High Spectral Resolution SOFIA/EXES observations of C_2H_2 towards Orion IRc2

7 February 2018

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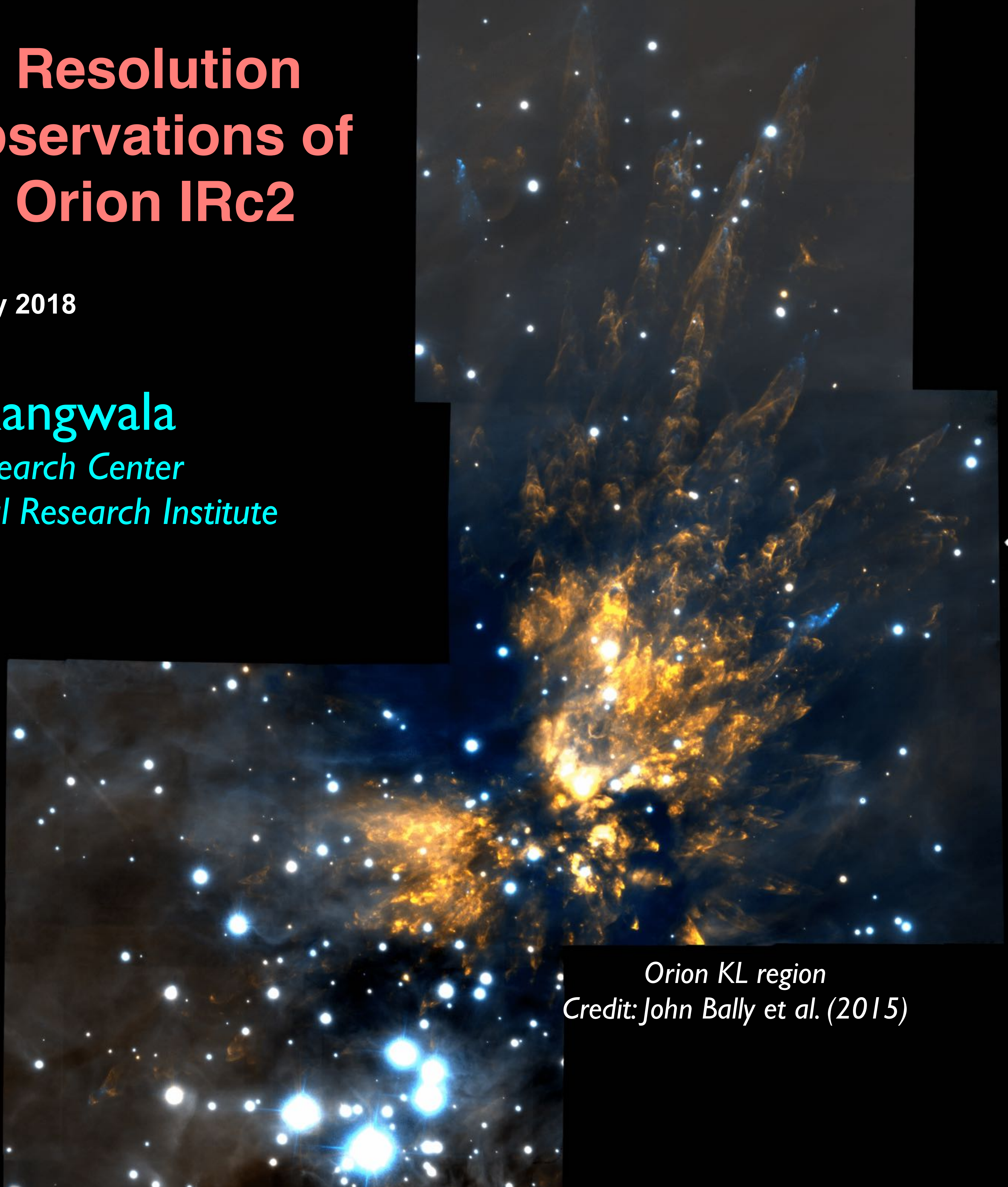
NASA Ames Research Center

Bay Area Environmental Research Institute



Orion KL region
Credit: John Bally et al. (2015)

Collaborators

Xinchuan Huang (NASA Ames/SETI)
Sean Colgan (NASA Ames)
Kinsuk Acharyya (PRL, India)
Romane Le Gal (University of Virginia)
Timothy J. Lee (NASA Ames)
Eric Herbst (University of Virginia)
Lou Allamandola (NASA Ames)
SOFIA/EXES Instrument Team
(Matt Richter, Curtis De Witt,
Adwin Boogert, Mark McKelvey)

My Background

- Univ. of Colorado - Boulder (2010 - 2017)

  Herschel to measure CO in nearby galaxies (ULIRGs (ARP 220) and Starbursts (M82))

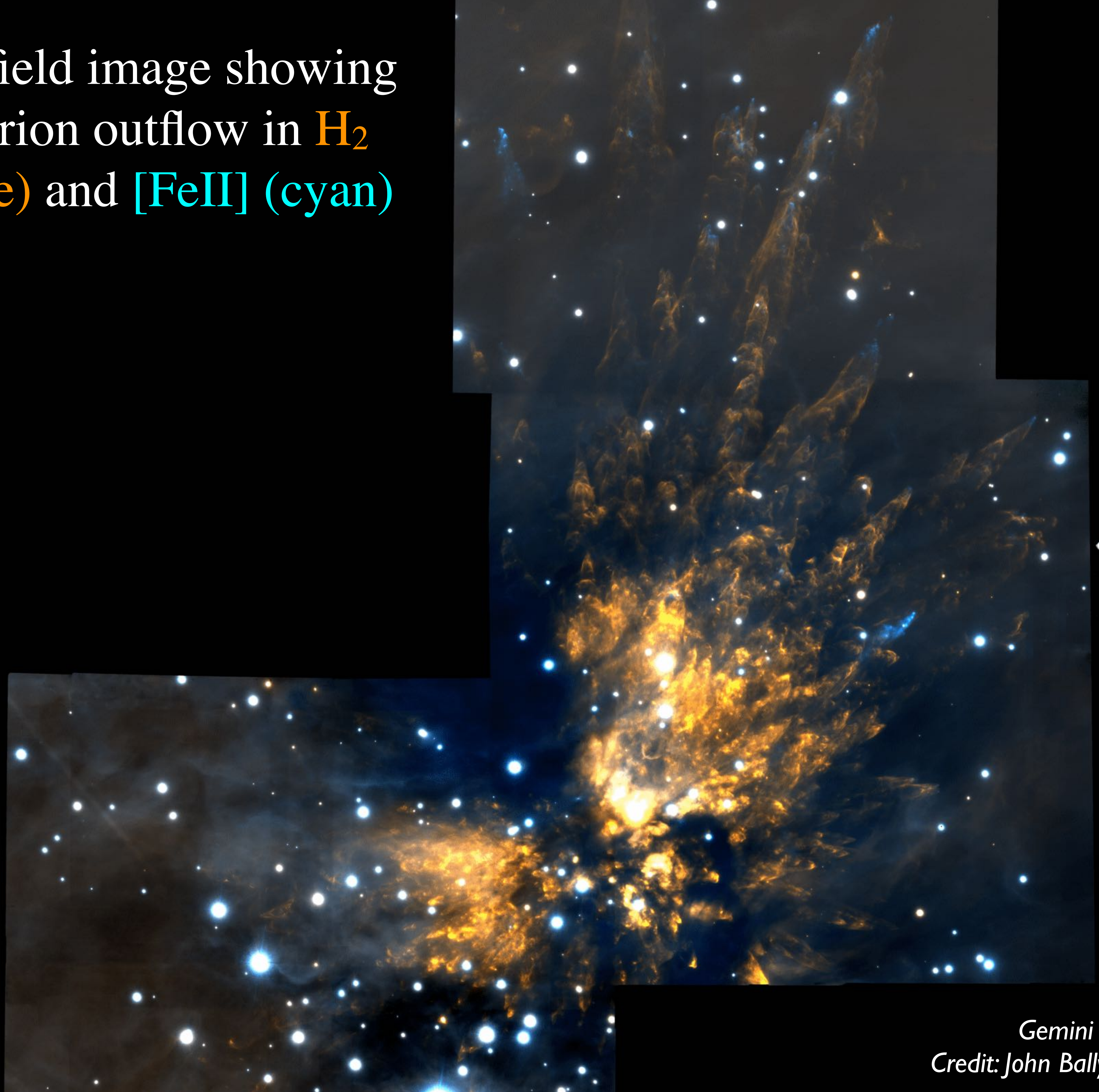
- Univ. of Colorado - Boulder (2013 - present)

  ALMA CO maps of nearby galaxies

- NASA Ames (2015 - present)

  Astrochemistry using ALMA, Herschel and SOFIA (soon JWST) - Galactic sources

Wide-field image showing the Orion outflow in H_2 (orange) and [FeII] (cyan)



Gemini South
Credit: John Bally et al. (2015)

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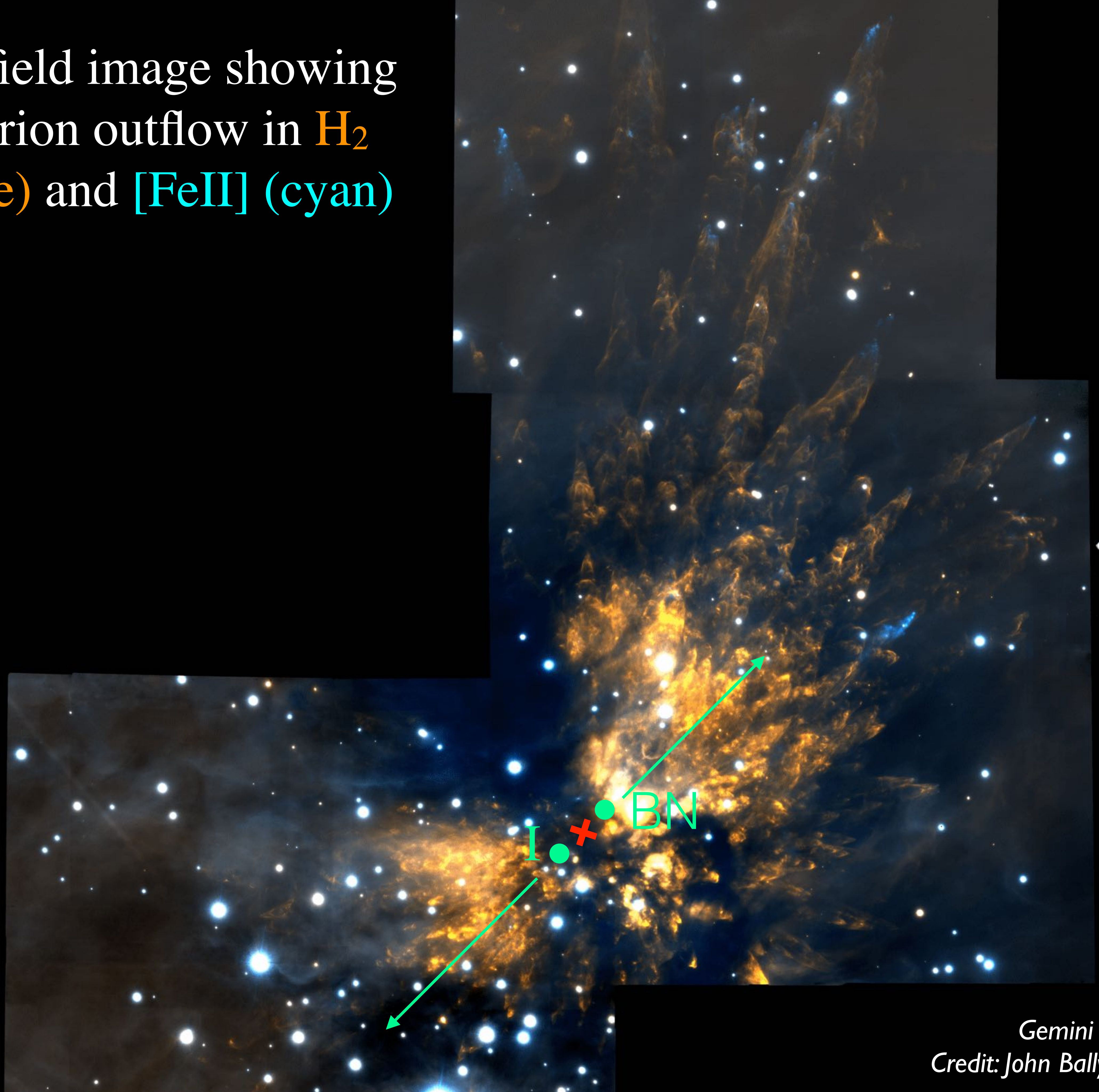

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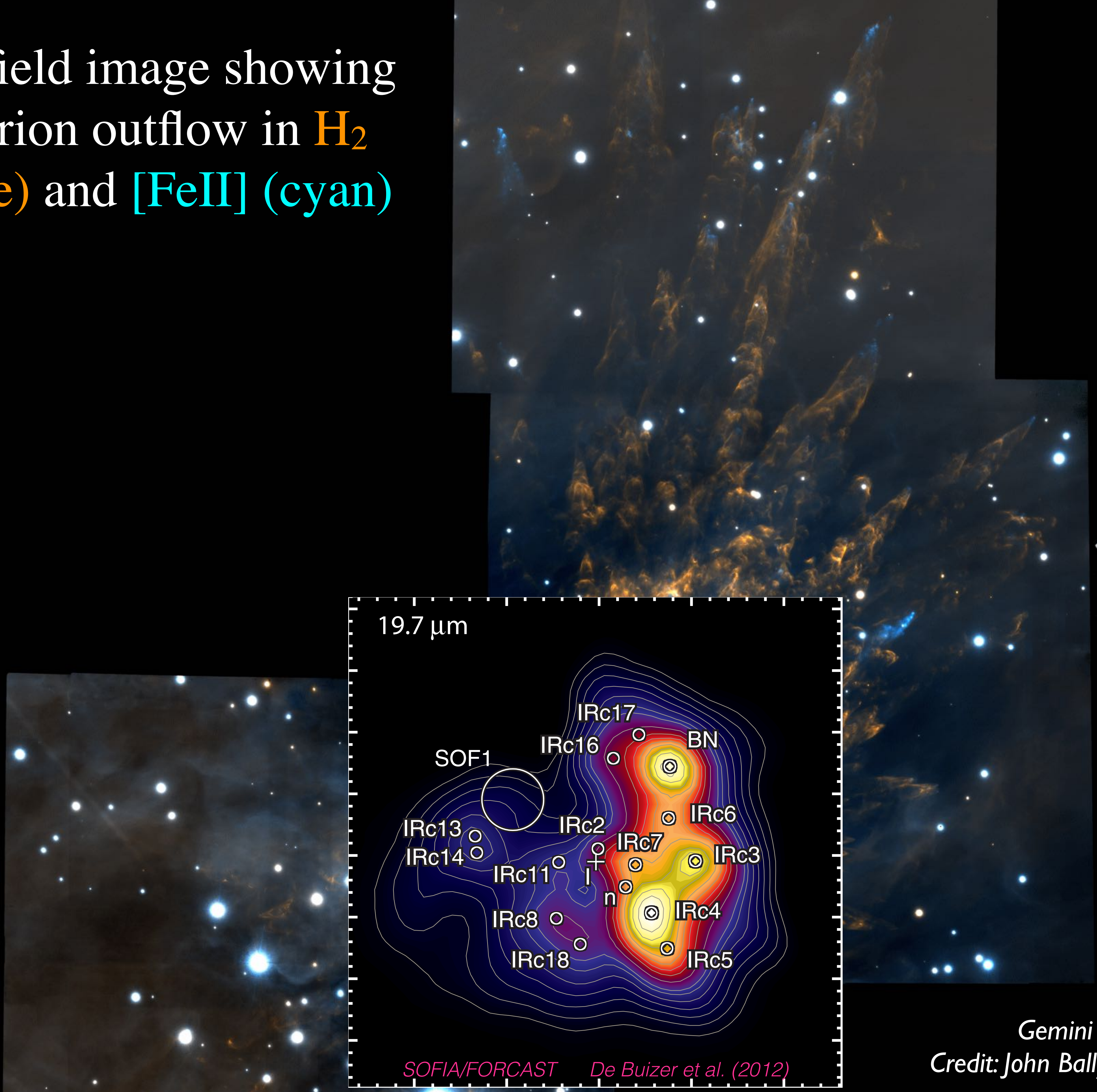

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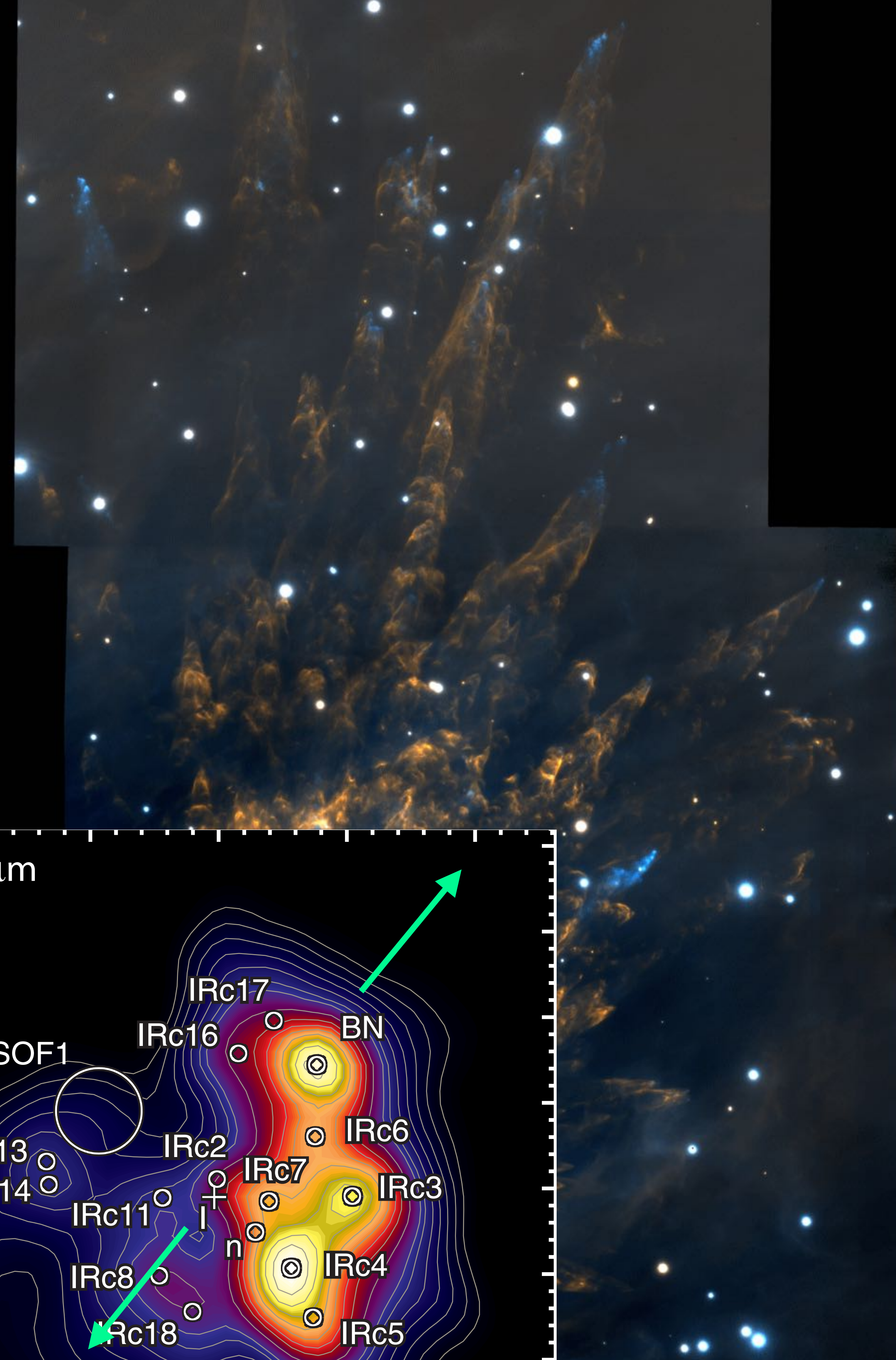

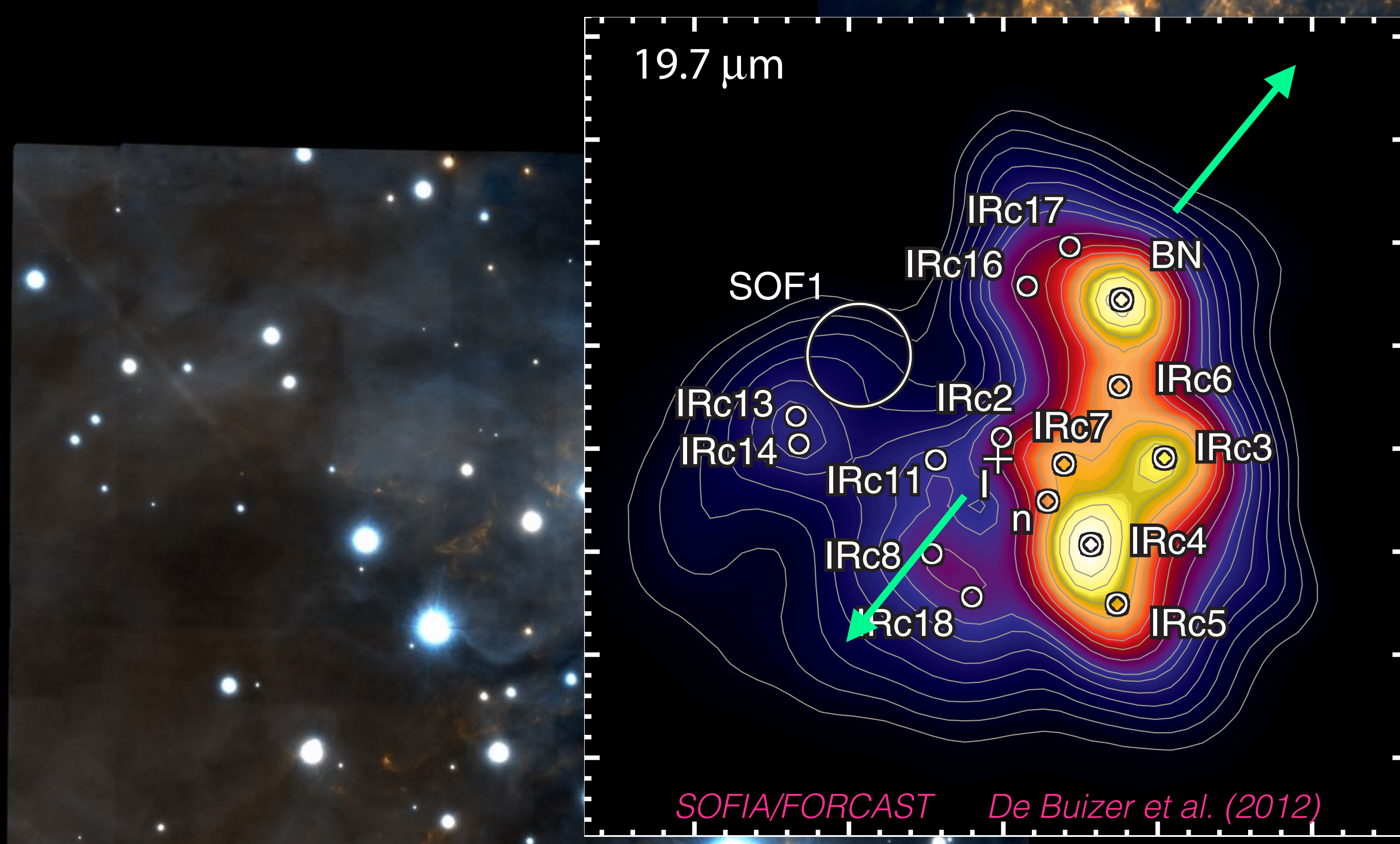

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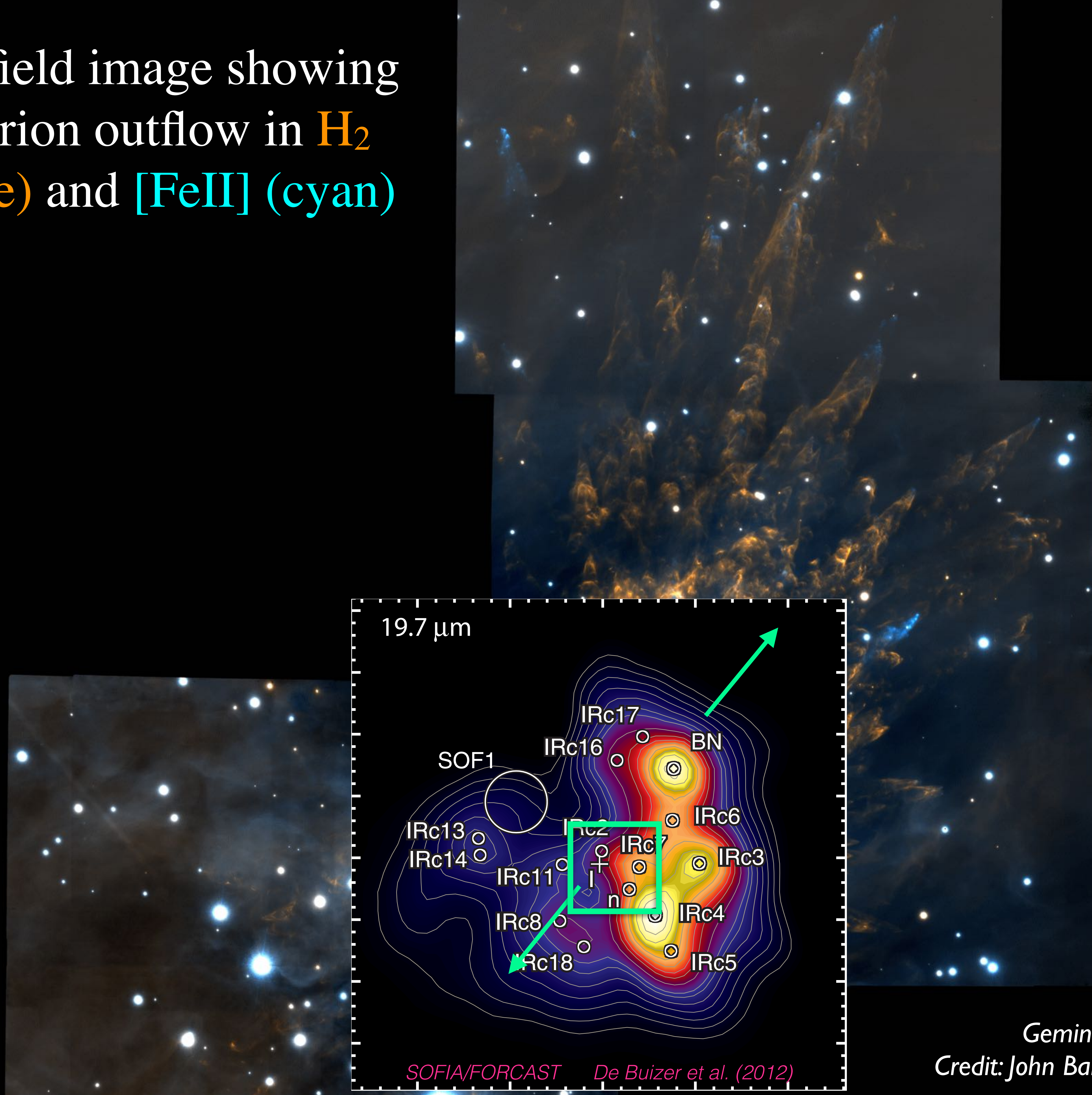

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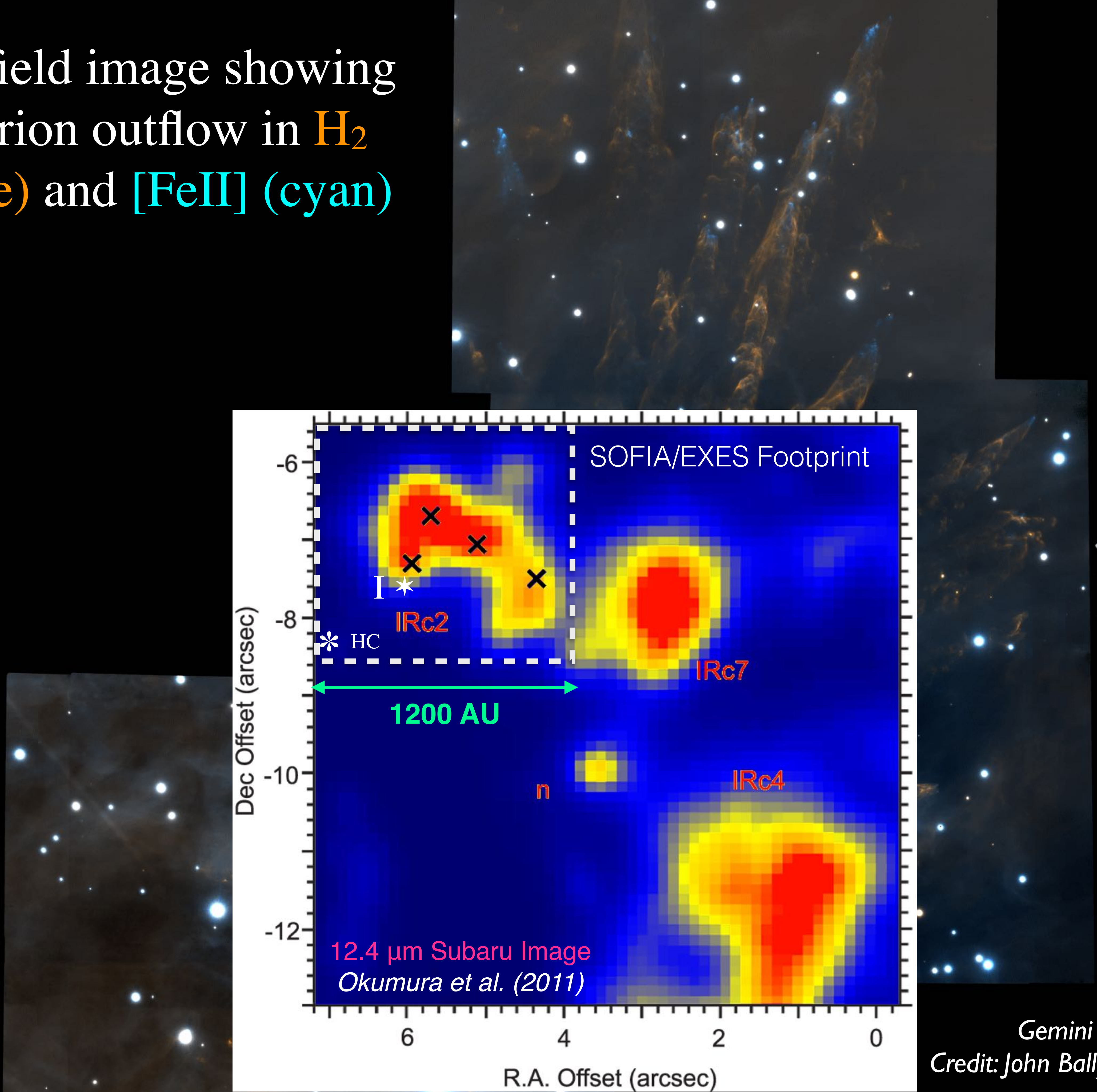
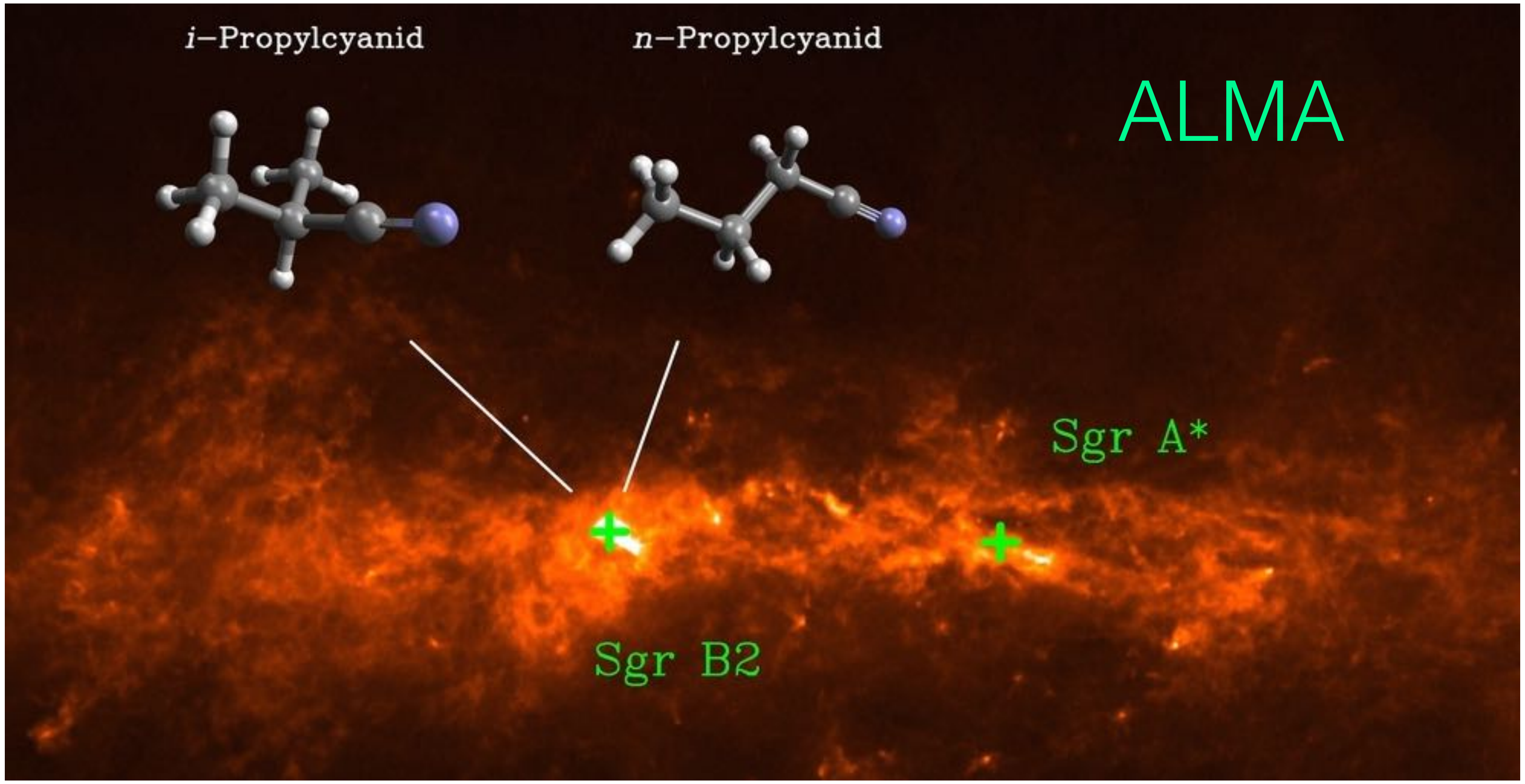


Gemini South
Credit: John Bally et al. (2015)

Characteristics of Hot Cores

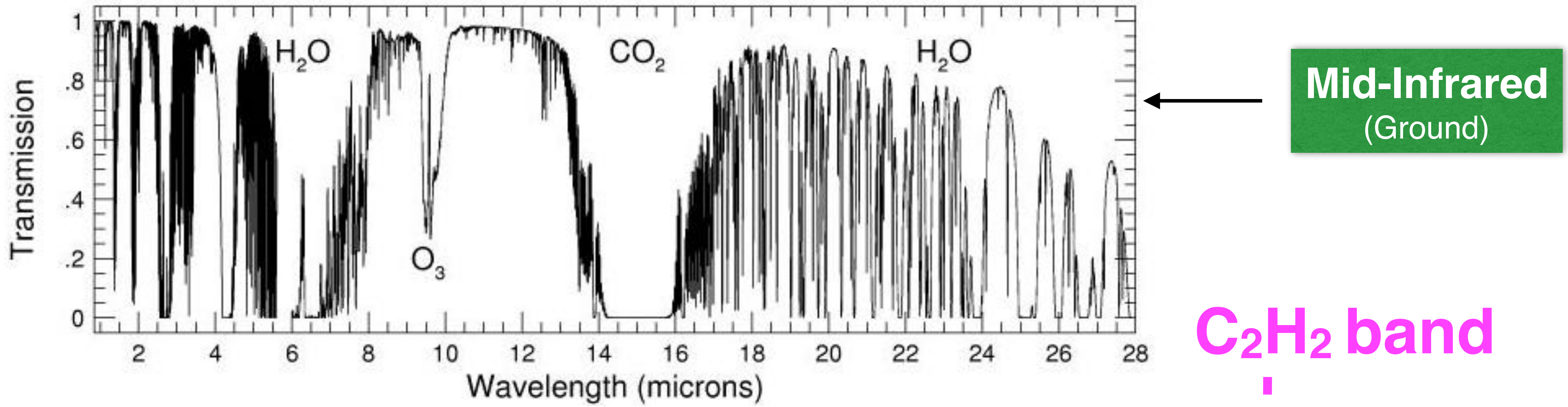
- Warm (100 - 300 K), dense (10^6 - 10^8 cm^{-3}), compact (up to 0.05 pc) regions around massive young stellar objects or protostars.
- Typically heated internally by the protostellar radiation; some by shocks
- Primary sites for the formation and evolution of complex organic molecules in space ——> Prebiotic molecules involved in the processes leading to the origin of life.
- Probes of physical conditions and chemistry associated with high mass star formation.
- Orion hot core is thought to be externally heated by shocks generated from the explosive event 500 yrs ago.



Outline

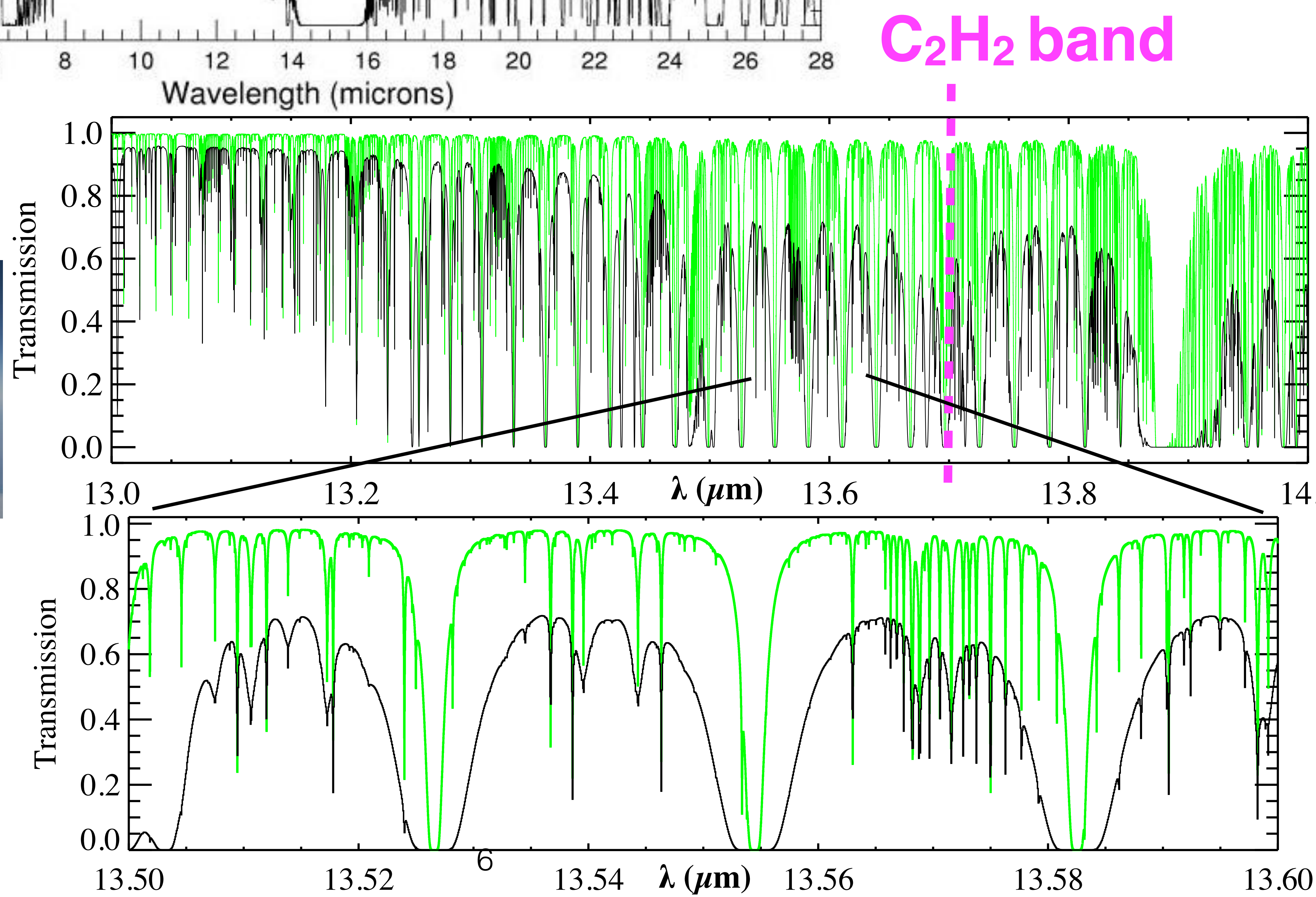
- SOFIA/EXES (Cycle-3) observations of Orion IRc2
    - Primary goal: to search for c-$C_3H_3^+$
    - high spectral resolution ~4.5 km/s
    - **12.96 - 13.33 μm** or 750 - 772 cm^{-1}
    - present first high spectral resolution acetylene (C_2H_2) observations towards the Orion hot core
- Orion hot core line survey in MIR (80 hours) with SOFIA/EXES and IRTF/TEXES (**8 - 28.3 μm)** - ongoing

Atmospheric Transmission at 13 μm



43,000 ft
(SOFIA)

14,000 ft
(Mauna Kea)



Importance of C_2H_2 in interstellar chemistry

- Acetylene (C_2H_2) is thought to play a major role in interstellar chemistry

- Common precursor in the formation of larger hydrocarbons, ring molecules and PAHs

$$C^+ + C_2H_2 \rightarrow C_3H^+ + H$$
$$C_3H^+ + H_2 \rightarrow C_3H_3^+ + h\nu$$
$$C_3H_3^+ + e^- \rightarrow C_3H_2 + H$$

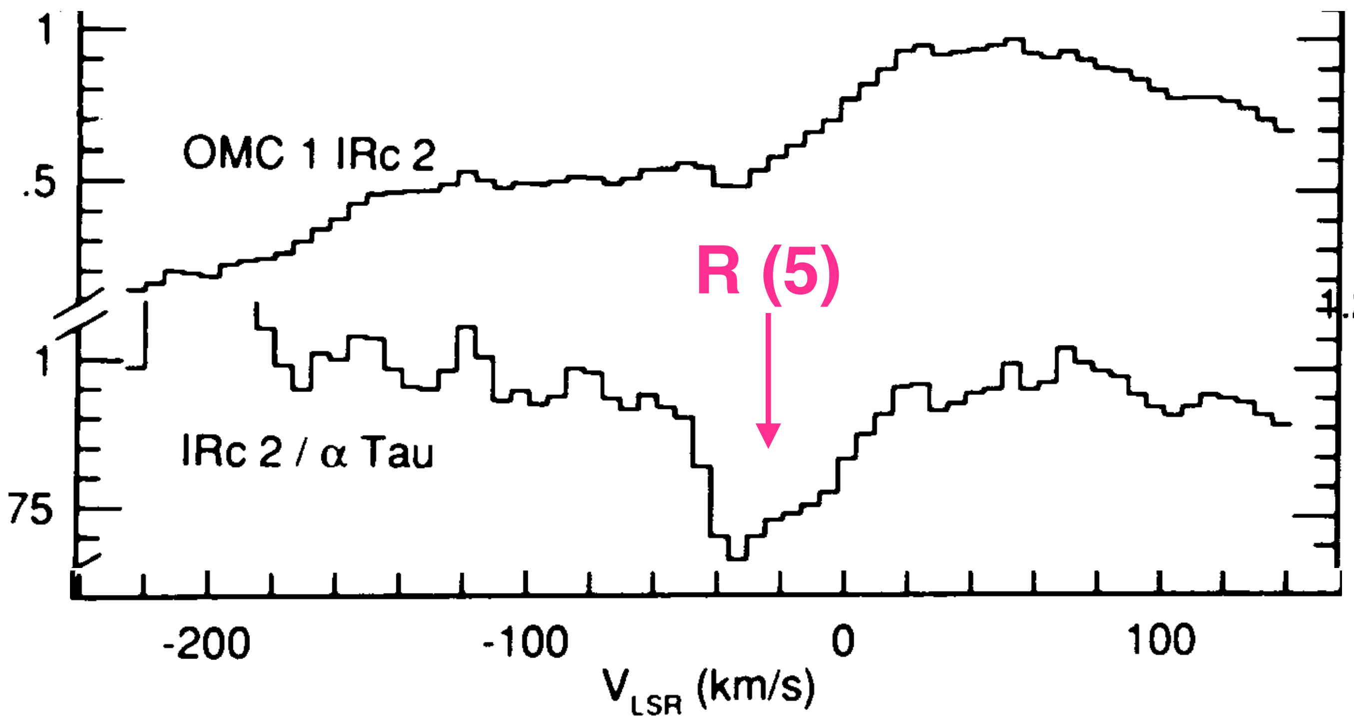
- Important in the formation of Nitriles (Cyanopolyynes) in the ISM/hot cores

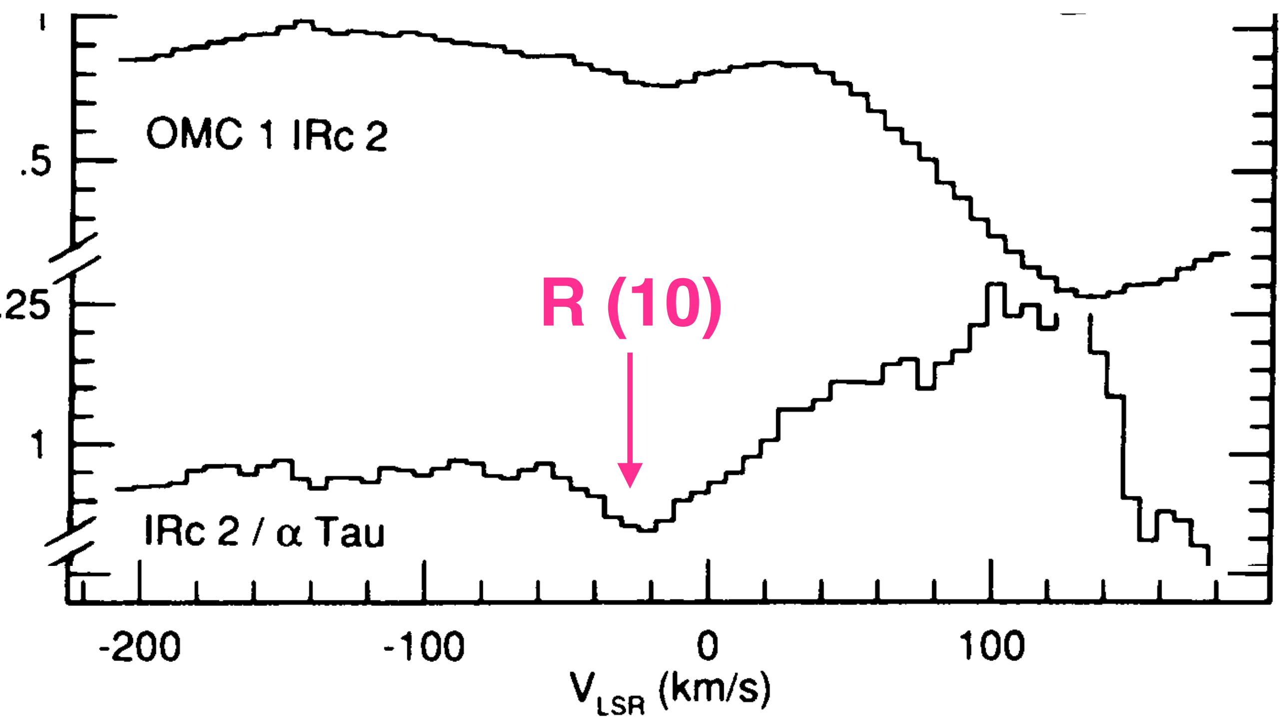
$$C_2H_2 + CN \rightarrow HC_3N + H$$

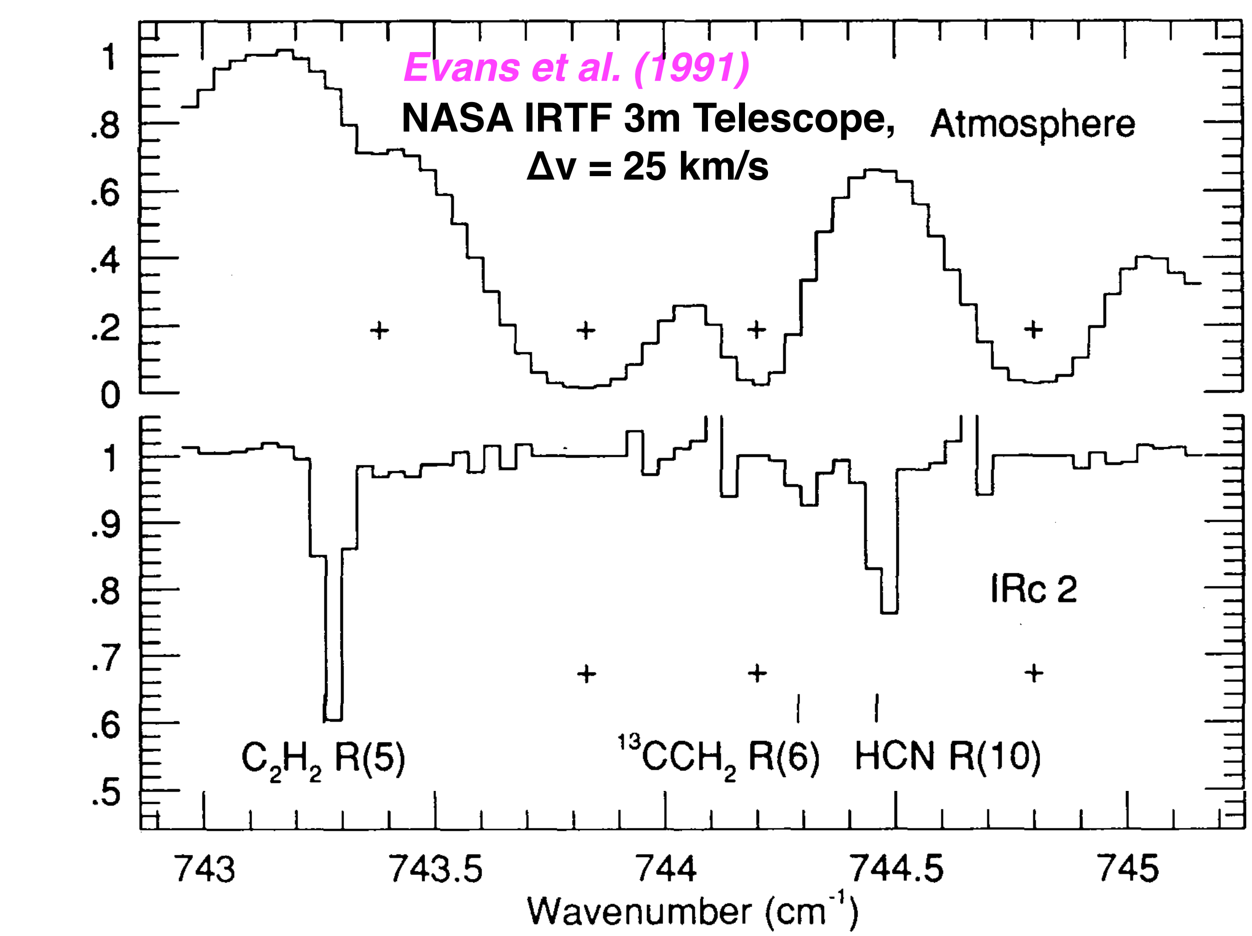
- C_2H_2 has no dipole moment, hence studied primarily via rovibrational transitions in the Mid-IR; strongest band ~13.7 μm

Previous Ground Observations

NASA IRTF 3m Telescope, R = 15000, Δv = 20 km/s *Lacy et al. (1989)*

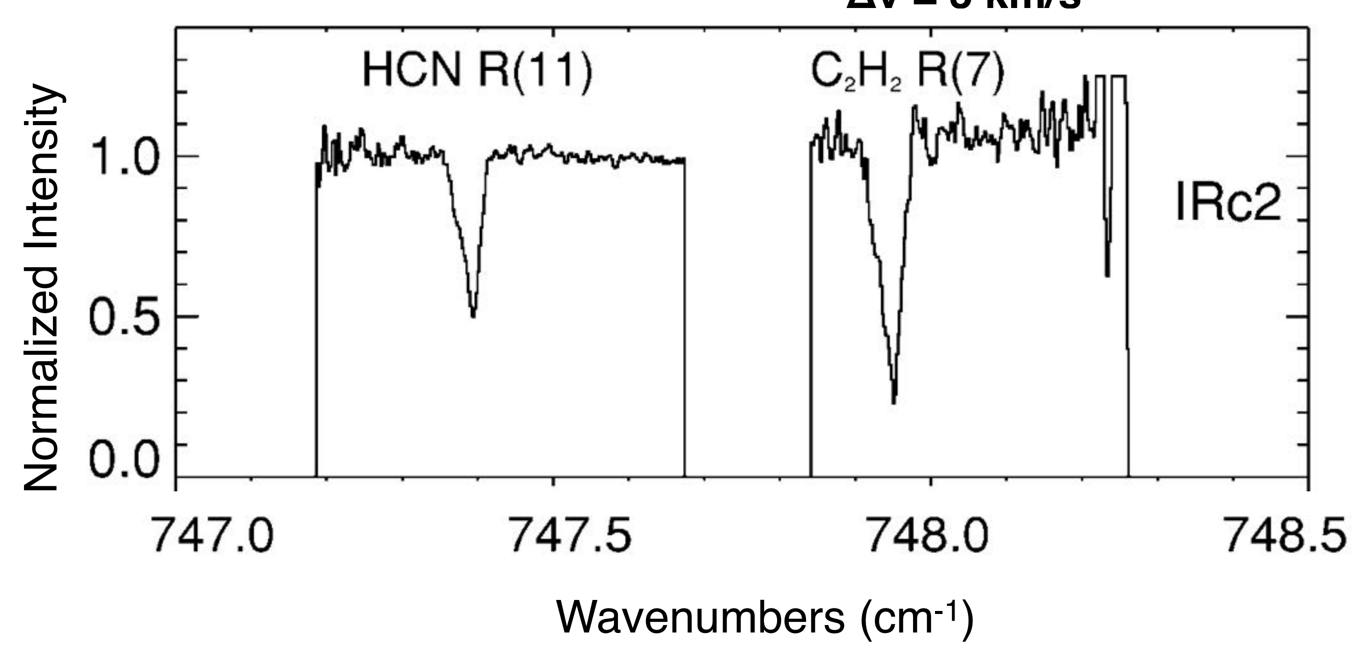




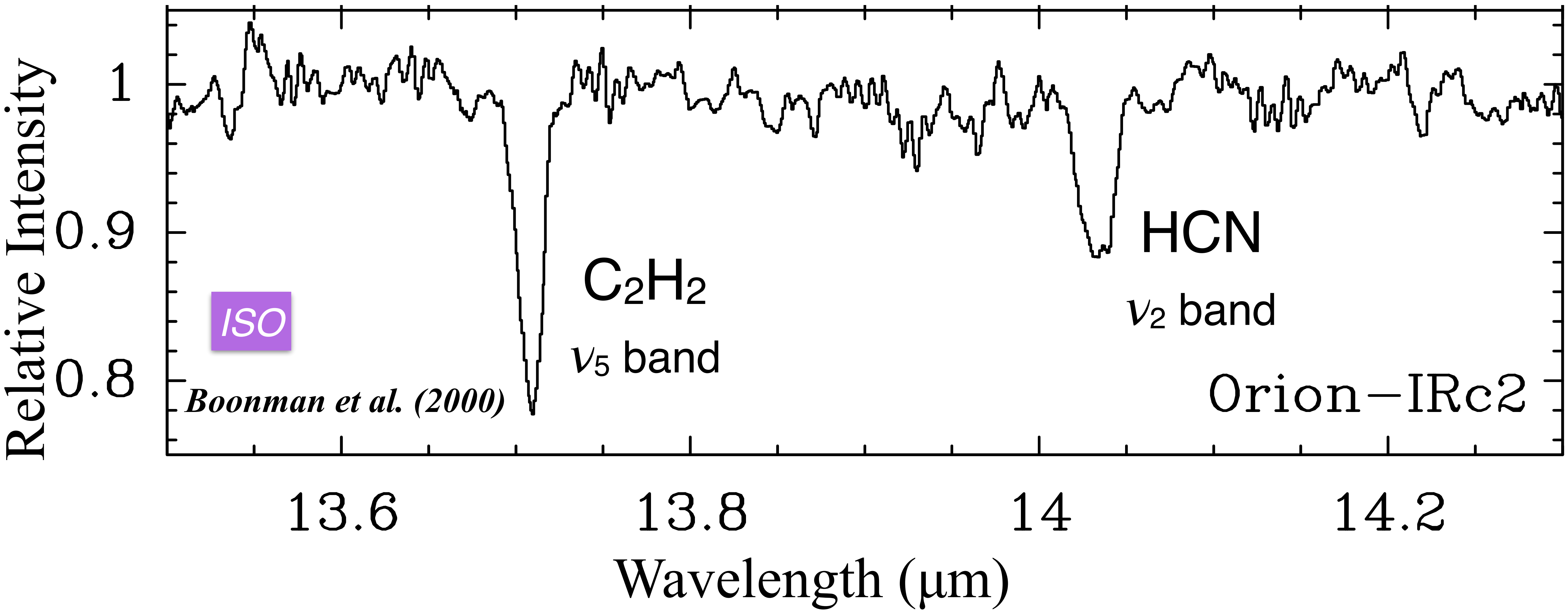


Lacy et al. (2002)

TEXES on NASA IRTF
Δv = 3 km/s

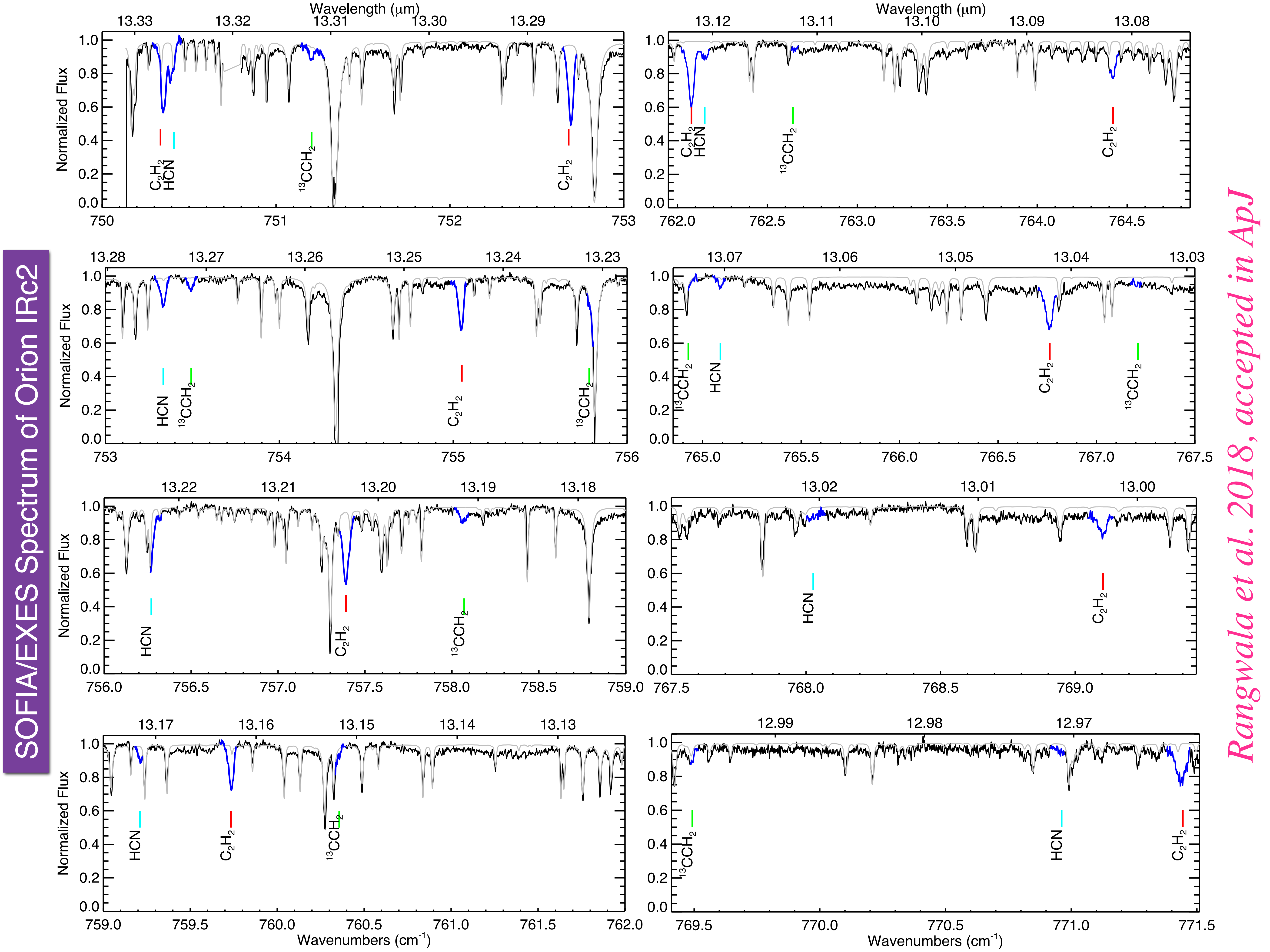


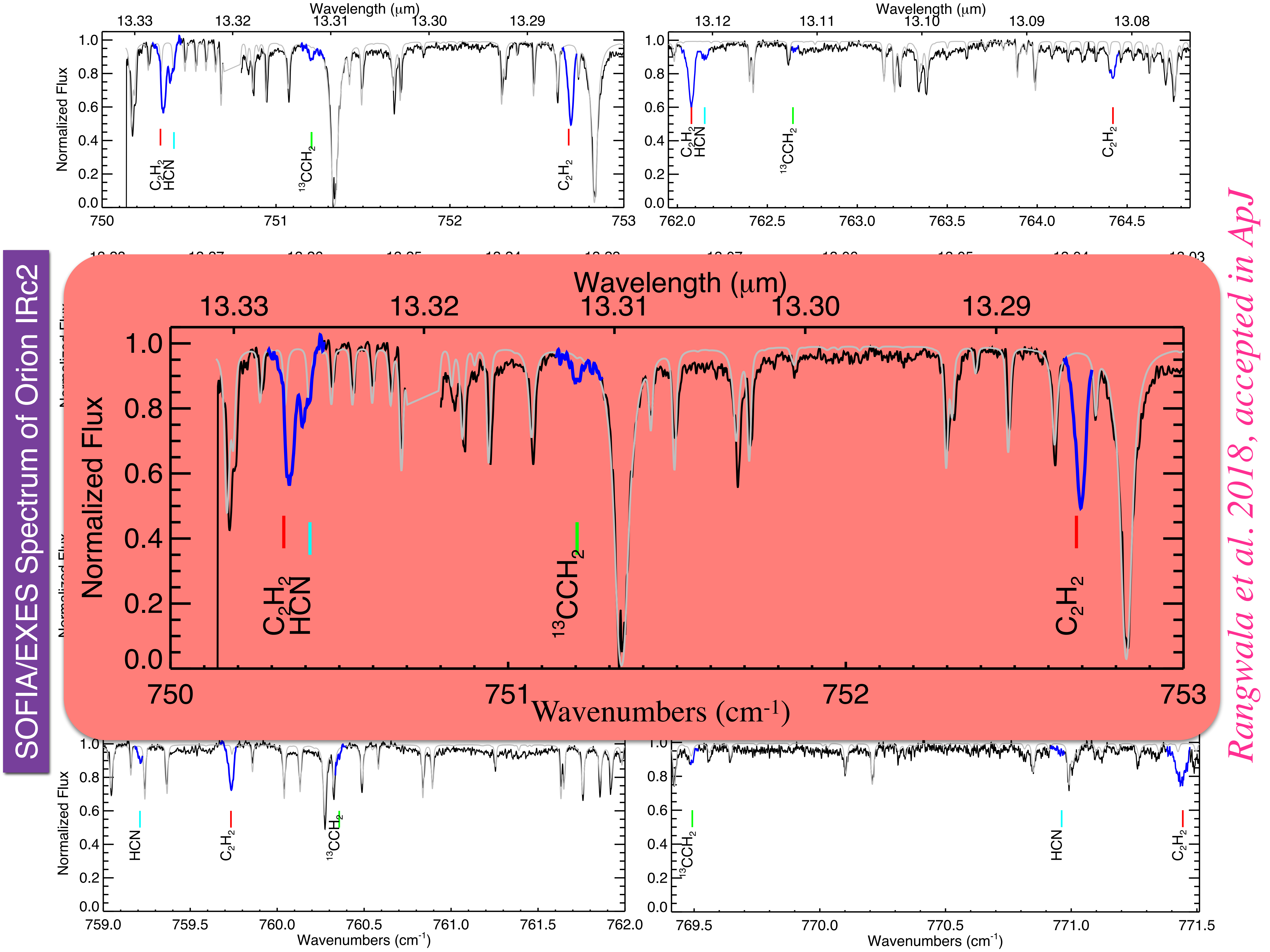
Previous Observations from Space



ISO: low spectral resolution; cannot detect the individual rovibrational transitions

JWST: Exceptional sensitivity but low-medium spectral resolution


SOFIA/EXES Spectrum of Orion IRc2
Rangwala et al. 2018, accepted in ApJ
Wavelength (μm)
Normalized Flux
Wavenumbers (cm^{-1})
C_2H_2
HCN
$^{13}CCH_2$


SOFIA/EXES Spectrum of Orion IRc2
Rangwala et al. 2018, accepted in ApJ
Wavelength (μm)
13.33
13.32
13.31
13.30
13.29
Normalized Flux
1.0
0.8
0.6
0.4
0.2
0.0
750
751
752
753
Wavenumbers (cm-1)
C2H2
HCN
13CCH2
13.12
13.11
13.10
13.09
13.08
762.0
762.5
763.0
763.5
764.0
764.5
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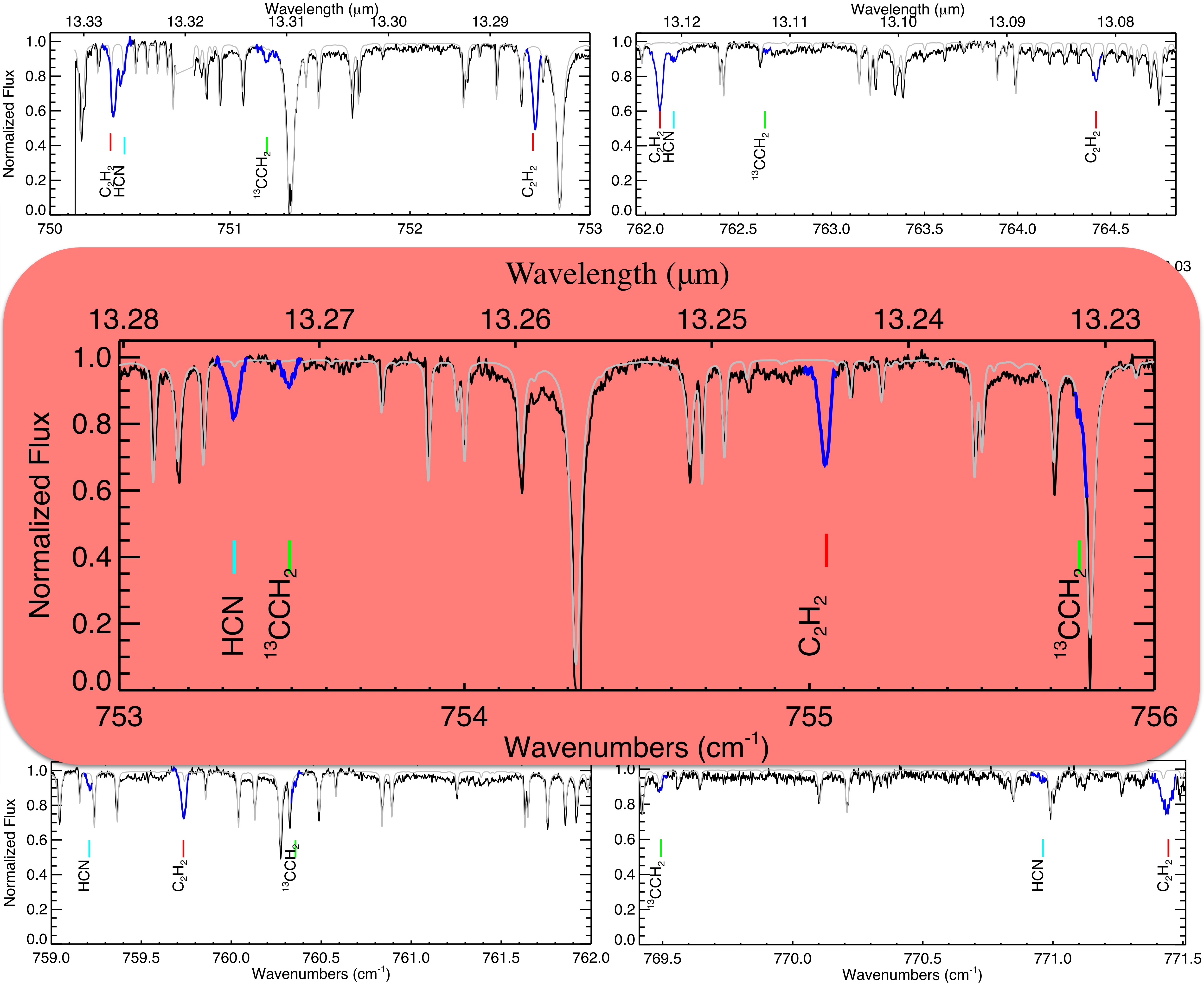

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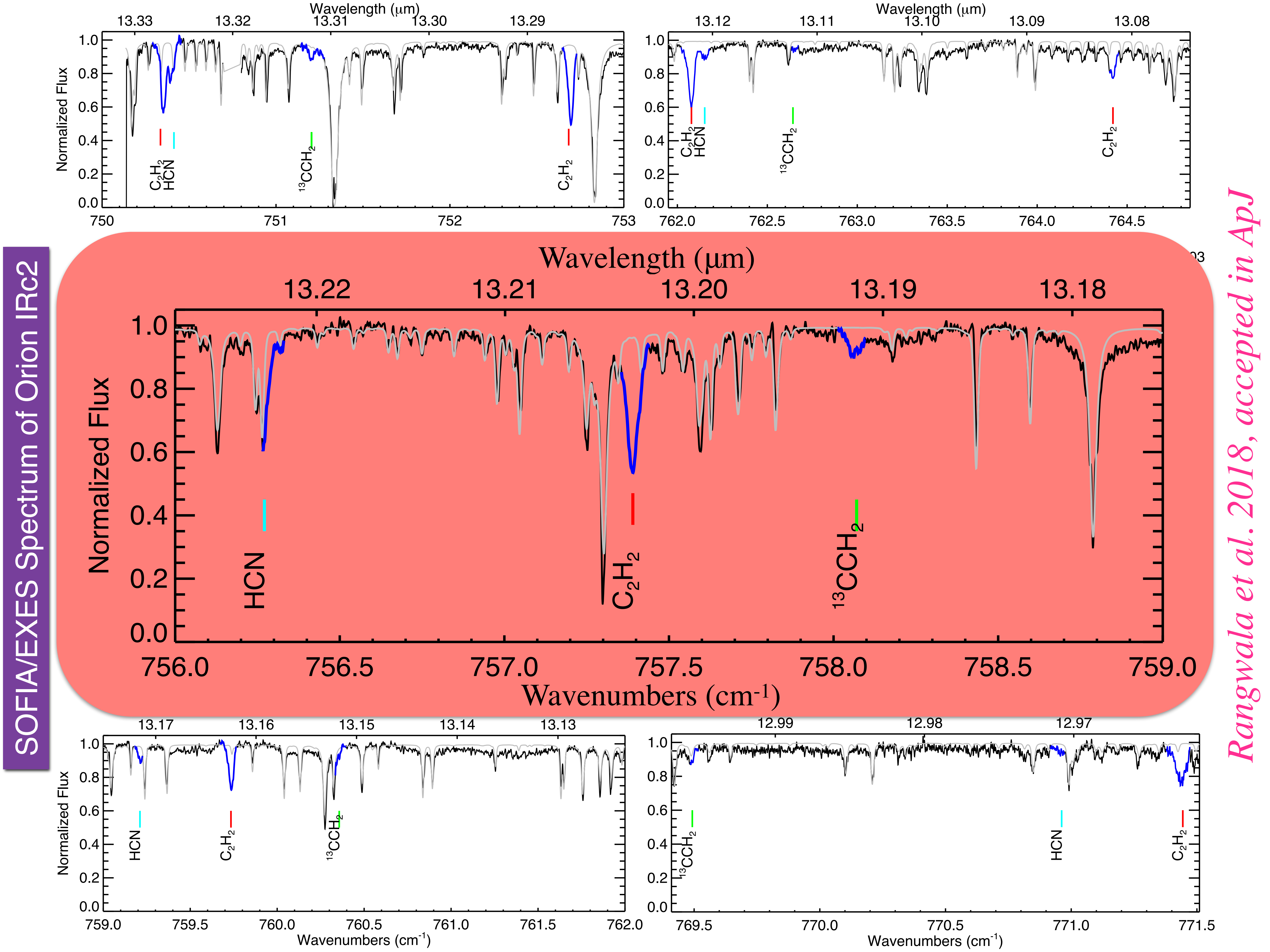


SOFIA/EXES Spectrum of Orion IRc2
Rangwala et al. 2018, accepted in ApJ
Wavelength (μm)
Wavenumbers (cm-1)
Normalized Flux
HCN
C2H2
13CCH2

Detections

Between 12.96 - 13.33 μm (20 wavenumbers) we detected

C_2H_2 - 10 R-branch lines (continuous coverage from J = 9 - 8 to J = 18 - 17; high S/N)

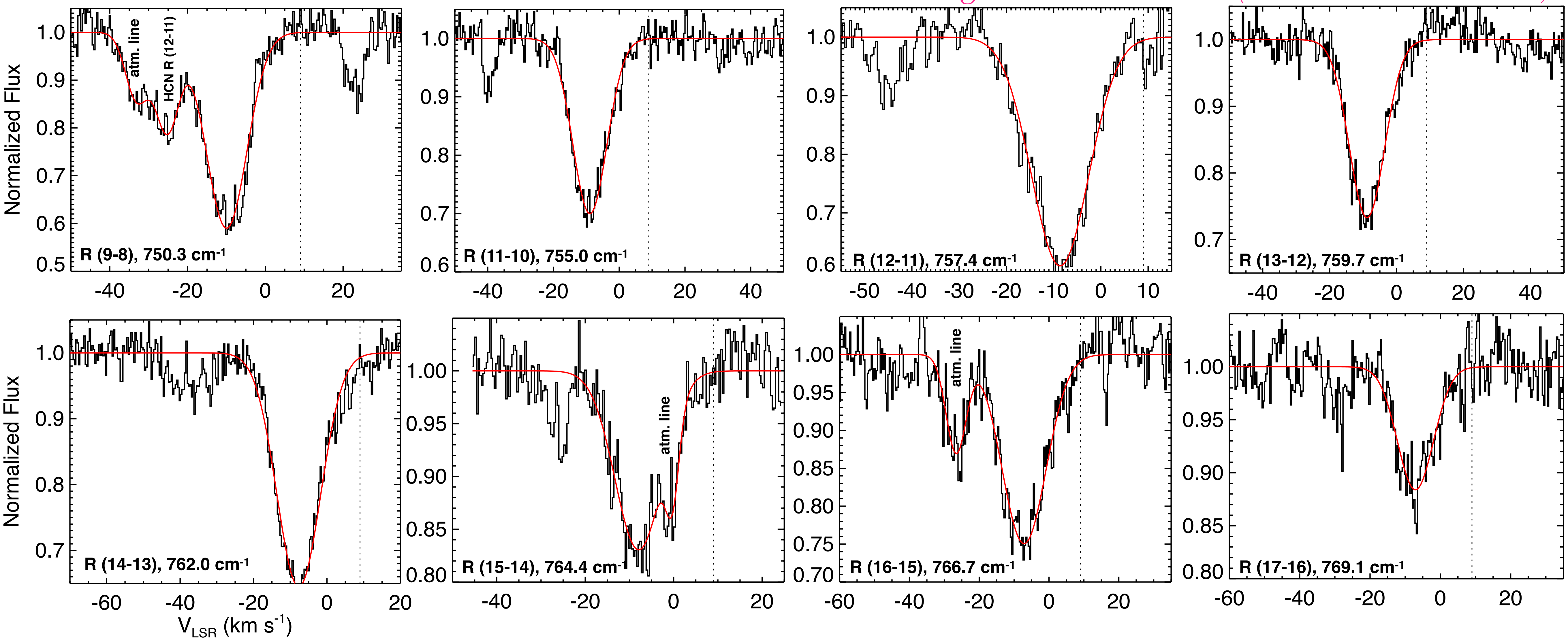
- 5 Para Transitions
- 5 Ortho Transitions

$^{13}C^{12}CH_2$ - 3 Transitions + Upper Limits

HCN - 7 Transitions + 1 Upper Limit

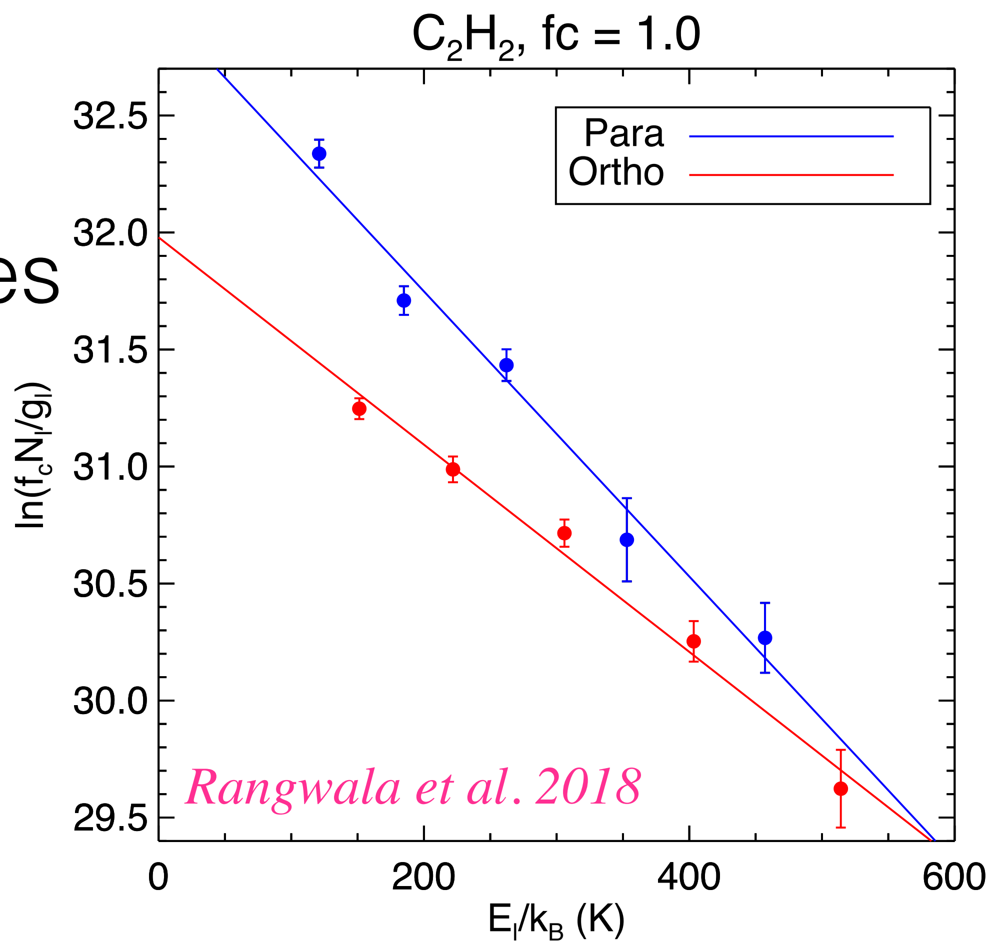
Results: C_2H_2 and HCN are in the outflow

Rangwala et al. 2018 (arXiv: 1709.04084)



- Observed V_{LSR} are significantly blue-shifted relative to the ambient cloud velocity.
- Both EXES & TEXES (J. Lacy; private comm.) measure same V_{LSR}.
- Absorption is 18 km/s blueward of the molecular cloud - consistent with the molecular outflow originating in the vicinity of source I.

Results: C_2H_2 ortho to para ratio



- Detect both Ortho (O) and Para (P) species
- Line of sight velocity difference:
  V_{LSR} (O) - V_{LSR} (P) = 1.8 ± 0.2 km/s
- Line width difference:
  V_{FWHM} (O) - V_{FWHM} (P) = 0.7 ± 0.2 km/s
- Ortho and Para C_2H_2 trace different temperatures: T(P) = 164 K and T(O) = 226 K
- Non-equilibrium O/P ratio (OPR) = 1.7 ± 0.1
- $^{12}C/^{13}C \lesssim 21$ (average $^{12}C/^{13}C \sim 45 \pm 20$ in the Orion KL region; *Tercero et al. 2010*)

$$ln(\frac{N_l}{g_l}) = ln(\frac{N_T}{Q}) - \frac{E_l}{k}(\frac{1}{T_{ex}})$$

Y — Intercept — X — Slope

Non-equilibrium OPR

- Both NH_3 and C_2H_2 have non-equilibrium OPRs

C_2H_2

- Low OPR (*Rangwala et al. 2018*)

NH_3 *(Goddi et al. 2011)*

- Enhancement of ortho with respect to para in the Orion hot core
- offset of hot NH_3 emission peaks from known (proto)stellar sources.
- the NH_3 molecules have been released from dust grains into the gas phase through the passage of shocks and not by stellar radiation.

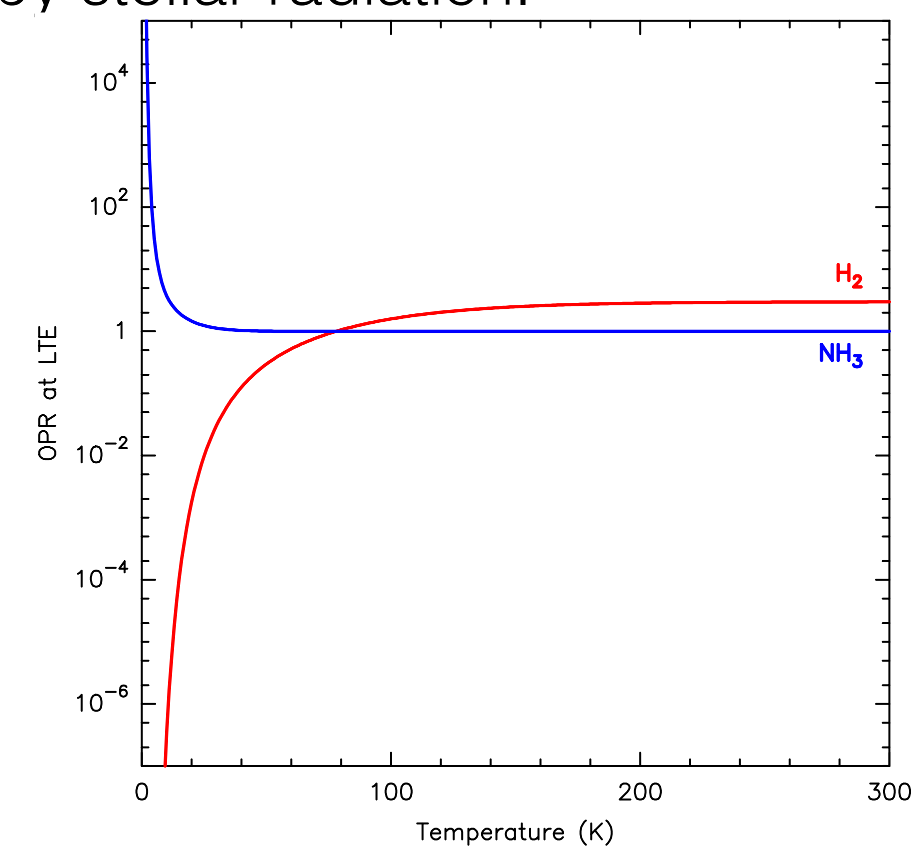


Figure 8. H_2 (as a proxy for C_2H_2) and NH_3 ortho-to-para ratio computed as a function of temperature at thermal equilibrium. This computation is based on Le Gal et al. (2016).

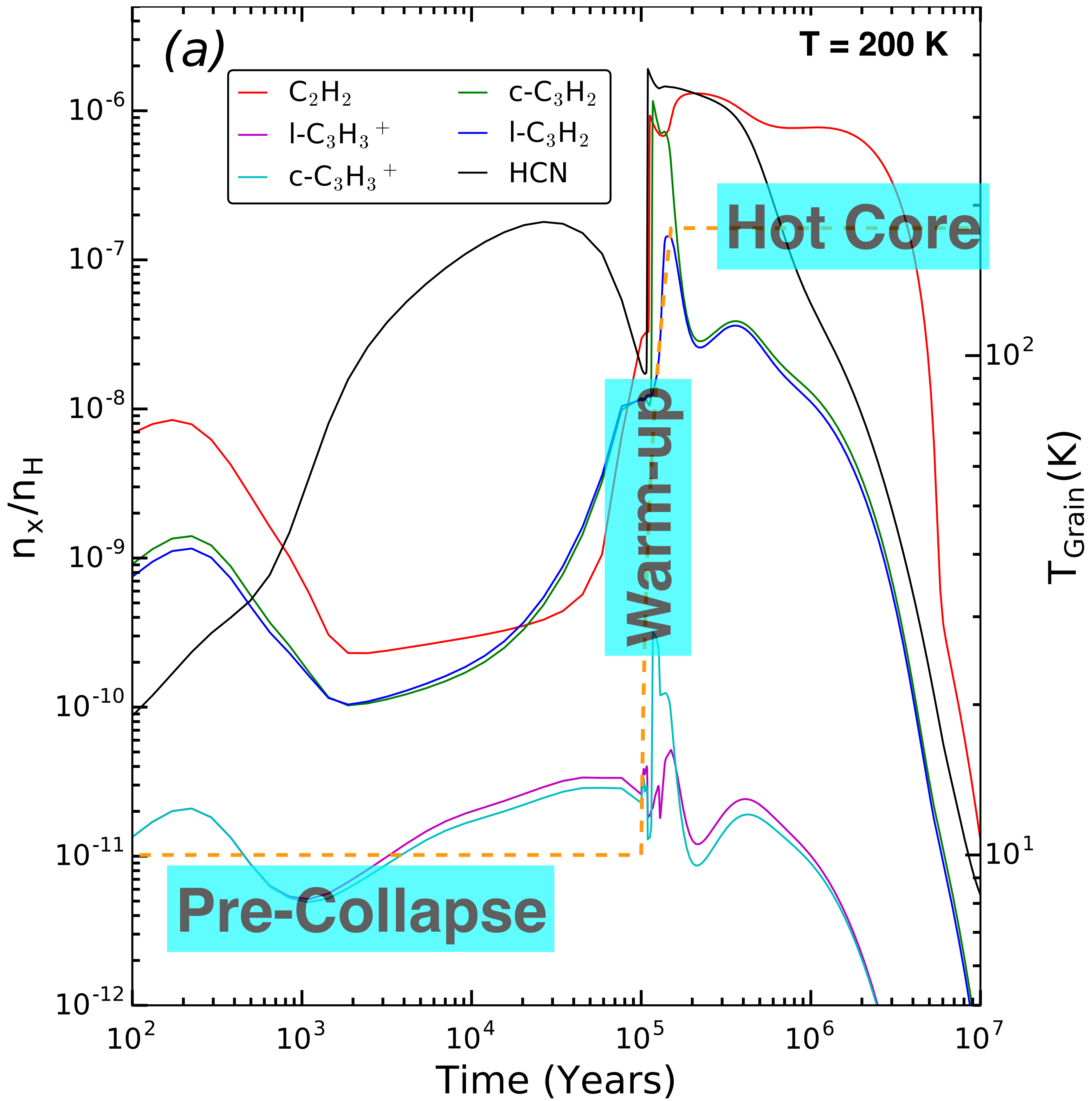
Shocks Responsible for the Low C_2H_2 Ortho to Para Ratio

<u>Orion Hot is externally heated</u> ***(e.g, Zapatta et al. 2011, Bally et al. 2015, Wright et al. 2017)***

- by impact of (low-velocity) shocks generated from the BN/I explosive event on a pre-existing dense clump 500 yrs ago OR Low- velocity outflow from source I ***(Goddi et al. 2011, Wright et al. 2017)***
- Shock models ***(e.g., Wilgenbus et al. 2000)*** show for a low-velocity shock the post-shock OPR does not reach its high-temperature LTE value, because the OPR thermalization timescale is longer than the shock timescale
- Hot core chemistry models are not appropriate for this scenario: longer time scale are needed compared to 500 yrs to reach the observed abundances of C_2H_2 and HCN
- Need detailed shock chemistry models to understand the low OPRs

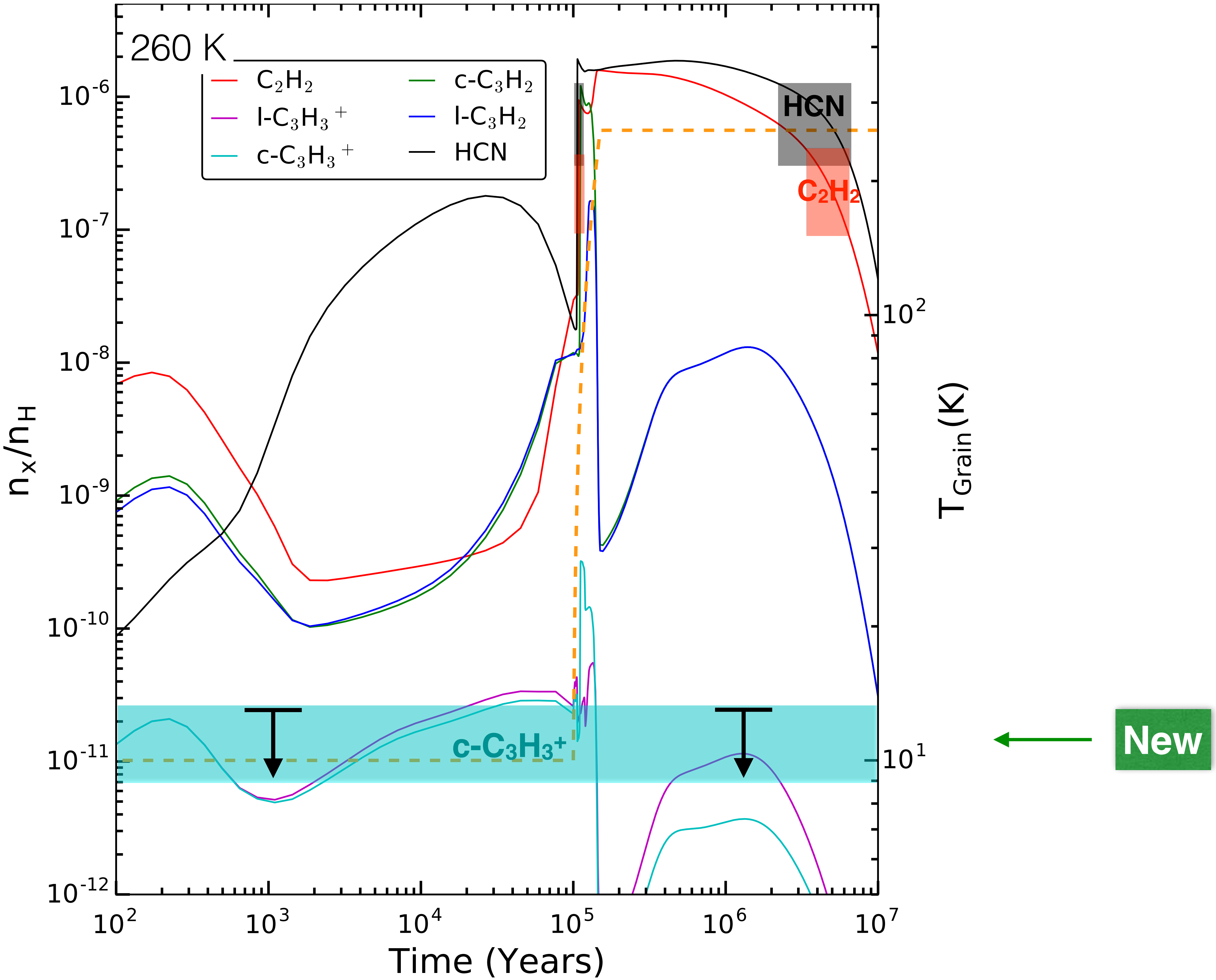
Low C_2H_2 OPR could be a remnant from an earlier, colder phase, before the density enhancement (now hot core) was impacted by shocks

Hot core chemistry models



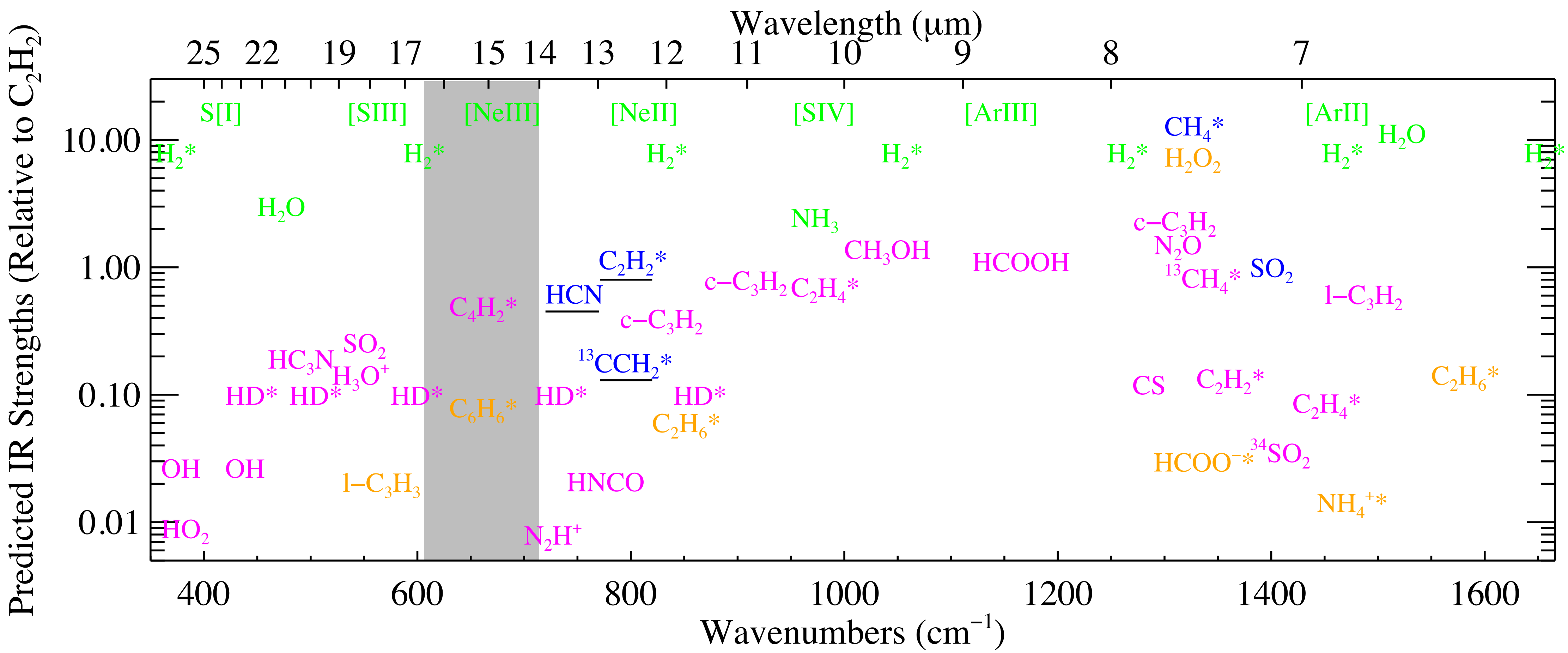
Rangwala et al. 2018

Hot core chemistry models



Rangwala et al. 2018

Orion Line Survey in the Mid-Infrared (EXES and TEXES)



Rangwala et al.
SOFIA, Cy-5

● IR bands detected towards IRc2 ● Not detected in IR towards IRc2 ● Never detected in ISM ● Very bright/not to scale

- First unbiased, high-spectral resolution, high S/N (~100) line survey (SOFIA Cycle-5 and IRTF/TEXES (2018) programs)
- 50 times more sensitive than ISO
- MIR is the only way to study molecules that have no dipole moment.
- Goals: (a) Detect new molecules/measure upper limits, (b) Test astrochemistry models and (c) Provide reference database to the JWST and ALMA scientific communities

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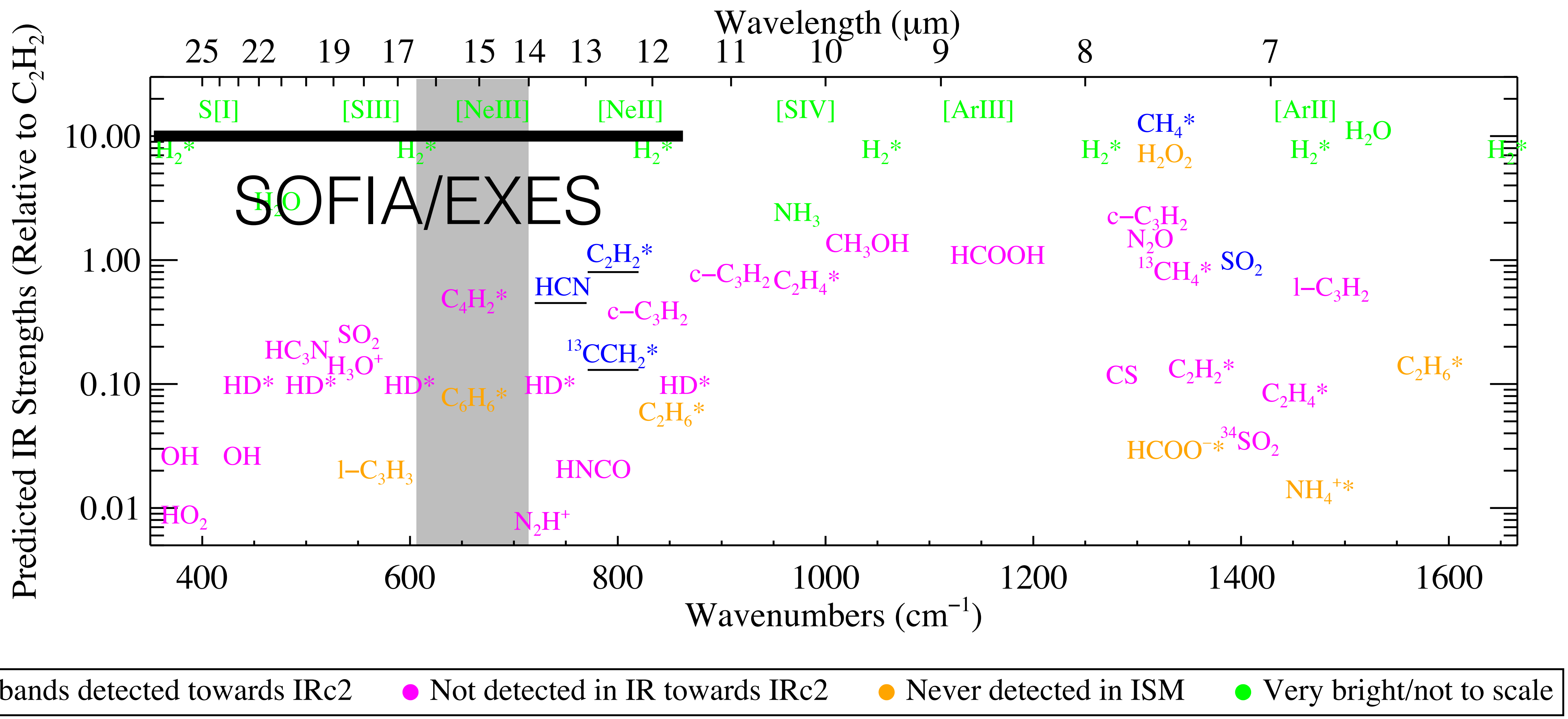

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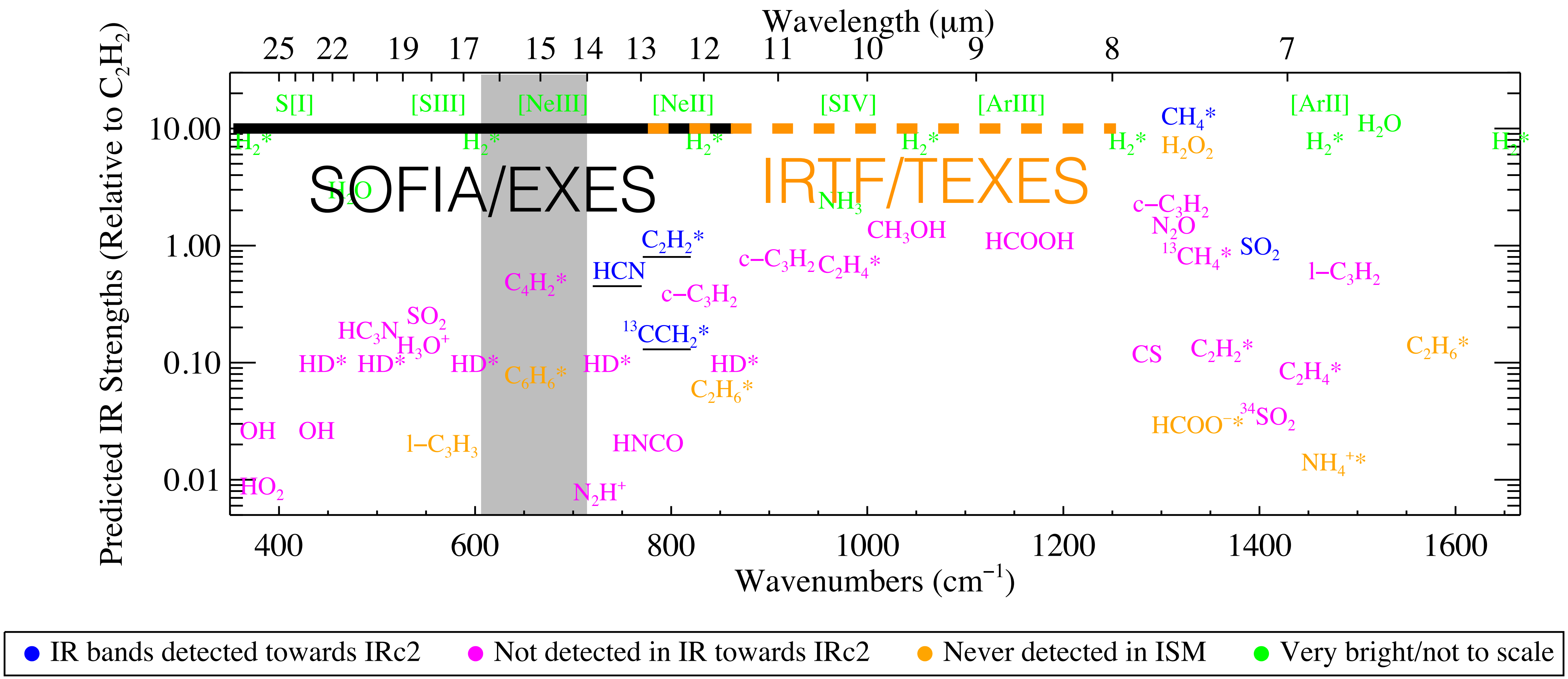

Rangwala et al. SOFIA, Cy-5

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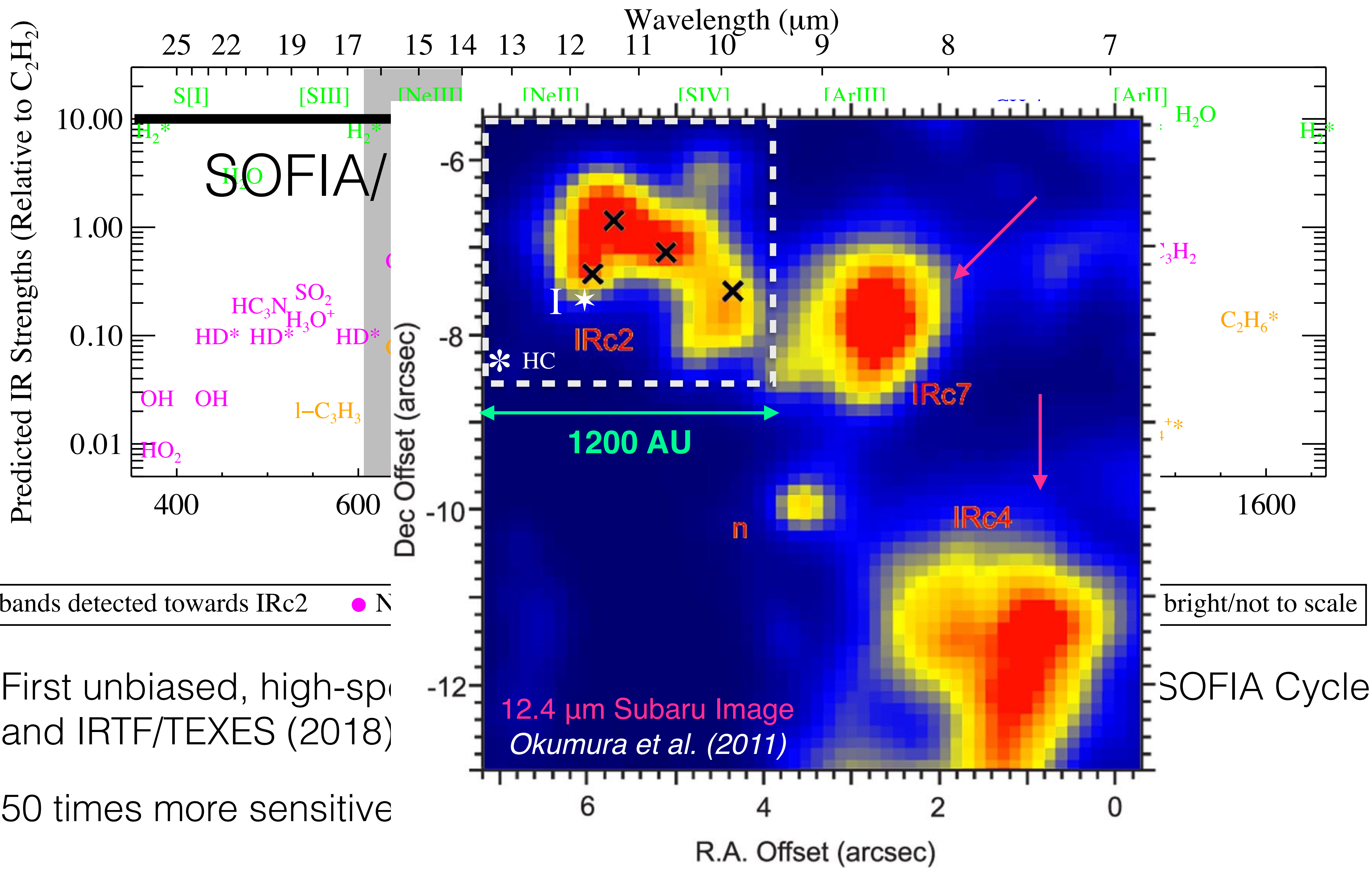

Rangwala et al.
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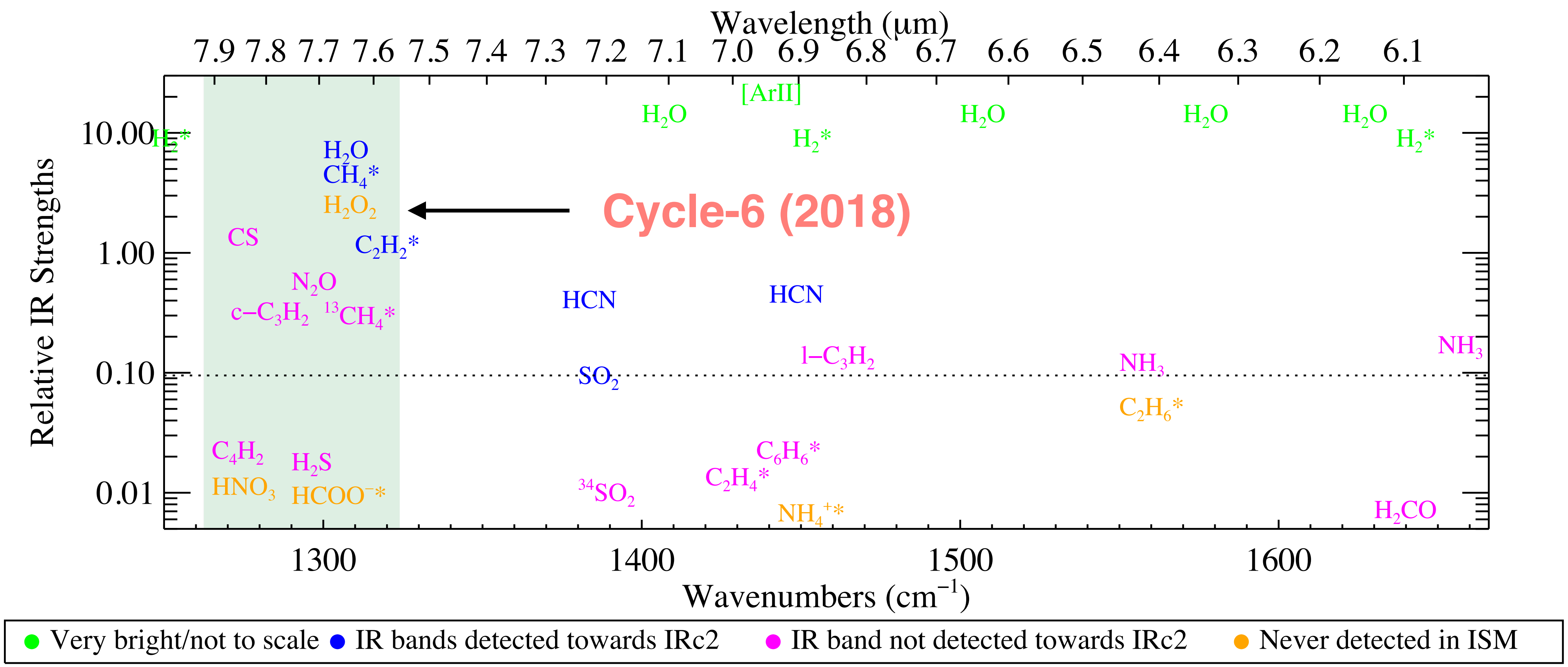
SOFIA/EXES Orion Line Survey - extension

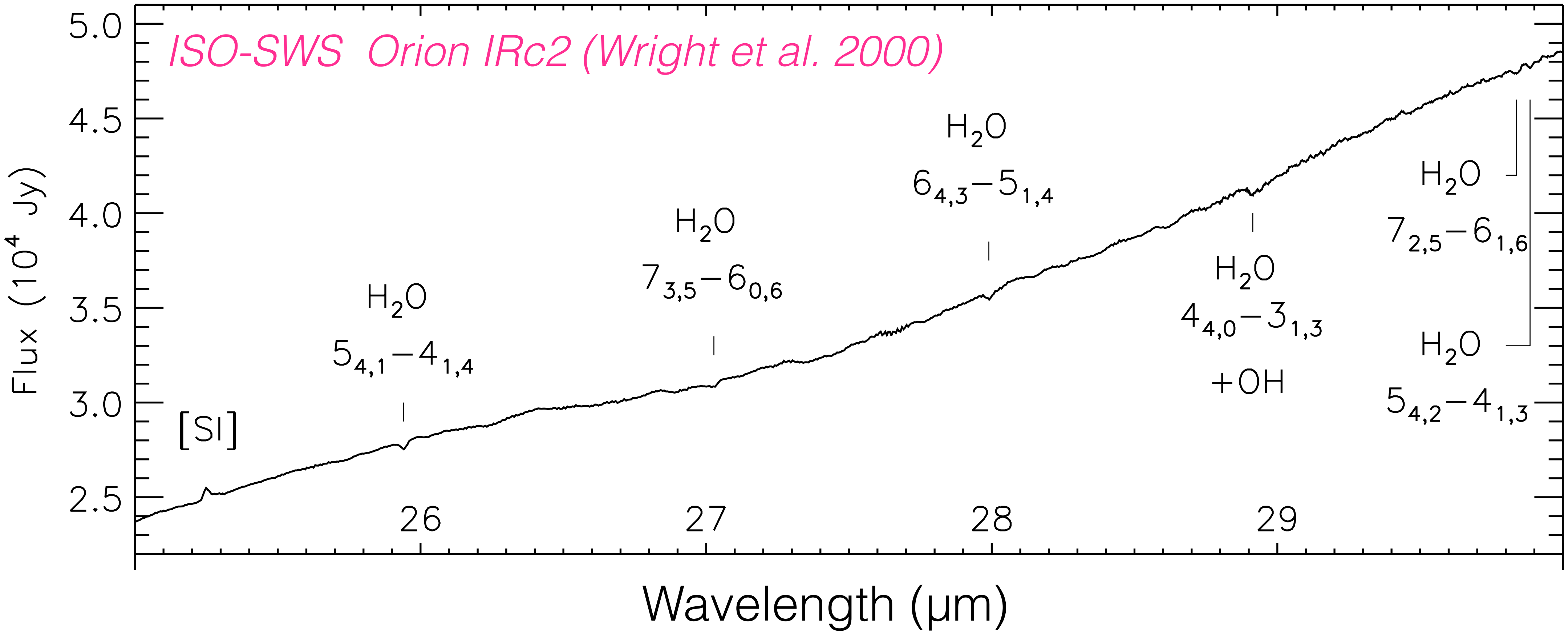


Rangwala et al.
SOFIA, Cy-6

- Proposed in Cycle-6 : Targeted extension of our line survey to shorter wavelengths
- coverage: **7.56 - 7.92 μm**
- Compare chemistry with typical hot cores that are heated internally by stellar radiation

Another ongoing SOFIA hot core line survey (PI: Alexander Tielens), which covers 5.4 - 8 μm in two hot cores: AFGL 2136 & AFGL 2591 (R~50,000, S/N = 100)

SOFIA/EXES Orion Line Survey- Observations (so far…)



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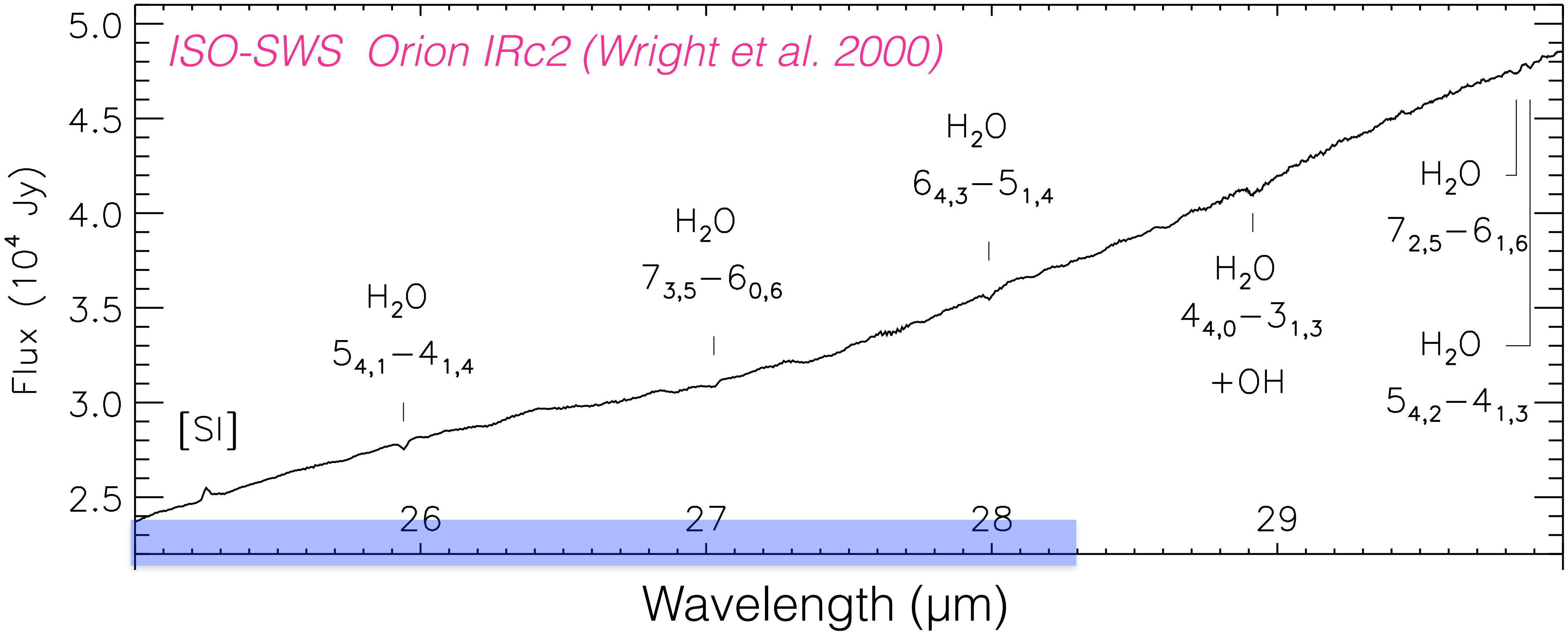

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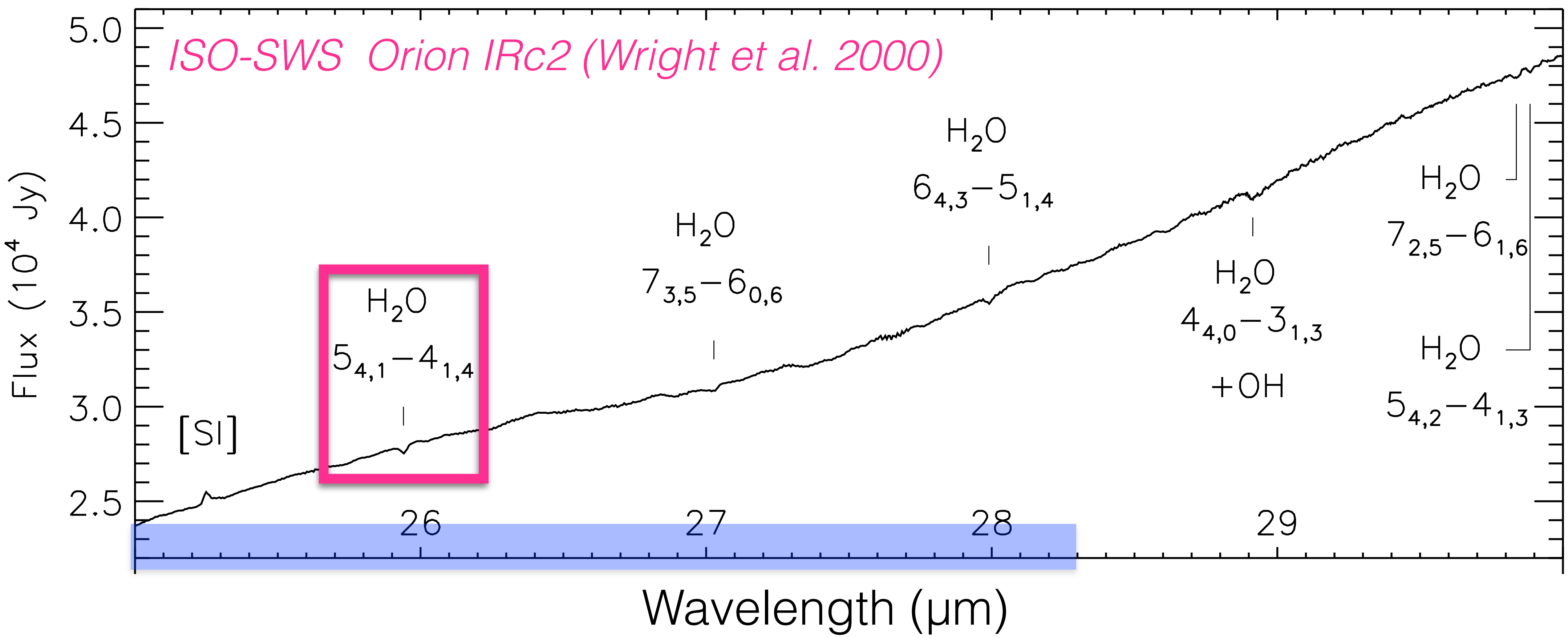

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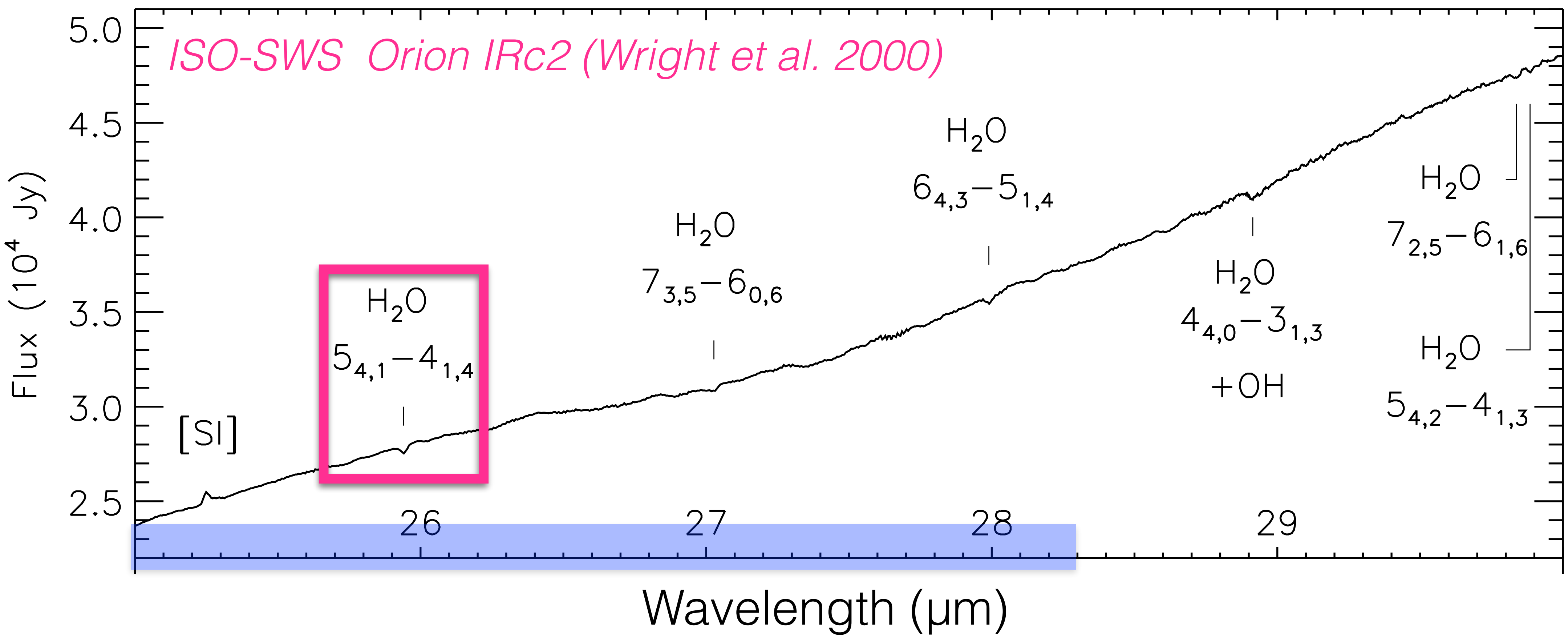
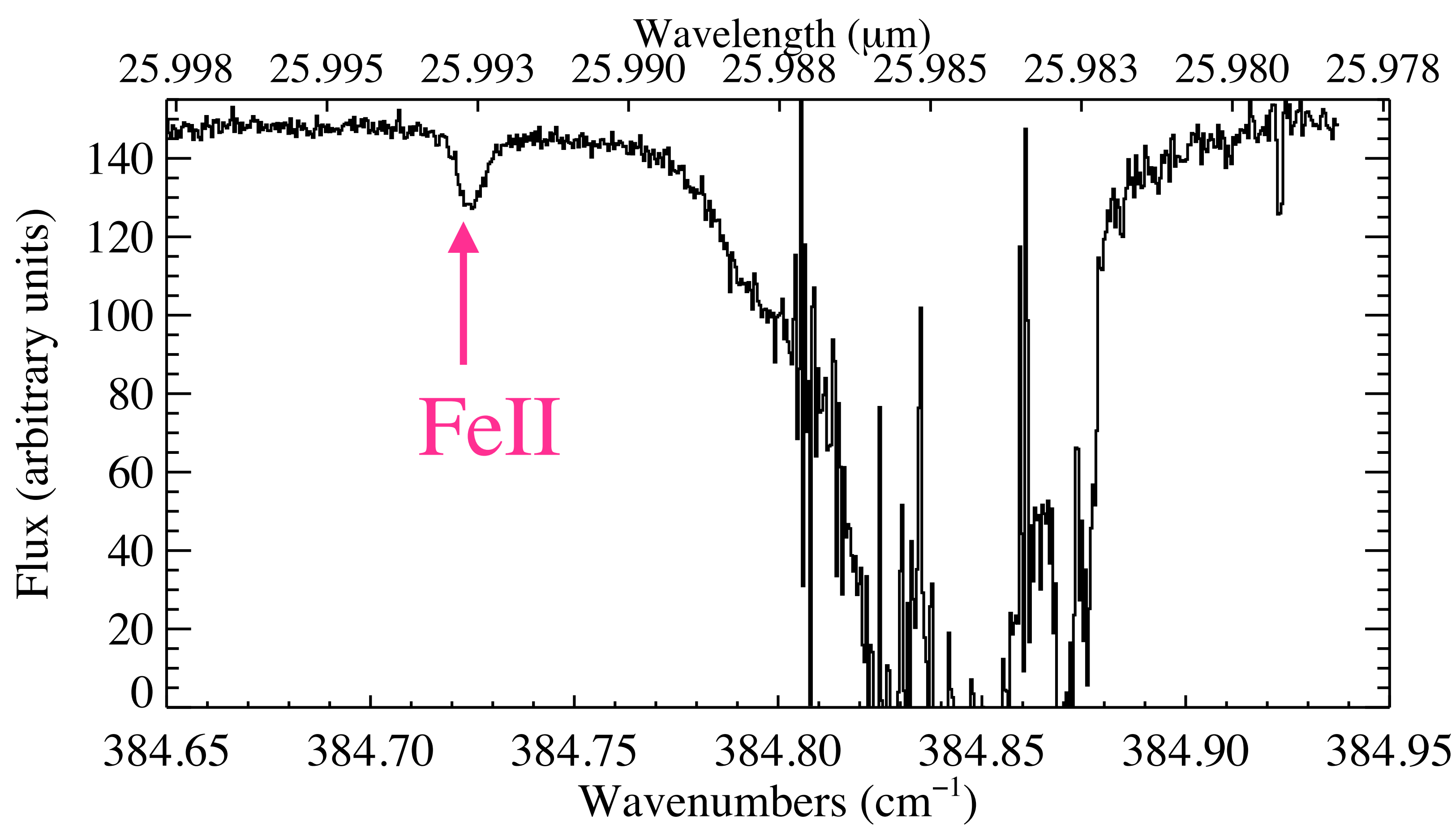
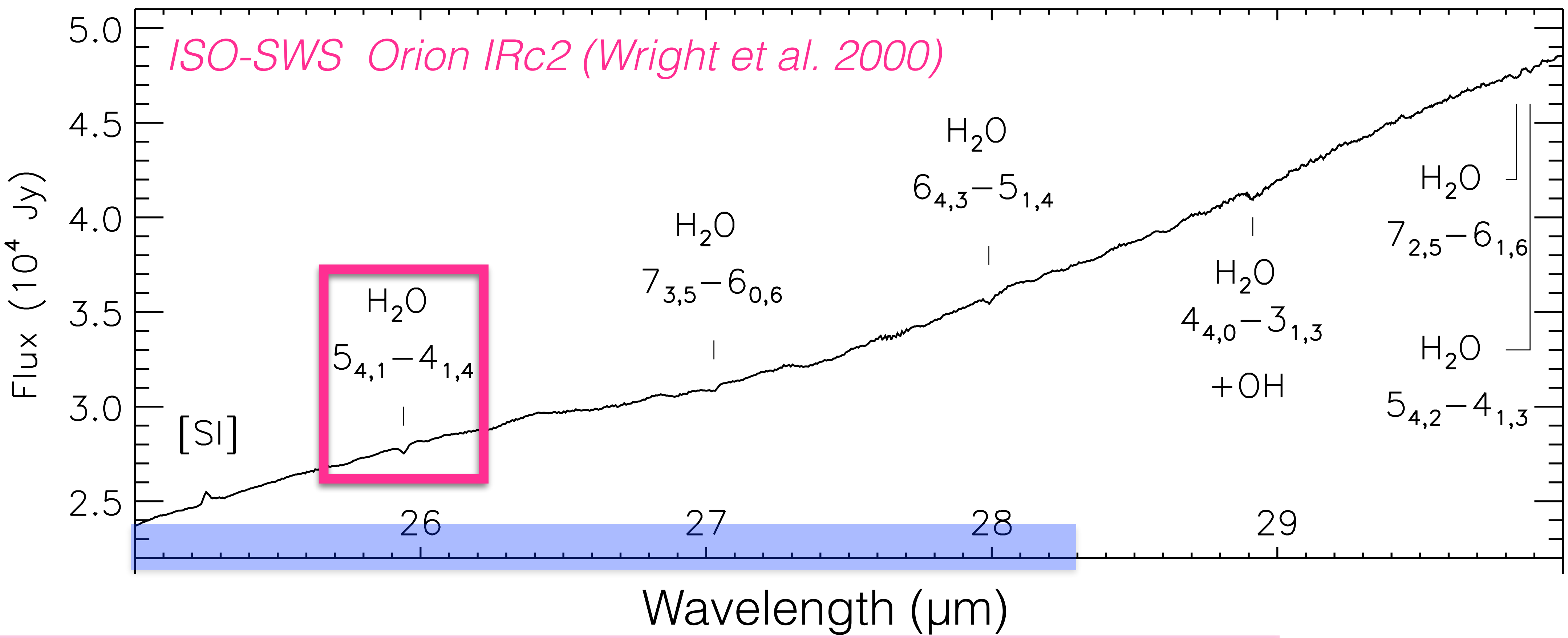
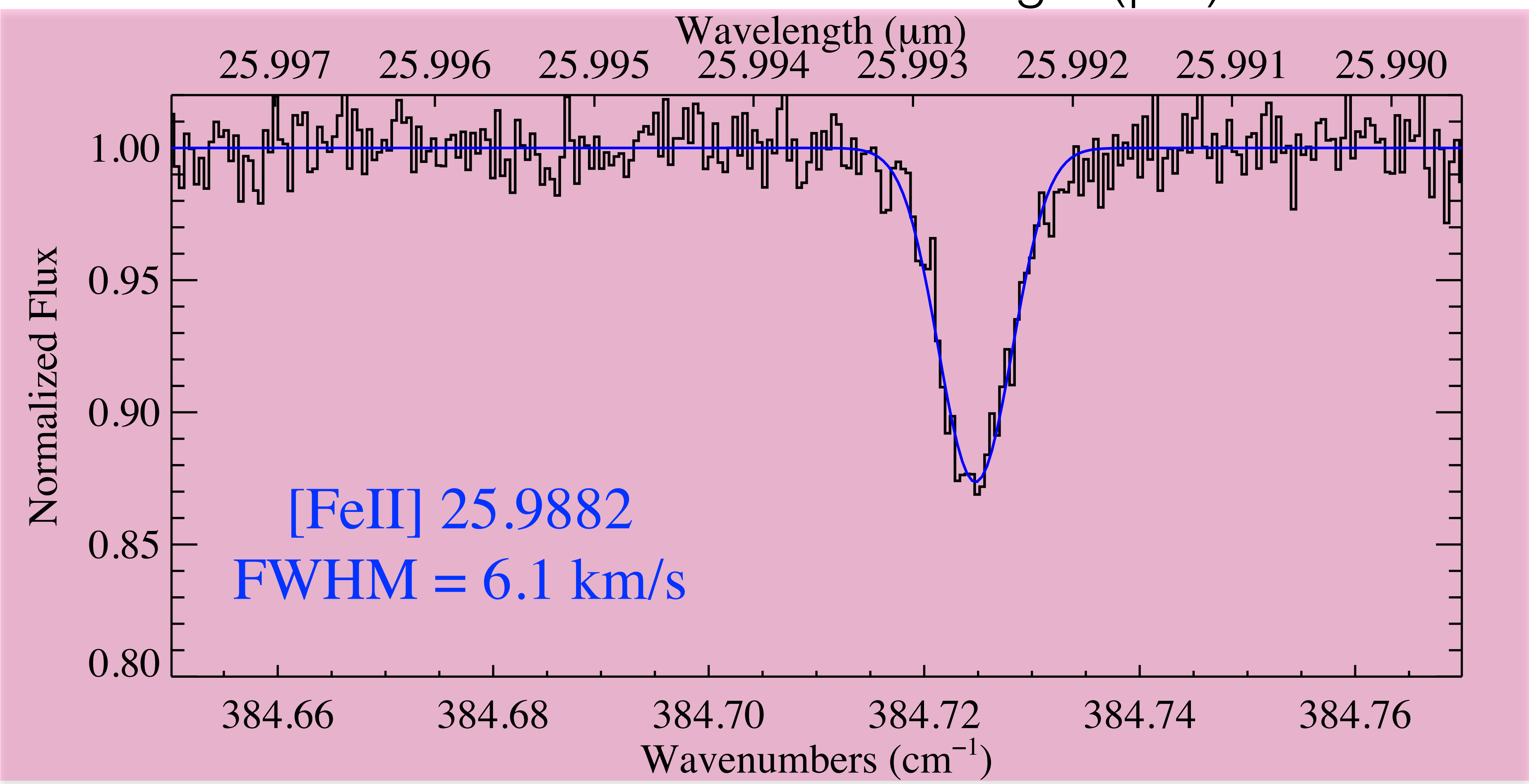




SOFIA/EXES Orion Line Survey- Observations (so far…)

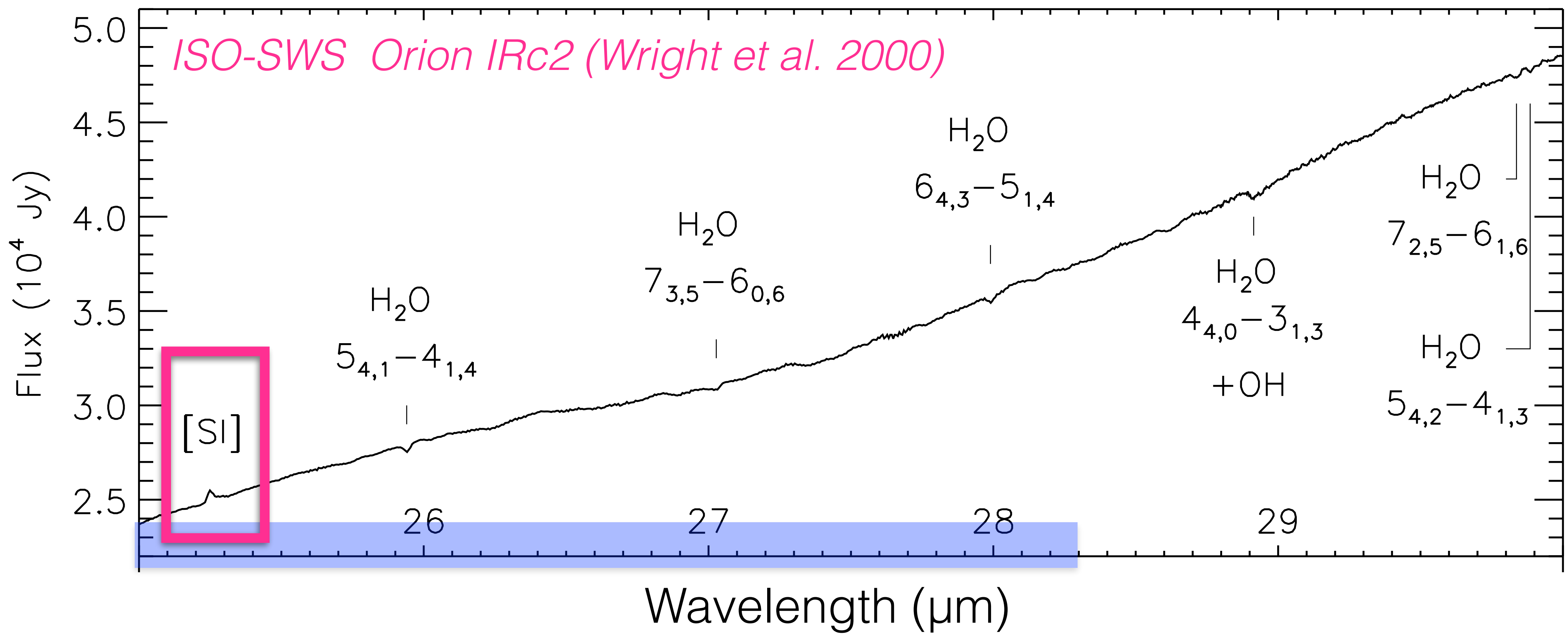


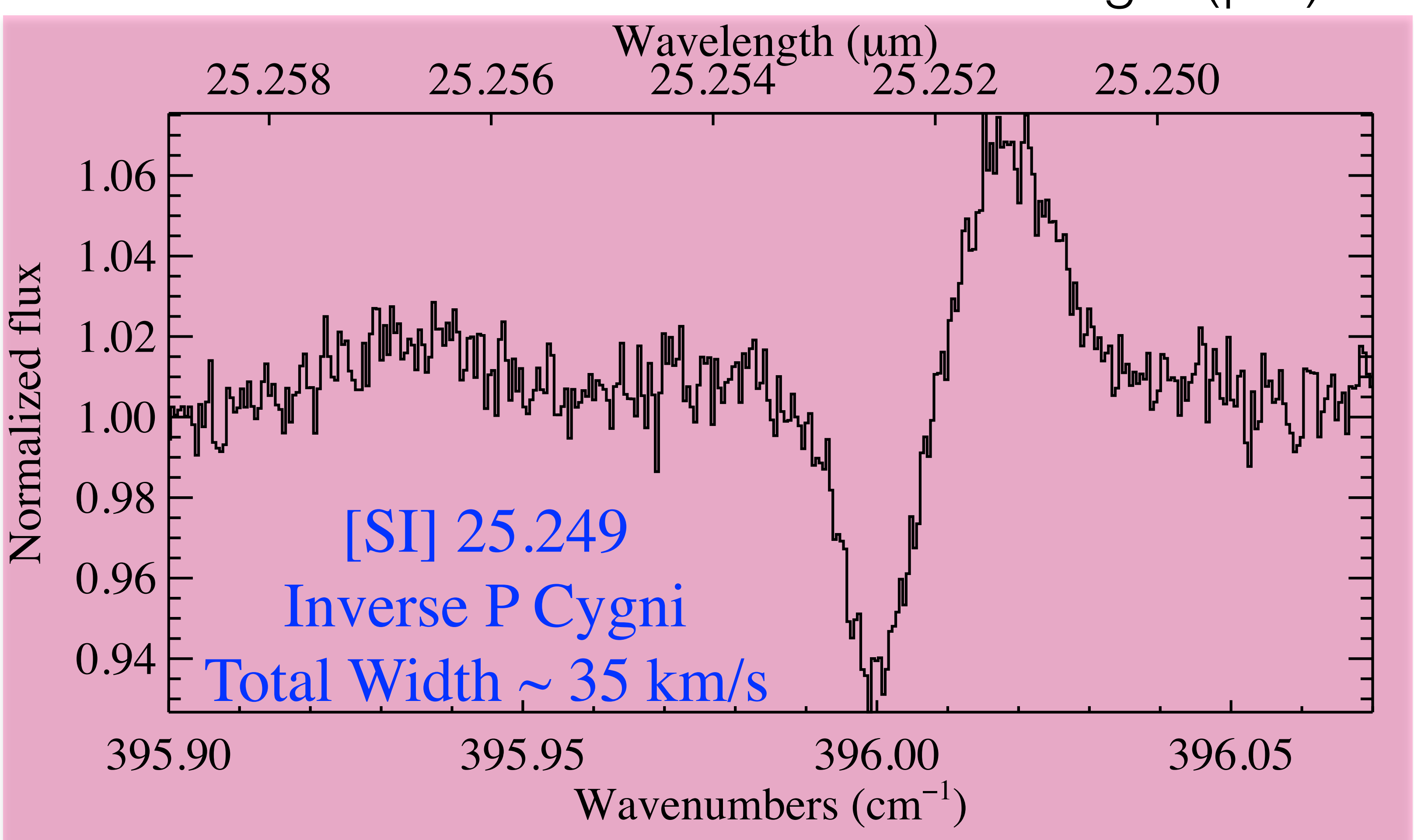


[FeII] is a shock tracer and will provide information on the geometry of the source

FWHM (C_2H_2): 12 - 14 km/s

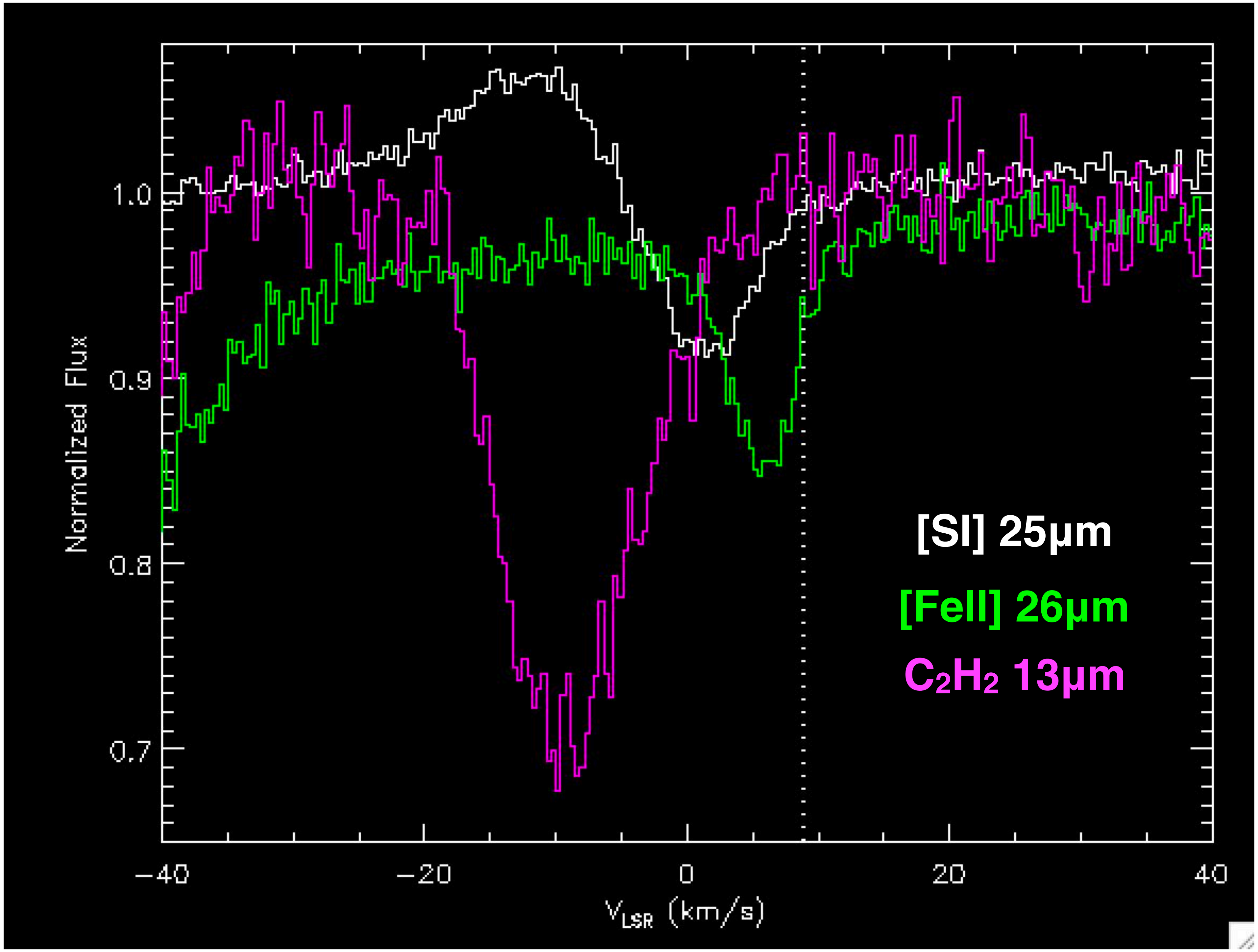
SOFIA/EXES Orion Line Survey- Observations (so far…)





[SI] line profile shows signature of infall

[FeII], [SI] and C_2H_2 towards Orion Hot core



line of sight velocity

Preliminary

Conclusions

- We obtained high-spectral resolution observations λ~13 μm towards Orion hot molecular core using SOFIA/EXES.
    - detect C_2H_2 rovibrational lines with high-S/N that allowed us to unambiguously show that the ortho and para species in Orion hot core are tracing different temperatures
    - Measure Non-equilibrium OPR ~ 1.7 +/- 0.1. Low OPR likely from an earlier, colder pre-shock phase (indicative of shock heated core)
    - velocity information show that Ortho and Para may not be exactly co-located.
    - Isotopic Ratio $^{12}C/^{13}C < 21$
    - C_2H_2 and HCN appear to be in the outflow originating from Source I.
- Ongoing high-resolution line survey (8 - 28.3 μm) of the Orion Hot core from SOFIA/EXES and IRTF/TEXES.

Thank you for your attention!

Thanks to all my Collaborators

Sean Colgan (NASA Ames)
Xinchuan Huang (NASA Ames/SETI)
Kinsuk Acharyya (PRL, India)
Romane Le Gal (University of Virginia)
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Adwin Boogert, Mark McKelvey)

Orion KL region
Credit: John Bally et al. (2015)

Search for c-$C_3H_3^+$

- Most important precursor in the formation of c-C_3H_2 - an interstellar organic ring molecule ubiquitous in the ISM

$$C^+ + C_2H_2 \rightarrow C_3H^+ + H$$

$$C_3H^+ + H_2 \rightarrow C_3H_3^+ + h\nu$$

$$C_3H_3^+ + e^- \rightarrow C_3H_2 + H$$

- Along with PAHs, c-C_3H_2 is of particular interest because of its possible relationship both to more complex aromatic compounds in the ISM as well as terrestrial biochemistry.

- c-$C_3H_3^+$ has never been detected in the ISM and has very limited experimental data.

- It has no dipole moment - hence only accessible in the MIR using the ro-vibrational transitions.

- *Ab initio* quantum calculations (NASA Ames group :Tim Lee, Yinchuan Huang, and Partha Bera) have improved significantly and can provide accurate line positions to search for new molecules, e.g., c-$C_3H_3^+$.