Observational Opportunities to Study Star Formation on Different Scales

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Purpose of This Talk

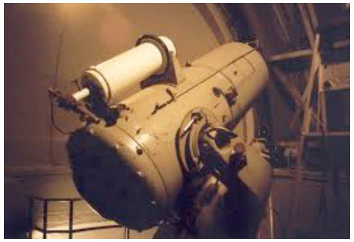
- Examine what aspects of star-formation can be probed on different scales (small = stars => large = galaxies)
- Give (selective) overview of what facilities are currently available to observe different phenomena associated with star formation
- Try to motivate the connection between the observations and the topics of interest to this workshop
- Talk briefly about what may become available in the future

This talk will not be organized exactly in this fashion.

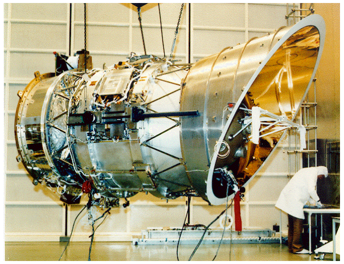
I will try to discuss things in terms of SCALE and refer to observational possibilities relevant to studying star formation on that scale

What About Those Stars?

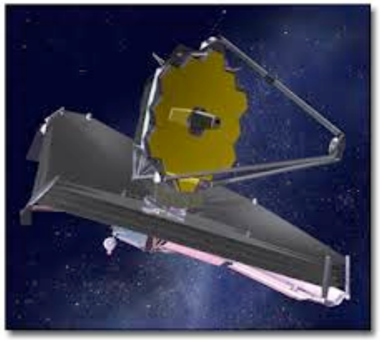
Astronomers sometimes do want to study individual stars. For this, there are many observational opportunities



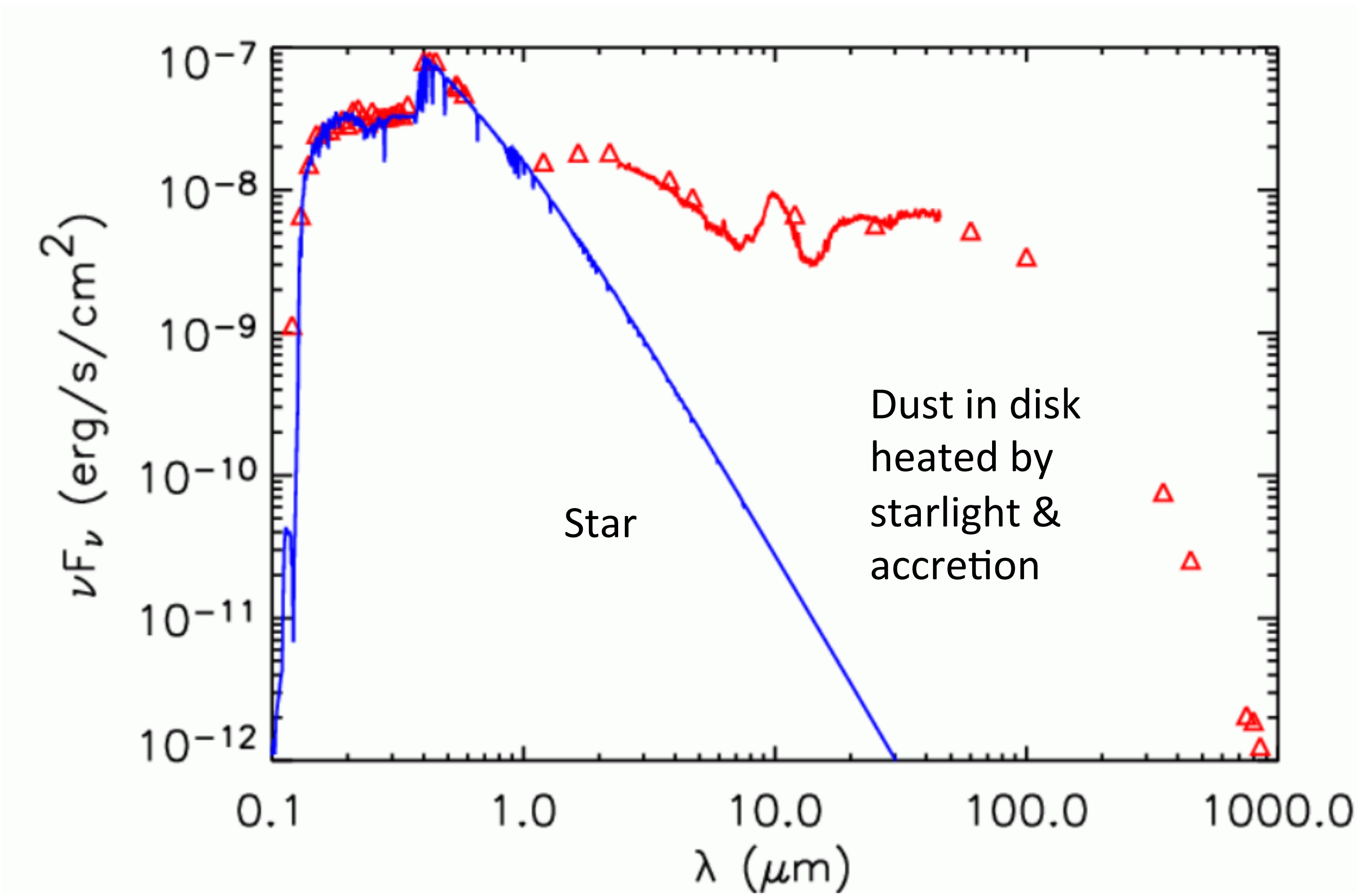
- You can use your eyes
- Existing Extensive databases of stars from ground-based & space-based facilities at many wavelengths
  - Palomar + others*
  - HST*
  - WISE
  - Spitzer*
  - IRAS
  - Herschel
  - ALMA (some stars)*
- Coming soon (we hope)
  - JWST
  - WFIRST



* currently active



Spectrum of Radiation Emitted by a Young Star With Protostellar Disk



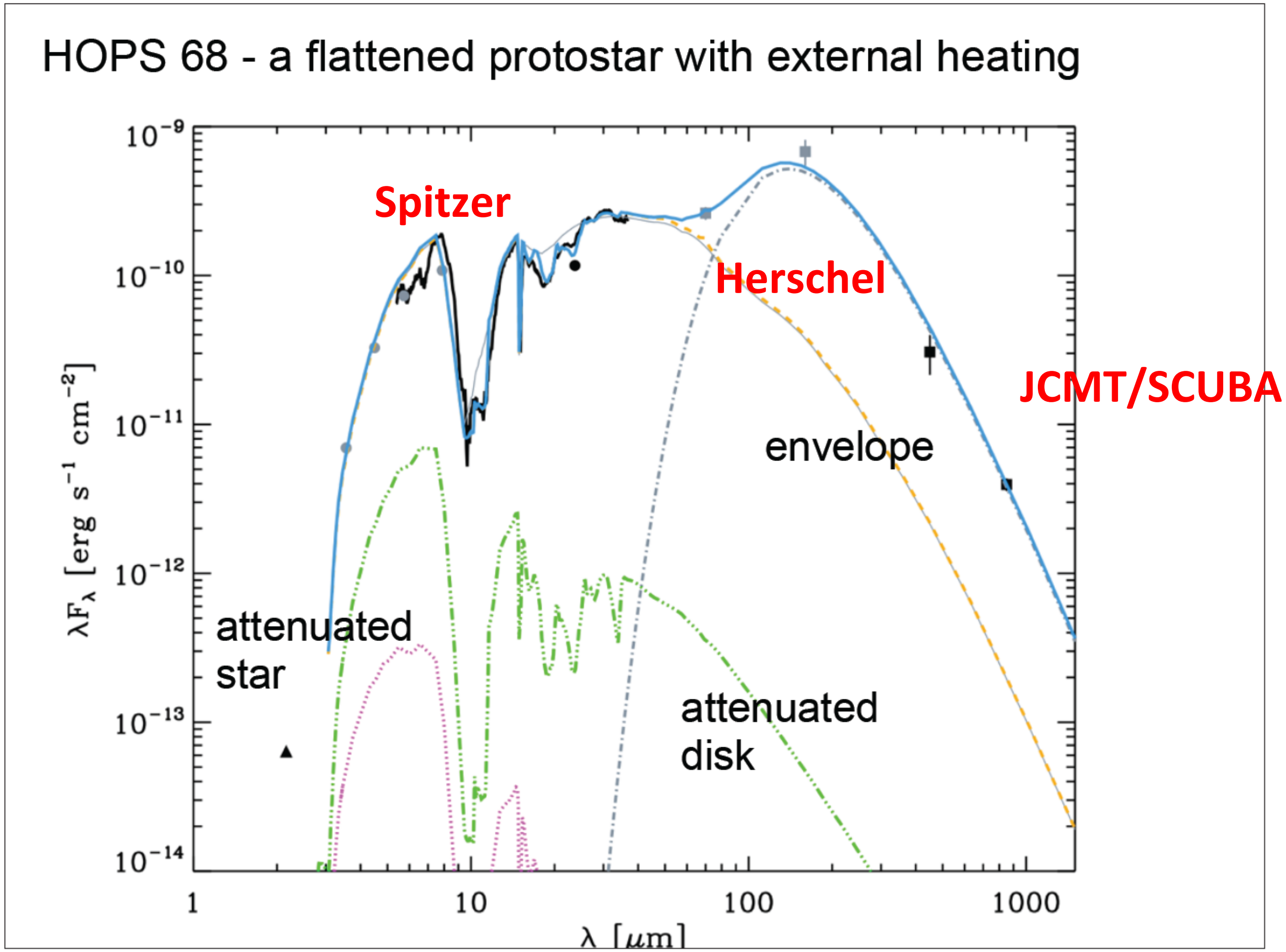
Wavelength

From T. Megeath

Observing the Spectral Energy Distribution (SED) Determines Status of Forming Star

A wide range of wavelengths is required due to big range of dust temperatures

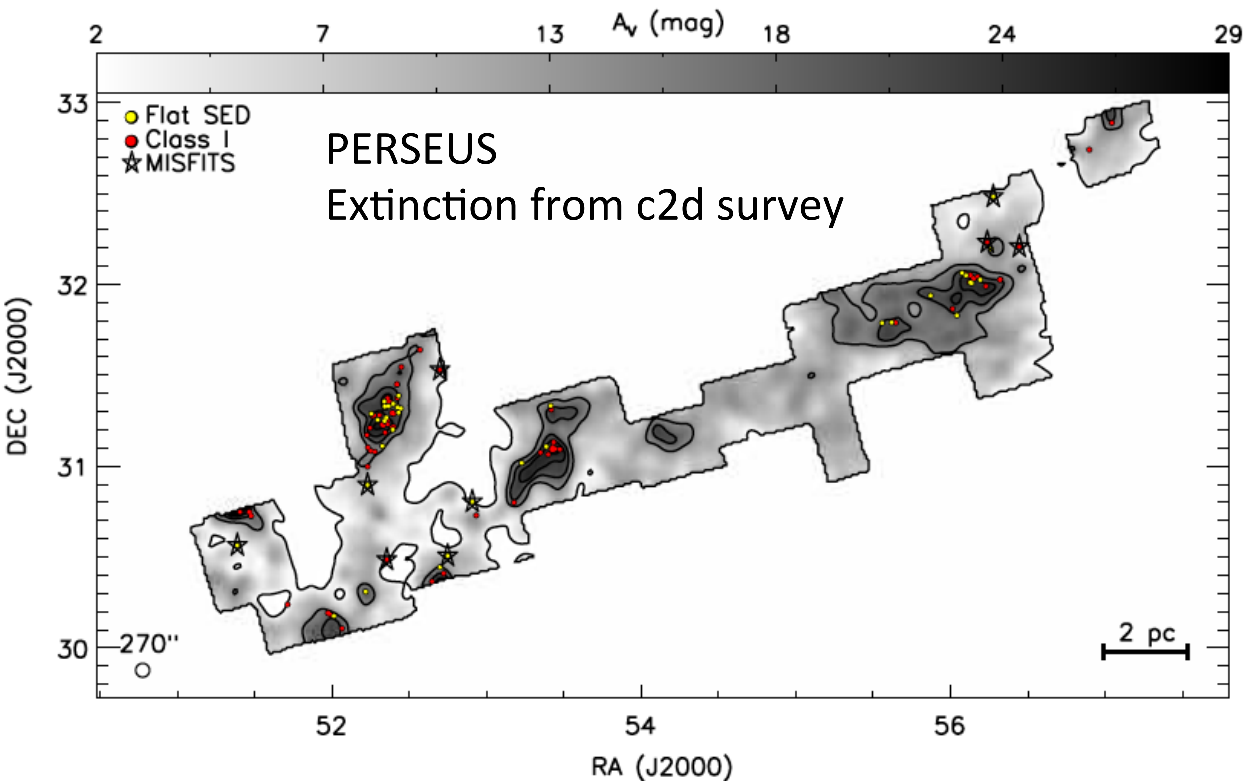
This will generally necessitate using multiple telescopes and/or instruments



From Poteet et al. (2011); data from **Spitzer** + **Herschel** + **JCMT/SCUBA**

When You Might Want to Study Individual Stars

Detailed study of the rate of star formation within local clouds: sum up mass of individual stars and compare to gas mass (e.g. Heiderman et al. 2010)



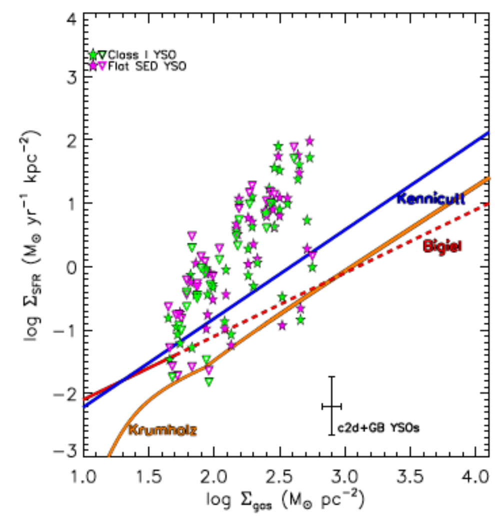
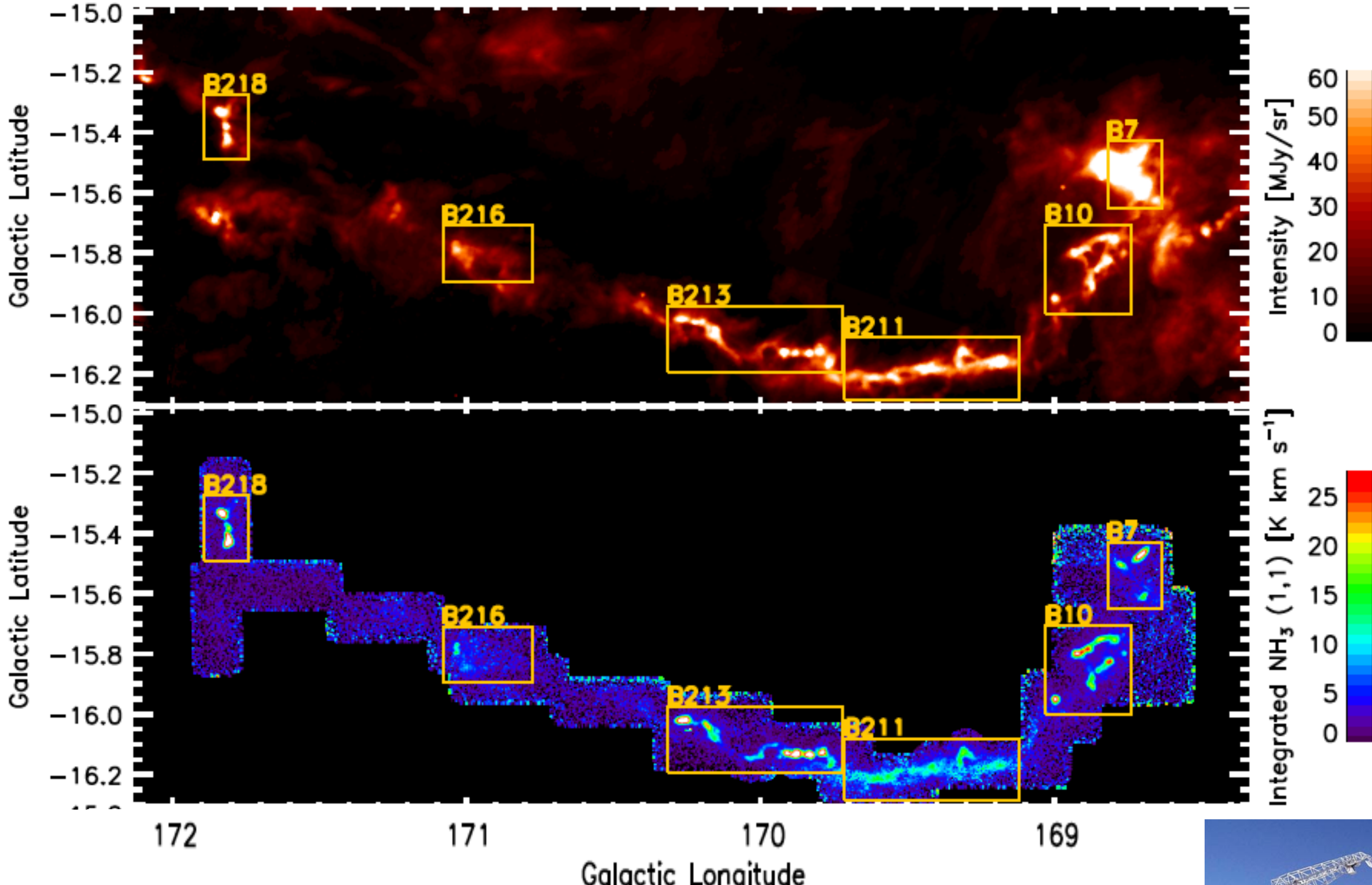


Figure 3. Gas surface densities measured from extinction maps and SFRs estimated from Class I (green stars) and Flat SED (magenta stars) YSO number counts in c2d and Gould's Belt clouds are shown. For contour levels that do not contain any YSOs, we calculate an upper limit for that region using one YSO (open inverted triangles). Extragalactic observed relations are shown for the sample of Kennicutt (1998b) and Bigiel et al. (2008) (blue solid and red lines, respectively).

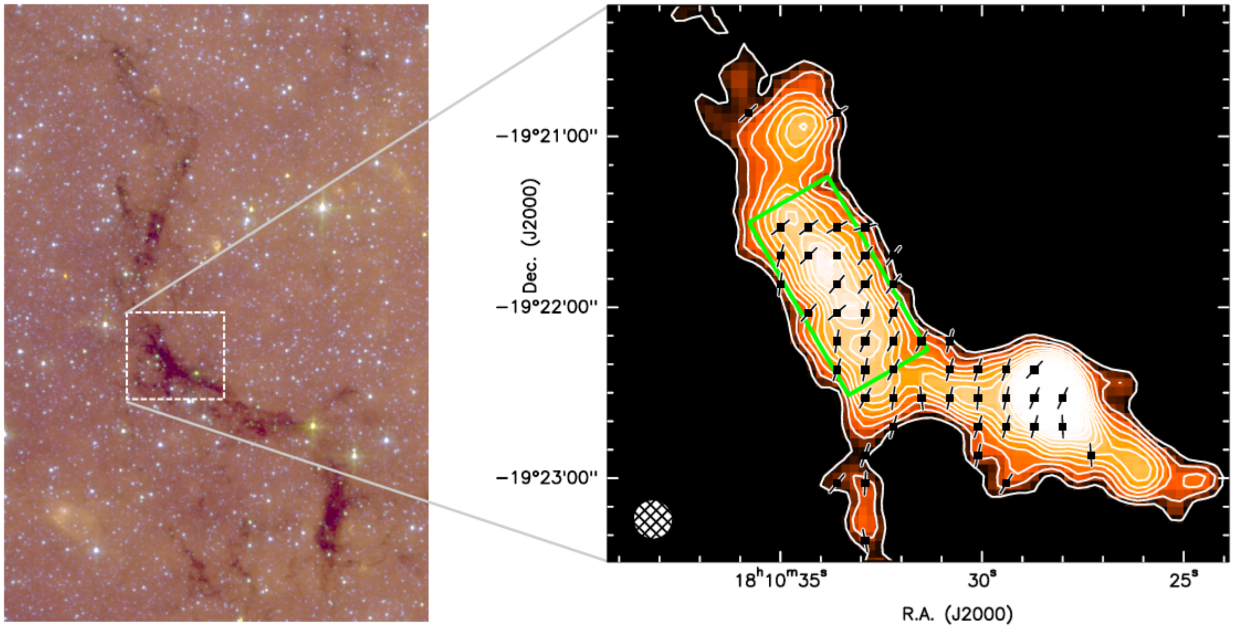
Dense Cores are Condensations in which New Stars Form



Taurus Molecular Cloud Observed in DUST (top) and NH3 (bottom)
Seo, Shirley, Goldsmith, et al. (2014) using GBT and K-band FPA

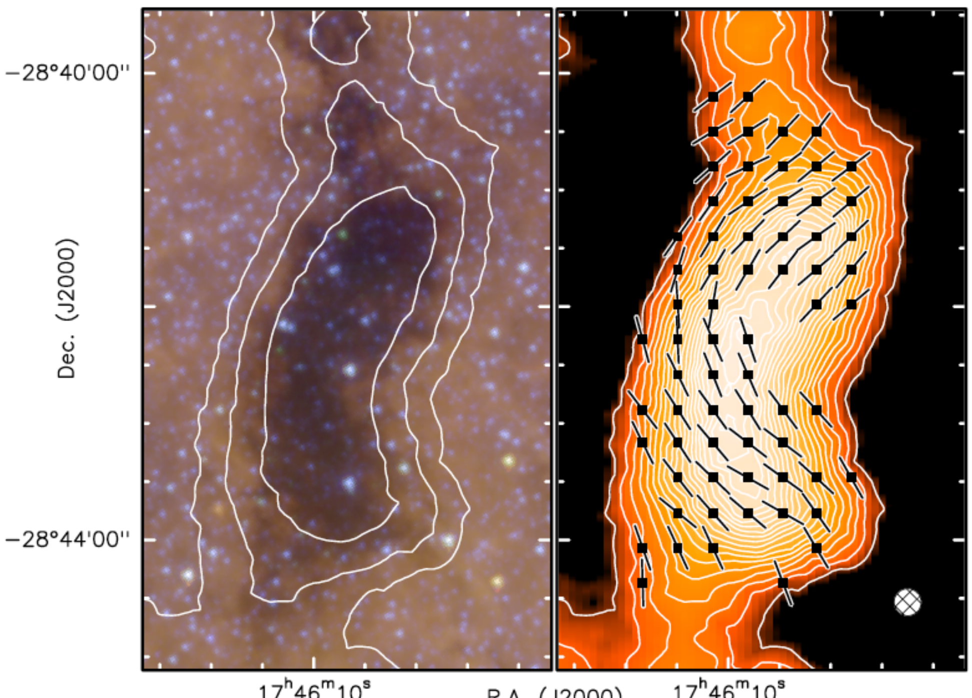
The Magnetic Field in Infrared Dark Clouds (IRDCs)

Pillai, Kauffmann, Tan, Goldsmith, Carey, & Menten 2014



G11.11-0.12

Archival data from JCMT and CSO



G0.253+0.016

Analysis of Measurements of Plane-of-Sky B-Field Using C-F Method

Table 1: Physical Properties and Magnetic Field Parameters

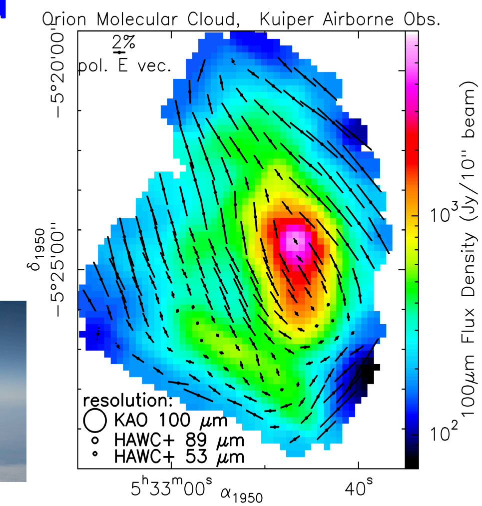
Source	Distance pc	$\sigma_{\rm obs}(v)$ km s^{-1}	Mass M$_\odot$	$\langle N_{\rm H_2}\rangle$ 10^{23} cm^{-2}	Density 10^4 cm^{-3}	σ_ϕ deg.	B$_{\rm tot}$ μG	$\mathcal{M}_{\rm A}$	$\frac{(M/\Phi_B)}{(M/\Phi_B)_{\rm cr}}$
G11.11−0.12[1]	3600	0.9 ± 0.1	$549\|^{1098}_{275}$	$0.4\|^{0.8}_{0.2}$	$3\|^{6}_{2}$	$< 16.2 \pm 1.6$	$> 267 \pm 26\|^{437}_{163}$	$< 0.8 \pm 0.1\|^{1.2}_{0.5}$	$< 1.1 \pm 0.1\|^{2.1}_{0.6}$
G0.253+0.016	8400	6.4 ± 0.4	$(2\|^{4}_{1}) \times 10^5$	$4\|^{8}_{2}$	$8\|^{16}_{4}$	$9.3 \pm 0.9\|^{11.2}_{7.8}$	$5432 \pm 525\|^{8908}_{3312}$	$0.4 \pm 0.1\|^{0.7}_{0.3}$	$0.6 \pm 0.1\|^{1.1}_{0.3}$

- The magnetic field in G11.11 is perpendicular to the axis of the filament
- The Mass to Flux Ratio (M/Φ_B) is close to the critical value
- The magnetic field **is comparable in importance to gravity** for these clouds
- The magnetic field **is plausibly strong enough to suppress fragmentation** as well as to slow collapse and star formation

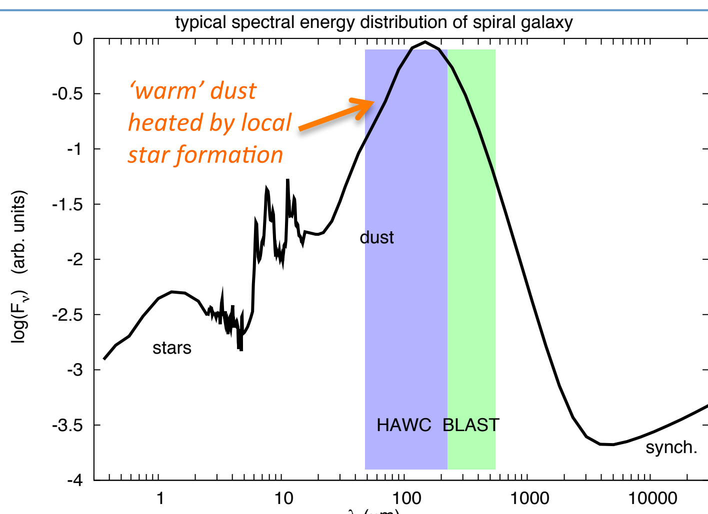
Near-Future Opportunity for B-Field Observations

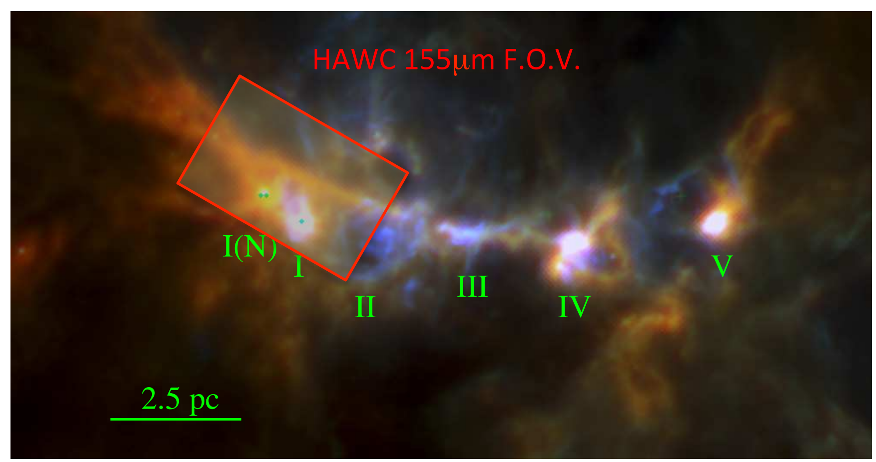
- **HAWC+ Polarimeter on SOFIA – measures linearly polarized radiation from dust grains**
- **50 μ – 200 μm wavelength**
- **Yields B-field direction in plane-of-sky**

- Compared to previous facilities (e.g., KAO):
  - 8× more sensitive to extended emission
    - can reach $A_V \approx 1$
  - 50× more sensitive to point sources
  - 3× better angular resolution
    - 5000 AU at distance of Orion Mol. Cloud
  - 20× as many beams on the sky at one time
  - 5 wavelength bands instead of 1



NGC 6334, Herschel far-IR image (Russeil et al. 2013)





NGC 6334 filaments ($A_V \approx$ 10) ashould be detectable in polarization with S/N ≈ 7 per beam in ~20 minutes per pointing

HAWC delivery from JPL to SOFIA (Palmdale) in August 2015, with first flights soon after

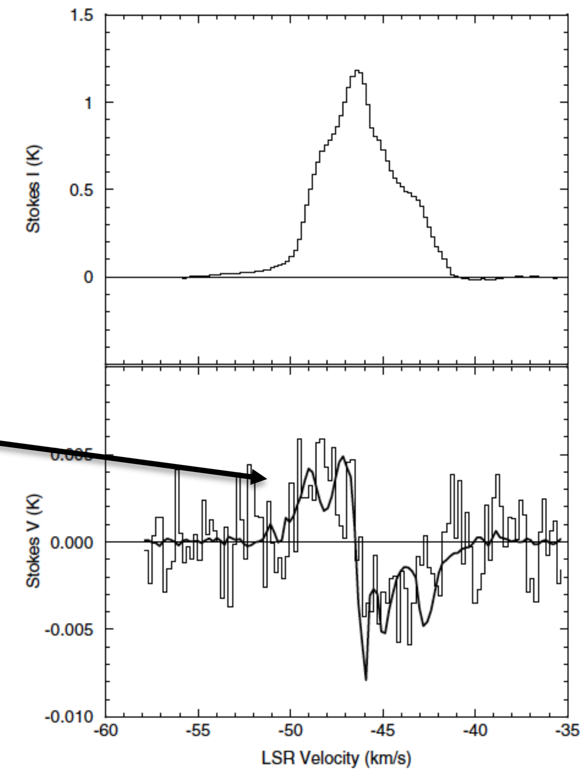
Zeeman Effect Probes Line-of-Sight Magnetic Field
CN Probes Dense Cores

Table 1. CN $N = 1\text{–}0$ hyperfine lines.

Line	ν (GHz)	RI[a]	Z (Hz/μG)[b]	RI $\times$ Z[c]
1	113.144	8	2.18	17.4
2	113.171	8	–0.31	2.5
3	113.191	10	0.62	6.2
4	113.488	10	2.18	21.8
5	113.491	27	0.56	15.1
6	113.500	8	0.62	5.0
7	113.509	8	1.62	13.0

[a] RI is the relative intensity of each hyperfine component.
[b] Z is the Zeeman splitting factor of each hyperfine component.
[c] RI $\times$ Z is the relative sensitivity to $B_{\rm los}$.

Solid curve: B_{los} = +1.10 mG



Other Opportunities for Zeeman Observations

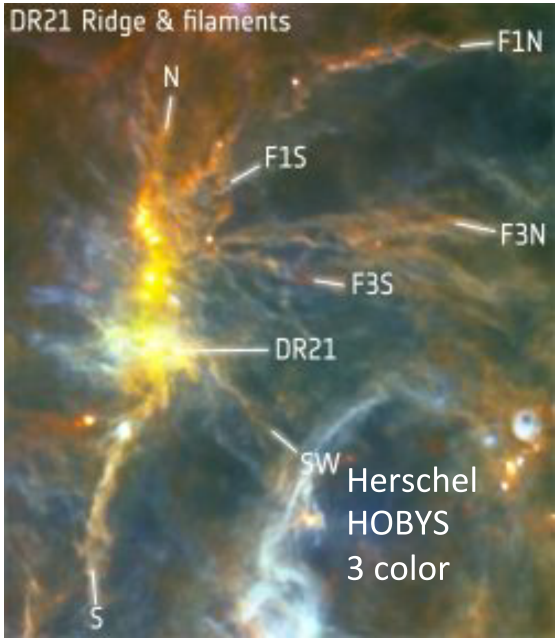
OH @ Arecibo and GBT
CN @ CARMA and ALMA

CN: **I** spectrum (top); **V** spectrum (bottom) in W3(OH)
Falgarone, Troland, Crutcher, & Paubert (2008) **IRAM 30m telescope**

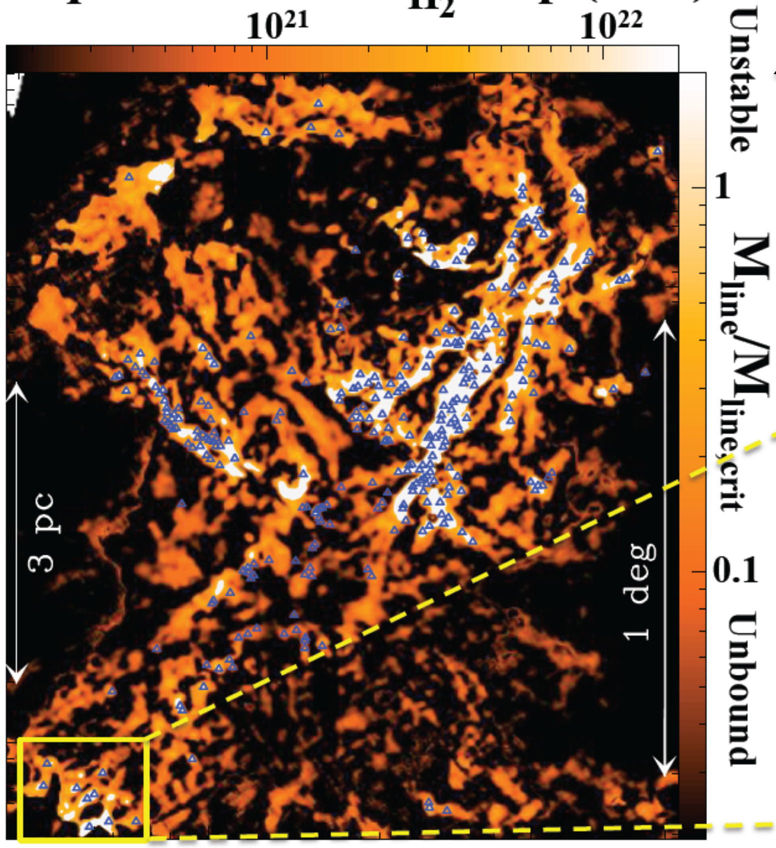
Conclusion: Cloud cores are *marginally* magnetically supported

Moving Outwards – Where Do we Find Dense Cores? How Do They Form?

Data from Herschel have confirmed idea that cores are primarily found in FILAMENTS within molecular clouds



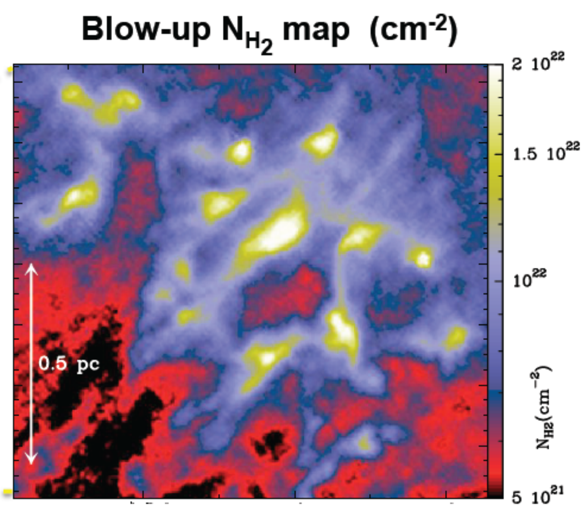
75^{+15}_{-5}% of Prestellar Cores Form in Filaments at Column Density Threshold $N(H_2) = 7x10^{21}cm^{-2}$



André et al. 2010, Könyves et al. 2010 + in prep

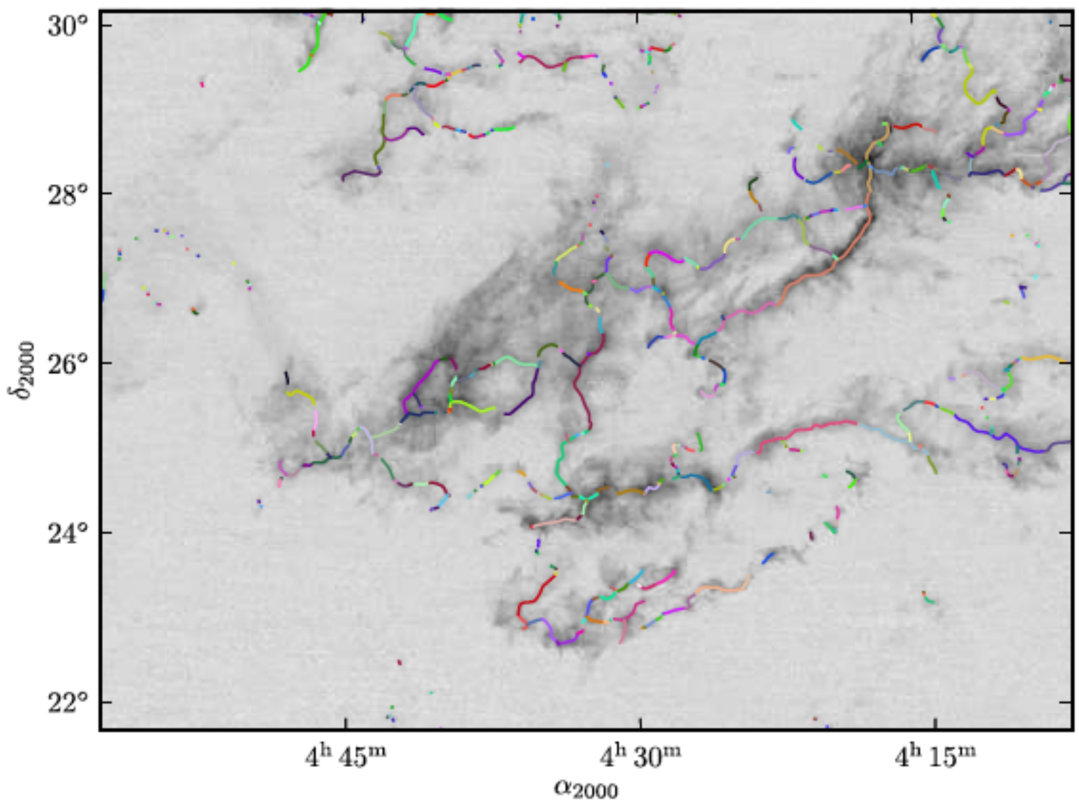
Great interest in understanding filament formation, evolution, role of turbulence, magnetic field,…

USE: SOFIA, ALMA, GBT, IRAM



Star-Forming Filaments are Found in Molecular Clouds of All Types & Sizes

Sometimes it is not so obvious what is a ``coherent filament" and what is not



Filaments identified in integrated ^{13}CO emission by DISPERSE software (Sousbie 2011) after post-processing to satisfy requirements on contrast and continuity Panopoulou, Tassis, Goldsmith, & Heyer (2014)

The 3mm Lines of ^{12}CO and ^{13}CO are Particularly Powerful Tools for Imaging Molecular Clouds

Work in quite different ways on different scales

- ^{12}CO is optically thick and is generally thermalized so it can
  - Directly give you information on the kinetic temperature of gas
  - When observing emission from virialized cloud, can be used to trace the mass (distant GMCs in MW; external galaxies)
  - Good tracer of **FEEDBACK** from young stars in terms of bipolar outflows

- ^{13}CO is optically thin or not far from it, and thus
  - Can trace column density along line of sight
  - Relatively faithful tracer of mass density except
    - If gas is cold (< 20 K) and dense; can deplete onto dust grains
    - If temperature variations are large, additional information is needed
  - Narrow line widths reveal systematic velocity structure

Spectral Line Imaging of Molecular Clouds

Cover relatively large areas (sq deg) with good angular resolution =>
A large SPATIAL DYNAMIC RANGE is required to identify and study structure

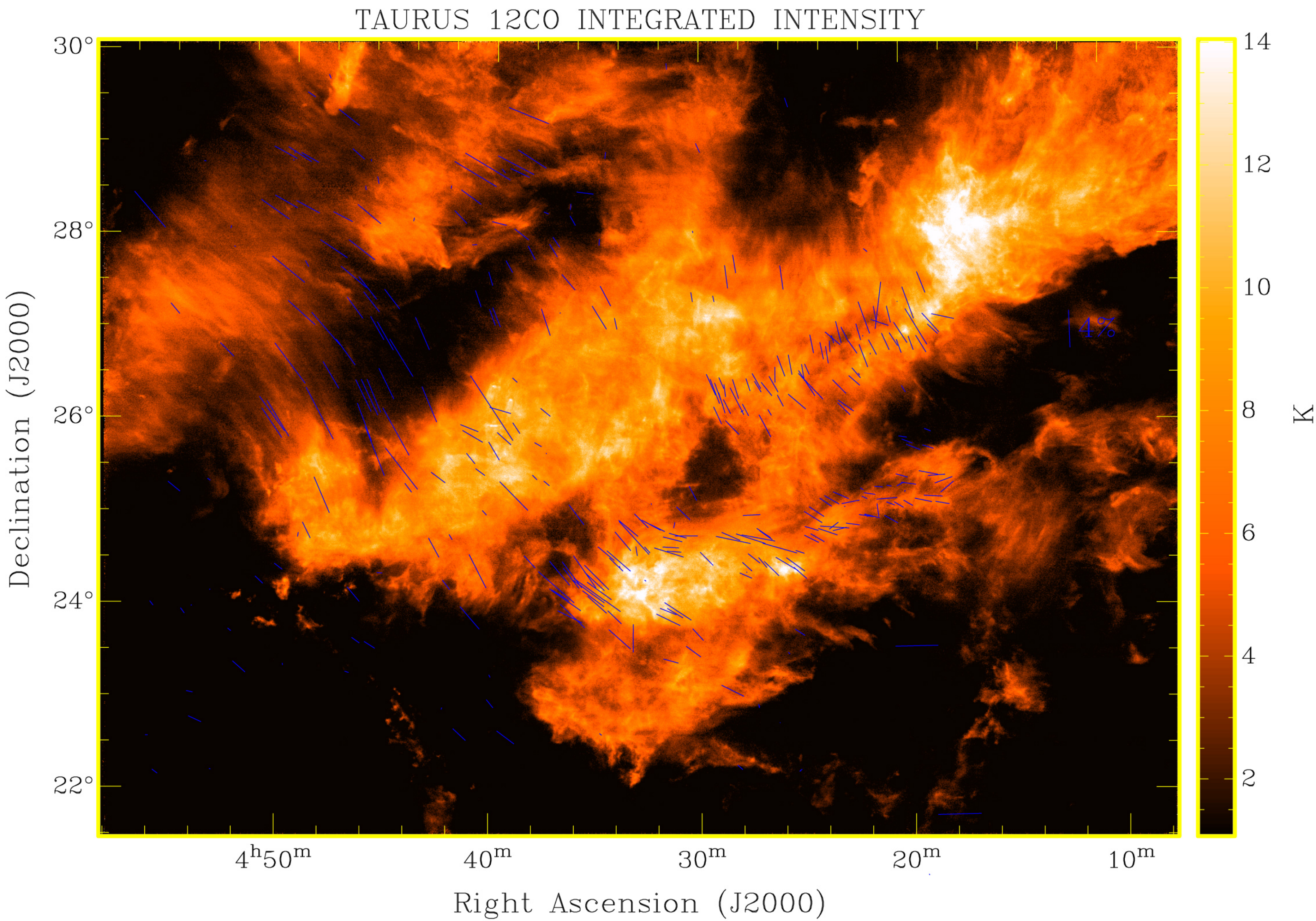
A de-facto requirement is focal plane array to increase mapping spped

SEQUOIA array – 16/32 pixels covering 80 – 115 GHz
Initially on FCRAO 14m telescope – will be on 50m LMT in Fall 2015

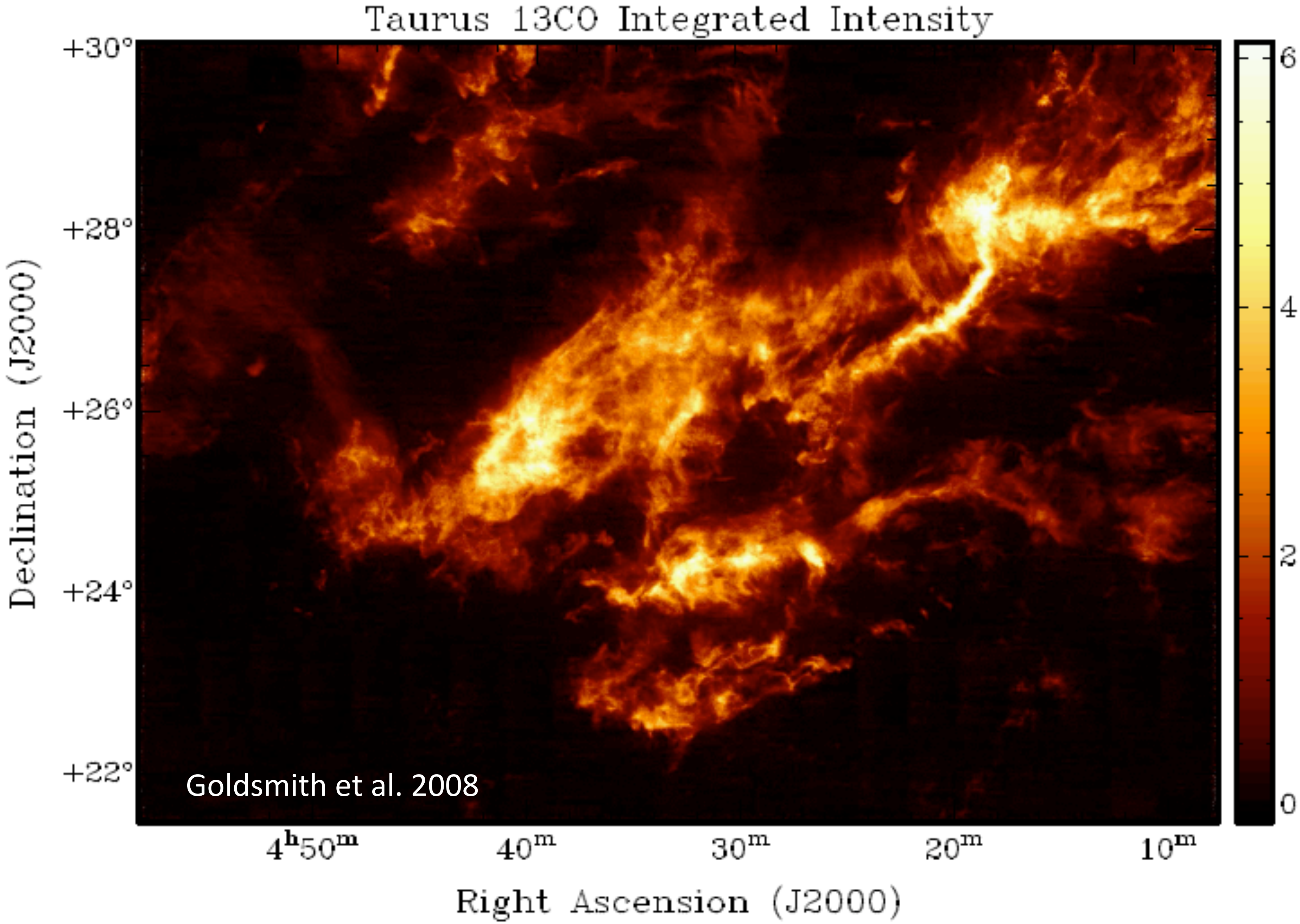
ARGUS – 16 pixel array covering 80 – 115 GHz on GBT Spring 2015

BEARS – 25 pixel array covering 82-116 Ghz on Nobeyama 45m telescope

HERA – 18 pixel array covering 220 – 270 GHz on IRAM 30m telescope



TAURUS 12CO INTEGRATED INTENSITY
30°
28°
26°
24°
22°
Declination (J2000)
4%
4^h50^m
40^m
30^m
20^m
10^m
Right Ascension (J2000)
14
12
10
8
6
4
2
K


Taurus 13CO Integrated Intensity
+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
0
2
4
6
Goldsmith et al. 2008

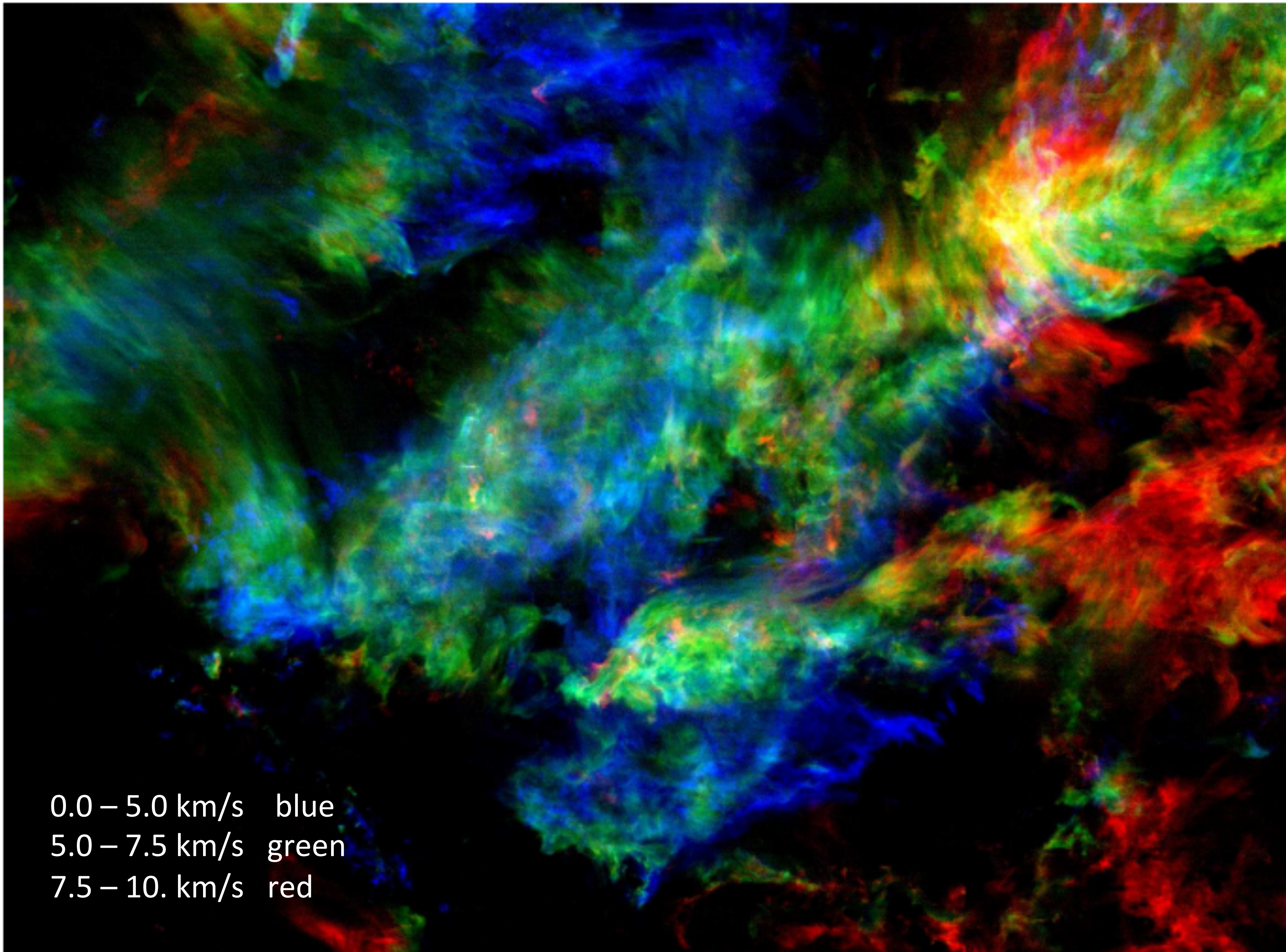
What's Going on Inside Molecular Clouds?

A key characteristic is that on all but smallest scales, the line widths are HIGHLY SUPERSONIC

Supersonic turbulence (generally) agreed to dissipate in ~ crossing time but molecular clouds have much longer lifetimes than this

Something regenerates turbulence – external or internal source of energy

This *may* be key role of feedback from star formation

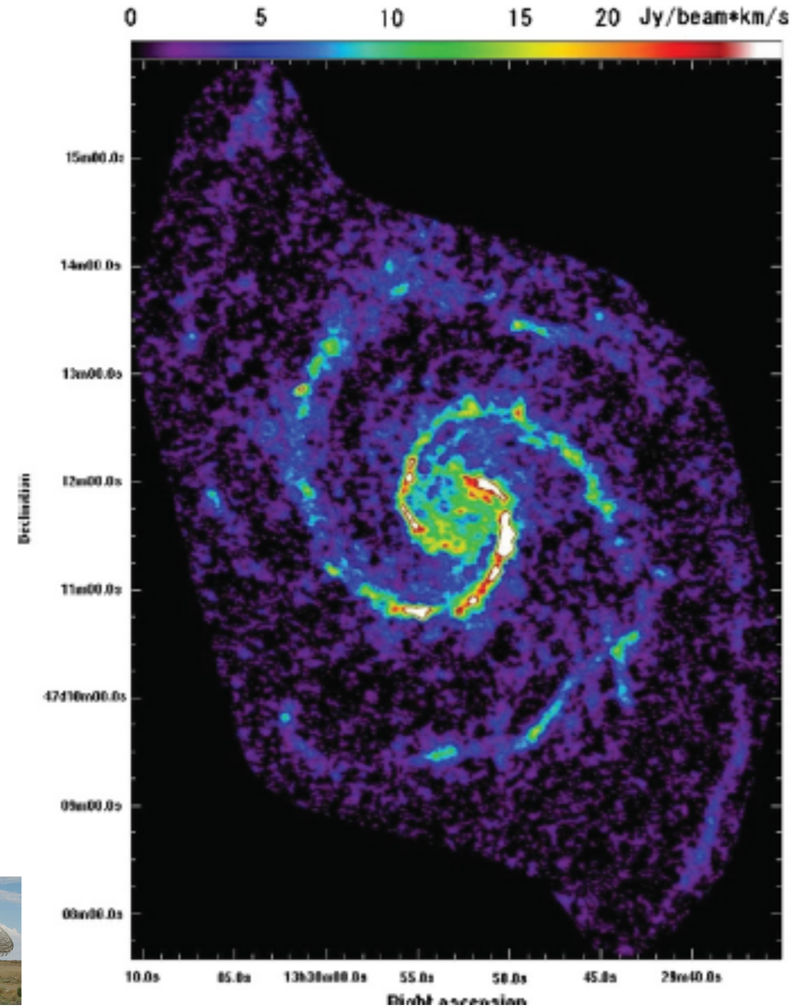

0.0 – 5.0 km/s blue
5.0 – 7.5 km/s green
7.5 – 10. km/s red

Where do Molecular Clouds Come From?

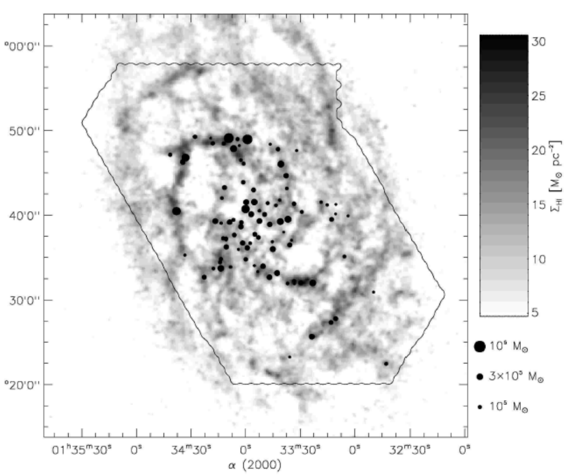
Does formation rate of molecular clouds ultimately control the rate of star formation in galaxies?

- More atomic than molecular gas in Milky Way within solar circle -> atomic clouds must be involved
- Details of transformation remain unclear
  - Spiral Density waves?
  - Instabilities related to the magnetic field?
  - Turbulent flows?
  - Cloud-cloud collisions and compression?
- Are molecular clouds returned to atomic form after passage through spiral arms? Extragalactic studies of nearby galaxies giving complex picture.
- OBSERVATIONS: 21cm- JVLA; CO – Single dish + Interferometer. Will be challenge for ALMA

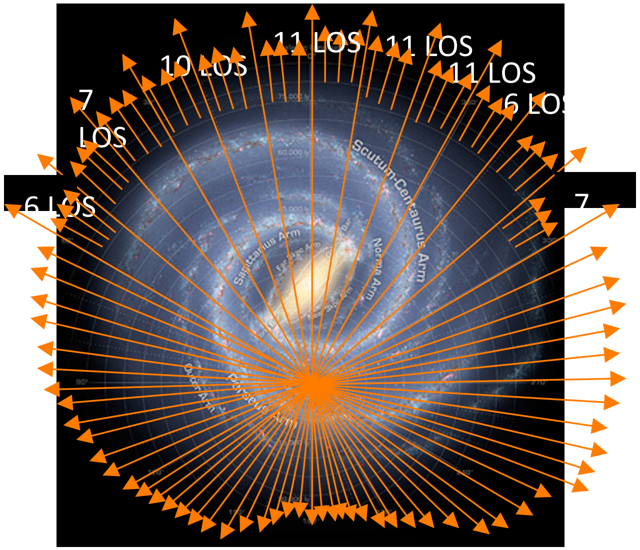
CO clouds in M51; Koda et al. 2009

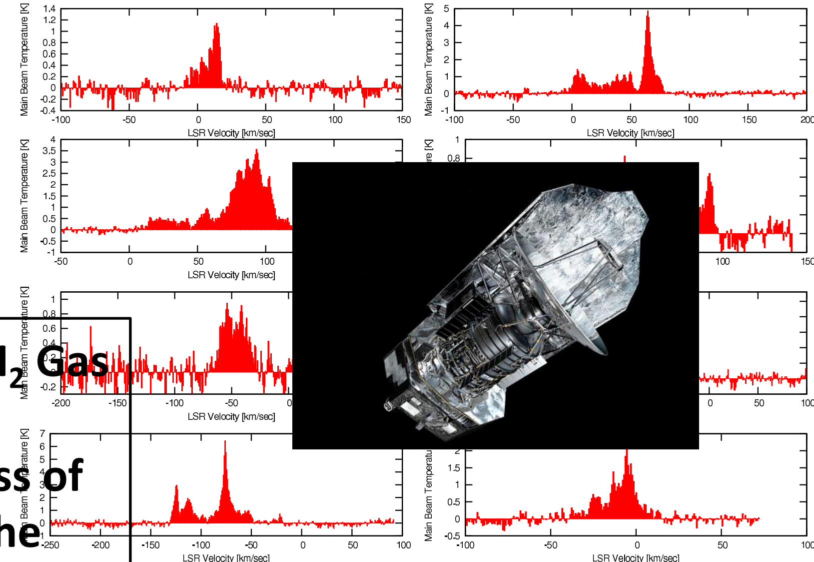


M33: Engargiola et al. 2013



Herschel Key Project "GOT C+" Surveyed [CII] 158 µm Line Through Disk of Milky Way using HIFI. Velocity-Resolved Spectra Essential for Locating Emission Within Milky Way





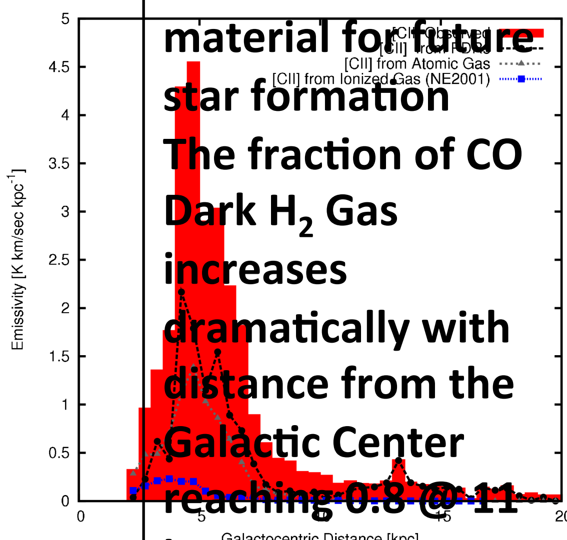
Source of [CII] Emission

47% from PDRs (massive young stars)

28% from CO-Dark H_2 Gas (cloud envelopes)

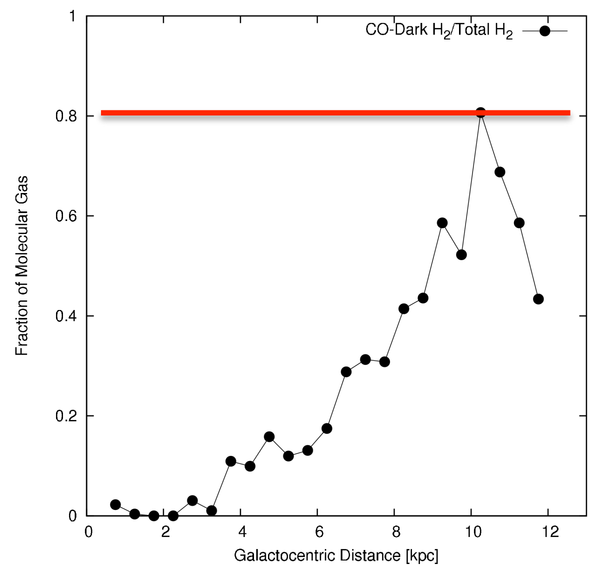
21% from cold Atomic Gas ("diffuse" ISM)

4% from Ionized Gas (produced by UV)



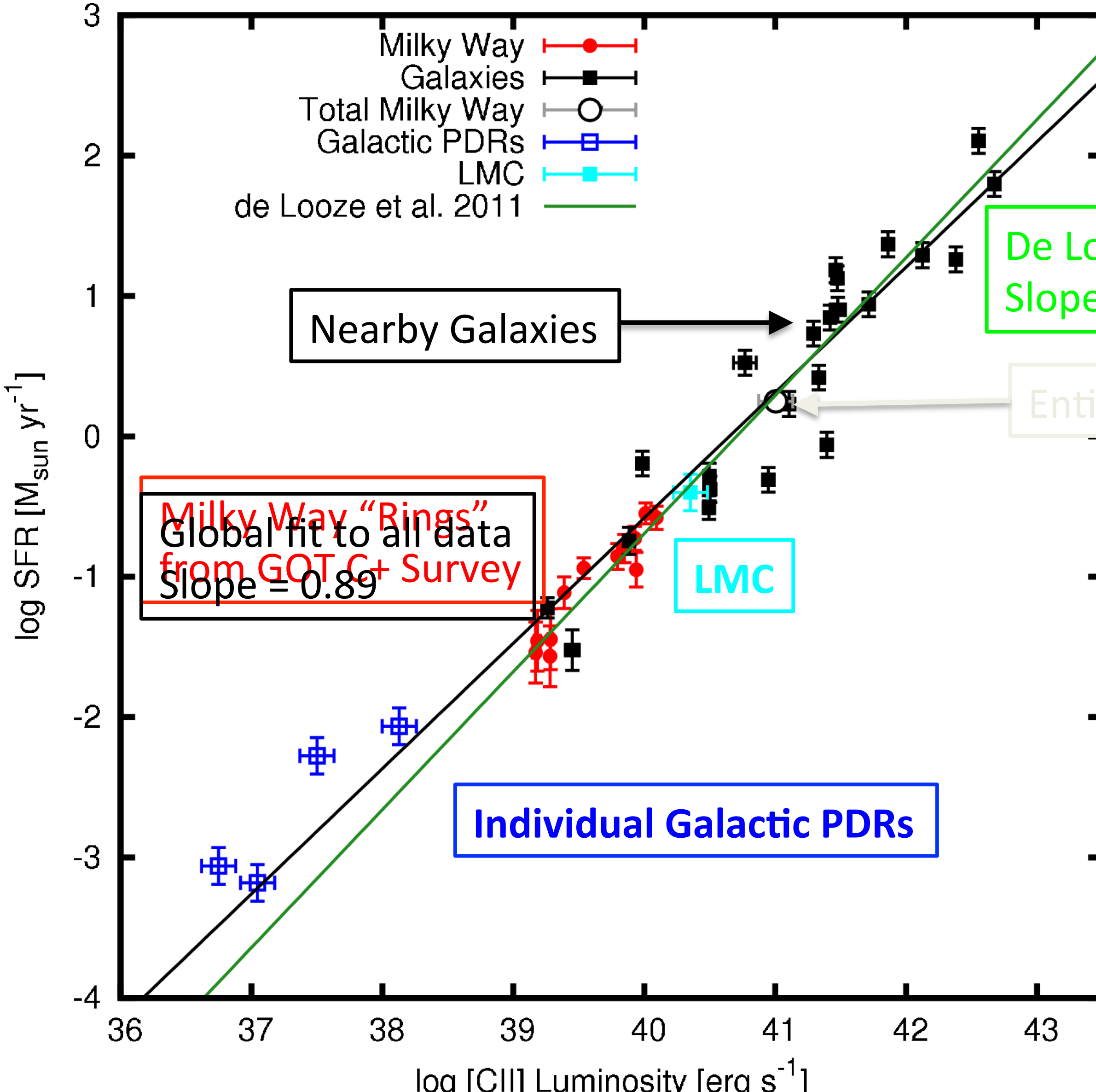
The CO Dark H_2 Gas adds ~30% to molecular mass of milky Way – the Reservoir of material for future star formation

The fraction of CO Dark H_2 Gas increases dramatically with distance from the Galactic Center reaching 0.8 @ 11 kpc



Implications for [CII] Studies of External Galaxies

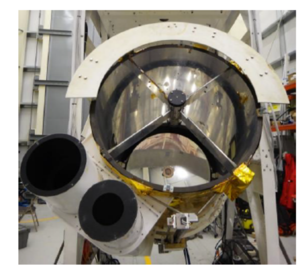
Q: Does [CII] Emission Trace Star Formation?



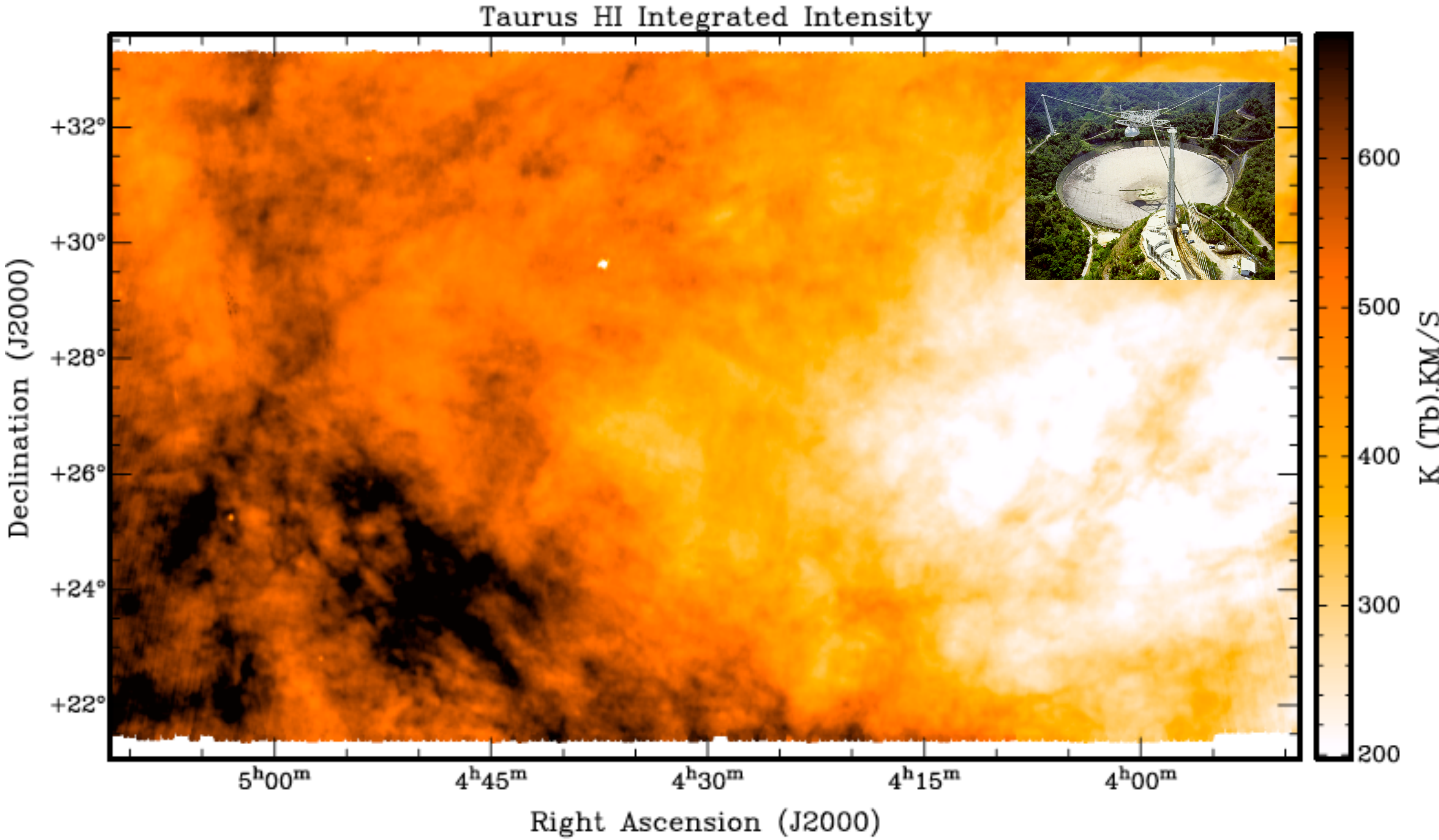
STO2 Balloon
Dec. 2015

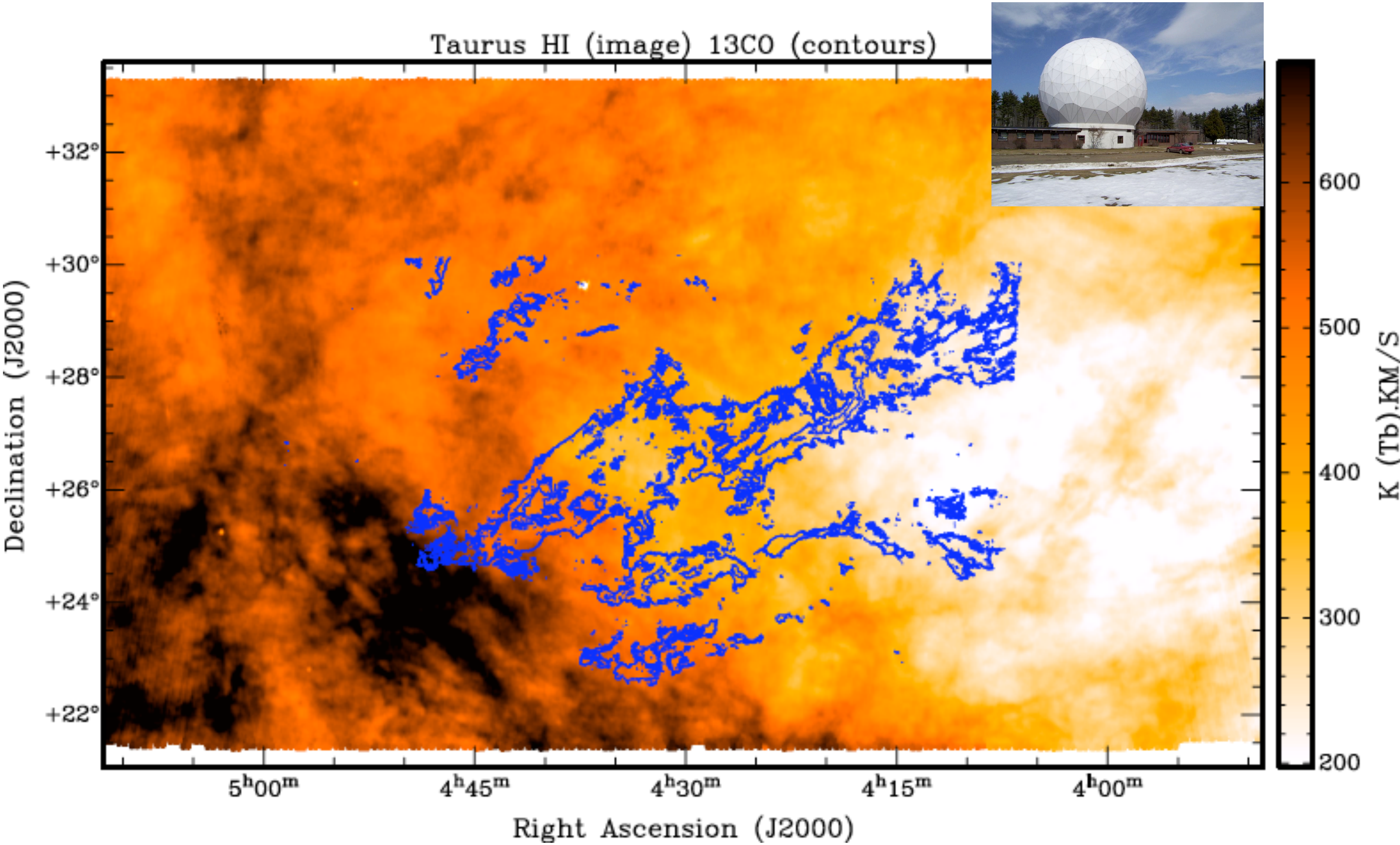
De Looze fit to galaxies
Slope =

Entire



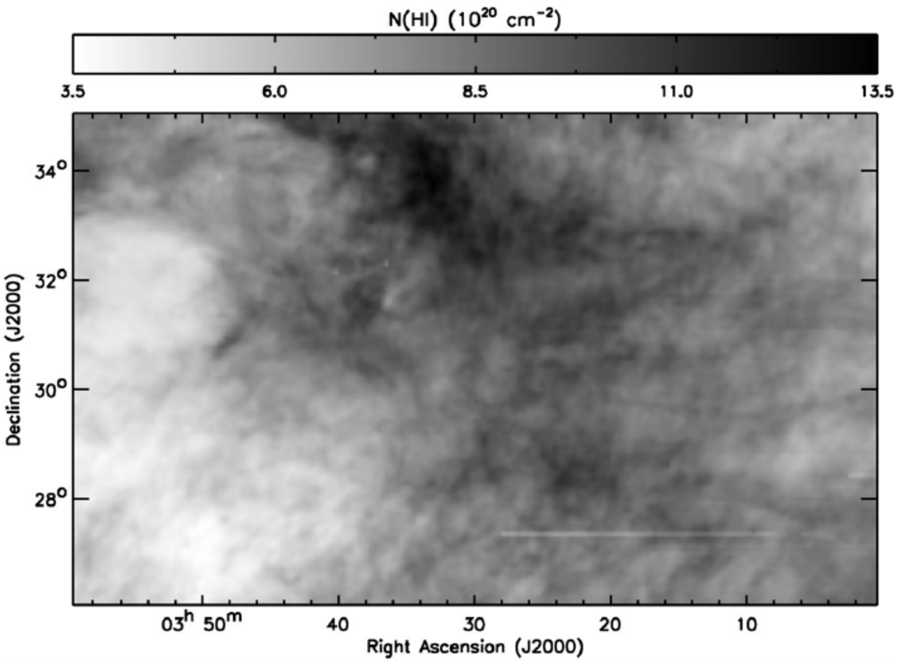
Pineda et al. (2014)


Taurus HI Integrated Intensity
Declination (J2000)
+32°
+30°
+28°
+26°
+24°
+22°
Right Ascension (J2000)
5^h00^m
4^h45^m
4^h30^m
4^h15^m
4^h00^m
600
500
400
300
200
K (Tb).KM/S

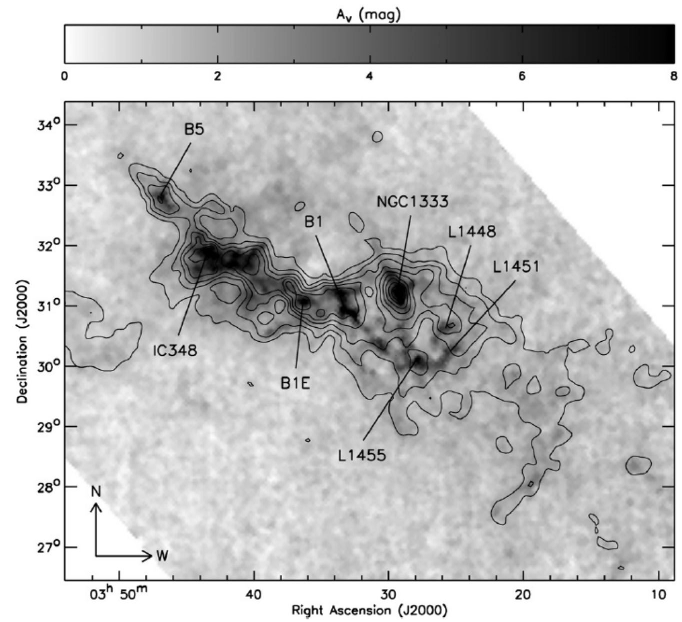

Taurus HI (image) 13CO (contours)
Declination (J2000)
+32°
+30°
+28°
+26°
+24°
+22°
Right Ascension (J2000)
5h00m
4h45m
4h30m
4h15m
4h00m
K (Tb).KM/S
600
500
400
300
200

The Origin of Molecular Clouds: Relating Atomic and Molecular Regions is a Challenge

Perseus region (D = 350 pc); Lee, Stanimirovic, Douglas et al. (2012)



HI -5 km/s - +15 km/s from Arecibo (4.3' resolution)



CO (contours) over 2 Micron dust emission

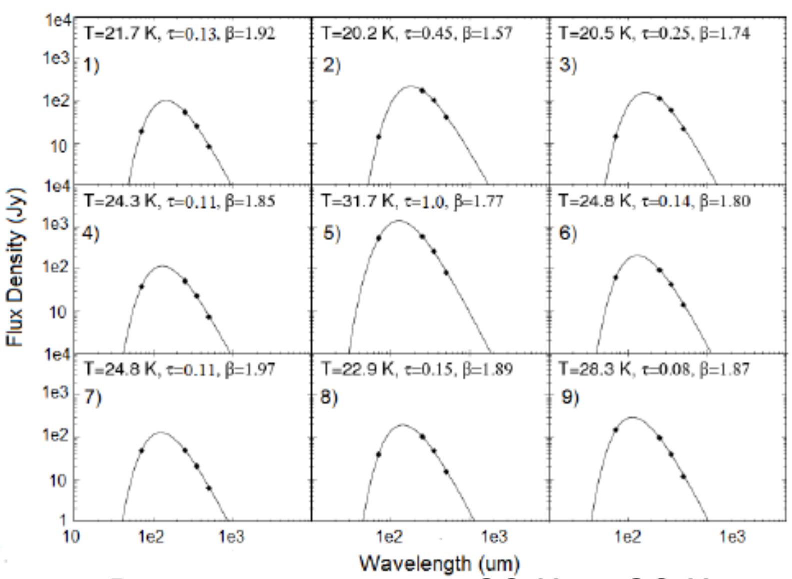
Find that (1) N(HI) is relatively constant (2) atomic-molecular transition occurs at $N(HI)+2N(H_2) = 10^{21}\ cm^{-2}$

Energy Return to ISM from Star Formation

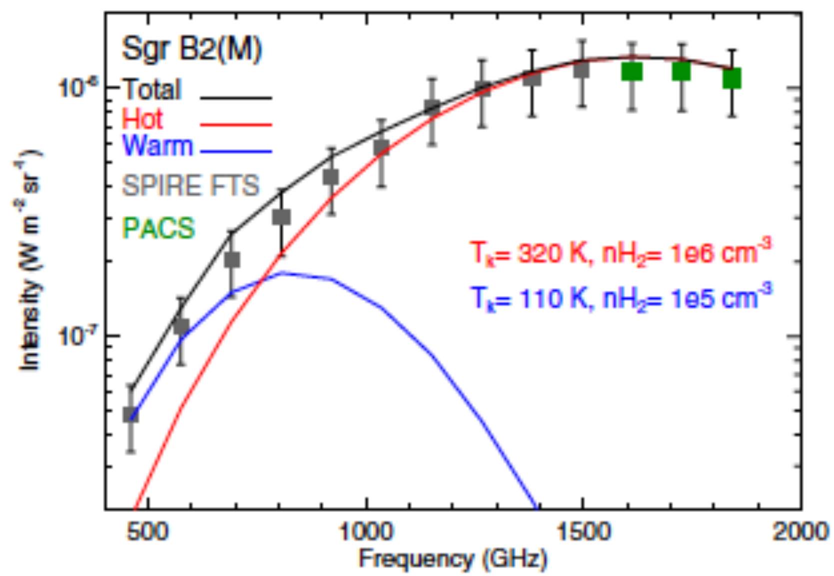
Giant Molecular Cloud (GMC) Energetics & Radiation

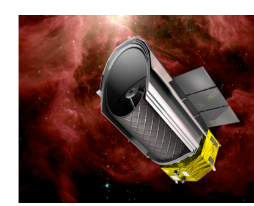
Radiation from newly-formed massive stars is the major **heating source** of GMCs
Dust radiation is **dominant coolant** in terms of energy radiated s^{-1} but gas is the dominant mass reservoir
The two will not be well coupled – if density & collision rate are insufficient
Example: GMC Sgr B2 (Etxalude et al. 2013)

Massive young stars also inject
mechanical energy



Dust temperature 20 K to 30 K



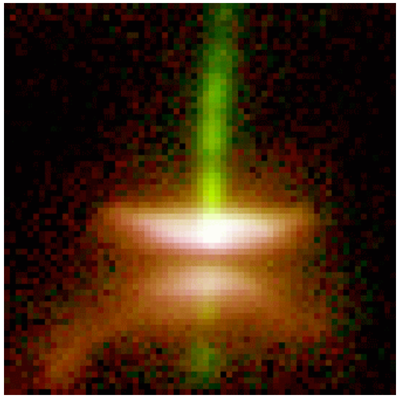


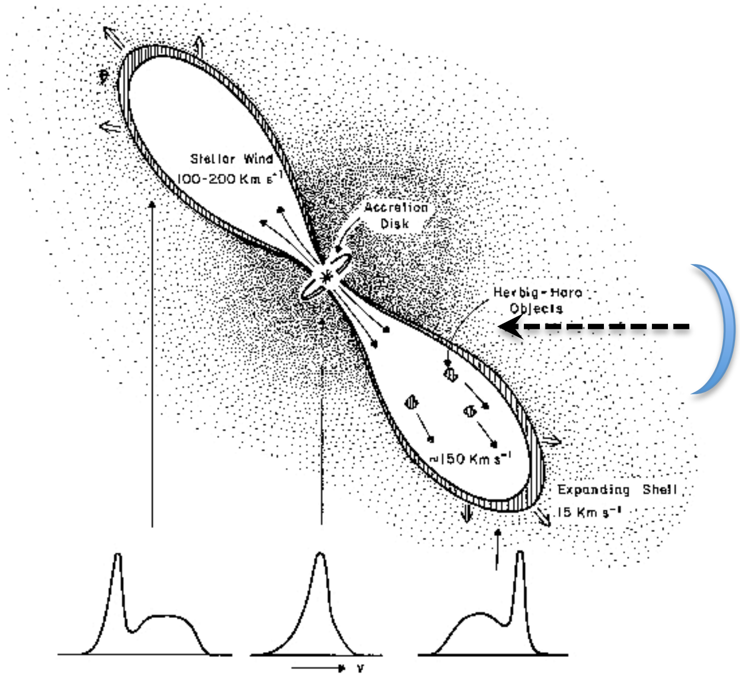
Energy Return to ISM from Star Formation (2)

Low mass stars return relatively less radiative energy but can inject significant MECHANICAL energy

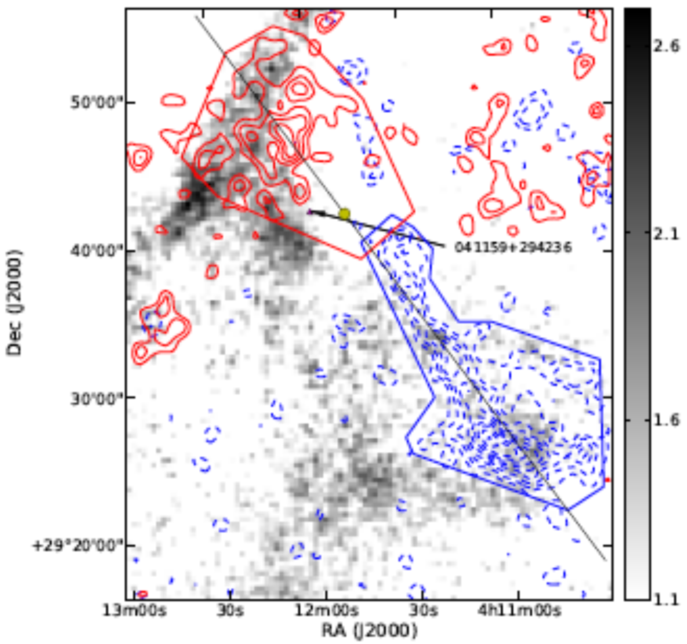
Young stars accompanied by DISK; rotation + magnetic field -> stellar JETS, which drive IONIZED GAS OUTFLOW, which in turn entrains surrounding molecular gas and dust into -

BIPOLAR OUTFLOW





Snell, Loren, Plambeck (1980)

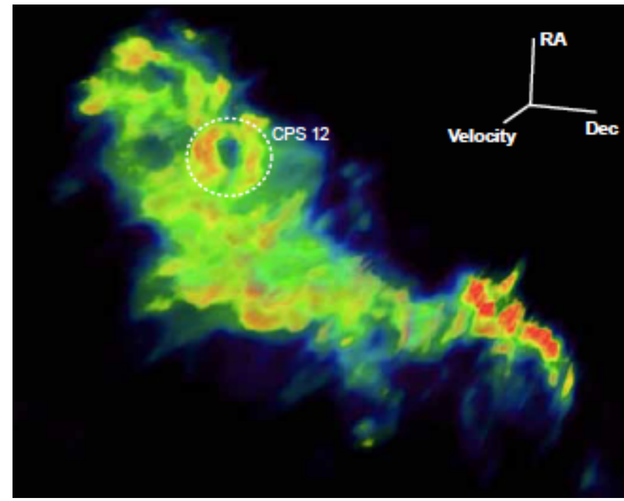


Narayanan, Snell, Bemis (2012)

Energy Return to ISM from Star Formation (3)

In addition to Outflows, Young Stars can Excavate Cavities & Form Shells

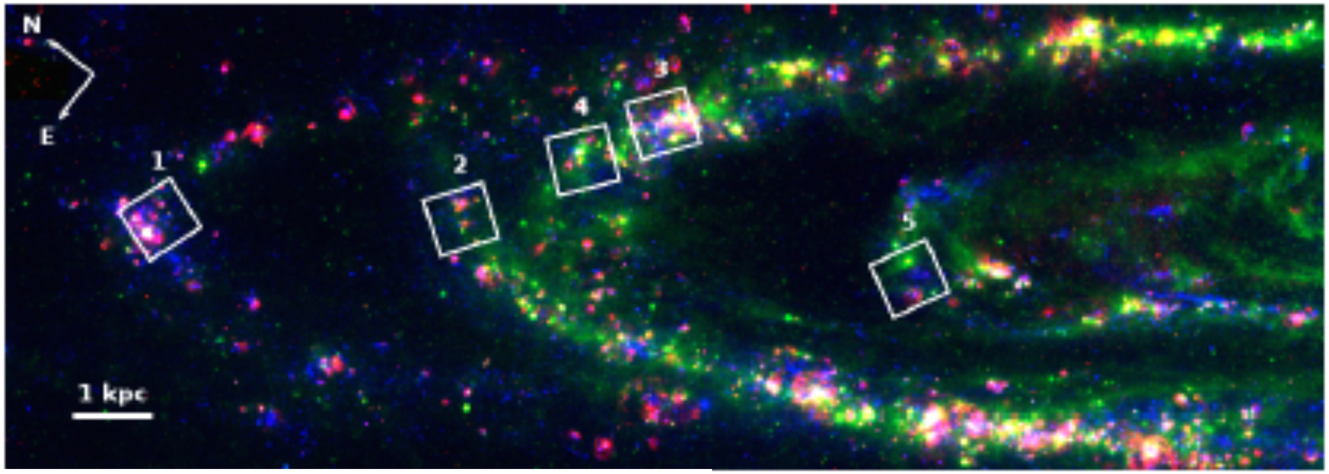
- Age, physical size, and angular size vary widely
- Difficult to determine mechanical energy content
- May trace effects of past generations of "young" stars
- Need to measure mass and velocity shifts over large areas of clouds to high sensitivity
- Census of both outflows and cavities requires single-dish (w. focal plane arrays) spectral line images; ALMA (with mosaicing) useful for more distant sources



SHELL excavated in B5 cloud (Arce 2011)

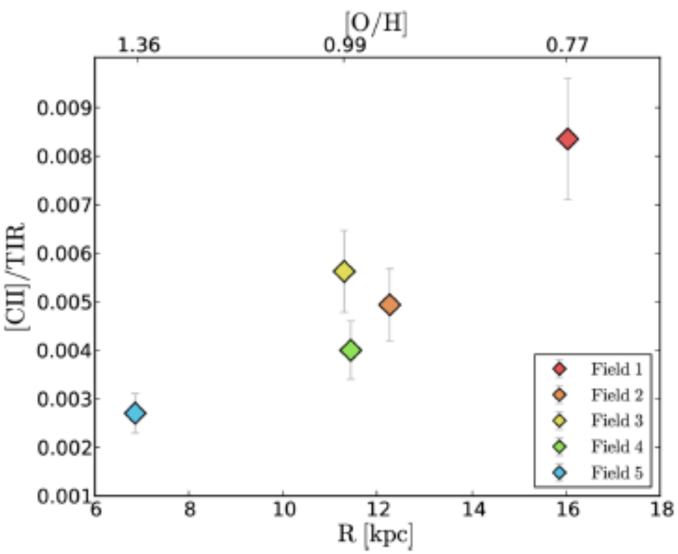
Local Group Galaxies –

Resolve key physical scales (50 pc @ M31 with 160 µm Herschel 11” beam



3’ x 3’ regions mapped in M31
Karska et al. (2014)

Compare [CII] and IR

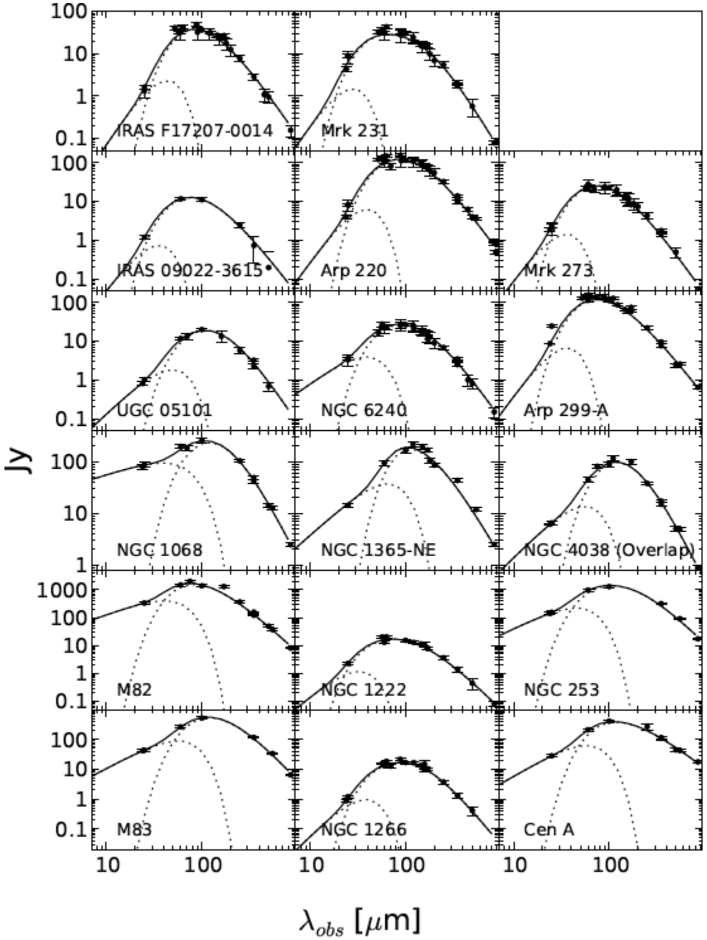


Observations -

SOFIA with upGREAT (7 pixel array) ~15” beam

Balloons – focal plane arrays but ~1’ beam

Tracing Star Formation in External Galaxies



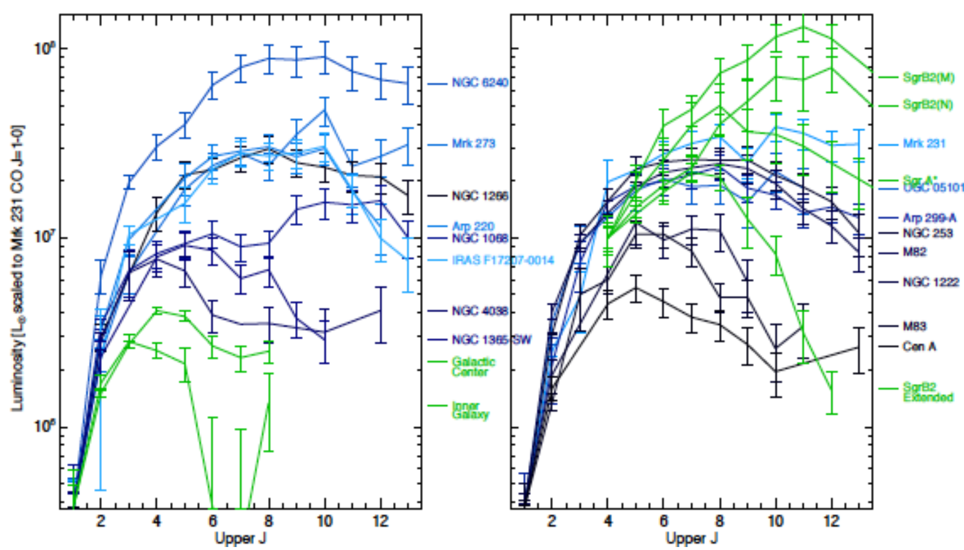
Dust Spectral Energy Distribution (SED) for different galaxies

Kamenetzky et al. (2014)

Angular resolution is the big issue, but you sometimes get less-confused picture than in the Milky Way

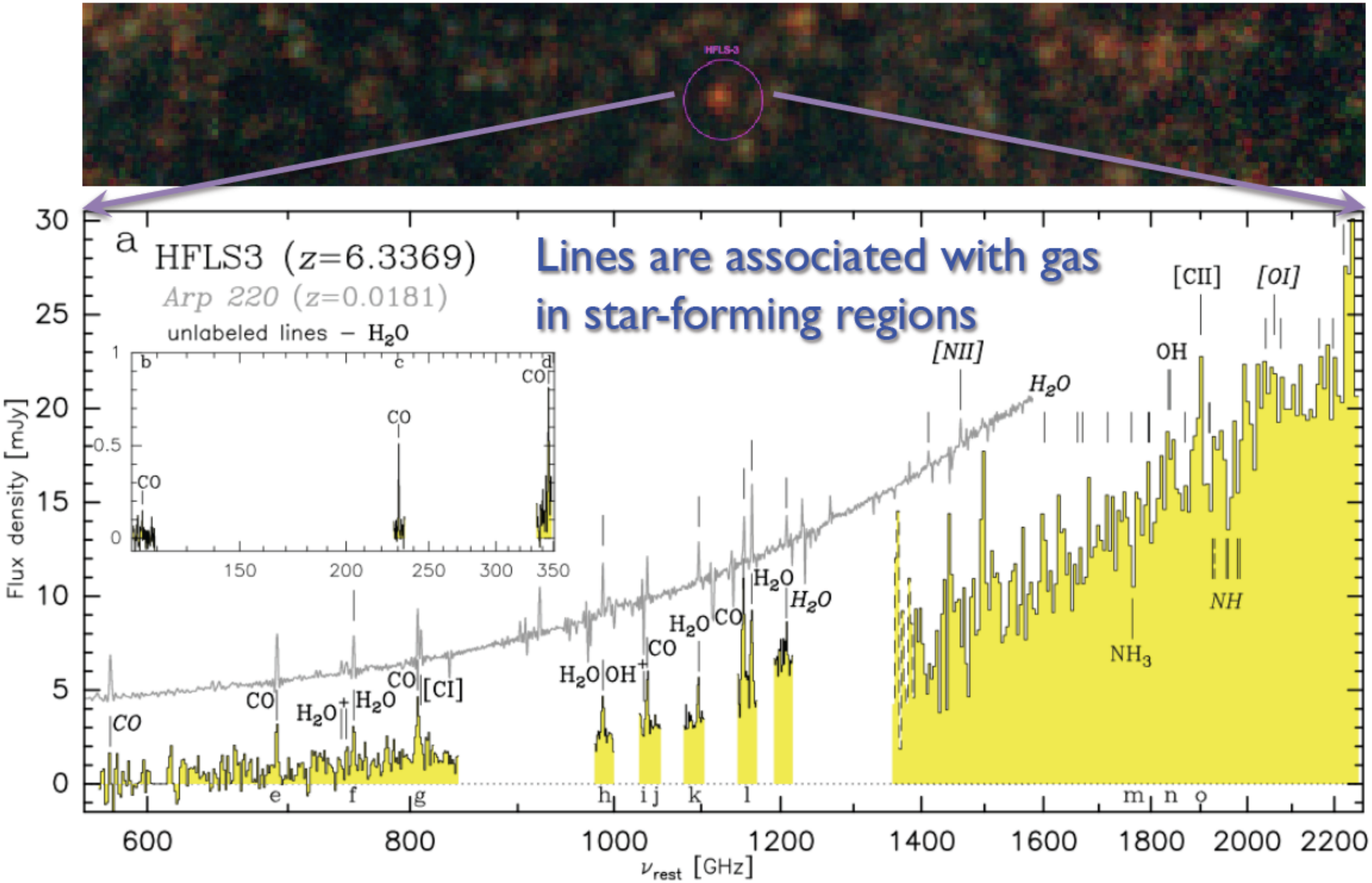
Determining IR luminosity requires observations between 1mm and 30 microns (for local universe). Multiple temperature components generally found.

This is an observational challenge!



CO SLEDs Kamenetzky et al. (2014)

HFLS3: The Most Distant Dusty Starburst Galaxy



Follow up with all we have:

Galaxy confirmed … at z=6.3369 !!

Detect
7 CO lines
7 H_2O lines
H_2O^+
NH_3 (absorption)
OH
OH^+ (absorption)
[CI]
[CII]
Hints of others…
⇒ Highly enriched

Observed 880 million years after the Big Bang (current age: 13.8 billion yrs)

Gray line is best existing spectrum of *nearby* starburst

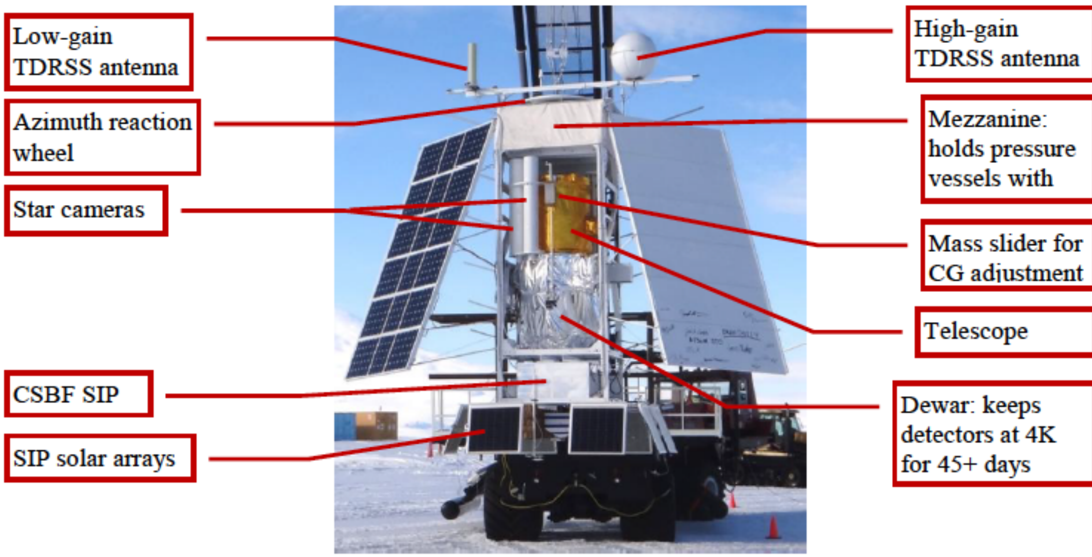
Big Bang — HFLS3 — today

Large redshifts move observed frequencies from submm/FIR to cm/mm -> entirely different telescopes: **CARMA/IRAM/ALMA/VLA**

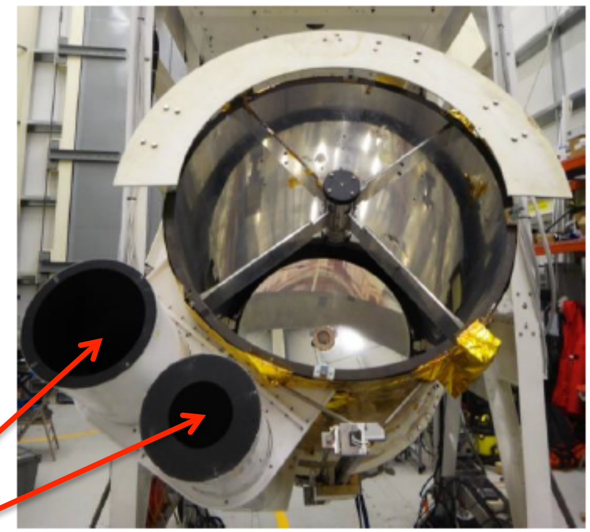
Riechers et al. 2013b, Nature

New Facility: STO-2 (C.Walker U of A PI)

NASA ADAP Antarctic U/LDB – Dec. 2015 launch



STO-1 before launch



80cm dia telescope; 1' resolution

Focal Plane Includes 12 HEB mixers:

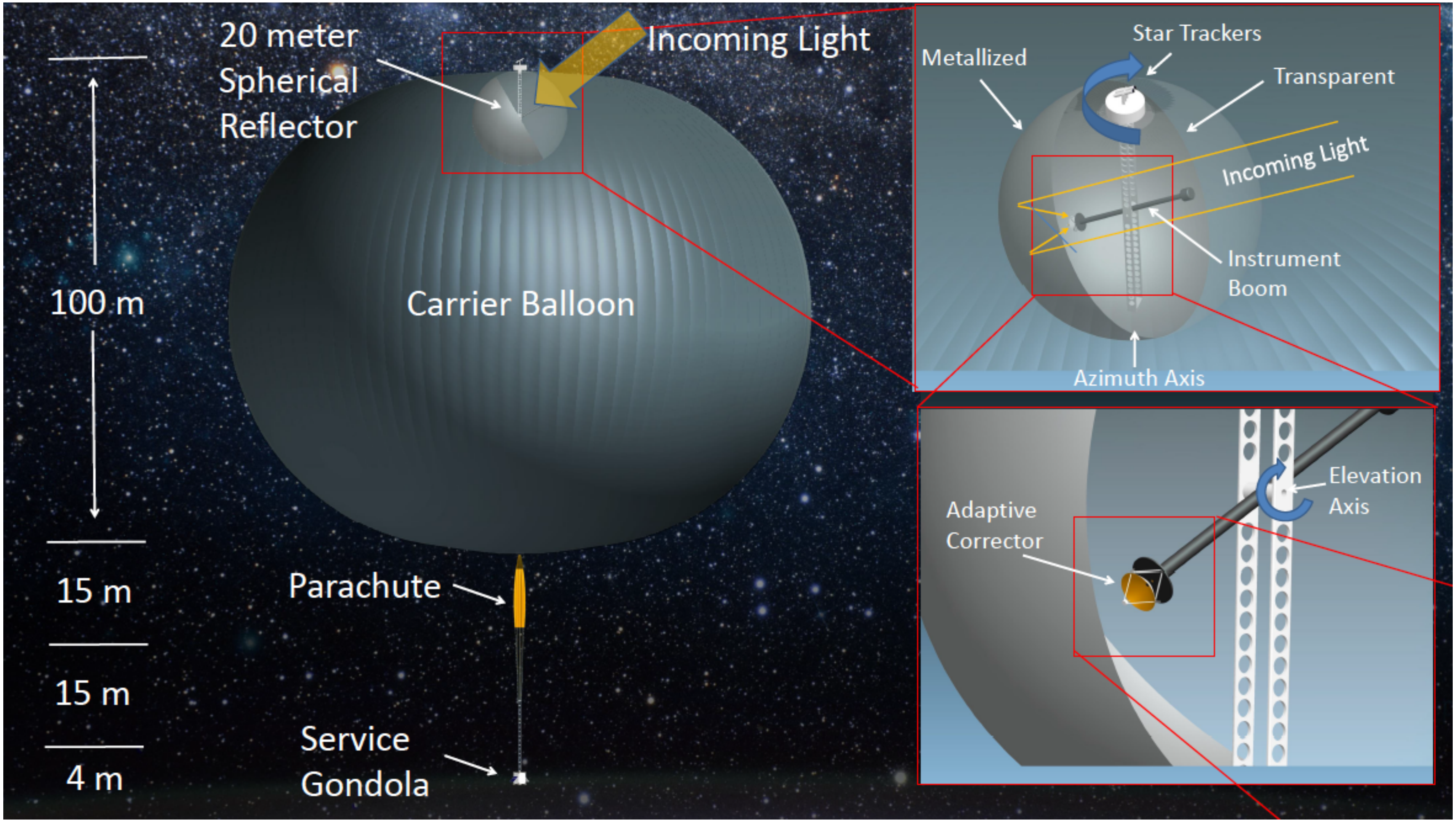
4 pixels @ 1.46 THz for **[NII]** $^3P_1$- $^3P_0$ frequency-multiplied LO (JPL)

4 pixels @ 1.90 THz for **[CII]** $^2P_{3/2}$- $^2P_{1/2}$ frequency-multiplied LO (JPL)

4 pixels @ 4.75 THz for **[OI]** $^3P_1$- $^3P_2$ QCL LO (SRON)

Goal: Image 50^{o}x2^o region of inner galaxy to trace molecular cloud evolution and star formation; 50^{o2} region of Large Magellanic Cloud to look at low metallicity environment

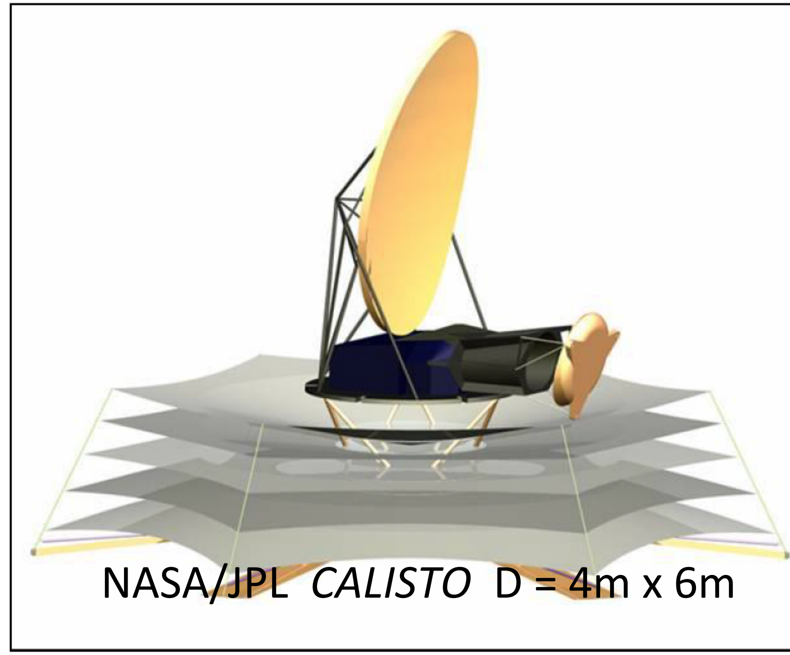
Large Balloon Reflector (LBR) – 10m dia submm Telescope for λ > 500μm

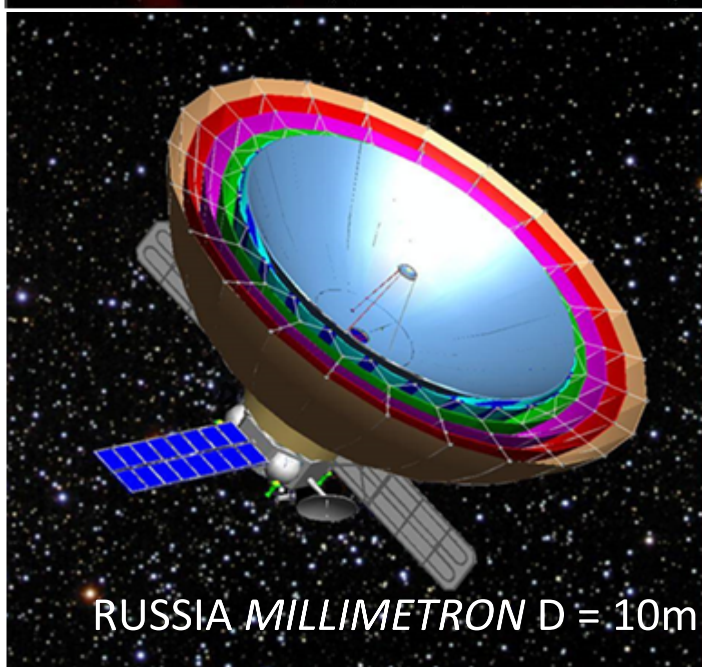


Provide ~ 3x angular resolution and ~6x point source sensitivity compared to Herschel at longer submm wavelengths – currently a Phase II NIAC Project

U of A, SWIRI, JPL, Cornell Univ.

Next Generation of Submm/FIR Space Observatories Have Optics cooled to 4K





Instrumental Highlights

SPICA: instrument complement in flux; SAFARI is imaging FTS something like SPIRE on Herschel but far more sensitive

MILLIMETRON: low/medium res. photometry and spectroscopy 60 µm- 1mm + High resolution (heterodyne) spectrometer w/ 3-7 pixels 60-600 µm

CALISTO: low/medium res.photometry & spectroscopy 30-300 µm

Unblocked aperture to minimize Galactic pickup and achieve astronomical background limited (ABL) sensitivity

CONCLUSIONS

- There is a rich and varied set of astronomical instruments to study young stars and the interstellar medium connected with star formation
- Some of the most valuable are no longer operational (Herschel, CSO)
- Some are being closed in near future (CARMA, Spitzer, GBT?)
- New facilities are becoming fully operational (ALMA, SOFIA)
- Powerful new facilities anticipated in near future (JWST, STO)
- People are developing concepts for next generation of facilities (SPICA, Millimetron, CALISTO, …)

So there is a very exciting observational future in store

Thank you for your attention!