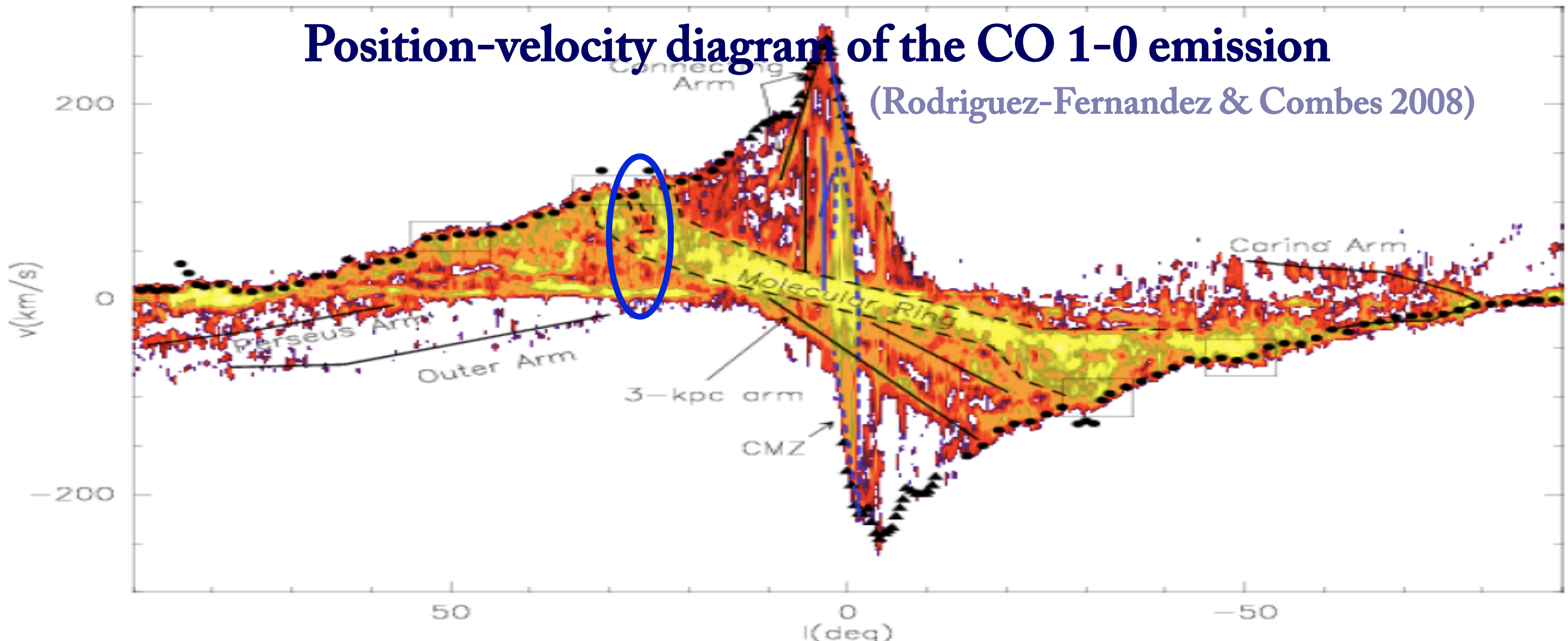
W43 in the Galactic Plane

Gas cloud traced by CO 1-0 emission (CfA, Dame et al. 2001)

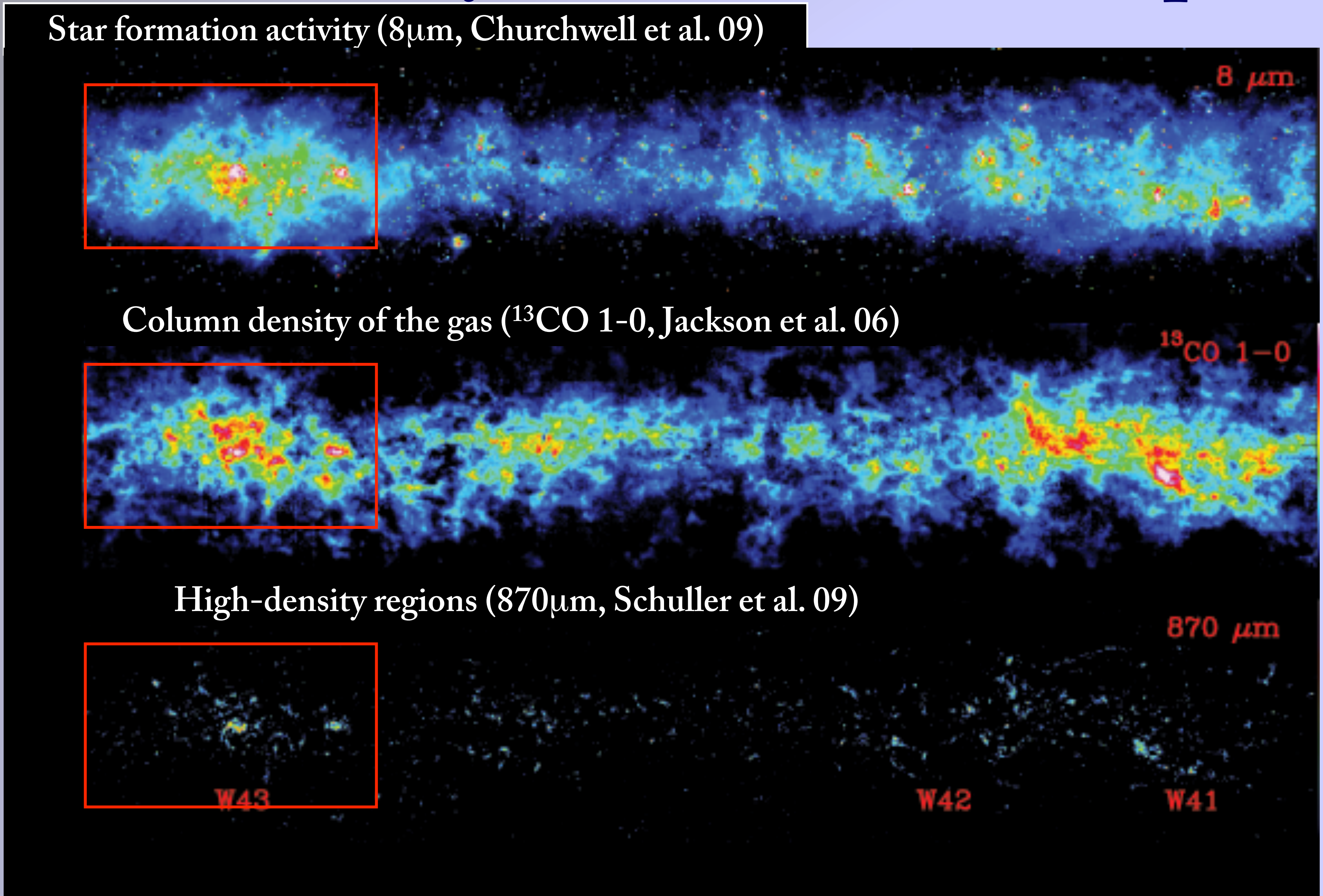


Position-velocity diagram of the CO 1-0 emission

(Rodriguez-Fernandez & Combes 2008)

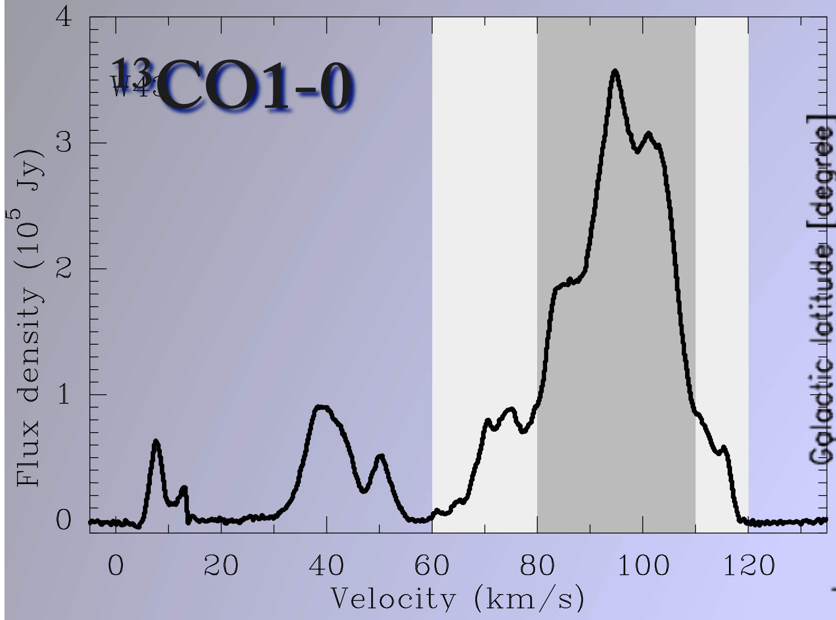


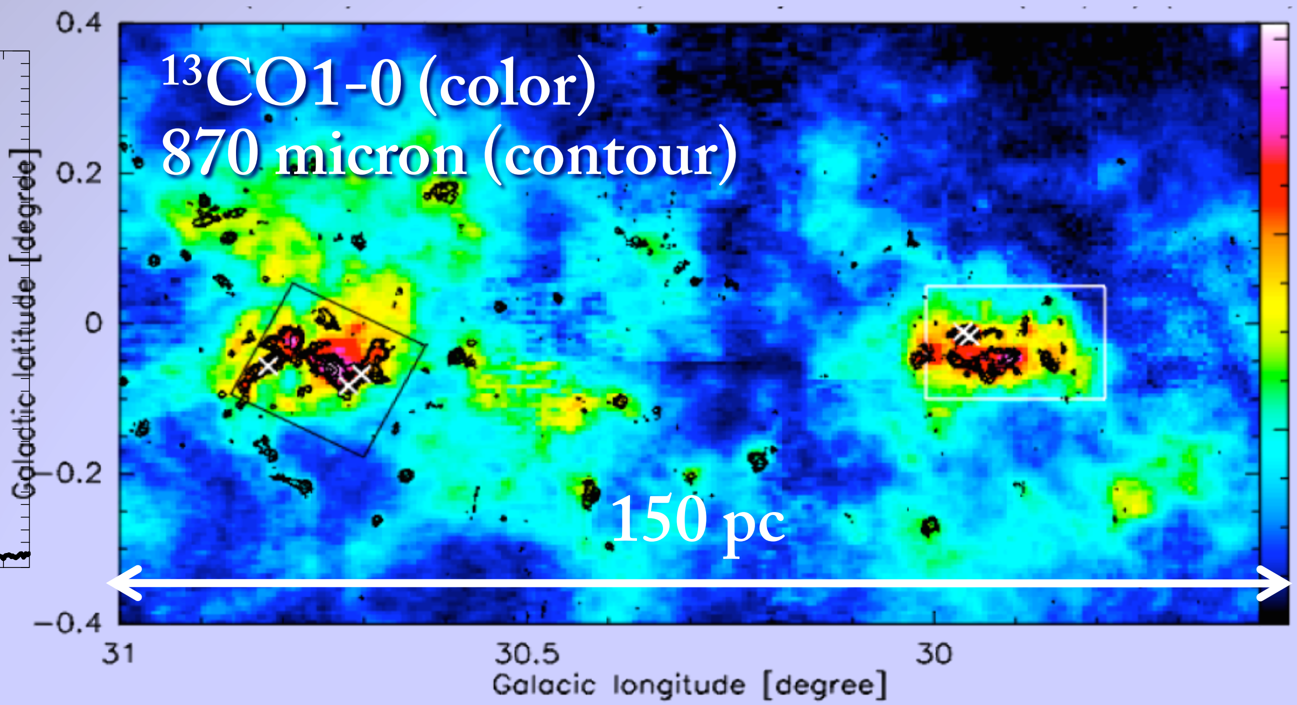
Discovery of the W43 complex



Nguyen-Luong et al. (2011a)

The W43 region



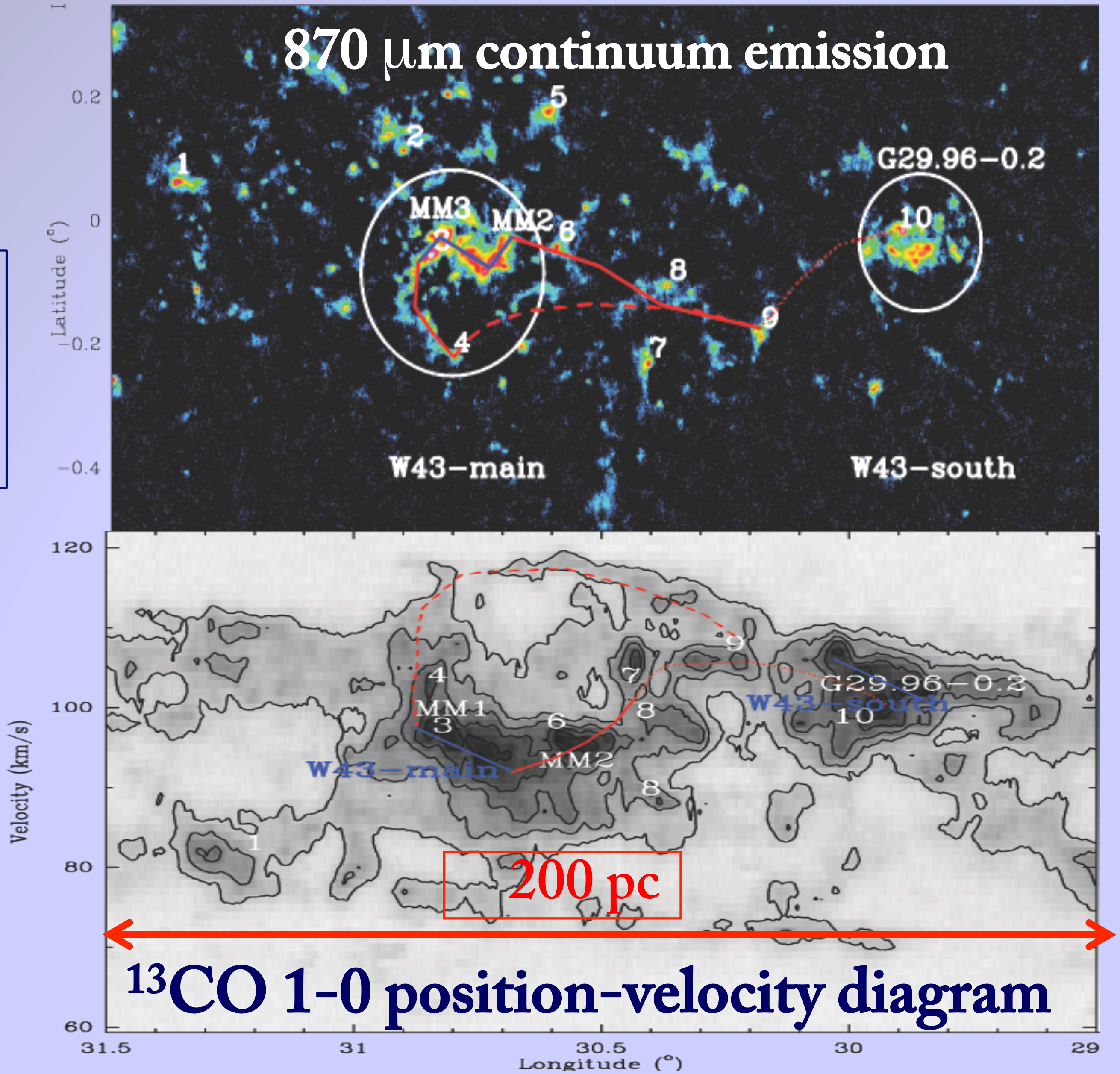


Main velocity range: 80-110 km/s → unusually large for molecular complex (5-10 km/s)

Nguyen-Luong et al. (2011a)

W43: A coherent molecular cloud structure

Velocity connections between W43-Main & South seen in ^{13}CO 1-0 & ^{12}CO 2-1 cubes



Nguyen-Luong et al. (2011a)

Cloud mass & concentration in W43

- Total mass of the molecular gas:

- From ^{12}CO 1-0 data (CfA, Dame et al. 2001):

$$M_{total} = 7.1 \times 10^6 \, M_\odot$$

- From ^{13}CO 1-0 data (GRS, Jackson et al. 2006):

$$M_{clouds} = 4.2 \times 10^6 \, M_\odot$$

- Mass of cold, dense clumps (<5 pc cloud structures):

From 870 μm image (ATLASGAL, Schuller et al. 2009):

$$\Rightarrow M_{clouds} = 8.5 \times 10^5 \, M_\odot$$

among the most massive and most concentrated

Nguyen-Luong et al. (2011a)

Global star formation activity

« past » Star Formation Rate

from the 8 μm luminosity (GLIMPSE, Churchwell et al. 2009)

similar to extragalactic method (Wu et al. 2005, Kennicutt et al. 2009)

⇒ SFR ~ 0.0 $M_{\odot} yr^{-1}$ & SFR density ~ 0.64 $M_{\odot} yr^{-1} kpc^{-2}$

« future » Star Formation Rate

from the total molecular mass of the W43 cloud and assuming typical star formation efficiency (2%) cloud lifetimes (1-3 x 10^6 yr)

⇒ SFR ~ 0.1 $M_{\odot} yr^{-1}$ & SFR density ~ 6.4 $M_{\odot} yr^{-1} kpc^{-2}$

W43 is in the ministarburst regime

(Nguyen-Luong et al. 2011a)

W43 distance & location in the Milky Way

Kinematic distance of W43:

$\langle V_{LSR} \rangle$ = 95.9 km/s @ l = 30.5°

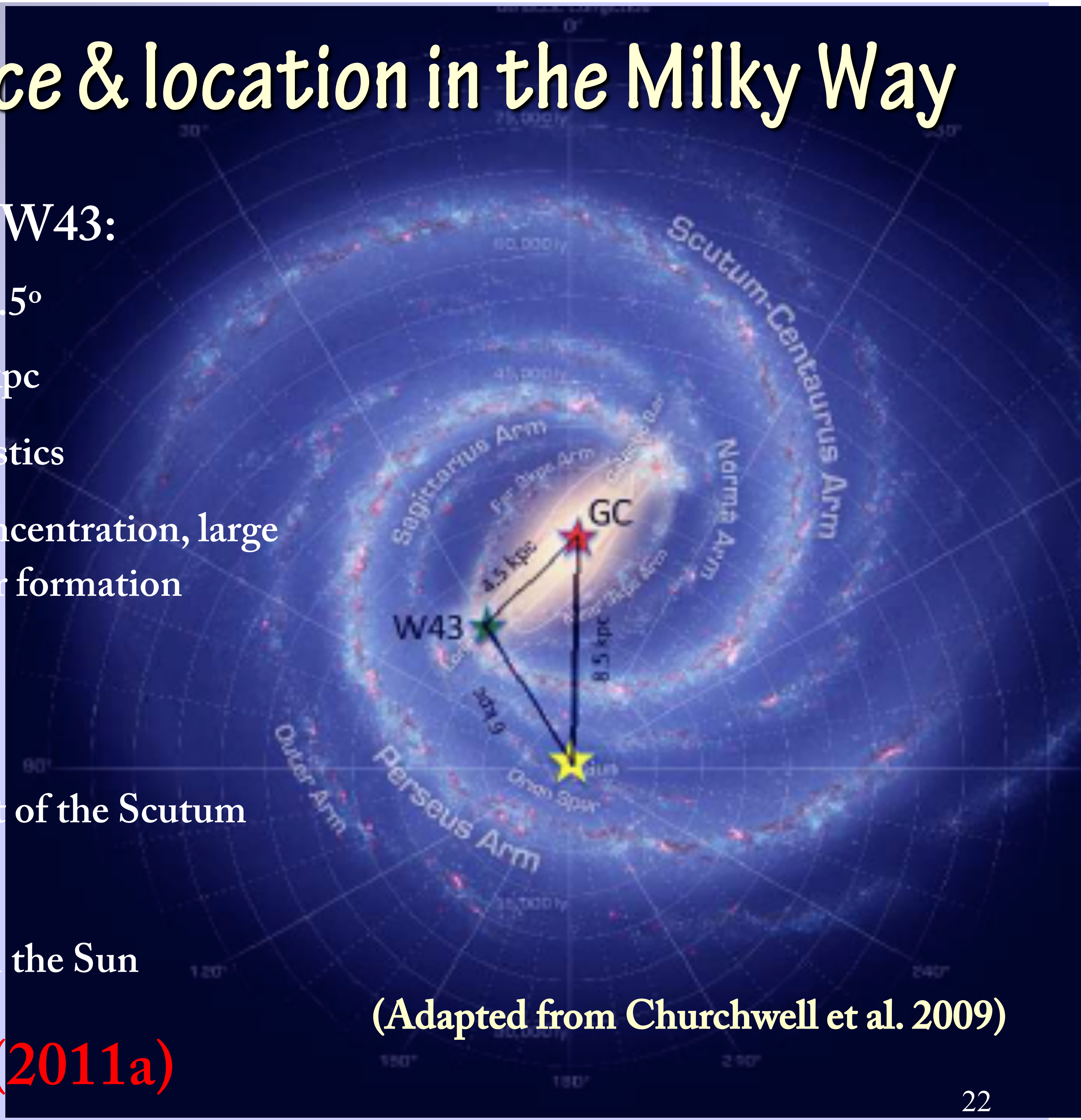
$\Rightarrow d_{near}$ = 5.9kpc, d_{far} = 8.7 kpc

Given its peculiar characteristics

(large mass, exceptionnal concentration, large velocity dispersion, high star formation efficiency),

→W43: at the meeting point of the Scutum -Centaurus arm & Bar

→ tip of the Bar ~6 kpc from the Sun



(Adapted from Churchwell et al. 2009)

Nguyen-Luong et al. (2011a)

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   4.1 Models of molecular cloud formation
   4.2 First signature of converging flows
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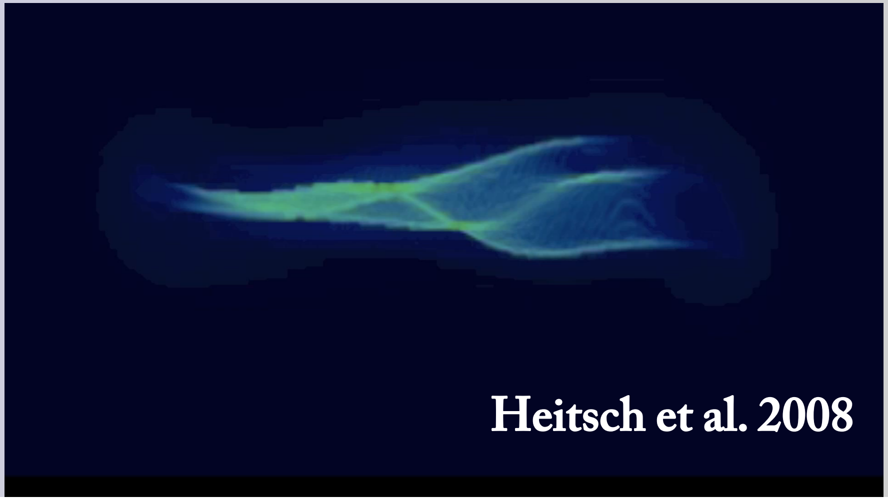
Models of molecular cloud formation from Converging flows

From large-scale converging flows of atomic gas
Dense structures form in the atomic phase & quickly cool down
(e.g. Heitsch et al. 2008, Audit & Hennebelle 2010)

At stagnation point, high-density HI seeds become neutral & form massive dense core in a rapid fashion
(e.g. Tsuribe & Inutsuka 2001, Heitsch et al. 2008b, Banerjee et al. 2009)

These models are more consistent with:
MC lifetime (10^6 yr, Roman-Duval et al. 2009)
The measured SFR (5 $M_{\odot}$/yr, Evans 1999, GLIMPSE)

than the previous static-box models



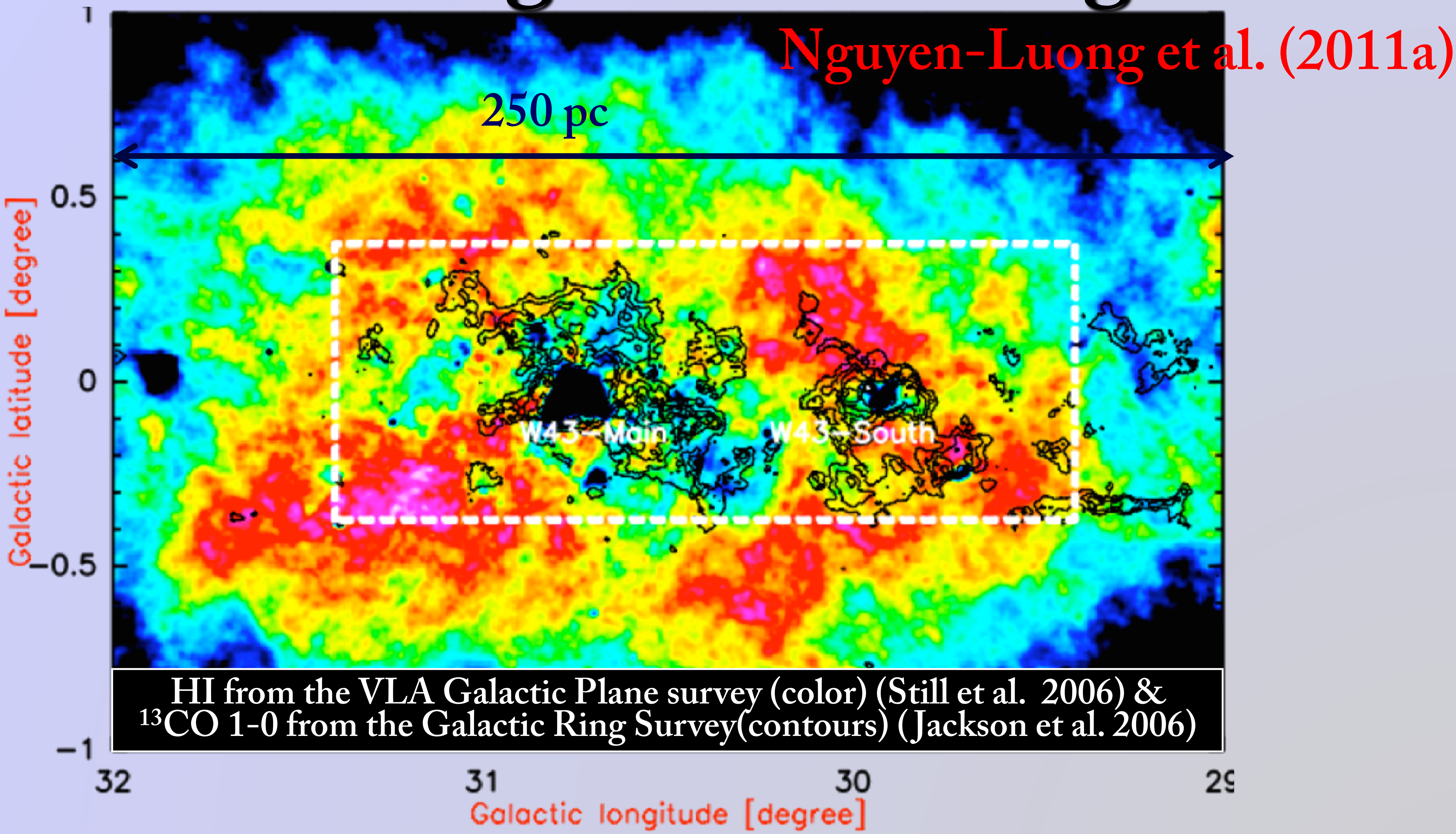
Searching for signatures of Converging flows

1. Diffuse atomic envelope around the molecular gas
2. Coherent velocity structures between atomic and molecular gas

3. Global collapse signature
4. Rapid star formation and short lifetime
5. Extended shock around the dense structures

…

Atomic gas surrounding W43



HI self-absorption on the heart of the molecular complex and on individual filaments

Correlated velocity pattern of HI & CO

Origin of molecular cloud & star formation in W43

An IRAM 30m large program

- PI: F. Motte, P. Schilke
- Time: 152 hr
- Receiver: HERA/EMIR

- Full CO mapping of the entire cloud:

P. Carlhoff, P. Schilke e al. in prep.

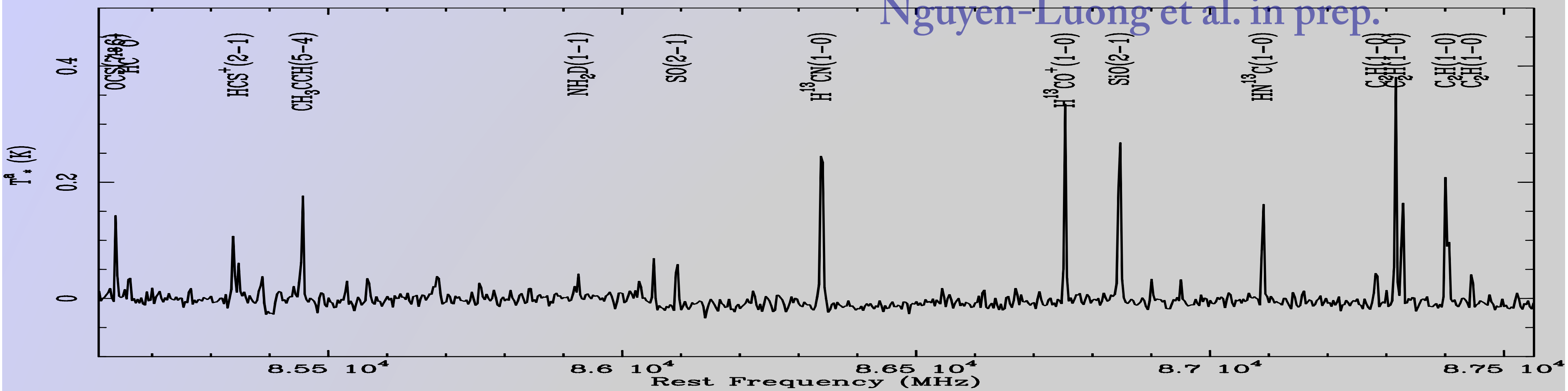
- Line survey of the high density part:

My role: planning, observations, data reduction

Q. Nguyen Luong, F. Motte in prep.

A line mapping survey toward W43-Main

Nguyen-Luong et al. in prep.



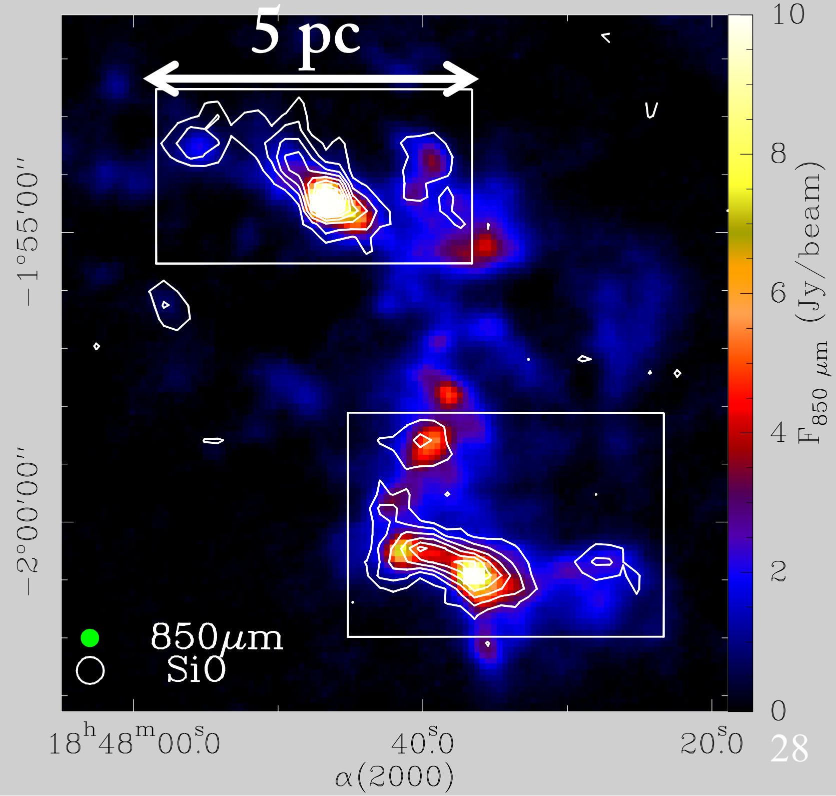
Receiver: new EMIR

Backend: new FTS

→Large bandwidth (8 GHz)

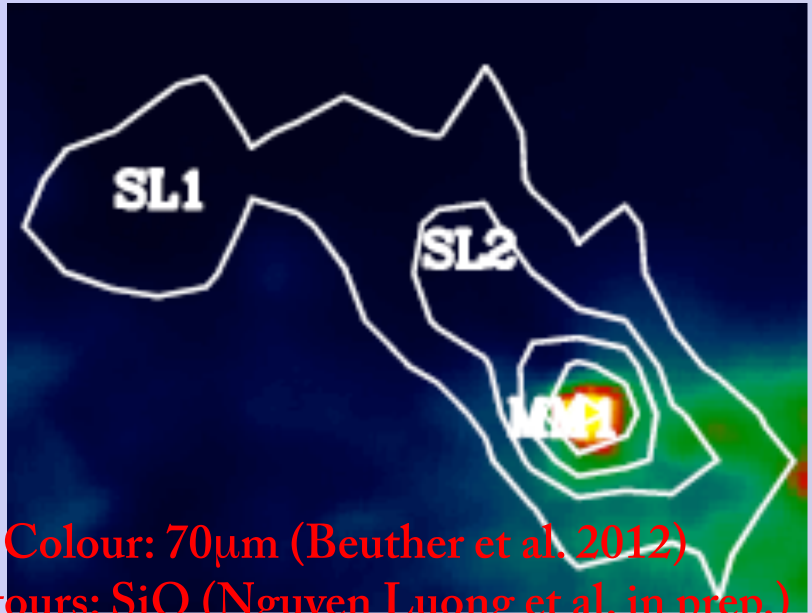
→lines of > 26 molecules in W43

1st unexpected result: Extended SiO emission

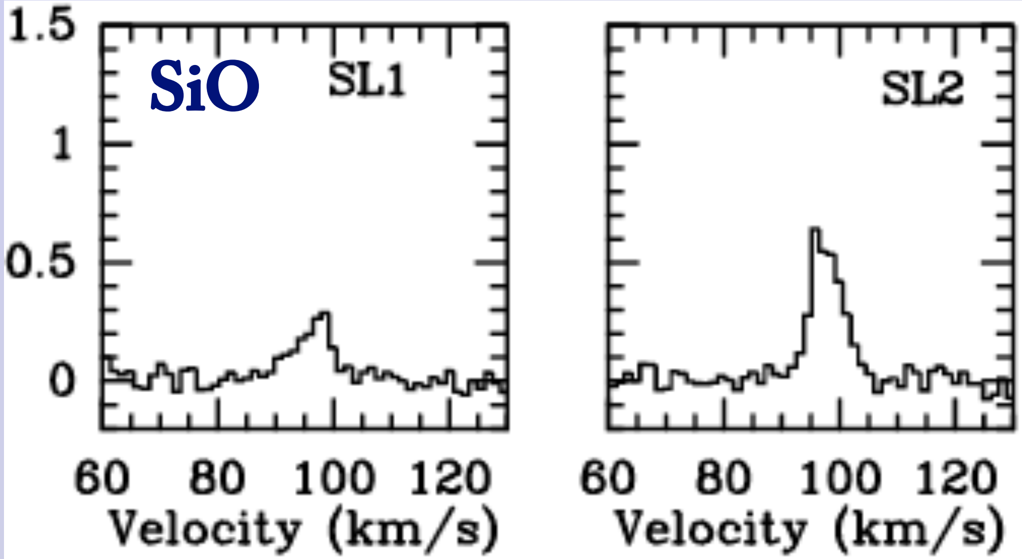


Low-velocity shock?

5 pc

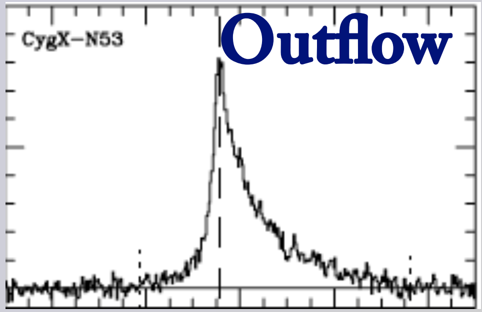


Colour: 70μm (Beuther et al. 2012)
Contours: SiO (Nguyen Luong et al. in prep.)



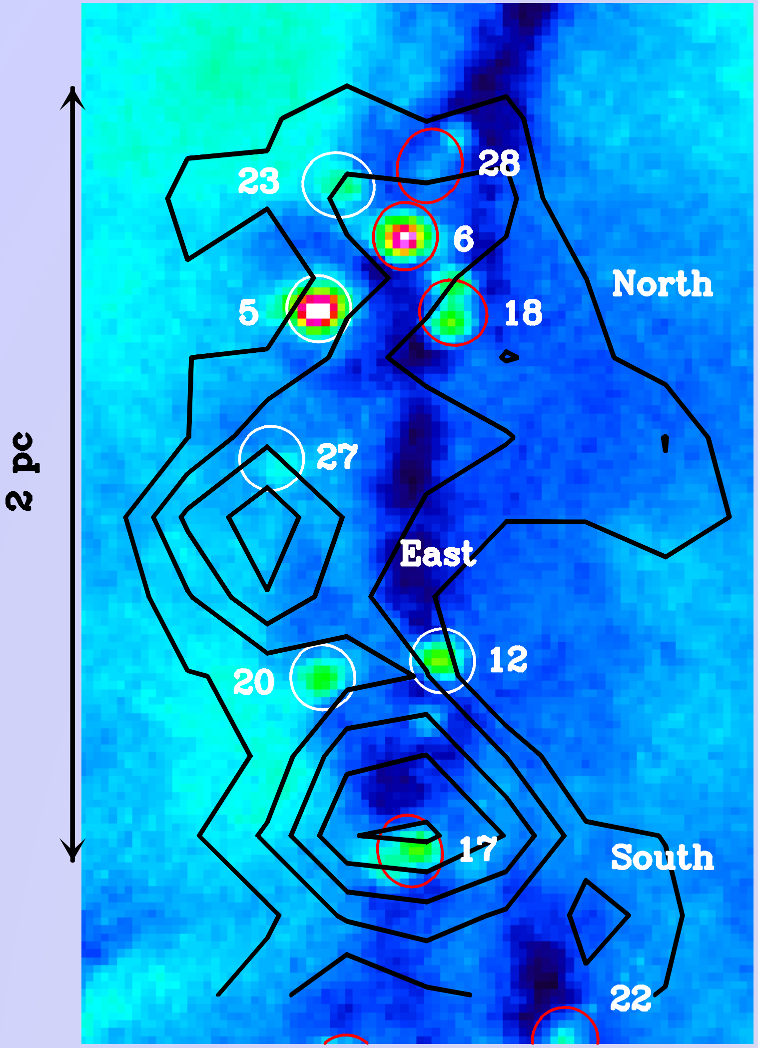
SiO extended over ~ 5 pc
Clearly detected at position far from protostars
Spectra lines at rest, no clear wings

→ Low velocity shock → Converging flow signatures?



Extended SiO emission: not only in W43-Main

a)



Colour: 70μm (Nguyen-Luong, et al. 2011)
Contours: SiO (Jimenez-Serra et al. 2010)

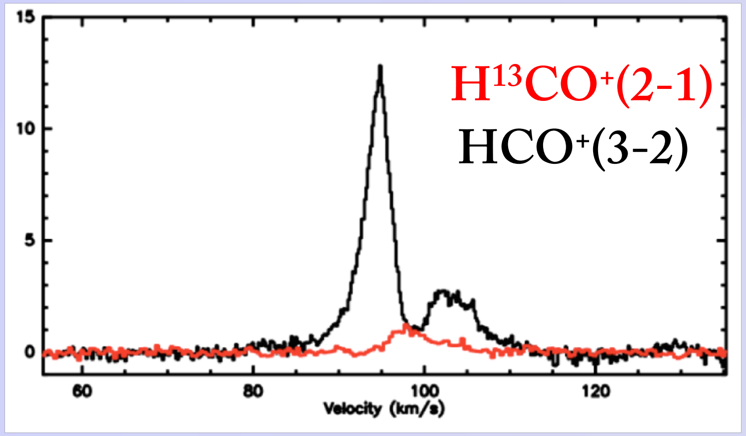
G035.39-00.33:
1 SiO peak is not associated with any protostar

→low-velocity shocks associated with cloud formation

Low-velocity SiO shocks may be the first univocal signature of converging flows

Supersonic global infall
Another signature of converging flows

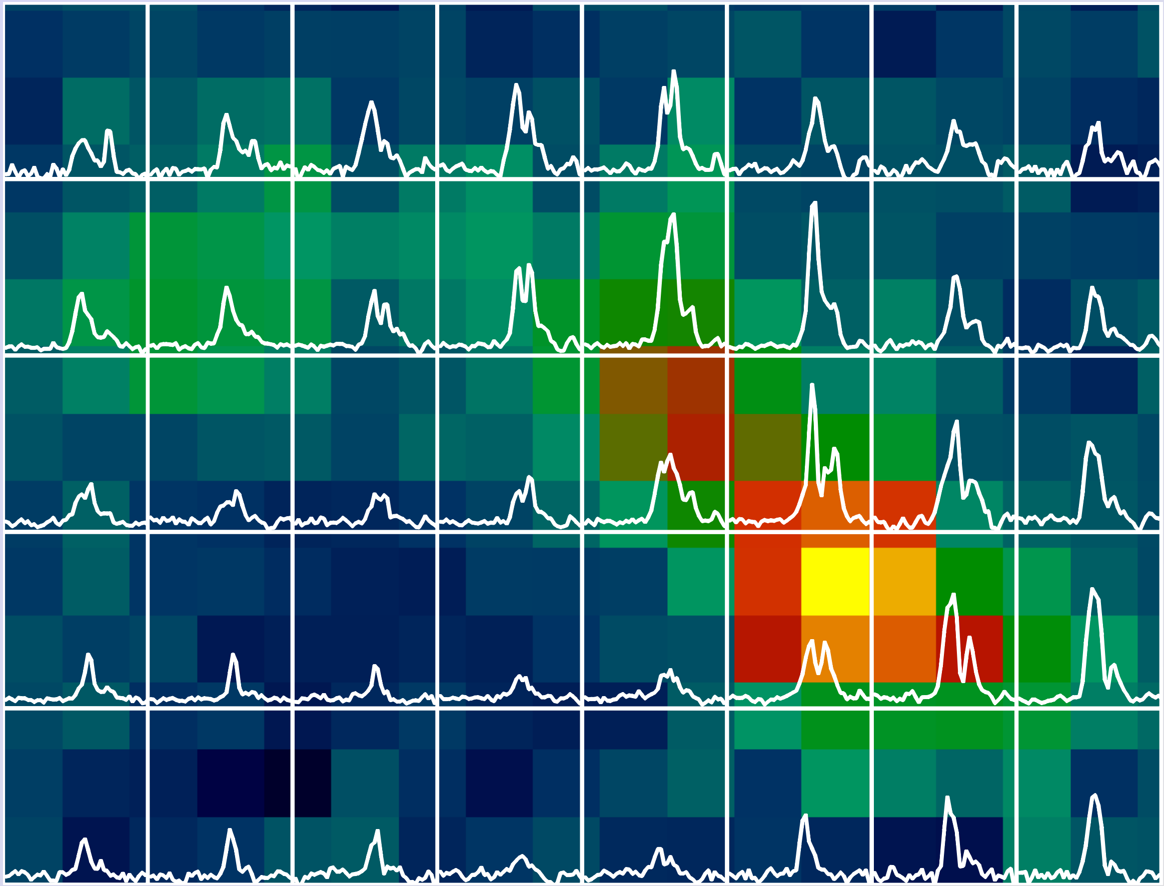
Classical collapse signature:
Red-shifted self-absorbed profile



In W43-MM1: v_{infall} ~ 1 km/s over 5 pc using Myers et al. 96 method

Similar infall velocities on all high-density parts of W43-Main

HCO+ 1-0 (white spectra) on SiO map



Already observed in other regions (e.g. Schneider et al. 10)

Conclusion

- W43 & G035.39-00.33 are typical examples of ministarburst at two different scales. (Nguyen Luong et al. 2011a; Nguyen Luong et al. 2011b)
- W43 & G035.39-00.33 are extreme in terms of mass, concentration (Nguyen Luong et al. 2011a; Nguyen Luong et al. 2011b)
- W43 is an extreme molecular cloud complex, located at a very dynamic place of the Milky Way (Nguyen Luong et al. 2011a)
- W43 displays several signatures of converging flows: tight position and velocity link of HI and CO gases, low-velocity shock on the densest part of the cloud, global collapse (Nguyen Luong et al. in prep.)
- Converging flows maybe neccesary for forming ministarbursts

Perspectives

• Investigate the link between the formation of molecular clouds and stars using the rich database of W43 and specific numerical models

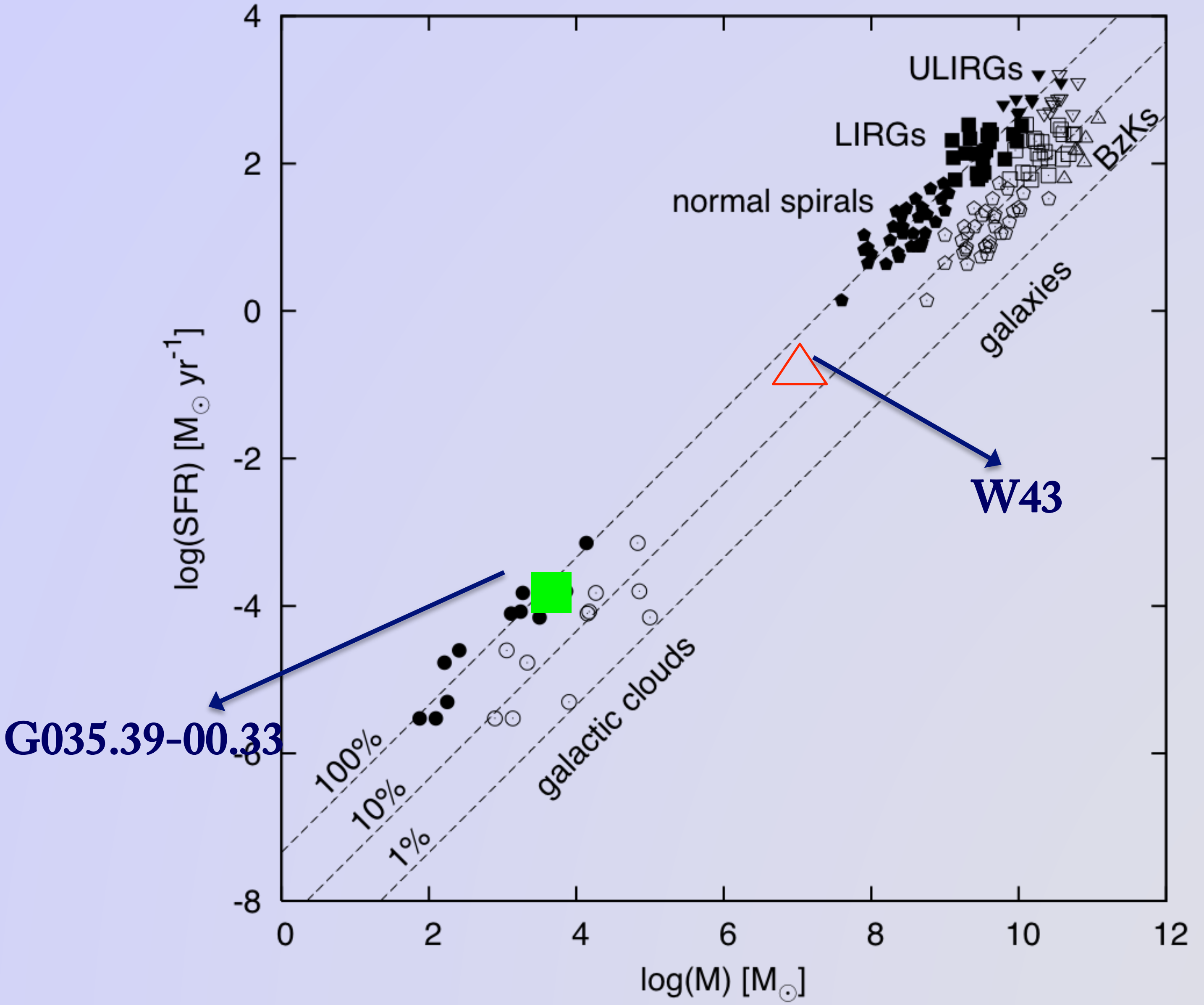
IRAM Large Program goal + interferometric follow-ups with e.g. ALMA

collaborations with numericians

• Make a large census of molecular cloud complexes in the Galaxy & measure their SFRs

Precisely count protostars to derive the present SFR in W43 (similar to G035.39-00.3)

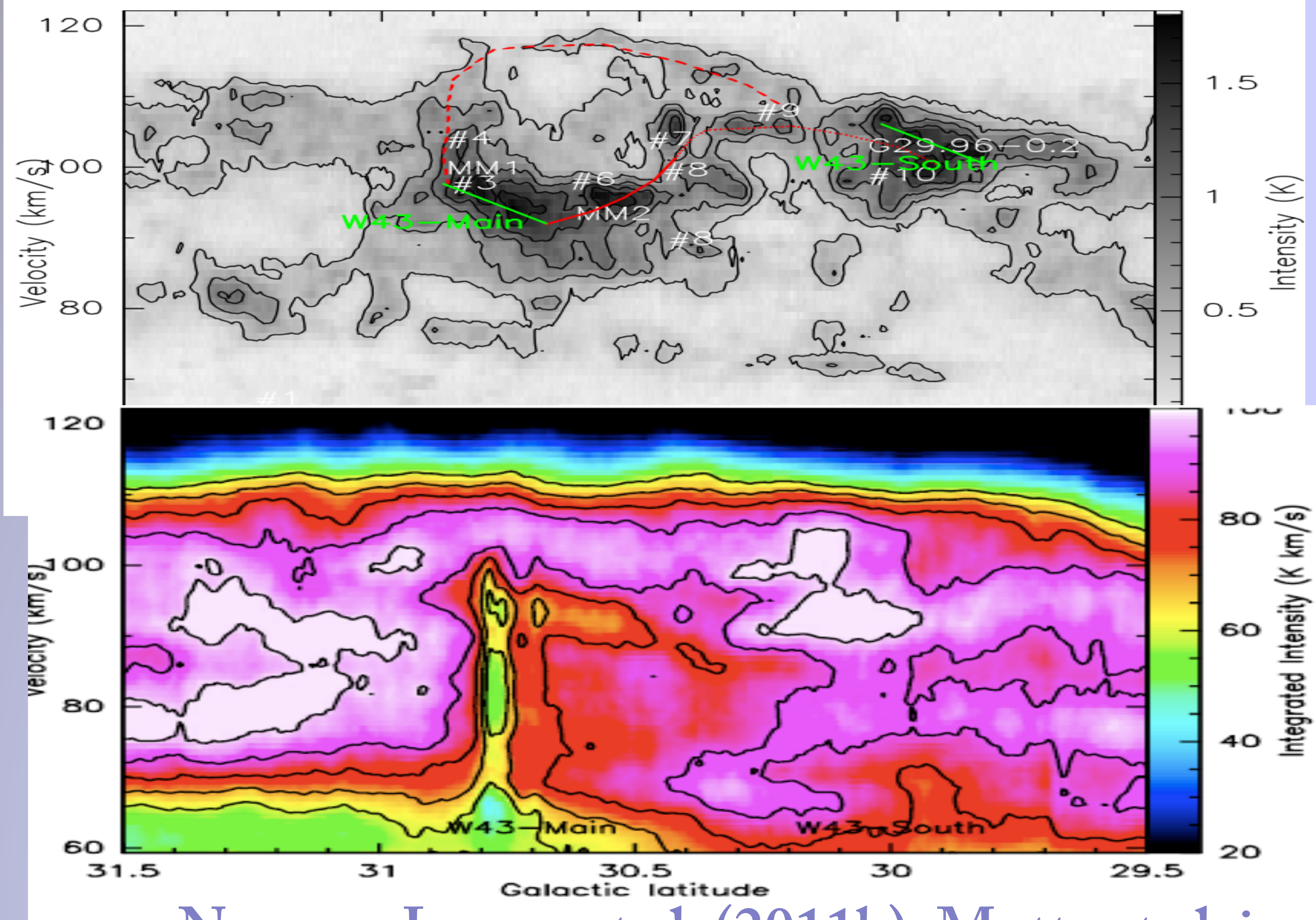
Gas density & Star formation



Adapted from Lada et al. (2012)

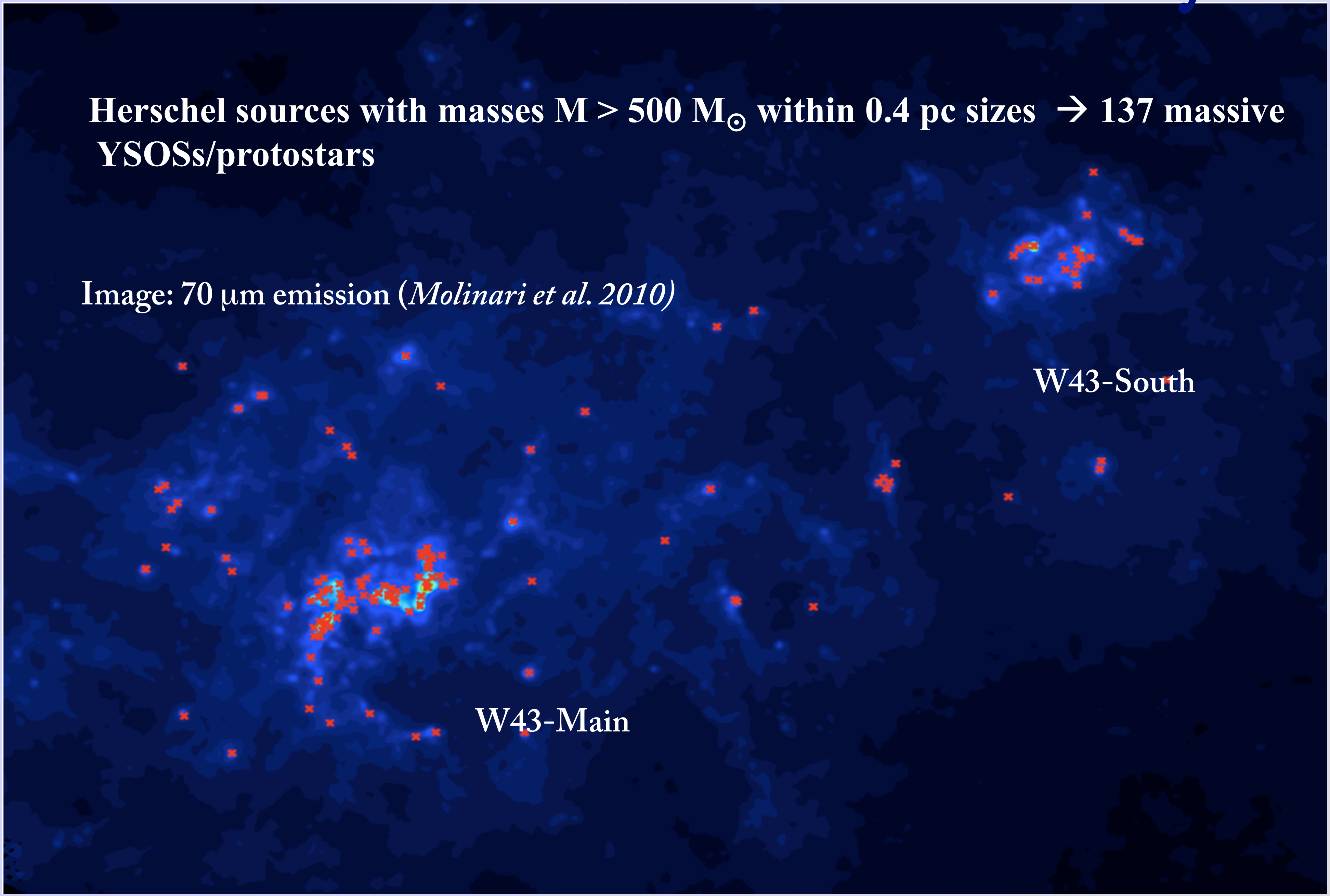
Thank you

Correlated velocity pattern of HI & ^{13}CO

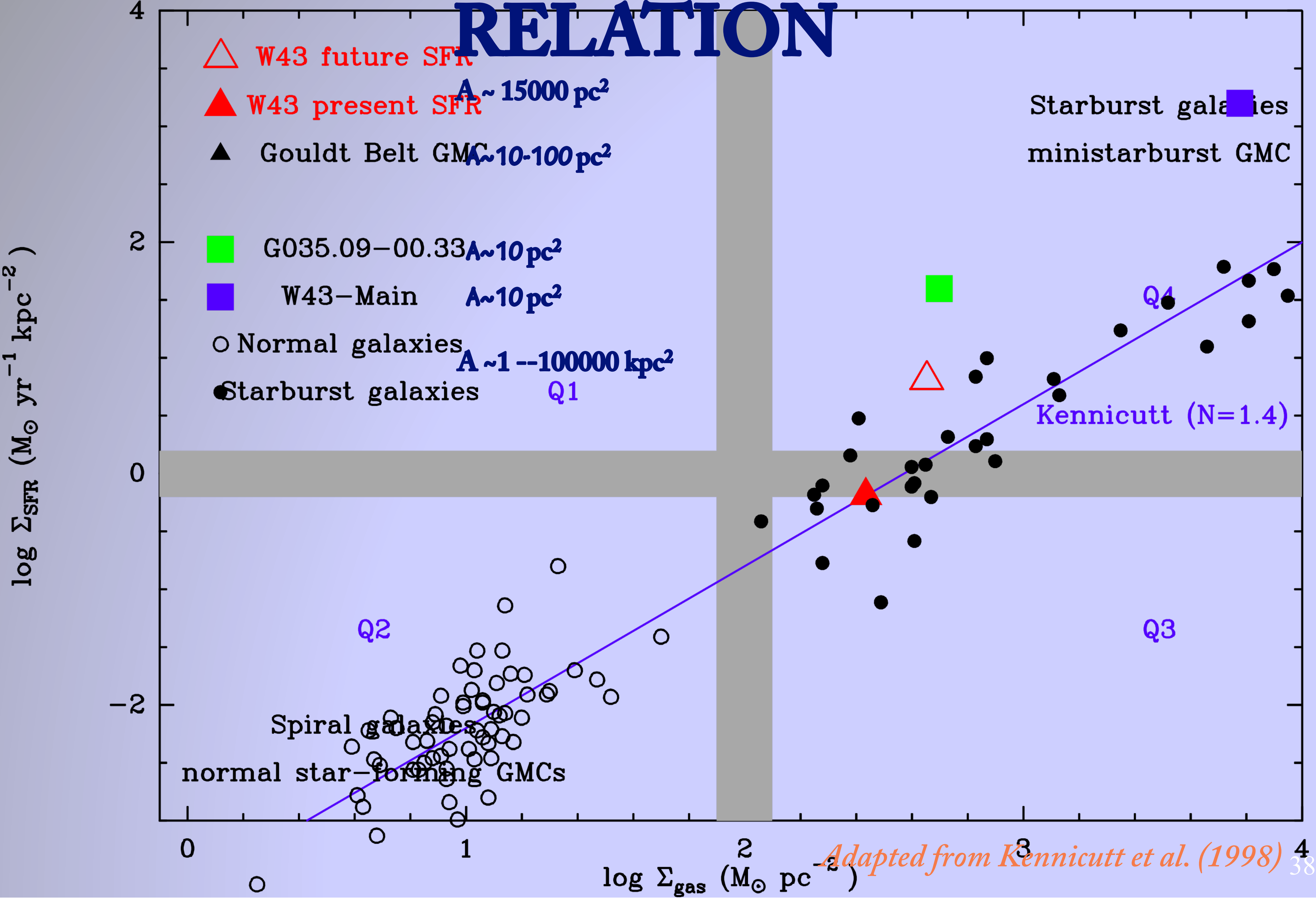


Nguyen-Luong et al. (2011b), Motte et al. in prep.

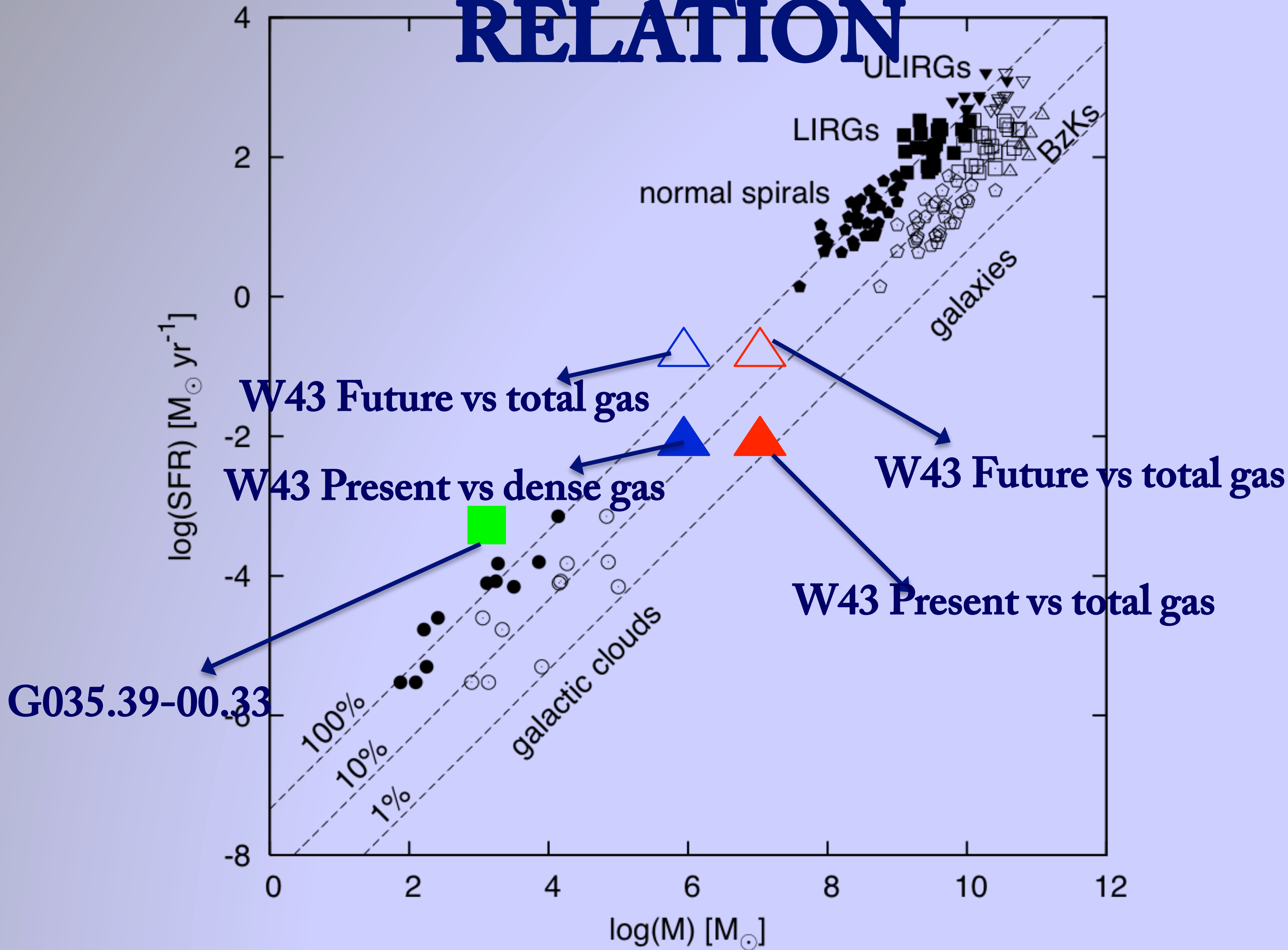
Direct measurement of current SF activity: W43



GAS DENSITY to SFR DENSITY RELATION

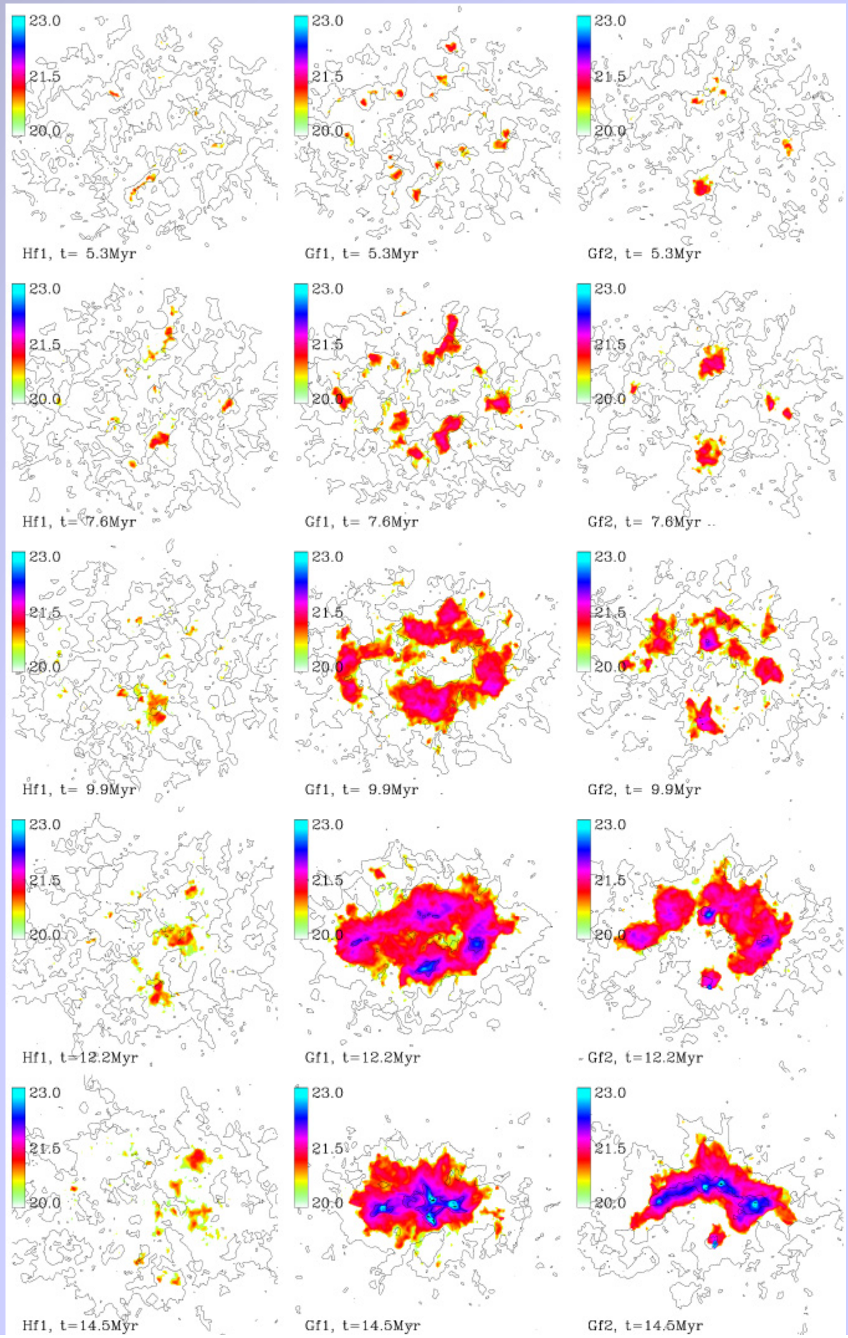


GAS DENSITY to SFR DENSITY RELATION



Adapted from Lada et al. (2012)

Converging flows model



Heitsch et al. 2008

Thermal equilibrium state