A Global View of Star Formation in the Milky Way

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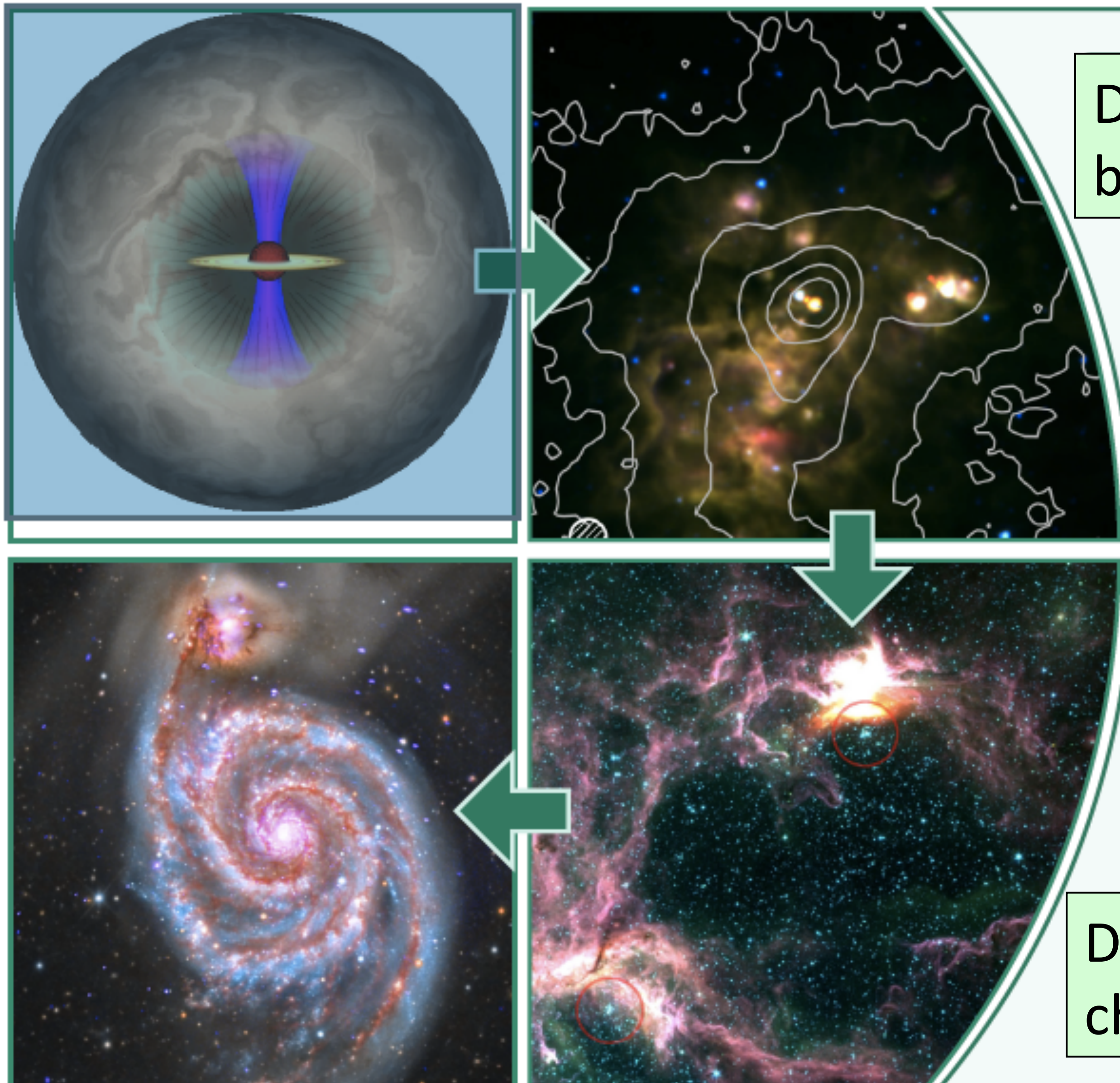
October 10, 2017

High mass stars: engines of galaxies



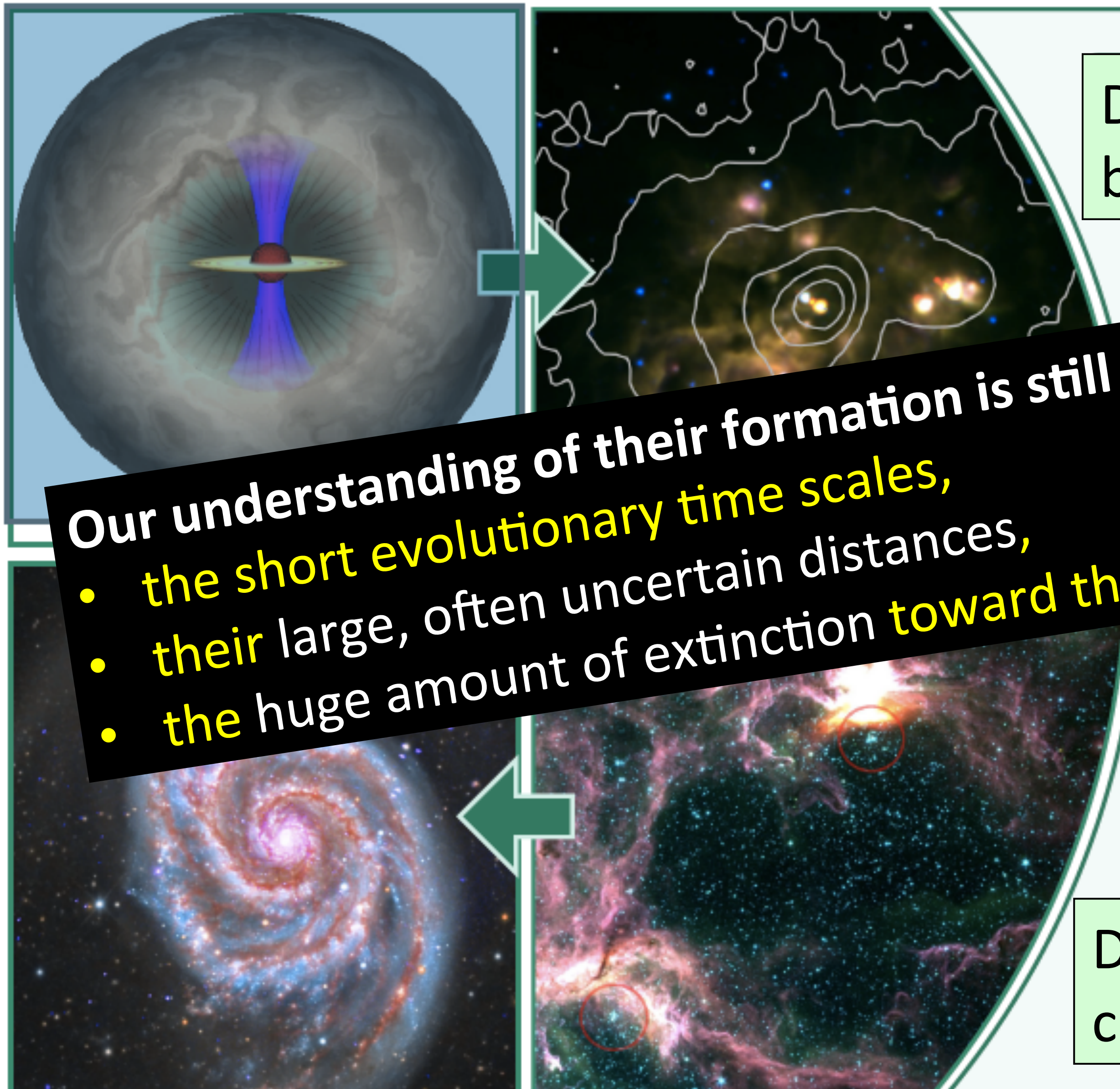
Dominate energy budget

Shape their environment: UV, winds, SN explosions

Produce heavy elements

Drive physics and chemistry

High mass stars: engines of galaxies



Dominate energy budget

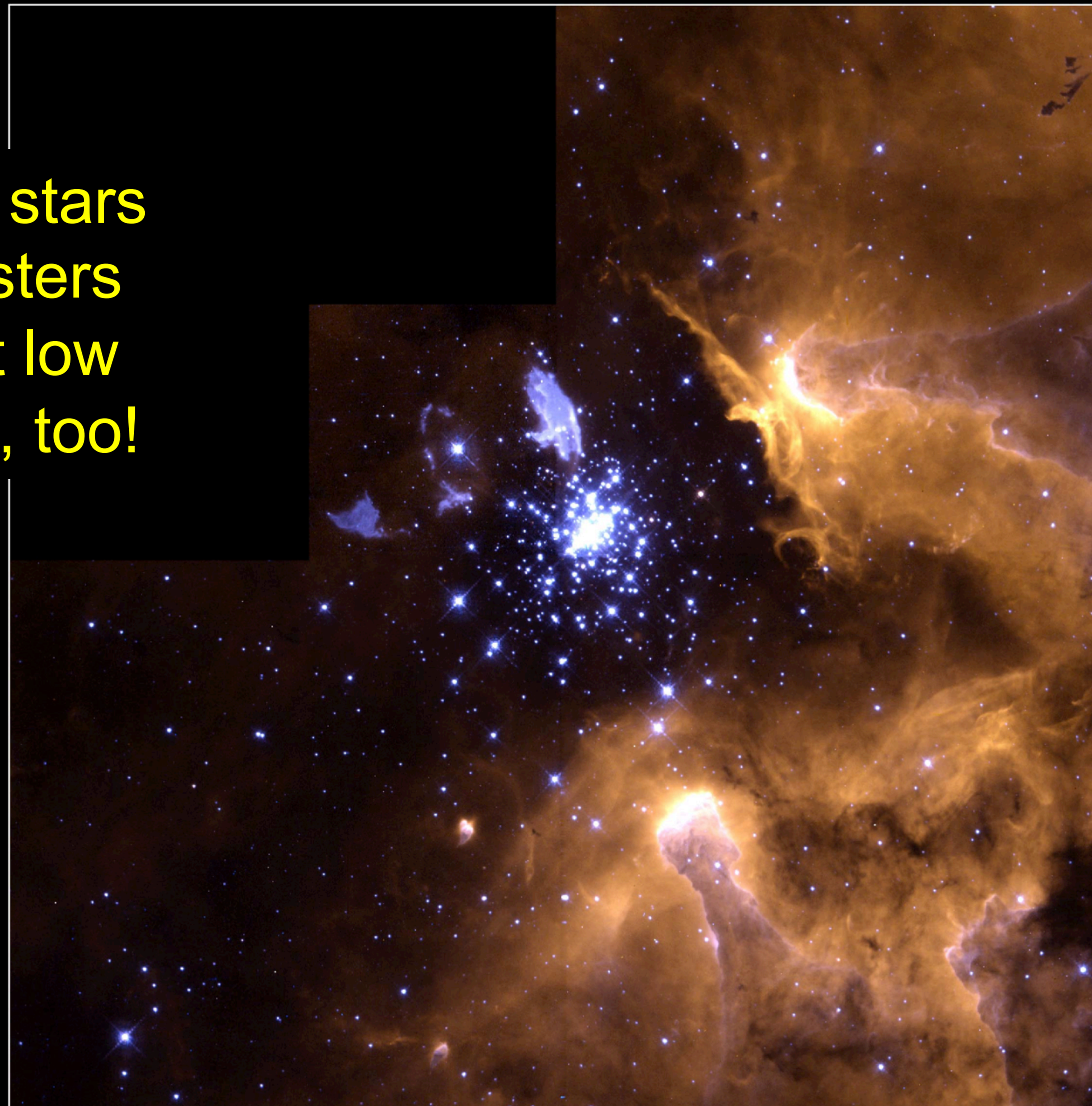
Our understanding of their formation is still sketchy, because of

- the short evolutionary time scales,
- their large, often uncertain distances,
- the huge amount of extinction toward their birth places

Produce heavy elements

Drive physics and chemistry

High mass stars form in clusters – and most low mass stars, too!



NGC 3603
Hubble Space Telescope • WFPC2

PRC99-20 • STScI OPO
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington),
You-Hua Chu (University of Illinois, Urbana-Champaign) and NASA

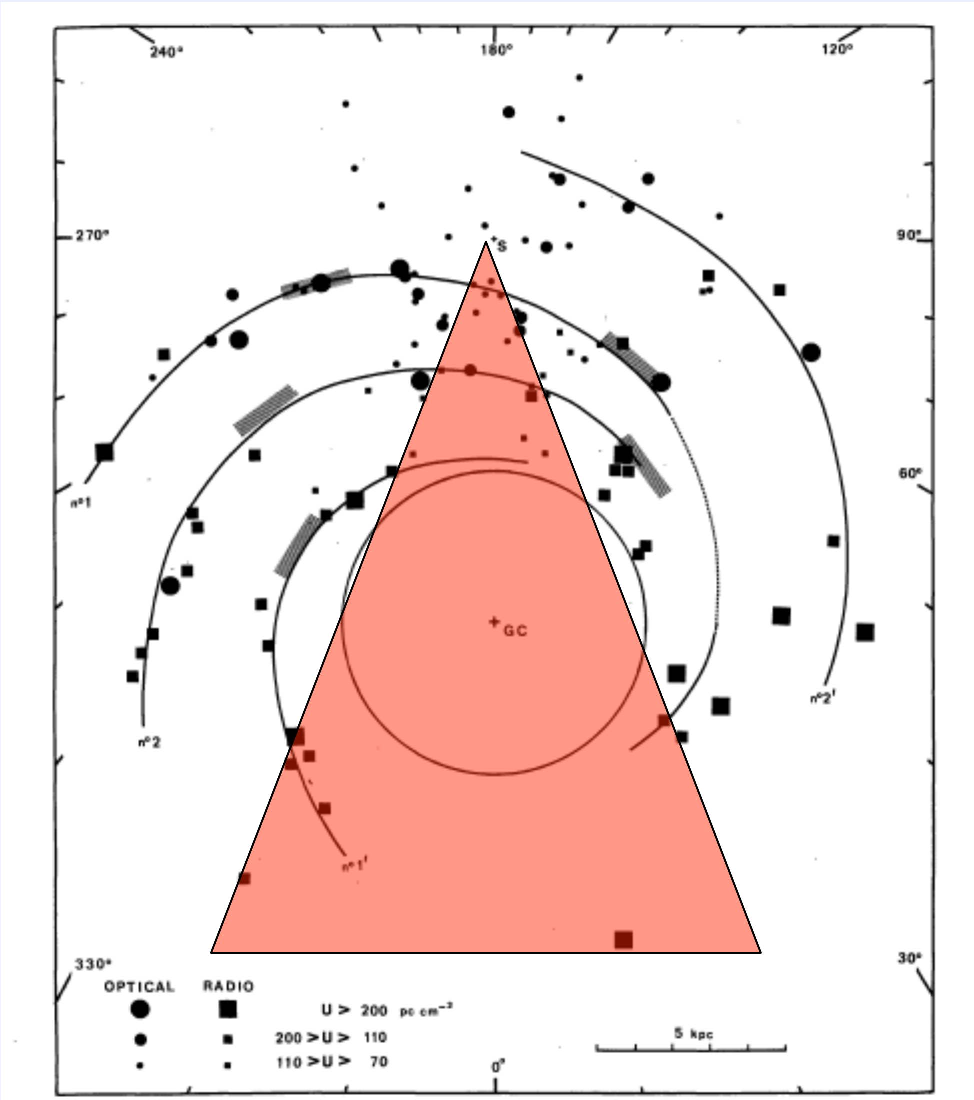
RCW 38 | Orion Nebula

Optical

Infrared

Alves, Muench

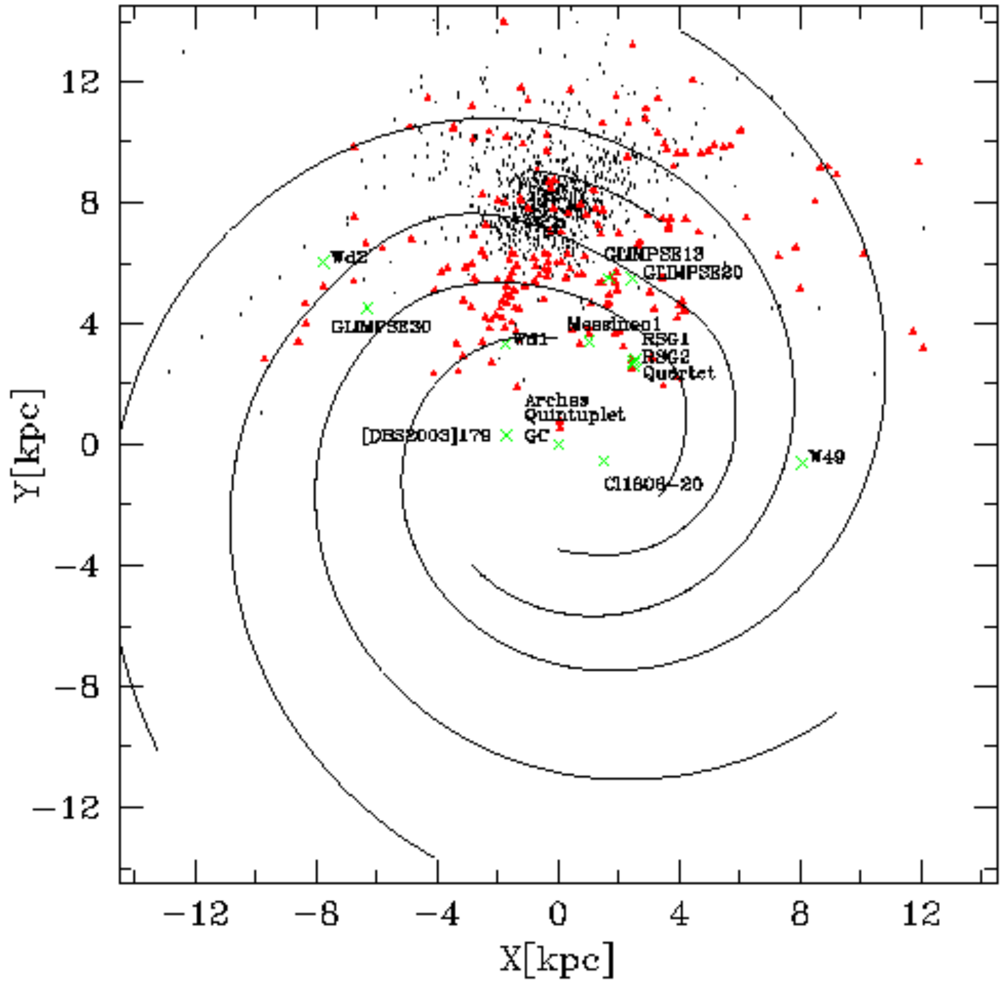
At visual wavelengths, some of the most interesting parts of the Milky Way are terra incognita



$$D = (10\,pc) \times 10^{(m - M_V)/5}$$

Georgelin & Georgelin 1976

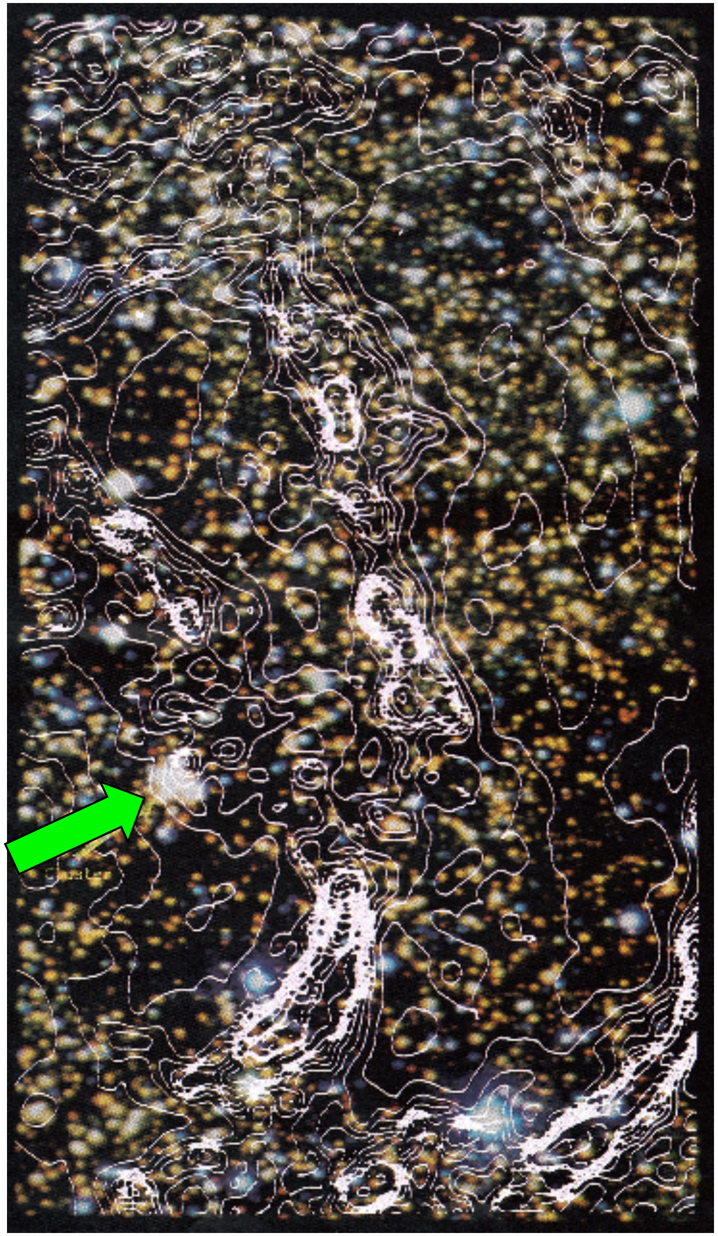
Distribution of Known Open Stellar Clusters



- IR clusters
- Optical clusters
- Massive young clusters($M > 10^4 M_{\odot}$)

Compilation: M. Messineo

Infrared candidate clusters can probe the inner Galaxy

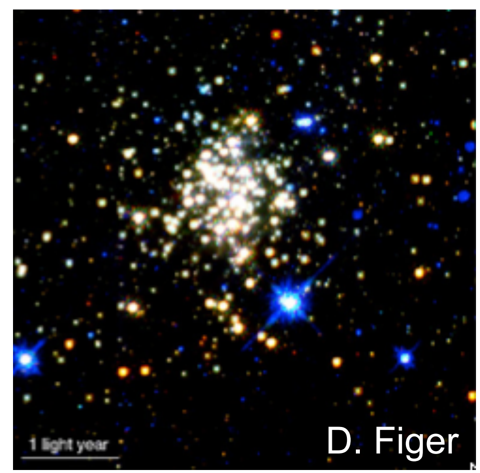


J, H, K’ on radio

Even in the IR, massive, luminous clusters are difficult to find in the Inner Galaxy…

The Arches cluster detection

Cotera+ 1996



Before we can study clusters, we have to find them!

→ Unbiased surveys

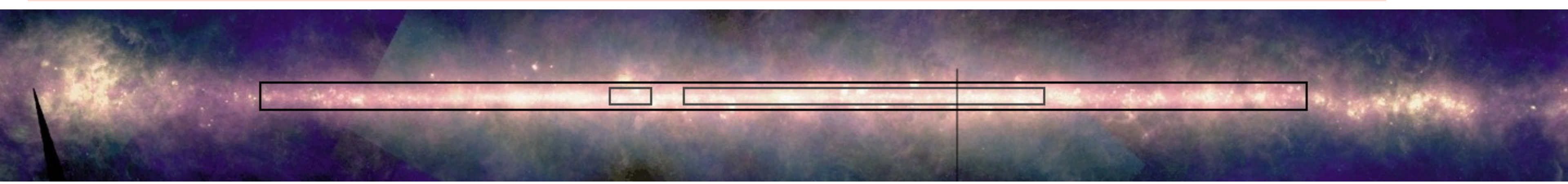
Unbiased Galactic Plane surveys

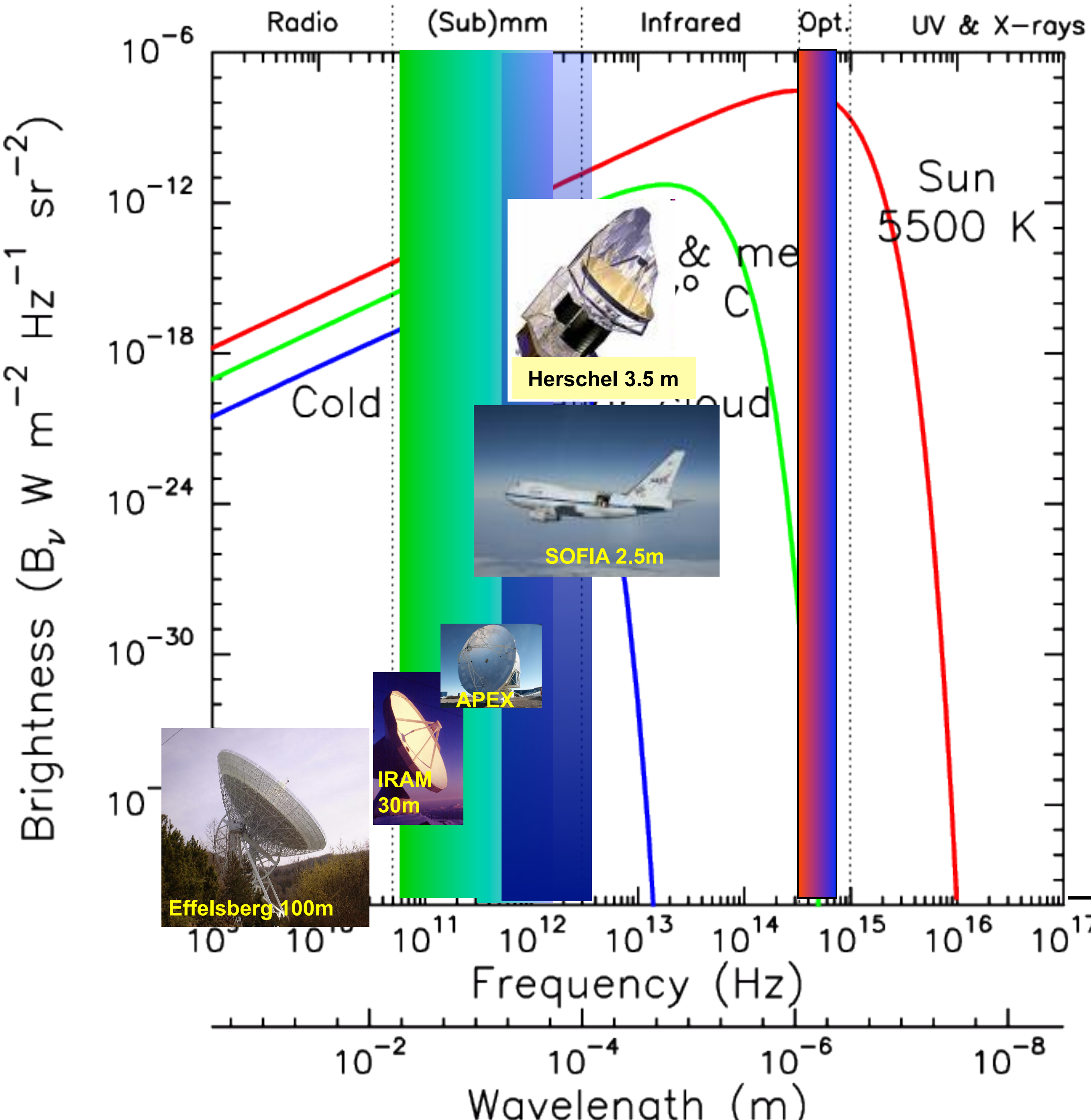
Find massive protostars

- ATLASGAL
  - LABOCA @ APEX (submm)
- BOLOCAM – CSO (mm)
- SCUBA-2 – JCMT (submm)
- Herschel: SPIRE/PACS – HiGAL FIR/submm (5 bands)
- Spitzer: GLIMPSE/MIPSGAL (N/MIR 4+2 bands)
- VLT: VVV (5 NIR bands)
- + 2MASS, WISE (all sky)
- MSX (MIR 5 bands)
- JVLA: THOR, GLOSTAR cm continuum/masers/absorption …
- Methanol Multi-beam Survey

Find massive stars

Find both

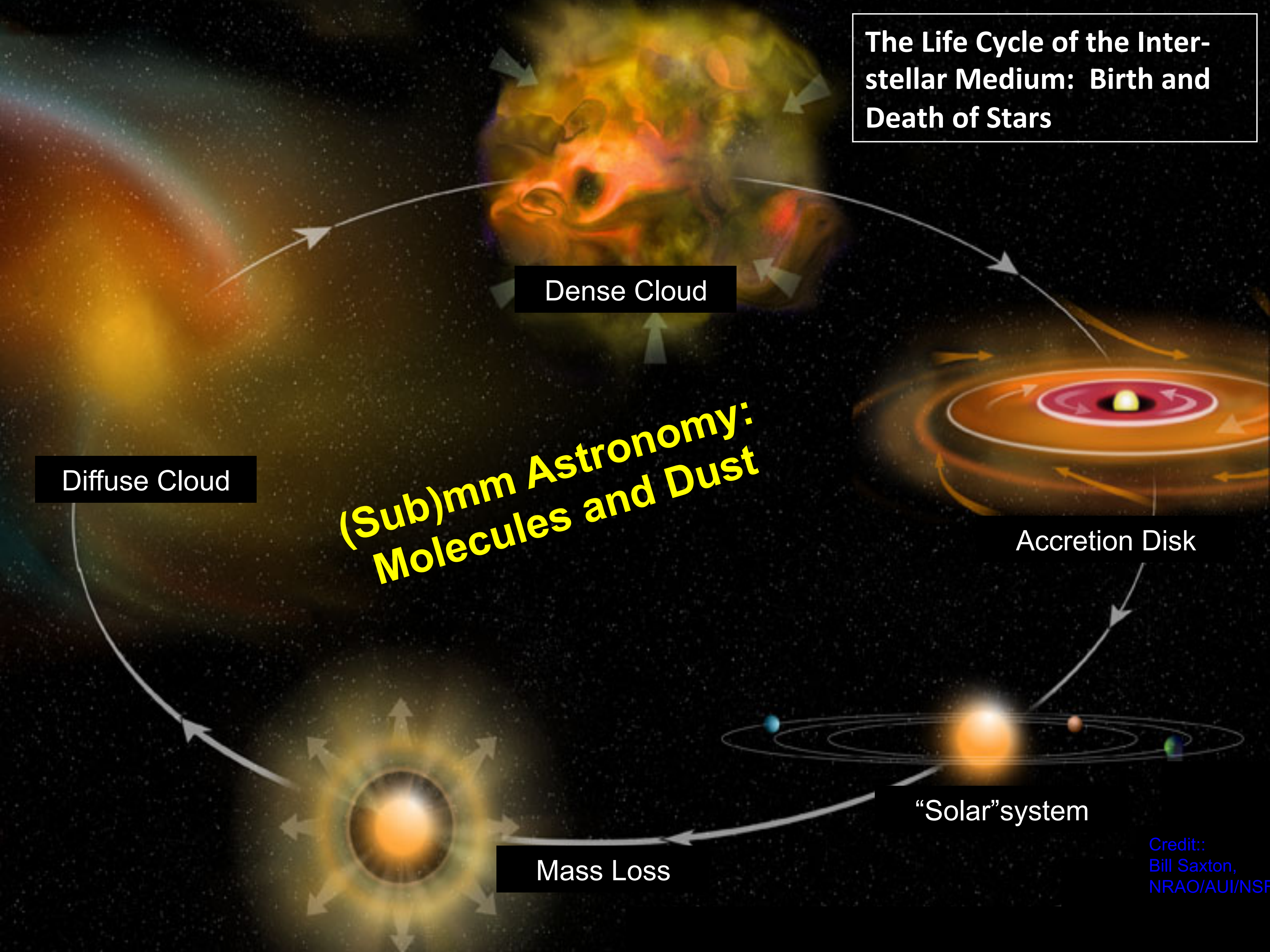




10^{23}

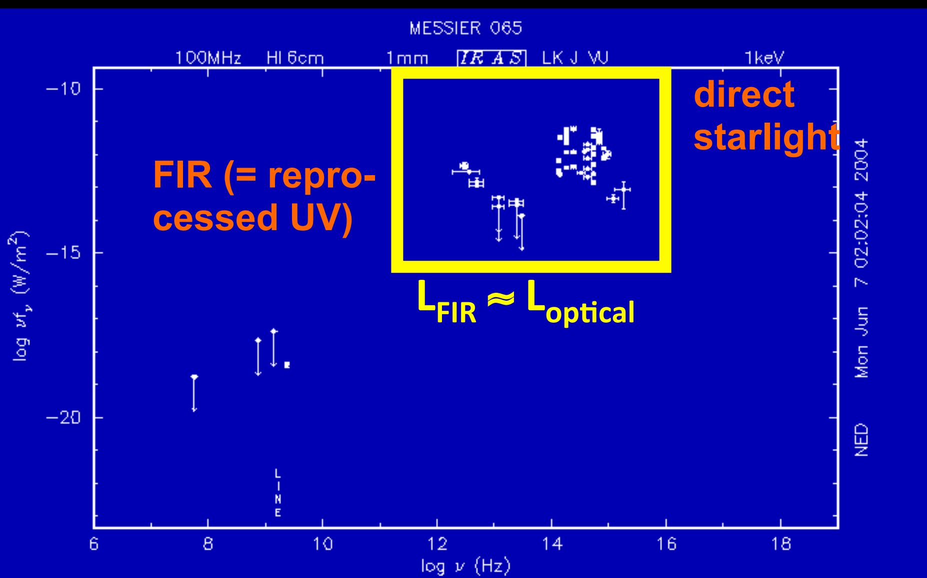
Max Planck
1858–1947

The Life Cycle of the Inter-stellar Medium: Birth and Death of Stars

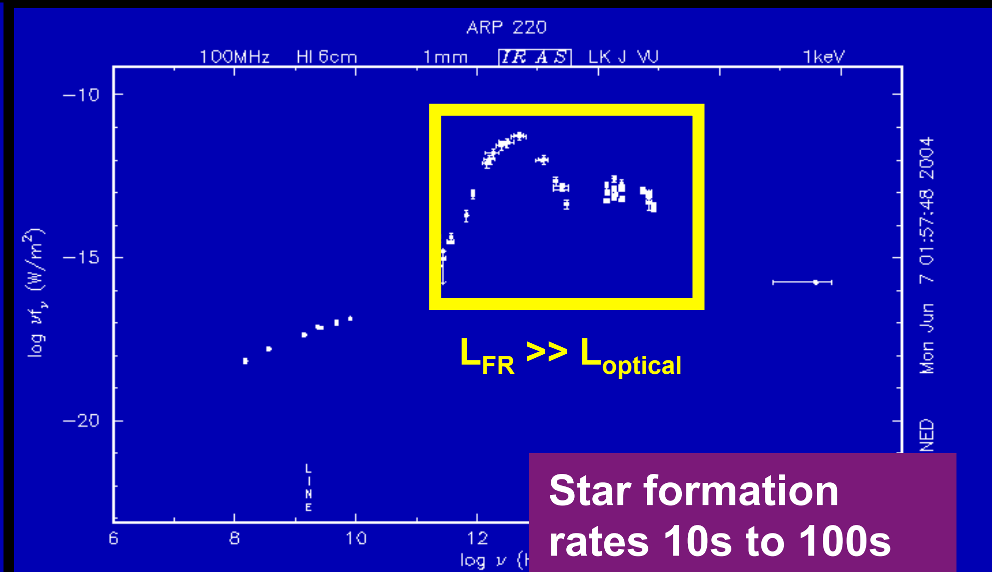


How can we observe hot (30000 K) stars at FIR and submm wavelengths?

Spectral energy distribution of the normal spiral galaxy M65

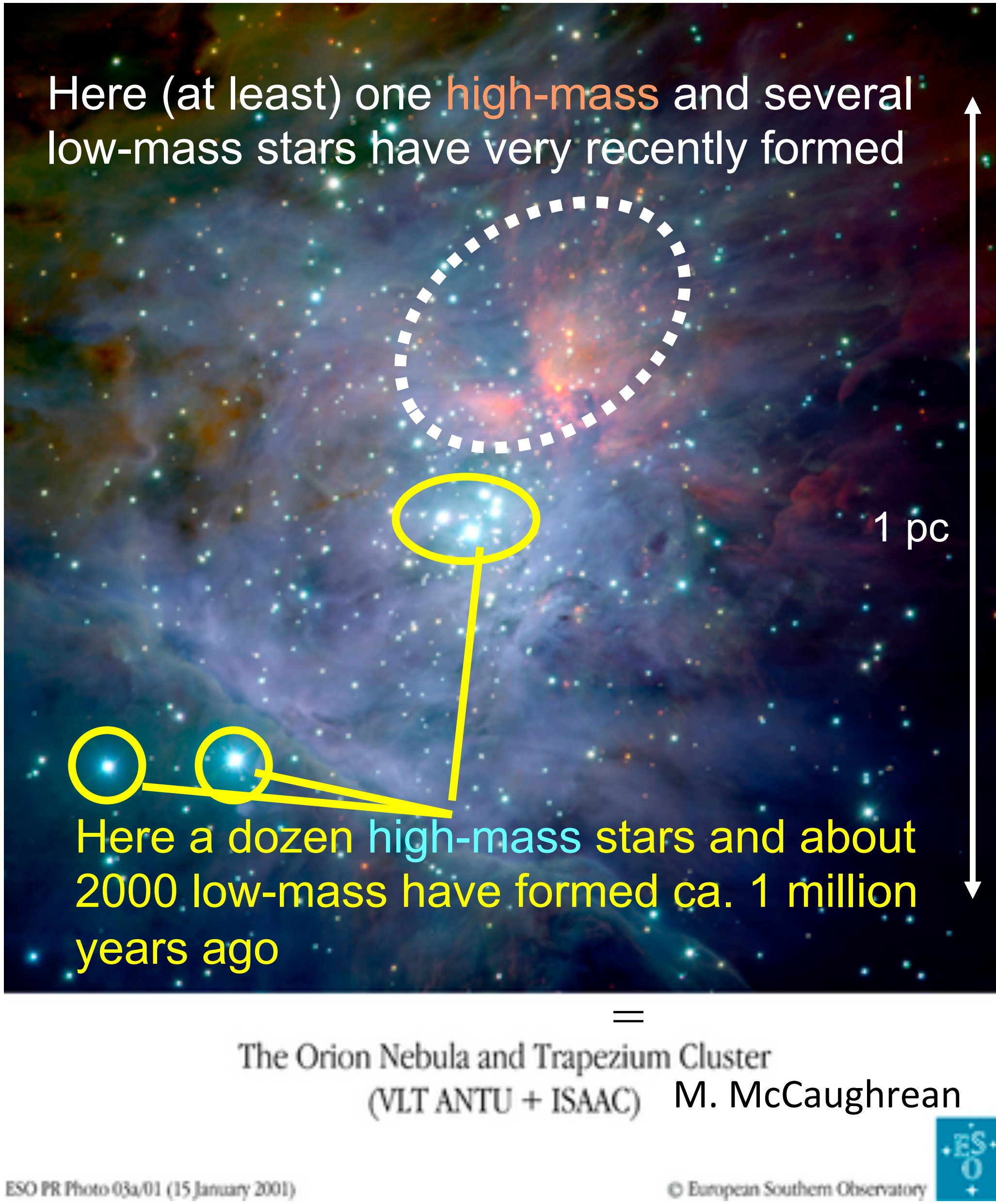


SED of the Ultra-Luminous InfraRed Galaxy Arp 220

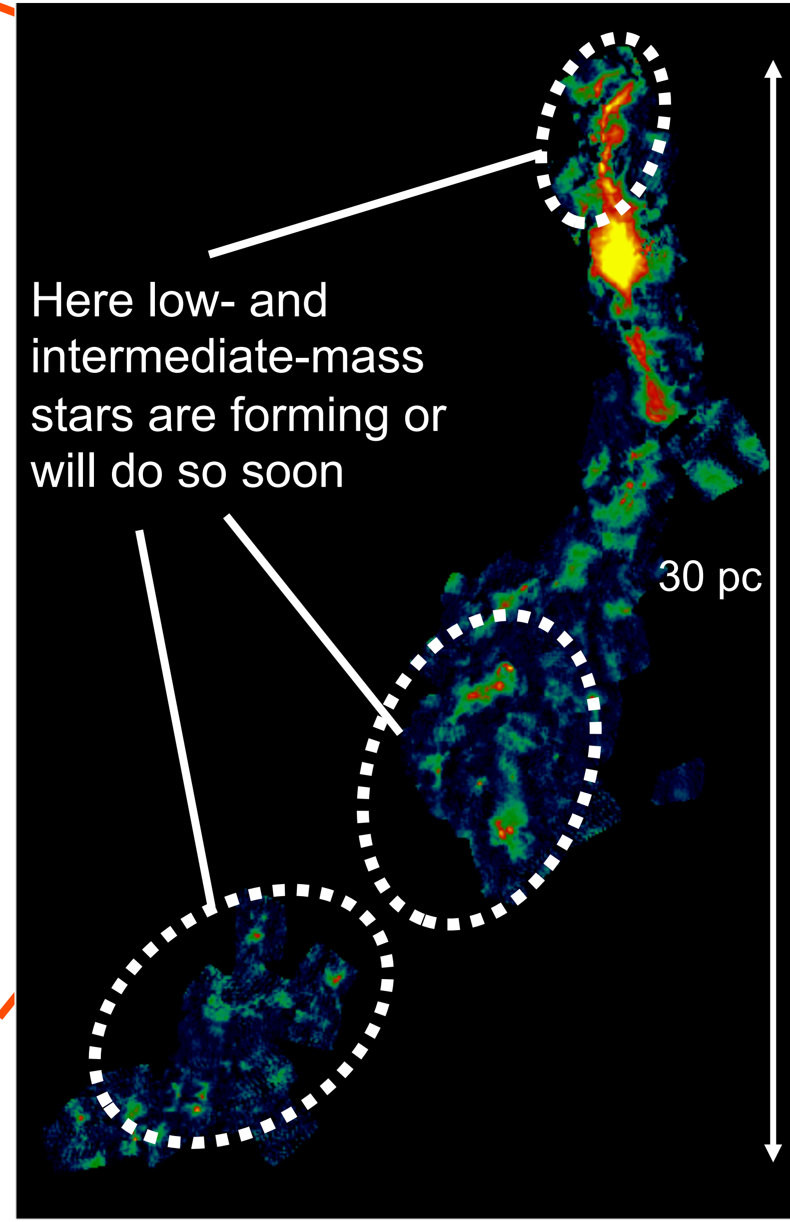


Star formation rates 10s to 100s of times higher than today in the Milky Way

NED



2.2 µm



1.2 mm dust emisson

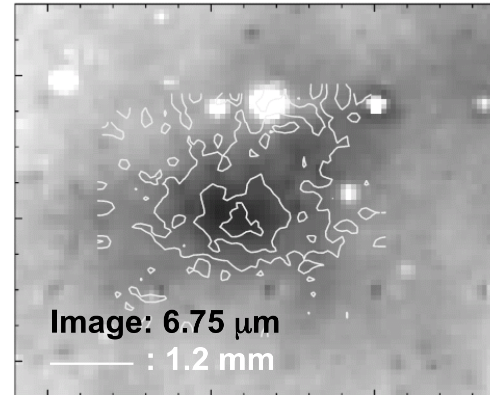
T. Stanke/IRAM 30 m

Why (sub)millimeter + FIR?

Tracing mass with submillimeter emission from dust

Source brightness

$$S_\nu = B_\nu(T_D)\left(1 - e^{-\tau_\nu}\right)$$



Continuum emission from interstellar dust is almost always optically thin for wavelengths > 100 µm (frequencies < 3 THz)

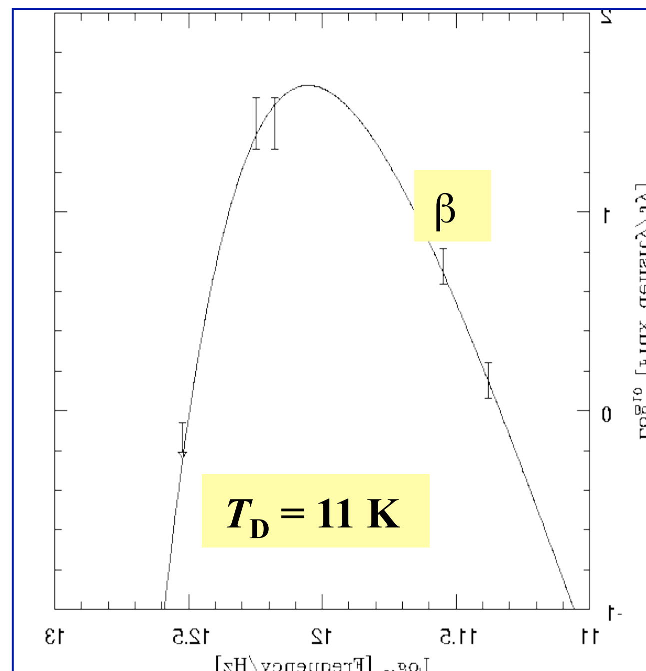
$$S_\nu \approx B_\nu(T_D)\tau_\nu \approx \frac{2k}{c^2} T_D \nu^2 \tau_\nu$$

$$\tau_\nu = \int \kappa dl = N_\mathrm{H}\sigma_\nu^\mathrm{H} \propto N_H \nu^\beta \; (1 < \beta < 2)$$

(Sub)mm observations of dust emission yield the total (hydrogen) column density and the gas mass

$$N_H \propto \frac{\nu^{-2-\beta}}{T_D} S_\nu$$

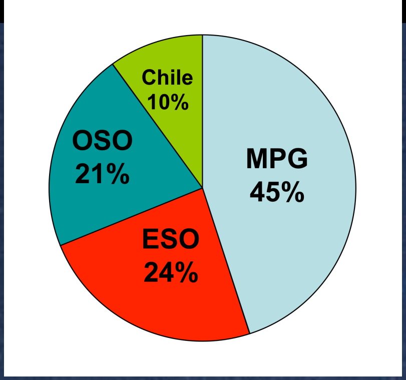
$$M \propto \frac{\nu^{-2-\beta}}{T_D} D^2 \int S_\nu d\Omega$$



The Atacama Pathfinder Experiment (APEX)

Built and operated by
- Max-Planck-Institut fur Radioastronomie
- Onsala Space Observatory
- European Southern Observatory

on
Llano de Chajnantor (Chile)
Longitude: 67° 45’ 33.2” W
Latitude: 23° 00’ 20.7” S
Altitude: 5098.0 m



- ∅ 12 m
- λ = 200 μm – 2 mm
- 15 μm rms surface accuracy
- In operation since September 2005
- PI and facility instruments:
  - 150 –1400 GHz GHz heterodyne RX
  - 295 element 870 μm Large Apex Bolometer Camera (LABOCA)

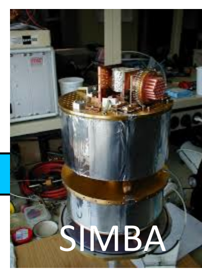
http://www.mpifr-bonn.mpg.de/div/mm/apex/

How APEX Came About:

MPIfR
mm astronomy since 1980s (IRAM 30m)
Sub-mm since 1990

Onsala Space Observatory
mm astronomy since 1980s (20 m dish)

ESO



SEST 15 m
(1987–2003)

Atacama Large Millimeter Array Phase I
→ Operate one of the (modified) ALMA prototype antennas as a single dish telescope: APEX (from 2005 on)

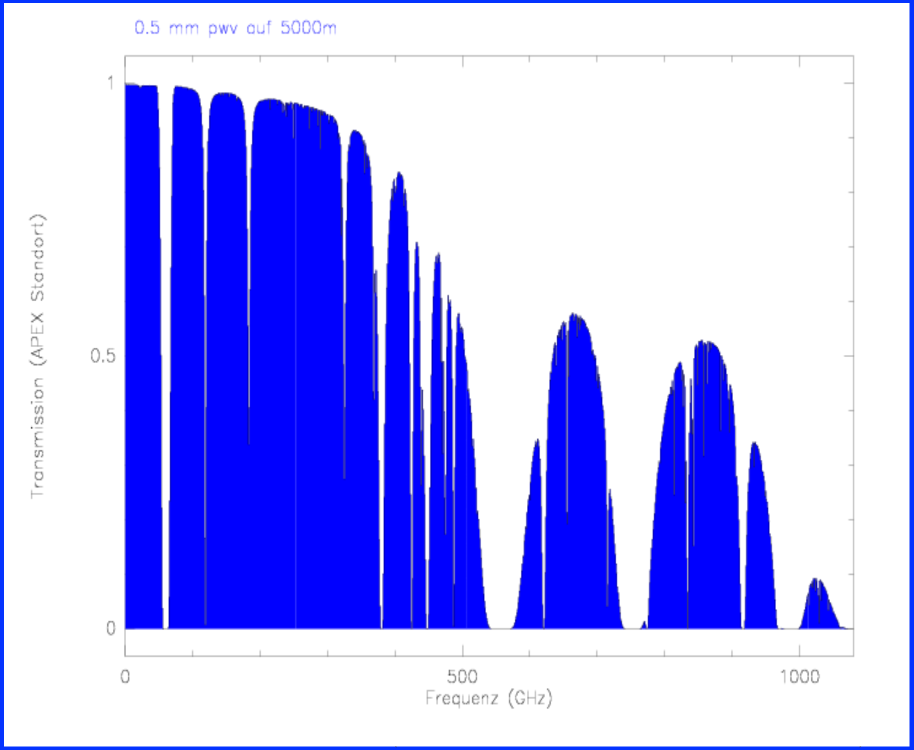
Chajnantor it was to be!

SW from Cerro Chajnantor, 1994 May

AUI/NRAO S. Radford


Ici!
Ici!

The biggest problem for submillimeter astronomy: The Earth's atmosphere



Transmission Chajnantor

Submillimeter range

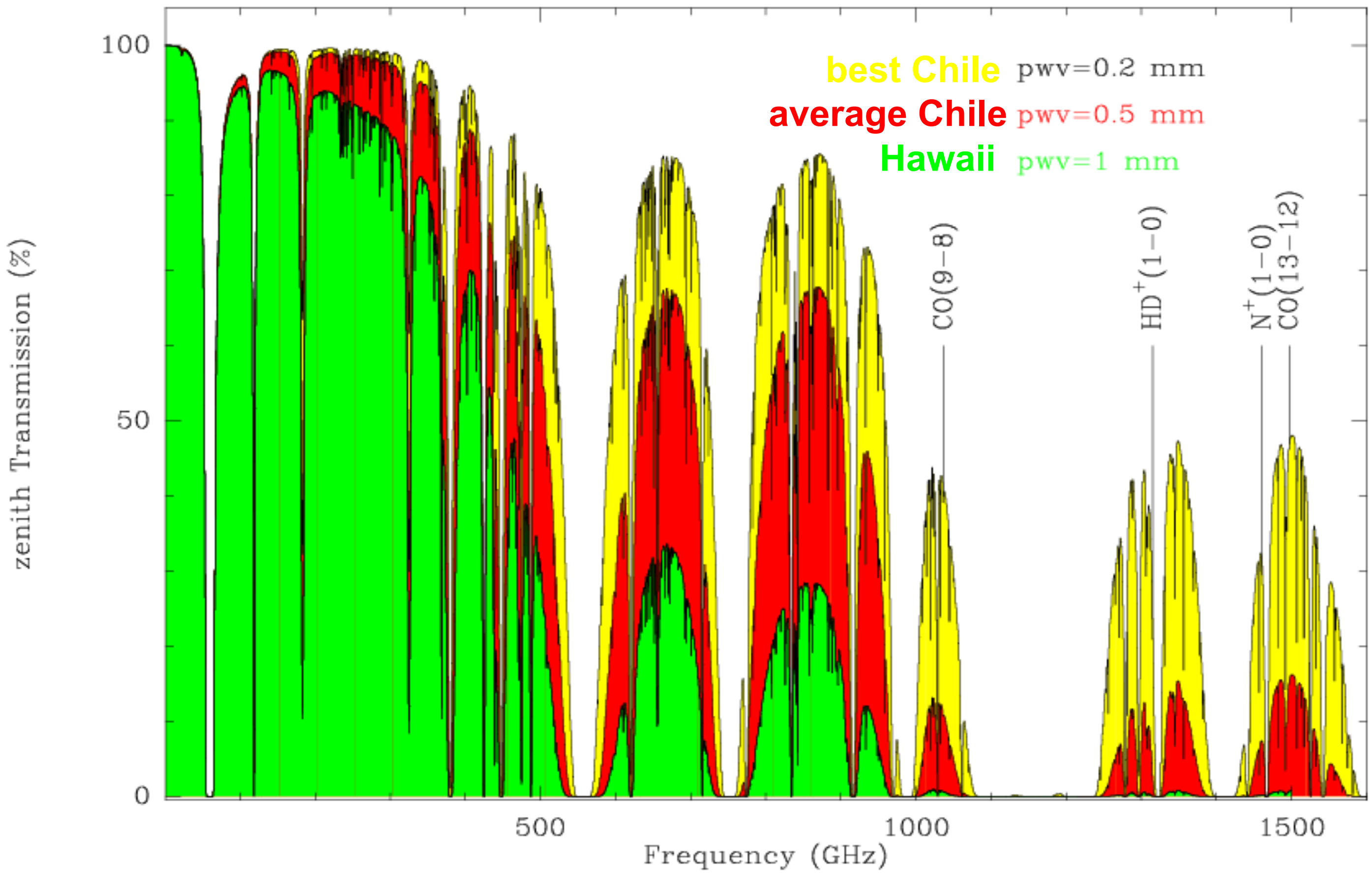
Transmission on a 5000 m high site unter good, very good, and **extremely good** weather conditions

1200µm 250 GHz

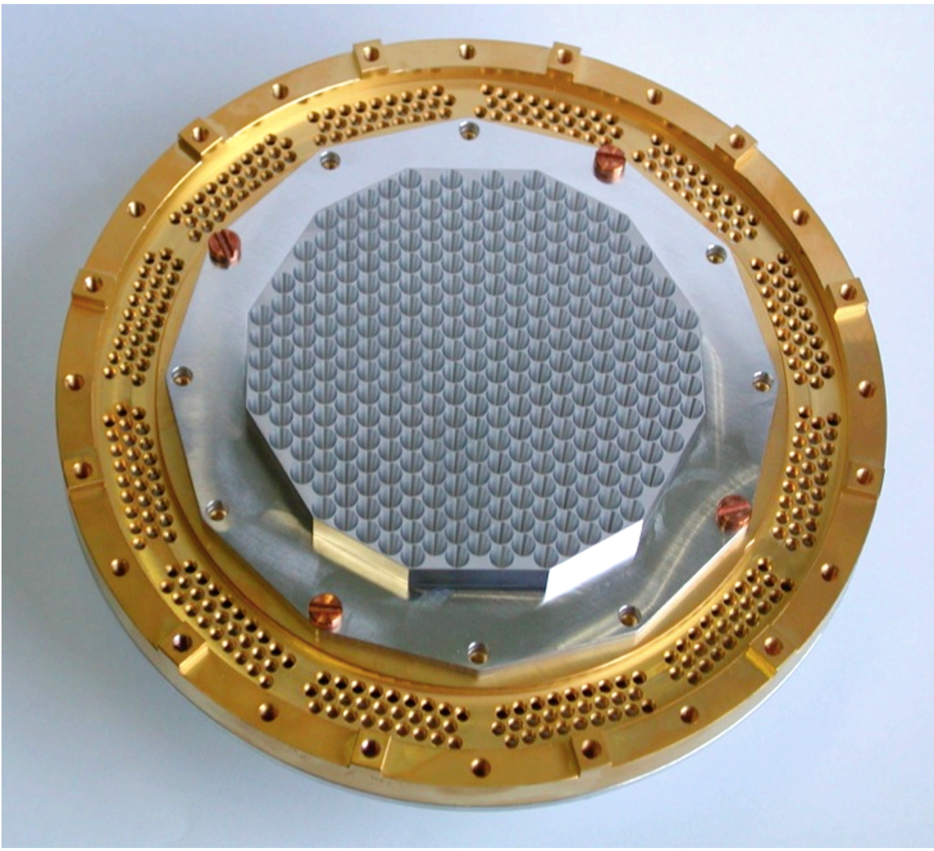
450µm 660 GHz

350µm 860 GHz

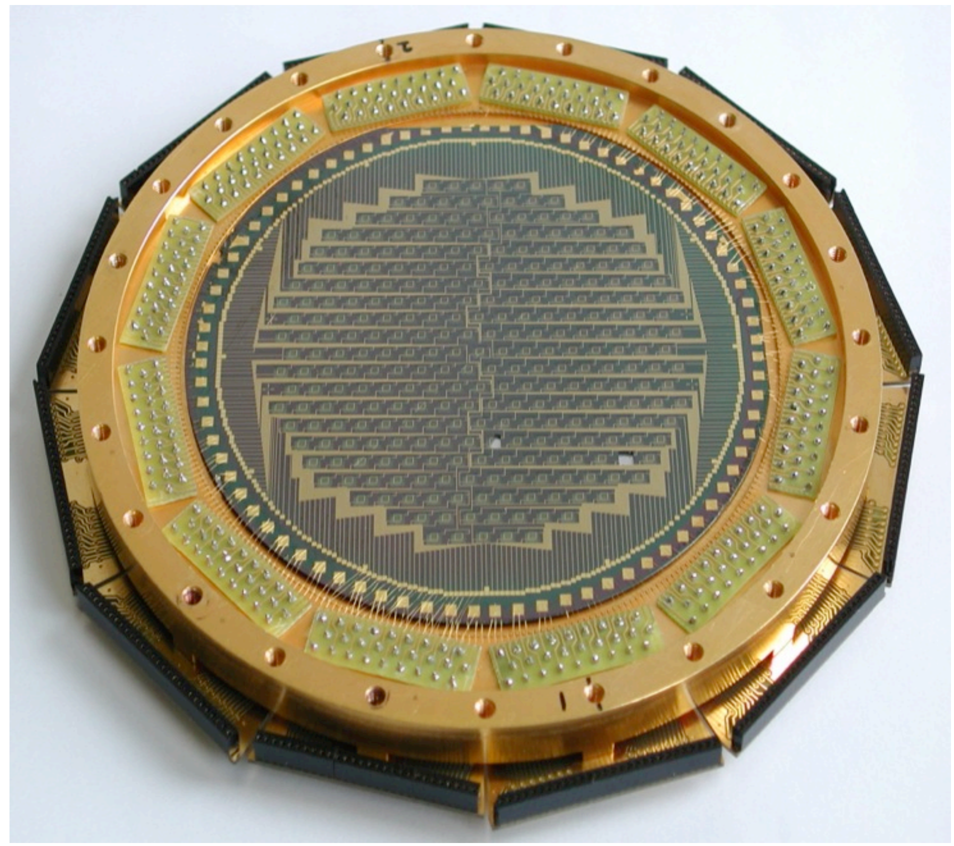
200µm 1.5 THz



The Large APEX Bolometer Camera – LABOCA

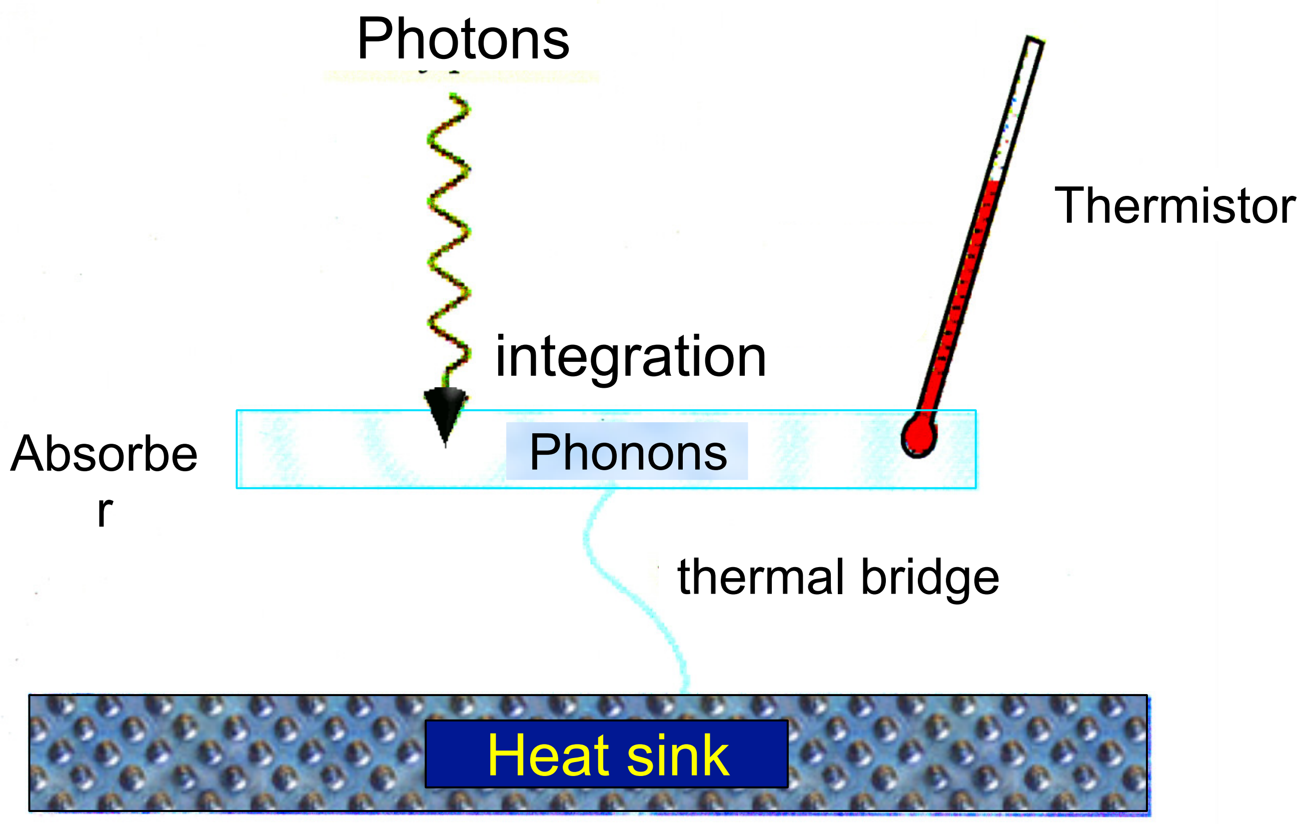


Horn array



Bolometer array

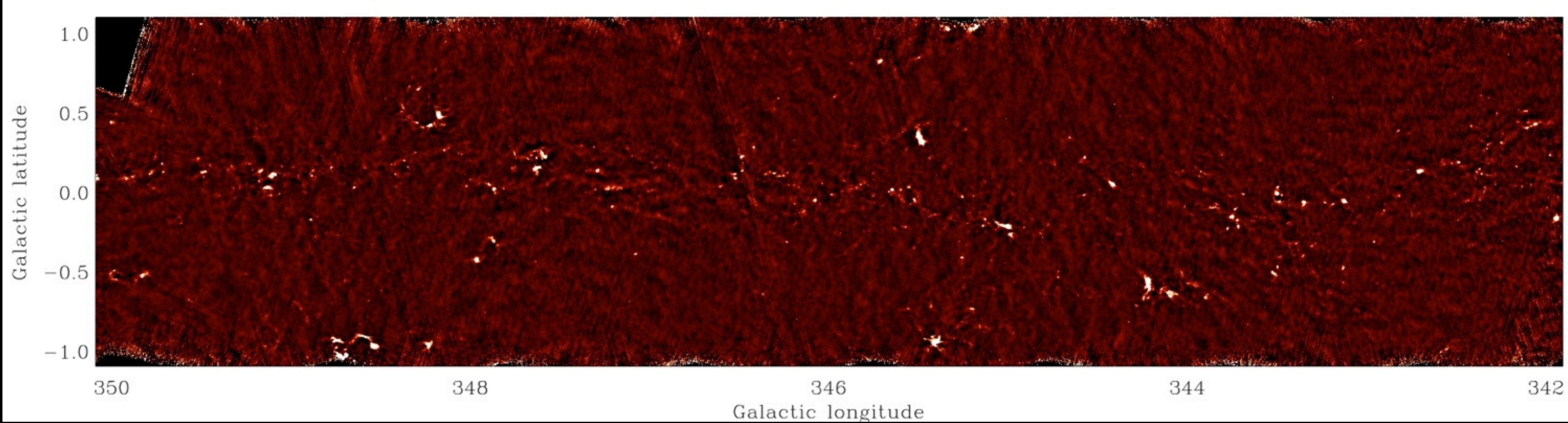
Bolometer detector: Principle



ATLASGAL:
APEX Telescope Large Survey of the Galaxy

- Main goals:
  - To have a complete 350 GHz (870 μm) census of high mass star formation in the Galaxy (= whole part of Galactic plane visible with APEX)
  - To detect protostellar condensations down ~ a hundred of solar *masses* throughout the Milky Way

Total observing time: ~1000 hours



ATLASGAL

European Southern Observatory

The APEX Telescope Large Area Survey of the Galaxy

Universidad de Chile

MPG : F. Schuller (PI), Y. Contreras, K. Menten, P. Schilke, F. Wyrowski, H. Beuther, T. Henning, H. Linz

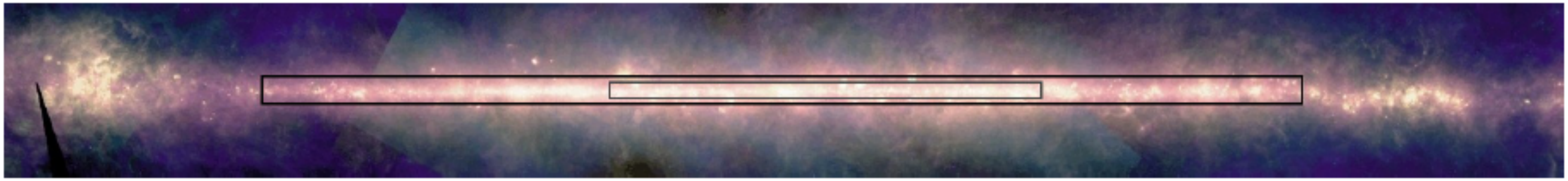
ESO : M. Walmsley (co-PI), S. Bontemps, R. Cesaroni, L. Deharveng, F. Herpin, B. Lefloch, S. Molinari, F. Motte, V. Minier, L.-Å. Nyman, V. Reveret, C. Risacher, N. Schneider, L. Testi, A. Zavagno

Chile : L. Bronfman (co-PI), G. Garay, D. Mardones

ATLASGAL – Short Description:

- Unbiased survey of the inner Galactic Plane at 870 μm
- **Main goals :**
  - study massive star formation throughout the Galaxy
  - pre-stellar initial mass function down to a few $M_\odot$
  - study large scale structure of the cold ISM
  - associate w. other Galactic surveys (Spitzer, MSX, Hi-GAL)

IRAS 12+60+100 μm, $|l| \leq 90°$, $|b| \leq 10°$

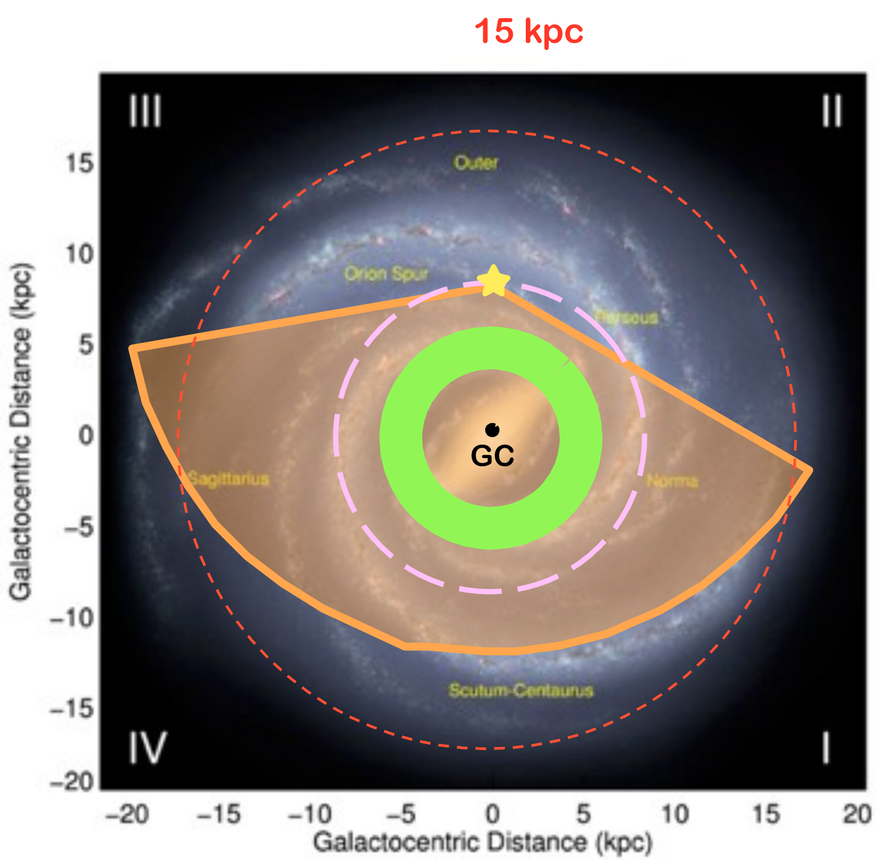


- Mapping $|l| \leq 60°$, $|b| \leq 1.5°$, sensitivity 1-σ = 50 mJy/beam

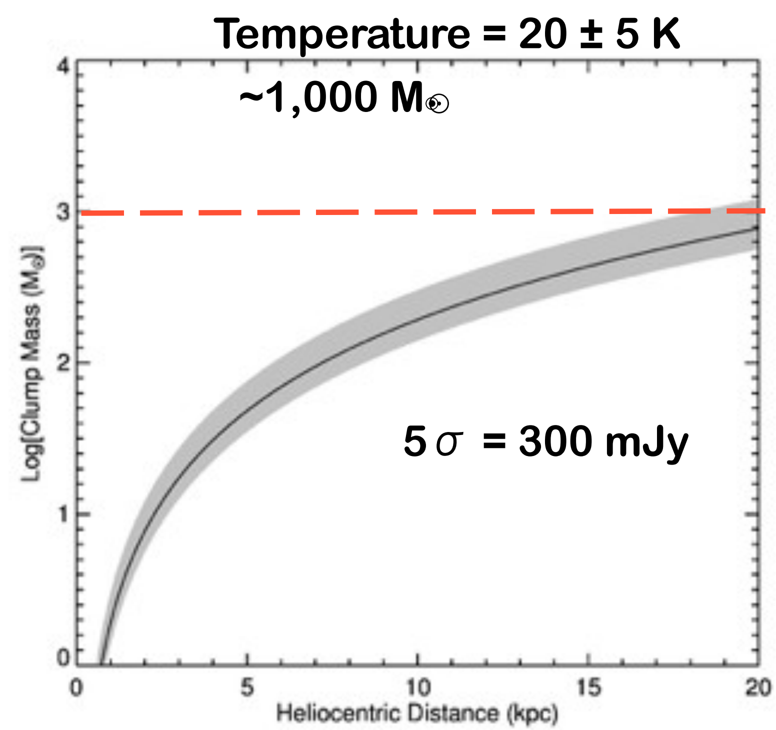
➔360 deg^2, 5σ detection:
0.5 $M_\odot$ at 500 pc, 20 $M_\odot$ at 3 kpc, 100 $M_\odot$ at 8 kpc

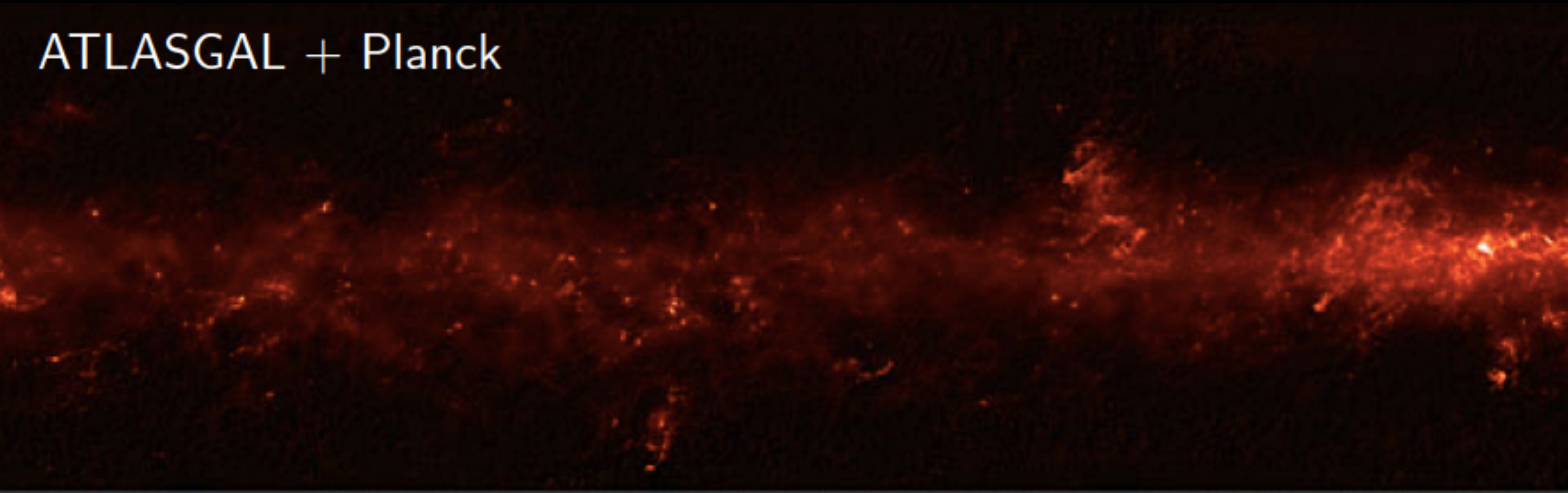
ATLASGAL

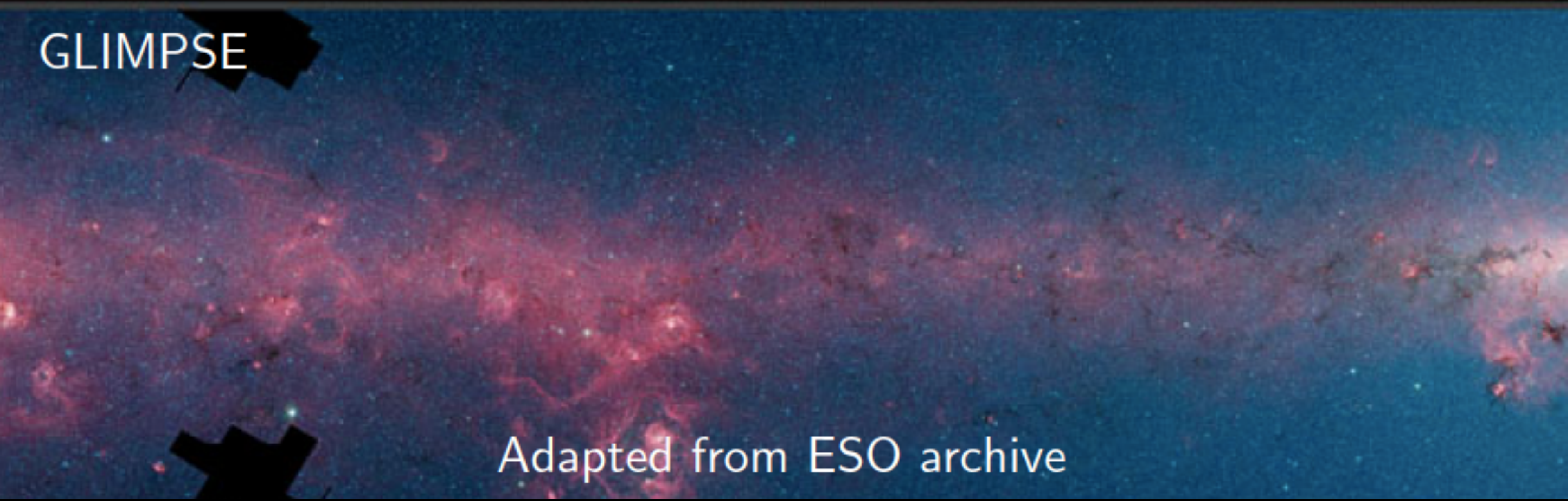
Coverage



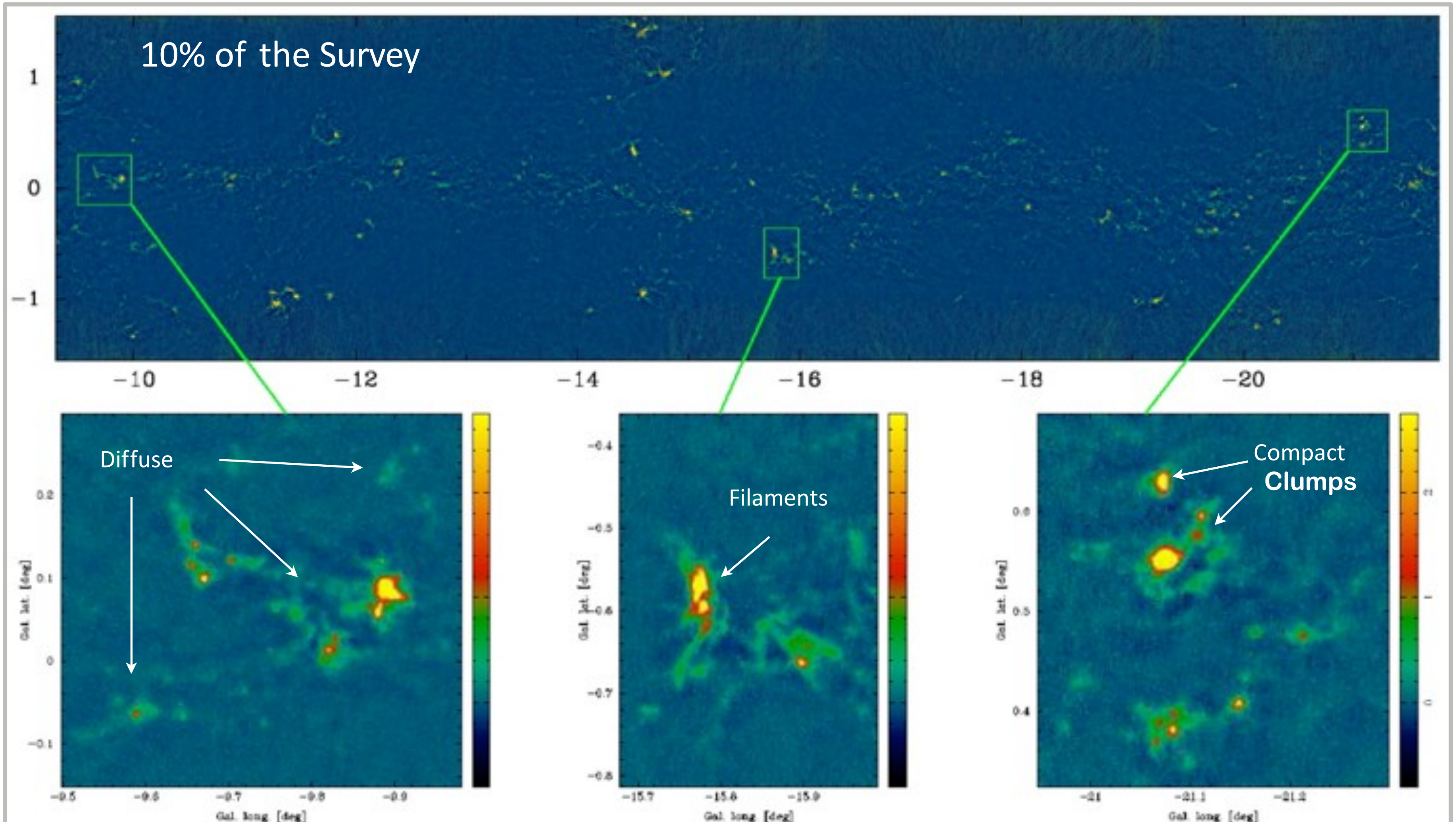
Mass Sensitivity

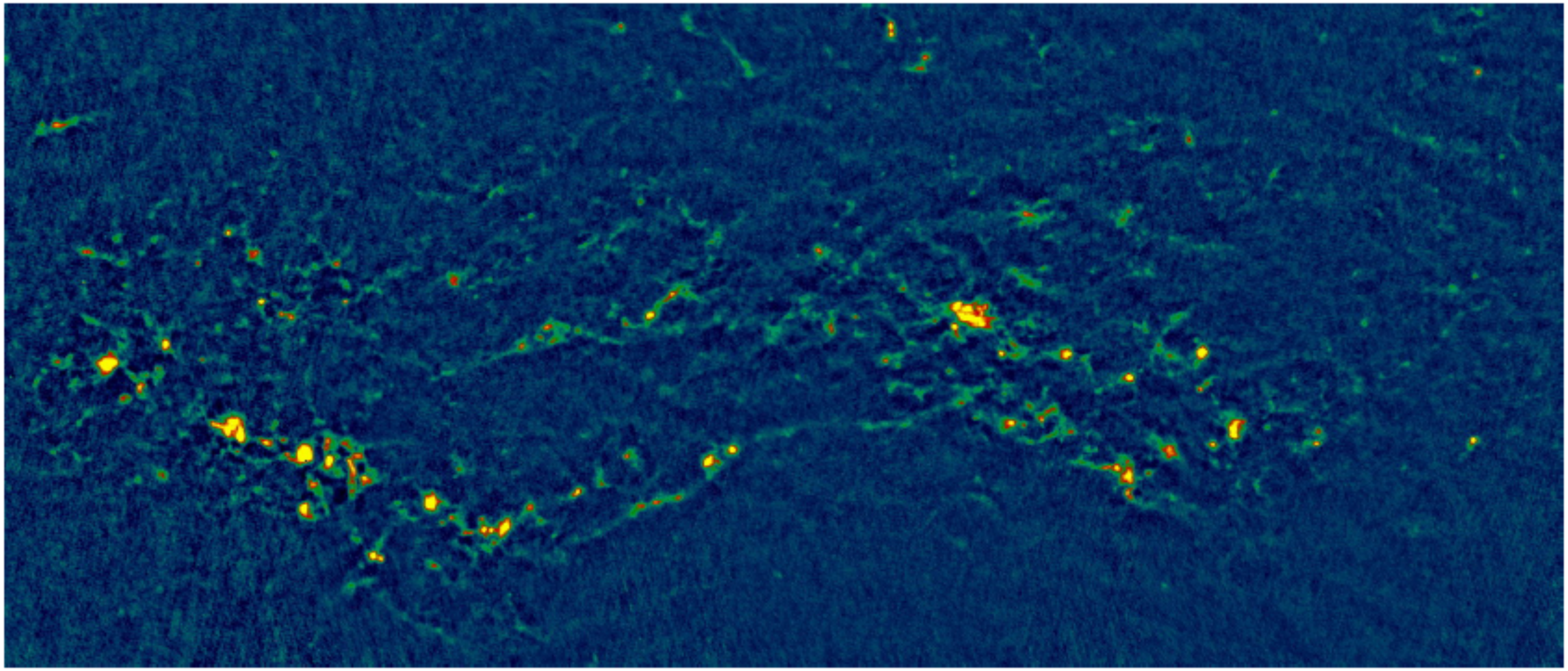



ATLASGAL + Planck


GLIMPSE
Adapted from ESO archive

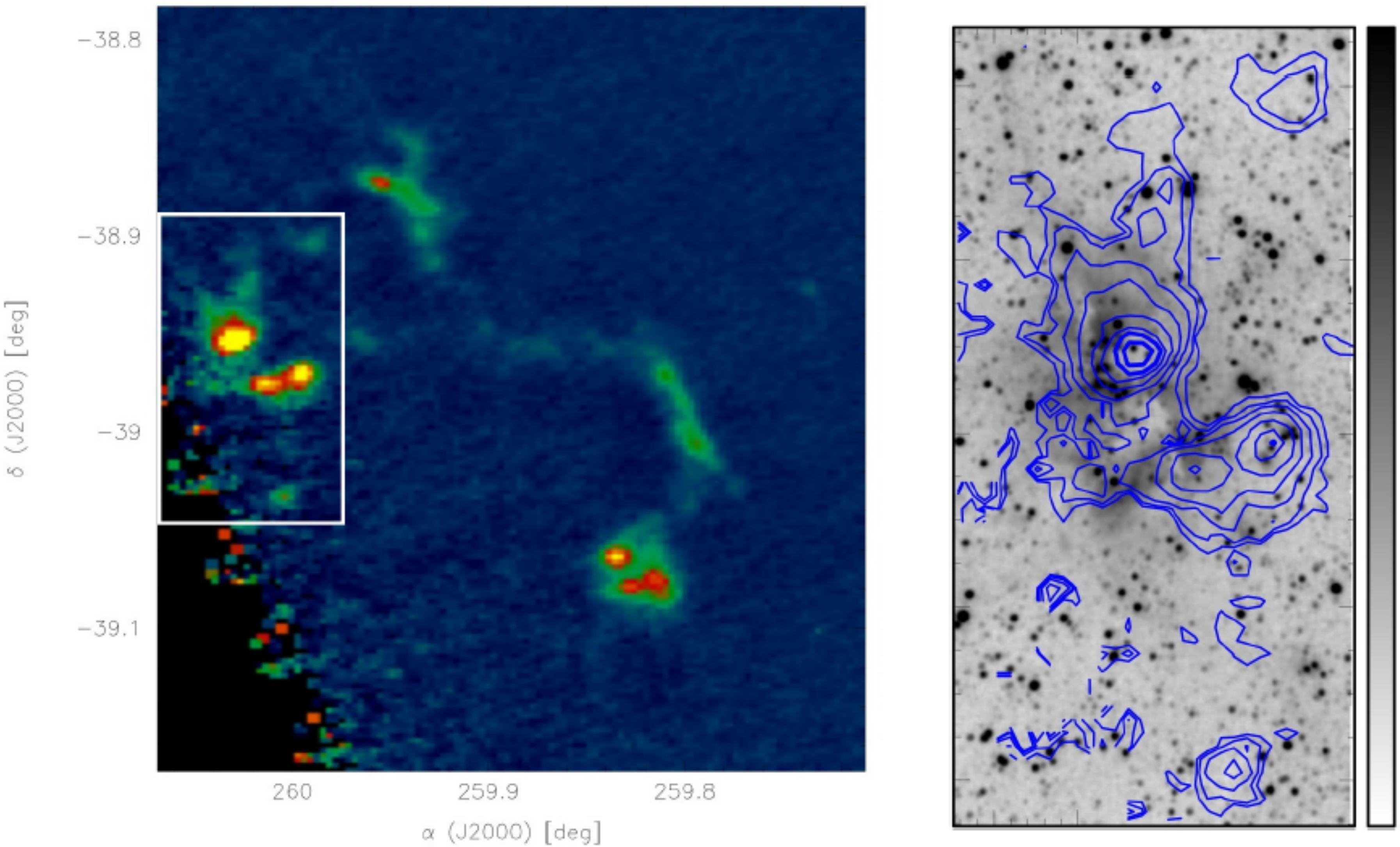
ATLASGAL Structures



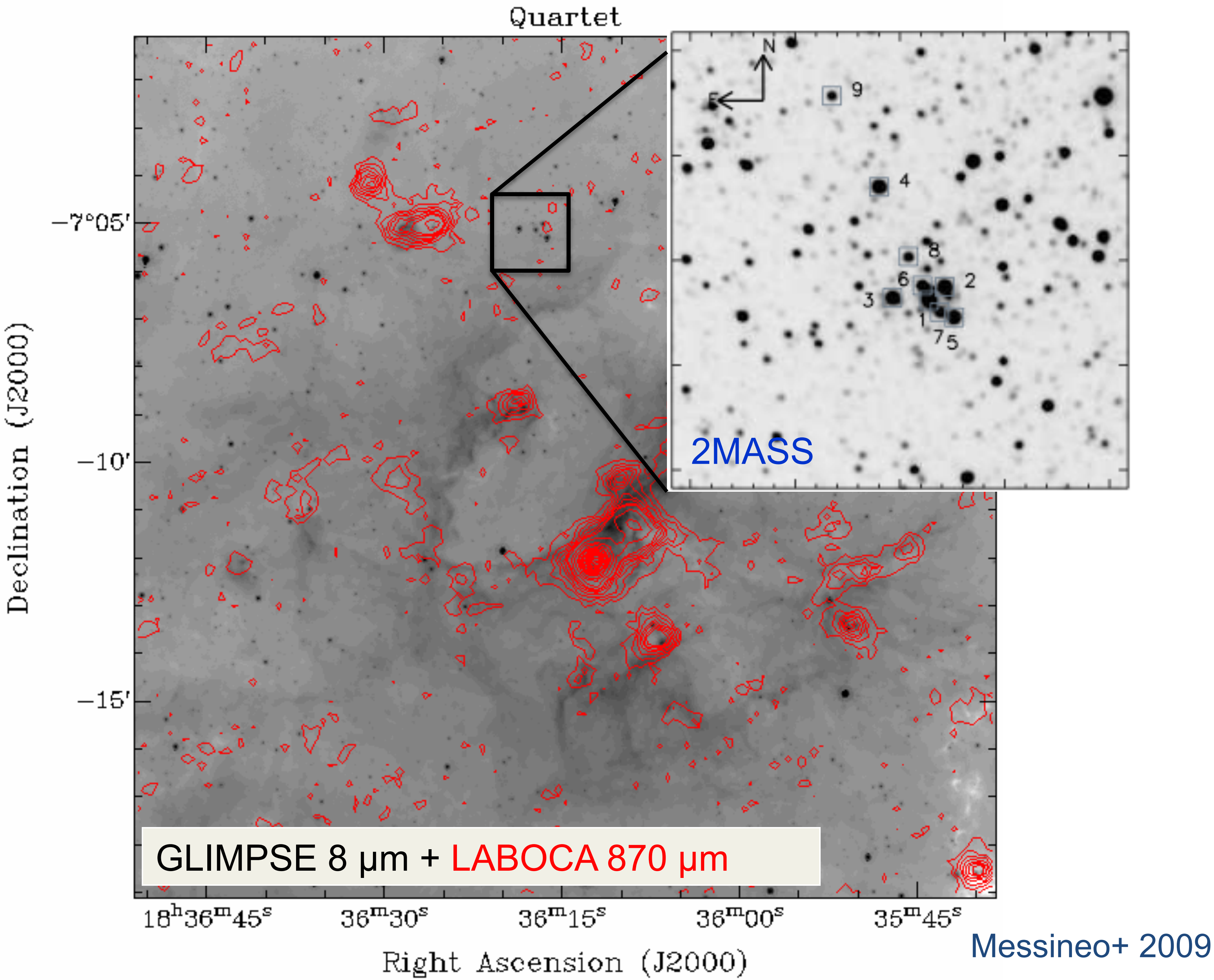


- > 10000 compact sources, brighter than 300 mJy
- extended objects on arcmin scale
- very long filaments, up to the degree scale!

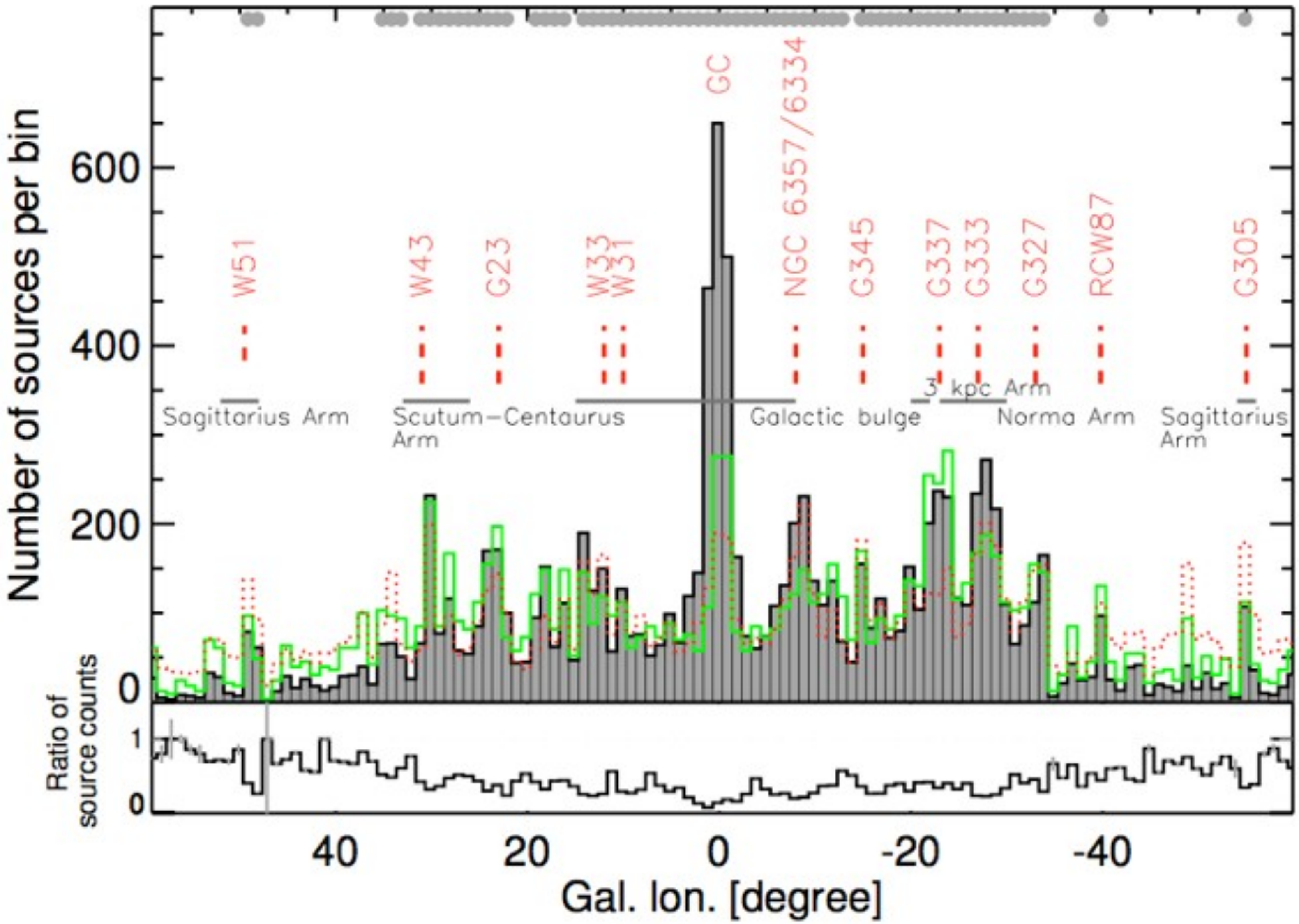
RCW 122 : embedded cluster and IR-quiet sources



on 2MASS K


Quartet
Declination (J2000)
−7°05′
−10′
−15′
18h36m45s
36m30s
36m15s
36m00s
35m45s
Right Ascension (J2000)
N
E
9
4
8
6
2
3
1
7
5
2MASS
GLIMPSE 8 μm + LABOCA 870 μm
Messineo+ 2009

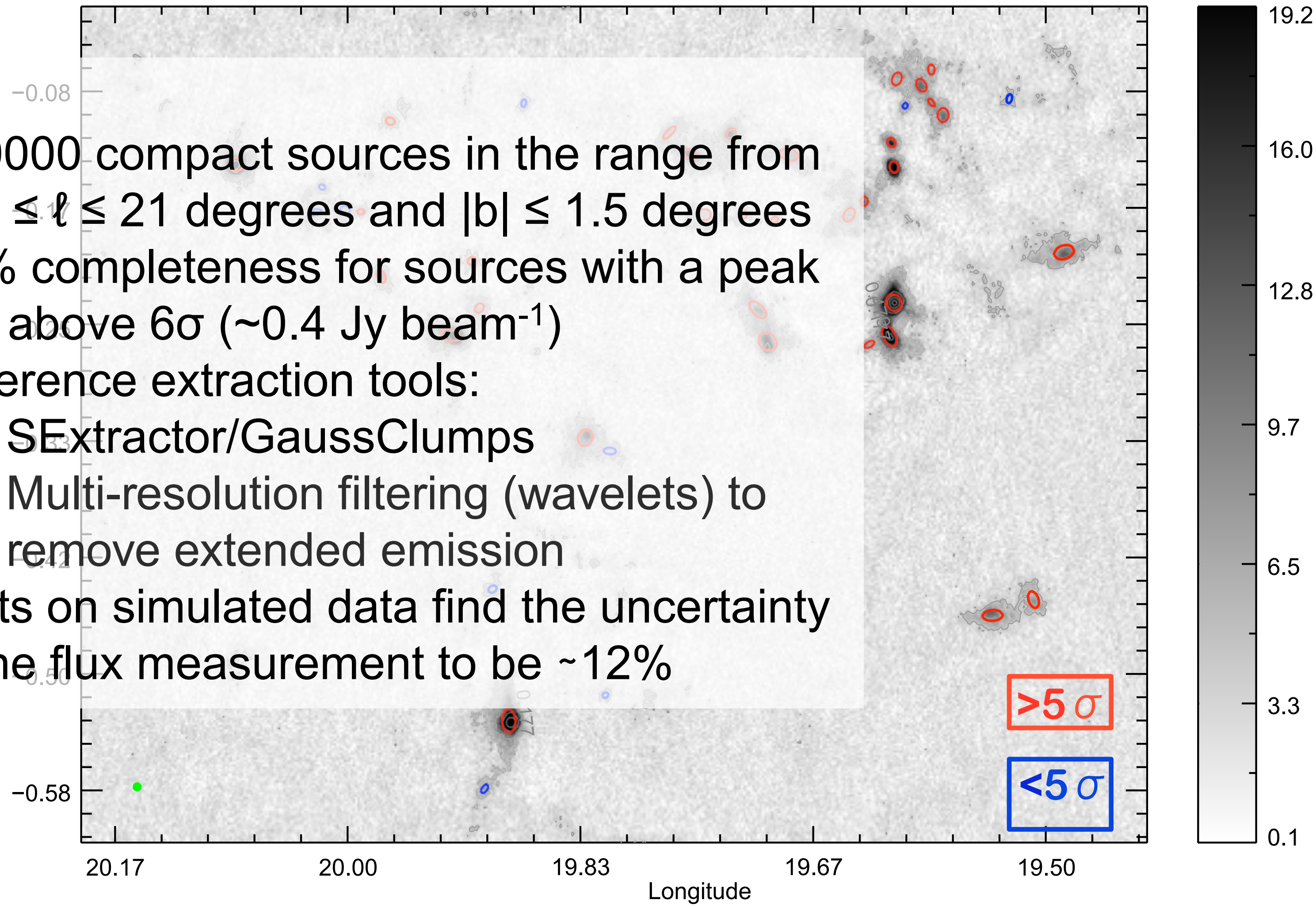
Galactic Distribution of ATLASGAL Sources



Csengeri+ 2013

Compact Source Catalogues

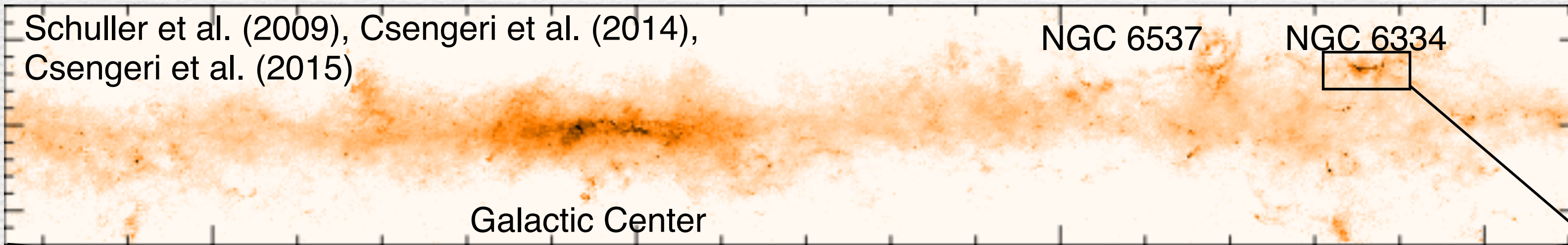
- >10000 compact sources in the range from 330 ≤ ℓ ≤ 21 degrees and |b| ≤ 1.5 degrees
- 99% completeness for sources with a peak flux above 6σ (~0.4 Jy beam[-1])
- Difference extraction tools:
  - SExtractor/GaussClumps
  - Multi-resolution filtering (wavelets) to remove extended emission
- Tests on simulated data find the uncertainty in the flux measurement to be ~12%



Contreras+ 2013, Urquhart+ 2014, Csengeri+ 2014

ATLASGAL Follow-up Programmes

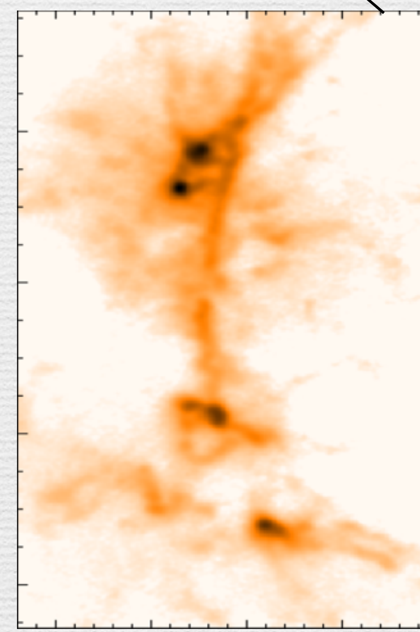
APEX Telescope Large Area Survey of the Galaxy: *~ 420 sq. degree of the inner Galaxy*



APEX

870 μm

ℓ < 60° ⟵ ⟶ *ℓ > -80°*



1. Continuum

Catalogs:

- compact sources,
  Contreras+2013,
  Csengeri+ 2014,
  Urquhart+ 2014
- filaments
  Li+ *in prep*

Large scale statistics:

- time-scale estimates
  Csengeri+ 2014,
- dense gas fraction
  Csengeri, Weiss+ 2015
- evolutionary stage indicators
  Urquhart+ 2013a,2013b

2. Distances

kinematic

Wienen+ 2012
Wienen+ 2015
Giannetti+ 2015

maser: BeSSeL

Brunthaler+ 2009
Reid+ 2014

3. Spectroscopy

astro-chemistry

Csengeri+ 2015 (SiO)
Leurini+ 2014 (H_2O)
Giannetti+ 2014 (CO)

4. Young massive clumps

ALMA follow-up

Csengeri+ *in prep*

~ 40 sources

> 400 sources

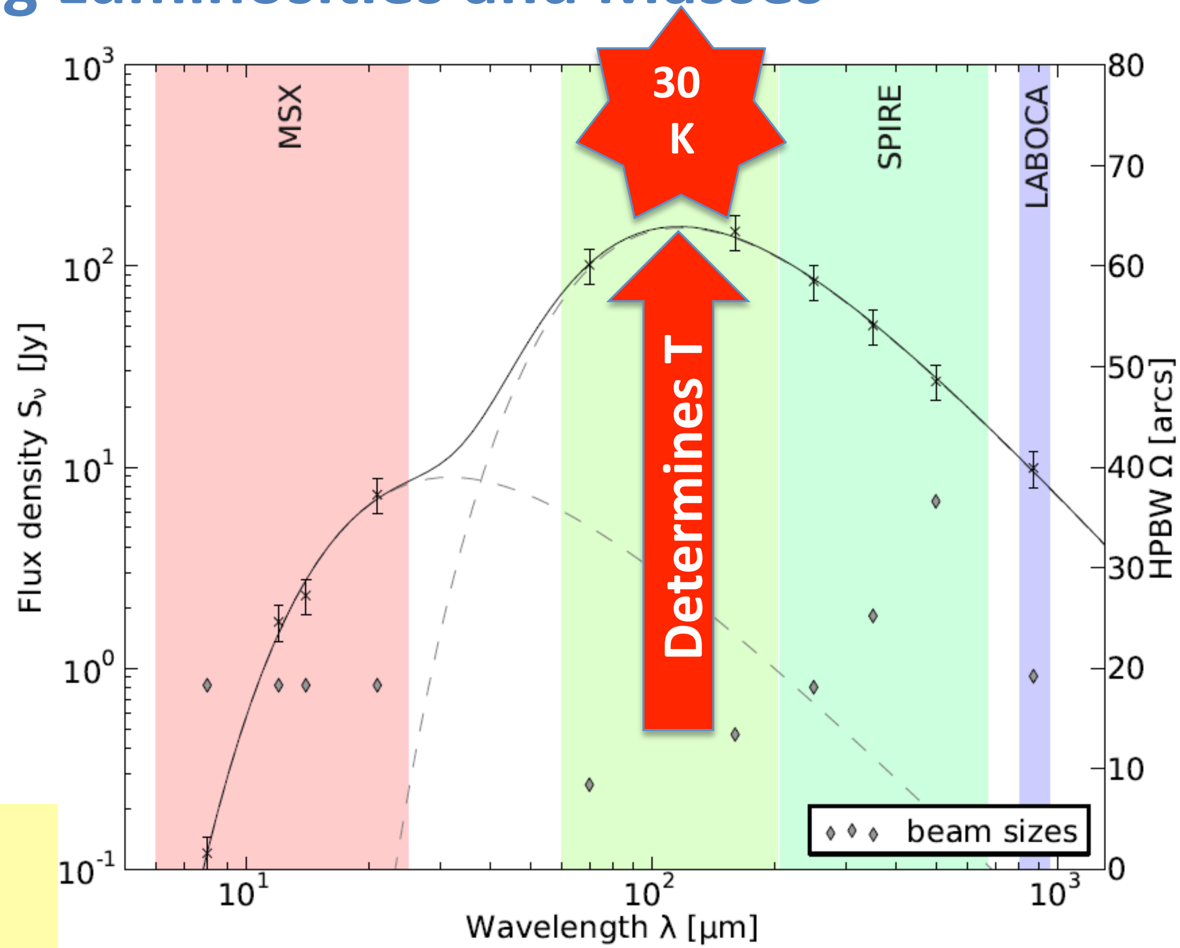
> 3000 sources

> 10 000 sources

ATLASGAL database: http://atlasgal.mpifr-bonn.mpg.de/

Spectral Energy Distributions:

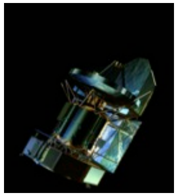
Determining Luminosities and Masses



$$N_H \propto \frac{\nu^{-2-\beta}}{T_D} S_\nu$$

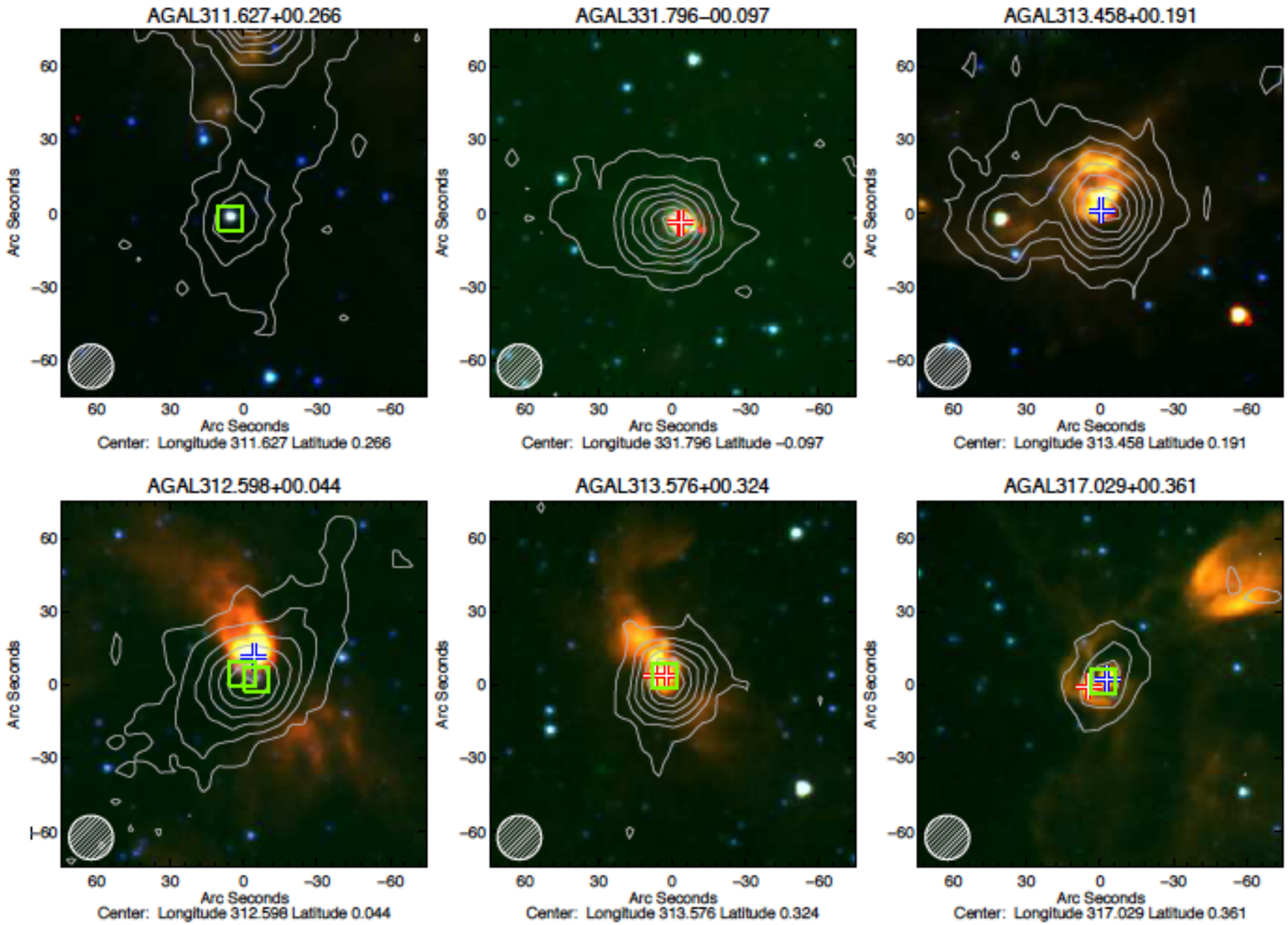
$$M \propto \frac{\nu^{-2-\beta}}{T_D} D^2 \int S_\nu \, d\Omega$$

König, dissertation



$$\theta(3.5\ \mathrm{m}) = \theta(12\ \mathrm{m})$$

Different source classes → Evolution



Methanol masers MYSOs UCHIIRs

Evolution

Urquhart+ 2014

Molecular line follow ups

- Velocity and linewidth information:
  - Kinematic distances
  - Internal kinematics – Infall and outflow
  - GMC velocity dispersions
  - Virial masses
- Physical conditions:
  - T, n
- Chemical conditions:
  - Cold vs. hot core chemistry
  - Chemical clocks

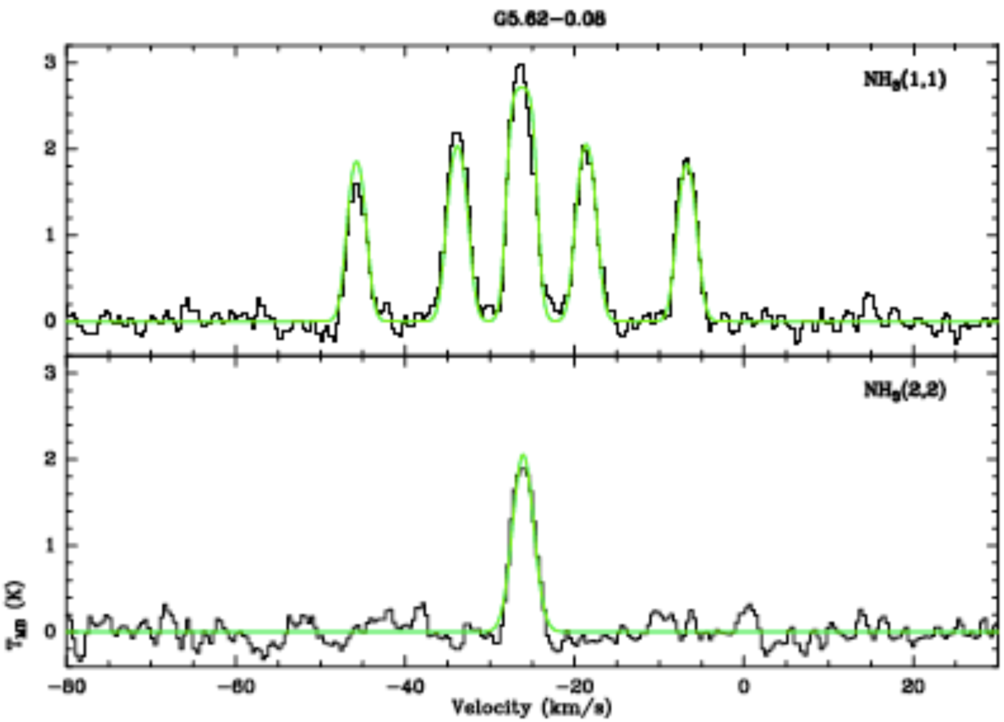
ATLASGAL: Distances & temperatures → masses

> 10 000 sources identified

Physical parameters?

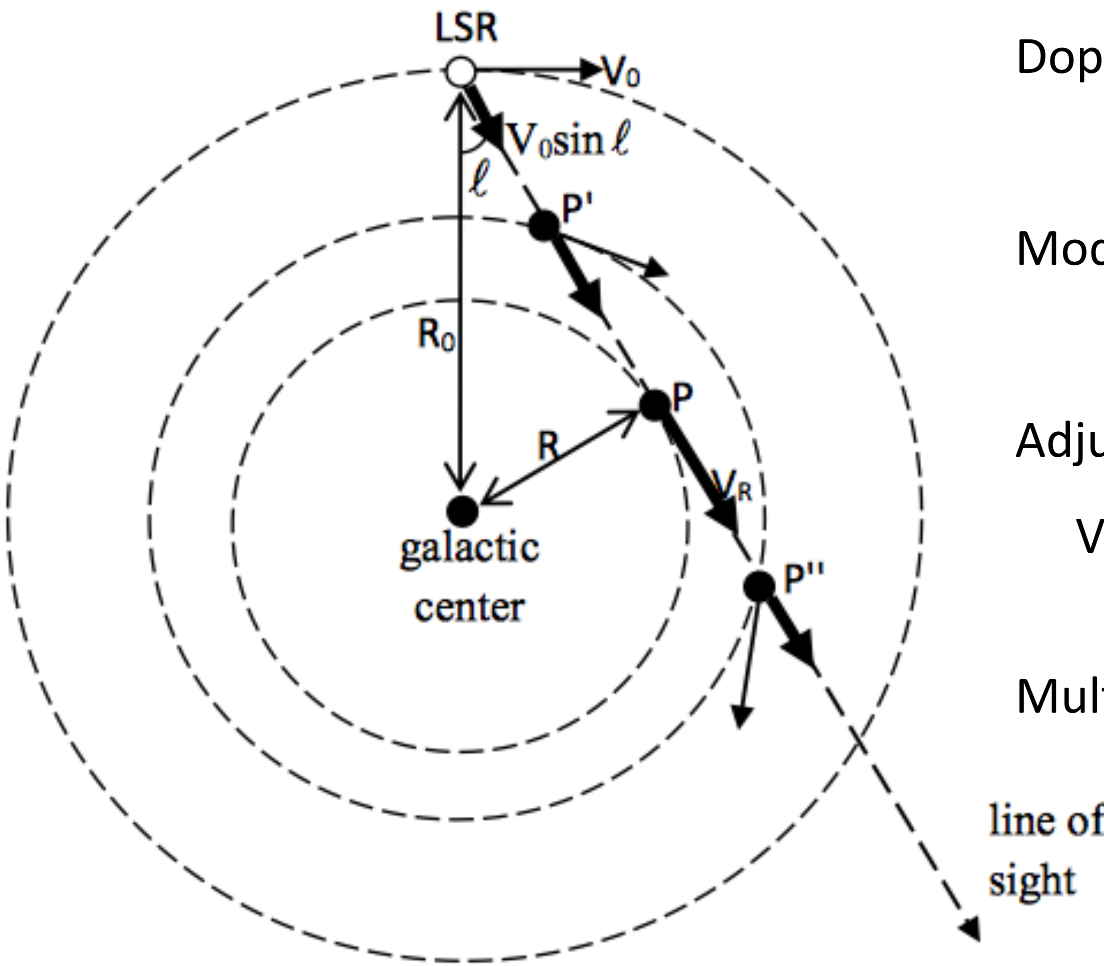
- > 2000 sources followed-up in NH_3 with the Effelsberg and Parkes telescopes (Wienen+ 2012, 2015)
  - → Kinematic distance
  - → Temperature (from NH_3 1,1 and 2,2 lines)

→ Mass and luminosity
→ can be derived!



Lines from many other molecules with Mopra and APEX

Kinematic Distances



Doppler shift:

$$V_{Dop} = V - V_{sun}$$

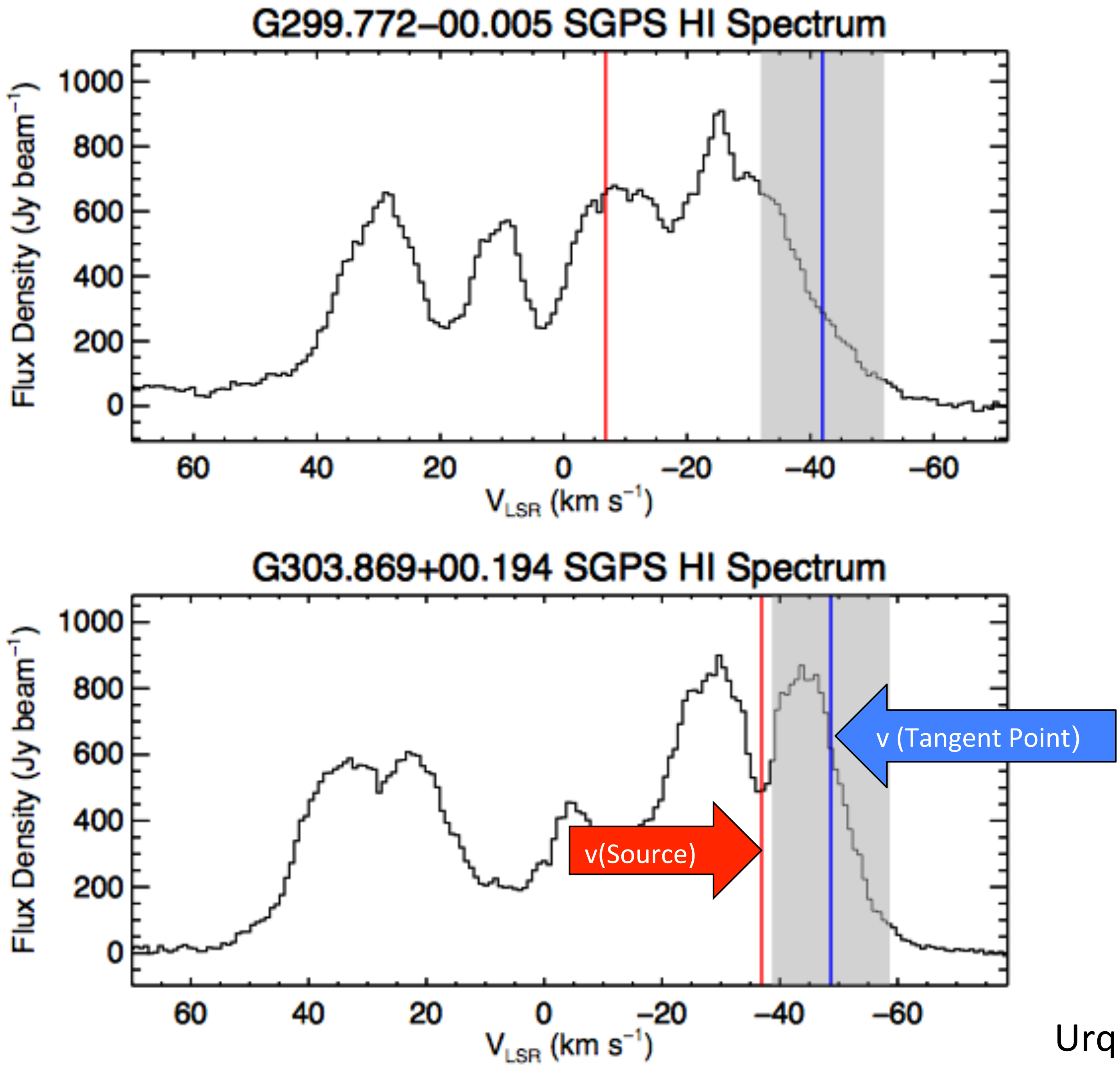
Model (Gal. Rotation):

$$V_{mod}(R_o, Q_o, l, D)$$

Adjust D to match

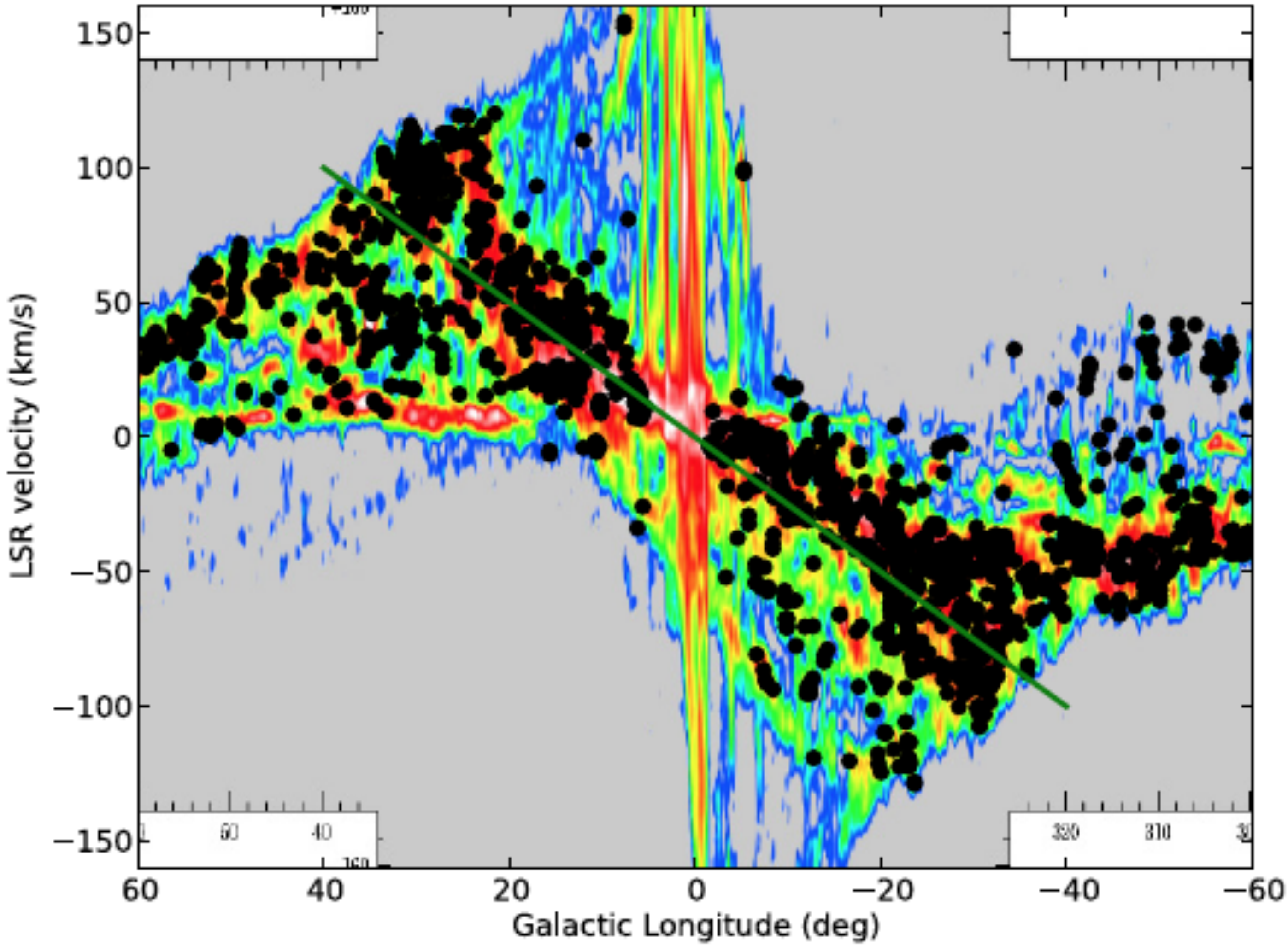
V_{mod} to V_{dop}

Multi-valued in inner Galaxy



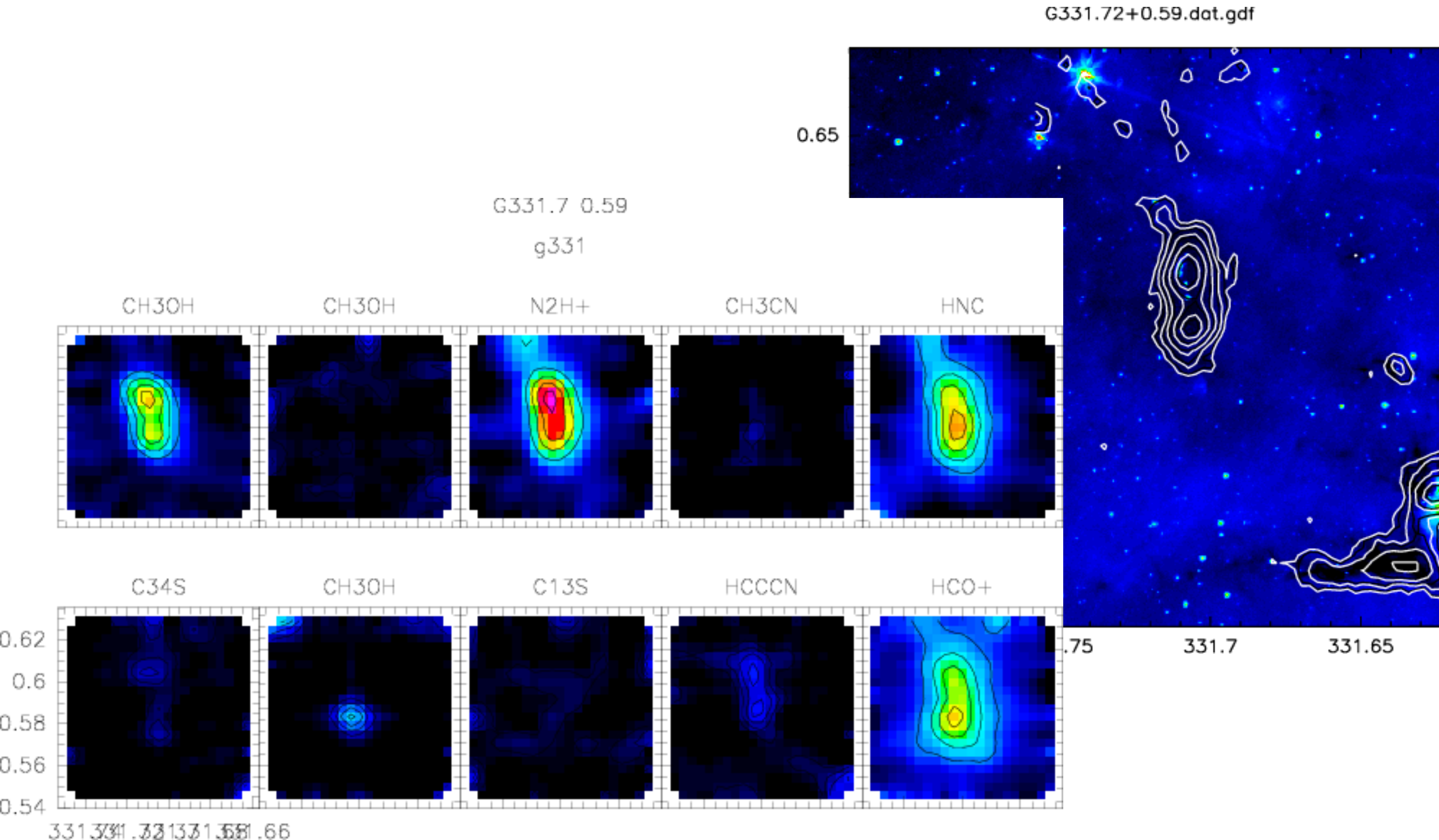
Urquhart+ 2015

ATLASGAL source velocities on CfA CO

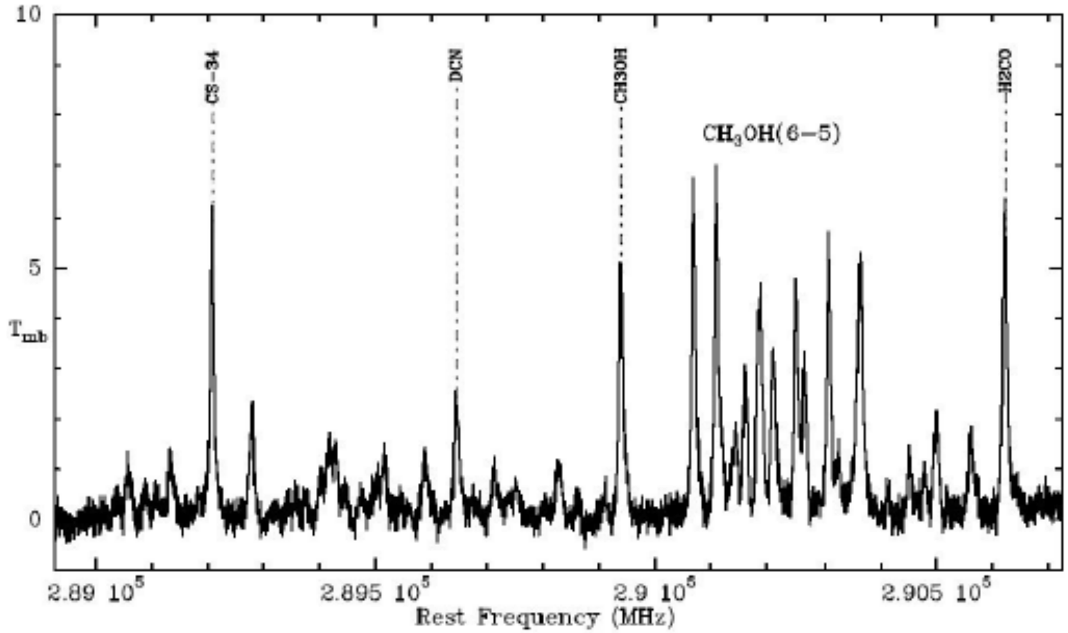


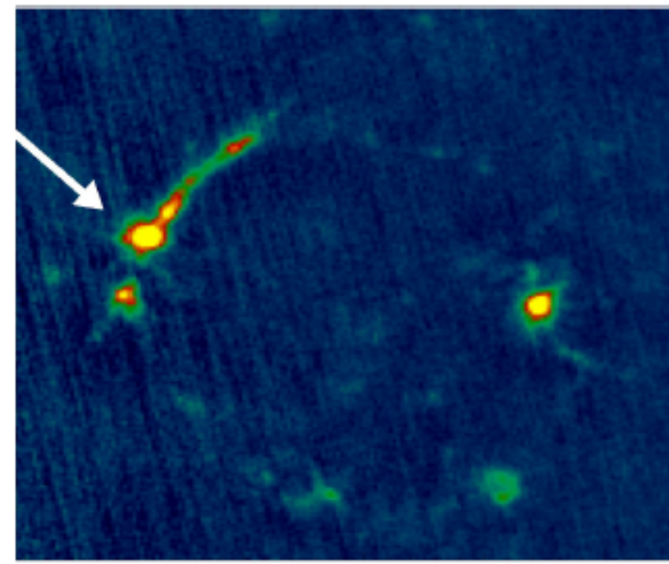
Wienen+ 2015

Molecular line maps / examples:

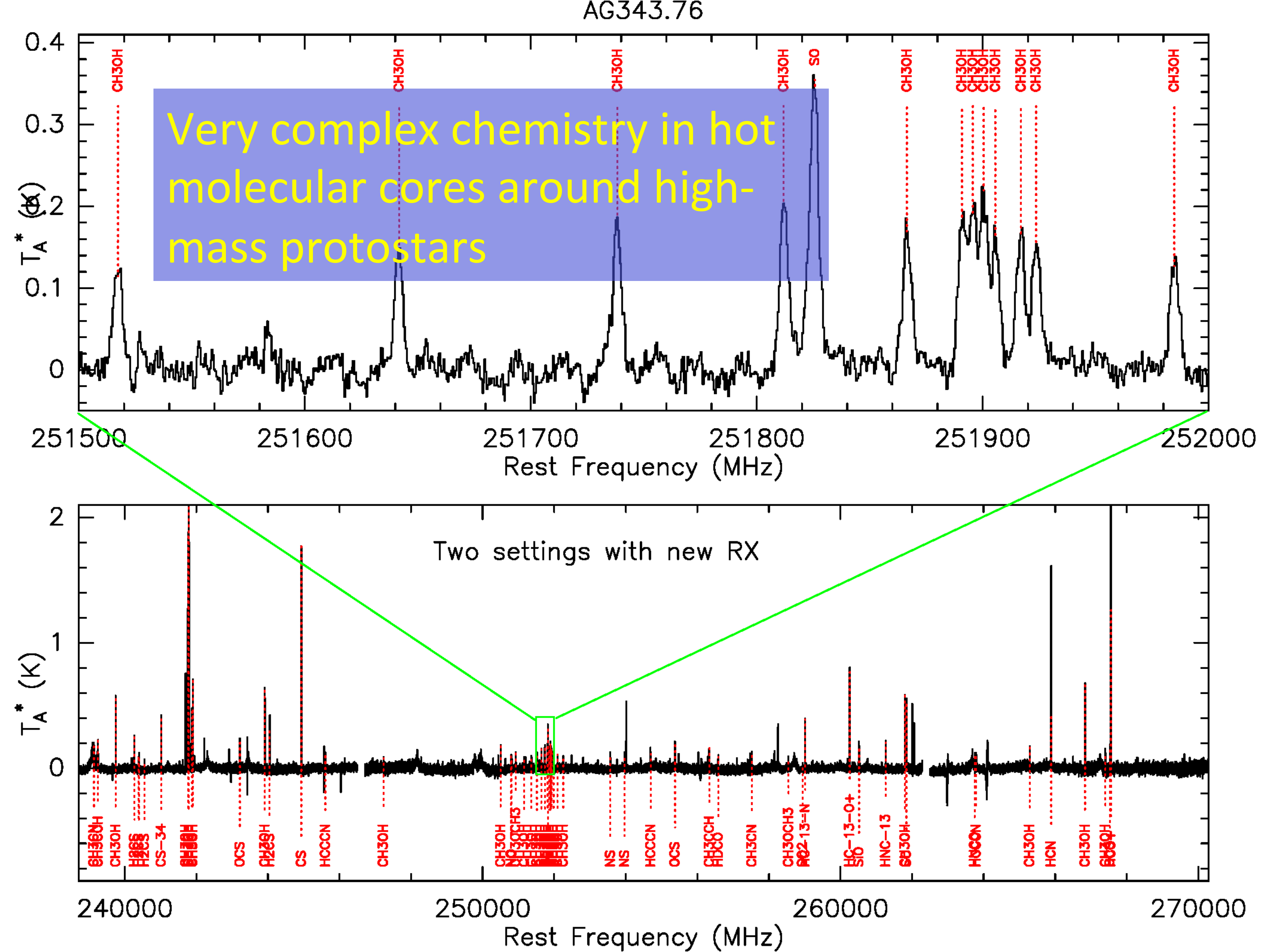


IRAS 17233-3606 : hot molecular core



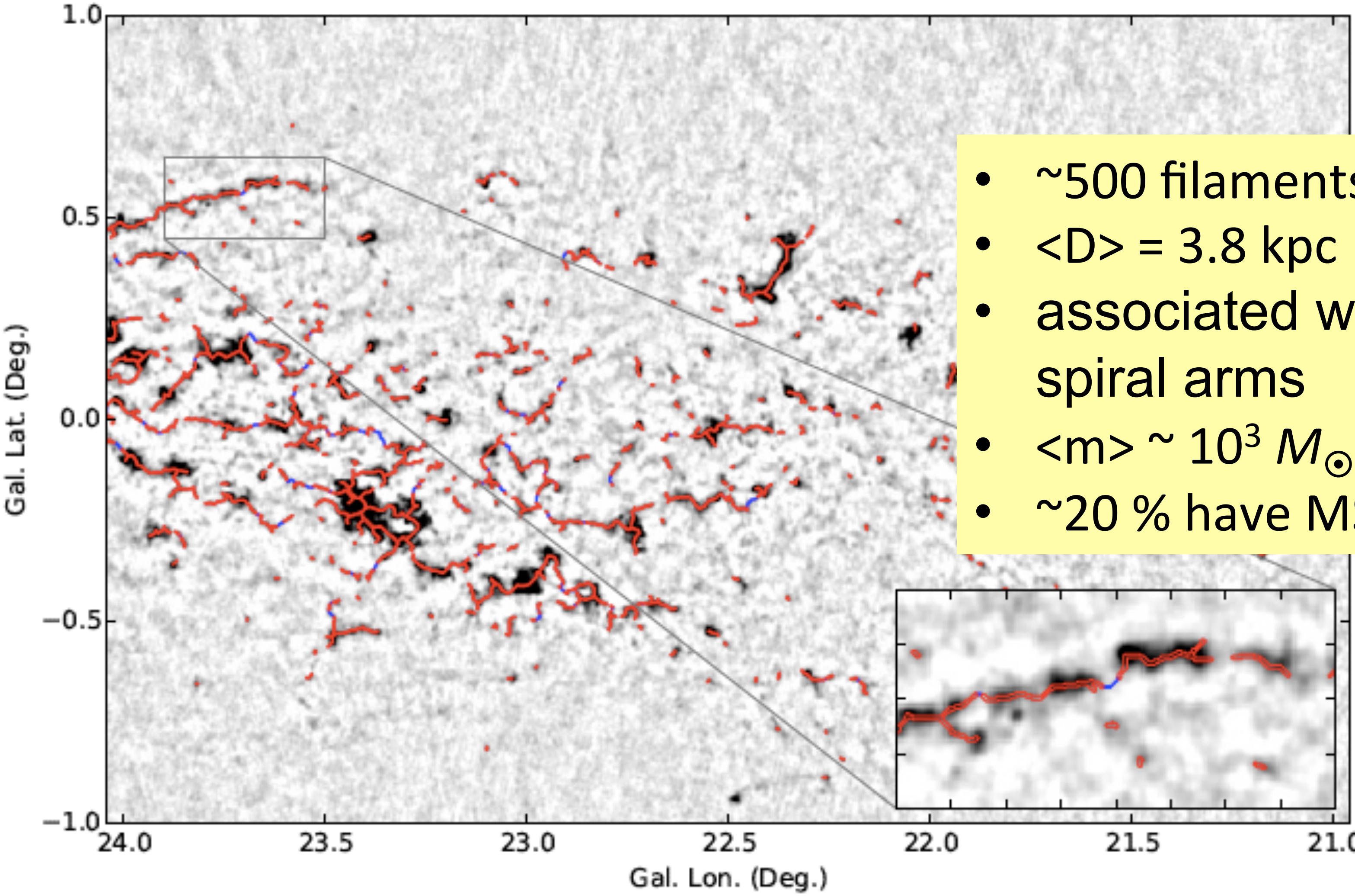


- $F_{\nu,peak}(870\ \mu m) = 47$ Jy, $F_{\nu,integ}(870\ \mu m) = 155$ Jy
- if $D = 1$ kpc, $T = 50$ K : $M \approx 500\ M_\odot$
- if $D = 1$ kpc, bubble diameter ≈ 5 pc

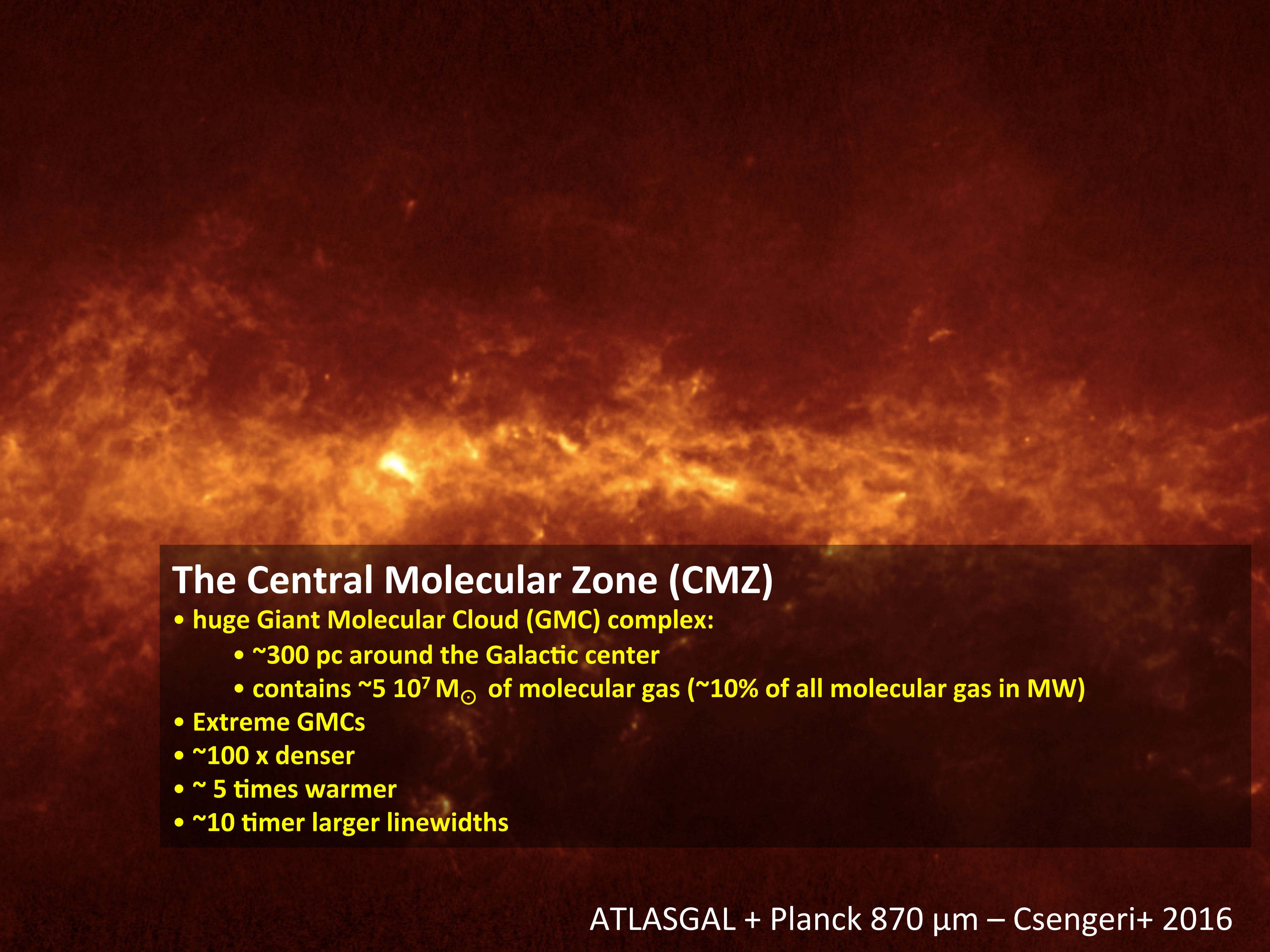

AG343.76
Very complex chemistry in hot molecular cores around high-mass protostars
CH3OH
SO
T_A^* (K)
0.4
0.3
0.2
0.1
0
251500
251600
251700
251800
251900
252000
Rest Frequency (MHz)
Two settings with new RX
2
1
0
T_A^* (K)
CH3OH
CS−34
OCS
CS
HCCCN
NS
CH3CN
HNC−13
HCN
240000
250000
260000
270000
Rest Frequency (MHz)

ATLASGAL — A Galaxy-wide sample of dense filamentary structures★

Guang-Xing Li[1,2★★], J. S. Urquhart[1,3], S. Leurini[1], T. Csengeri[1], F. Wyrowski[1], K. M. Menten[1] and F. Schuller[4]



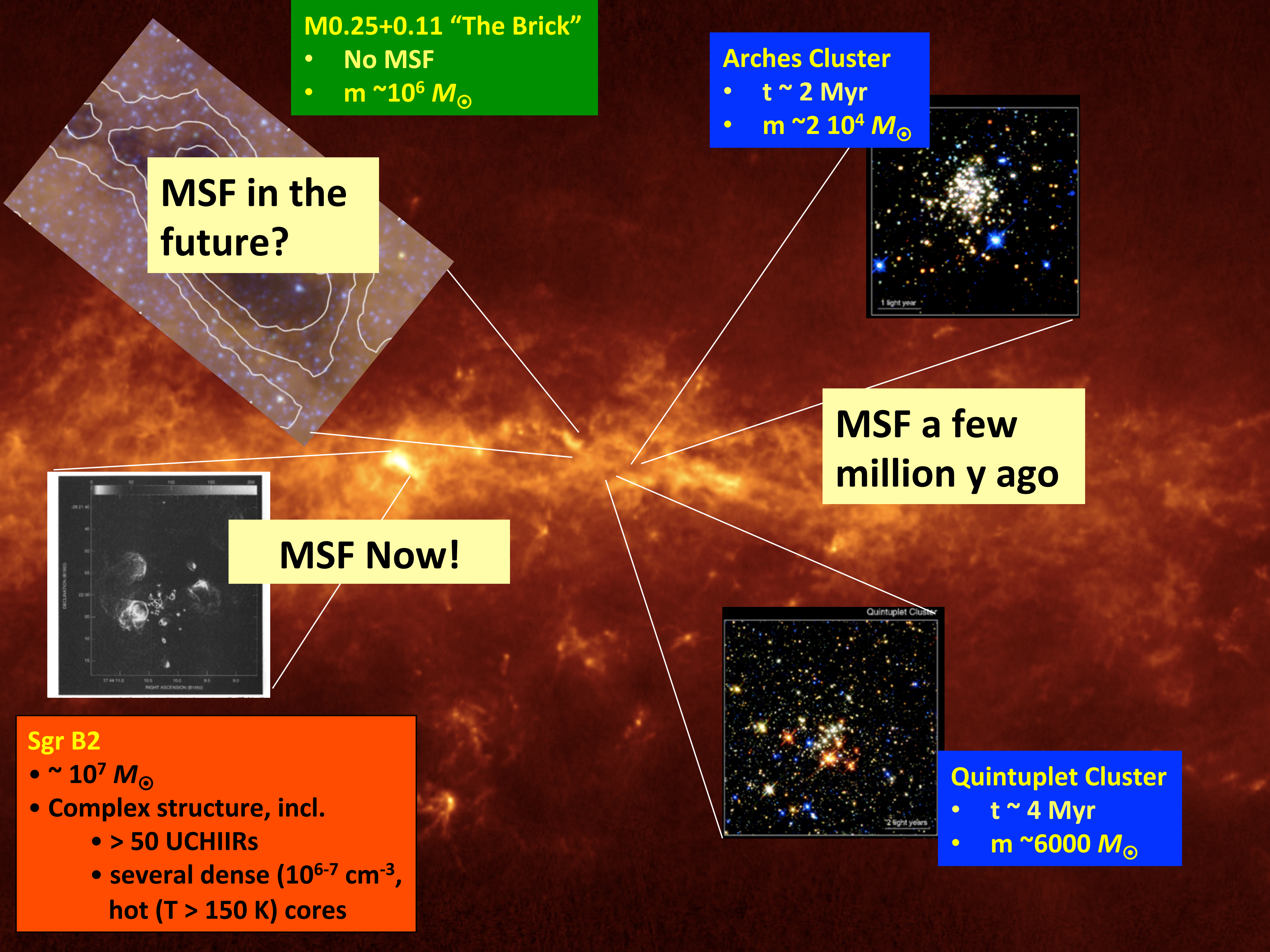
- ~500 filaments
- <D> = 3.8 kpc
- associated with spiral arms
- <m> ~ $10^3\ M_\odot$
- ~20 % have MSF



The Central Molecular Zone (CMZ)

- huge Giant Molecular Cloud (GMC) complex:
    - ~300 pc around the Galactic center
    - contains ~5 10^7 $M_\odot$ of molecular gas (~10% of all molecular gas in MW)
- Extreme GMCs
- ~100 x denser
- ~ 5 times warmer
- ~10 timer larger linewidths

ATLASGAL + Planck 870 µm – Csengeri+ 2016


M0.25+0.11 “The Brick”
• No MSF
• m ~10^6 $M_\odot$
MSF in the future?
Arches Cluster
• t ~ 2 Myr
• m ~2 10^4 $M_\odot$
1 light year
MSF a few million y ago
MSF Now!
Quintuplet Cluster
2 light years
Quintuplet Cluster
• t ~ 4 Myr
• m ~6000 $M_\odot$
Sgr B2
• ~ 10^7 $M_\odot$
• Complex structure, incl.
• > 50 UCHIIRs
• several dense (10^{6-7} cm^{-3}, hot (T > 150 K) cores

The future has arrived!!

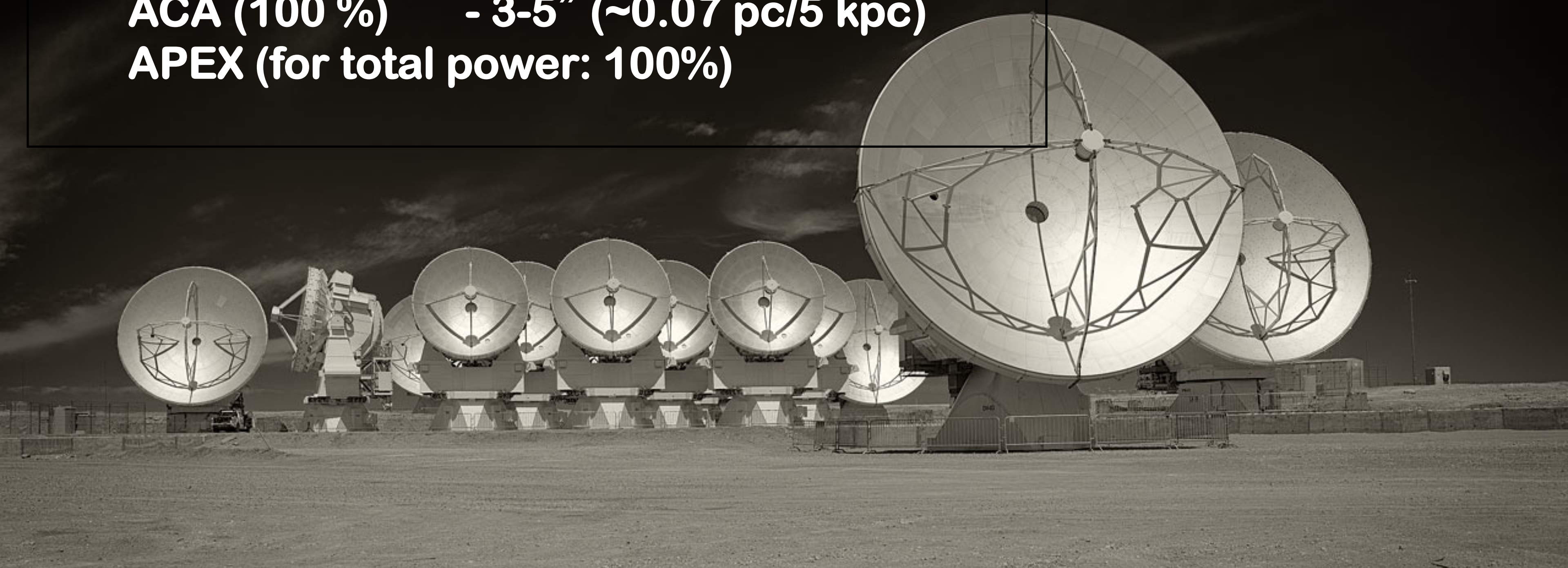
Atacama Large Millimeter/submillimeter Array

- 50 x 12 m ∅ antennas + 12 x 7 m ∅ antennas
- Interferometer
- maximal resolution 0.01“ (1000 times higher than APEX)
- European-North-American-Japanese project

ALMA follow-up of massive ATLASGAL clumps. Image:

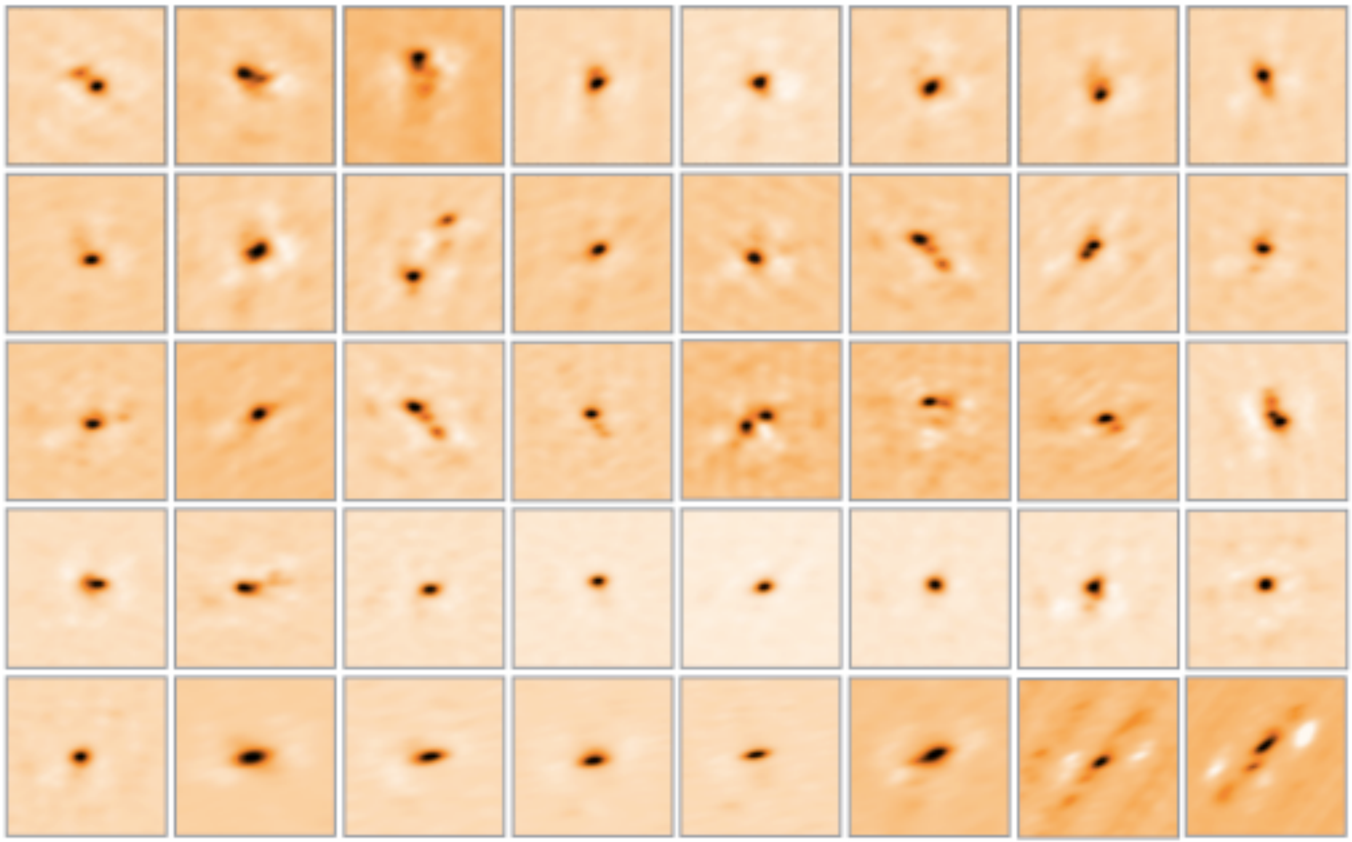
- Fragmentation
- Energetics
- Chemistry

46 sources imaged
ALMA (100 %) - 0.6" (3000 AU/5 kpc)
ACA (100 %) - 3-5" (~0.07 pc/5 kpc)
APEX (for total power: 100%)



The first step: from clump to core scales…

ACA: 3”-5” resolution for all sources completed (FWHM ~ 0.05 pc)



870 μm continuum

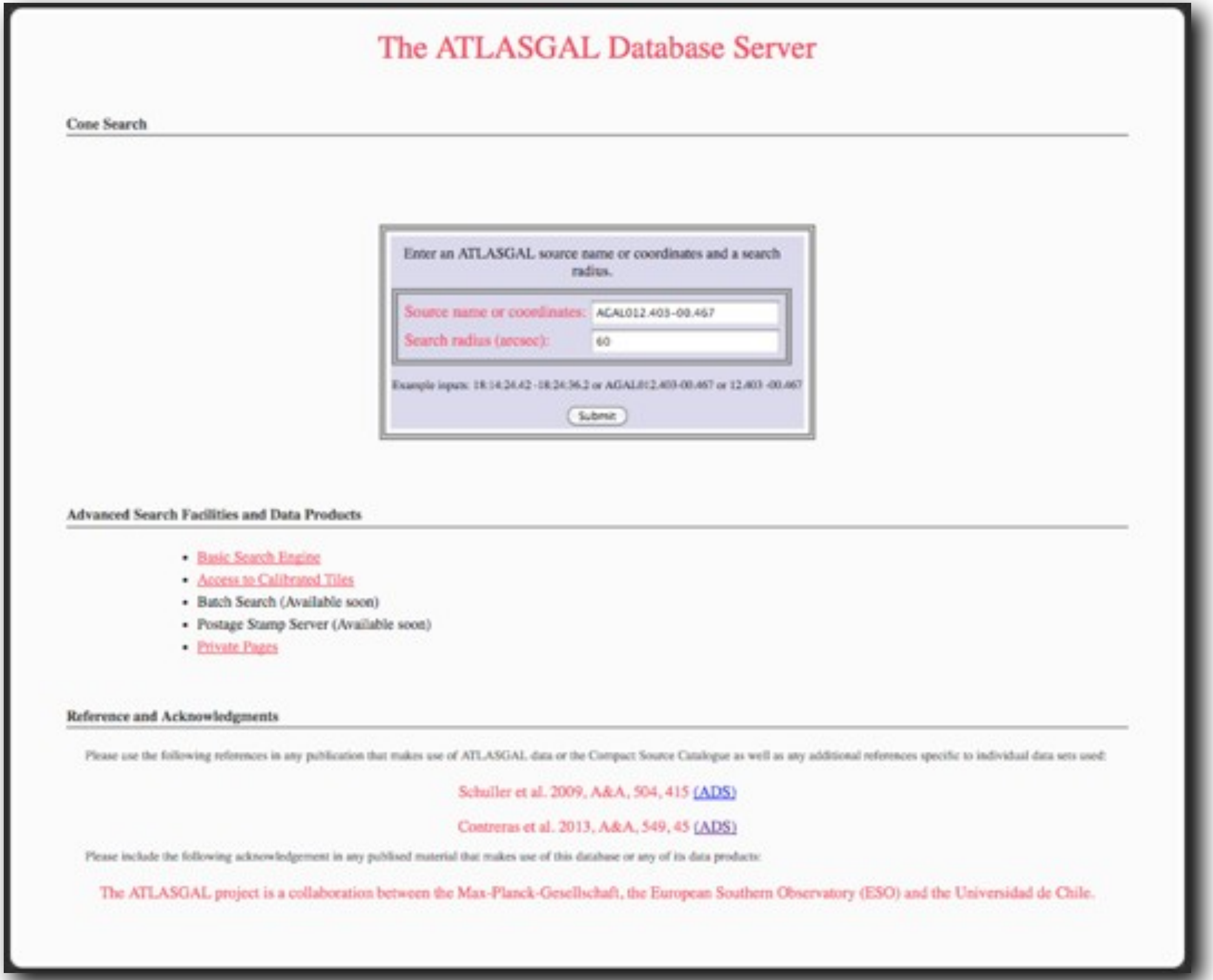
Csengeri+ (in prep.)

ATLASGAL – a path-finding survey for star formation in the Galaxy

- Large scale distribution of dense material
  - unbiased, the only survey covering the Inner Galaxy (±60° in *l*)
    - northern submm telescopes limited to $l > 10°$
    - discovery of very extended molecular cloud complexes
- Complete census of protoclusters down to moderate mass
- “Finding charts” for ALMA
- Great synergy with Herschel SPIRE and PACS
  - full characterization of dust properties
  - with HiGAL and MIPSGAL: continuous database at ~20” resolution
- molecular spectroscopy follow-ups deliver
  - distances
  - chemistry, physical conditions, internal kinematics
- Great legacy value:
  - Calibrated images
  - Catalogs of
    - compact sources
    - extended objects
    - cross IDs with Spitzer/Herschel data: SEDS from 3 to 870 µm

ATLASGAL Database

Max-Planck-Institut für Radioastronomie



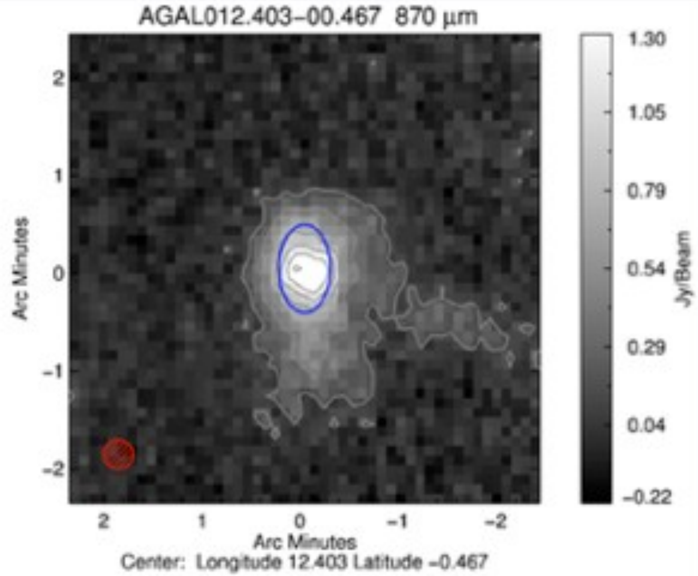
http://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi

ATLASGAL Database

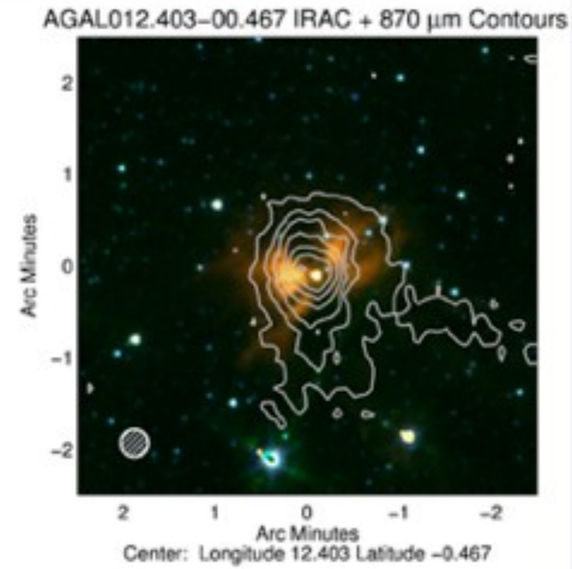
Max-Planck-Institut für Radioastronomie

Dust Emission Image and Catalogue Parameters

ATLASGAL 870 μm Emission Map (5' x 5')



(fits file) (postscript file)



(3.5μm 4.6μm 5.8μm 8.0μm fits files) (postscript file)

Catalogue Parameters

Source Name	RA	Dec	Size	PA	Eff. Radius	Peak Flux	Integrated Flux	Detection
	(J2000)	(J2000)	(")	(°)	(")	(Jy beam^{-1})	(Jy)	Flag
AGAL012.403-00.467	18:14:24.42	-18:24:36.2	27 x 16	0	46	1.50	11.66	0

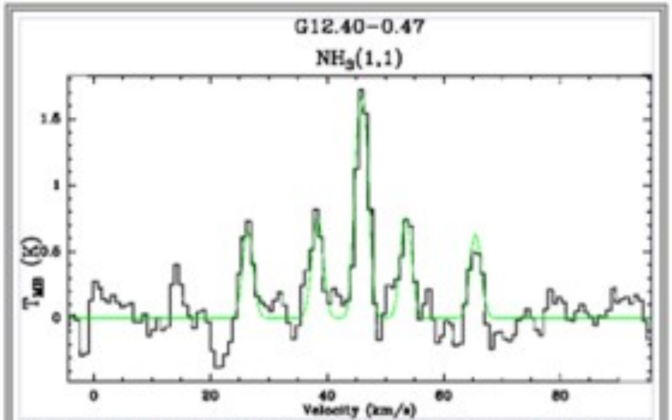
http://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi

ATLASGAL Database

Max-Planck-Institut für Radioastronomie

Effelsberg NH_3 Observations

Ammonia Spectra



NH_3 (1,1) emission is shown in black and the fit to the data is overplotted in green.

(Postscript file available)

Ammonia Fit Parameters

			Line Transition														
			NH_3 (1,1)					NH_3 (2,2)				NH_3 (3,3)				
Cat. Id.	Cat. Name	Offset (")	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	Optical Depth	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	Reference
197	G12.40-0.47	9.43	90	45.43	1.66	1.75	1.03	80	45.01	0.45	2.74	70	45.38	0.30	2.05	Wienen et al. 2012

http://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi

ATLASGAL

Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

European Southern Observatory

Universidad de Chile

Th

L xy

A long line of students

Laura Gomez-Gonzalez, Esteban Morales, Kazi Rygl, Tobias Troost, Katharina Immer, Guang-Xing, Li, Marion Wienen, Michael Mattern, Yanett Contreras, …

MP K. Menten, P. Schilke,

er, T. Henning, H. Linz

ESO : M.), S. Bontemps, R. Cesaroni, L. Deharveng,

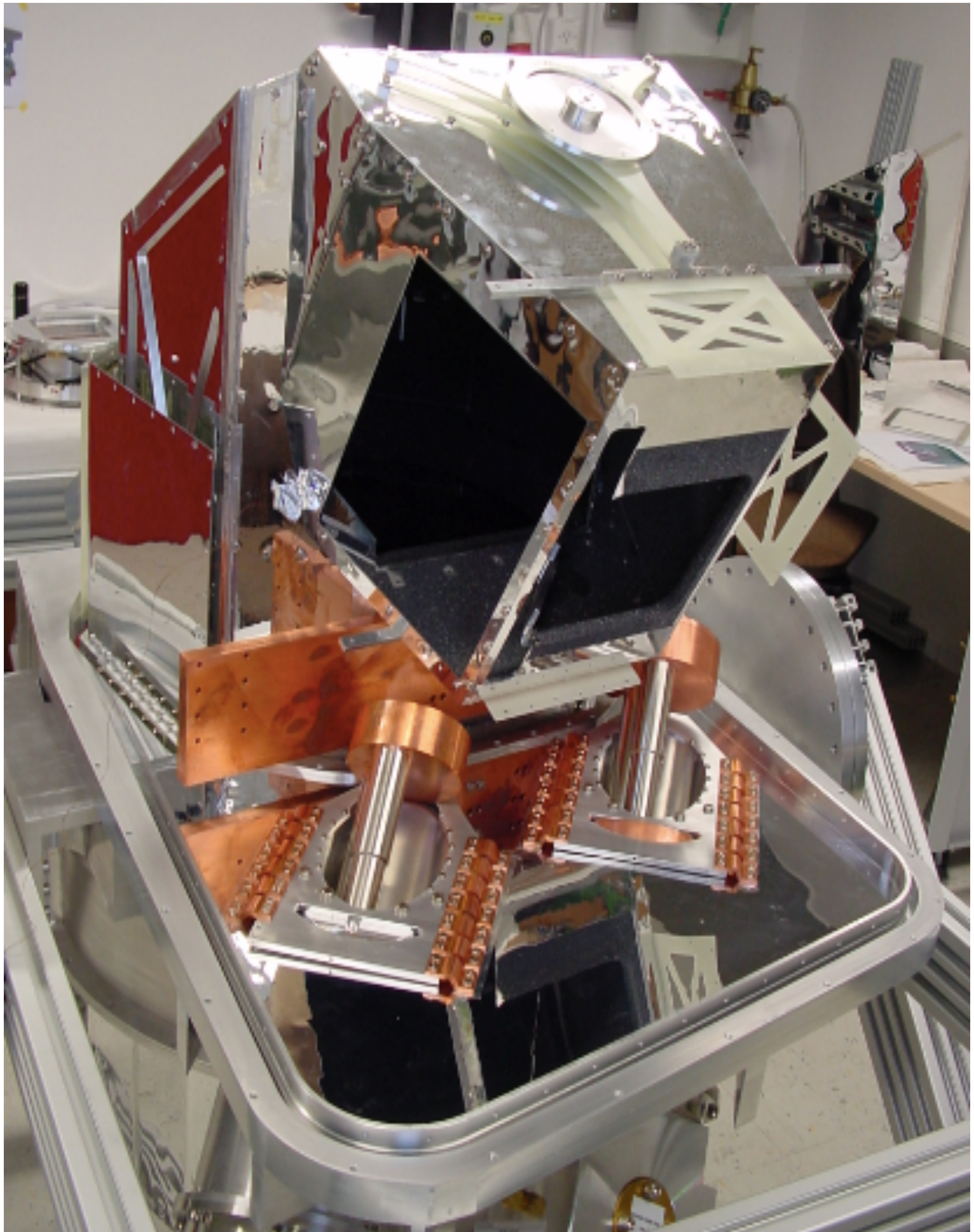
F. Herpin, och, S. Molinari, F. Motte, V. Minier, L.-Å. Nyman,

V. Reveret, C. Risacher, N. Schneider, L. Testi, A. Zavagno

Chile : L. Bronfman (co-PI), G. Garay, D. Mardones

+ T. Csengeri, J. Urquhart (→ U. Kent), A. Giannetti


YouTube DE
atlasgal
Close look at the ATLASGAL image of the plane of the Milky Way
European Southern Observatory (ESO)
ESO
Subscribe
11,269
324,211 views
Add to
Share
More
2,241
31

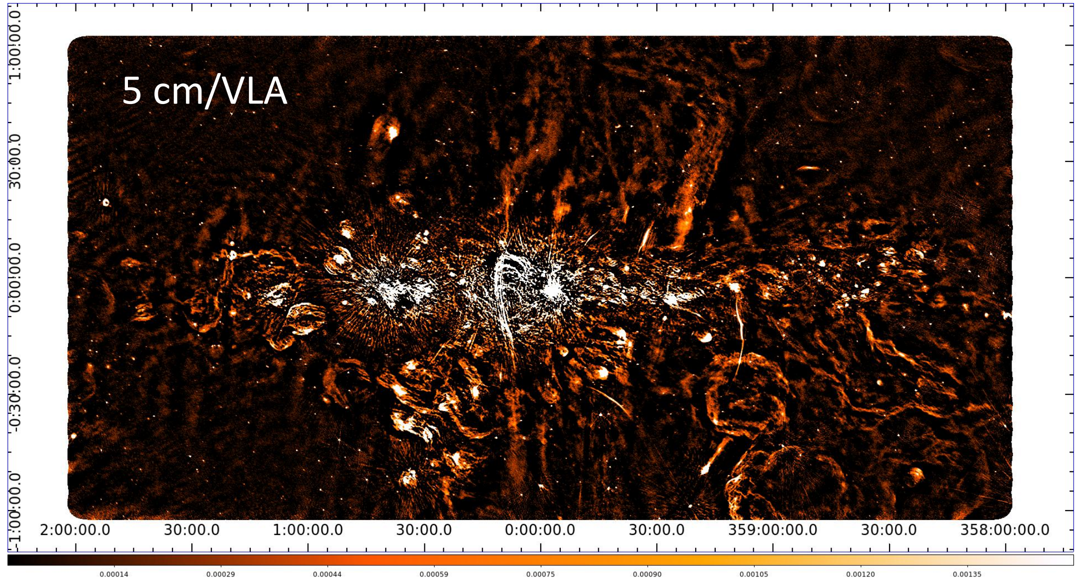


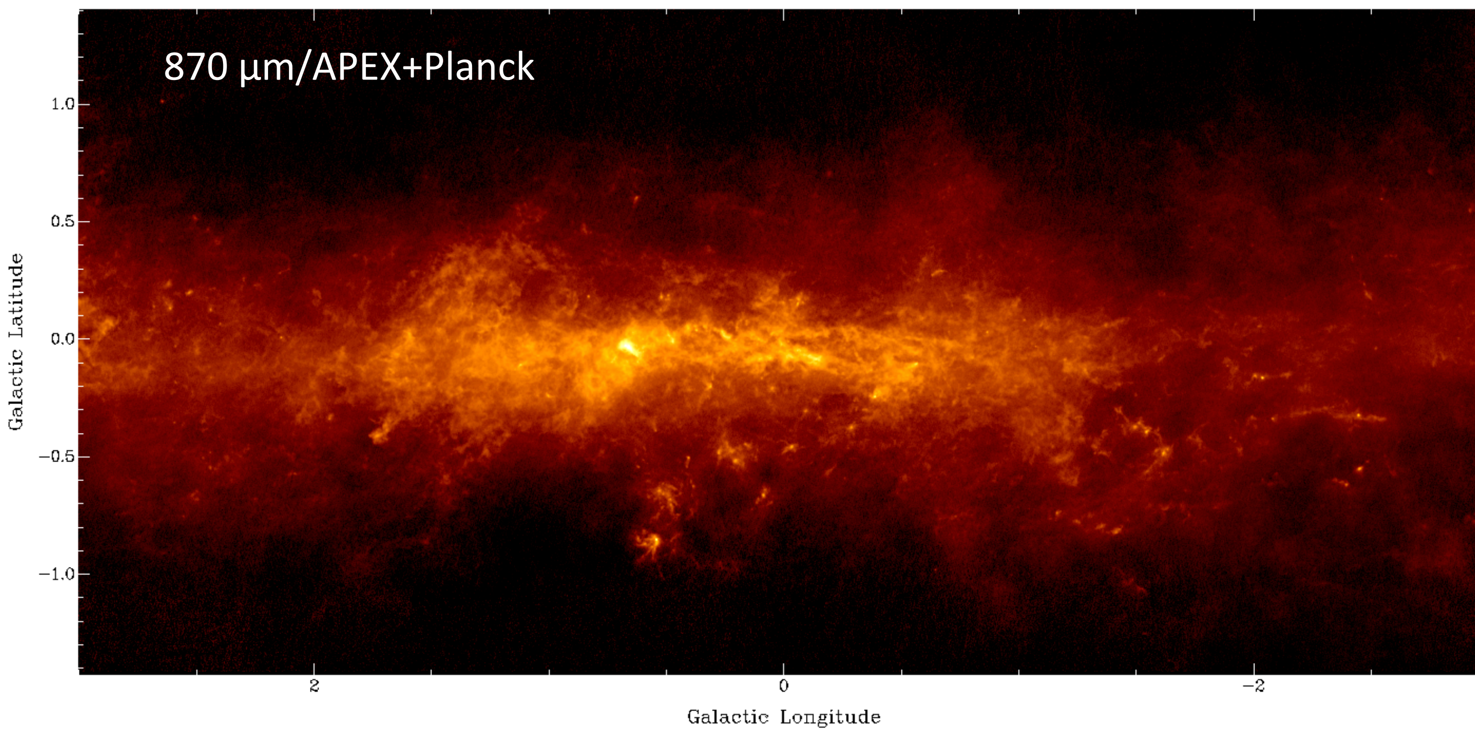
Repeat ATLASGAL with much more sensitively and in different colors

A-MKID
3520 pixel at 870 µm
21600 pixel at 350 µm
(filling 15’ FOV)
→ 2016

+ArTéMiS
5760 pixel 250+350+450 µm each
→2016

The NRAO Karl G. Jansky Very Large Array





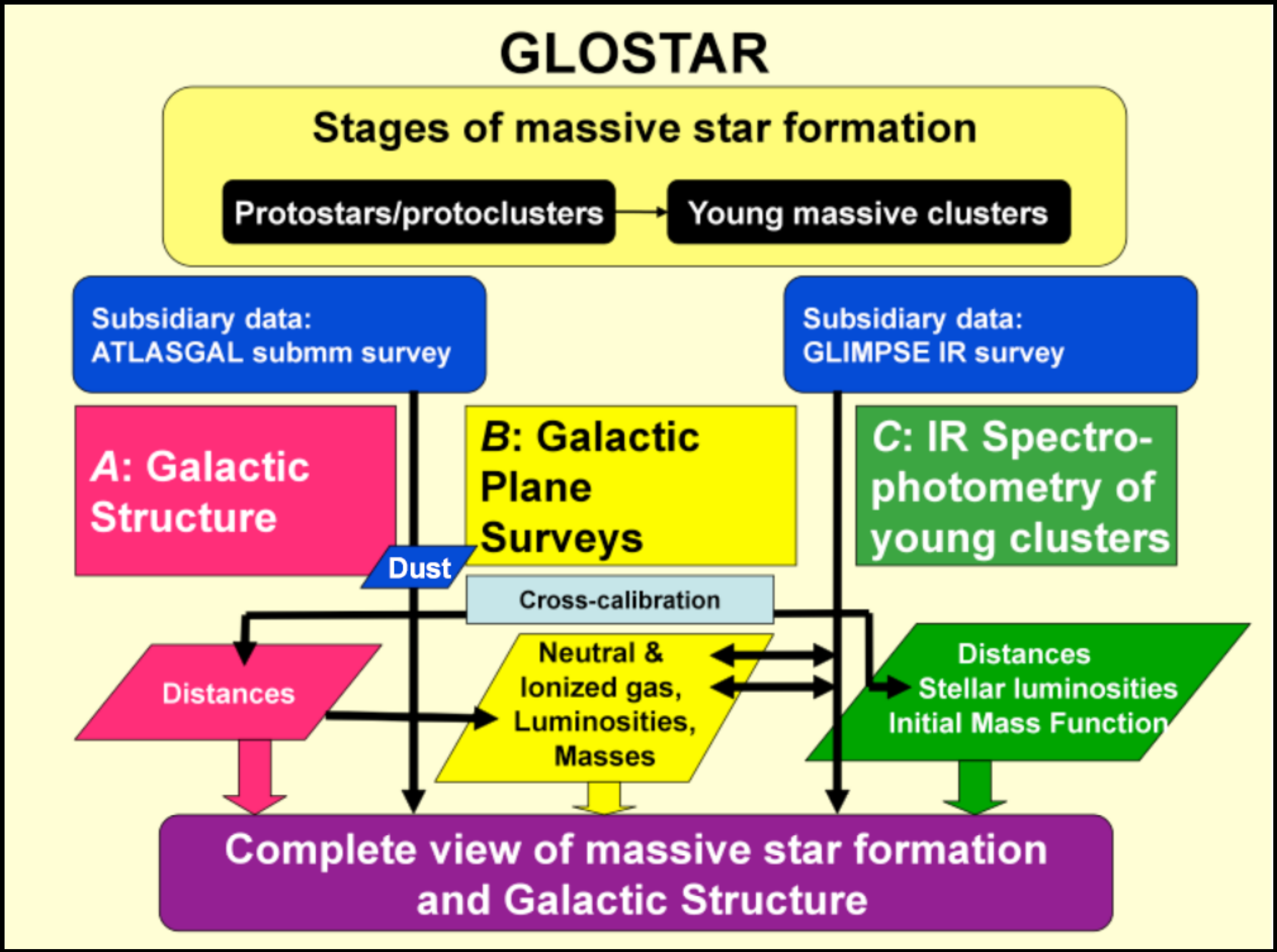
Questions of high-mass star formation and Galactic structure are intimately linked

M51 optical

M51 Hα

http://www.caha.es

GLOSTAR: A Global View of Star Formation in the Milky Way
European Research Council Advanced Investigator Grant



ERC Advanced Investigator Grant Contract No. 247048, PI: Karl M. Menten

HIPPARCOS

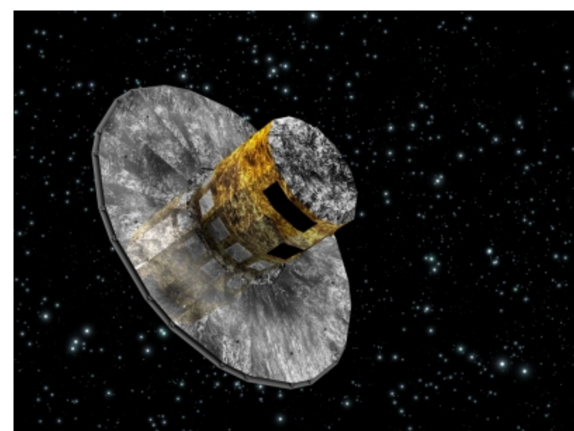
(HIgh Precision PARallax COllecting Satellite)

- 118,000 stellar parallaxes out to 150 pc
- σ_π ~ 0.001 arcseconds (1 mas)
- 10% accuracy at 100 pc…

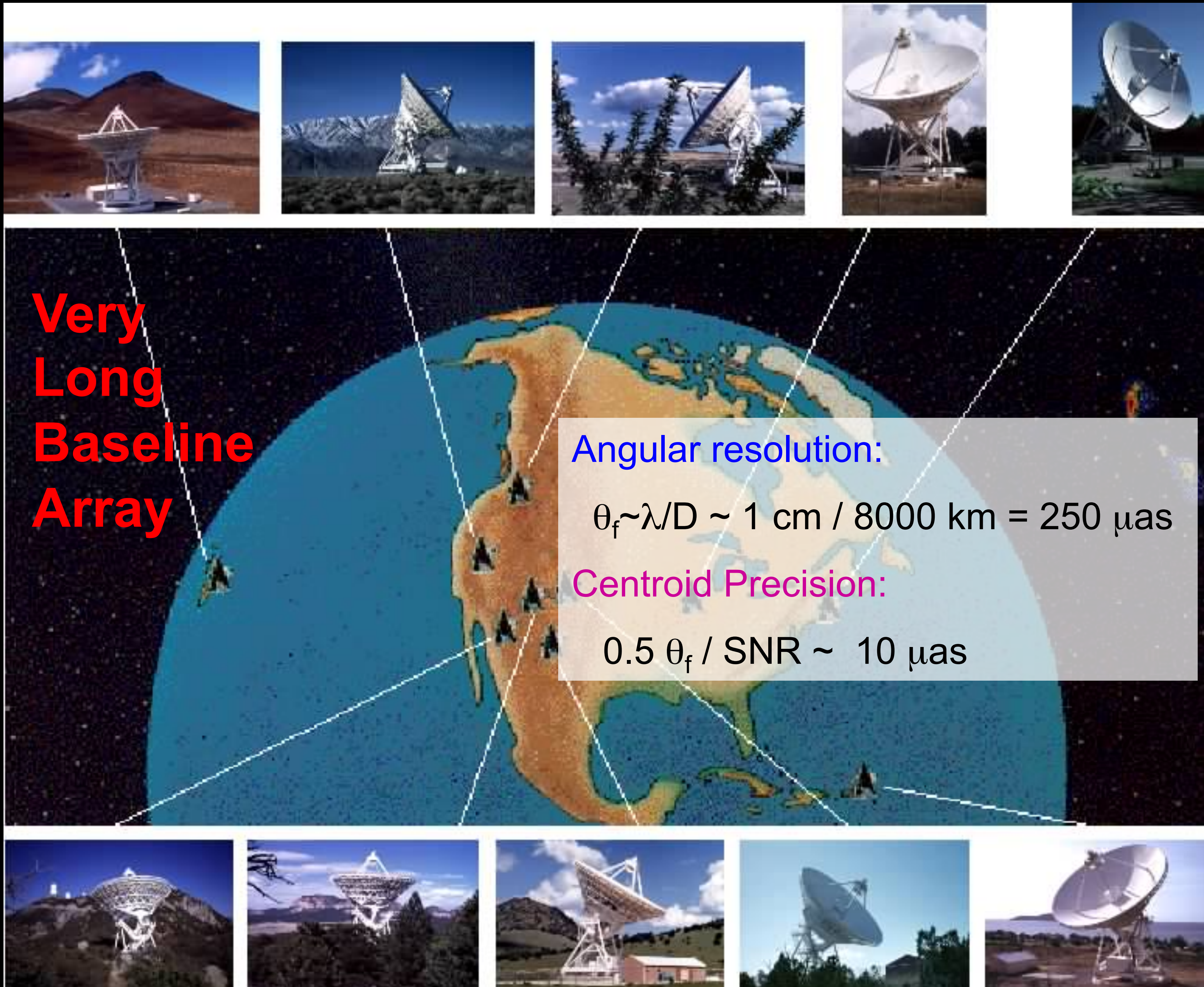
→ mapped solar neighborhood

Gaia space mission:

- Gaia: ~7–10 μas
- 10^8 stars out to 10 kpc

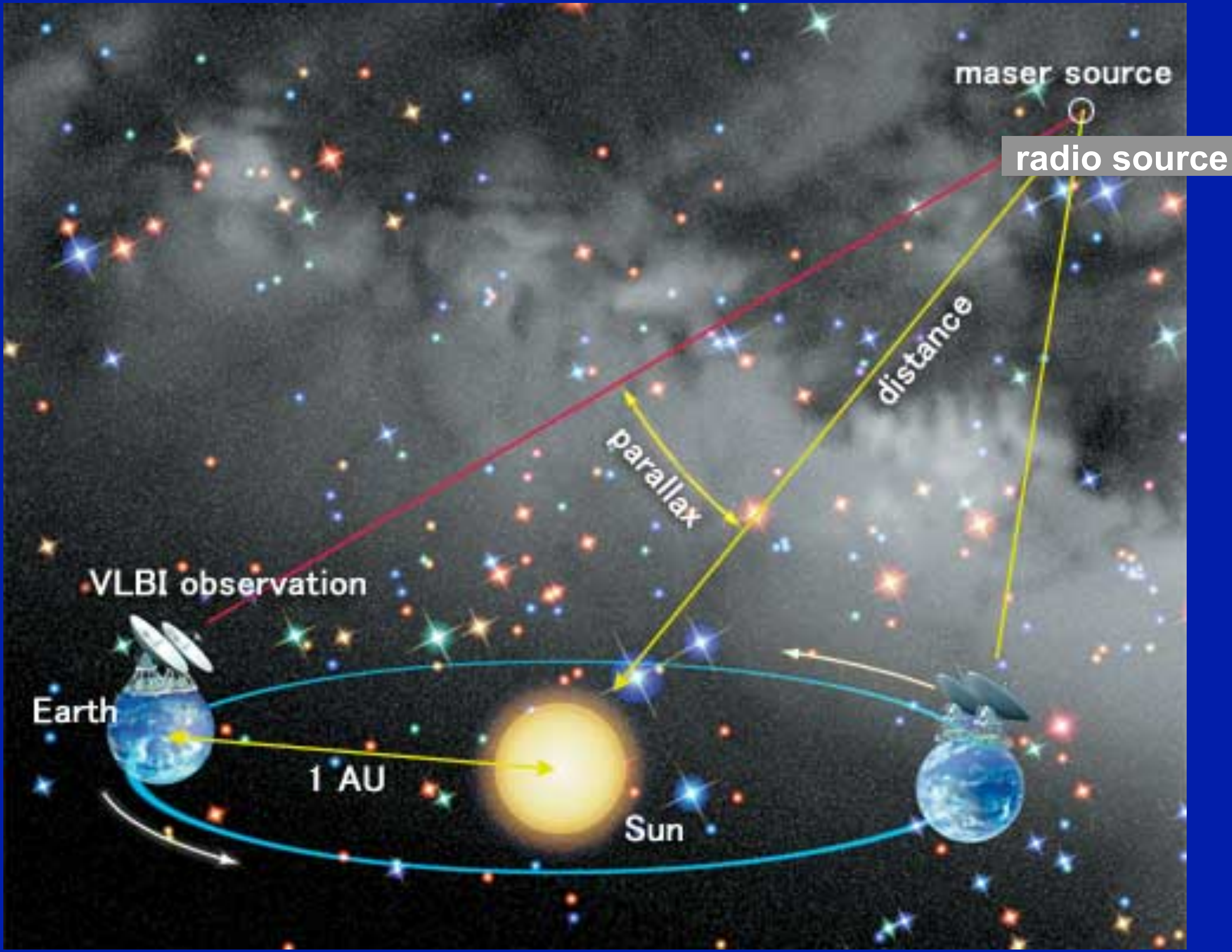


Perryman et al 1997 A&A 323 49



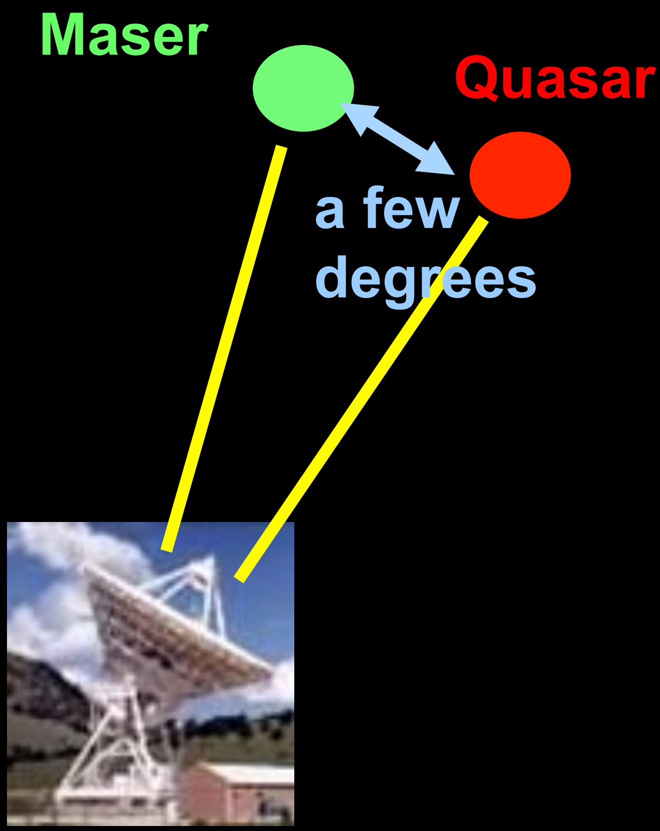
Very Long Baseline Array
Angular resolution:
$\theta_f \sim \lambda/D \sim 1$ cm / 8000 km = 250 μas
Centroid Precision:
$0.5\ \theta_f$ / SNR ~ 10 μas

VLBI Trigonometric Parallaxes



http://veraserver.mtk.nao.ac.jp/outline/vera2-e.html

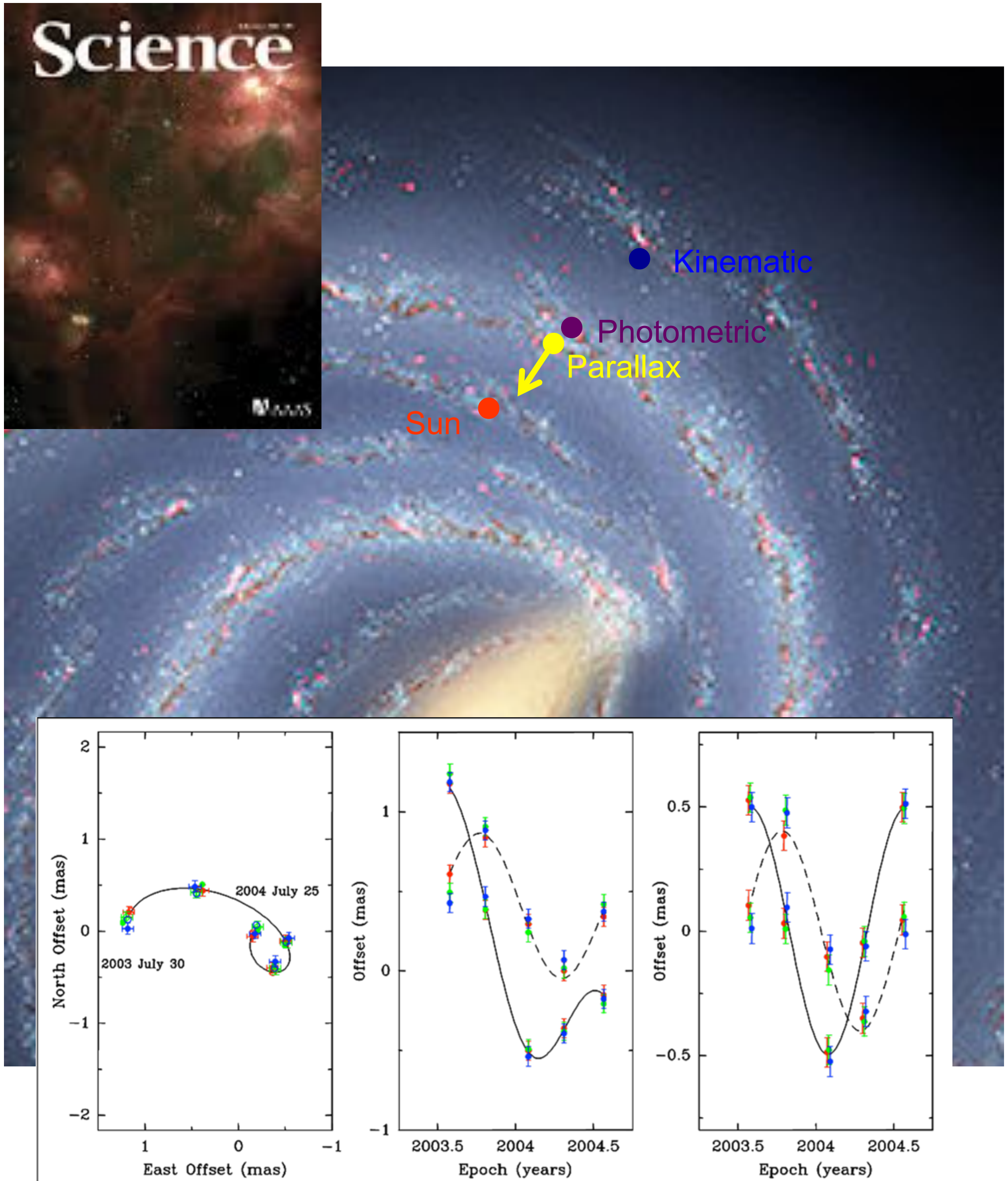
Phase referencing



VLBA: Switch every 15 second between maser and quasar

~50% duty cycle

The Distance to the Perseus Arm: W3OH Parallaxes



Distance estimates:

Kinematic = 4.3 kpc

Photometric = 2.2 kpc

R. Humphreys 1970s

Maser parallaxes:

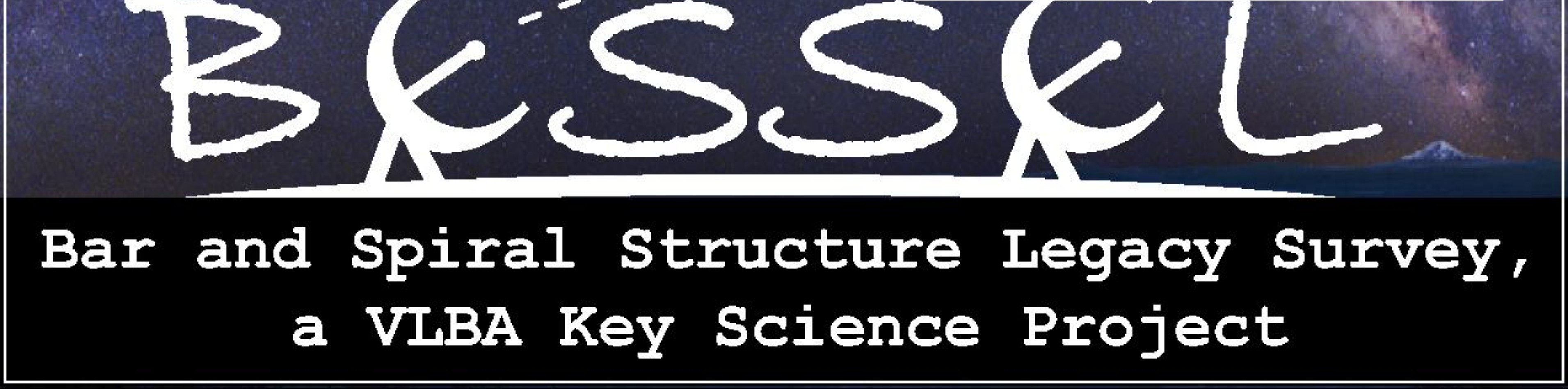
CH_3OH 1.95±0.04 kpc

Xu et al. 2005

H_2O 2.04±0.07 kpc

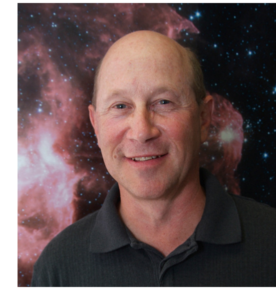
Hachisuka et al. 2006

- $D_{photo} \sim D_{parallax}$
- D_k way off
- In Perseus Arm, not in Outer Arm
- Large peculiar V



Friedrich Wilhelm Bessel
(1748 –1846)

The BeSSel Team:



Mark Reid (PI), Tom Dame, Harvard-Smithsonian Center for Astrophysics, USA
Karl Menten, **Andreas Brunthaler**, Mayumi Sato, Alberto Sanna Max-Planck-Institut für Radioastronomie, Germany
,

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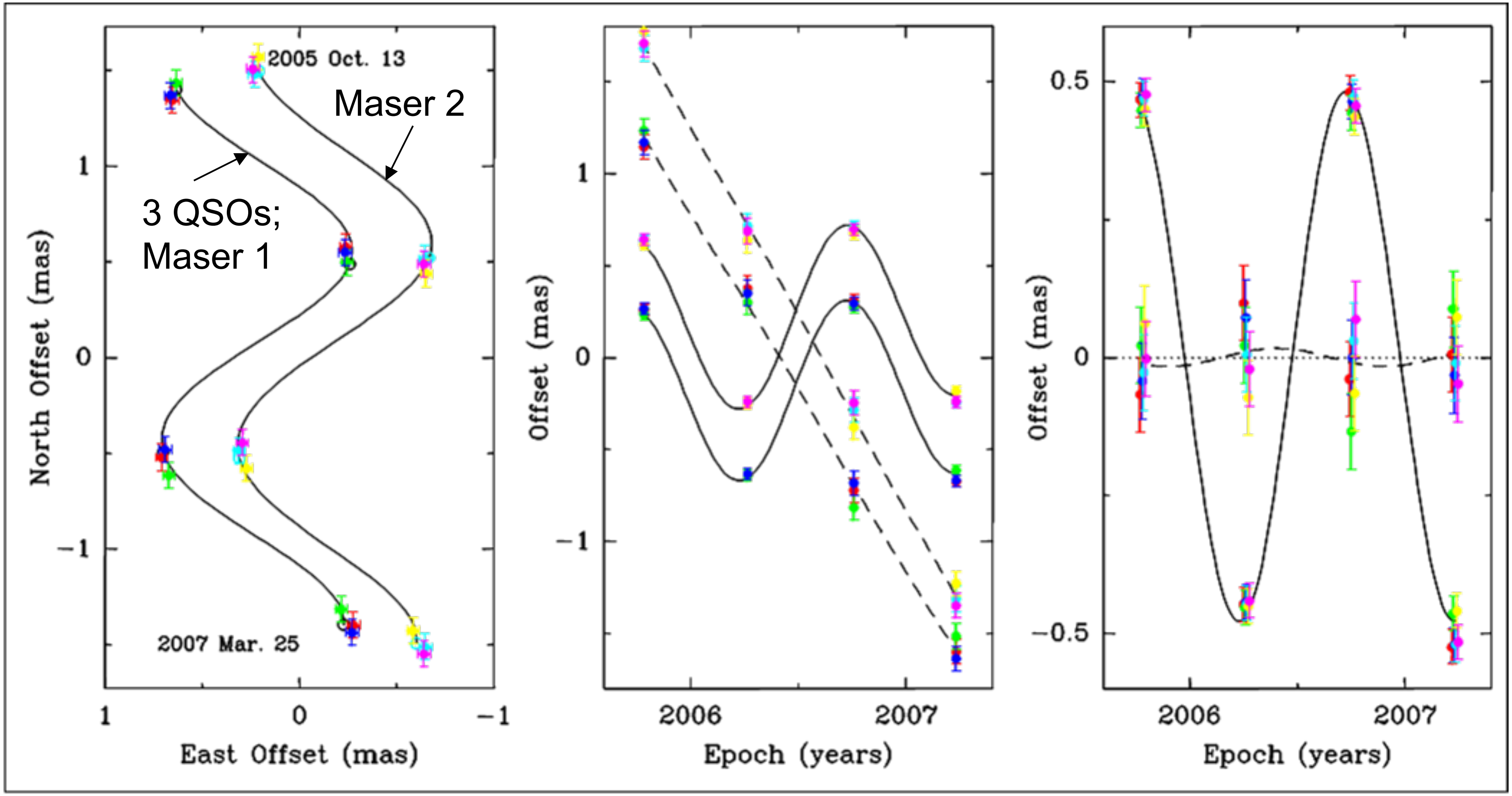
Yuanwei Wu	ex-MPifR, now NAOJ
Ye Xu, Jing Jing Li	ex-MPIfR, now PMO, Nanjing, China
Bo Zhang	ex-MPIfR, now Shanghai Astronomical Obs., China
Yoon Choi	ex-MPIfR, now Korean Astronomy & Space Science Inst.
Katharina Immer	ex-MPIfR, now ESO
Kazuya Hachisuka	ex-MPIfR, now Yamaguchi University, Japan
Kazi Rygl	ex-MPIfR, now INAF Bologna, Italy
Luca Moscadelli	ex-MPIfR, now Osservatorio di Arcetri, Florence, Italy

S 252 Parallax: using CH_3OH masers



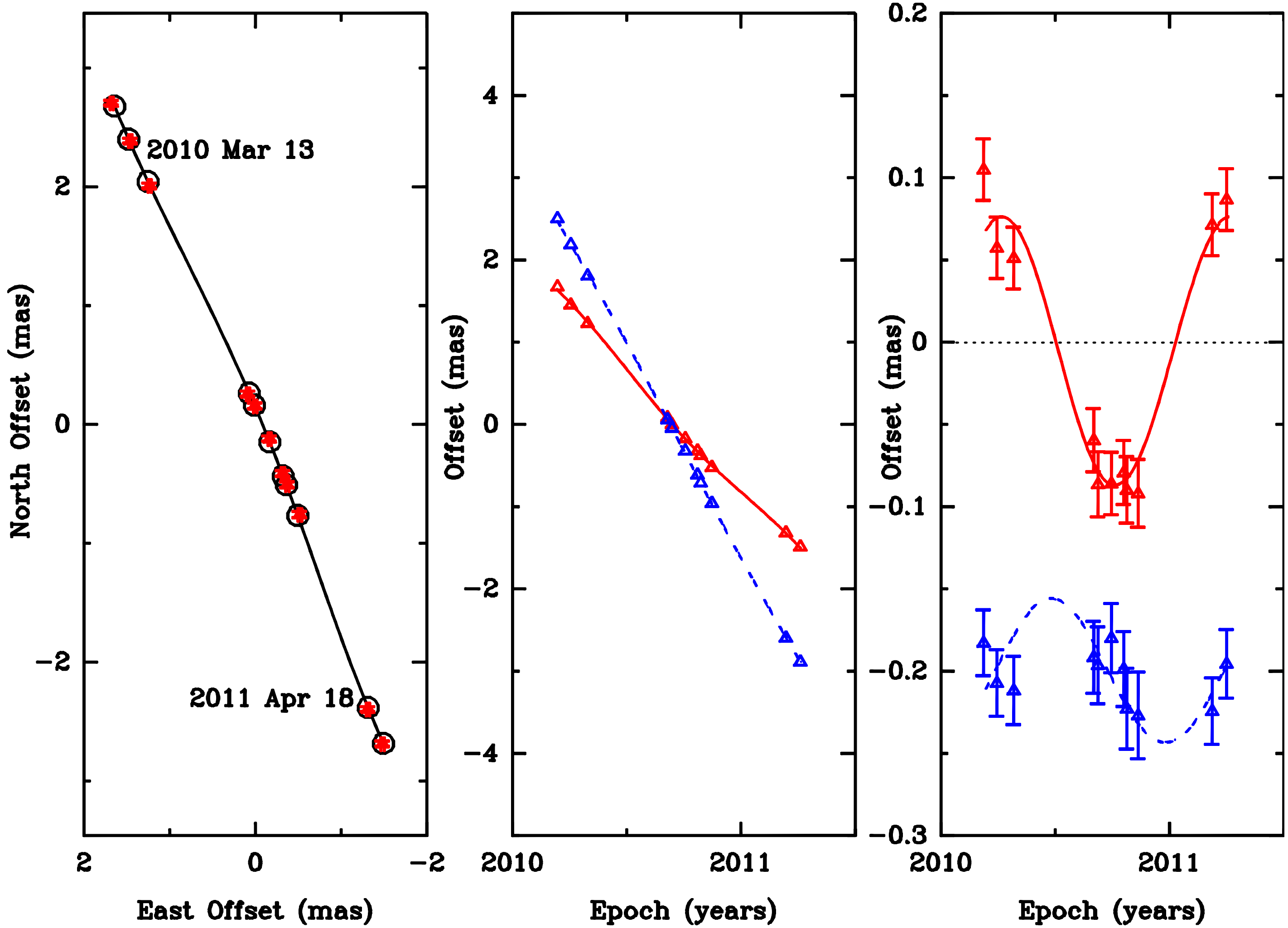
Reid+ (2009)

π = 0.480 +/- 0.010 mas

D = 2.08 +/- 0.04 kpc

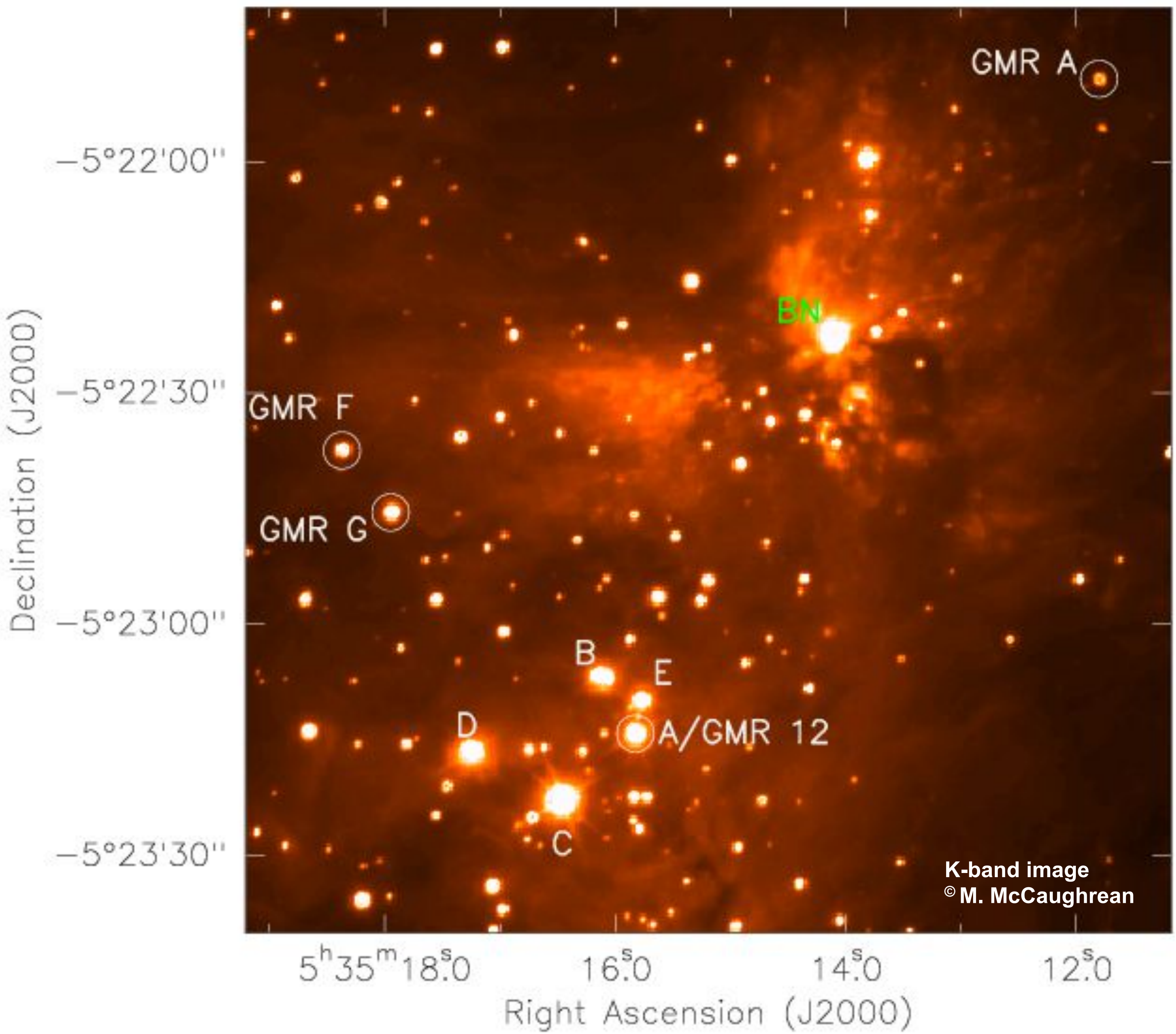
BeSSeL Parallaxes: Example

Parallax for W 49N H_2O masers

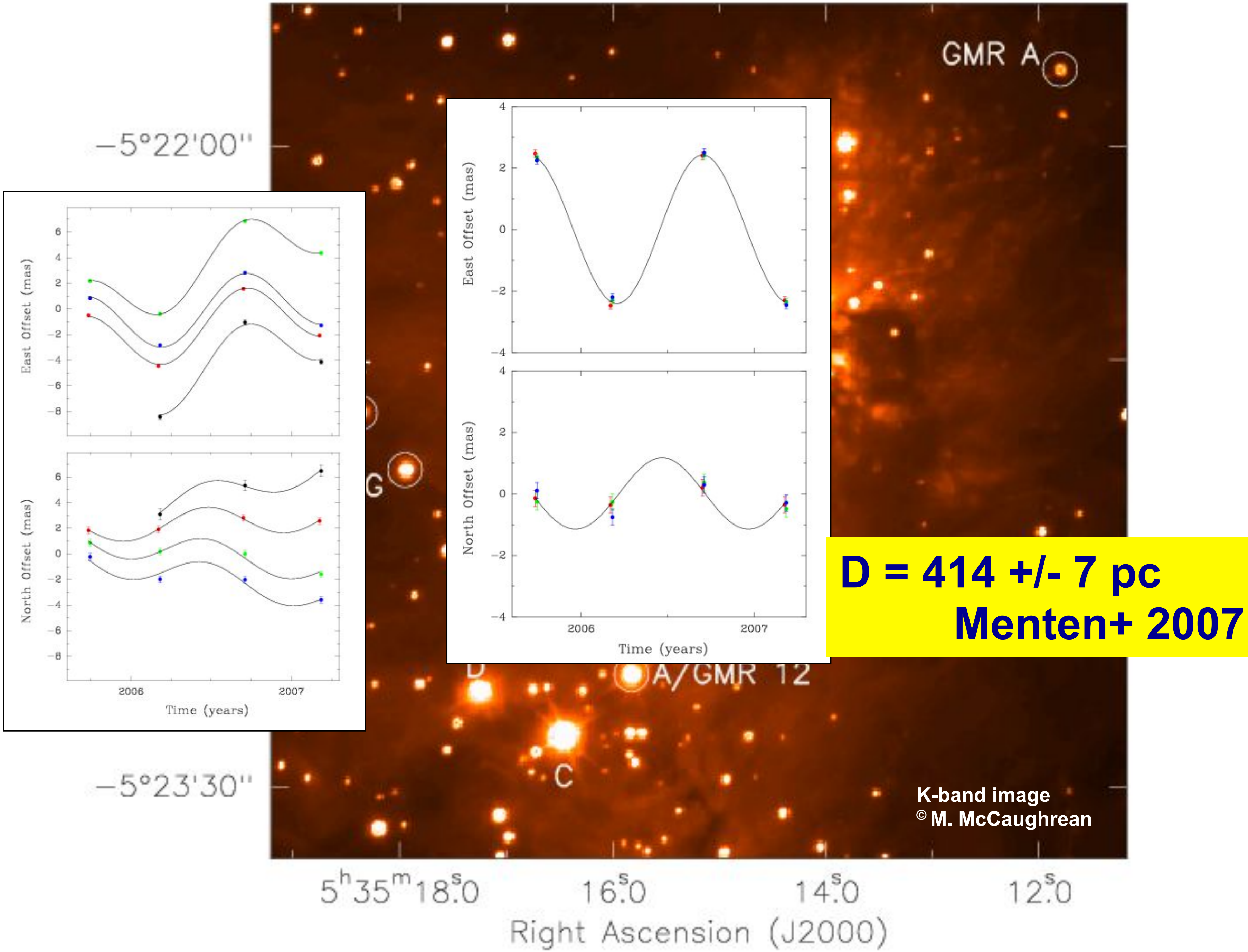


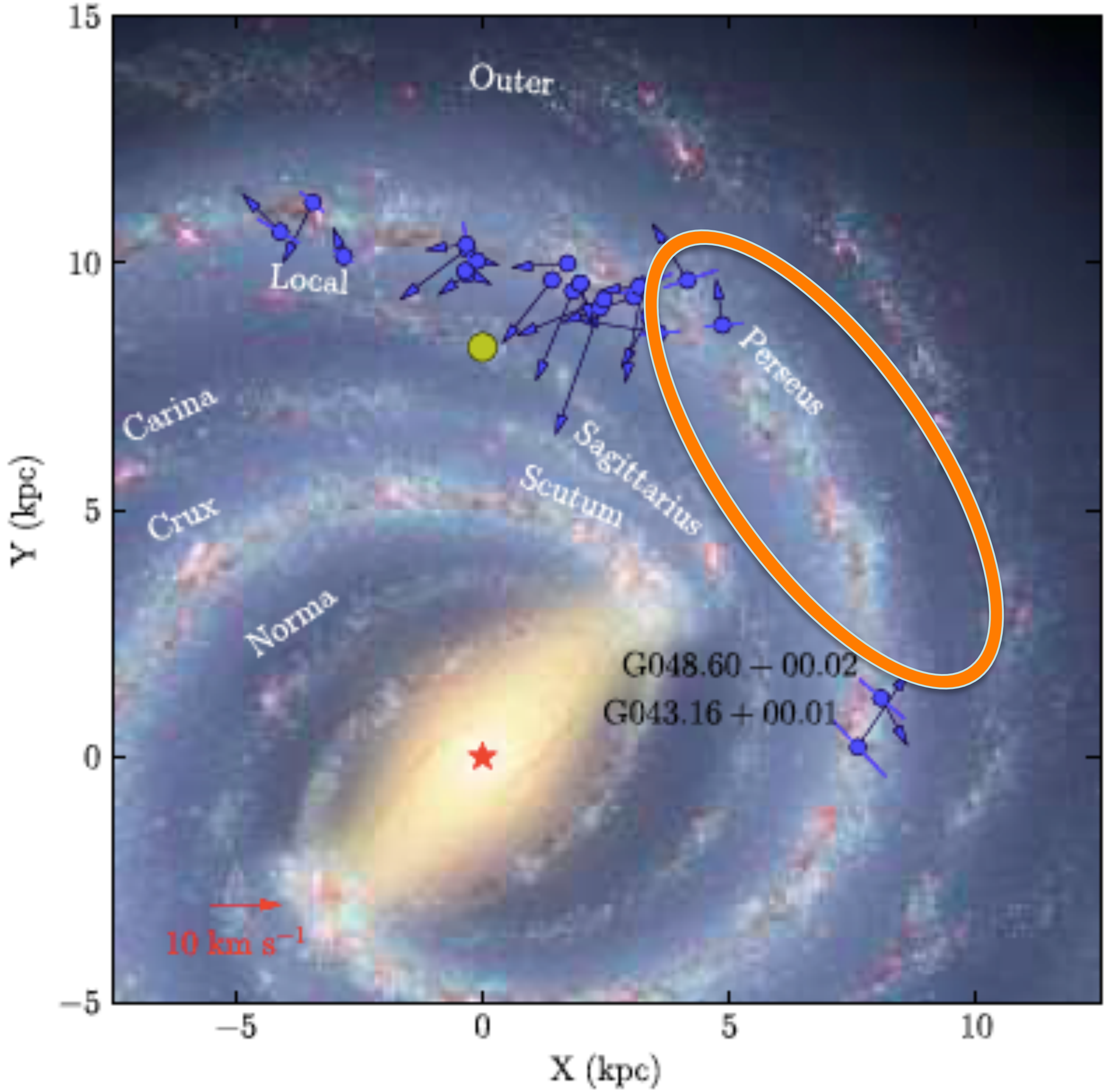
$\Pi = 90 \pm 6\ \mu as$ (D=11.1 ± 0.8 kpc)

Zhang et al. 2013



GMR A
BN
GMR F
GMR G
B
E
A/GMR 12
D
C
K-band image
© M. McCaughrean
−5°22'00''
−5°22'30''
−5°23'00''
−5°23'30''
Declination (J2000)
5h35m18.0s
16.0s
14.0s
12.0s
Right Ascension (J2000)


GMR A
−5°22'00''
−5°23'30''
G
D
A/GMR 12
C
East Offset (mas)
North Offset (mas)
Time (years)
2006
2007
D = 414 +/- 7 pc
Menten+ 2007
K-band image
© M. McCaughrean
5h35m18.0s
16.0s
14.0s
12.0s
Right Ascension (J2000)

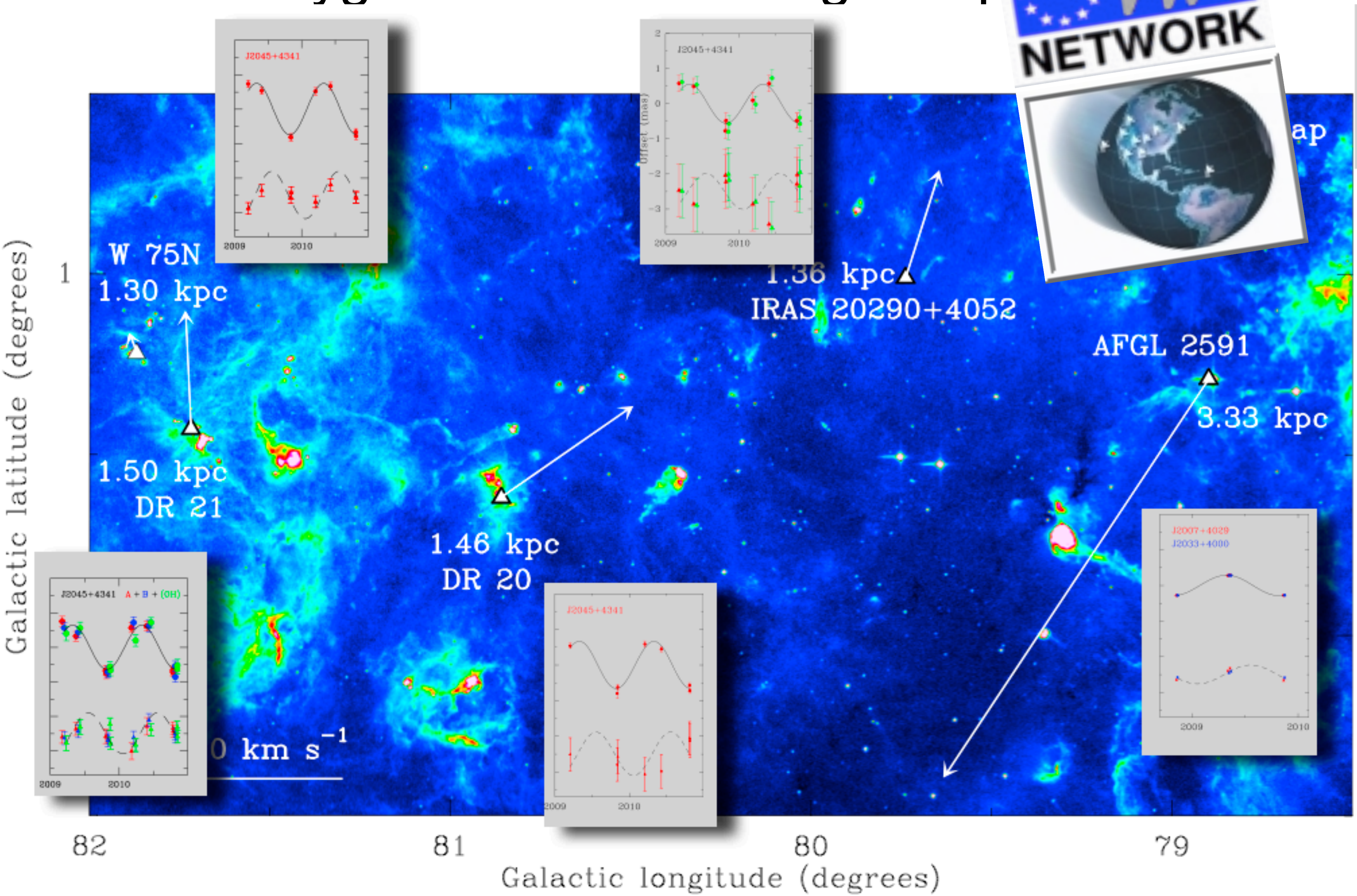


Inner Perseus Arm (Zhang et al. 2013)

Background: artist conception by Robert Hurt (NASA: SSC)

BeSSeL Parallaxes: Example

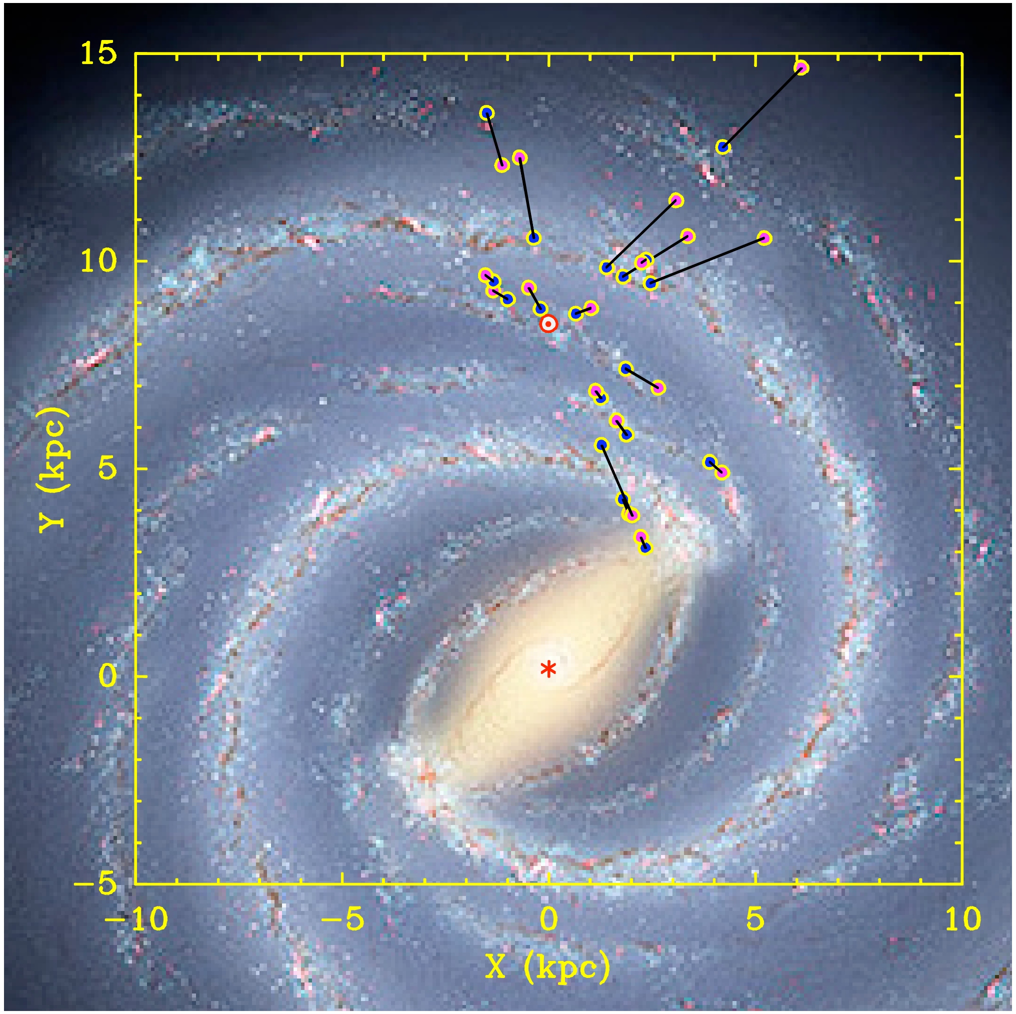
Cygnus X Star forming comp



Rygl et al. (2012)

Image: van Langevelde

Star Forming Region Parallaxes



Kinematic distances (D_k):

Problem: $D_k > D_\pi$

Partial fix:

$R_o < 8.5$ kpc and/or

$\Theta_o > 220$ km/s

Sgr A* p.m. requires

$\Theta_o/R_o = 29.5$ km/s/kpc

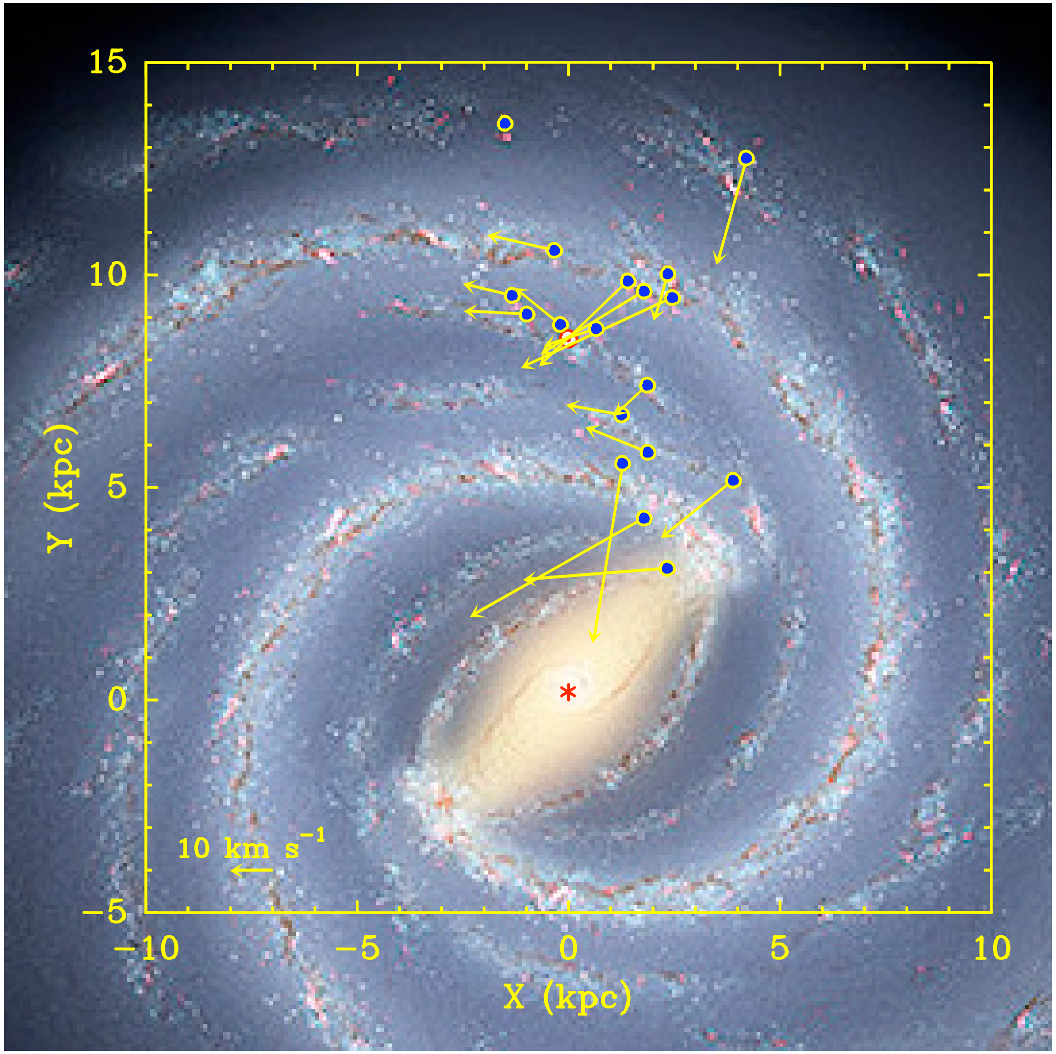
$= 236 / 8.0$

$= 251 / 8.5$

≈

Reid et al. 2009

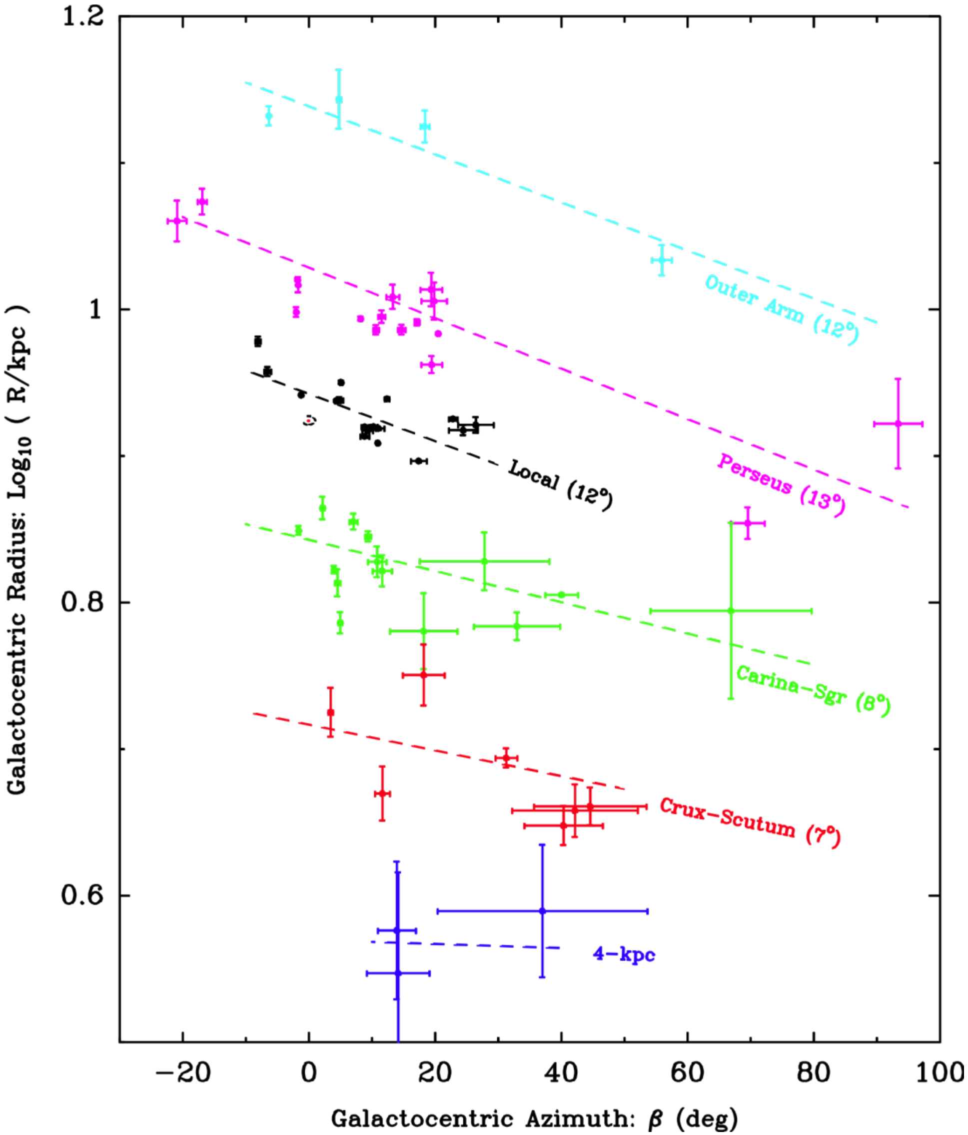
Peculiar Motions of Star Forming Regions



- In rotating frame:
  R_o = 8.5 kpc
  Θ_o = 220 km/s

Clear systematic motions

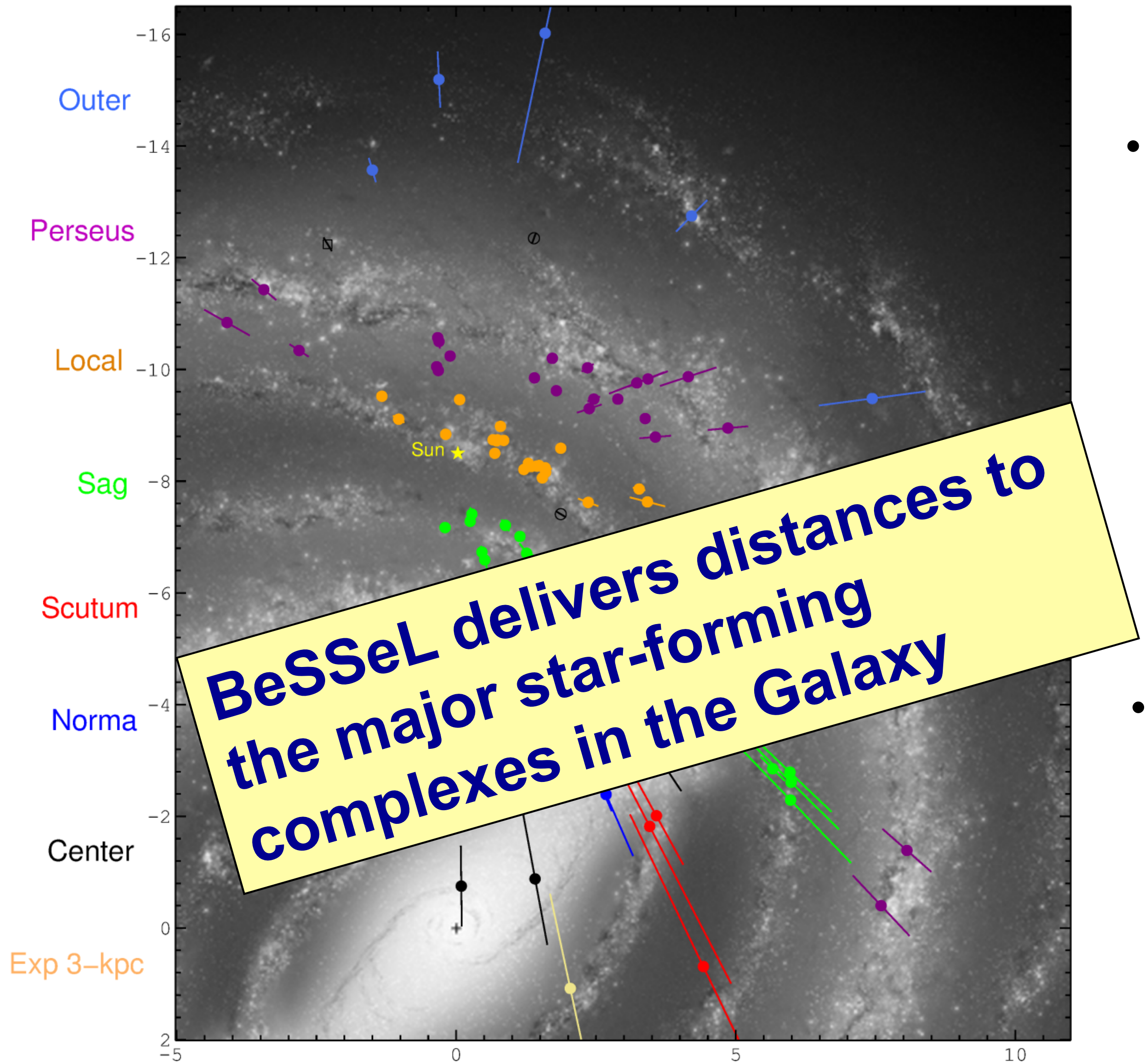
The BeSSeL Survey



- Preliminary results of parallaxes from VLBA, EVN & VERA:
- ~ 100 sources
- Arms assigned by CO l-v plot
- Tracing most spiral arms
- Inner, bar-region is complicated
- Pitch angles ~ 10°

Reid et al. 2014

The BeSSeL Survey



Background: artist conception by Robert Hurt (NASA: SSC)

- Preliminary results of parallaxes from VLBA, EVN & VERA:
  - ~ 100 sources
- Arms assigned by CO l-v plot
- Tracing most spiral arms
  - fit log-periodid spirals
- Inner, bar-region is complicated

Reid et al. 2014

Model Fitting Results

Priors (km/s)	R_0	Θ_0 (kpc)	$(\Theta_0+V_{sun})/R_0$ (km/s) (km/s/kpc)
$V_{sun}=15\pm10$; $\langle V_{src}\rangle=-3\pm10$	8.34 ± 0.16	240 ± 8	30.6 ± 0.4
$V_{sun}=12\pm 2$; $\langle V_{src}\rangle$ no prior	8.33 ± 0.16	243 ± 6	30.6 ± 0.4
V_{sun} n .p. $\langle V_{src}\rangle=-3\pm5$	8.30 ± 0.19	239 ± 8	30.6 ± 0.4

Notes:

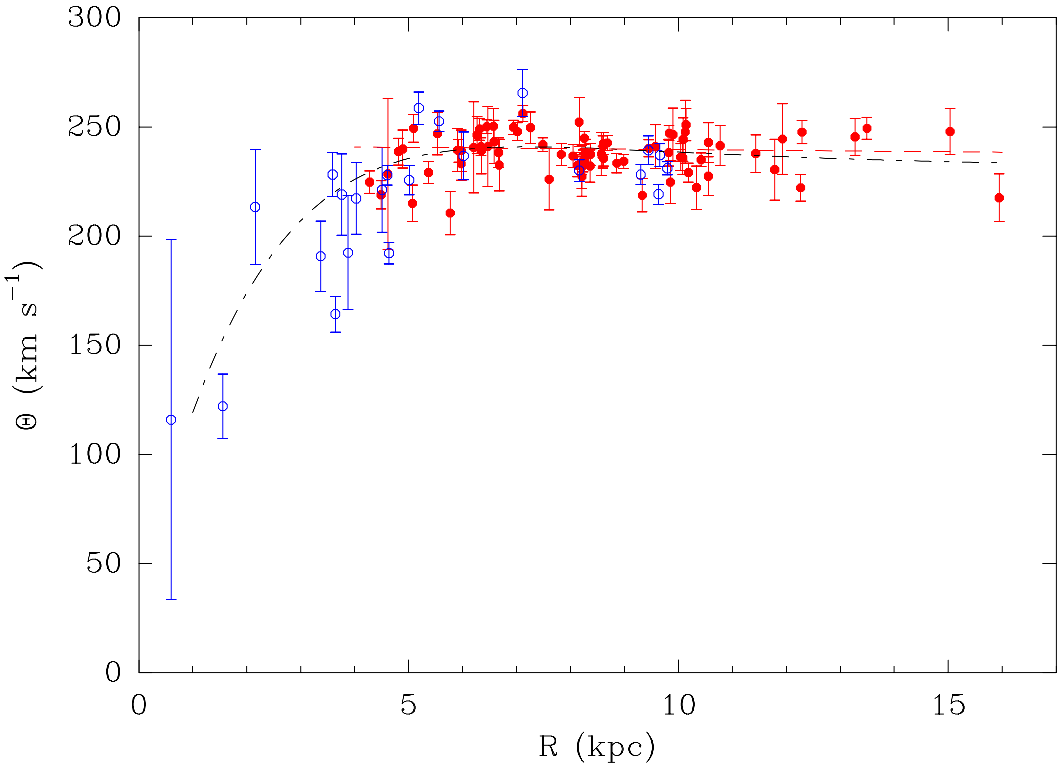
Solar Motion V_{sun} component: 5 km/s (Dehnen & Binney 1998)
(in direction of Galactic rotation) 12 km/s (Schœnrich, Binney & Dehnen 2010)
26 km/s (Bovy et al 2012)

$(\Theta_0+V_{sun})/R_0 = 30.35 \pm 0.05$ km/s/kpc
directly from proper motion of Sgr A* (Reid & Brunthaler 2004,2014)

Parameters determined from posteriori probability density functions based on McMC trials evaluated by the Metropolis-Hastings algorithm

Reid et al. 2014

The Milky Way's Rotation Curve



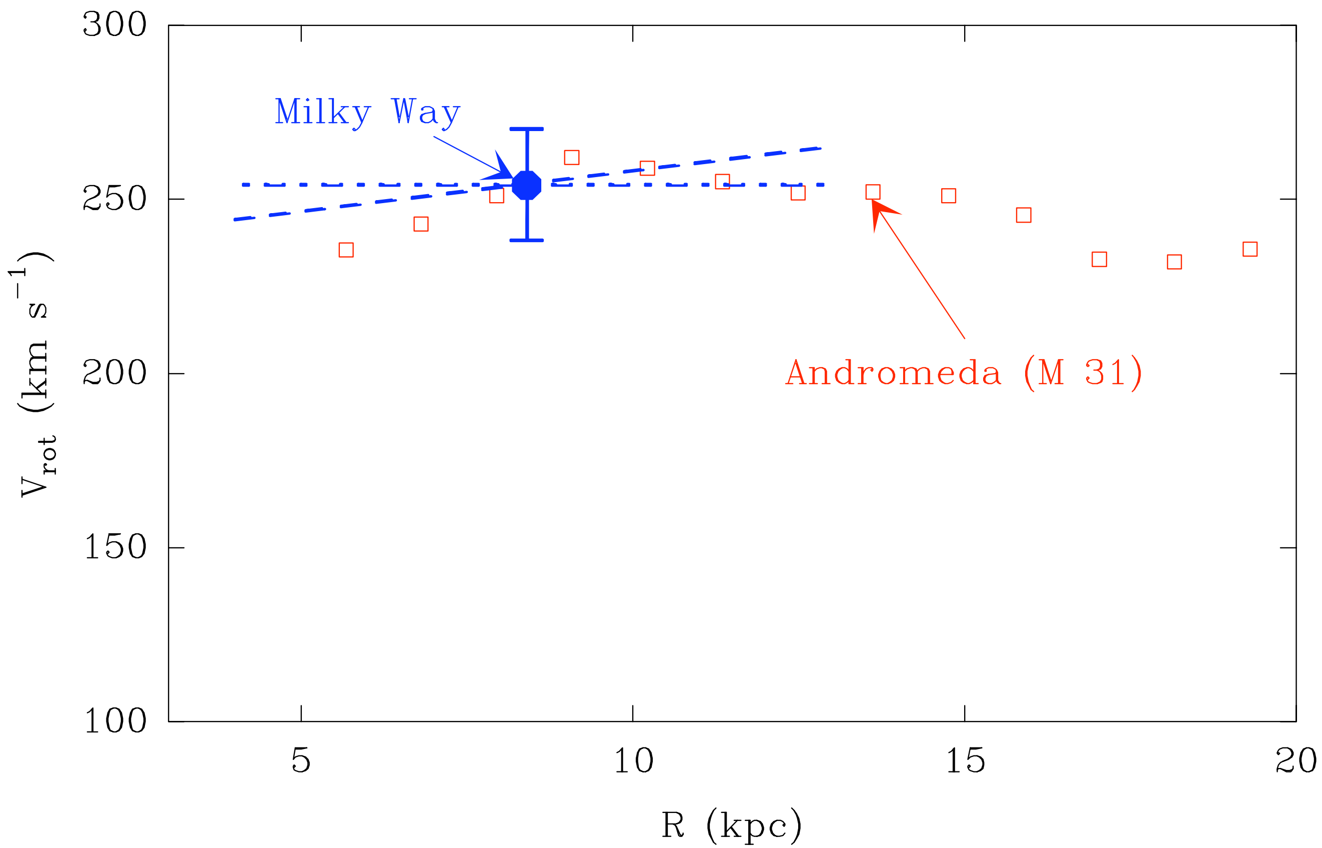
- For R_0 = 8.34 kpc, Θ_0 = 240 km/s
- 80 red points used for fitting
- 23 blue points not used
  (most near galactic bar)
- linear RC (dashed red line)
- "Universal" RC (dot-dash black line)

Direct result based on
3-D motions
"gold standard" distances

	R_0	Θ_0
IAU:	8.5 kpc	220 km/s
BeSSeL+VERA:	8.34±0.16 kpc	240±8 km/s

Reid et al. 2014

Rotation Curves

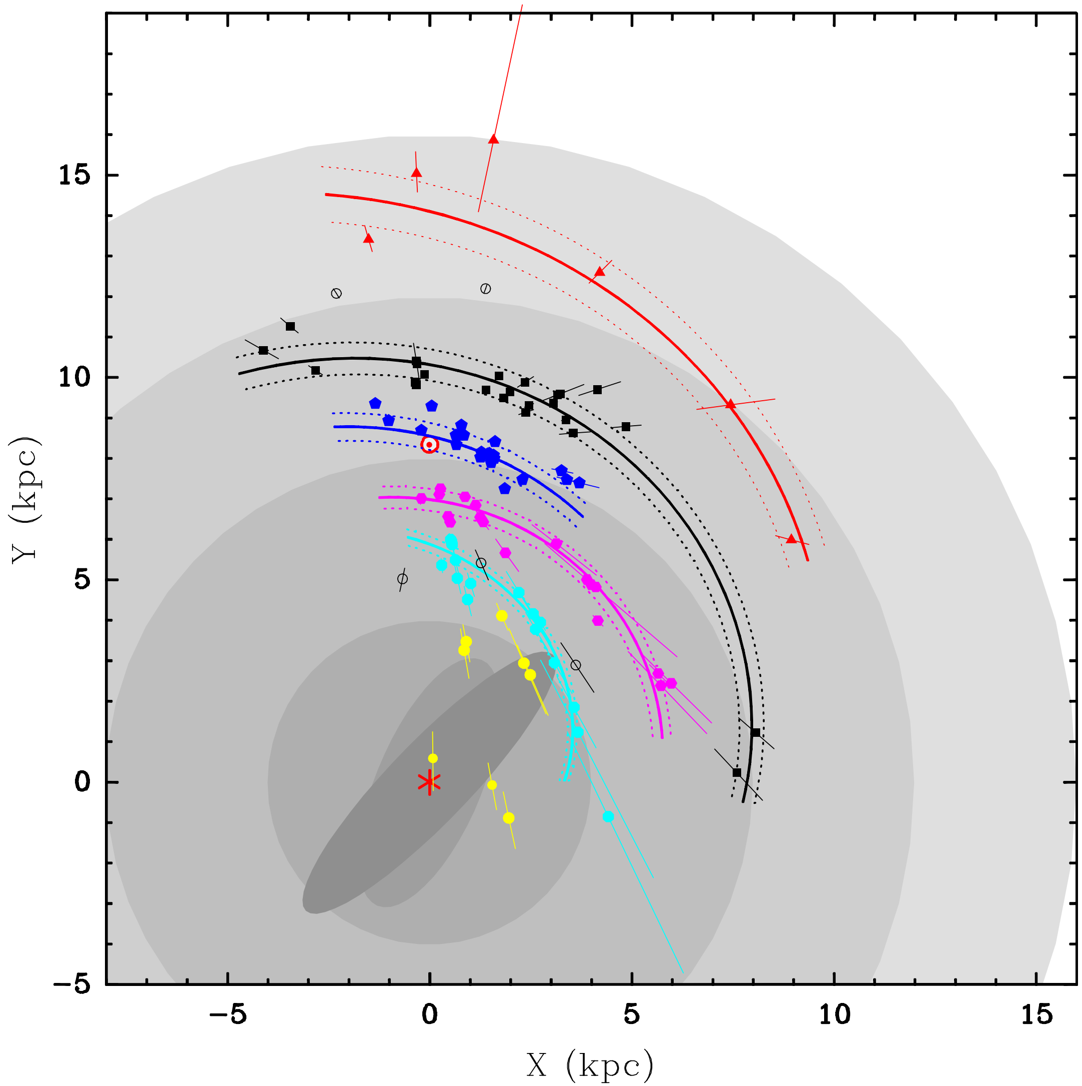


Milky Way parallaxes/proper motions: Reid et al (2009, 2014)

Andromeda H I emission: Carignan et al (2006)

$M_{total} \approx 4\ 10^{11} M_\odot$

Fitting Spirals

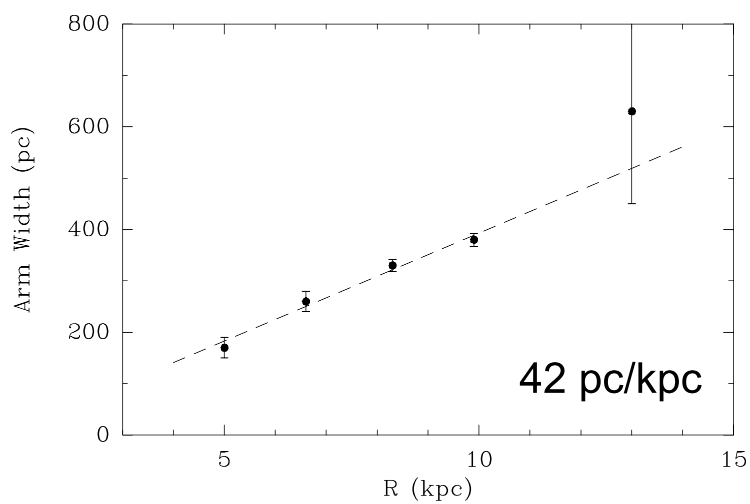


- For a log-periodic spiral:

$$\log(R / R_{ref}) = -(\beta - \beta_{ref}) \tan \psi$$

- Measuring pitch angles ~7° to 20°

- Scatter ➔ arm widths grow with R



Multi-wavelength surveys really deliver a global view of star formation in our Galaxy

Thanks for your attention!

The Karl G. Jansky Very Large Array (JVLA)

The Expanded Very Large Array

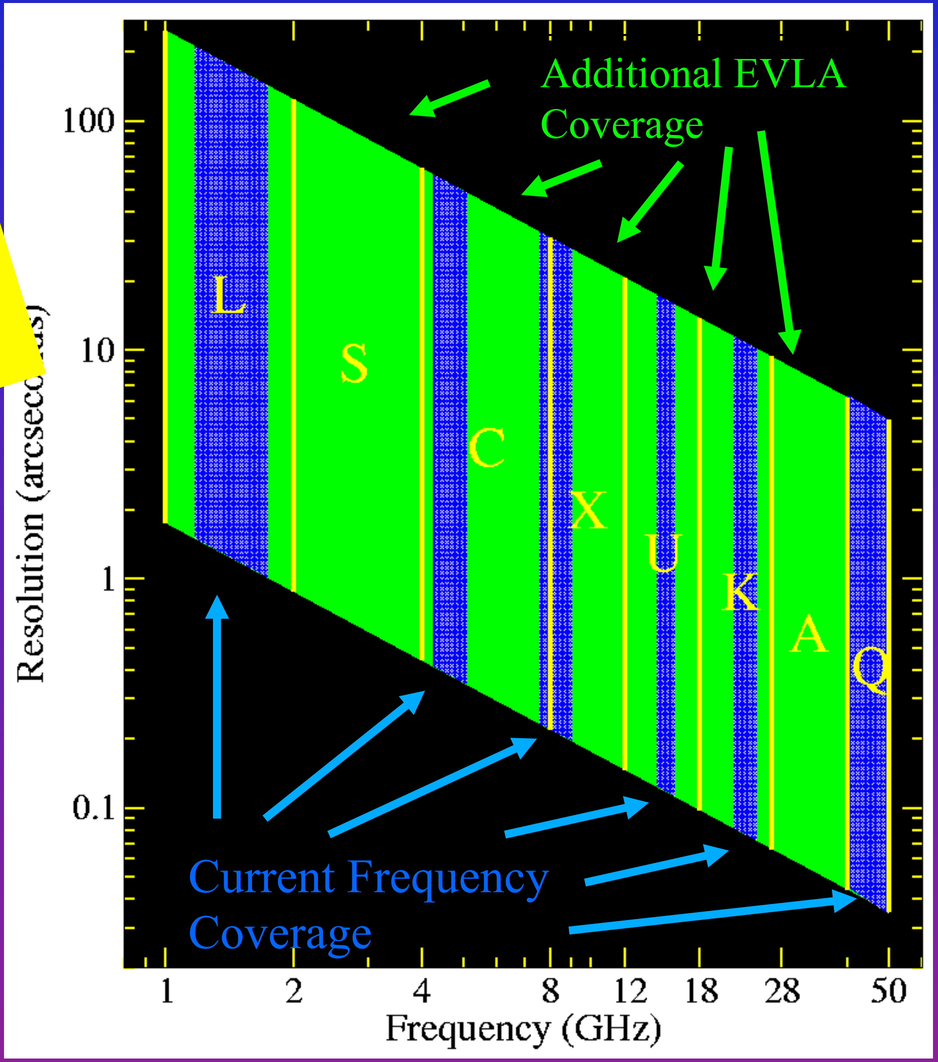
Transforming a 1970s facility into 2010++ state of the art

- **The EVLA Project:**
  - builds on the existing infrastructure - antennas, array, buildings, people – and,
  - implements new technologies to produce a new array whose top-level goal is to provide
- **Ten Times the Astronomical Capability of the VLA.**
  - Sensitivity, Frequency Access, Image Fidelity, Spectral Capabilities, Spectral Fidelity, Spatial Resolution, User Access
  - With a timescale and cost far less than that required to design, build, and implement a new facility.

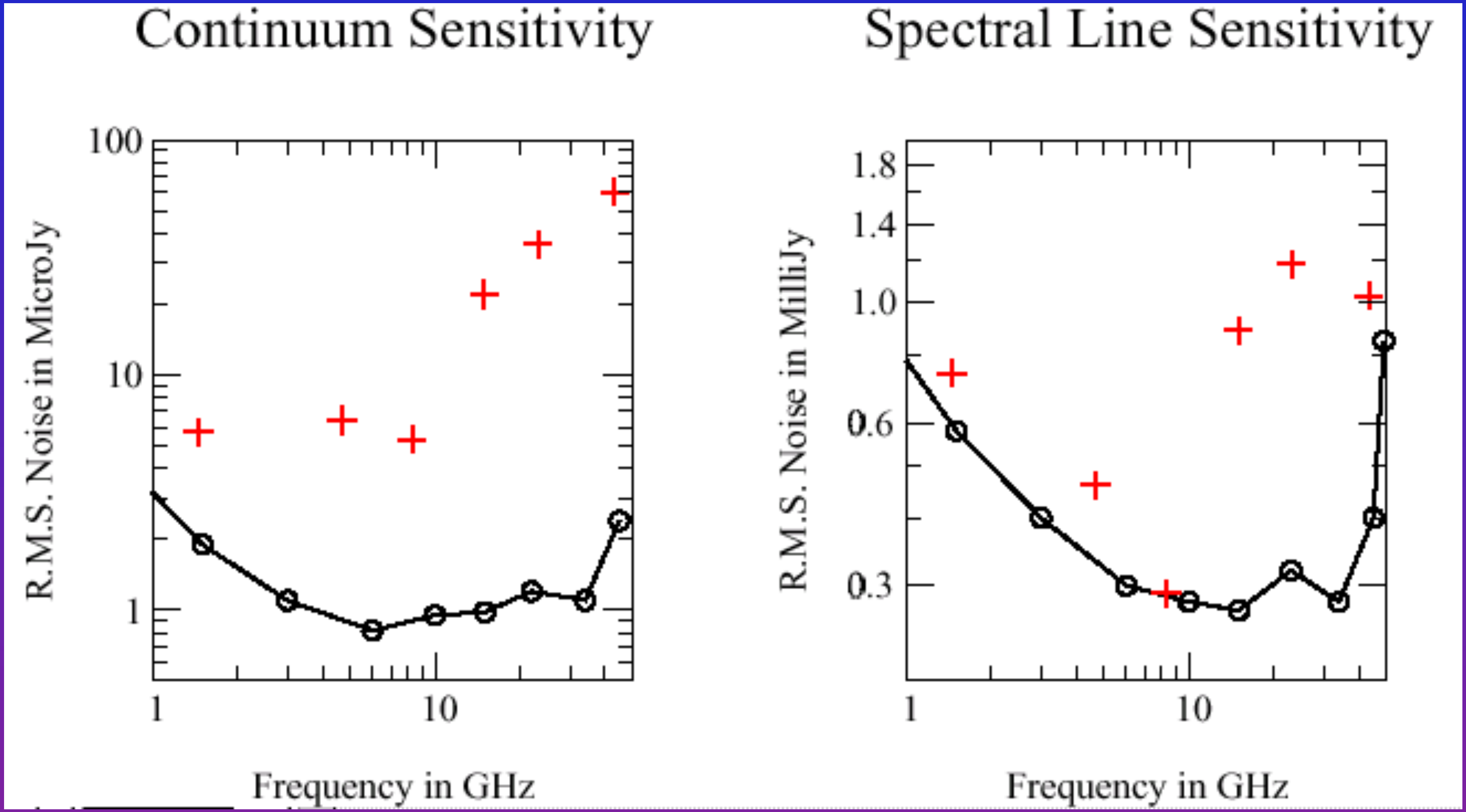
Frequency – Resolution Coverage

- A key EVLA requirement is continuous frequency coverage from 1 to 50 GHz.
- This will be met with 8 fr
  bands:
  - T
  - (L, C, X, U)
  - new (S, A)
- Existing meter-wavelength bands (P, 4) retained with no changes.
- Blue areas show existing coverage.
- Green areas show new coverage.

Up to 10x more sensitive than classic VLA



Sensitivity Improvement (1σ, 12 hours)



Red: Current VLA, Black: EVLA Goals

EVLA-I Performance Goals

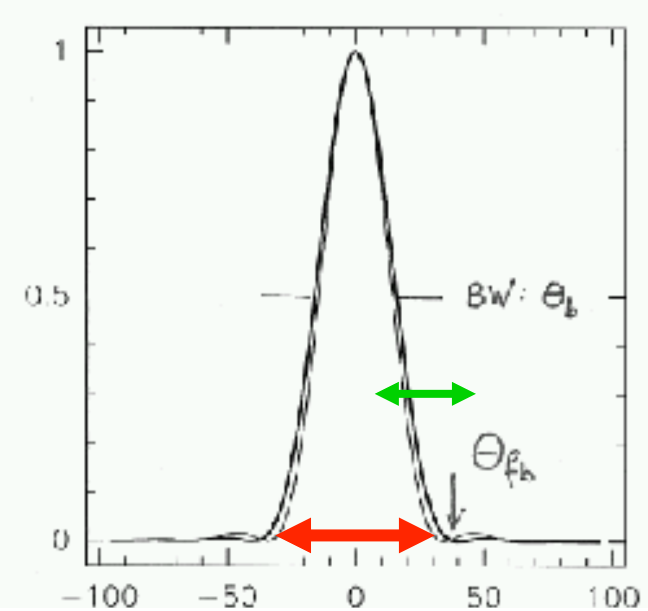
The EVLA's performance is vastly better than the VLA's:

Parameter	VLA	EVLA-I	Factor
Point Source Sensitivity (1-s, 12 hours)	10 mJy	1 mJy	10
Maximum BW in each polarization	0.1 GHz	8 GHz	80
# of frequency channels at max. bandwidth	16	16,384	1024
Maximum number of frequency channels	512	4,194,304	8192
Coarsest frequency resolution	50 MHz	2 MHz	25
Finest frequency resolution	381 Hz	0.12 Hz	3180
(Log) Frequency Coverage (1 – 50 GHz)	22%	100%	5

!

Blind surveys with the EVLA

Blind interferometer surveys mean "mosaicing"

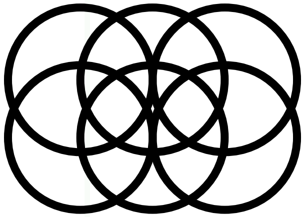


Interferometer field of view = FWZP of unit telescope

Practically: Useful data within FWHM (≈ FWZP/2.3)

θ_{FWHM} = 1.22 λ/D

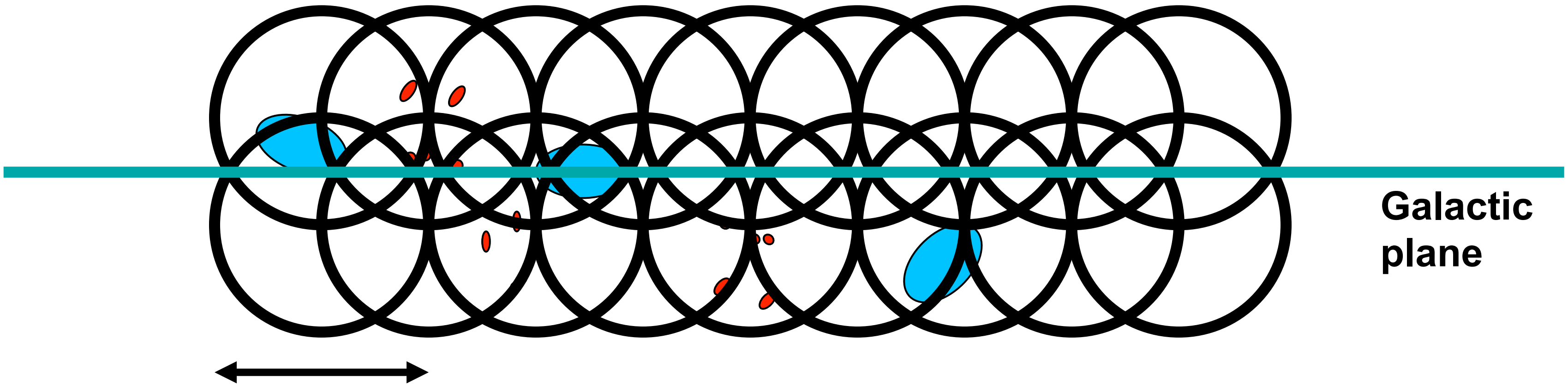
Realize larger fields by "Mosaicing"



VLA (25m ∅): θ_{FWHM}(arcmin) = 45/ν(GHz) → 6.7′@6.7 GHz

ALMA (12m ∅: θ_{FWHM}(arcmin) = 104/ν(GHz) → 0.30′@345 GHz

A comprehensive star formation survey of the Galactic plane



FWHM = 6.7 arcmin/6.7 GHz

Radio continuum emission

Full polarization

Band 4 … 8 GHz → determ

JVLA B + D array + Effelsberg: θ_B~ 2 arcsec

PLUS: Do 6.7 GHz CH_3OH maser, RRLs, 4.8 GHz H_2CO absorption (+ emission) … SIMULTANEOUSLY!

GLOSTAR

A Global View of Star Formation in the Galaxy

4–8 GHz K. G. Jansky VLA Survey

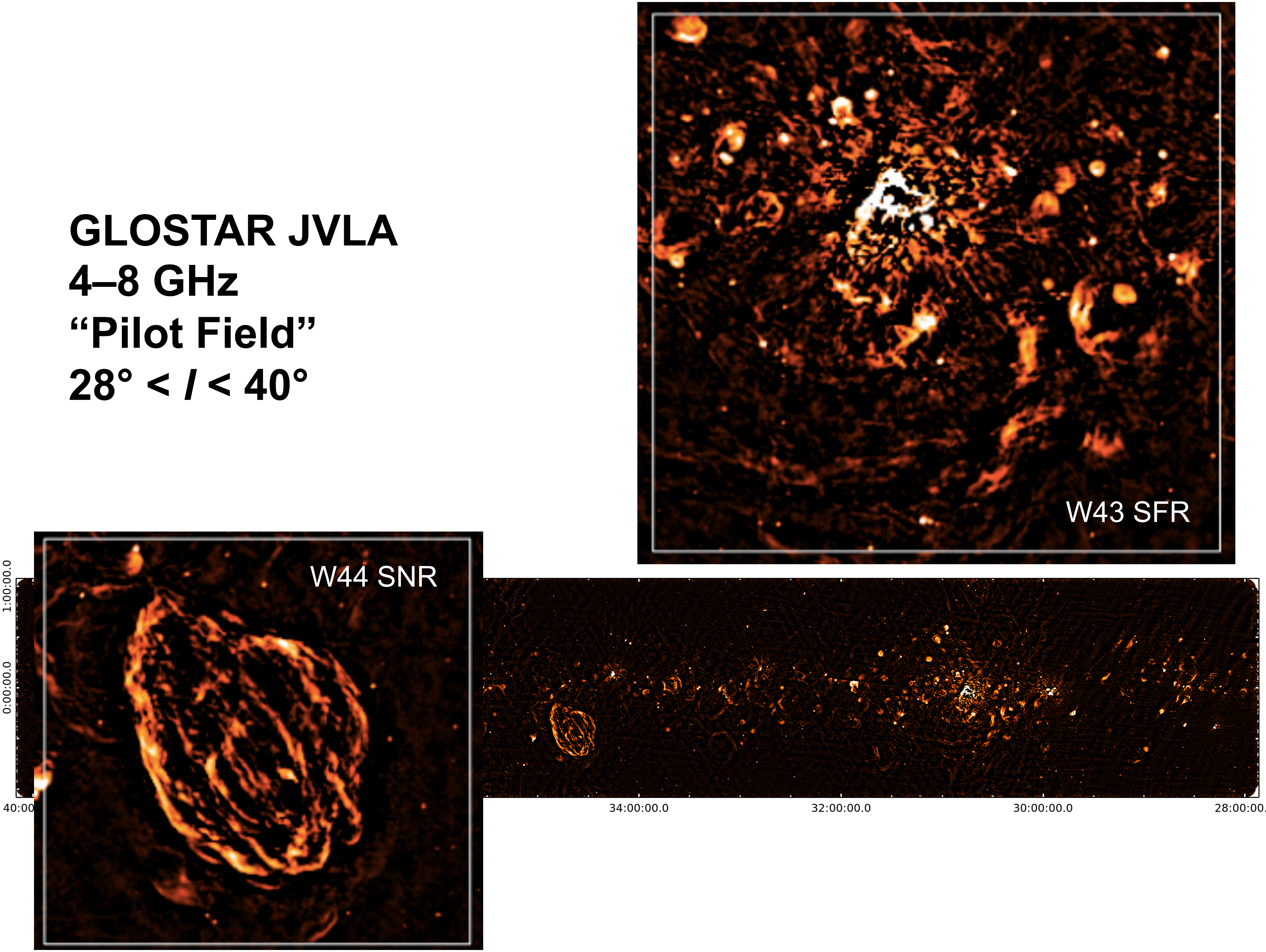
GLOSTAR VLA Galactic Plane Survey

- coverage from *l* = -2º to +60º |*b*| < 1º and *l* = +76º to +83º *b*= -1º to +2º
- ~2 x 45000 pointings, each 7-8 s duration
- in D-configuration (15” resolution) and B-configuration (1.5” resolution)
- **2 GHz continuum:**
  - 4.2–5.2 GHz & 6.4–7.4 GHz) → 40 µJy sensitivity
  - Full polarization
- **6.7 GHz methanol maser** (0.18 km/s; 370 km/s) → 20 mJy sensitivity
- **4.8 GHz H_2CO absorption** (0.25 km/s; 260 km/s) → 20 mJy sensitivity
- **7 RRLs** (3-4 km/s; ~400 km/s) → 5 mJy sensitivity

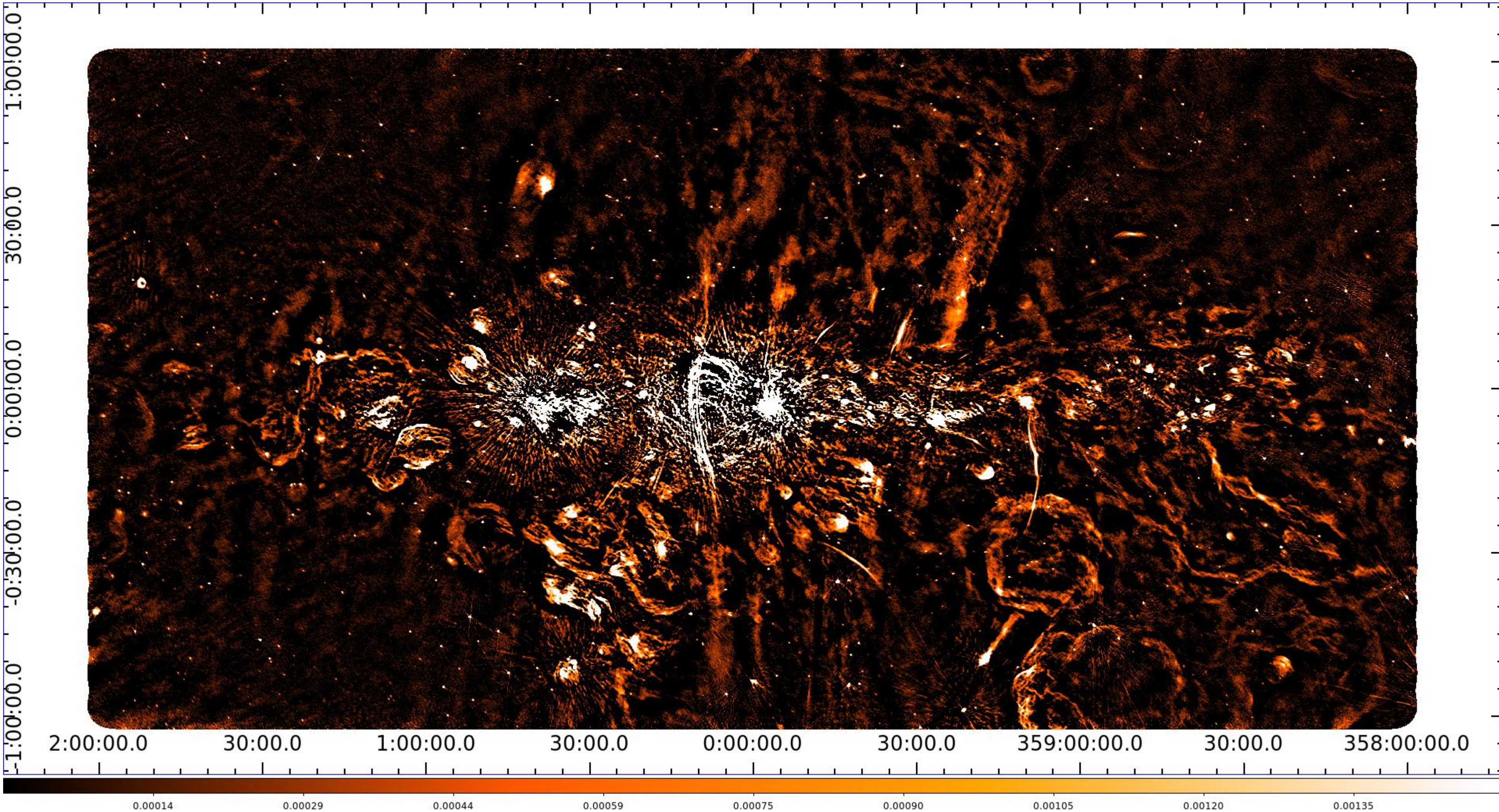
K. M. Menten, A. Brunthaler, T. Csengeri, S. Dzib, B. Winkel, F. Wyrowski (MPIfR); M .J. Reid, (CfA); J. Urquhart, (U Kent); C. Carrasco-Gonzales (UNAM); J. Ott, M. Claussen (NRAO); J. Pandian (IIST); P. Hofner (NMT); H. Beuther (MPA)

S. Medina, C. Murugeshan, H Nguyen, E. Sarkar (MPIfR students)

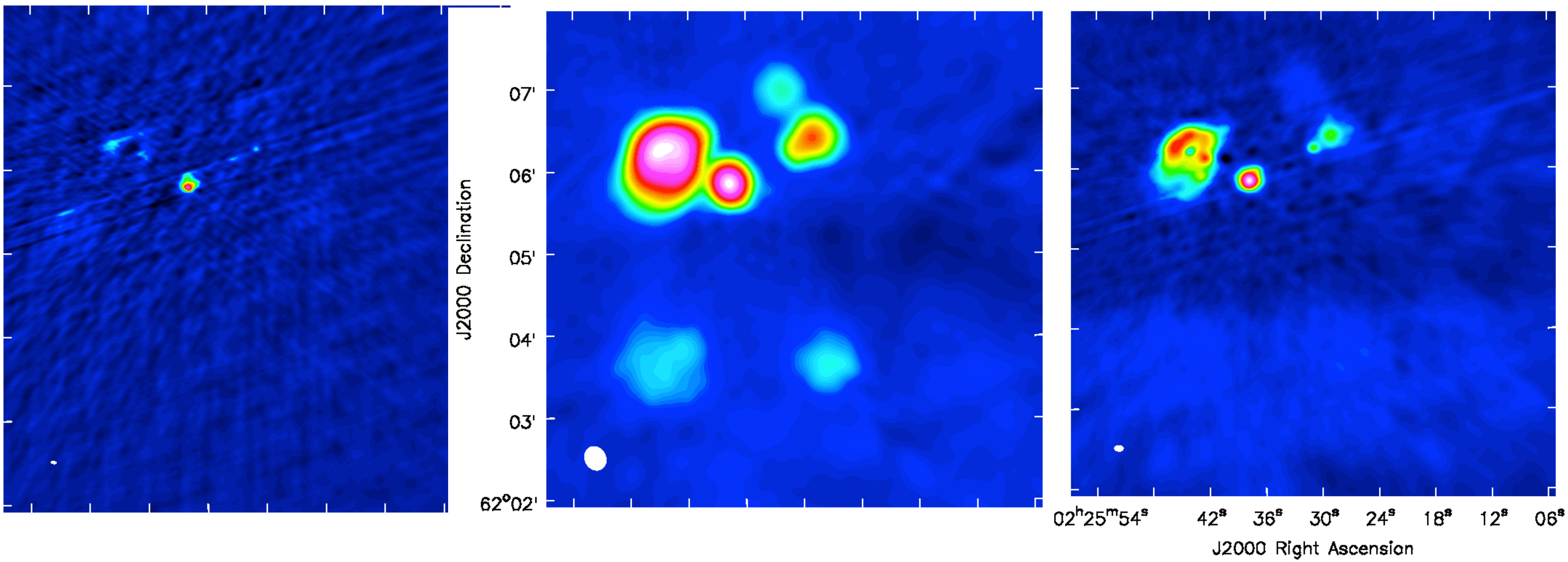
GLOSTAR JVLA
4–8 GHz
“Pilot Field”
$28° < l < 40°$



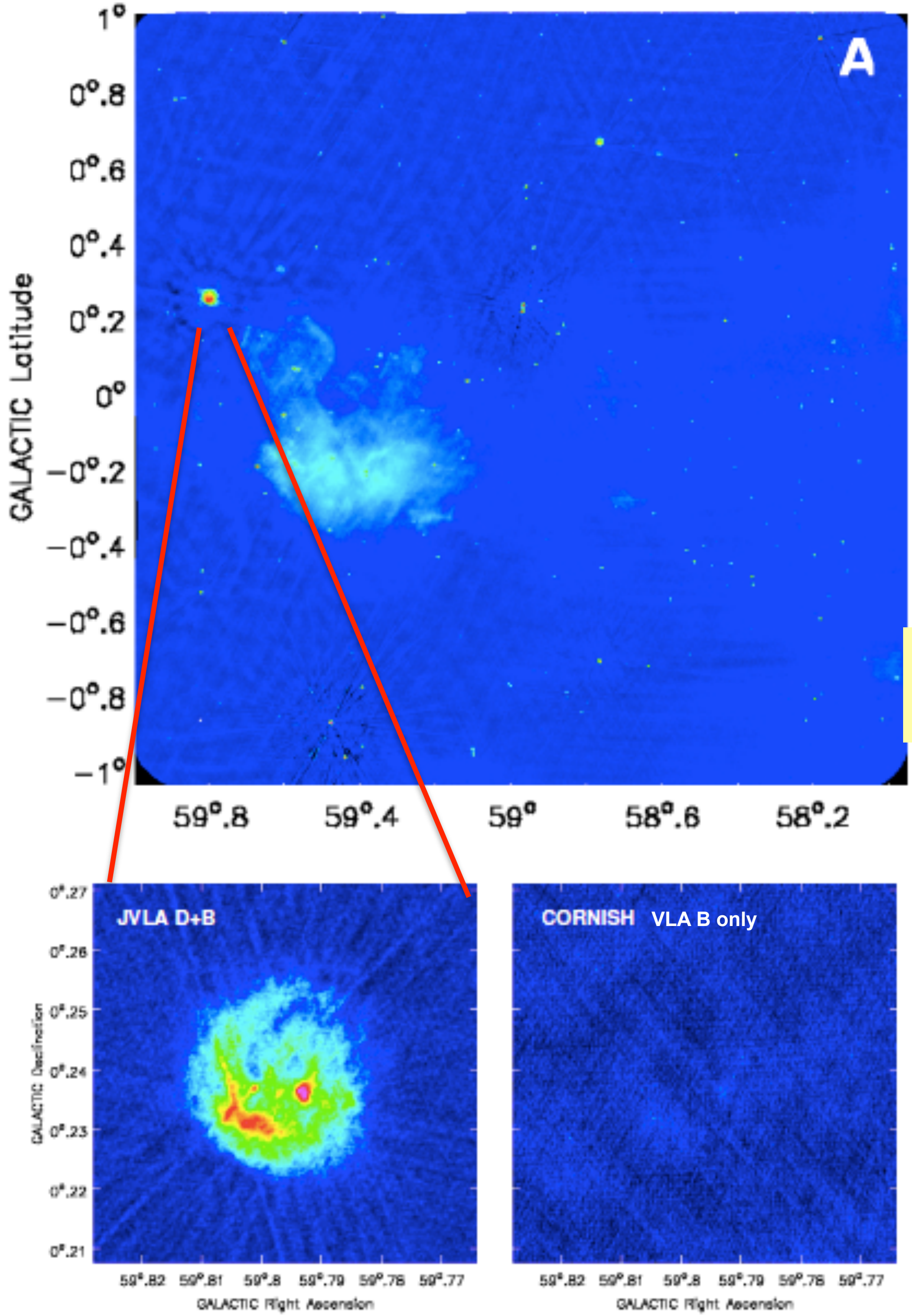
The Galactic center region (Central Molecular Zone)



Combining B and D configuration data

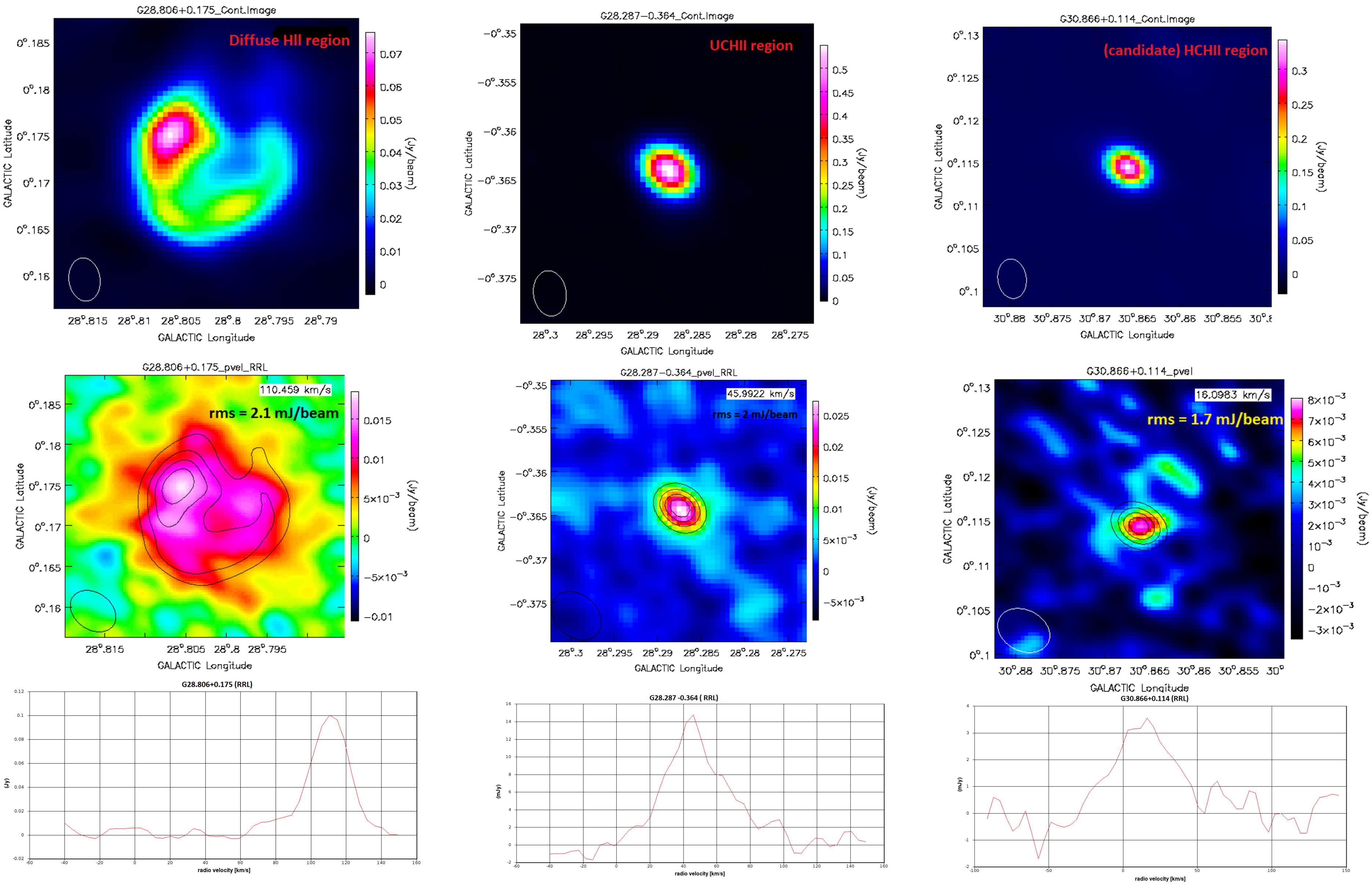


B-config. D-config. B+D config.



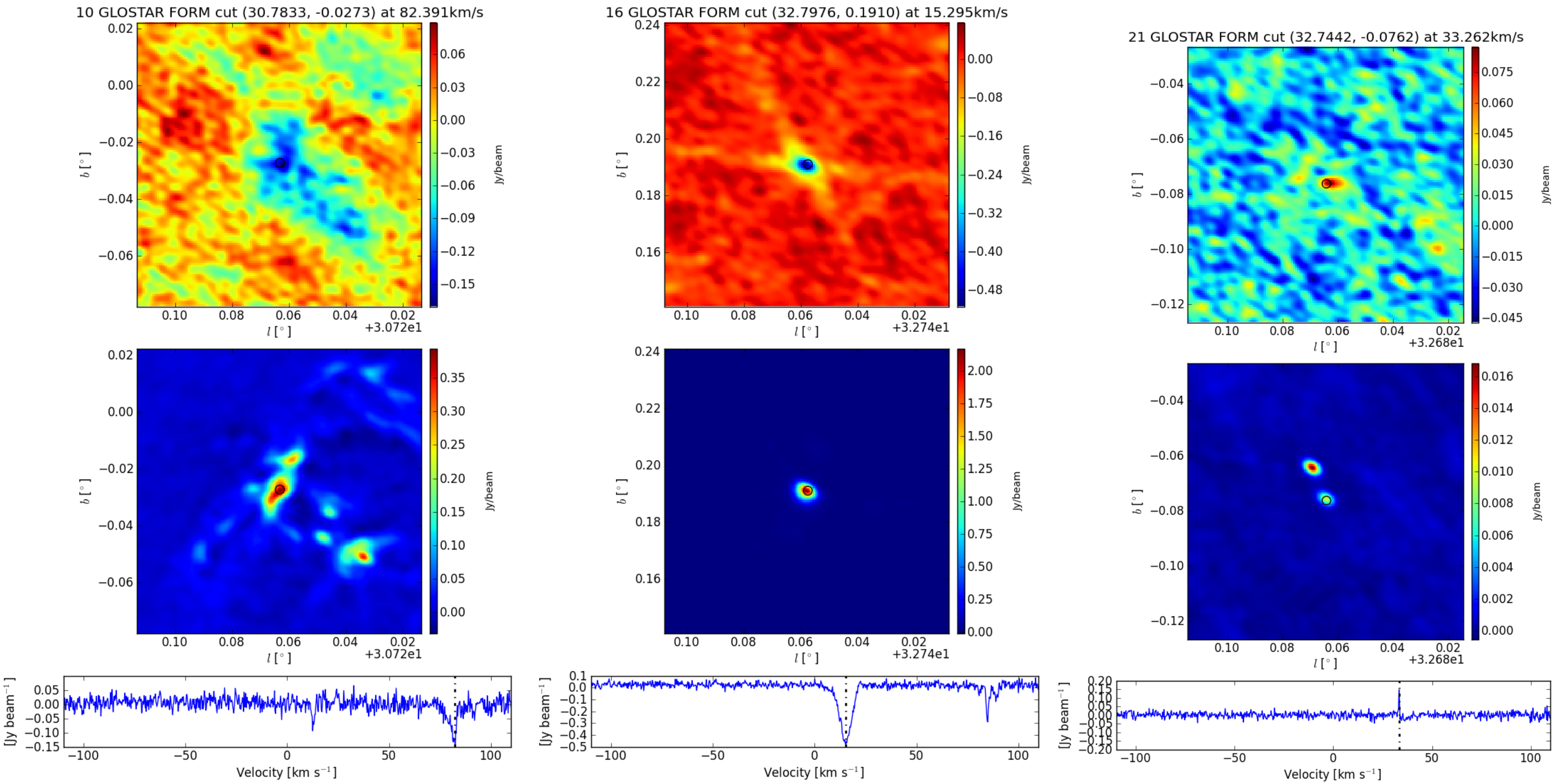
JVLA B + D + Effelsberg 100 m

Radio Recombination Lines



Emranul Sarkar (MSc)

4.8 GHz H_2CO Line

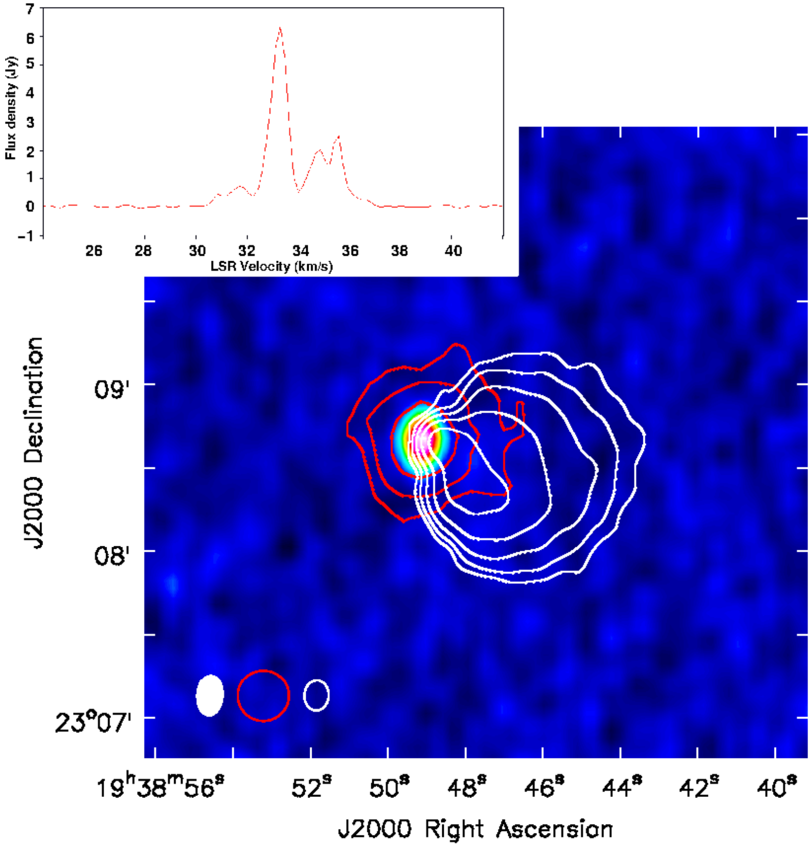


Hans Nguyen (MSc)

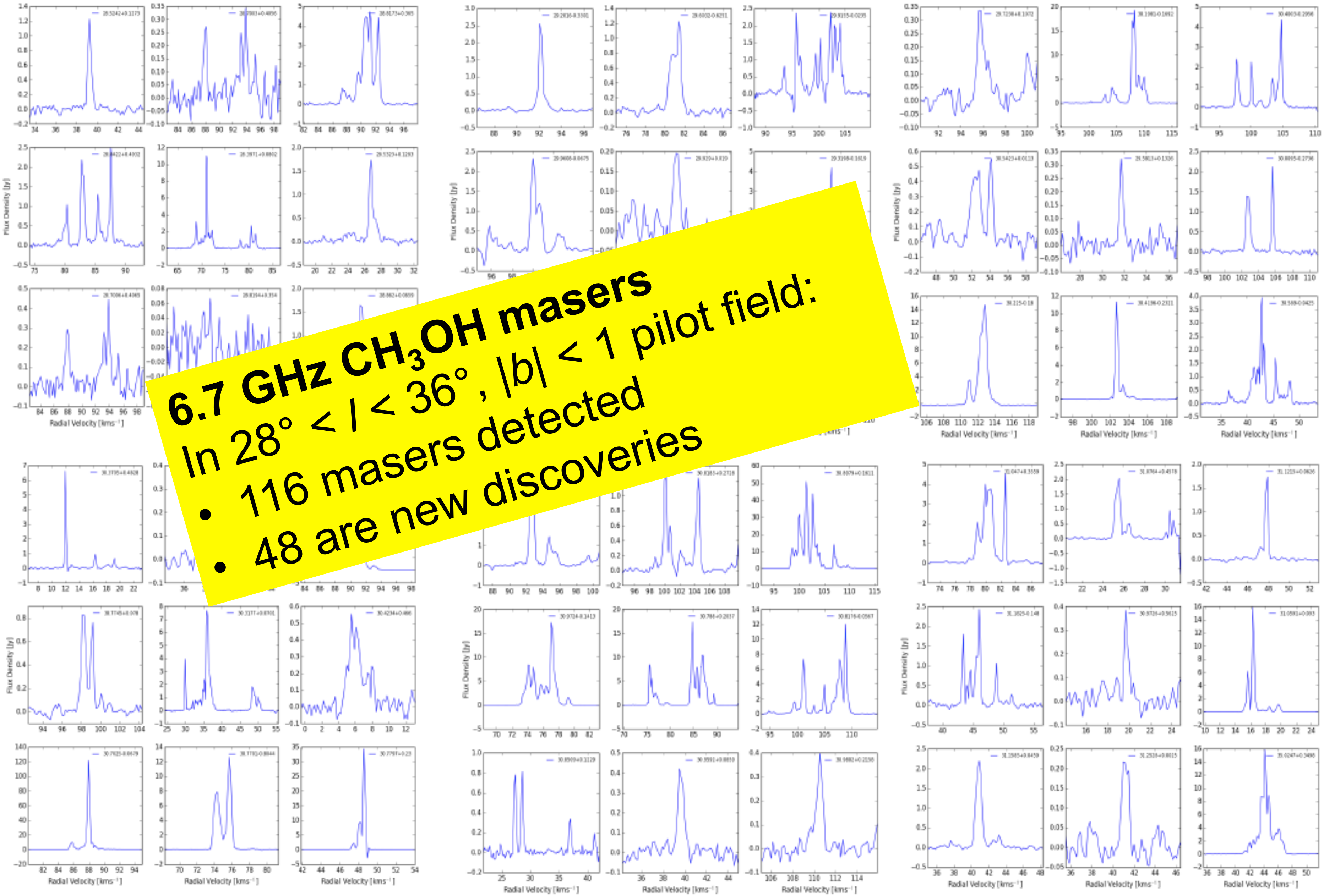
6.7 GHz CH_3OH masers

In 28° < *l* < 36°, |*b*| < 1 pilot field:

- 116 masers detected
- 48 are new discoveries



C. Murugeshan MSc thesis



6.7 GHz CH_3OH masers

In $28^\circ < l < 36^\circ$, $|b| < 1$ pilot field:

- 116 masers detected
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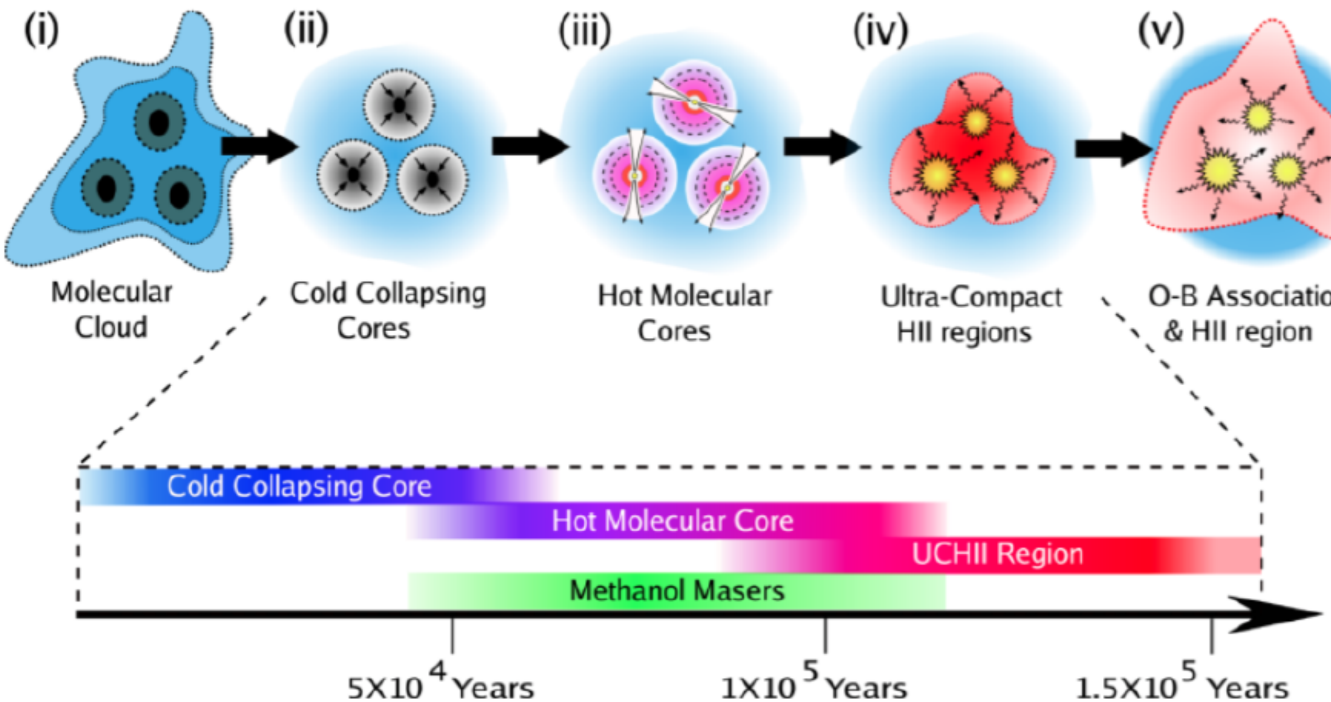
C. Murugeshan MSc thesis

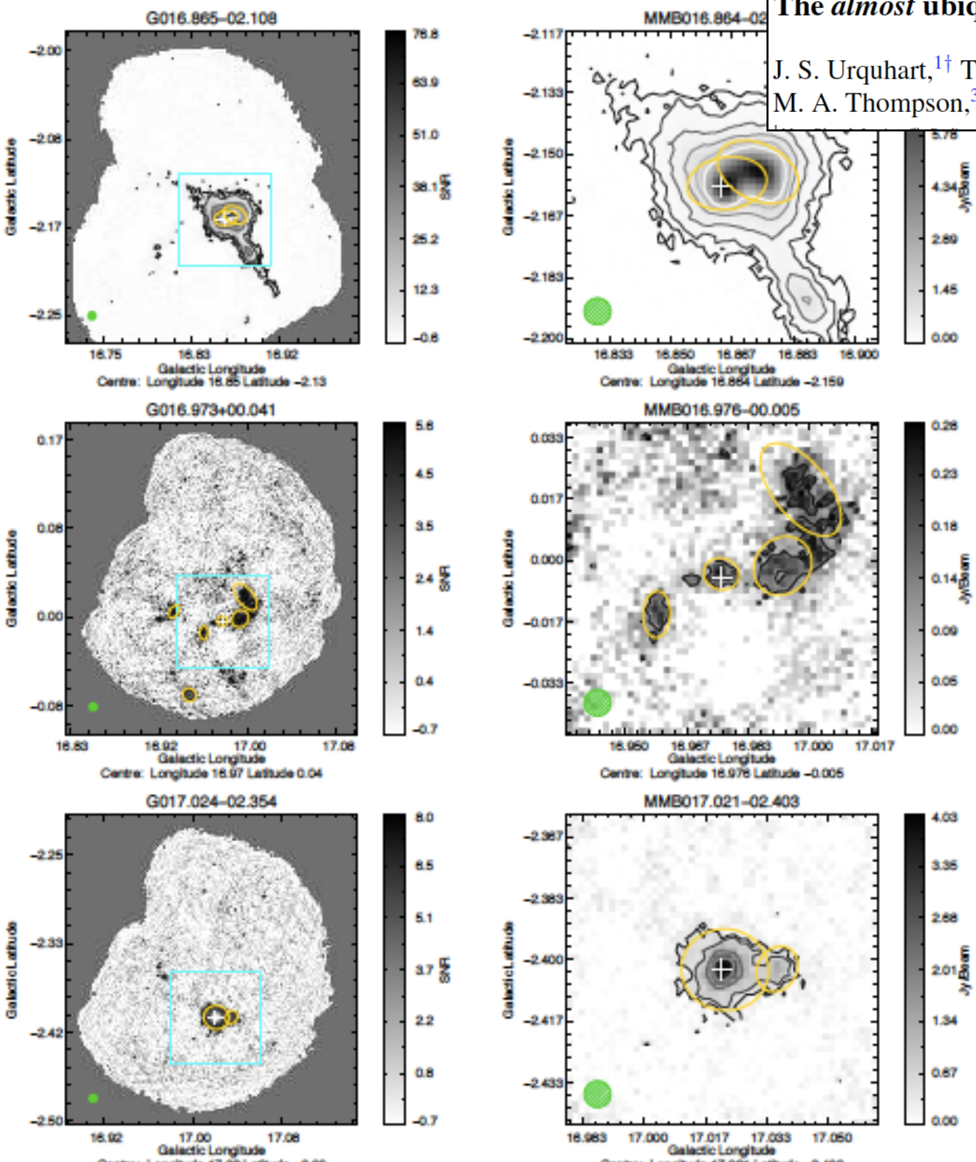
6.7 GHz masers and Massive Star Forming Regions



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 446, 3461–3477 (2015) doi:10.1093/mnras/stu2300

The *almost* ubiquitous association of 6.7-GHz methanol masers with dust★

J. S. Urquhart,[1†] T. J. T. Moore,[2] K. M. Menten,[1] C. König,[1] F. Wyrowski,[1]
M. A. Thompson,[3] T. Csengeri,[1] S. Leurini[1] and D. J. Eden[2,4]



A VLA Galactic plane survey

- **Pilot project with the VLA (Resident Shared Risk Observing)**:

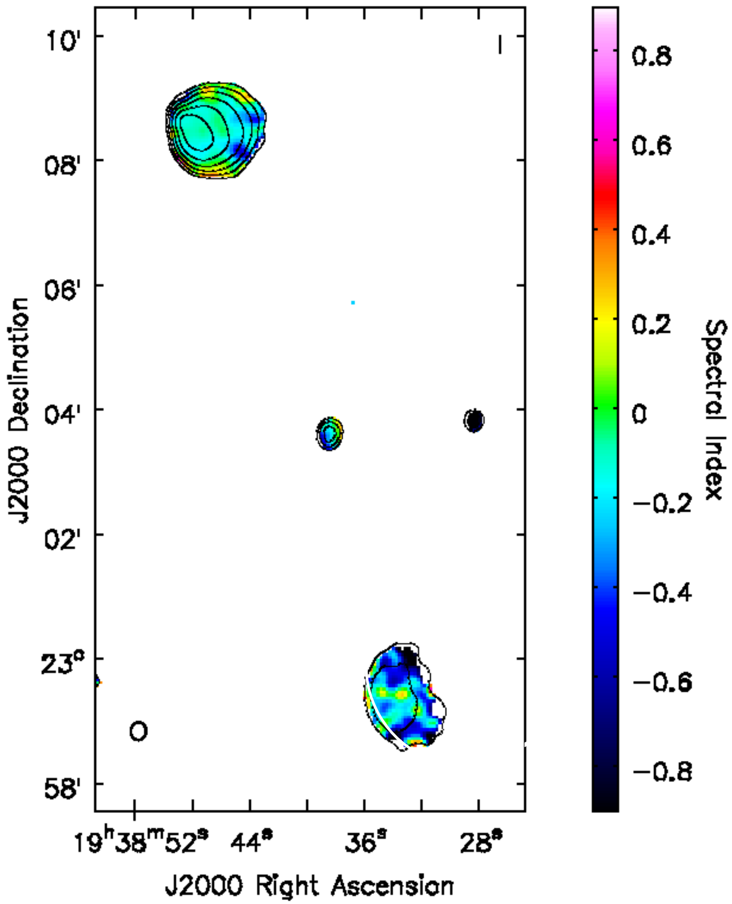
  - 2° x 2° field, centered on G59.0+0.0 (HERSCHEL science demonstation field)

  - 6.7 GHz methanol maser

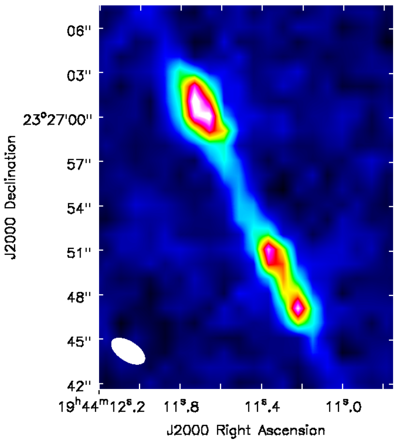
  - 4.8 GHz H_2CO absorption (DR21 test)

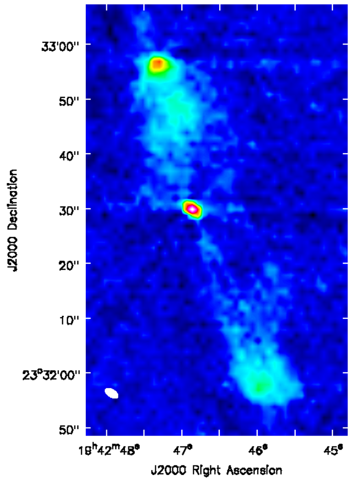
  - RRLs (DR21 test)

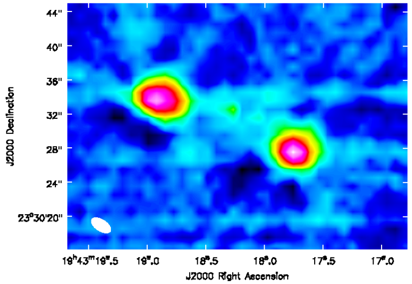
  - **spectral index information (4.2 –6.9 GHz)**

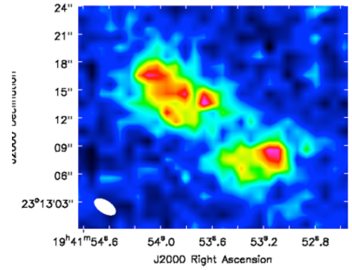


GLOSTAR VLA Galactic plane survey: "By-products"









Data

- Observations made using VLA in the D and B configurations. For current work only D configuration data used.
- Complete Galactic Plane survey, but only $l \sim 28^\circ$ to 36° with $|b| = 1^\circ$ covered for current work. Total of 16 deg^2.
- Observations split into $1^\circ \times 1^\circ$ regions.
- Each region composed of over 400 pointings (targets).
- Integration time on targets $\sim$ 15 sec.

Table: Details of the 6.7 GHz methanol data.

Freq. [MHz]	Bandwidth [MHz]	No. of Chans	Chan. width [kHz]	Vel. resolution [kms^{-1}]	Vel. Coverage [kms^{-1}]
6668	8	2048	3.906	0.18	370

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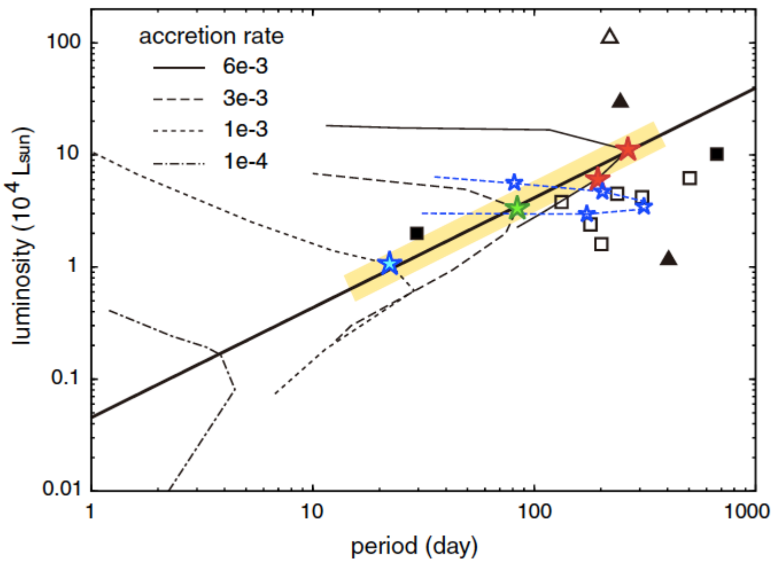
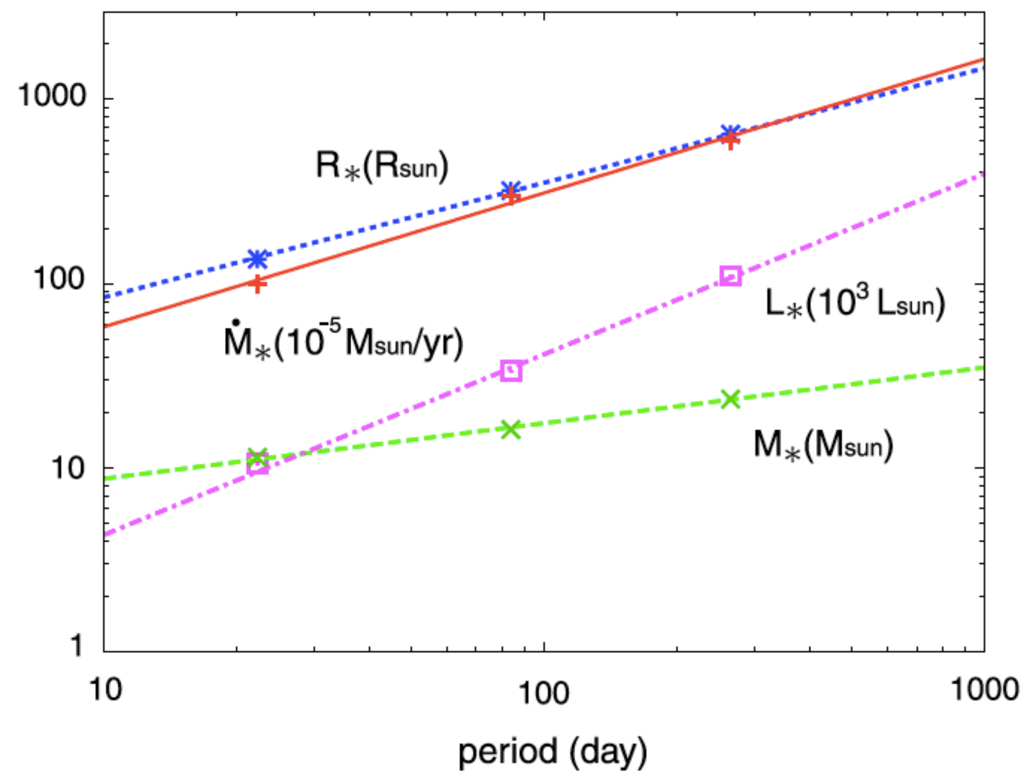
Recently, Inayoshi et al. (2013) proposed that periodic variations of clIMMs could be explained by the pulsation of massive protostars growing under rapid mass accretion with rates of $dM/dt > 10^{-3}\ M_{\odot}\ yr^{-1}$





Periodic temperature and size change could cause periodic change of pump *and* seed photons

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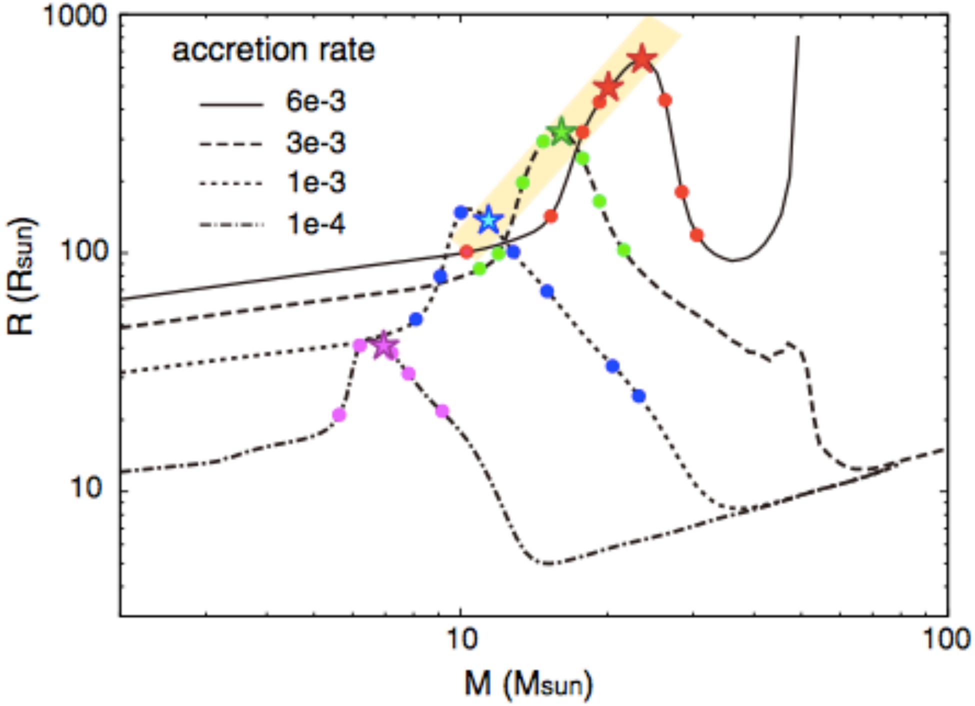
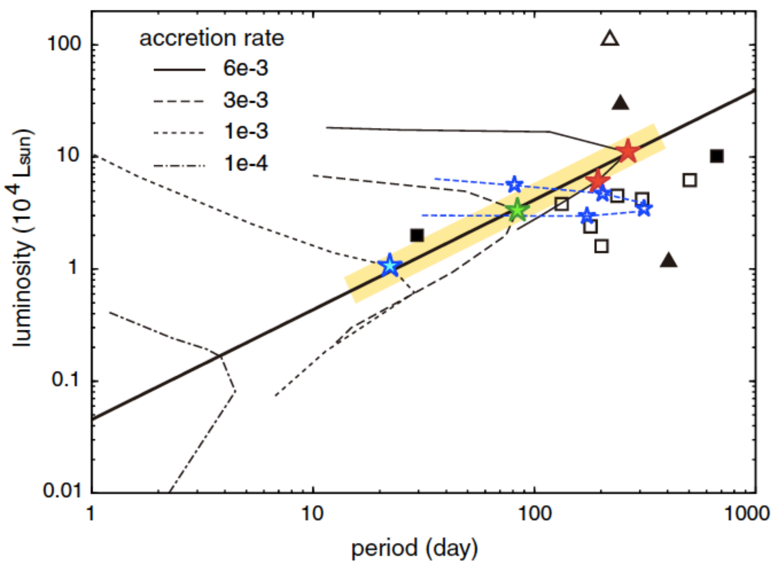
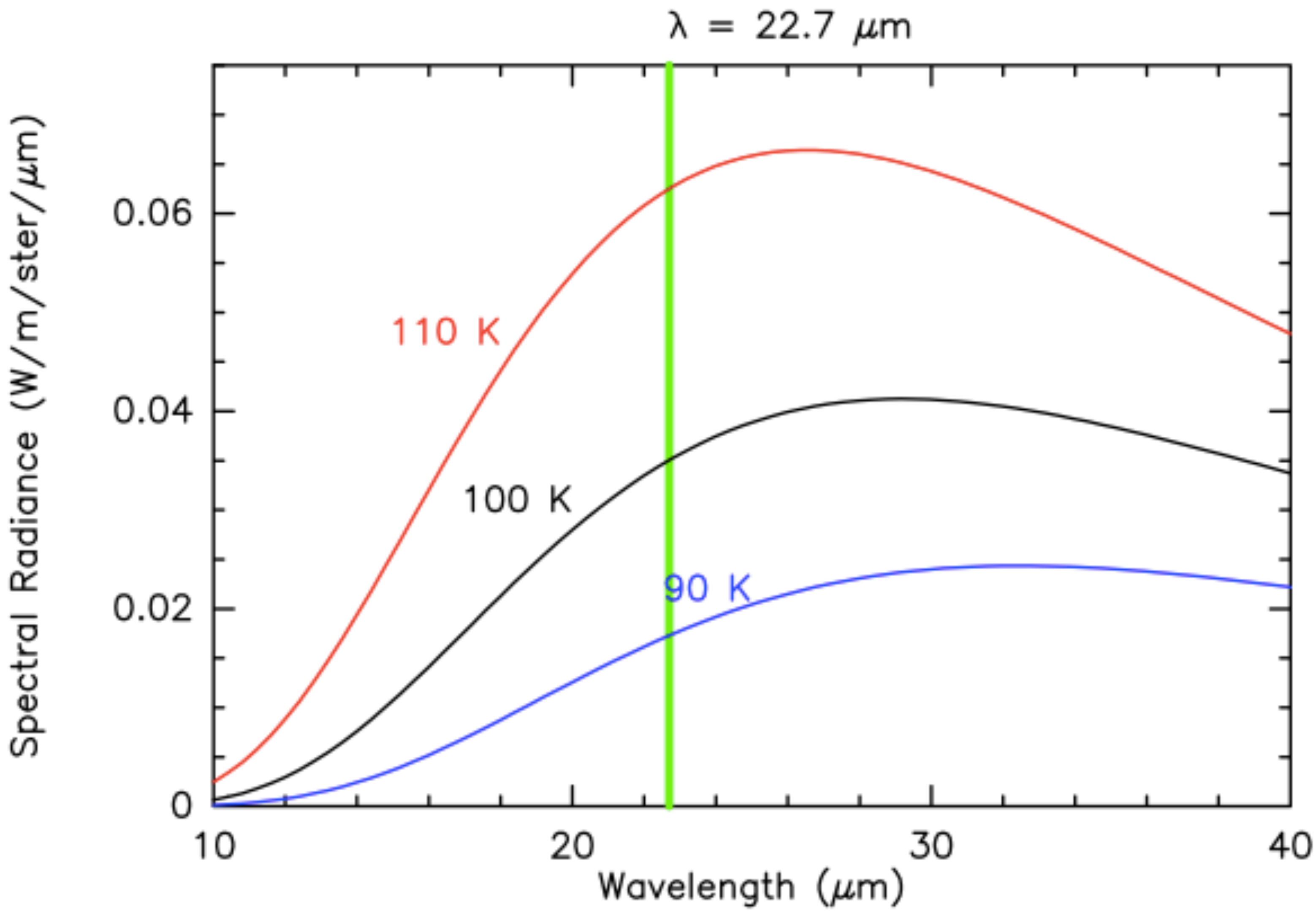




Periodic temperature and size change could cause periodic change of pump *and* seed photons



λ = 22.7 μm
Spectral Radiance (W/m/ster/μm)
0.06
0.04
0.02
0
110 K
100 K
90 K
10
20
30
40
Wavelength (μm)

Thermal Radio emission from High Mass Protostellar Objects

- No obvious relationship between radio luminosity and total luminosity - Panagia (1973) doesn't work!
- Radio emission is "choked off" (Walmsley 1995) for high enough ("critical") mass accretion rates:

$$dM/dt(crit) = [4\pi L(LyC) G M_* m_H^2 \beta]^{\frac{1}{2}}$$

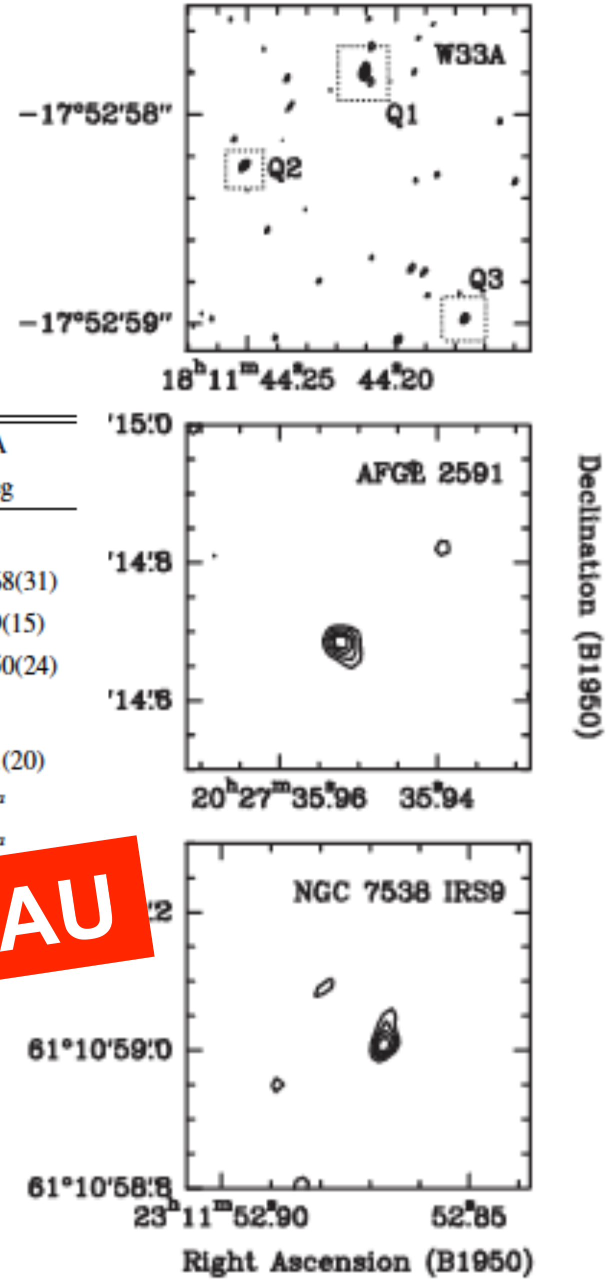
- Radio luminosity is only a tiny fraction of total luminosity
- Radio source almost certainly is the protostar itself!

Trigonometric Parallax Distances (from BeSSeL survey):

W33 D = 2.47 ± 0.16 kpc (Immer et al. 2013)

AFGL 2591 D = 3.33 ± 0.11 kpc (Rygl et al. 2012)

NGC 7538 D = 2.65 ± 0.12 kpc (Moscadelli et al. 2009)



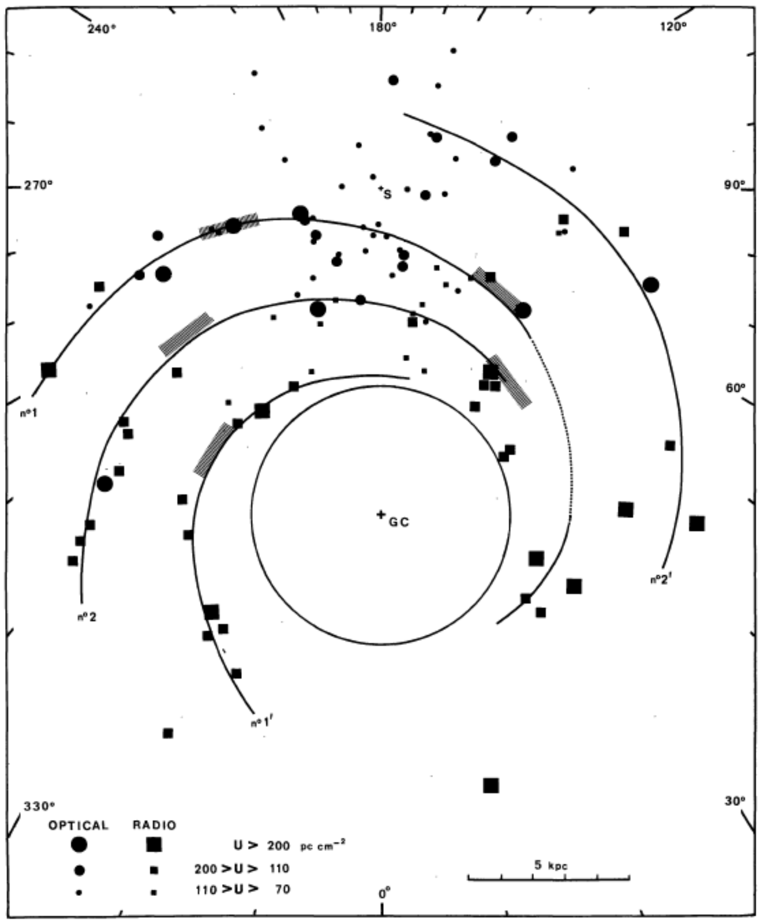
Source	α (B1950)	δ (B1950)	Peak I_ν	Total S_ν	Major axis	Minor axis	PA
	hh mm ss	° ′ ″	mJy/beam	mJy	mas	mas	deg
			C-array				
W 33A	18 11 44.2121(12)	−17 52 57.793(29)	3.0(2)	4.3(5)	530(140)	270(110)	168(31)
AFGL 2591	20 27 35.9523(22)	+40 01 14.694(17)	2.6(2)	3.3(5)	440(110)	<160	89(15)
NGC 7538 IRS9	23 11 52.8696(14)	+61 10 58.998(12)	3.1(2)	2.9(3)	150(110)	<250	150(24)
			A-array				
W 33A Q1	18 11 44.2104(4)	−17 52 57.804(9)	0.80(17)	1.7(5)	87(57)	<67	41(20)
W 33A Q2	18 11 44.2510(3)	−17 52 58.241(6)	0.79(18)	0.62(27)	<49	<12	...[a]
W 33A Q3	18 11 44.1769(3)	−17 52 58.972(5)	0.76(18)	0.53(25)	<37	...[a]	...[a]
AFGL 2591	20 27 35.9520(3)	+40 01 14.682(4)	0.95(16)	1.9(5)	50(15)	[illegible]	[illegible]
NGC 7538 IRS9	23 11 52.8671(3)	+61 10 59.017(4)	1.1(2)	[illegible]	[illegible]	[illegible]	[illegible]

[a] No solution was found for this parameter.

≤ 20 –150 AU

Van der Tak & Menten 2005

GLOSTAR C: Infrared Spectro/Photometry of massive young open clusters



Georgelin & Georgelin 1976

Annu. Rev. Astron. Astrophys. 2003. 41:57–115
doi: 10.1146/annurev.astro.41.011802.094844

EMBEDDED CLUSTERS IN MOLECULAR CLOUDS

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Lad

- M
- 90
  clu
- Hig ... only ~5%
  evo ... usters

Lada & Lada (2003) sample:

- $\Sigma = 76$
- $D < 2.5$ kpc
- $23\ M_\odot < m < 1100\ M_\odot$
- ONC most massive ($m \sim 1100\ M_\odot$)