Galactic studies of FIR fine-structure lines

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Paul Clark (Cardiff)

M17
credit: HST/WFPC2

Apologies…

- I am a newcomer to the field
- I am an ISM researcher, so I will be biased toward [CII] and [OI]

The first part of this talk…

- Scientific framework
- A Galactic focus

Galactic studies at this workshop

- *Herschel* Galactic plane surveys - GOT C^+, [NII]

  Jorge Pineda, Paul Goldsmith

- Circumnuclear disc with SOFIA / FIFI-LS

  Aaron Bryant

- Warm, diffuse gas in and around infrared-dark clouds

  Henrik Beuther

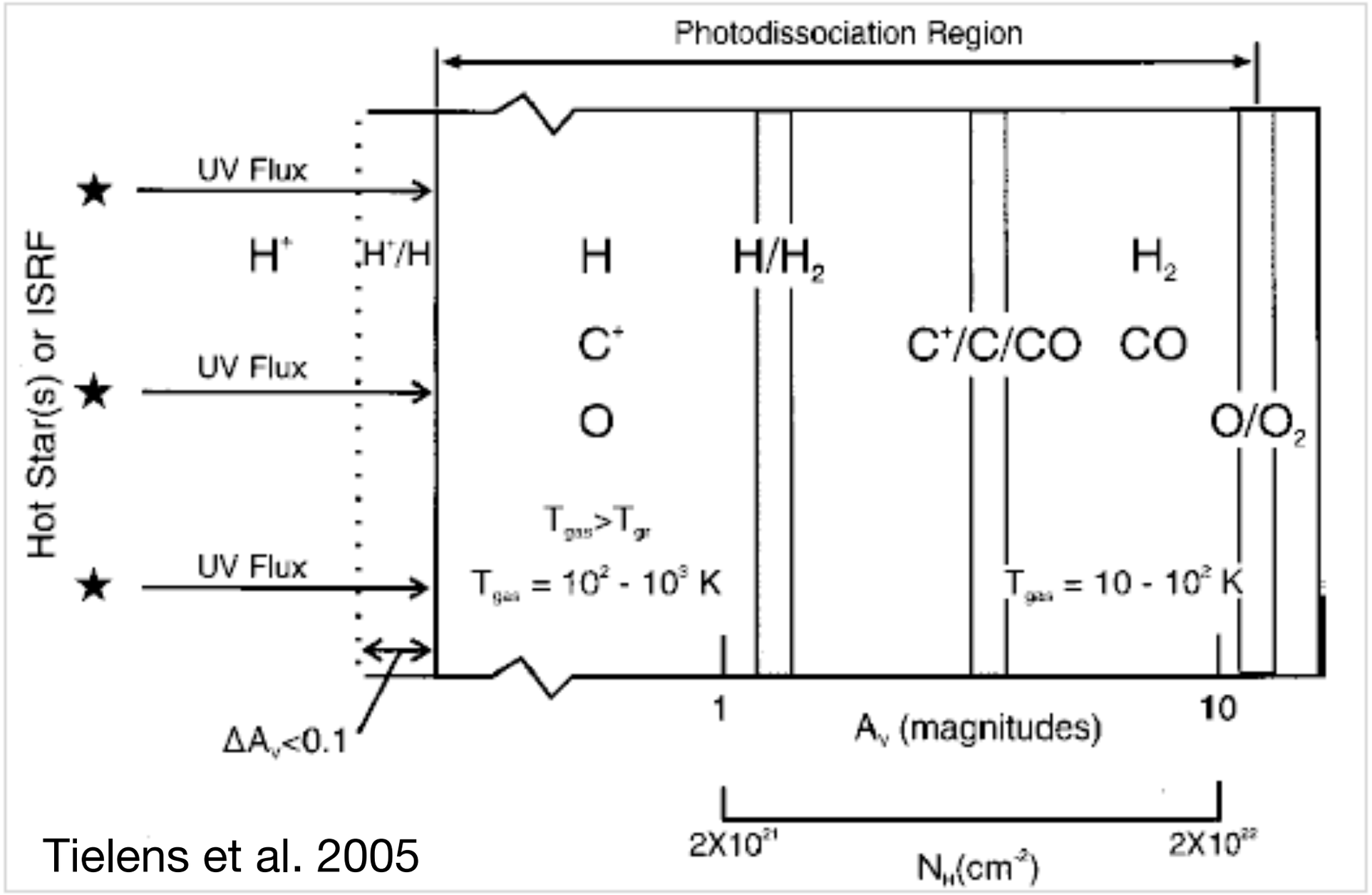
- [CII] and [OI] in regions of active star formation

  Evgenia Koumpia, Volker Ossenkopf, Cristian Guevara, J.P. Perez-Beaupuits

- Young planetary nebulae

  Helmut Wiesemeyer

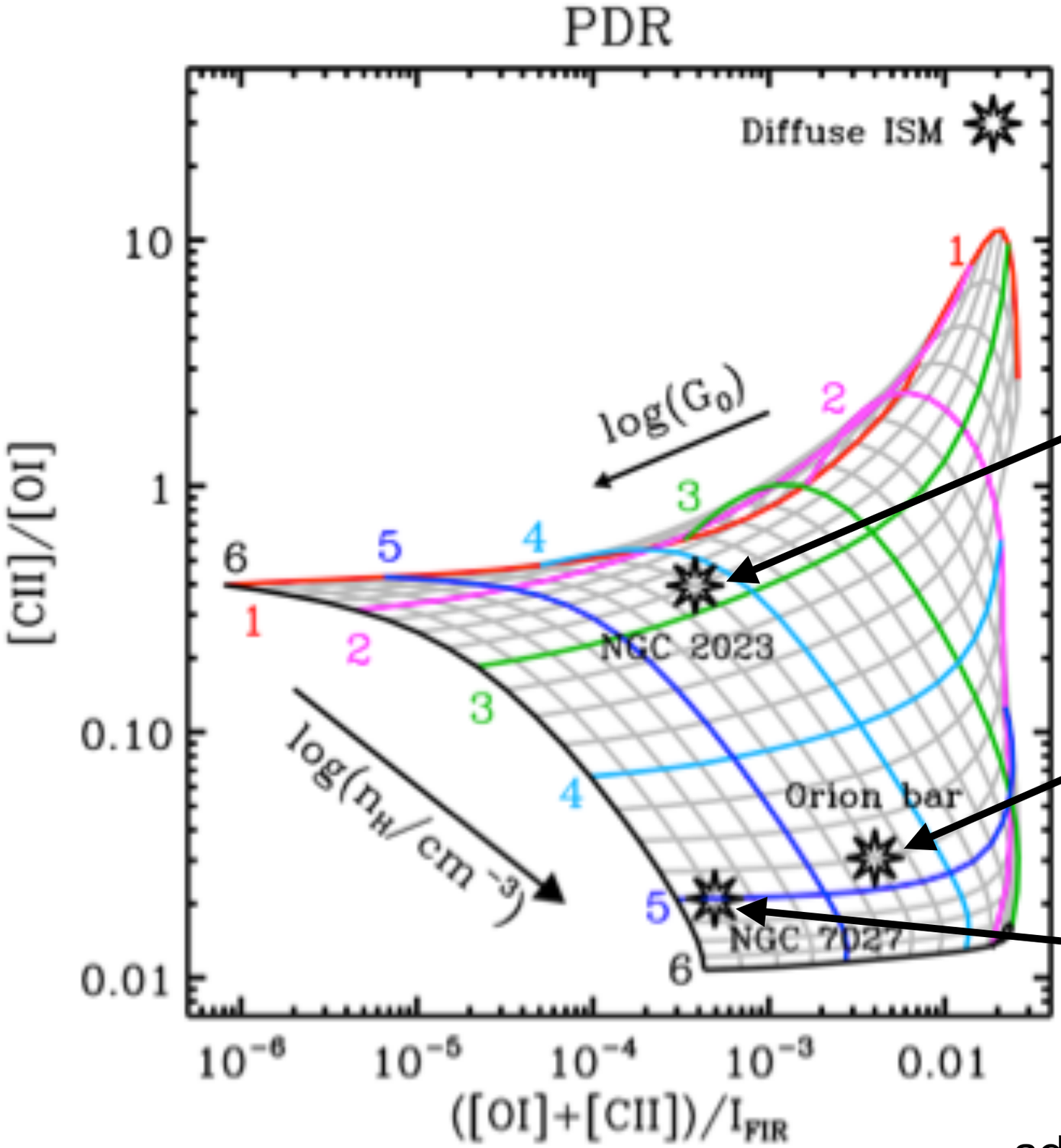
Photodissociation regions



Tielens et al. 2005

Neutral gas (CNM and WNM) is predominantly cooled by ionised carbon and atomic oxygen (Tielens & Hollenbach (1985)

FIR FSLs: idealised PDR model



G_o = strength of UV in ISRF
= 1 solar neighbourhood

NGC 2023
reflection nebula

Orion Bar
classical PDR

NGC 7027
young planetary nebula

adapted from Kaufman et al. 1999

The first observations of [CII]

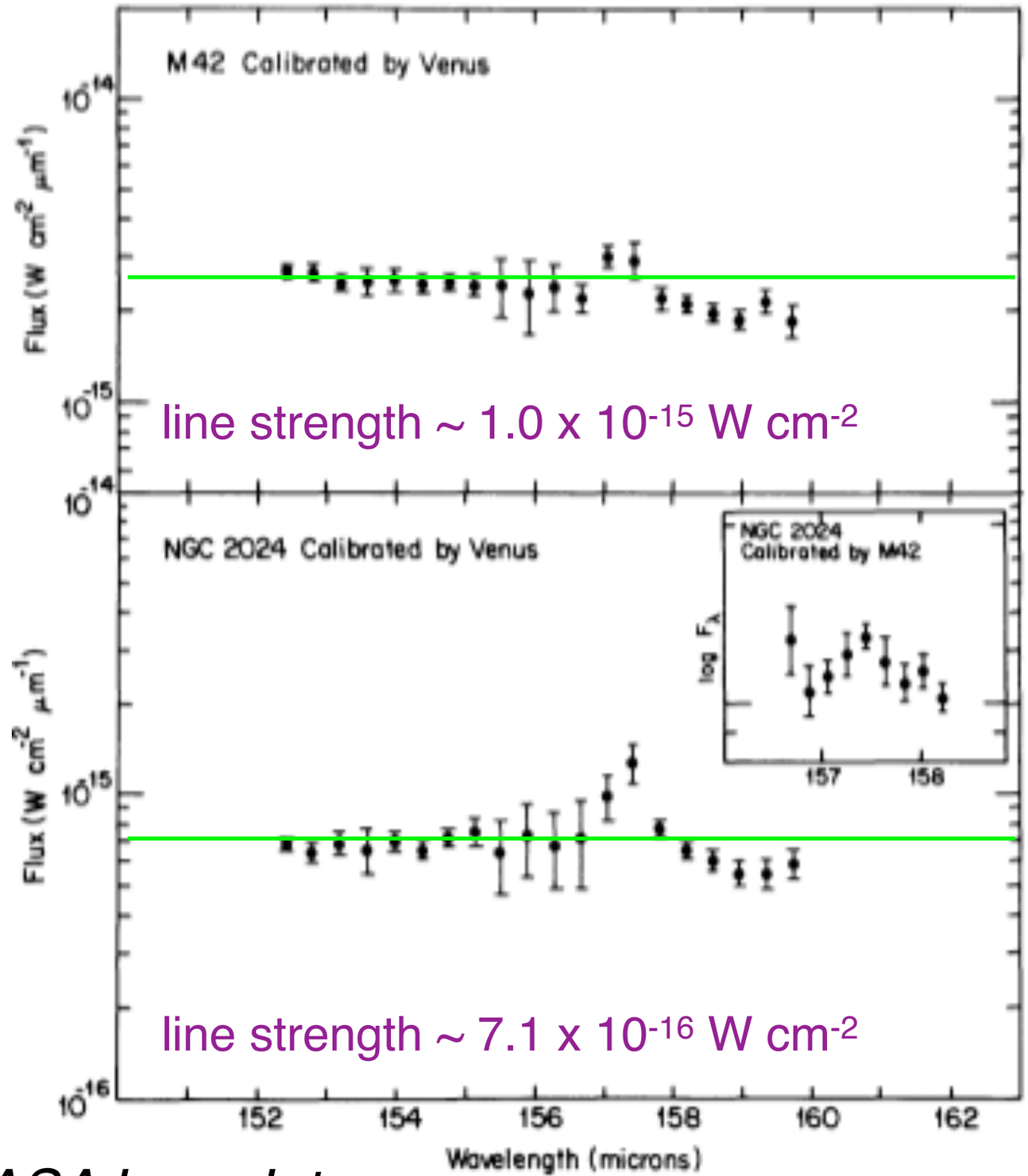
The first observations of [CII]

The Orion Nebula
credit: ESA / Herschel

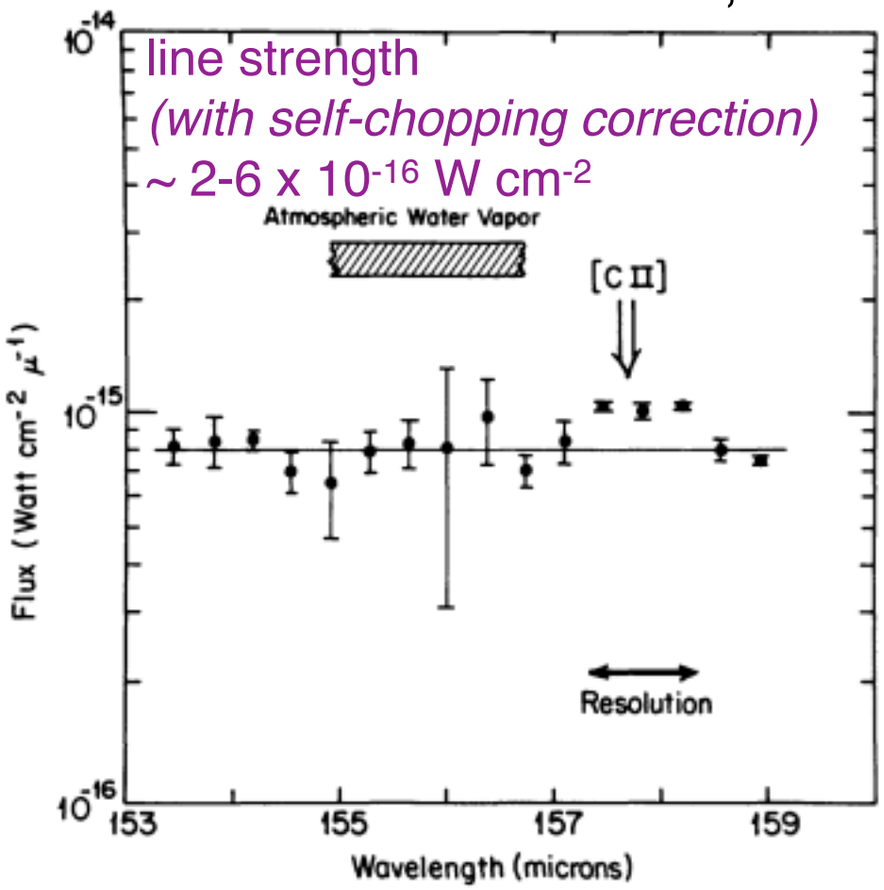
The Orion B molecular cloud
credit: ESA / Herschel

The first detections of [CII]

Russell et al. 1980, M42, NGC2024



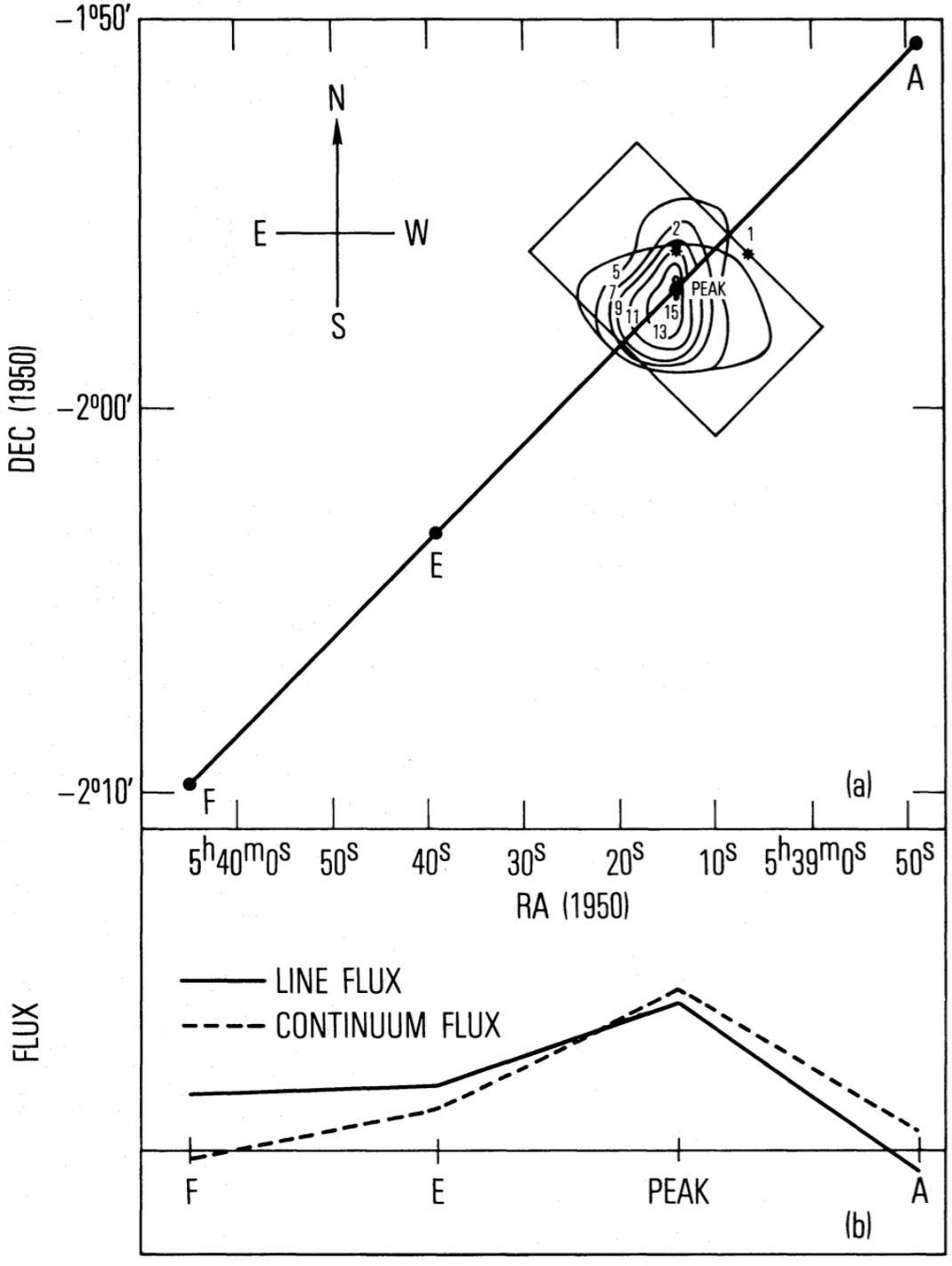
Russell et al. 1981, M17



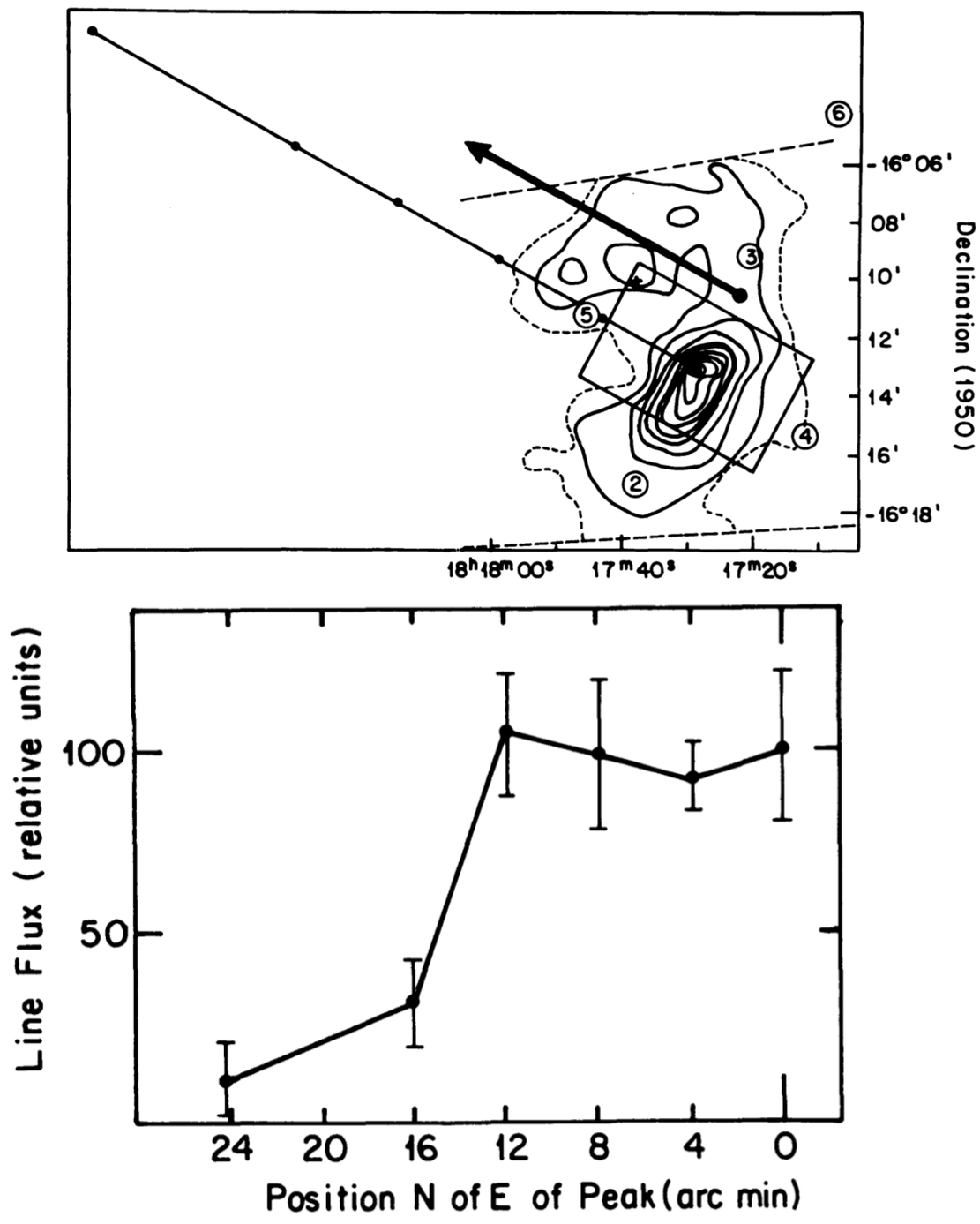
NASA Lear Jet

[CII] is extended!

Kurtz+1983, NGC2024 (map)



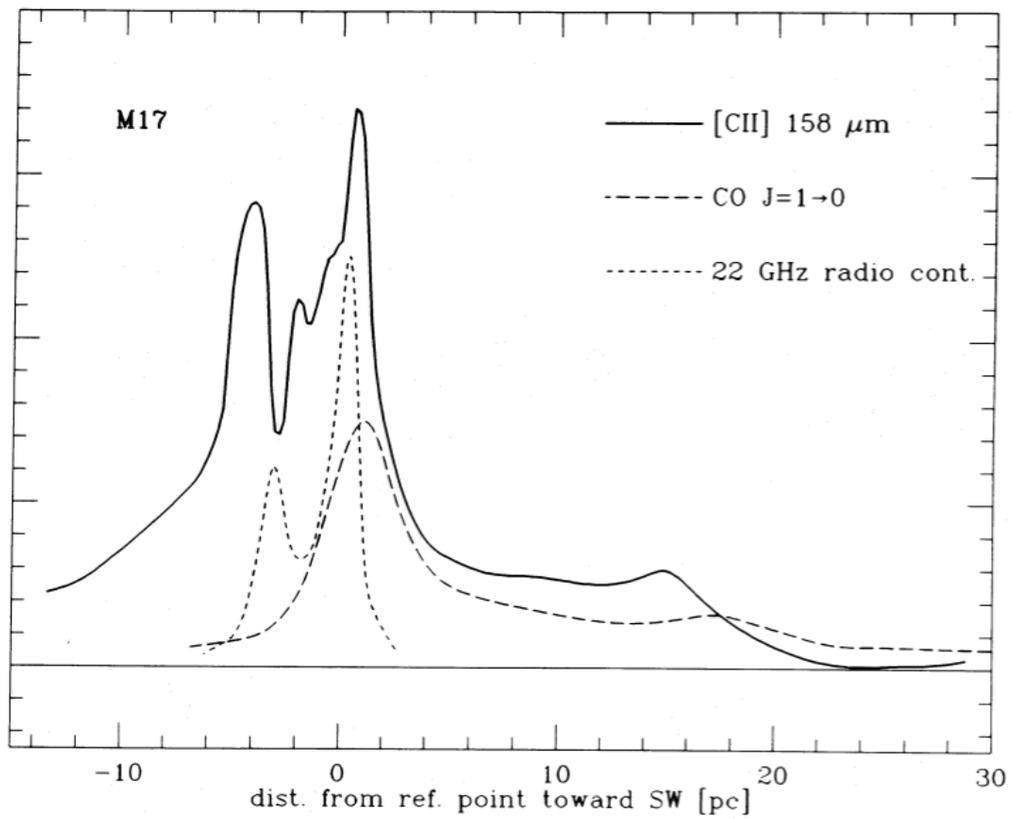
Russell+1981, M17 (map)

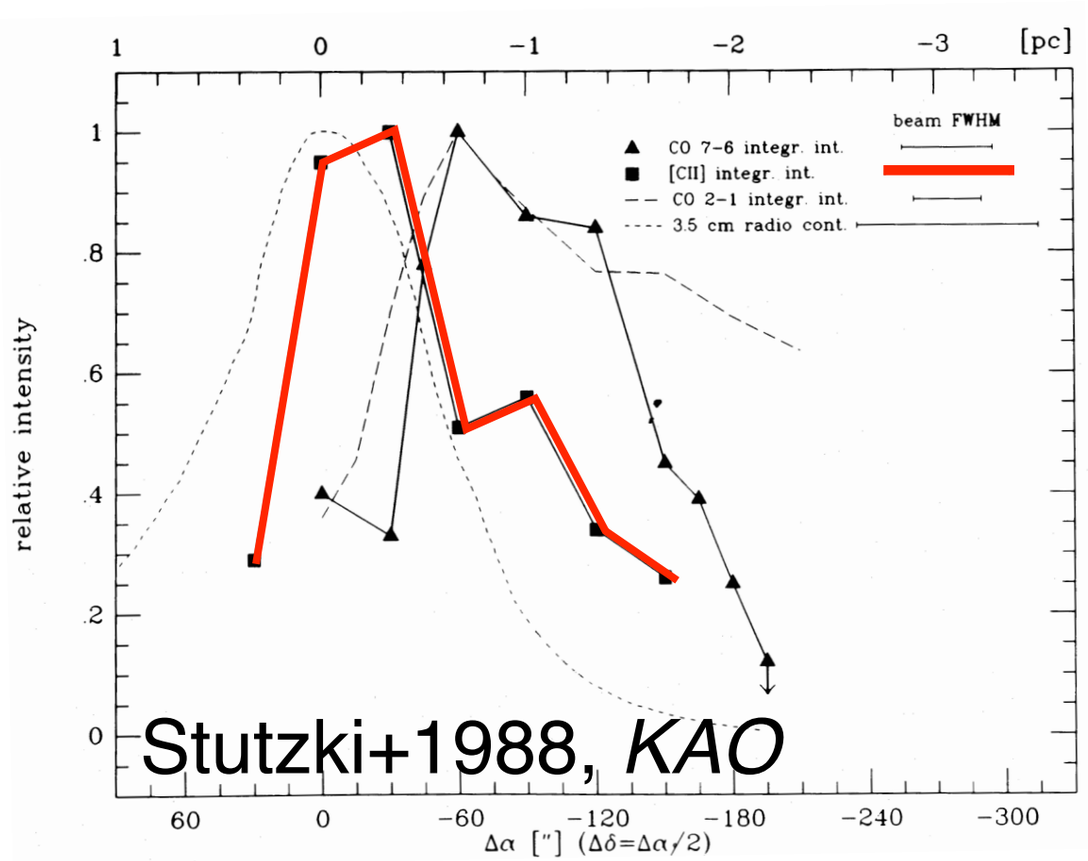


NASA Lear Jet & Kuiper Airborne Observatory

What is the origin of [CII] emission?

The origin of [CII]



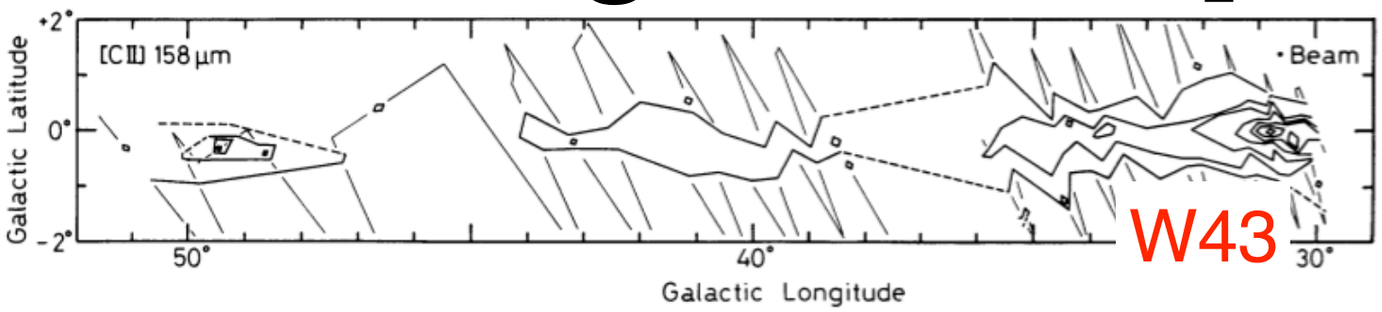


Stutzki+1988, *KAO*

- Only small fraction of [CII] from *within* HII regions
- [CII] originates from the UV-heated dense gas at cloud surfaces (PDR)
- Clumpy medium necessary for UV to penetrate the cloud
- But extended [CII] is also seen throughout the bulk of the molecular clouds (CO)
- Elevated ISRF and/or embedded OB sources throughout needed to supply UV

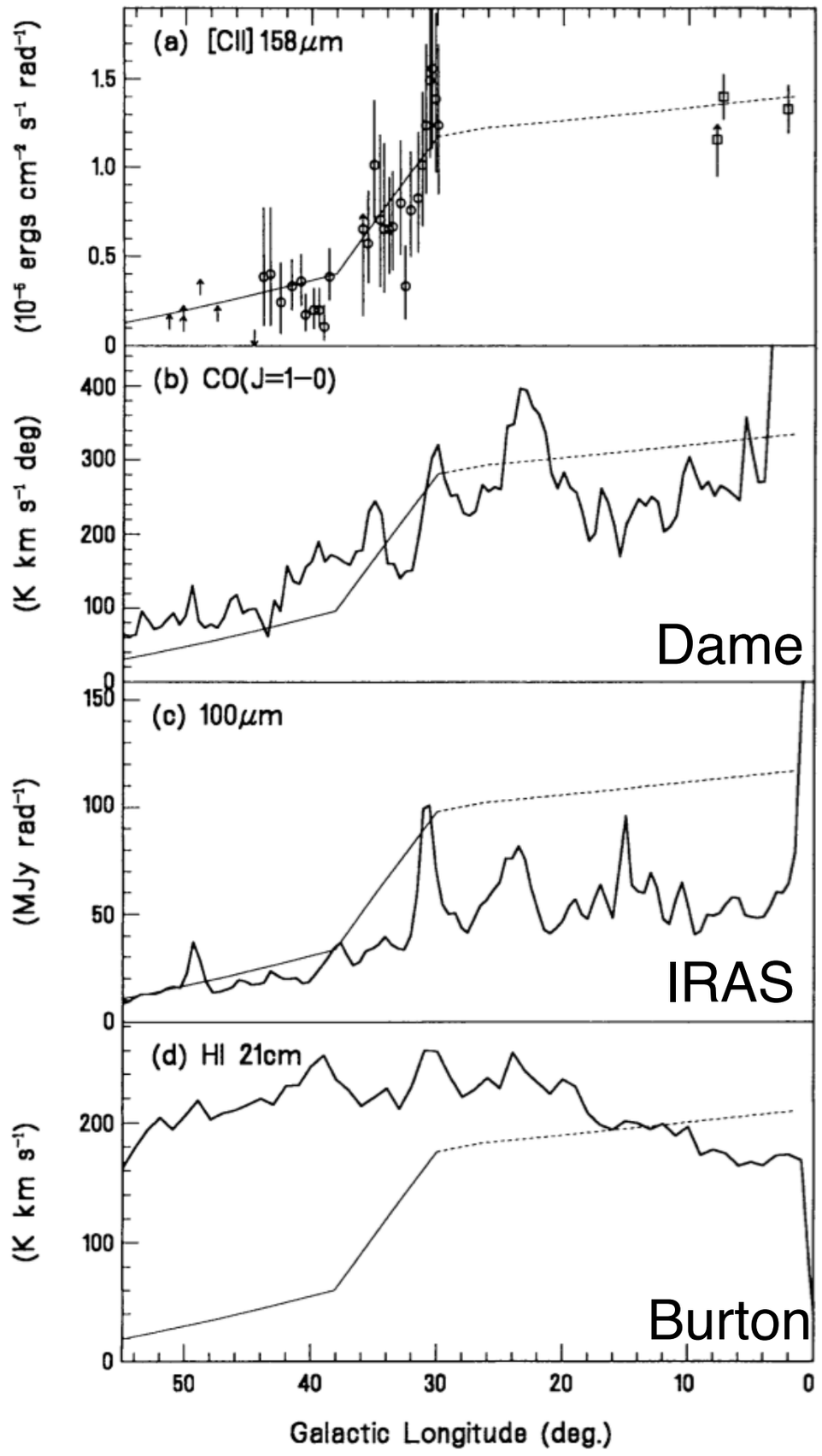
see also Melnick+1986, Howe+1991, Stacey+1993, Mizutani+2004

Large scale [CII] emission



- Total [CII] luminosity (inside solar circle) 2.8 x 10^7 L_{sun}, or [CII]/FIR ~0.36%
- [CII] correlates with CO
- Σ FIR (known HII regions) x ([CII]/FIR) = < 8% of observed [CII] level!
- Large scale extended [CII] not associated with HII regions, dominates line luminosity

Shibai+1991
BIRT (50cm telescope)



The [CII] to FIR ratio in discrete galactic sources

- [CII] / FIR ~ 5 x 10^{-4}, **lower** than extragalactic or galactic values found over large scales (~3-5 x 10^{-3})

high UV

[CII] limited by dust absorption of FUV photons (much slower)

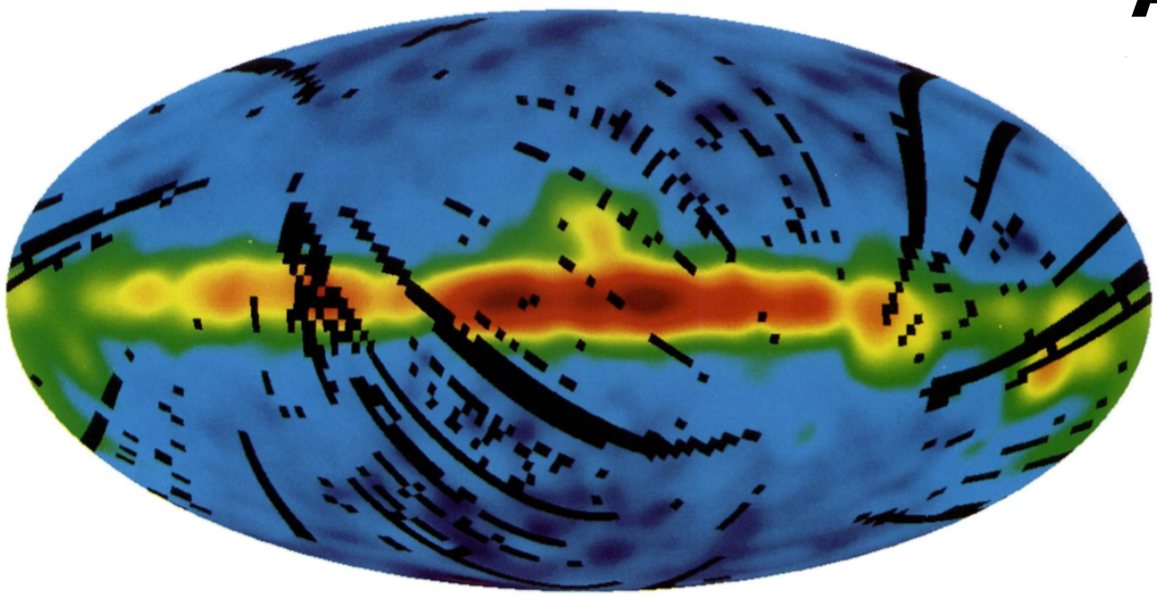
depends on incident FUV

- Result: [CII] line intensity saturates, other lines (like [OI]) take over; gas heating efficiency decreases due to drop in dust photoelectric heating

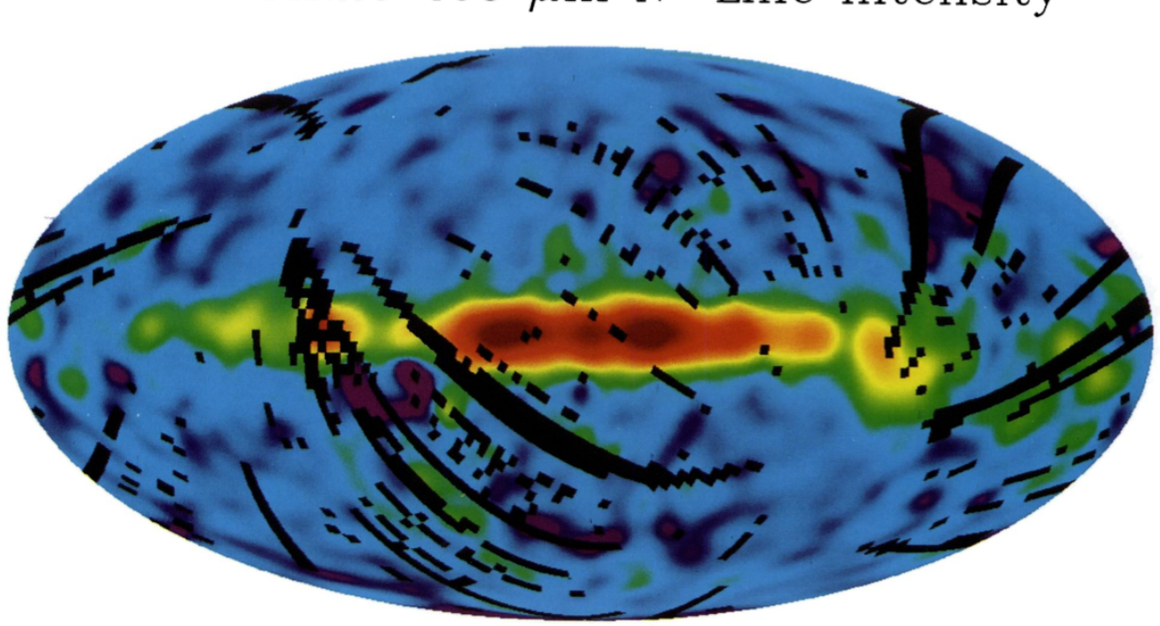
Melnick+1986, *Lear Jet & KAO study of W3 and W51*

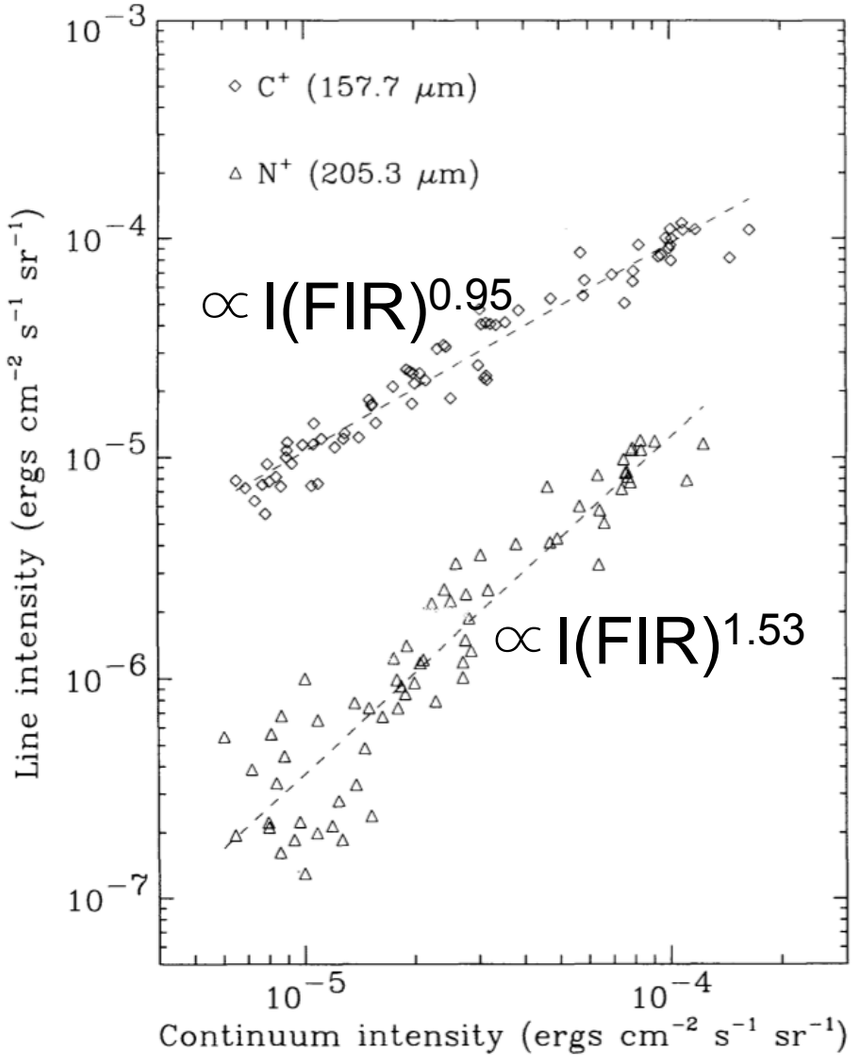
All-sky survey of [CII] & [NII]

COBE FIRAS 158 μm C^+ Line Intensity



COBE FIRAS 205 μm N^+ Line Intensity

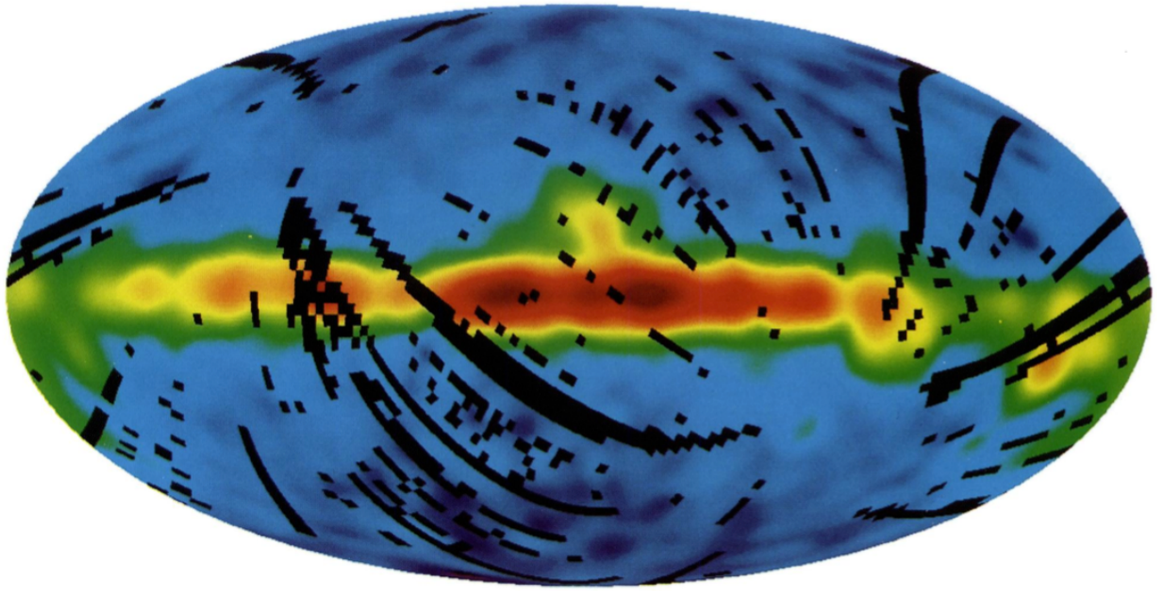




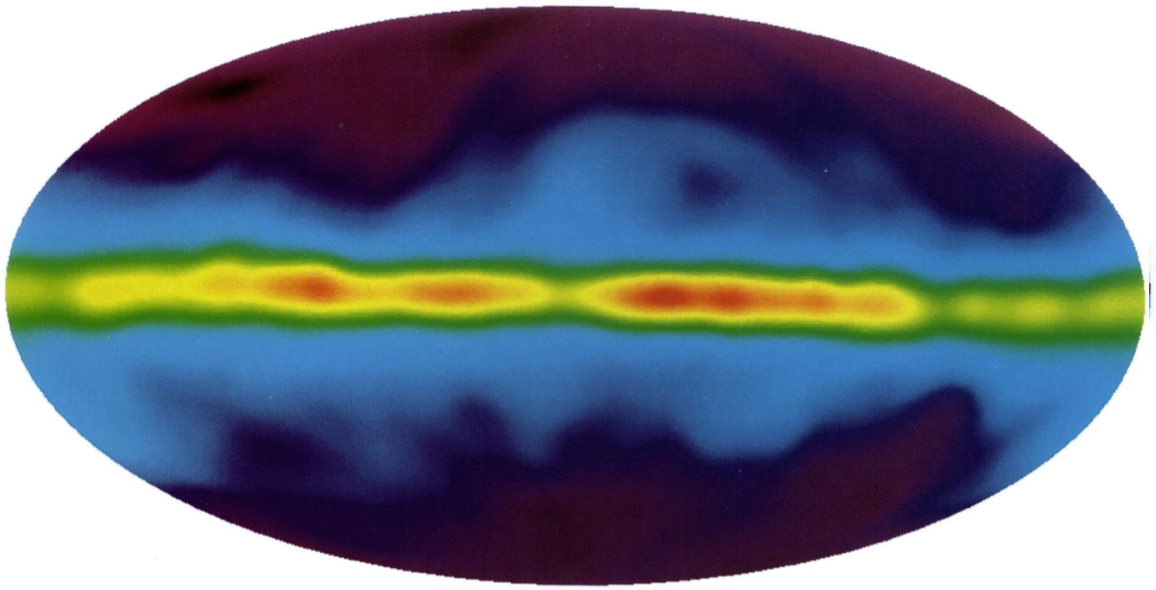
[CII] / [NII] ~ CNM conditions

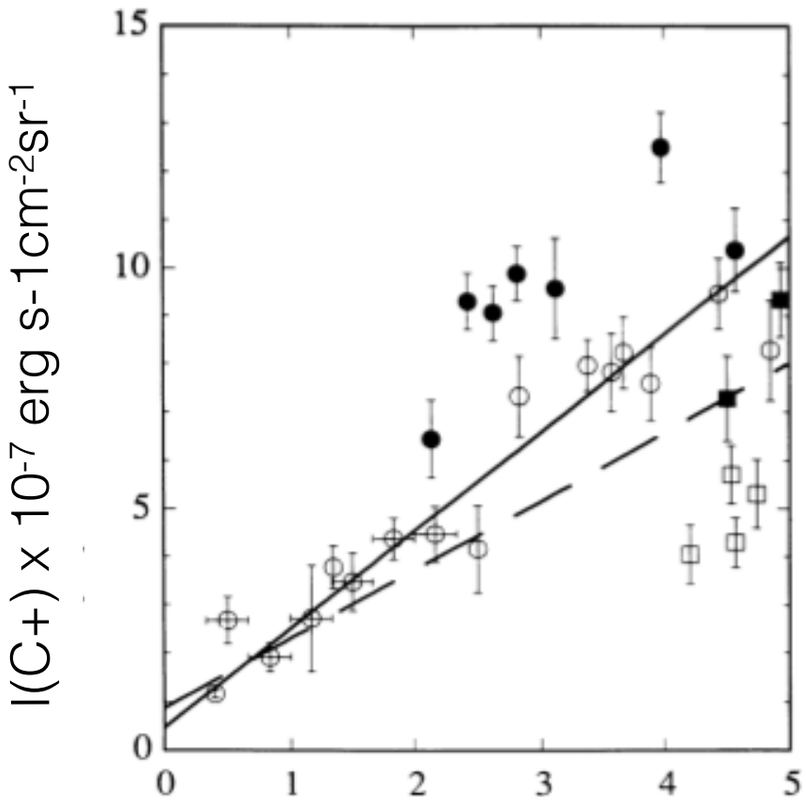
Wright+1991, Bennett+1994
COBE/FIRES (7^o beam)

COBE FIRAS 158 μm C^+ Line Intensity



N(H I)



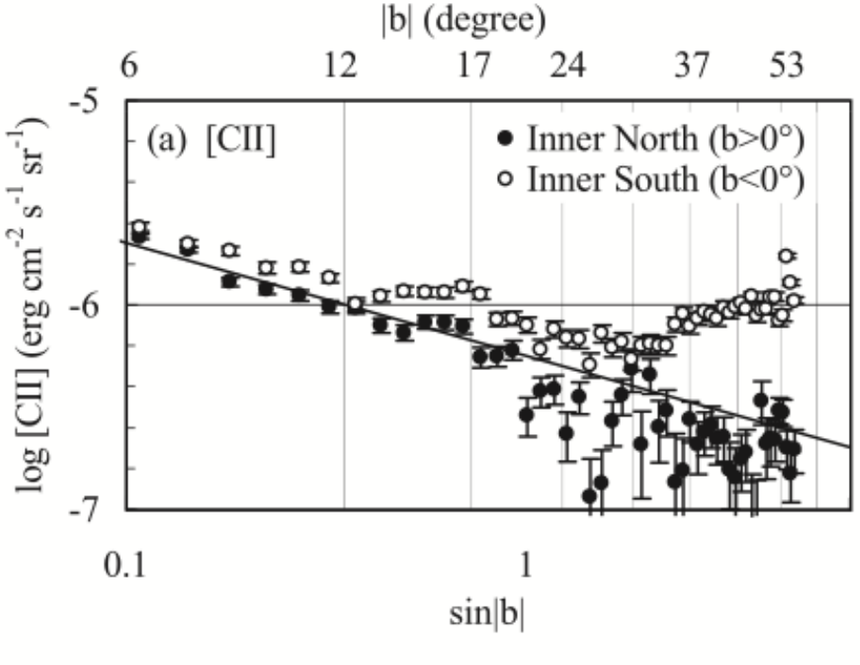


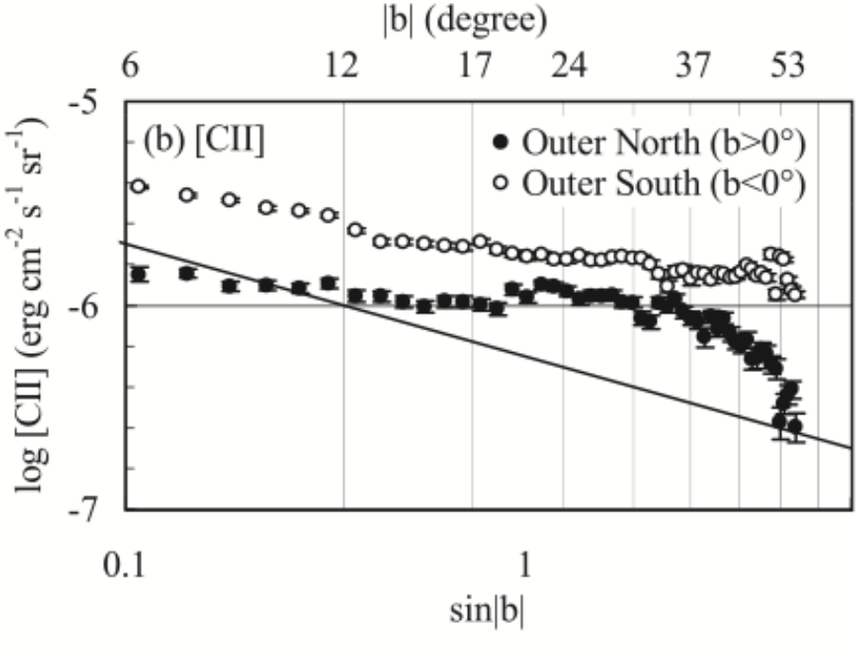
Bock+1993
sounding rocket
10cm telescope

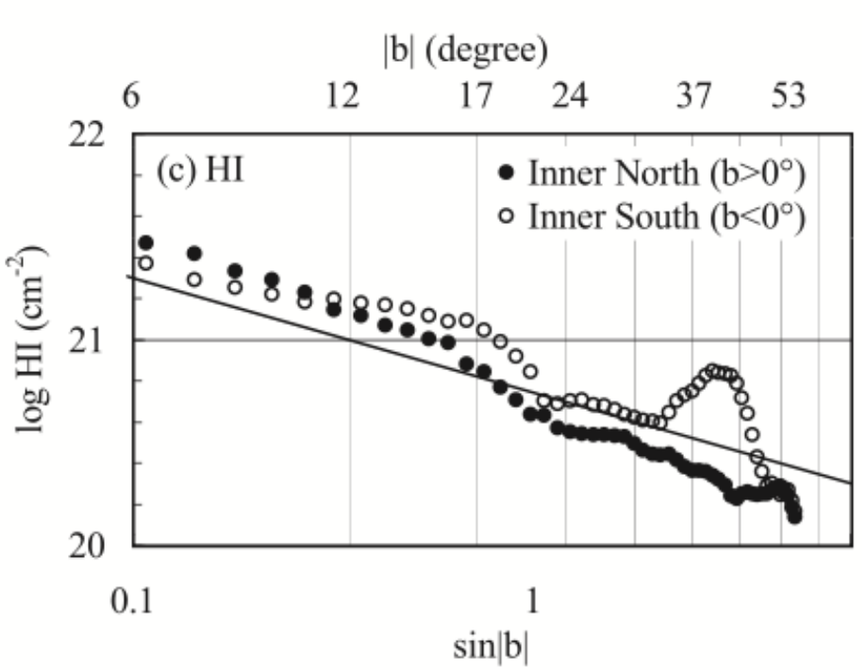
High galactic latitude [CII] from CNM.

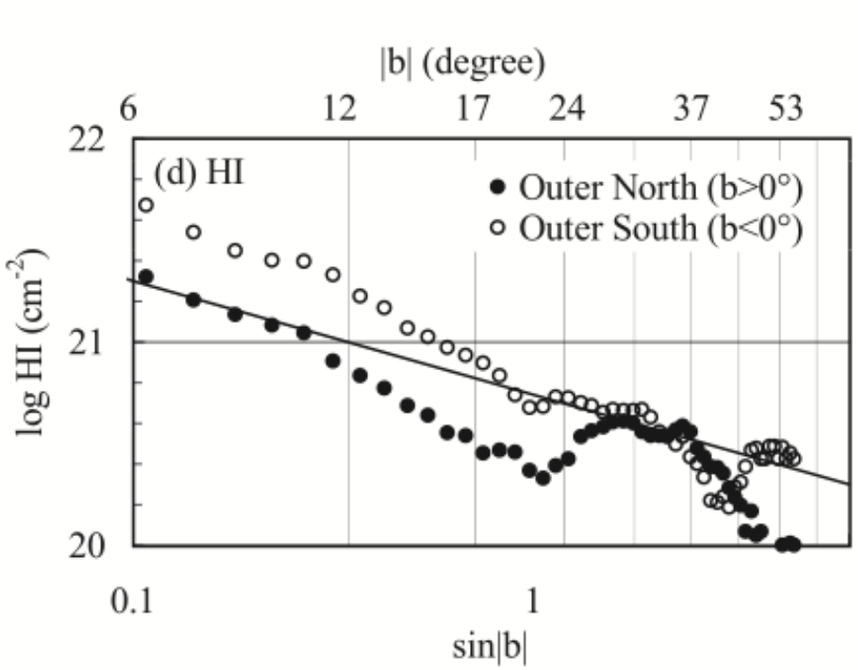
Wright+1991, Bennett+1994
COBE/FIRES (7^o beam)

High galactic latitudes







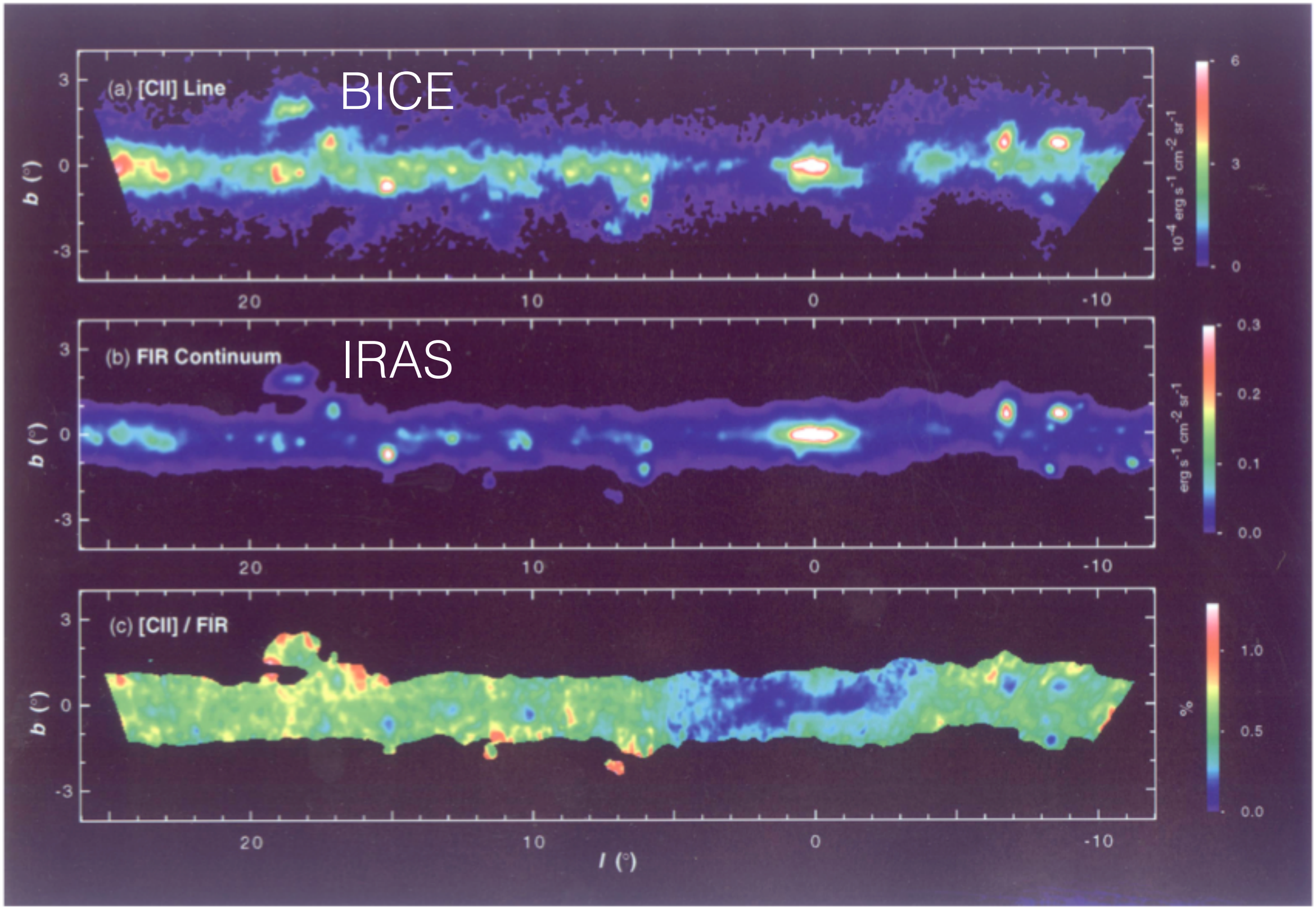


- [CII] *uncorrelated* with HI, must come from WIM at high b (in contradiction to COBE result)

Makiuti+2002

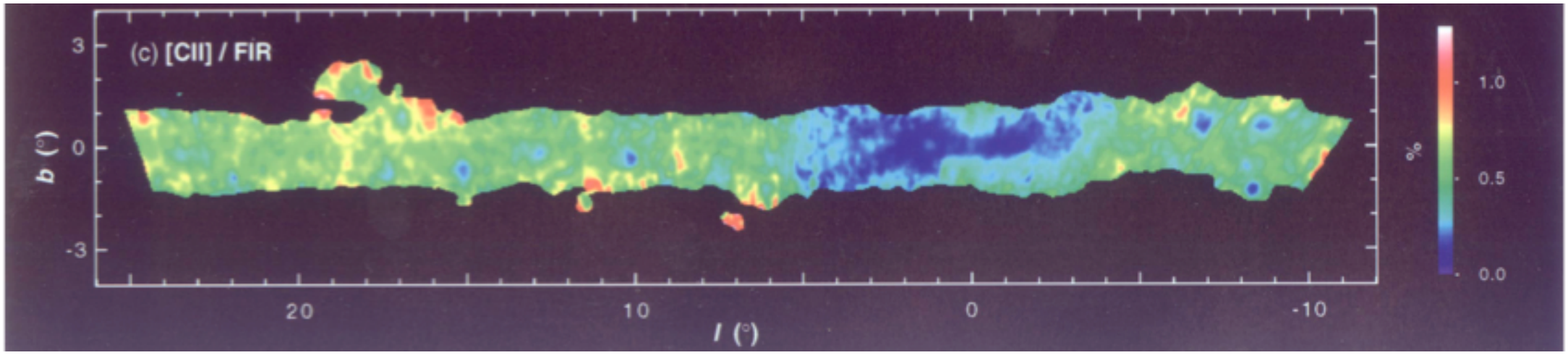
IRTS 15cm telescope

Nakagawa et al. (1998): 35° of Galactic plane



BICE - 20cm telescope

Galactic centre / CMZ



- Low [CII] / FIR - elevated UV (~ 10^3 G_o)

- Higher average gas densities means there is more molecular self-shielding, which leads to large scale (molecular) gas heating (Bennett +1994, Nakagawa+1998)

- Bulk gas temperature 100 - 200K. Additional heating from low-velocity C-shocks induced by turbulence? (Rodríguez-Fernandez+2004)

see also Poglitsch+1991, Genzel+1995, Mizutani+1994, Rodríguez-Fernandez+2004

Summary so far

- [CII] originates from UV-heated gas on the surfaces of molecular clouds
- Large warm molecular regions indicate that clumpiness of clouds is an important factor
- Extended (but low-level) [CII] correlates with CO(1-0)
- Uncertain origin of high galactic latitude [CII]
- Low [CII] to FIR ratio in CMZ

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credit: HST/WFPC2

Herschel results on FSL

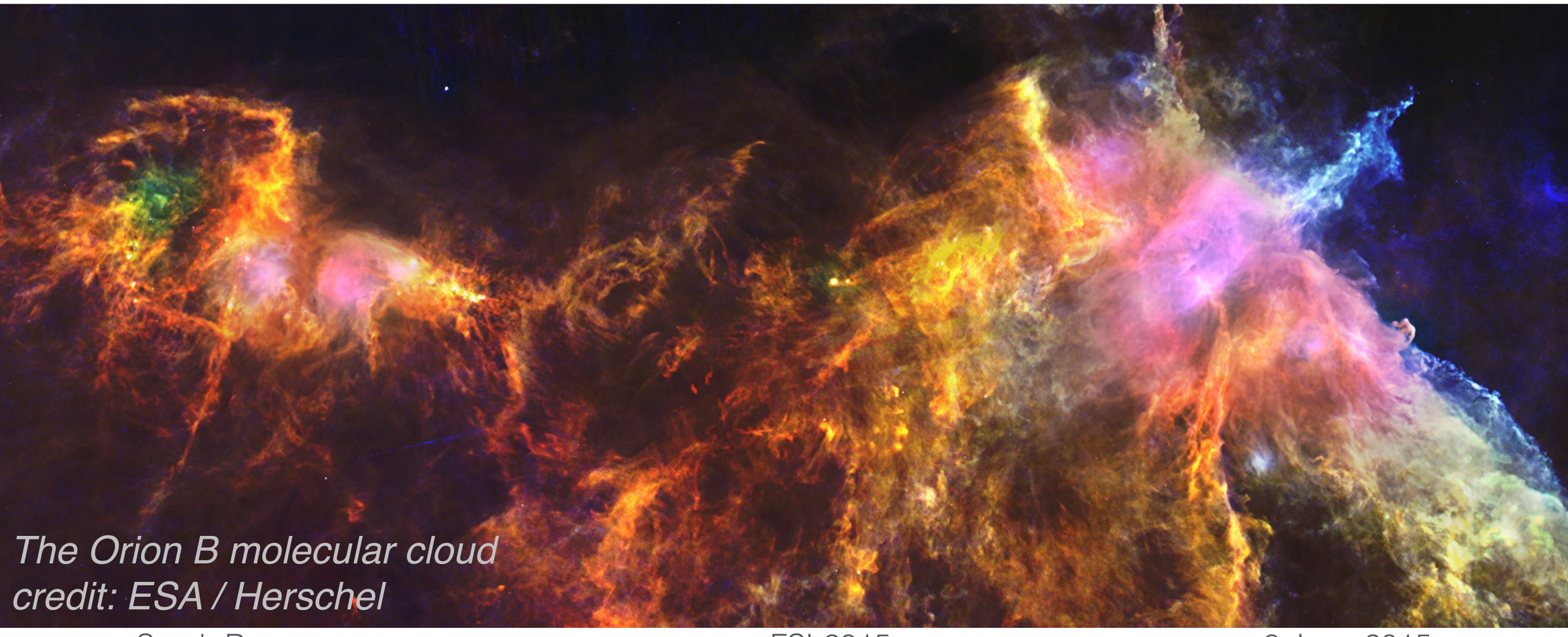
- GOT C^+ survey (Jorge Pineda's talk), [NII] survey (Paul Goldsmith's talk)
- Infrared-dark cloud survey (Henrik Beuther's talk)
- [CII] and [OI] in the Herbig AeBe and T Tauri stars, used to constrain n, T in $G_o \sim 10^3$-10^7 (DIGIT; Fedele+2013)
- *Herschel* observations [OI] as a tracer of dissociative shocks in inner envelopes of YSOs (WISH; Karska+2013)

SOFIA/GREAT

- Detailed studies of PDRs (Graf+2012, Okada+2012, Perez-Beaupuits+2012,2015)
- Circumnuclear disc (Requena-Torres+2012)
- **Dynamics of warm gas (Simon+2012, Schneider+2012)**

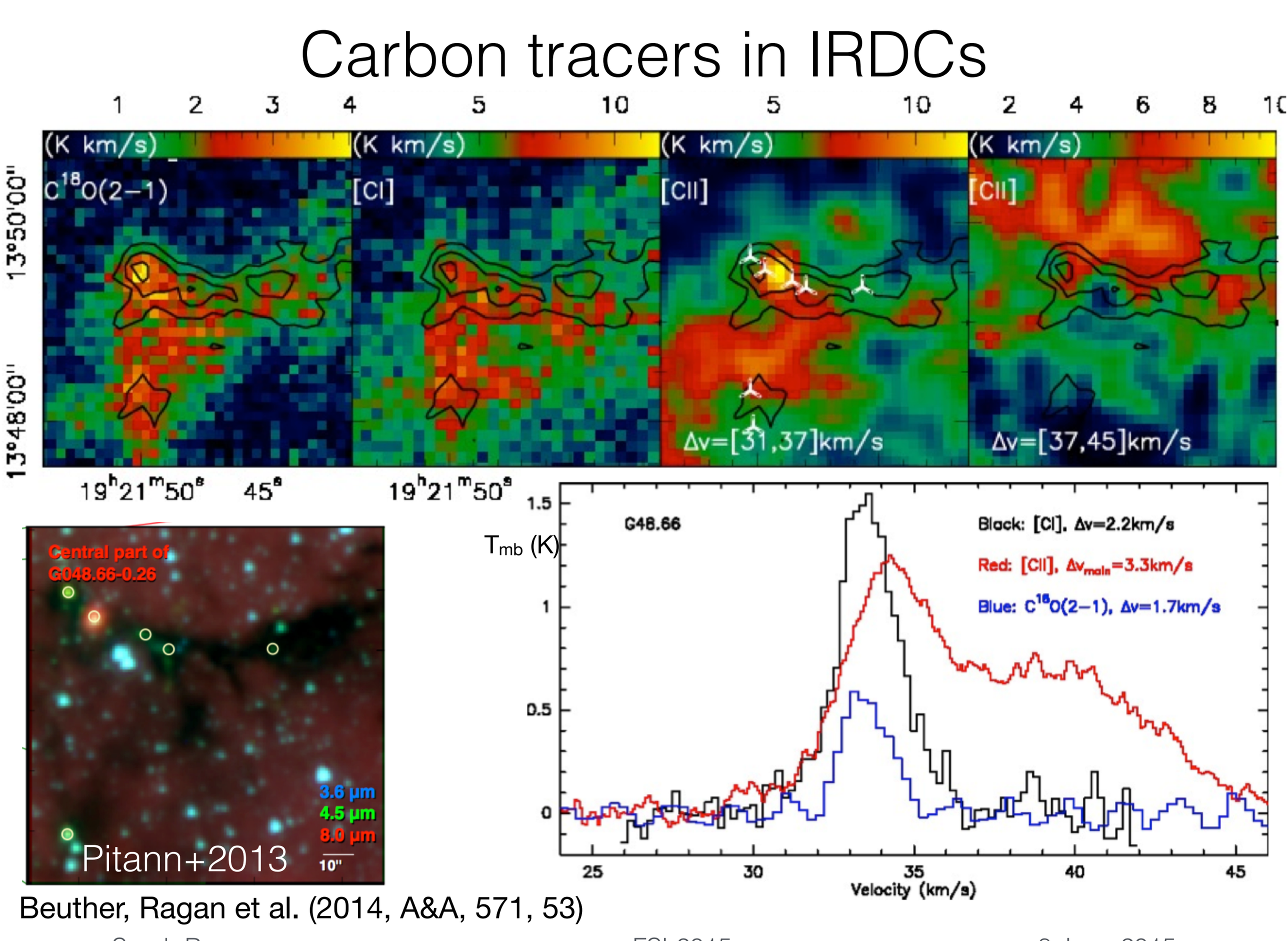
Lurking questions in galactic star formation research

- How do molecular clouds form?
- What is the effect of the environment on star formation?
- What is the temperature structure in regions of stellar feedback?



The Orion B molecular cloud
credit: ESA / Herschel

Carbon tracers in IRDCs



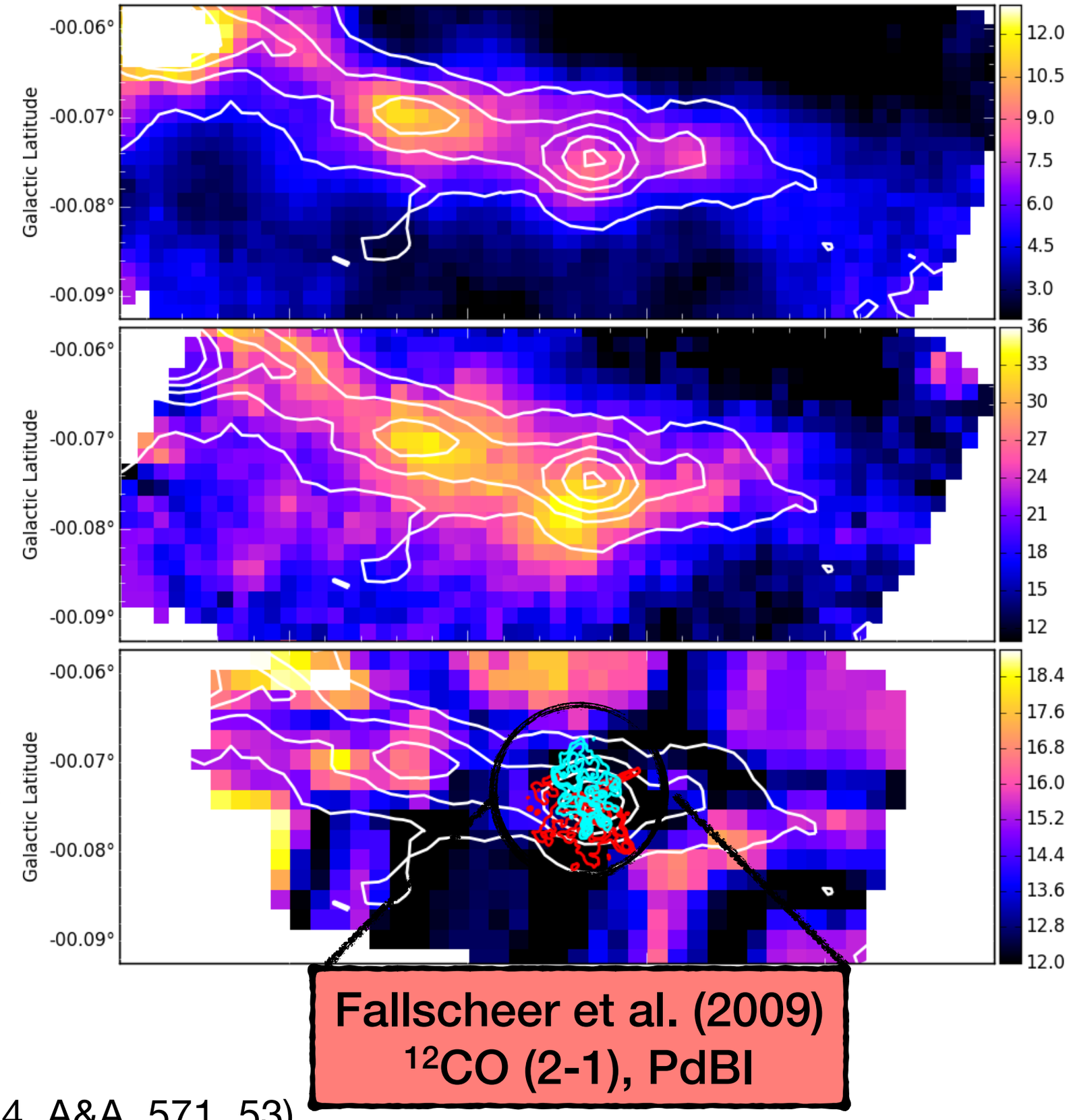
Beuther, Ragan et al. (2014, A&A, 571, 53)

Stellar feedback in IRDC18223

$C^{18}O$ (2-1)

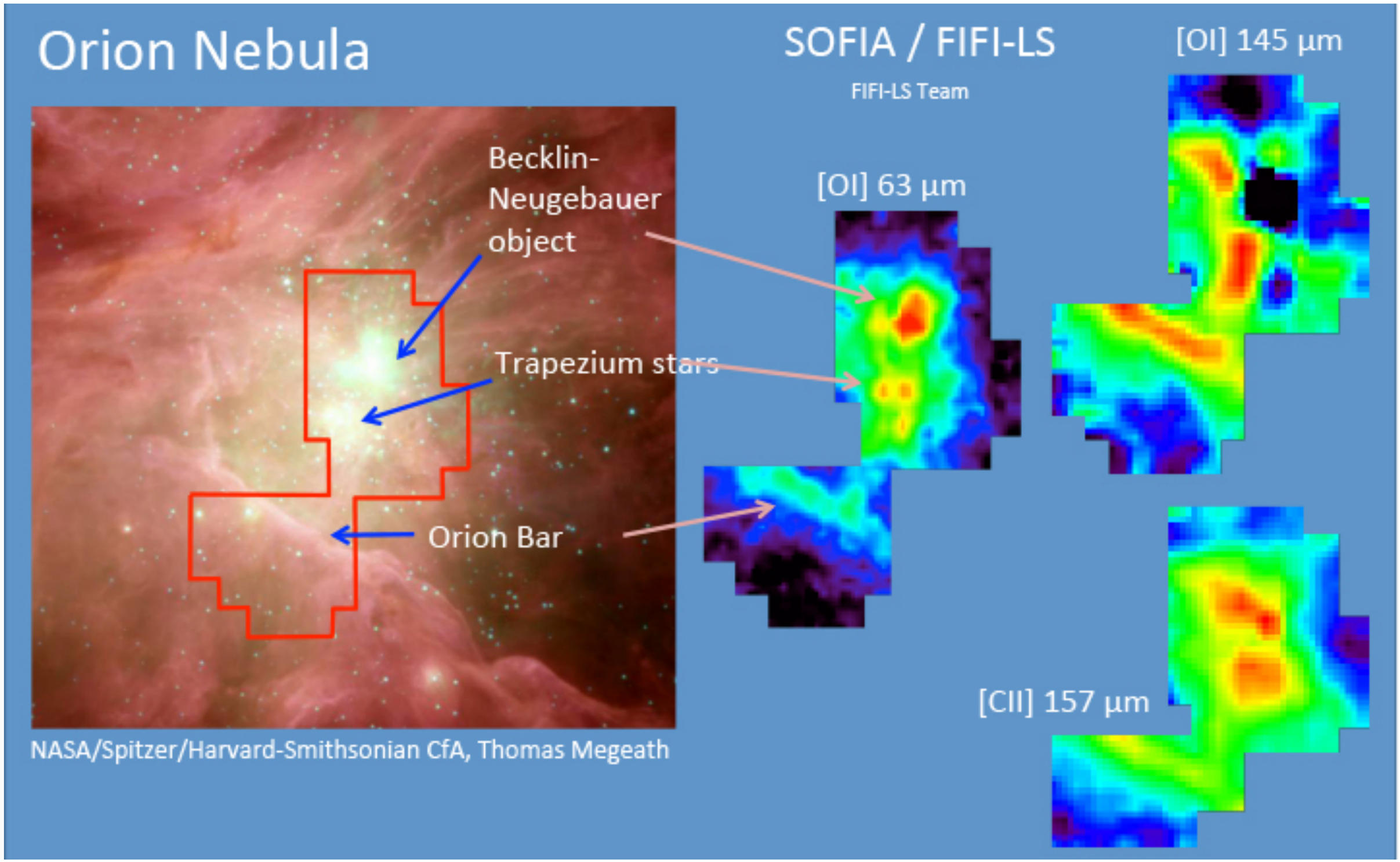
[CI] ($^3P_1$-$^3P_0$)

[CII] ($^2P_{3/2}$-$^2P_{1/2}$)



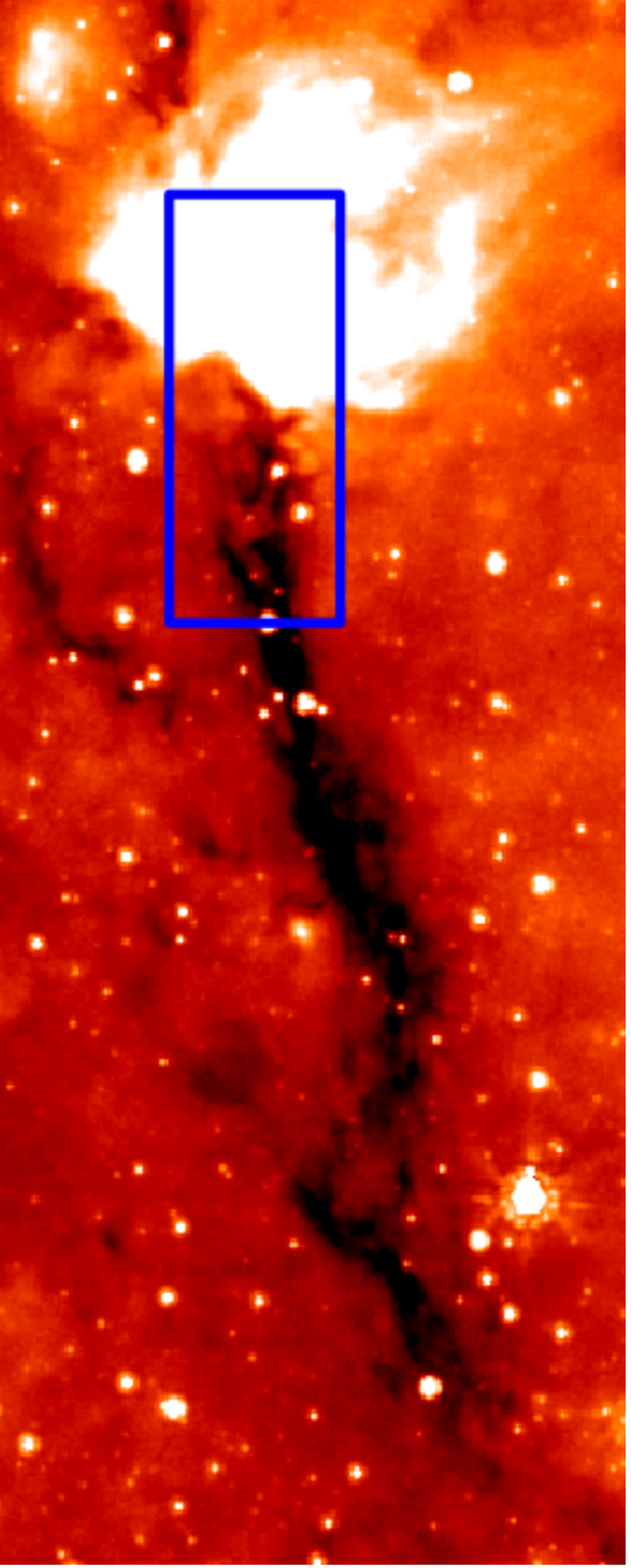
Beuther, Ragan et al. (2014, A&A, 571, 53)

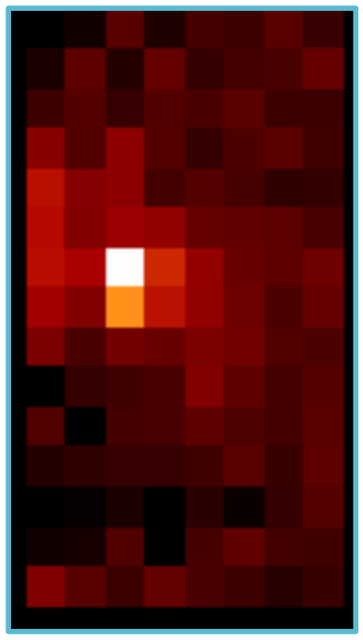
Commissioning of FIFI-LS



see Aaron Bryant's talk!

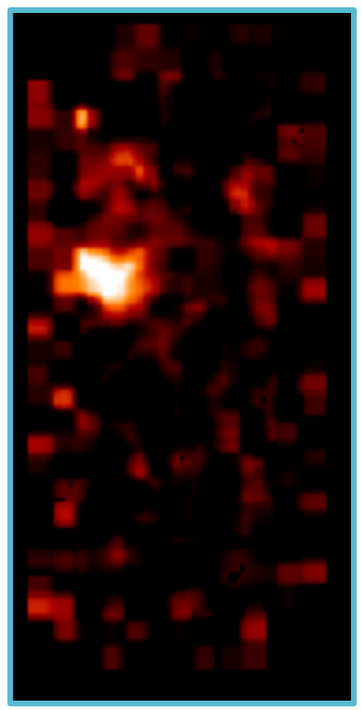
SOFIA/FIFI-LS view of IRDCs



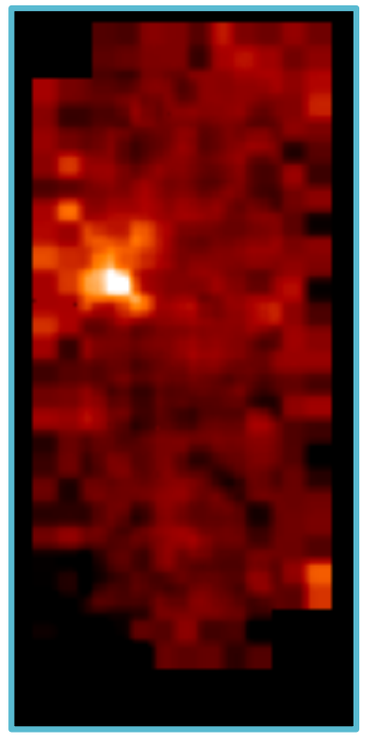


Red continuum

[CII] 157micron



Blue Continuum



[OI] 63 micron

Ragan et al. (in prep)

- FSLs aid in measuring the physical conditions in a wide range of environments
- Improved velocity resolution offered by new generation of instruments opens up new territory to study cloud formation and feedback processes

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credit: HST/WFPC2