Large-Scale Surveys of Star Formation in the Milky Way

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16th June 2014

Outline

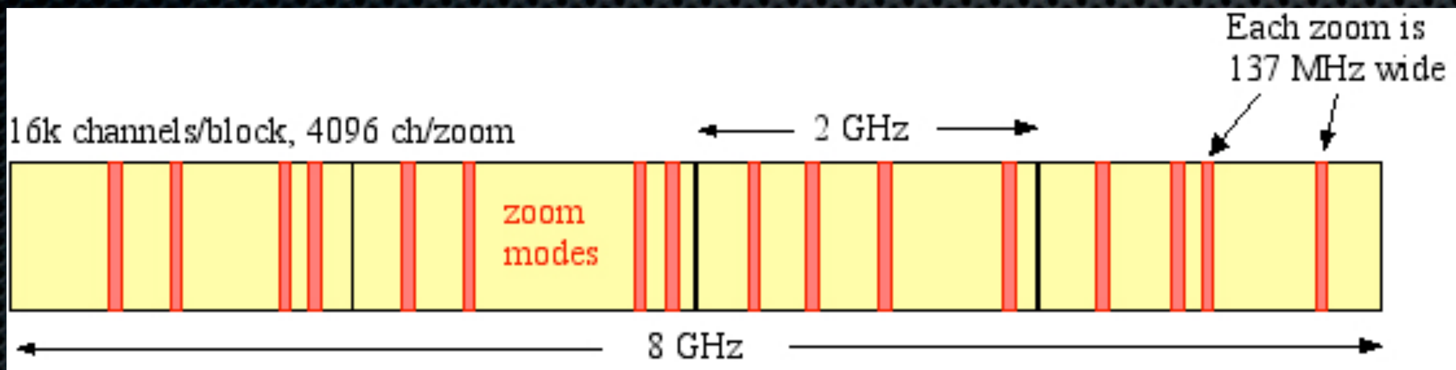
- Recent & current surveys of the Milky Way’s ISM
- Astrophysical context
- Description of CHaMP
- Description of ThrUMMS

The Mopra dish (part of ATNF)

- 22m dish
- covers 3mm band (74–116 GHz MMIC)
- 35″ beam
- $T_{sys} < 200$ K

OTF capability, flexible receivers & digital filterbank: a powerful tool to map molecular clouds

Mopra's spectrometer



Species	Transition	Frequency (GHz)	Utility	IF Zoom Number[a] Setup 1	Setup 2	Setup 3
NH_2D	$J_{K+K-} = 1_{11} \rightarrow 1_{01}$	85.925-8 (6hf)	Coldest dense gas		8	16
SiO	$J = 2 \rightarrow 1$ v = 1	86.243	Maser		7	15
$H^{13}CN$	$J = 1 \rightarrow 0$	86.339-44 (3hf)	Class I tracer	8	6	14
$H^{13}CO^+$	$J = 1 \rightarrow 0$	86.754	Densest gas			
HCO	$J_{K+K-} = 1_{01} \rightarrow 0_{00}$	86.777, 806(2hf)	PDR interface		5	13
SiO	$J = 2 \rightarrow 1$	86.847	Outflows			
HNCO	$J_{K+K-} = 4_{04} \rightarrow 3_{03}$	87.925	Chemistry			12
HCN	$J = 1 \rightarrow 0$	88.630-4 (3hf)	Class I tracer		4	11
CH_3OH	$J_{K+K-} = 15_{3,12} \rightarrow 14_{4,11}$ A	88.940	Hot core/maser			10
HCO^+	$J = 1 \rightarrow 0$	89.189	Infall, outflow	6	3	9
H^+	59α	89.247	H II regions			
CH_3CH_2CN	$J_{K+K-} = 10_{91} \rightarrow 9_{90}$	89.549	Organic chemistry			8
HNC	$J = 1 \rightarrow 0$	90.664	Chemistry			7
HC_3N	$J = 10 \rightarrow 9$	90.979	Prestellar gas			6
CH_3OCH_3	$J_{K+K-} = 3_{22} \rightarrow 3_{13}$	91.474-9 (4cpts)	Organic chemistry			5
CH_2DOH	$J_{K+K-} = 4_{13} \rightarrow 4_{04}$	91.587	Cold to hot gas			4
CH_3CN	$J = 5 \rightarrow 4$	91.959-87 (K-lad)	Thermometer		2	3
^{13}CS	$J = 2 \rightarrow 1$	92.494	Dense gas, infall			2
N_2H^+	$J = 1 \rightarrow 0$	93.171-6(7hf)	Cold dense gas	2	1	1
CH_3OH	$J_{K+K-} = 1_{01} \rightarrow 2_{12}$ E	93.197	Hot core/maser			

A survey of (southern) surveys

white = complete yellow = in progress orange = planned data D/L

cyan = continuum magenta = spectral line

SGPS, GASKAP	21cm		HI	✔
HOPS		(13mm)	H_2O, NH_3	
MALT45		(7mm)	CS	
CHaMP, MALT90		(3.3mm)	HCO^+, HCN, N_2H^+.....	✔
CHaMP,ThrUMMS,Nanten,CfA		(2.6mm)	^{12}CO, ^{13}CO, $C^{18}O$, CN	✔
BGPS	1100μm			
ATLASGAL	870μm			
Hi-GAL	60–350μm			✔
IRAS	12–100μm			✔
MIPSGAL	24,70μm			✔
MSX	8–21μm			✔
GLIMPSE	3–8μm			✔
2MASS	1–2μm			✔

GLIMPSE/MIPSGAL

A survey of (southern) surveys

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			data D/L
SGPS, GASKAP	21cm	HI	✔
HOPS	(13mm)	H_2O, NH_3	
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CHaMP, MALT90	(3.3mm)	HCO^+, HCN, N_2H^+.....	✔
CHaMP, ThrUMMS, Nanten, CfA	(2.6mm)	^{12}CO, ^{13}CO, $C^{18}O$, CN	✔
BGPS	1100μm		
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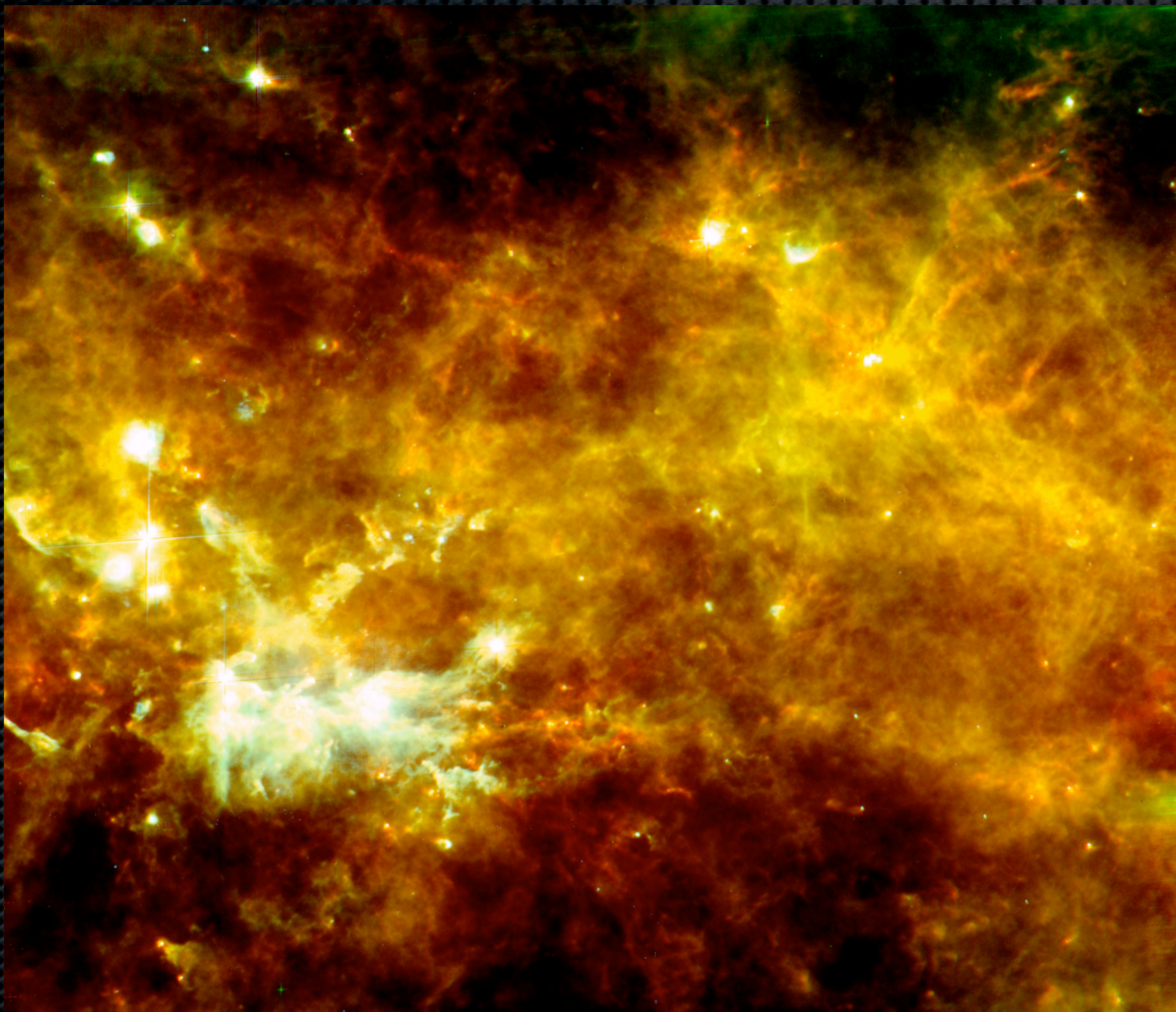
GLIMPSE	3–8μm		✔
2MASS	1–2μm		✔

Hi-GAL



70 µm
160 µm
350 µm

A survey of (southern) surveys

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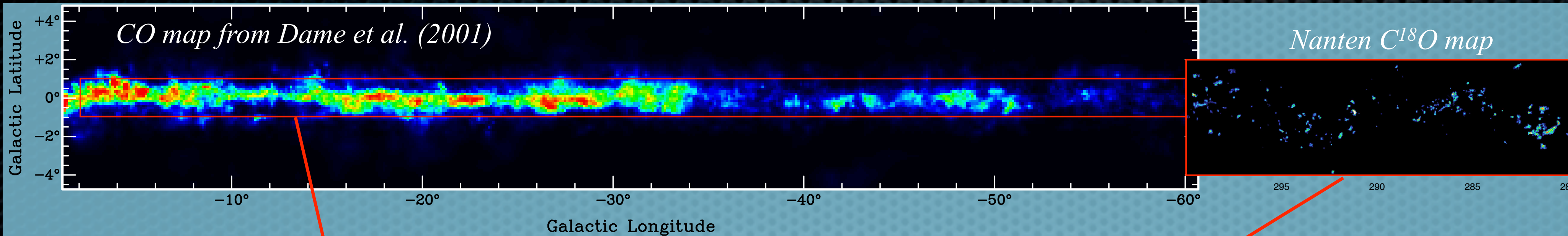
2MASS	1–2μm			✔

Census of High- and Medium-mass Protostars

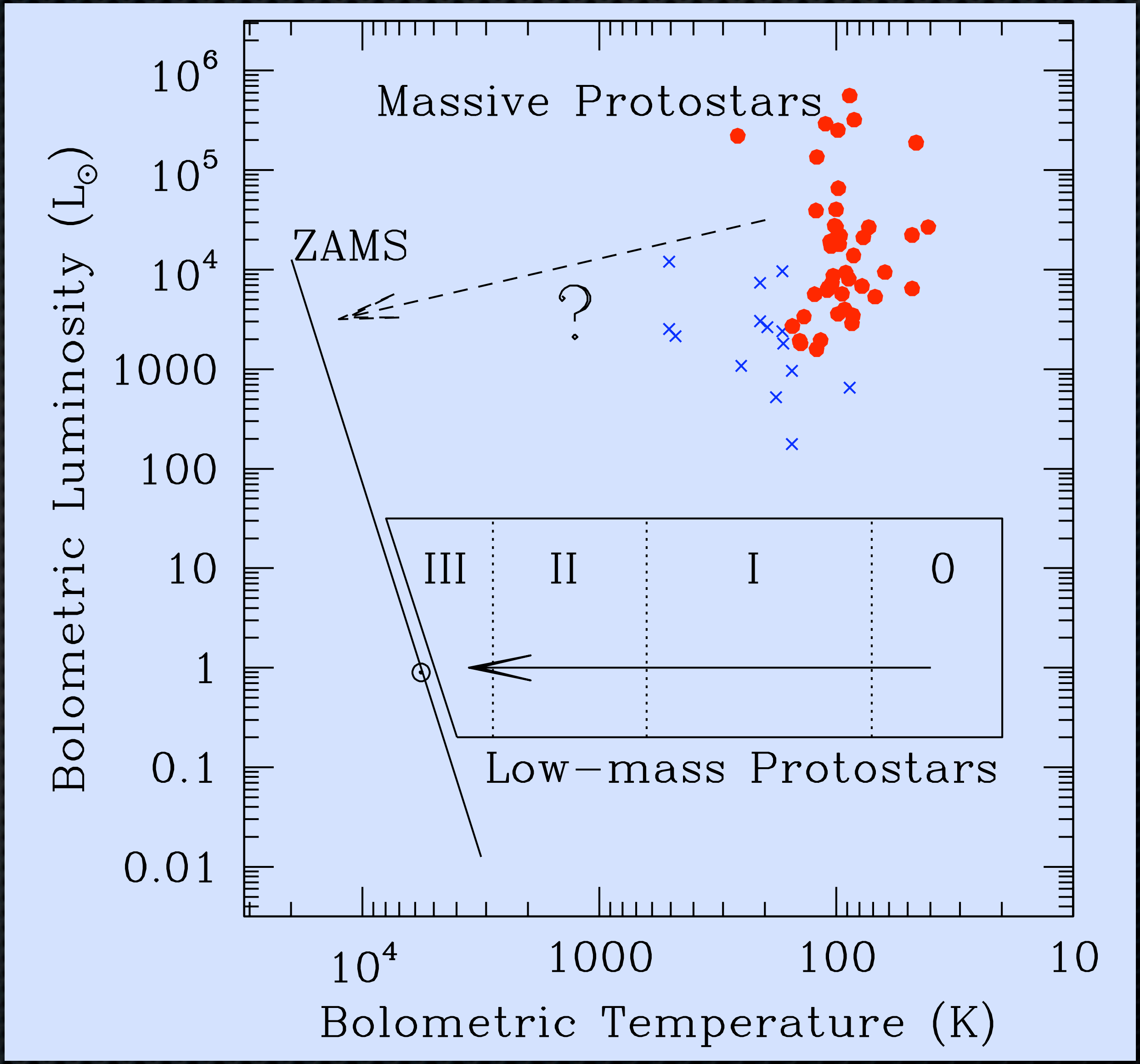


- Complete coverage over 58°x1°
- Now expanding |*b*| coverage to 60°x2°, ready by 2015
- Simultaneous maps of ^{12}CO, ^{13}CO, $C^{18}O$, CN (all J=1–0)
- 1′.2 resolution and T_A*(rms) ~ 1 K in 0.35 km/s channels
- Open project, data available now
- Enables many new projects on ISM & galactic structure, physics of thousands of GMCs, kinematics, cloud formation, magnetic fields, etc.

- Unbiased survey over 20°x6° of a complete population of massive dense clumps
- Simultaneous maps of 16 tracers near 90 GHz, incl. HCO^+, HCN, N_2H^+, SiO, isotopologues, **PLUS** another 16 lines near 110 GHz (CO-logues, CN, etc.)
- 40″ resolution and T_R*(rms) ~ 0.3 K in 0.11/0.09 km/s channels
- HCO^+ data release on 303 massive dense clumps now available, covering many popular regions, e.g. entire η Carinae GMC, NGC 3576, NGC 3603, etc. N_2H^+ release soon, more coming
- Analysis of cloud properties reveals new physics

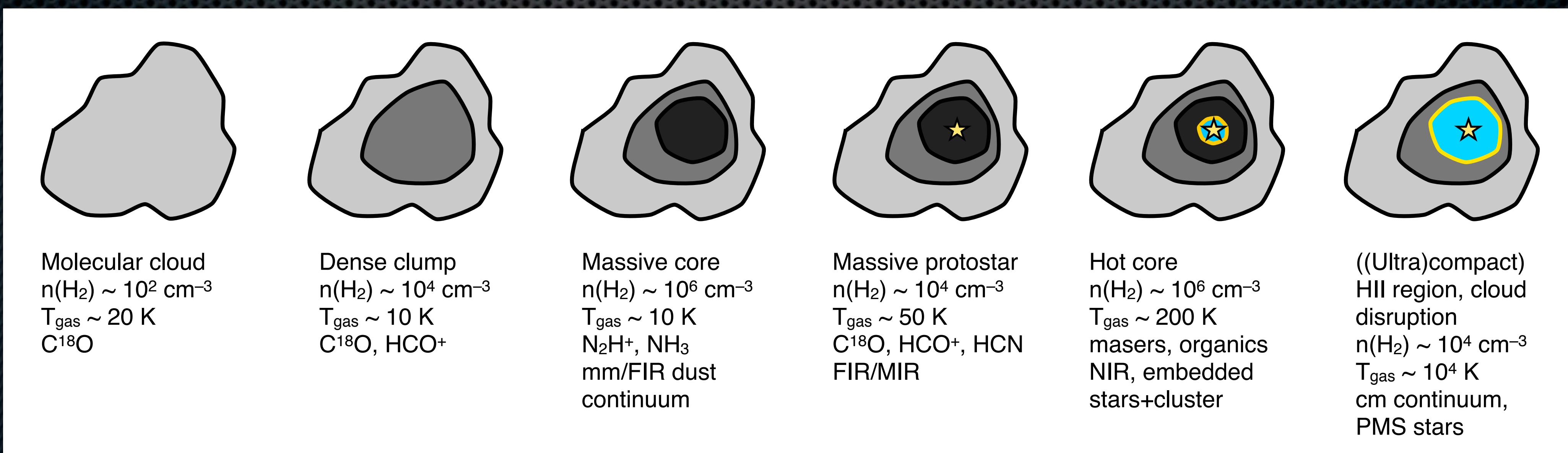
Context of the problem

1. Massive or clustered SF not as well-understood as low-mass SF



Context of the problem

1. Massive or clustered SF not as well-understood as low-mass SF
   - Mechanism? Massive core or competitive accretion?
   - Timescales? Few or many free-fall times?
   - No physical paradigm to fit multitude of phenomena, just a cartoon:



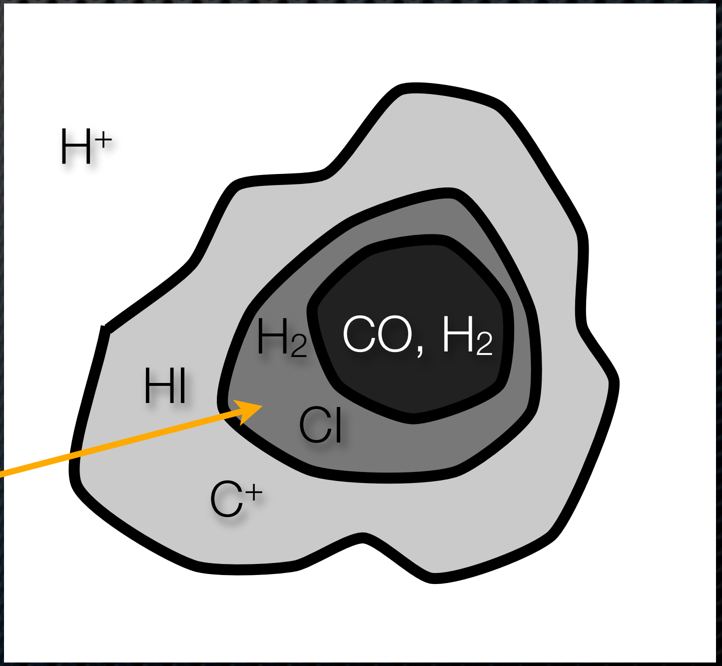
Context of the problem

2. Most stars probably form in clusters

- How do GMCs form the newly-discovered filamentary structures revealed by Hi-GAL? How do these filaments form clumps? Clumps form cores?
- What are the demographics of stars, the IMF, as formed in clumps & cores?

3. A detailed ecology of the ISM

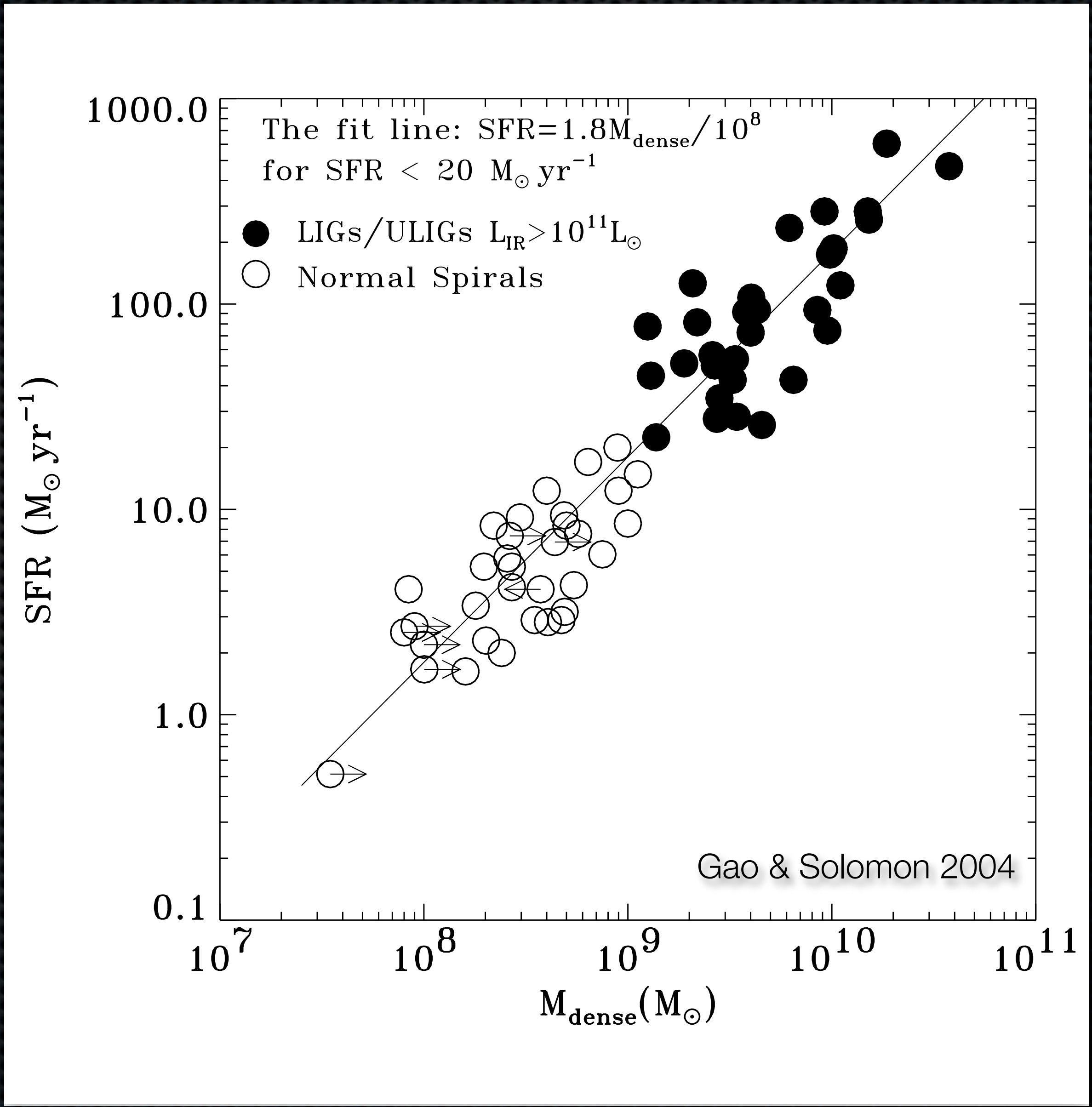
- ISM (except for HII regions) is roughly in pressure equilibrium: what maintains this? Cloud collisions in the WNM/WIM? What prevents SF in dense clumps & cores? What is the PDF of density/column density in the ISM? Relation to filaments?
- How do the H_2 clouds form from HI? eg, Herschel reveals “dark H_2” through C^+ & CI emission, where CO has not yet formed.



Context of the problem

4. Physical origin of Schmidt-Kennicutt Law, galactic-scale SF (extragalactic applications)

- Are the dependencies of SFR tracers truly superlinear, or an artifact of density sampling (as predicted by radXfer, theory)?
- A threshold density for star formation? (Lada et al 2013)

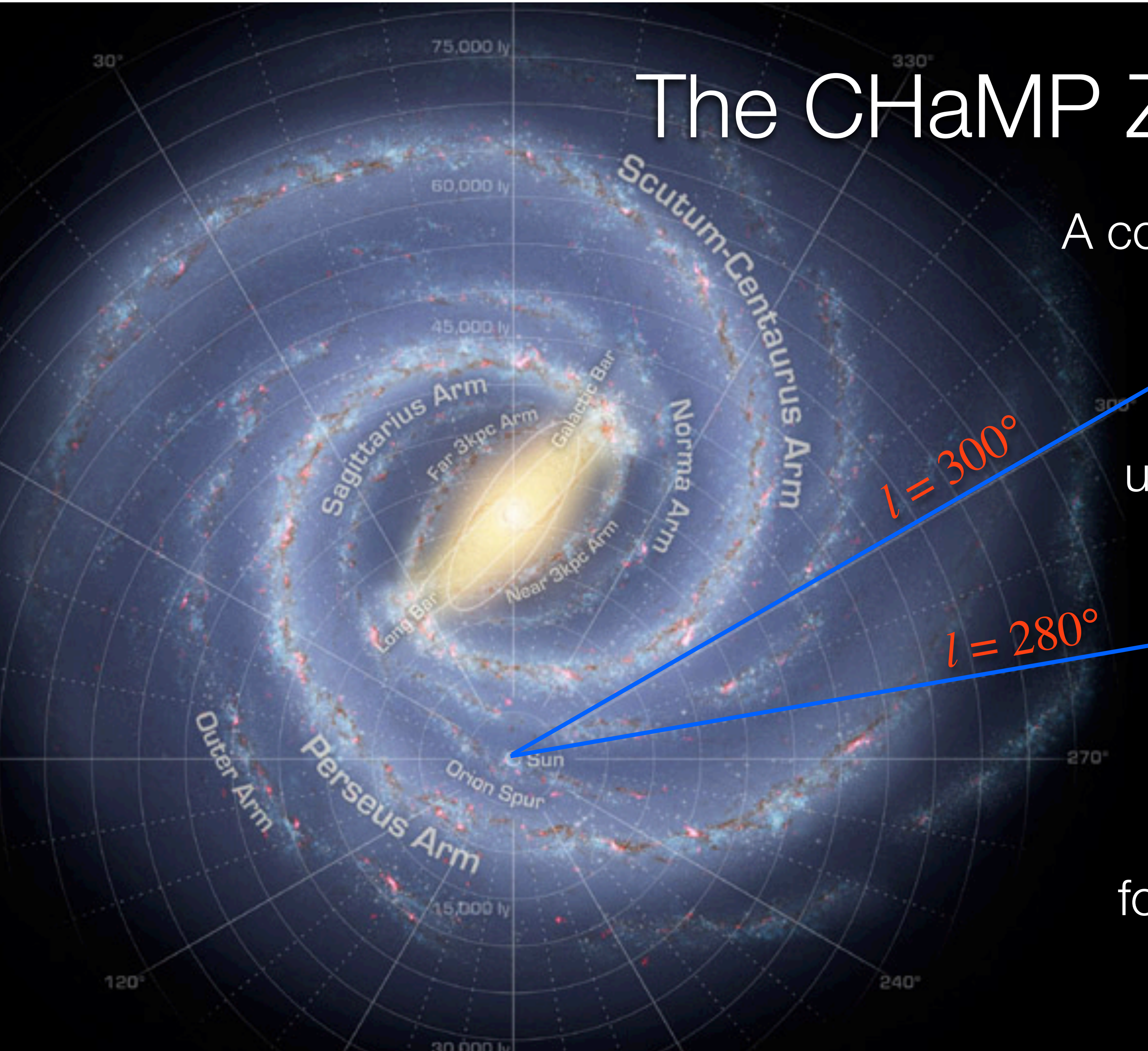


Context of the problem

5. A detailed model of Galactic structure & dynamics

- 1st quadrant shows expected “counterrotation” due to Perseus spiral arm shock, but 4th quadrant non-circular motions are opposite to this spiral arm model.
- Can we see the impact of the bar on Galaxy’s overall ISM, or details of the Far 3kpc Arm & new Far Arm?

The CHaMP Zone



A complete,

unbiased survey

of massive star formation

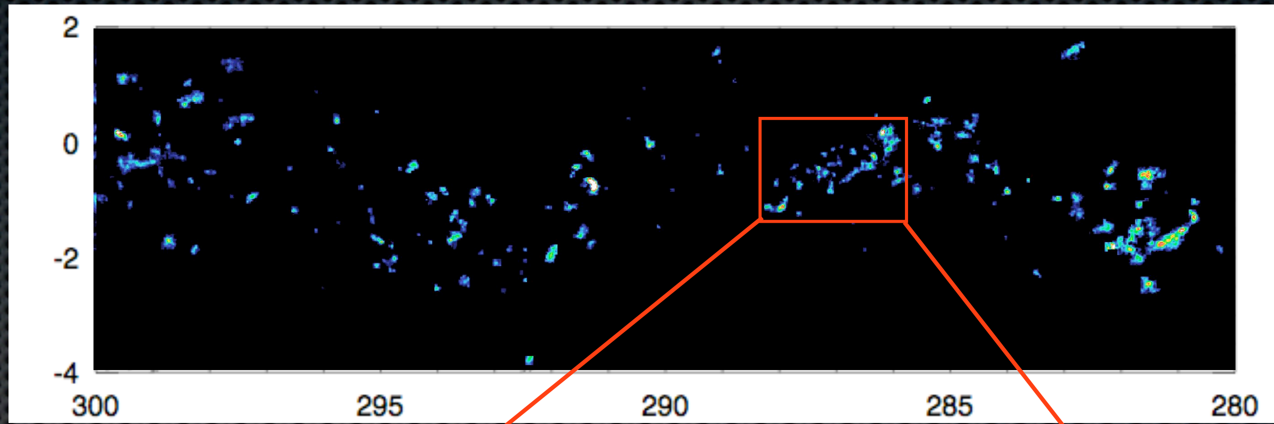
Image credit: R.Hurt

CHaMP colleagues

- Yoshi Yonekura, Ibaraki University
- Yasuo Fukui, Nagoya University
- Stuart Ryder + Andrew Hopkins, AAO
- Audra Hernandez, University of Wisconsin
- 13 University of Florida students/former students, including Stefan O’Dougherty, Luis Alvarez, Billy Schap
- Adam Ginsberg, ESO

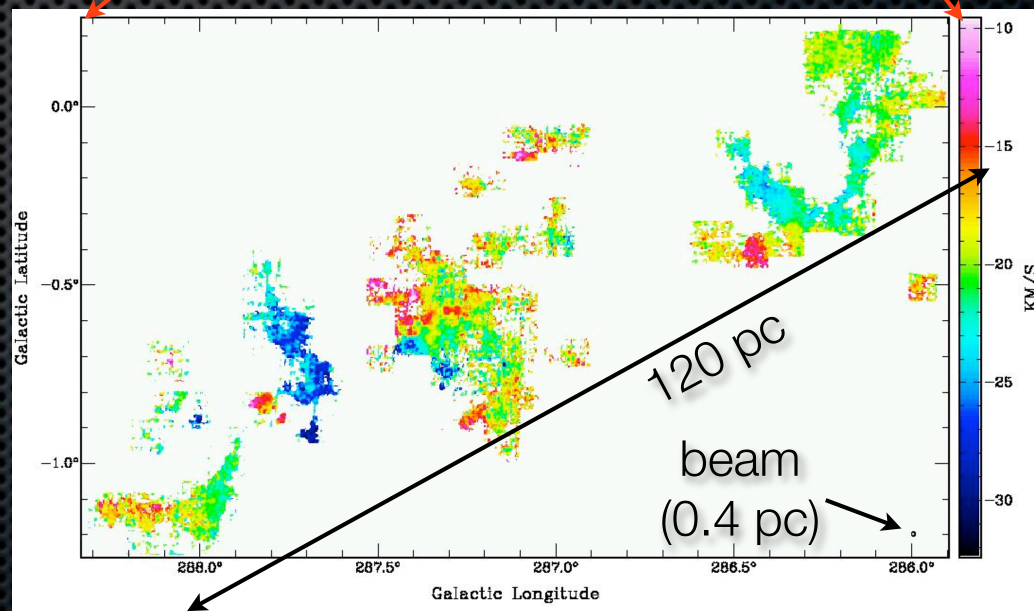
CHaMP in HCO^+

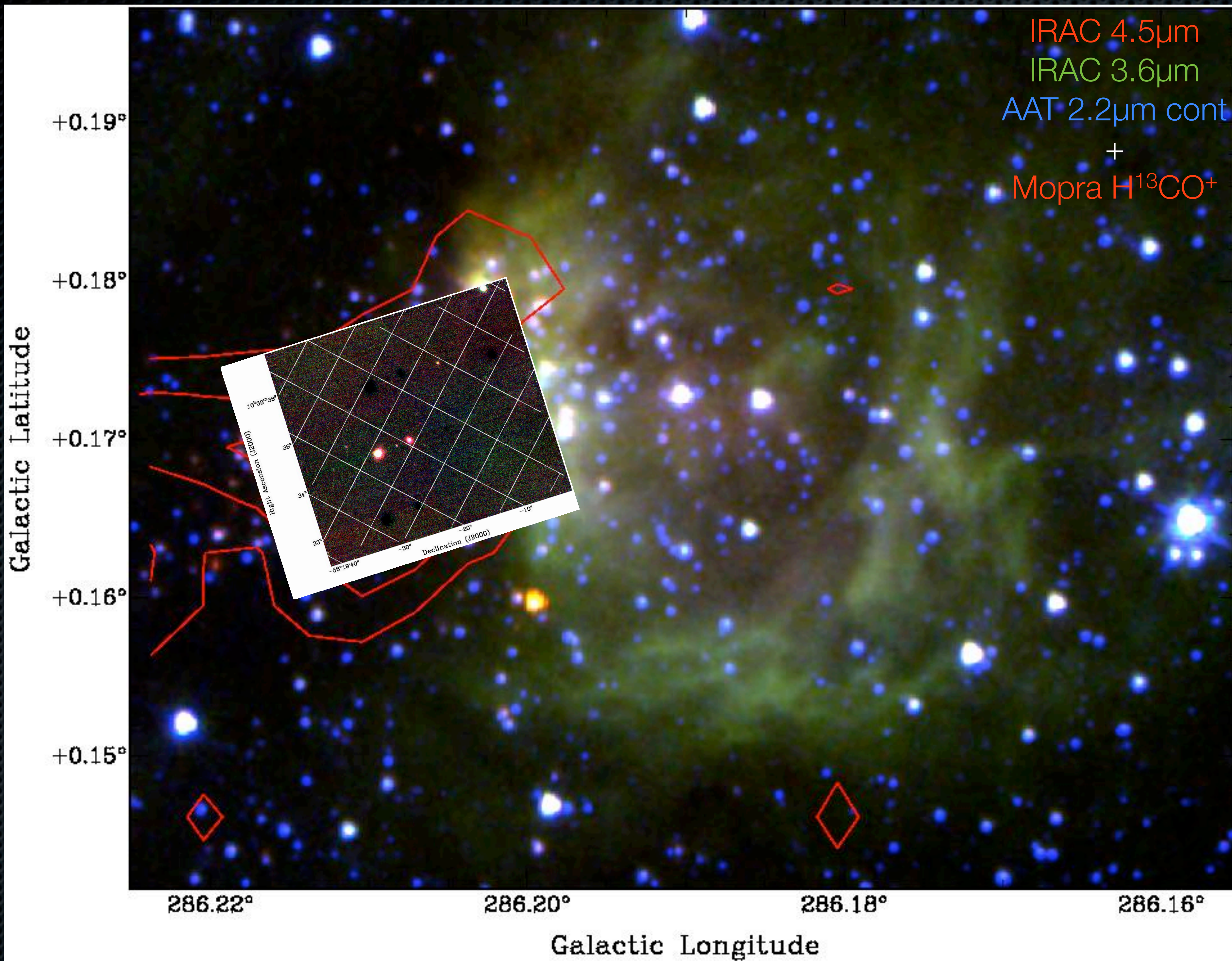
Identified 209 Nanten clumps: mapped brightest 121 at Mopra, which broke up into 303 massive, dense, parsec-scale clumps



All data cubes, moment maps (integrated intensity, velocity field, linewidth), and data tables of clump properties are available for download:

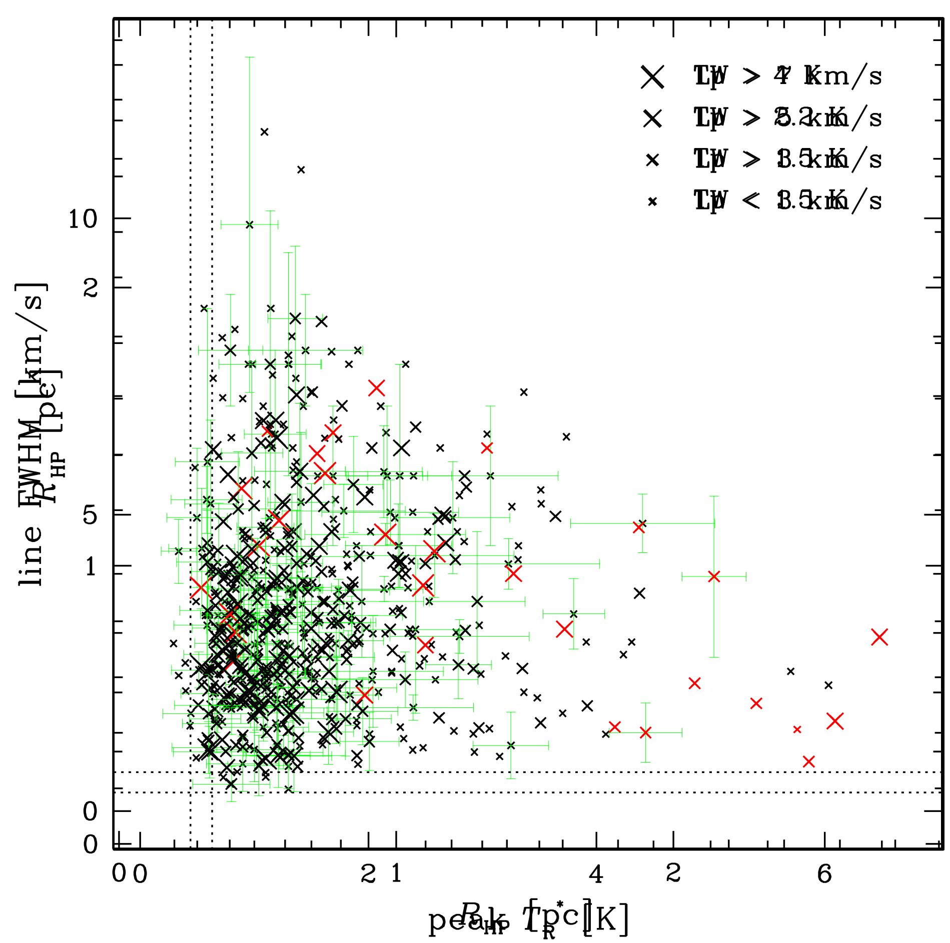
www.astro.ufl.edu/champ



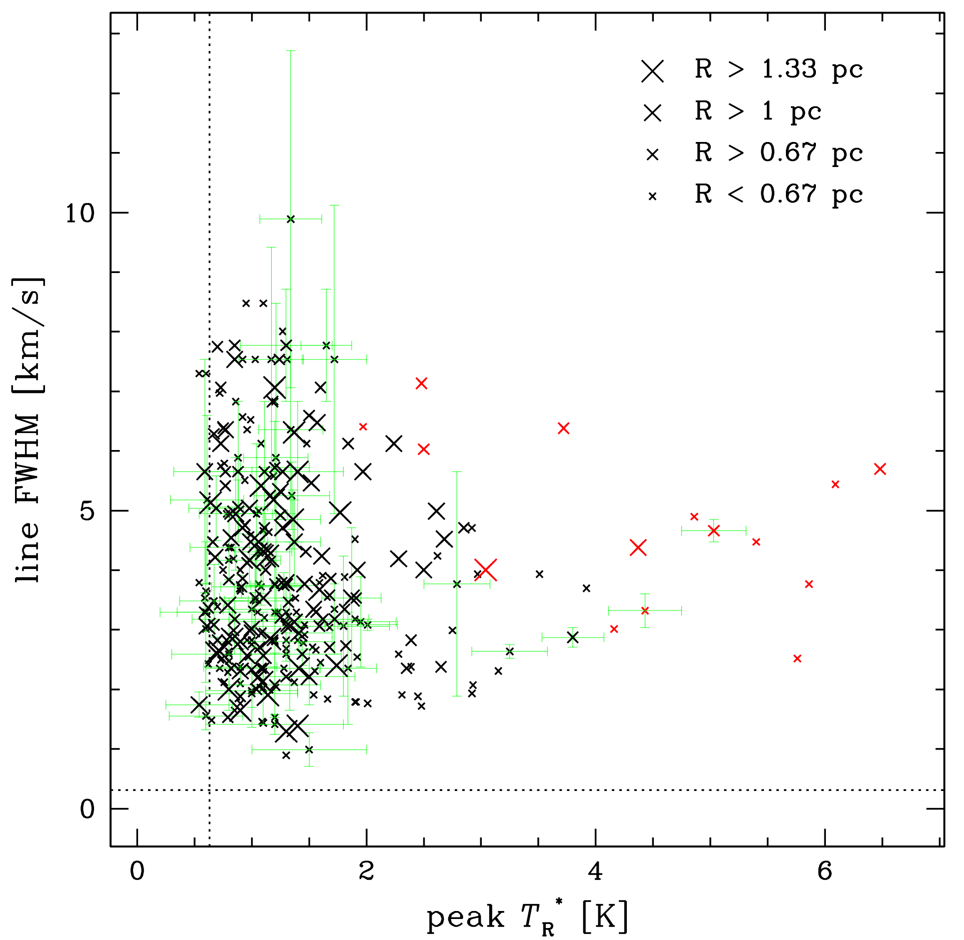


IRAC 4.5μm
IRAC 3.6μm
AAT 2.2μm cont
+
Mopra H13CO+
Galactic Latitude
+0.19°
+0.18°
+0.17°
+0.16°
+0.15°
Galactic Longitude
286.22°
286.20°
286.18°
286.16°
Right Ascension (J2000)
Declination (J2000)

CHaMP sample results

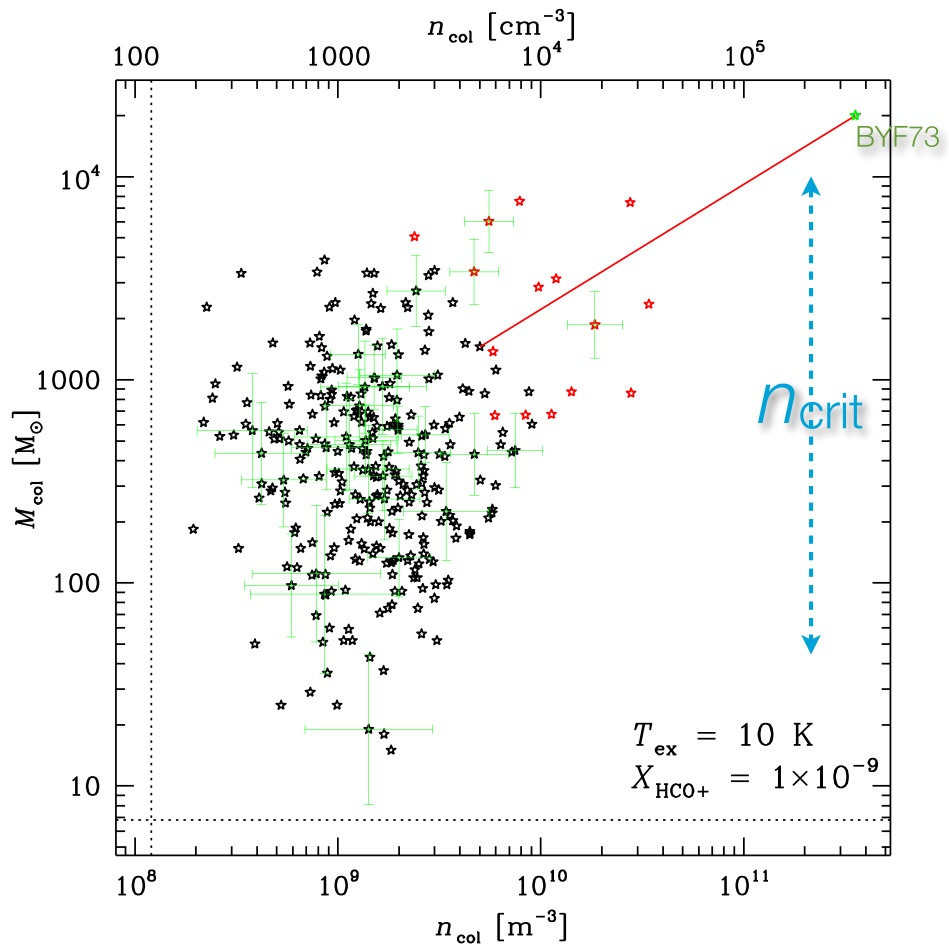


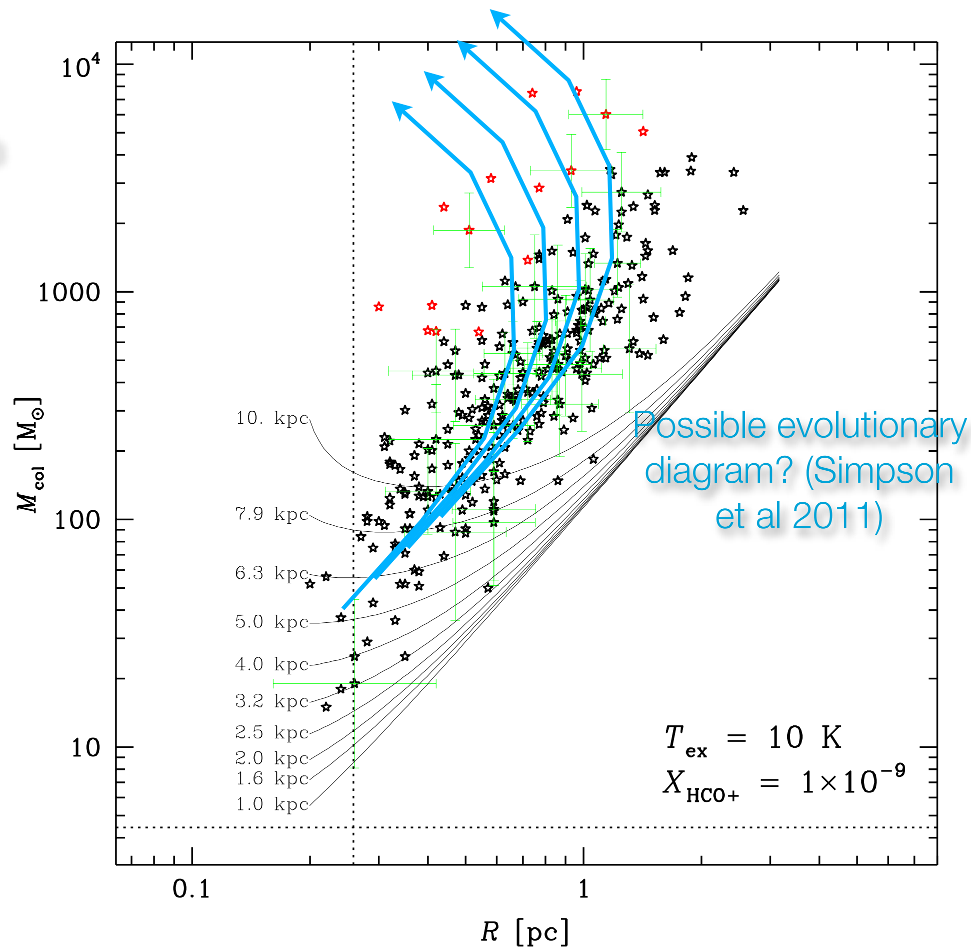
size-brightness



linewidth-brightness

CHaMP sample results

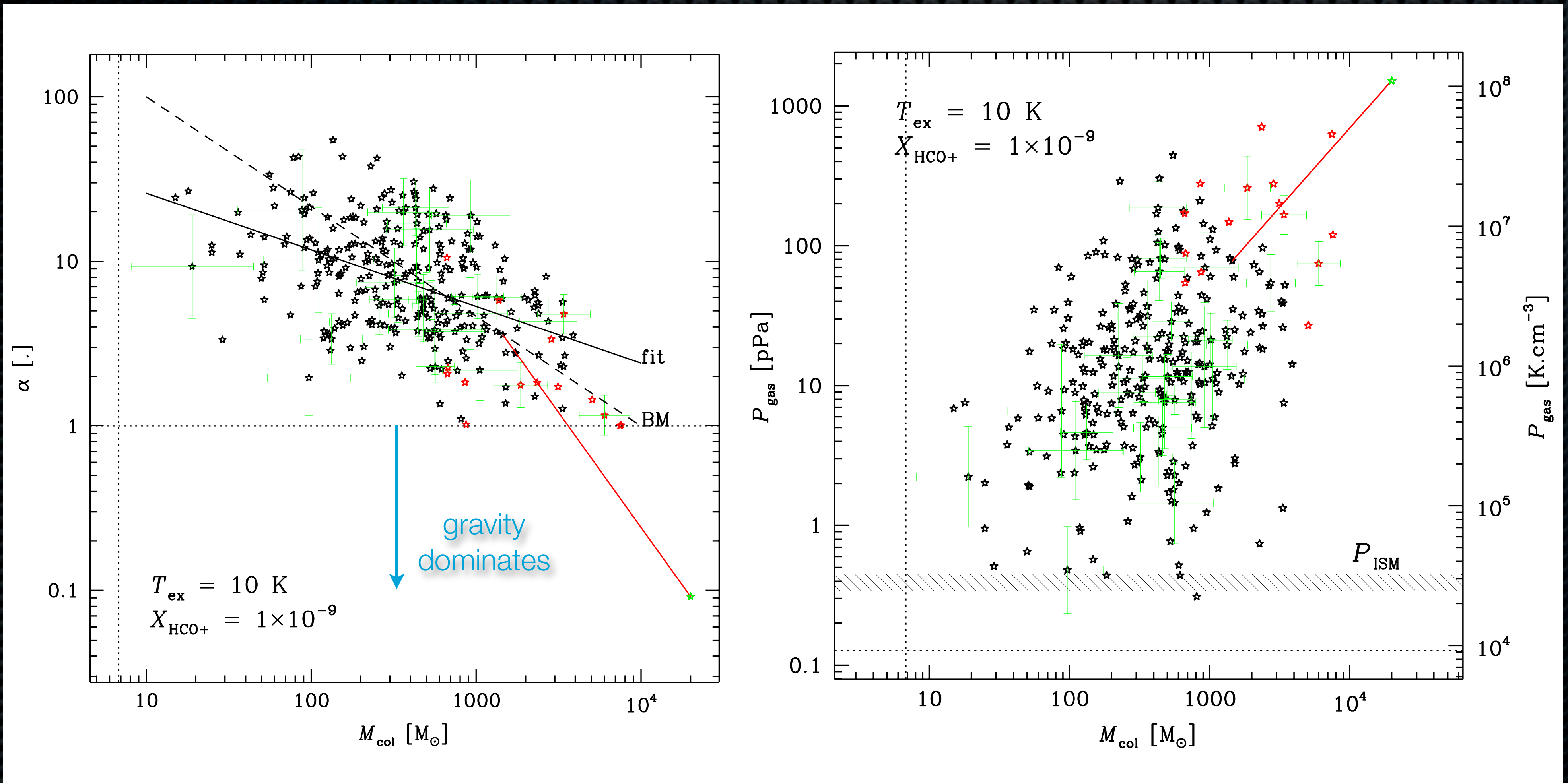




mass-density

mass-radius

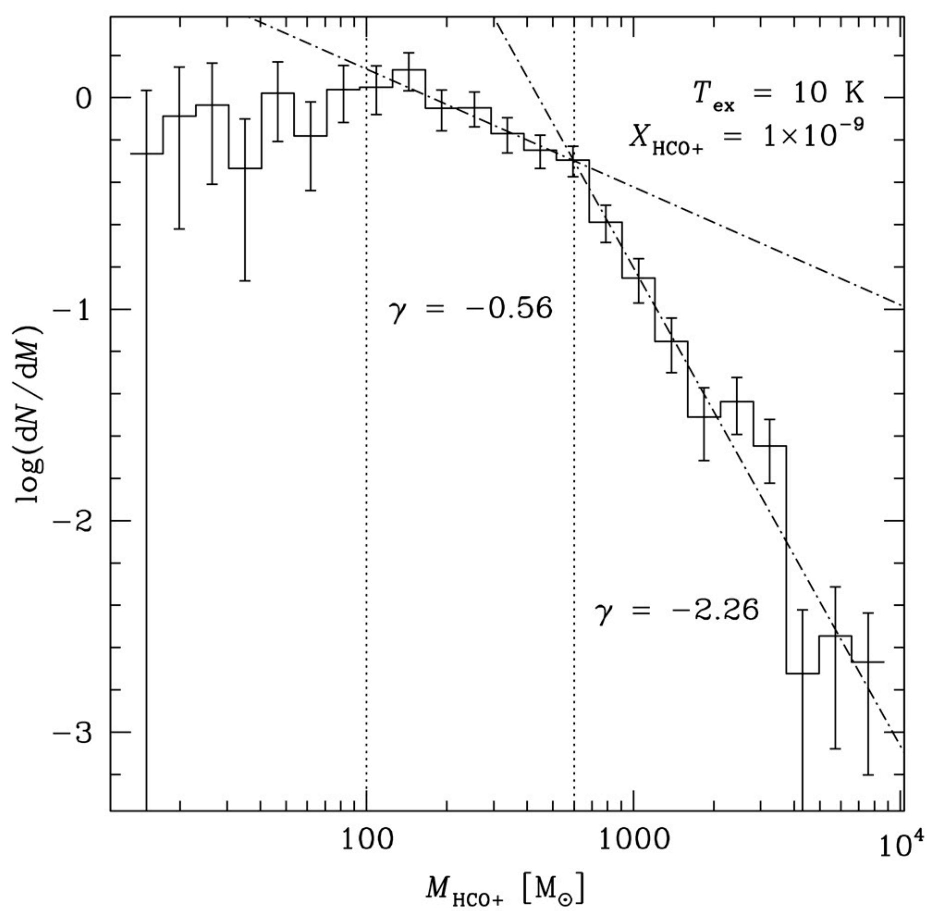
CHaMP sample results

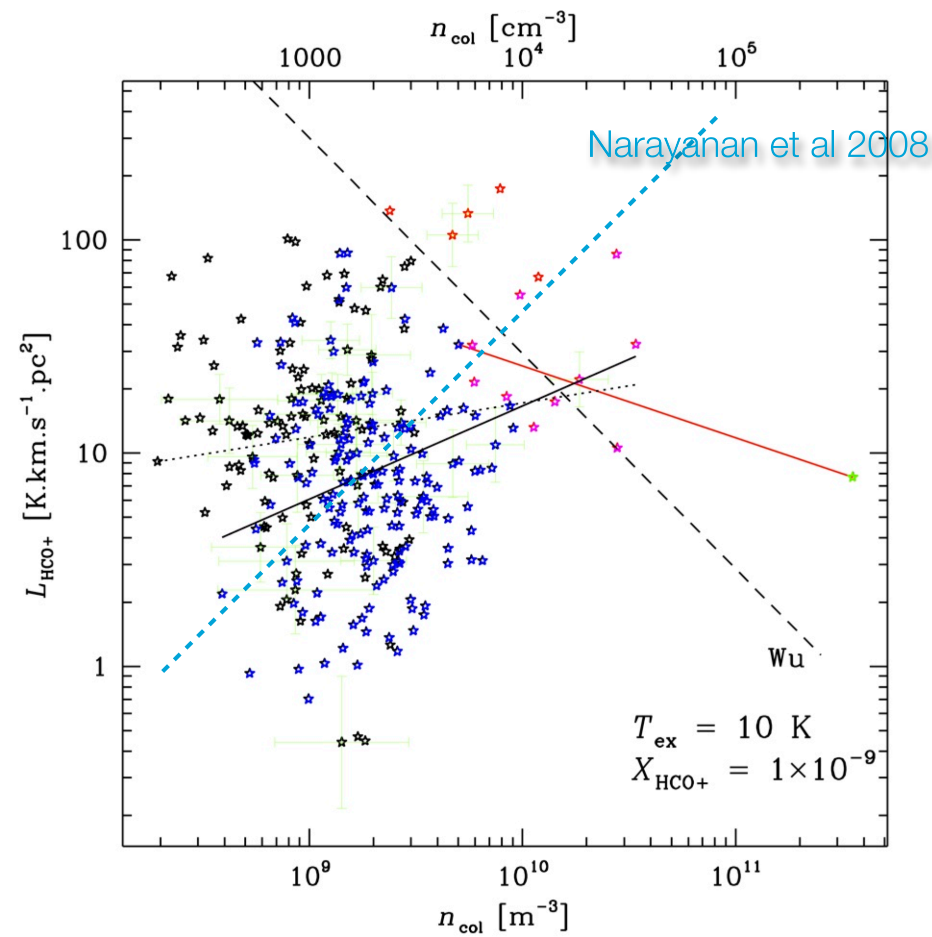


virial-α vs. mass

pressure-mass

CHaMP sample results





Clump Mass Function

→ Core Mass Function

→ IMF

KS-type laws

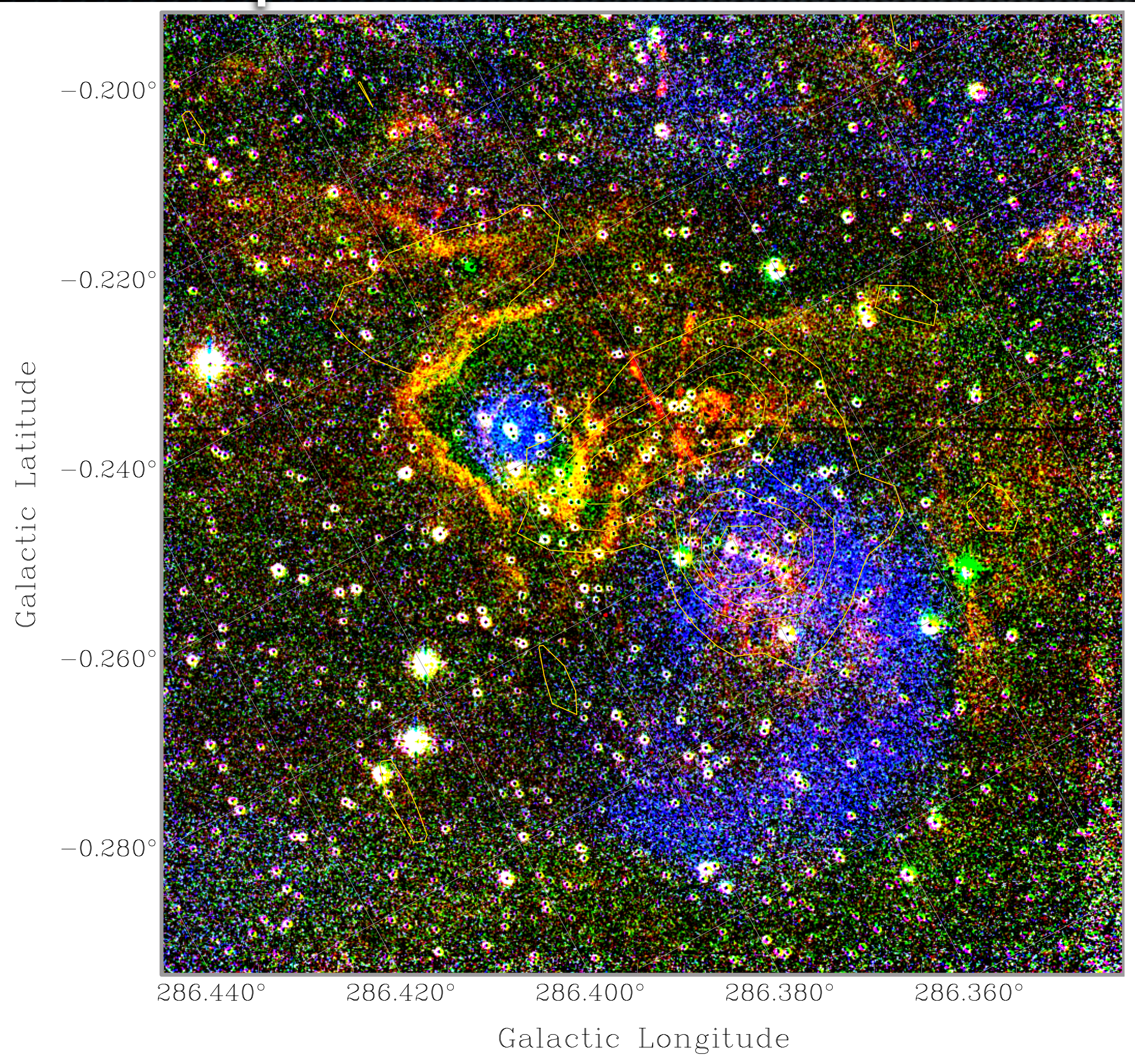
CHaMP HCO^+ conclusions

- Vast population of massive (~10–10^4 $M_\odot$), dense (~3x10^{2-4} cm^{-3}), pressure-bounded, but subthermally-excited clumps — predicted by Narayanan et al 2008! Confirms emerging view of KS laws being physically based on amount of dense gas present, not just all gas
- Most of these may be (relatively) quiescent in their massive SF activity
- Implies a long, quiescent lifetime for clumps (~50–100 Myr) before massive SF turns on
- Could reconcile "short-" and "long-lived" views of massive SF clumps

Next CHaMP releases

- ✔ HCO^+/N_2H^+ and near-IR comparisons, signposts of cloud and cluster evolution (Mopra+AAT survey: SDR, AMH, SNO, LA)
- Mass Probability Density Function in GMCs, comparison with theory (Mopra+Nanten: SNO, JCT, YY, YF)
- ✔ Spectral Energy Distributions of Clumps, examining quiescent/active ratio (NASA archives: BM, JCT)
- Large-scale near-IR embedded cluster demographics (AAT + Spitzer + CTIO surveys: HZ, KR, EAL)
- $H^{13}CO^+$ maps and analysis, excitation/column density (Mopra: SNO)
- HCN maps and analysis, hyperfine ratio physics, detailed comparison with HCO^+ abundances and kinematics (Mopra: WS, SNO, TO, AG)

Compare mm & IR tracers

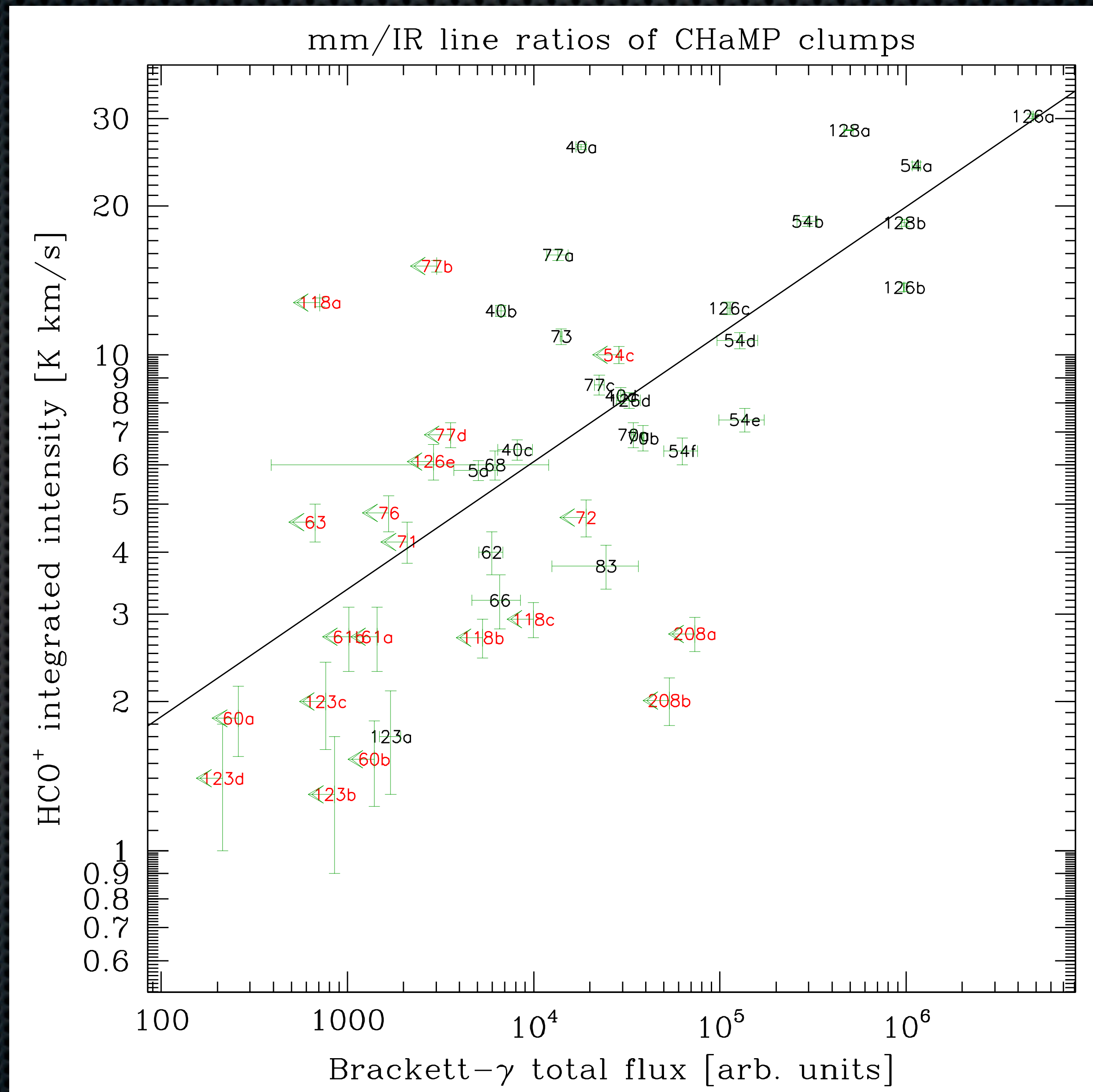


AAT images:
H_2 *v*=1-0 *S*(1)
H_2 *v*=2-1 *S*(1)
BrϒM

Mopra map:
N_2H^+ contours

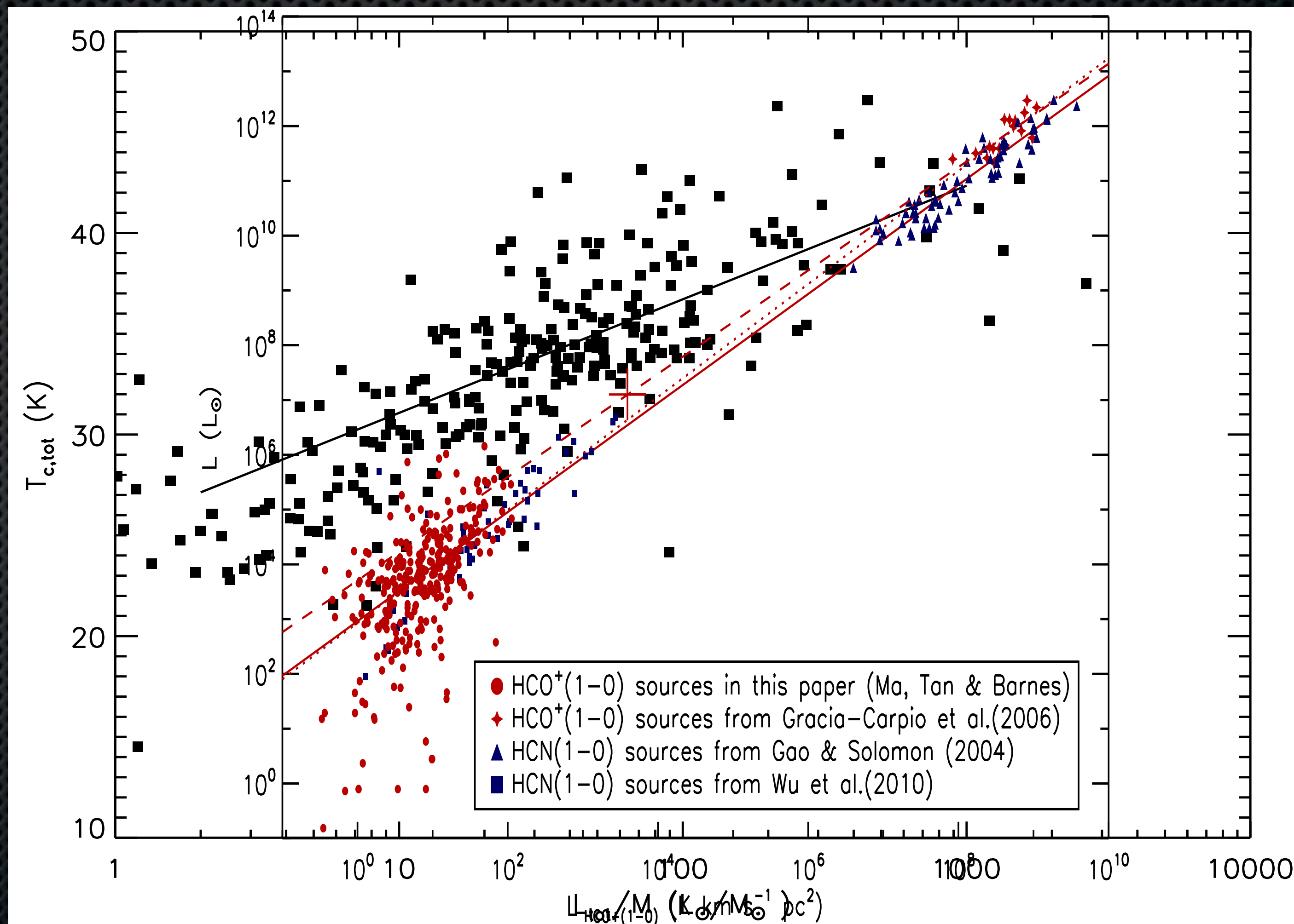
New signposts

- HCO^+ and Brϒ are signposting the same thing: a late-stage surge in massive star formation
- H_2 line ratios consistent with fluorescence, mostly in HCO^+ / Brϒ-bright sources; thermal excitation uncommon
- Some “dense gas” tracers do not trace a homogeneous population of clouds!



New signposts

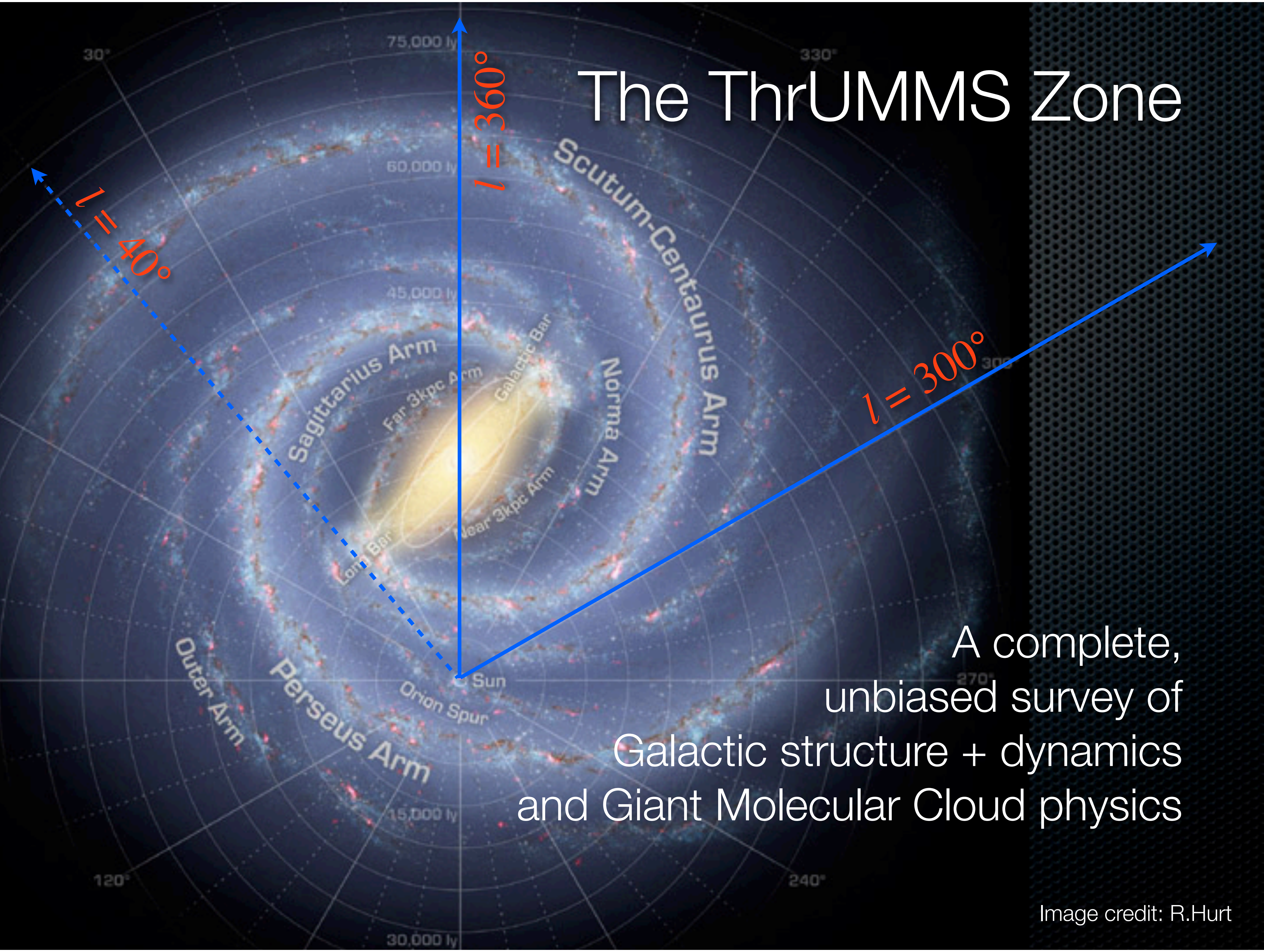
- SEDs of clouds reflect theoretical expectations
- Bright HCO^+ and BrΥ correlate with "more evolved" clumps
- Suggestion of turndown in L_{bol} for lower-mass clumps, following Krumholz-type S-K relation



New signposts

- Many "dense gas" tracers (HCO^+, HCN, etc.) do not trace dense gas, but rather a combination of column density and excitation
- Other dense gas tracers (N_2H^+, NH_3) preferentially trace colder, prestellar gas
- Most massive clumps are not actively forming massive star clusters
- Bright molecular emission signals terminal clump evolution as massive star/cluster forms
- Conversion to molecular mass needs careful calibration to interpret Kennicutt-Schmidt or Larson's relations

The ThrUMMS Zone



A complete,
unbiased survey of
Galactic structure + dynamics
and Giant Molecular Cloud physics

Image credit: R.Hurt

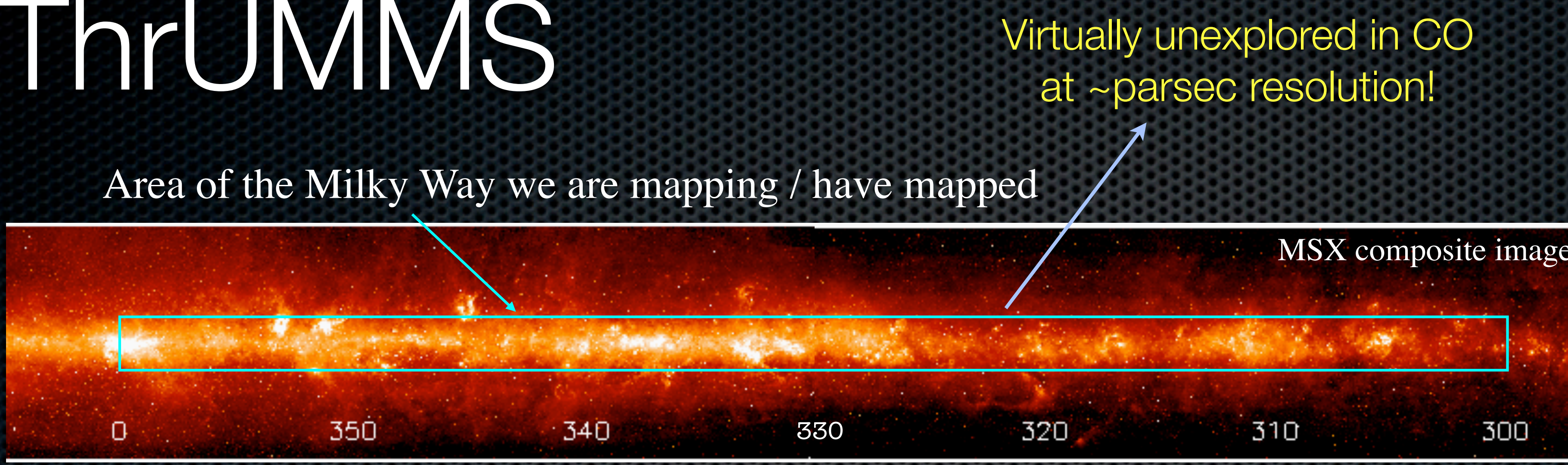

James Binney and Scott Tremaine
GALACTIC DYNAMICS
GALACTIC DYNAMICS
Binney and Tremaine

ThrUMMS colleagues

- Erik Muller, University of Tokyo (with help from Isaac)
- Vicki Lowe + Maria Cunnigham, UNSW
- Balt Indermühle, ATNF
- Audra Hernandez, Univ. of Wisconsin
- Gary Fuller, University of Manchester
- Dick Crutcher, University of Illinois
- Frederic Schuller, ESO
- Quang Nguyen Luong, CITA
- ....(~20 more people)....

- and whoever else wants to join: AN OPEN PROJECT!

ThrUMMS



~400 half-degree fields mapped so far: www.astro.ufl.edu/thrumms

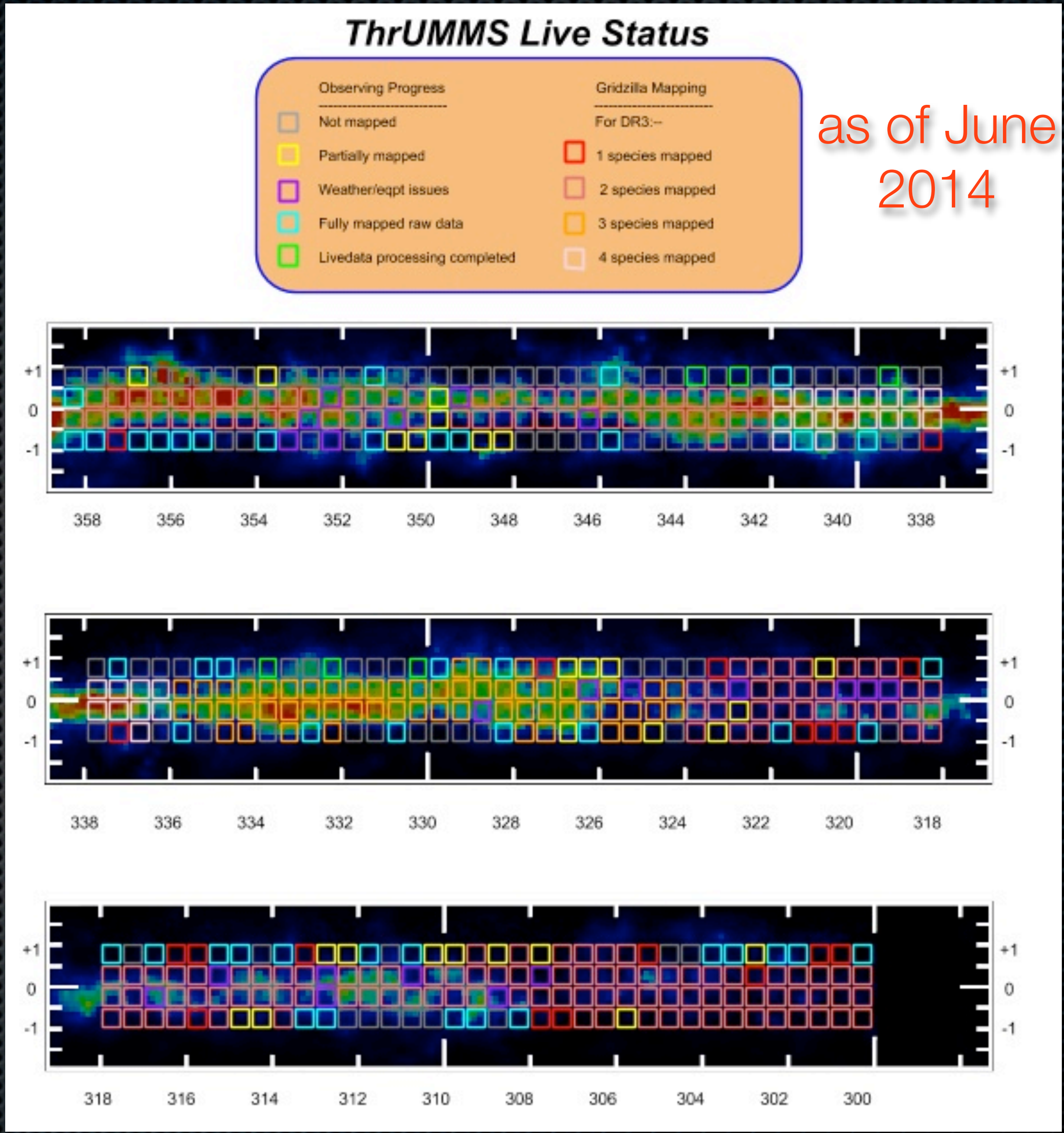
ThrUMMS is making complete, unbiased maps of ^{12}CO, ^{13}CO, $C^{18}O$ and CN across the 4th quadrant, ie 360°>l>300° and |b|<2°, at 1′.2 resolution (ie, ~beam-sampled).

Major aims are to derive global GMC & cloud formation physics, and support interpretation of Hi-GAL, GLIMPSE, GASKAP, ATLASGAL, MALT90, HOPS, etc. surveys with data on the embedding, lower-density GMCs around the brighter, denser clumps.

Many ALMA applications. Data made public **ahead of publication!**

ThrUMMS

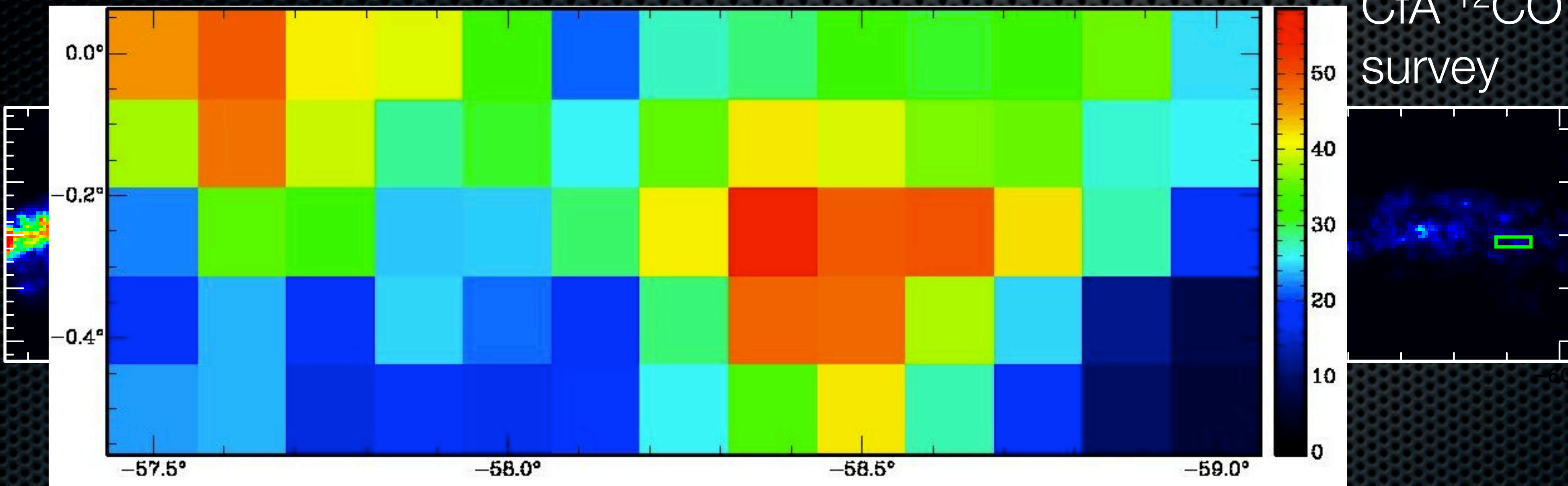
- Phase I of 4Q (60°x1° or |b|<0.5°) ~completed
- Phase II to double this to |b|<1.0° by 2015
- Prospects to eventually cover 100° x 3° (i.e., 1st +4th Quadrants, |b|<1.5°

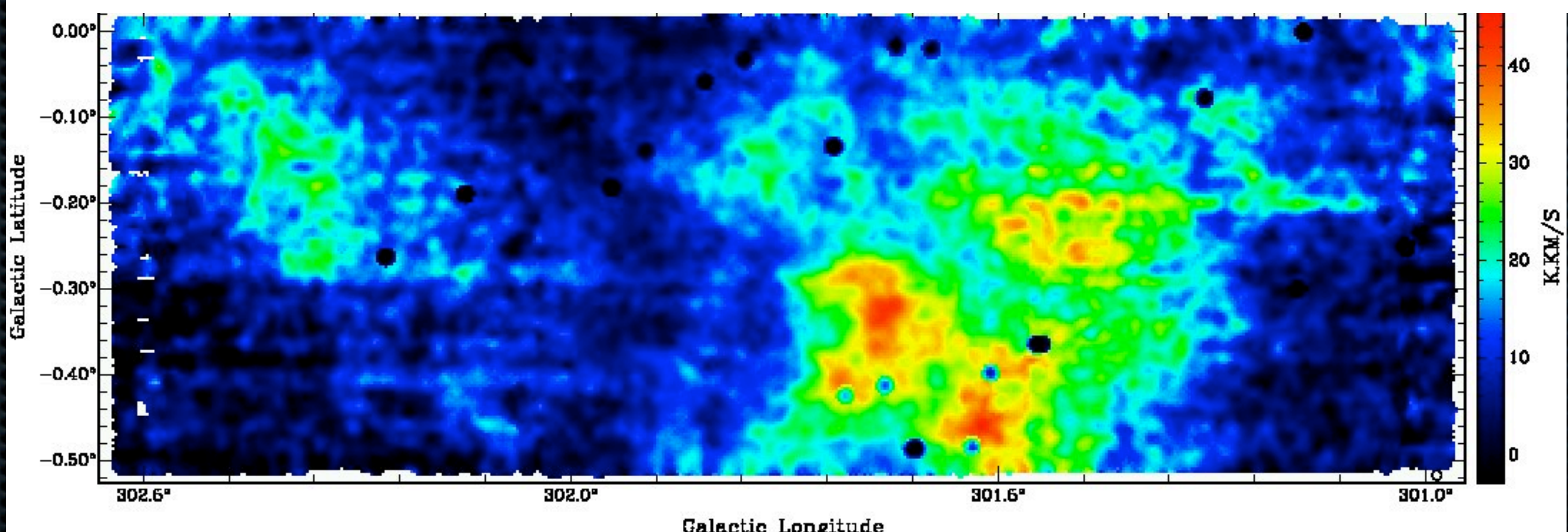


as of June 2014

ThrUMMS eye candy

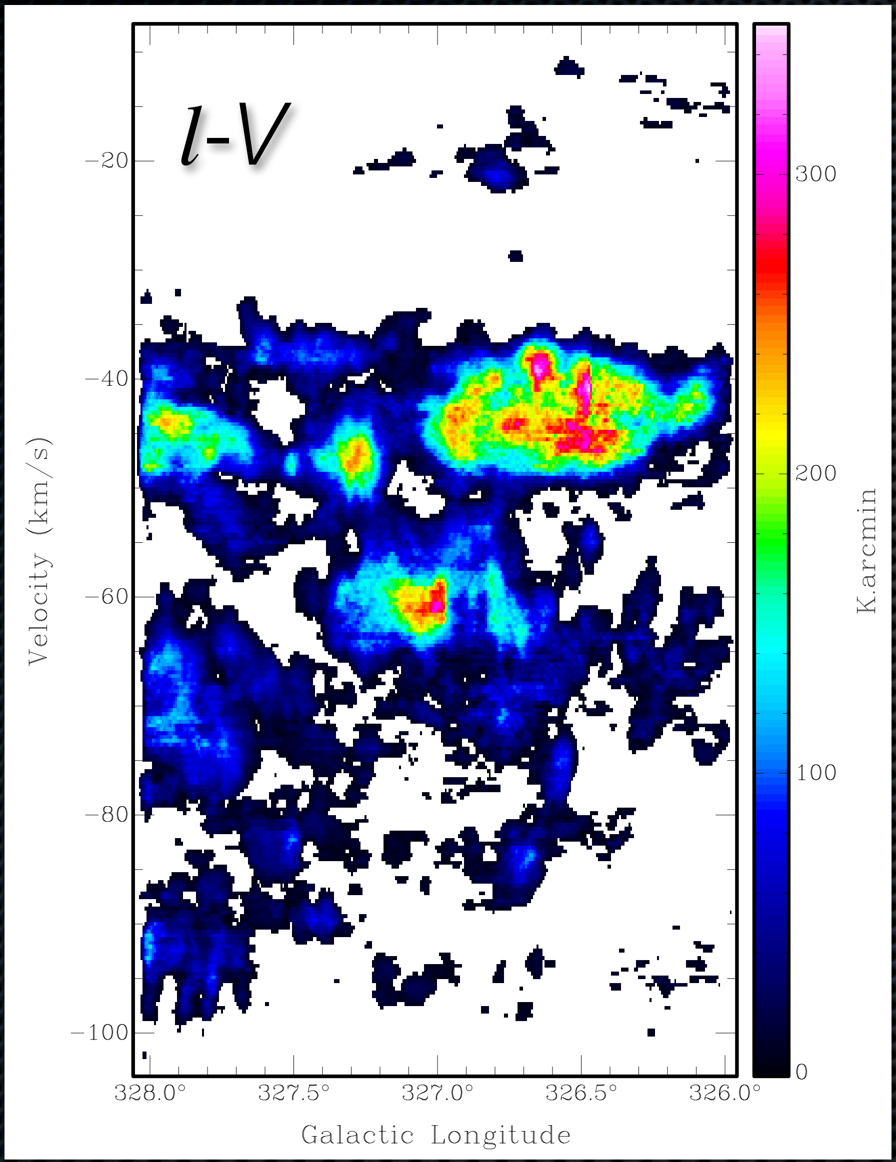
Columbia-CfA ^{12}CO survey

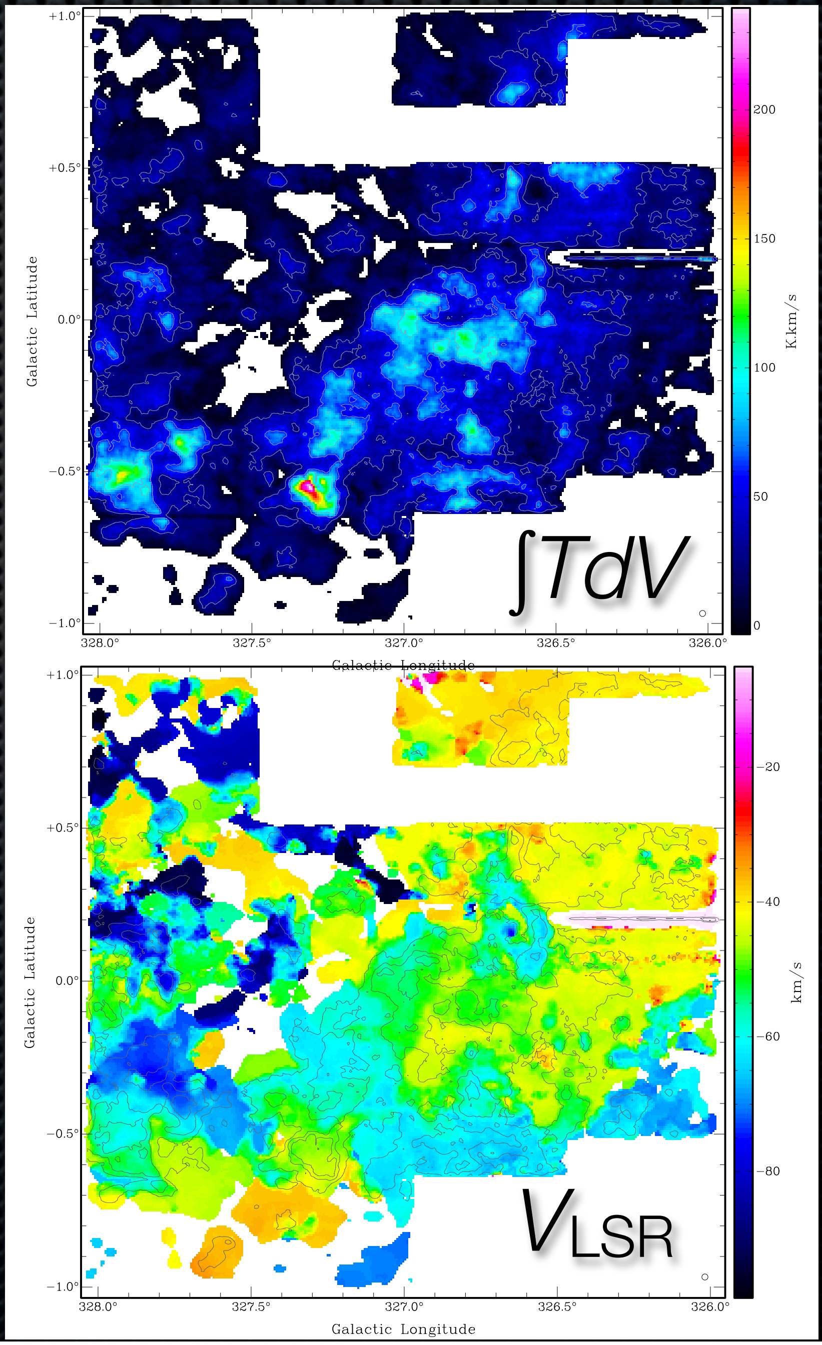




ThrUMMS ^{12}CO, 5hr clock time

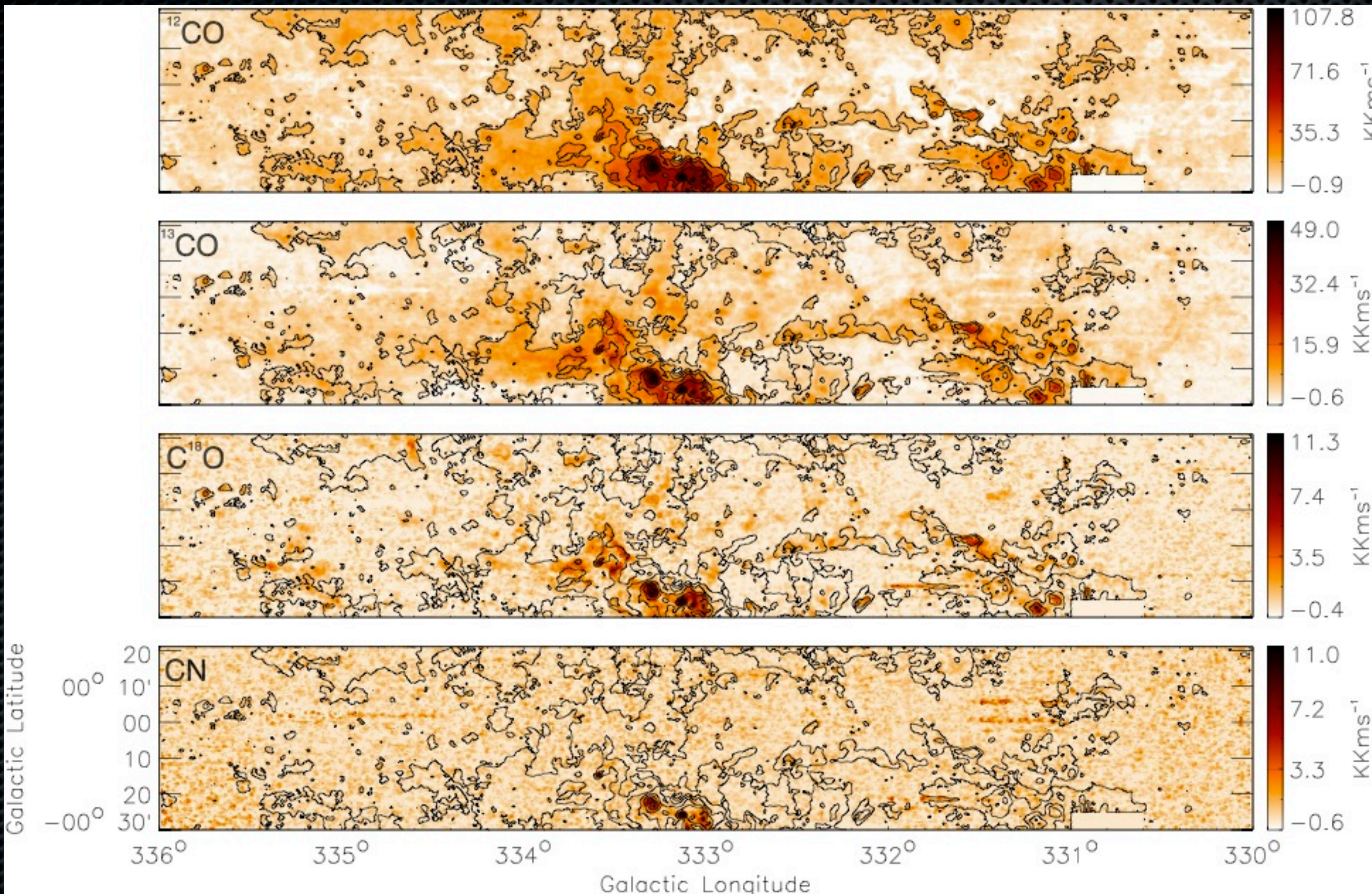
ThrUMMS eye candy





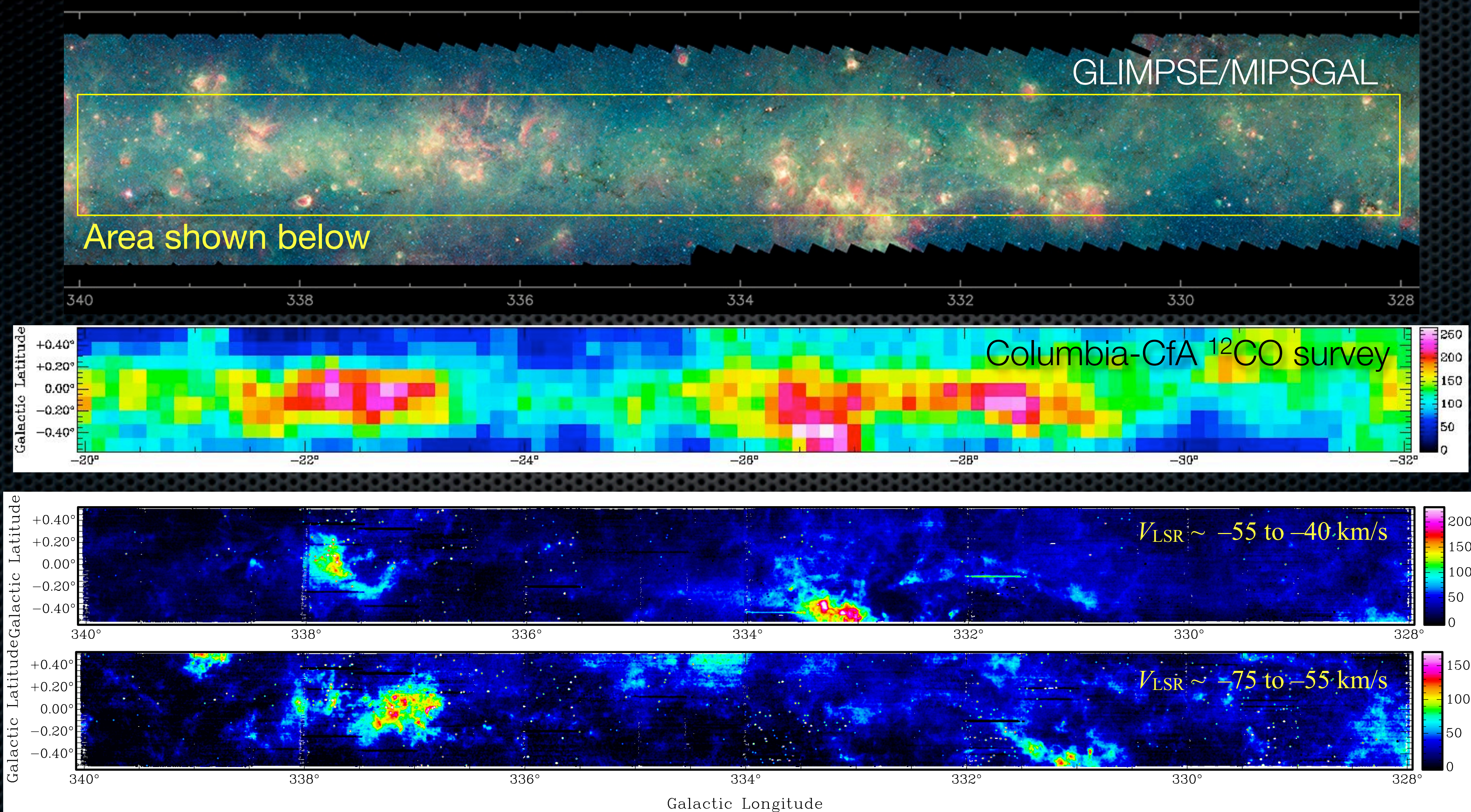
^{12}CO moment maps

ThrUMMS eye candy



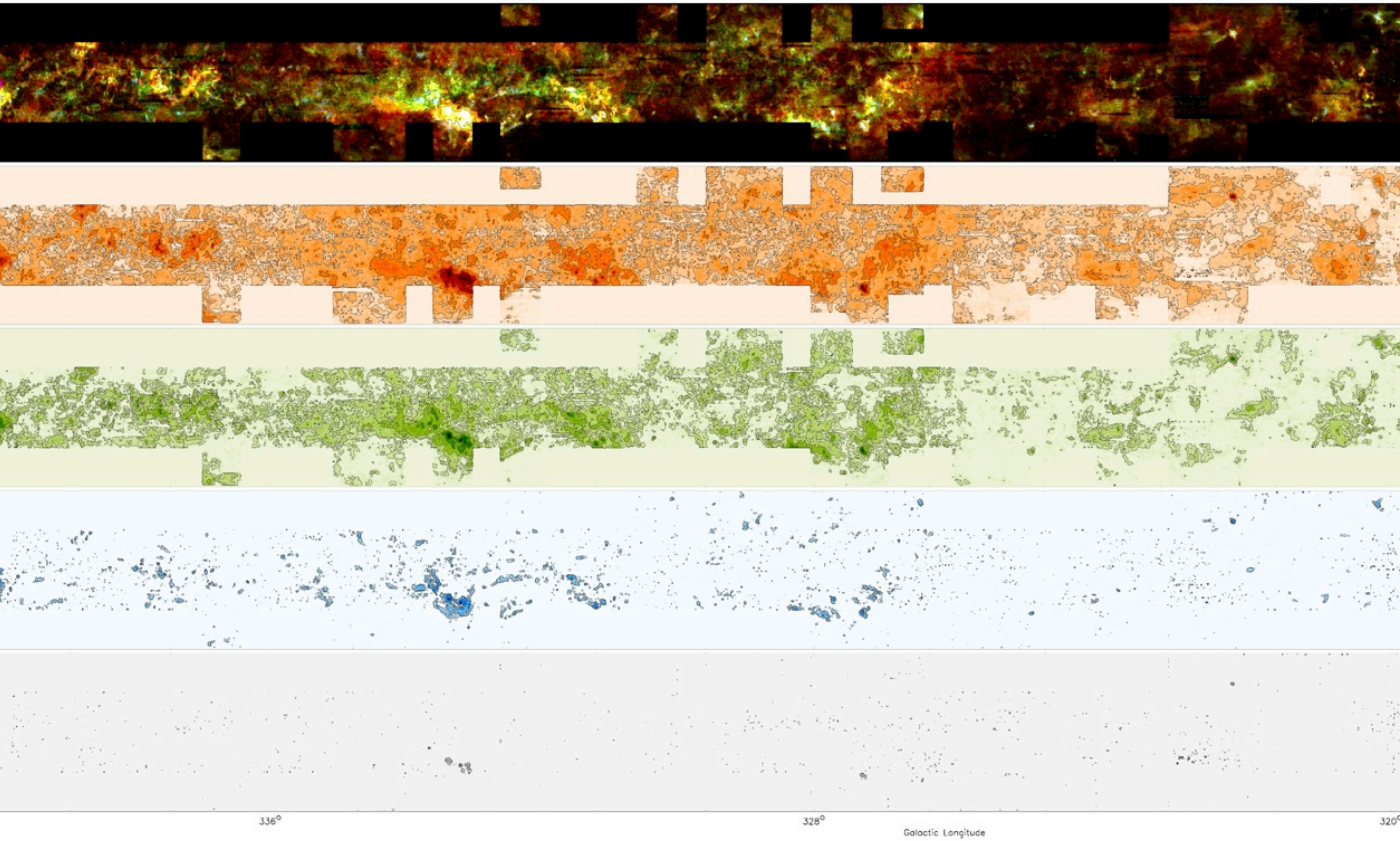
integrated intensity maps

ThrUMMS eye candy



A 12°x1° ThrUMMS field — compare to Spitzer & Herschel images
WOW! (See Nguyen et al 2014)

ThrUMMS eye candy

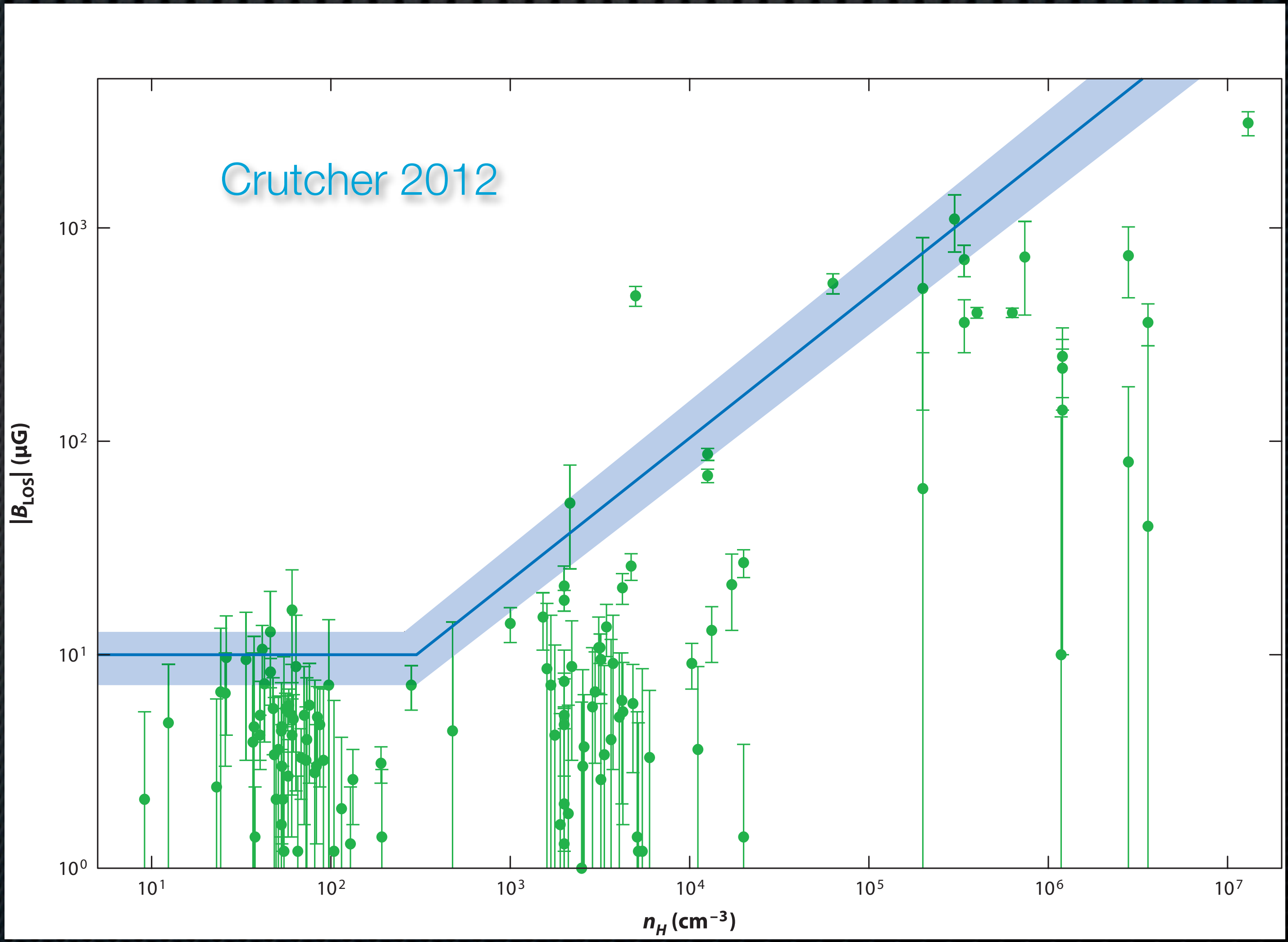


Anticipated ThrUMMS projects

- Widespread line ratio variations —> environmental dependence of astrochemistry, cloud physics
- Direct comparison of CO-GMC maps, including dynamics, to HI from GASKAP — physics of cloud formation
- Large-scale, yet detailed, structure of HI/H_2 cloud turbulence and dynamics — spatial dynamic range > 3000:1
- Spatially-resolved gas temperature maps of GMCs, compare to Planck/Herschel/GLIMPSE SEDs & $T_{\rm dust}$ fits (*cf.* complementary APEX ^{13}CO/C^{18}O J=2–1 line survey SEDIGISM, PI Schuller)
- Kinematic distances to all features!
- Galactic structure studies, eg arm-interarm, radio-FIR
- ....etc.

Anticipated ThrUMMS projects

- Excellent statistics of magnetic fields in dense, star-forming gas from CN Zeeman measurements
  - Requires CN clouds with integr. intensities > 6 K km/s
  - Already see 5 such clouds in ThrUMMS pilot data
  - Project ~50 CN-bright clouds suitable for Zeeman mapping with ALMA, quadrupling the sample



Summary

- Exciting times for Galactic ISM & star formation studies!
- Many continuum surveys (near-) complete
- Some molecular maps available now, much more to come within ~1-2 years
- Will provide a rich harvest of data for analysis & comparison with theory for many years
- Many opportunities for more detailed studies with CCAT, ALMA, SOFIA, JWST, Gemini-S, ATCA, ...