[C II] and [O I] Absorption and Self-Absorption Toward a Bubble-Shaped H II Region in the Nessie Nebula

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Outline

- The Nessie Nebula
- Widespread collapse throughout Nessie
- [C II] and [O I] absorption and self-absorption
- Triggered star formation in Nessie

The "Nessie Nebula": An extremely filamentary Infrared Dark Cloud

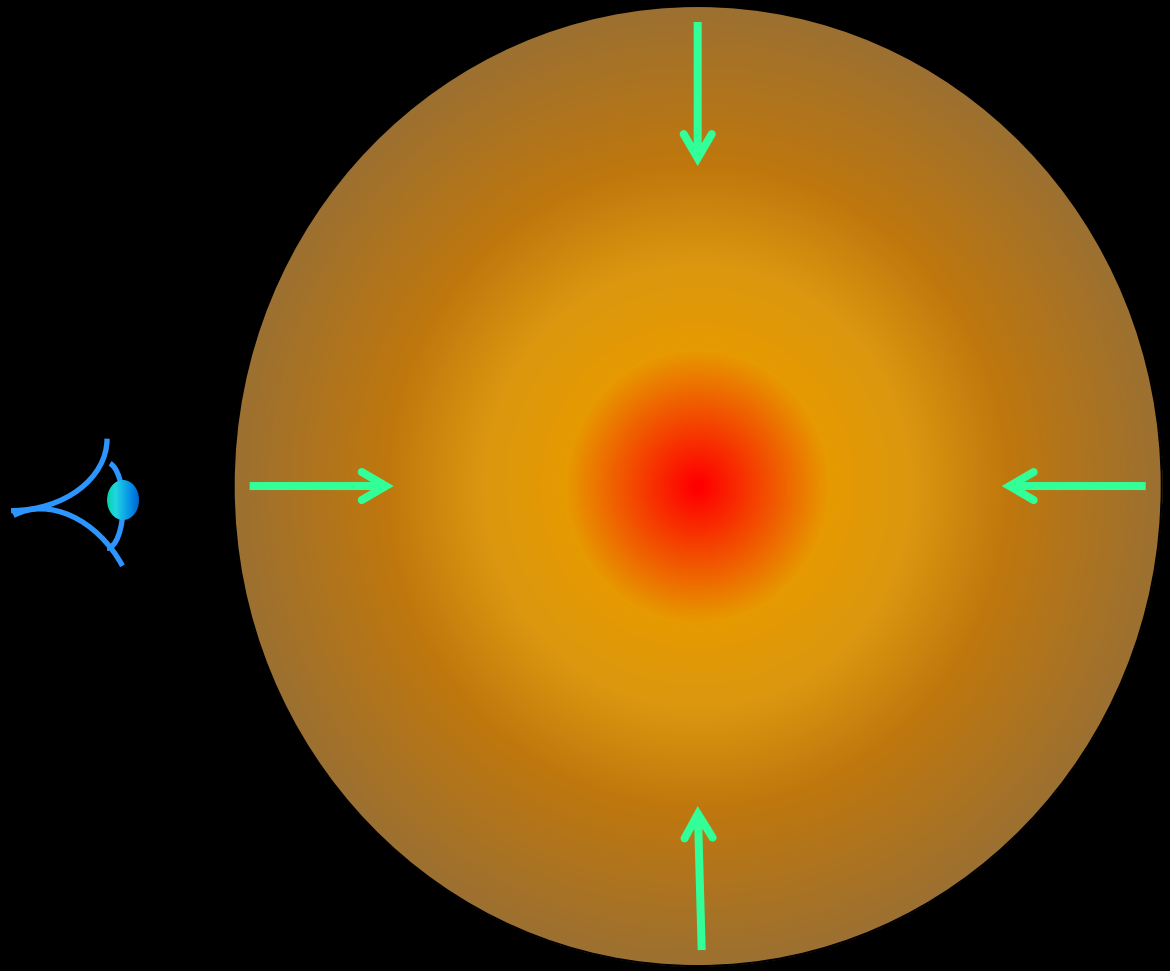
- >100 pc long, ~1 pc wide, aspect ratio >100:1
- Linear mass density ~110 $M_\odot$ pc^{-1}
- Cold (10 K), dense (10^5 cm^{-3}), opaque A_V>100
- Is Nessie static or collapsing? "Blue asymmetry"

Jackson et al. 2010 ApJL

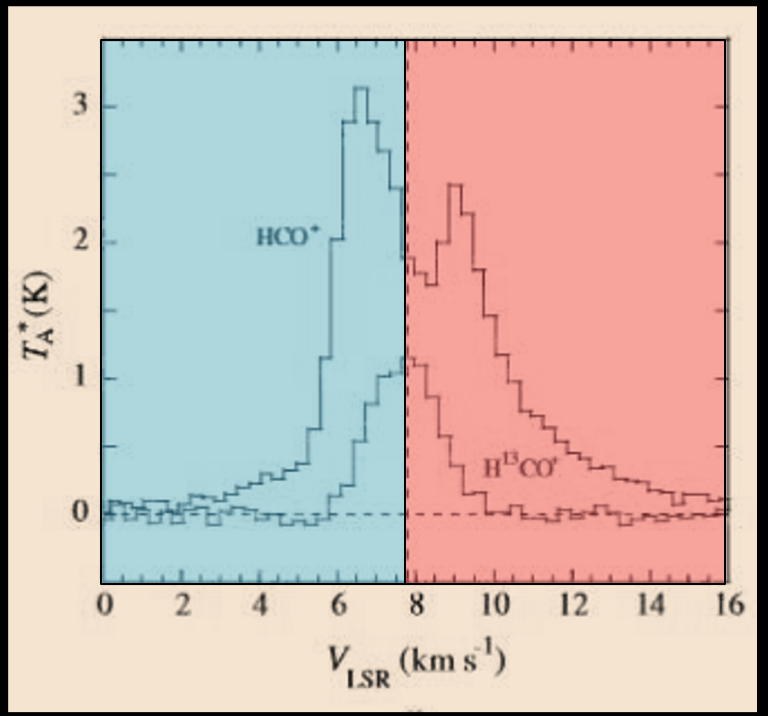
Blue - 3.6μm, Green - 8μm, Red - 24μm

Image credit: NASA/JPL-Caltech/Univ. of Wisconsin

The "blue asymmetry" in a collapsing cloud with a warm interior: Optically thick lines are brighter on the blue side



Hot, blue Cold, red

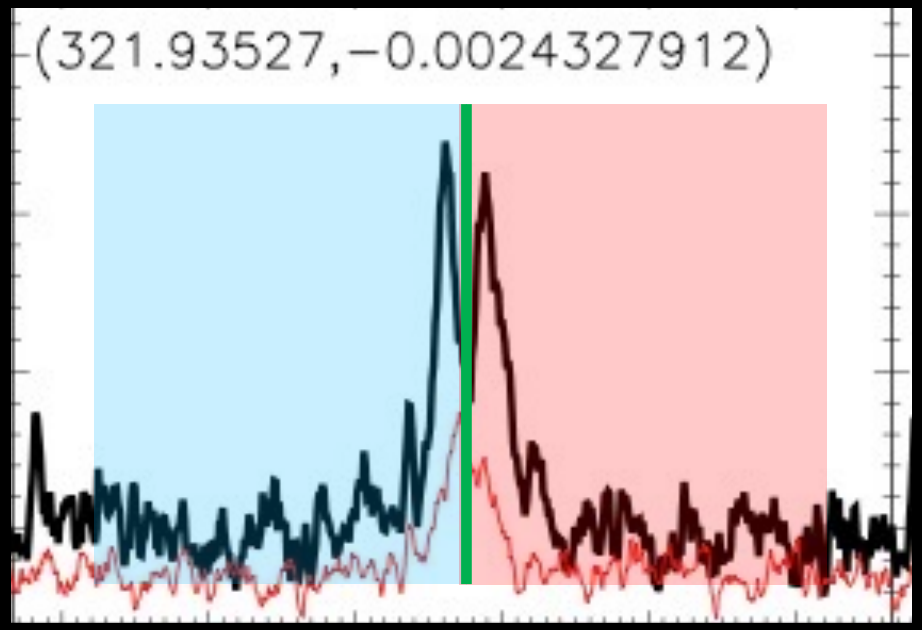


Optically thick line is asymmetric;
optically thin line is symmetric

Tanaka et al. 2013

Define the "Asymmetry Index"

$$A = \frac{I_{blue} - I_{red}}{I_{blue} + I_{red}}$$



Systemic velocity from optically thin N_2H^+

Blue asymmetry A > 0

Red asymmetry A < 0

A is the fraction of excess flux on the blueshifted side.

Jackson et al. 2019

Collapse in the Nessie Nebula

- To investigate collapse in the Nessie Nebula, we used Mopra to map Nessie in the HCO^+ (thick) and N_2H^+ (thin) 1-0 lines
- We search for the blue asymmetry collapse signature by measuring the asymmetry parameter A for HCO^+
- Collapse is indicated if A>0

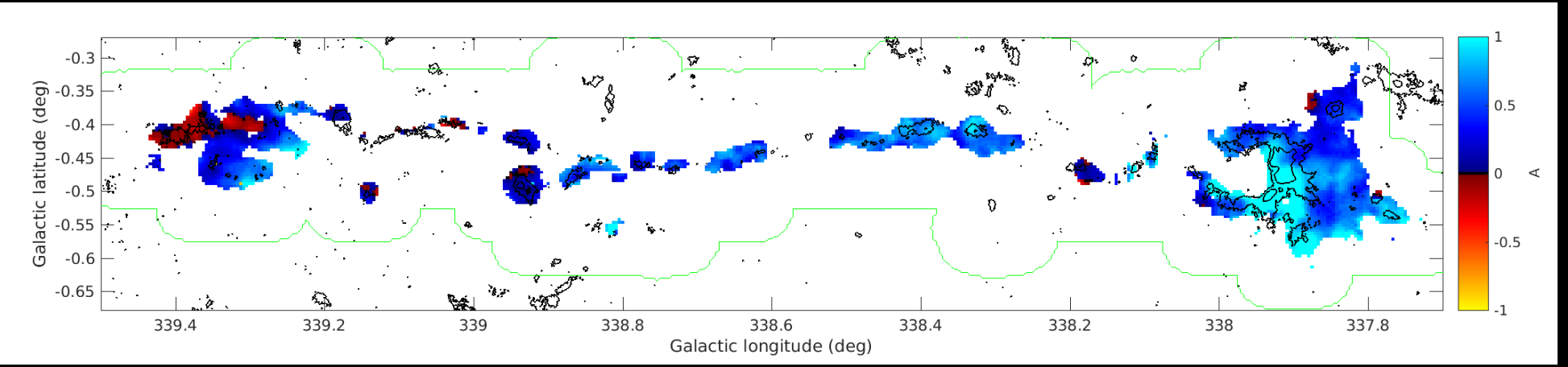
ATNF Mopra 22 m

Allingham et al., in prep.

Mid-IR (Spitzer)

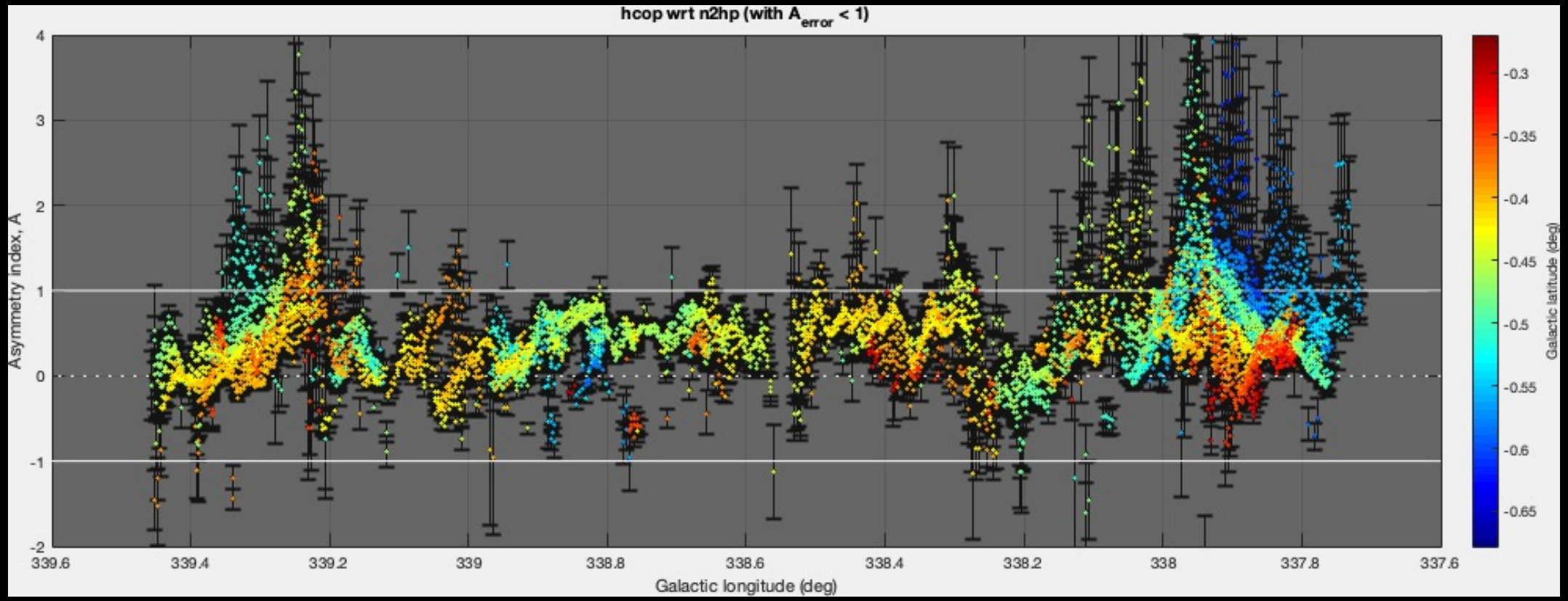
Asymmetry parameter A: HCO^+ referenced to N_2H^+

Widespread Blue Asymmetries

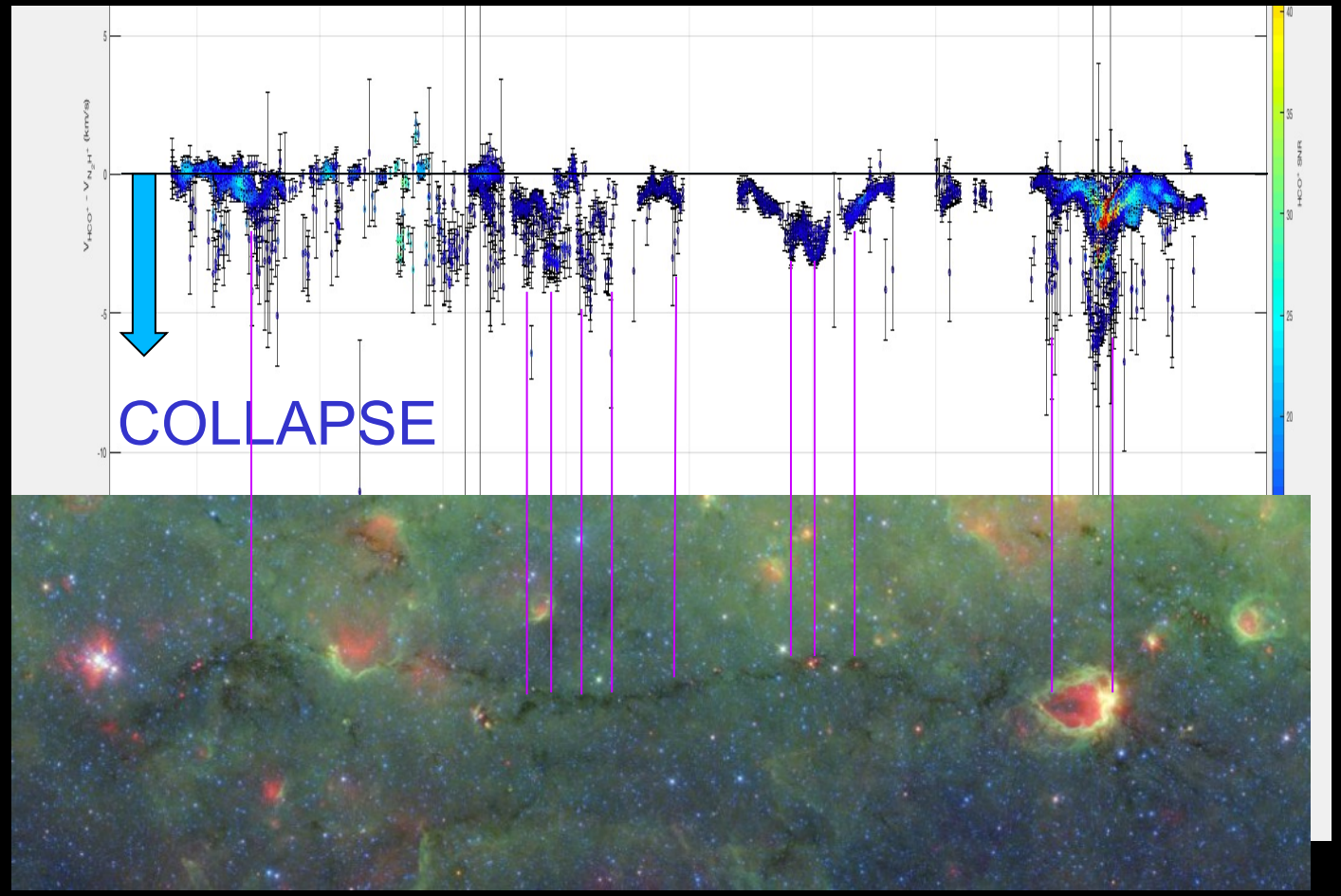


A>0 (Blue) indicates collapse, A<0 (Red) indicates expansion

Asymmetry Parameter has distinct peaks

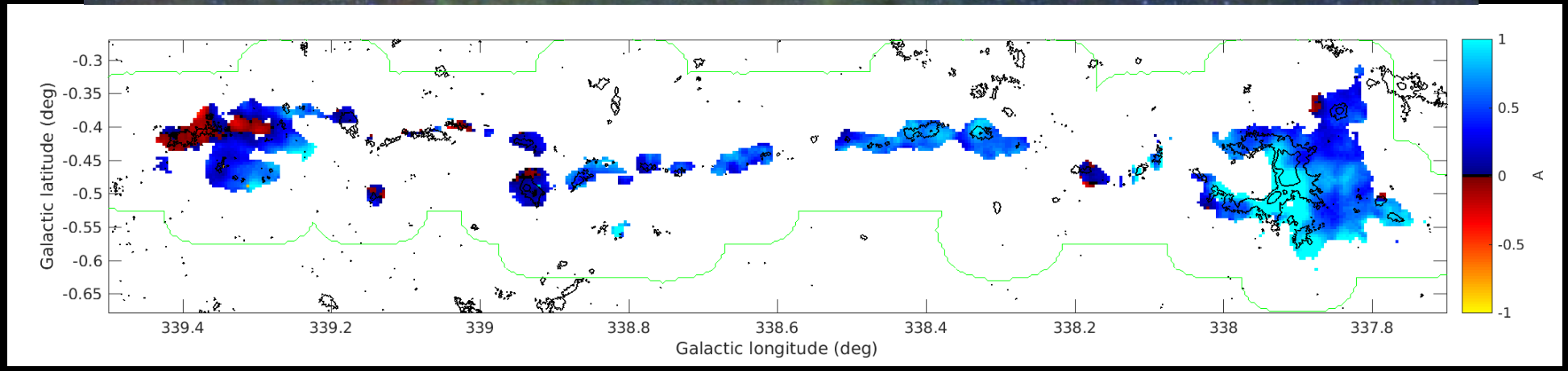


Asymmetry peaks line up with column density peaks, where optical depth is highest



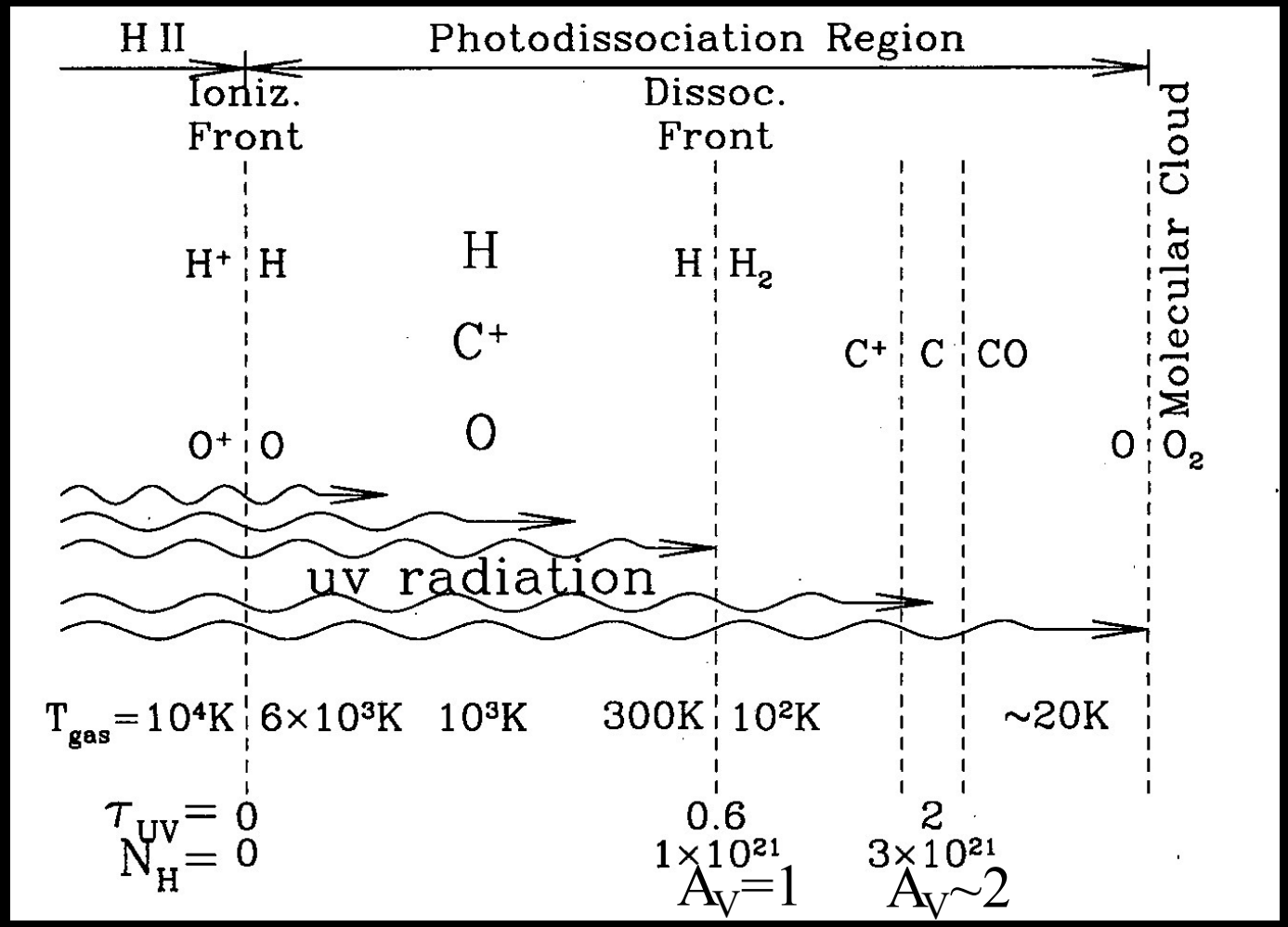
Allingham et al. 2021, in prep.

All of Nessie appears (or at least all of its clumps) appear to be collapsing everywhere along its length



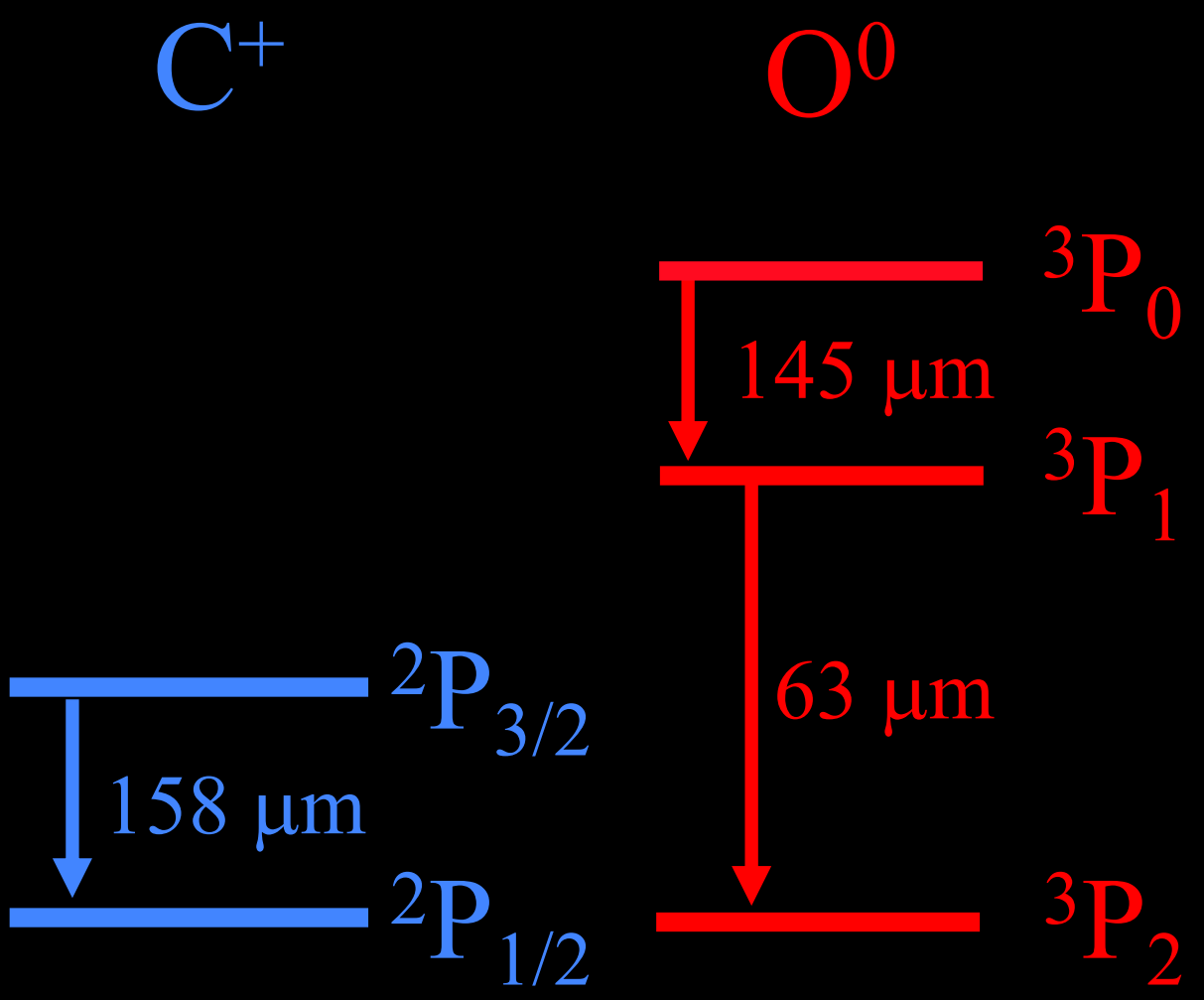
A>0 (Blue) indicates collapse, A<0 (Red) indicates expansion

Photodissociation Regions: The ionized/molecular interface in gas exposed to stellar ultraviolet radiation



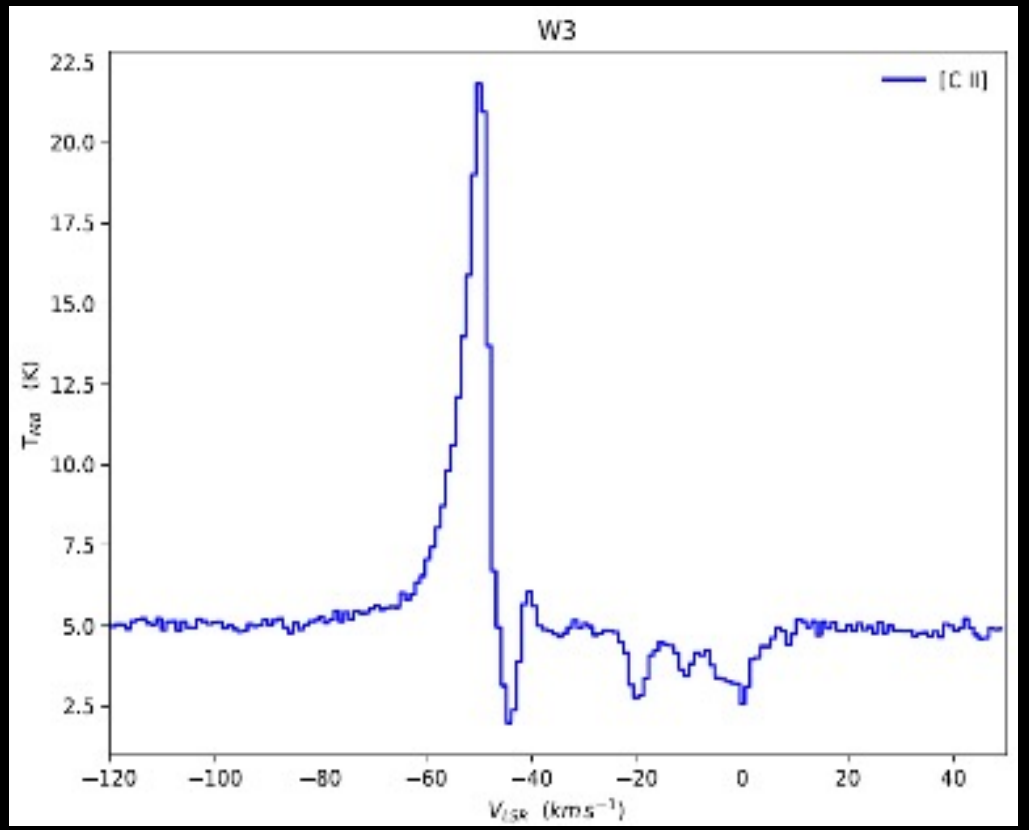
- Dust absorbs and attenuates UV radiation. This attenuation stratifies the gas composition.
- Hydrogen absorbs all UV photons with energies > 13.6 eV.
- Softer UV radiation, though, can penetrate further into the PDR.
- Atoms with low ionization potentials such as carbon (11 eV) are ionized.
- Atoms with high ionization potentials such as oxygen (13.6 eV) remain neutral.
- In the PDR, C is in the form C^+ and O in the form O^0.

C^+ and O^0 FIR Fine Structure Lines

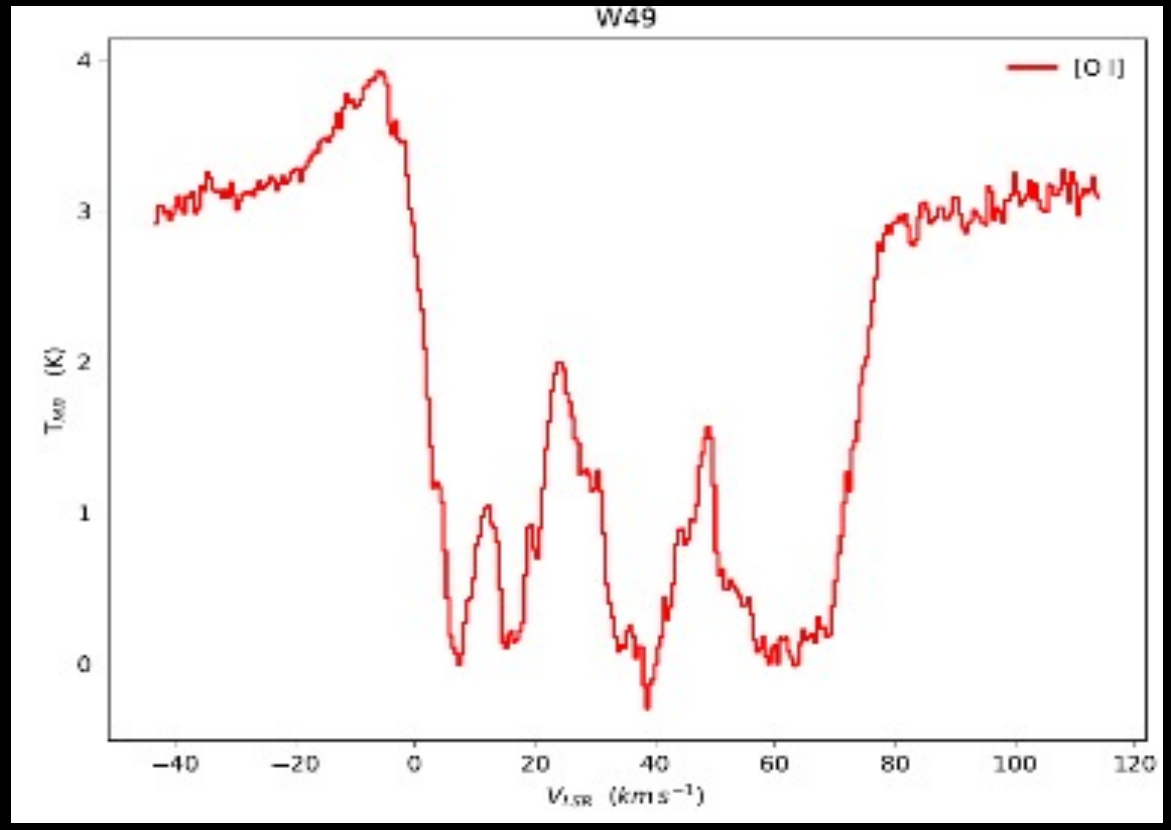


- Ionized carbon (C^+) has one far-infrared fine structure line at 158 μm.
- Neutral oxygen (O^0) has two lines: 63 and 145 μm.
- These FIR [C II] and [O I] lines are key diagnostic tracers of Photodissociation Regions.
- Yet, standard models assume they are unaffected by foreground material.

Both [C II] and [O I] display absorption features toward bright continuum sources



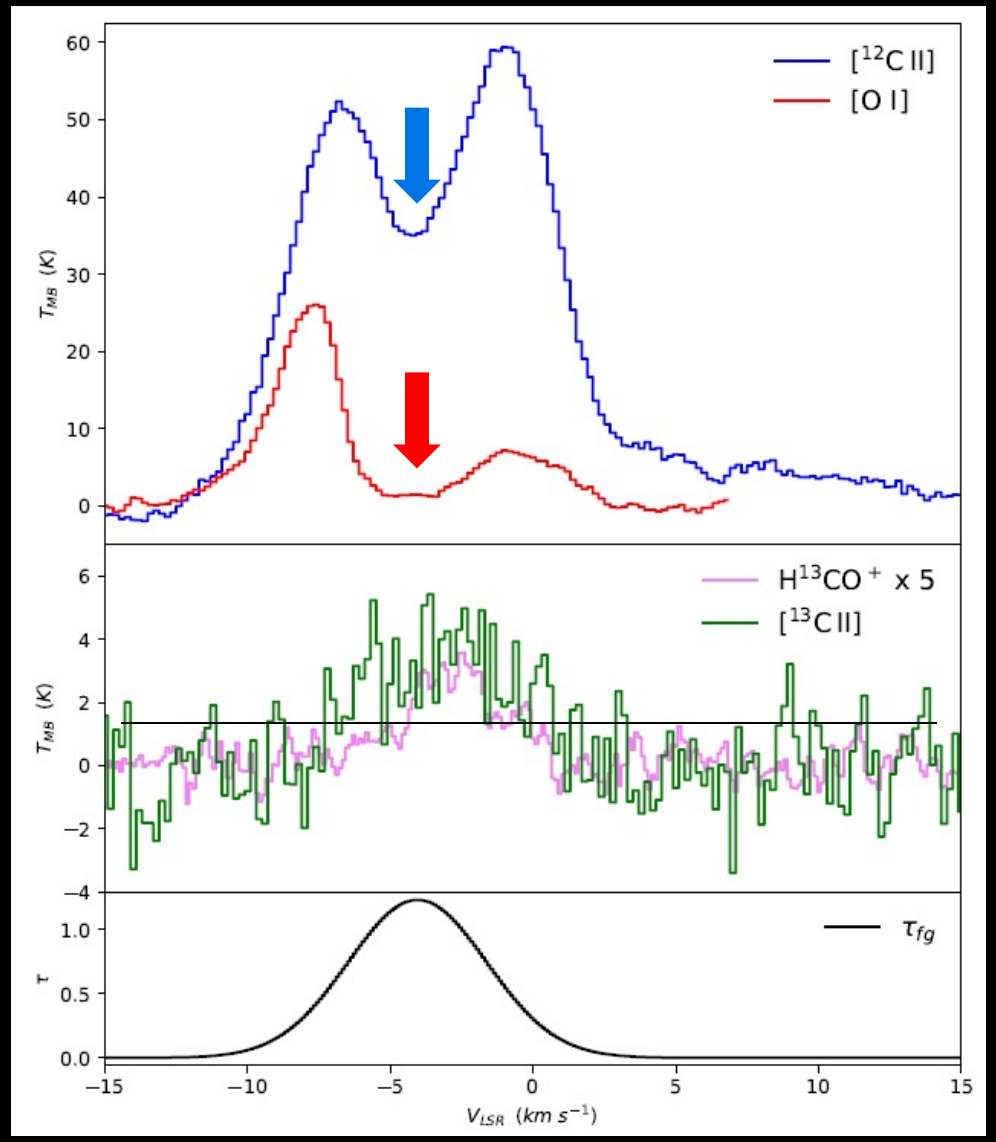
[C II] 63 μm, W3, Neufeld al., in prep



[O I] 63 μm, W49, Wiesenmeyer et al. 2016

See also Gerin et al. (2015), Risacher et al. 2016, …

[O I] and [C II] also exhibit self-absorption features



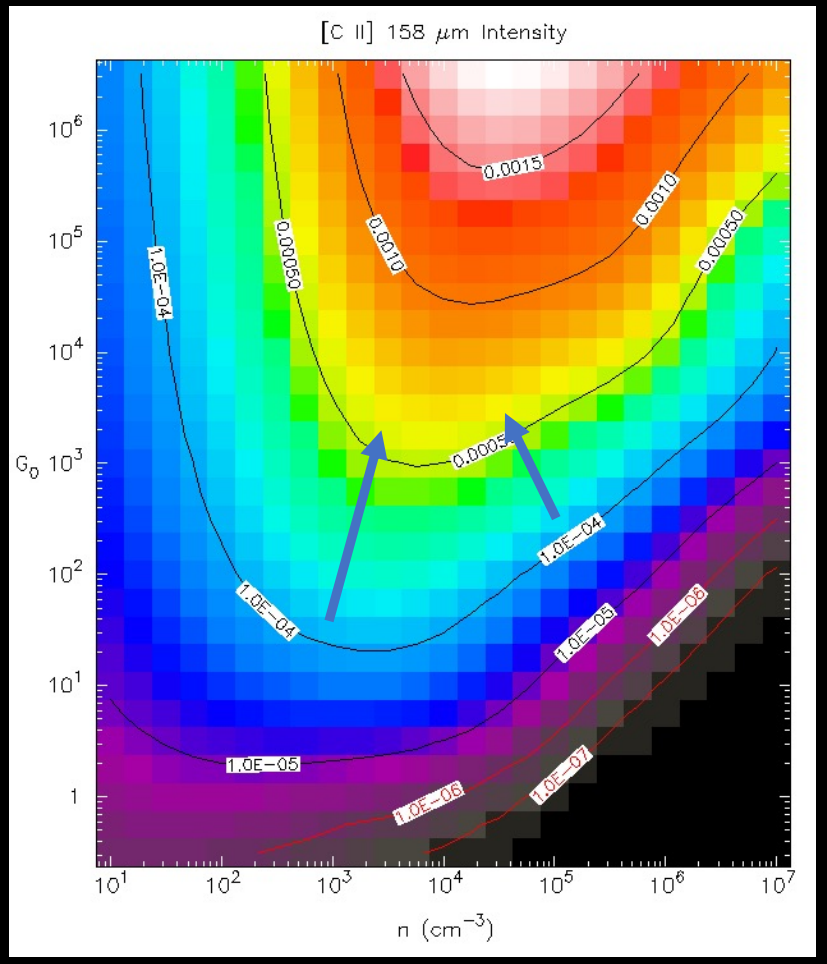
Self-absorption arises when line emission is absorbed by a foreground cloud.
They are manifest by dips in the line profile that match the velocity of optically thin lines, such as [^{13}C II] or H^{13}CO$^+$.

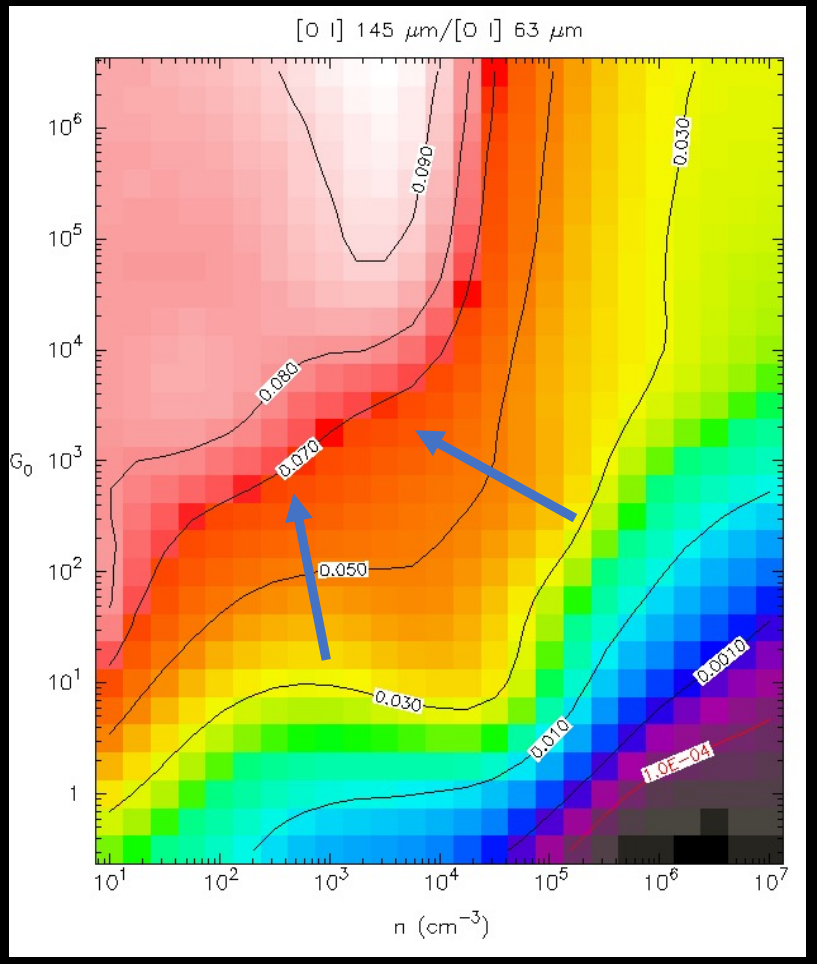
We find a self-absorption feature toward NGC6334 IV in both [O I] and [C II]. Using the techniques of Guevara et al. (2020), we estimate a foreground absorbing cloud with $\tau \sim 1.2$.

Such features are ubiquitous. **Where is the absorbing gas, and what are its properties?**

Jackson et al., in prep., Kraemer et al. 1996; Graf et al. 2015, Okada et al. 2019, Guevara et al. 2020, Goldsmith et al. 2021

Why it matters: PDR models are **very** sensitive to input fluxes for estimates of G_0 and n.





If self-absorption diminishes the observed flux by 50%, the estimates of G_0 and n can be **in error by a factor of 10 or more.**

University of Maryland PDR Toolkit (Kauffman, Wolfire, & Hollenbach 2006, Pound & Wolfire 2008)

Puzzles

- The C^+ absorbing gas is ubiquitous.
- The [C II] line is typically optically thickish (τ ~1).
- It appears to be cold (T_{ex}~20 K).

- The O^0 absorbing gas is also ubiquitous.
- The [O I] 63 μm line typically has larger optical depths.
- [O I] and [C II] velocities do not always match.

Guevara et al. 2020, Kirsanova et al. 2020, Liseau et al. 2006, Abel et al. 2007, Ossenkopf et al. 2015…

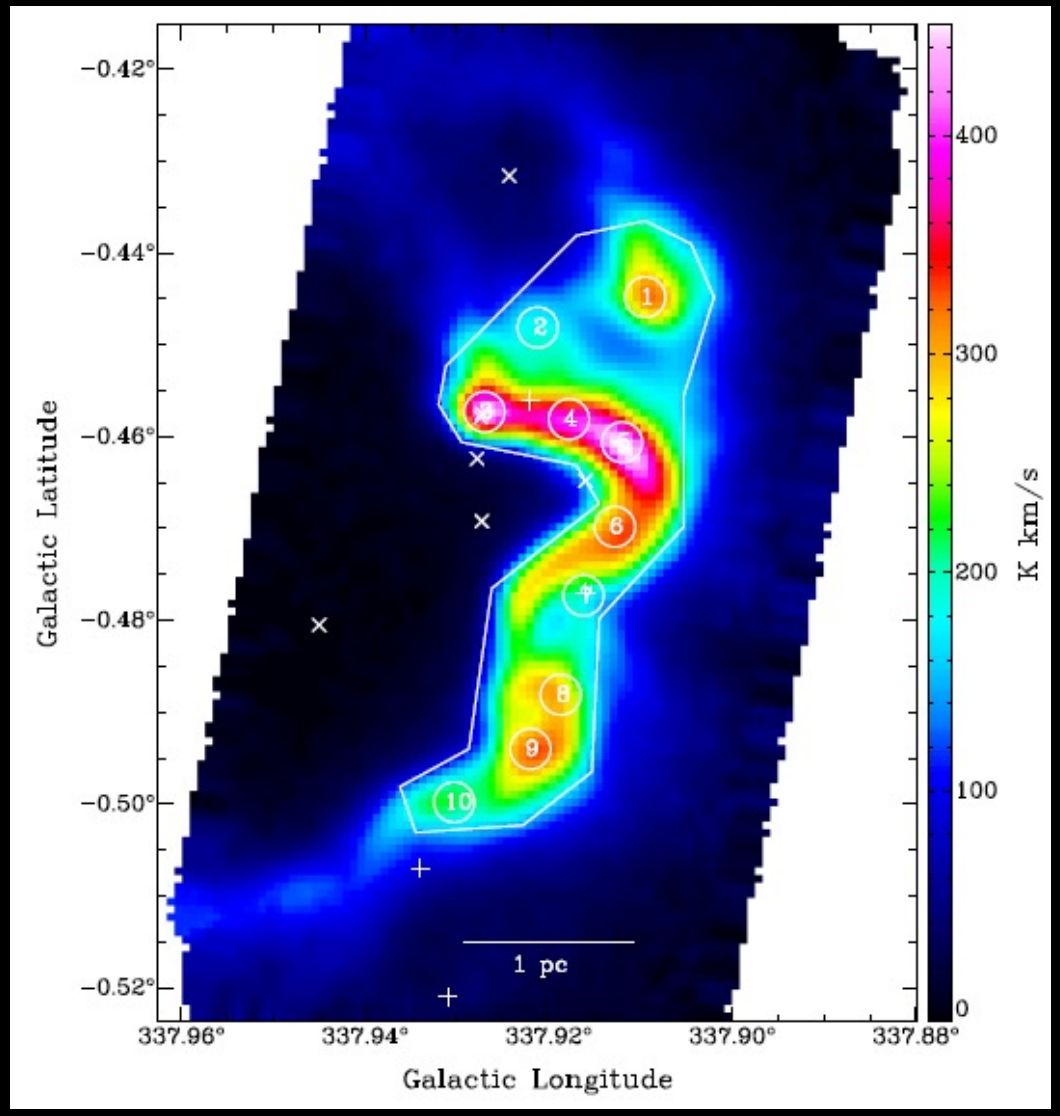
What do we see in Nessie?

The Nessie Bubble

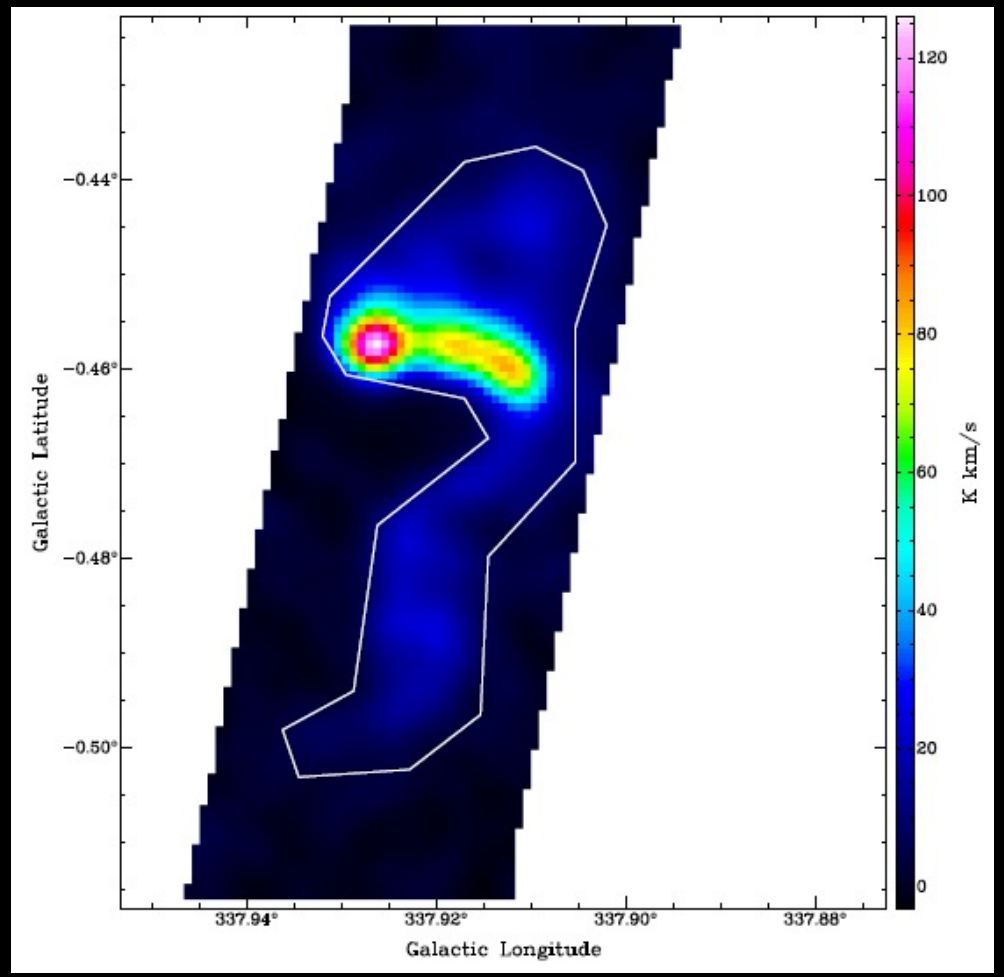
- Asymmetric ‘teardrop’ shape
- More luminous on the western side.
- Bright 8 μm emission in shell (PDR)

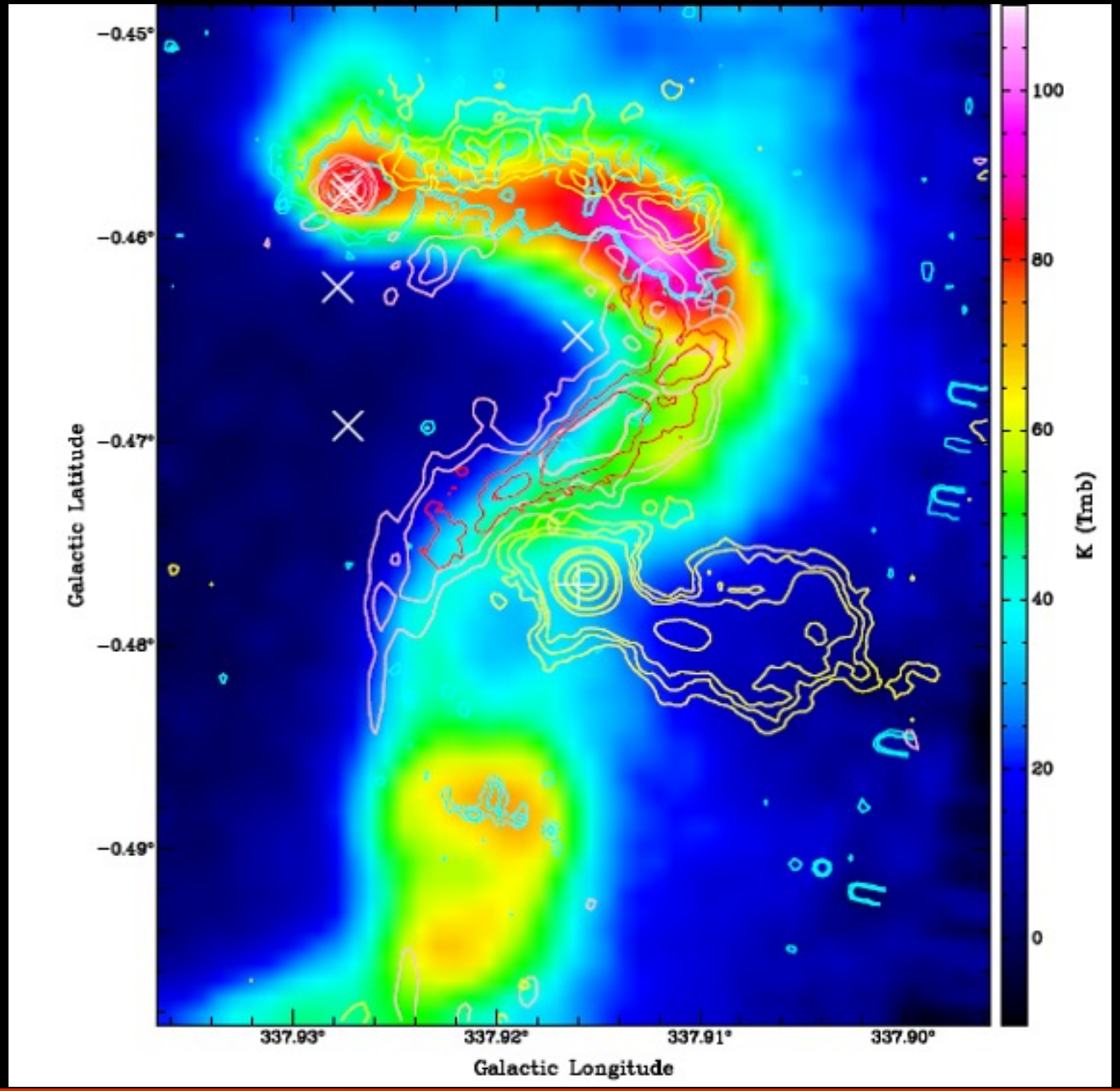
Region mapped with SOFIA and ATCA

[C II]


−0.42°
−0.44°
−0.46°
−0.48°
−0.50°
−0.52°
Galactic Latitude
337.96°
337.94°
337.92°
337.90°
337.88°
Galactic Longitude
1 pc
400
300
200
100
0
K km/s
1
2
3
4
5
6
7
8
9
10

[O I]

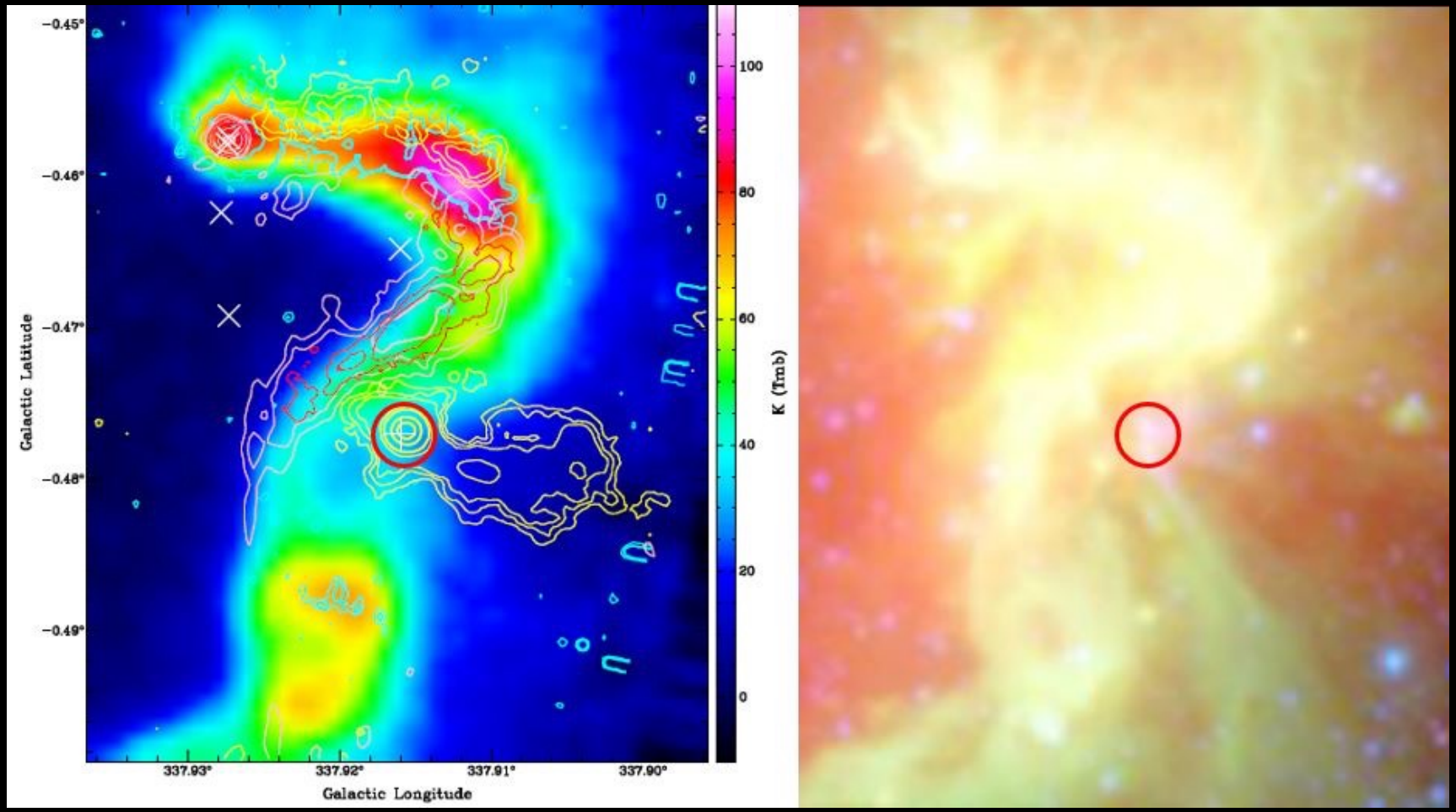

−0.44°
−0.46°
−0.48°
−0.50°
Galactic Latitude
337.94°
337.92°
337.90°
337.88°
Galactic Longitude
120
100
80
60
40
20
0
K km/s



Color: [C II]
Cyan: [O I]
Pink: 24 GHz Continuum
Red: H67α Recombination Line
Yellow: NH_3 (1,1)

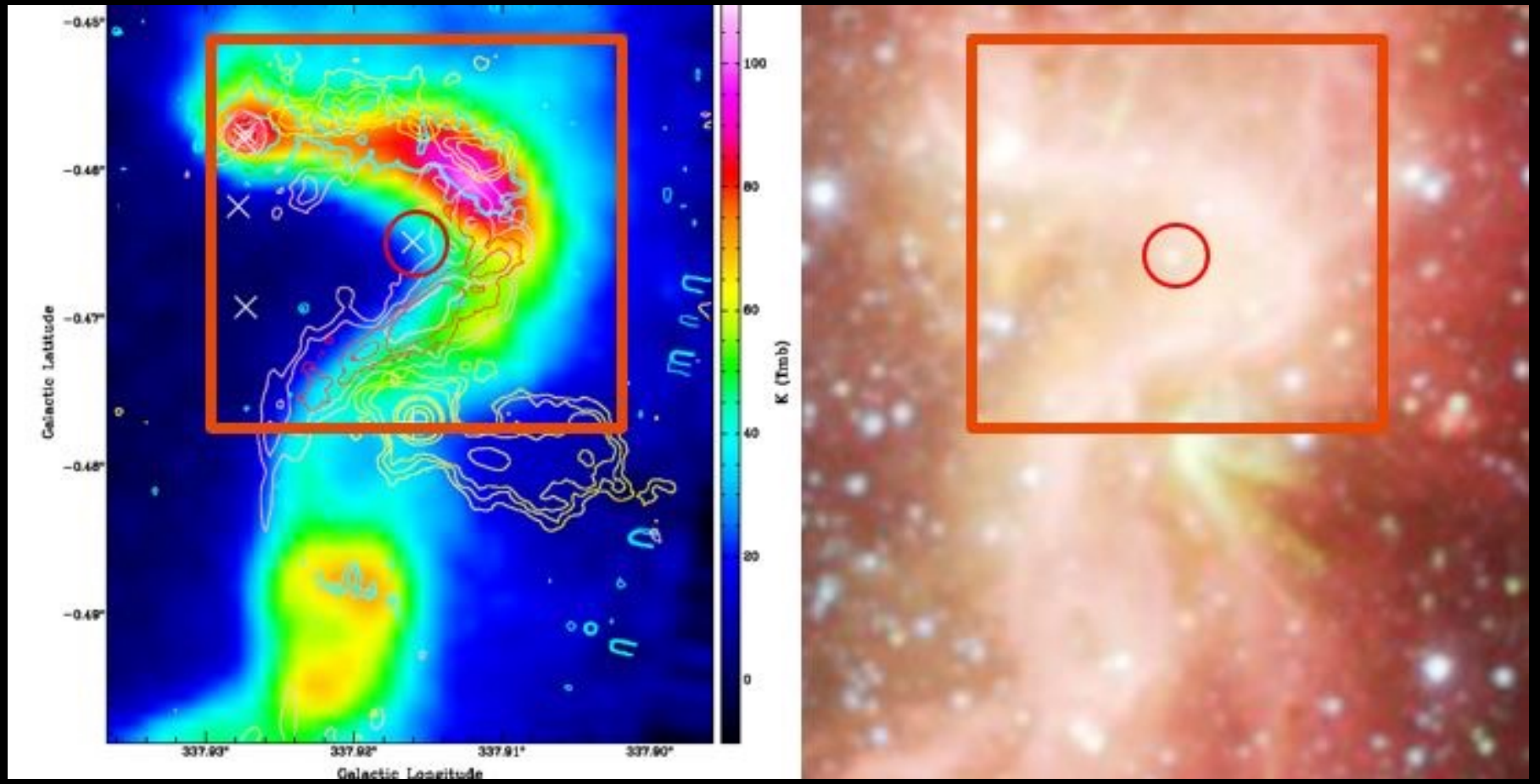
<u>Classic PDR structure:</u>
Ionized gas on the interior (radio continuum and H67α)
Photoionized gas in the middle ([C II] and [O I])
Molecular gas on the exterior (NH_3)

The luminous protostar

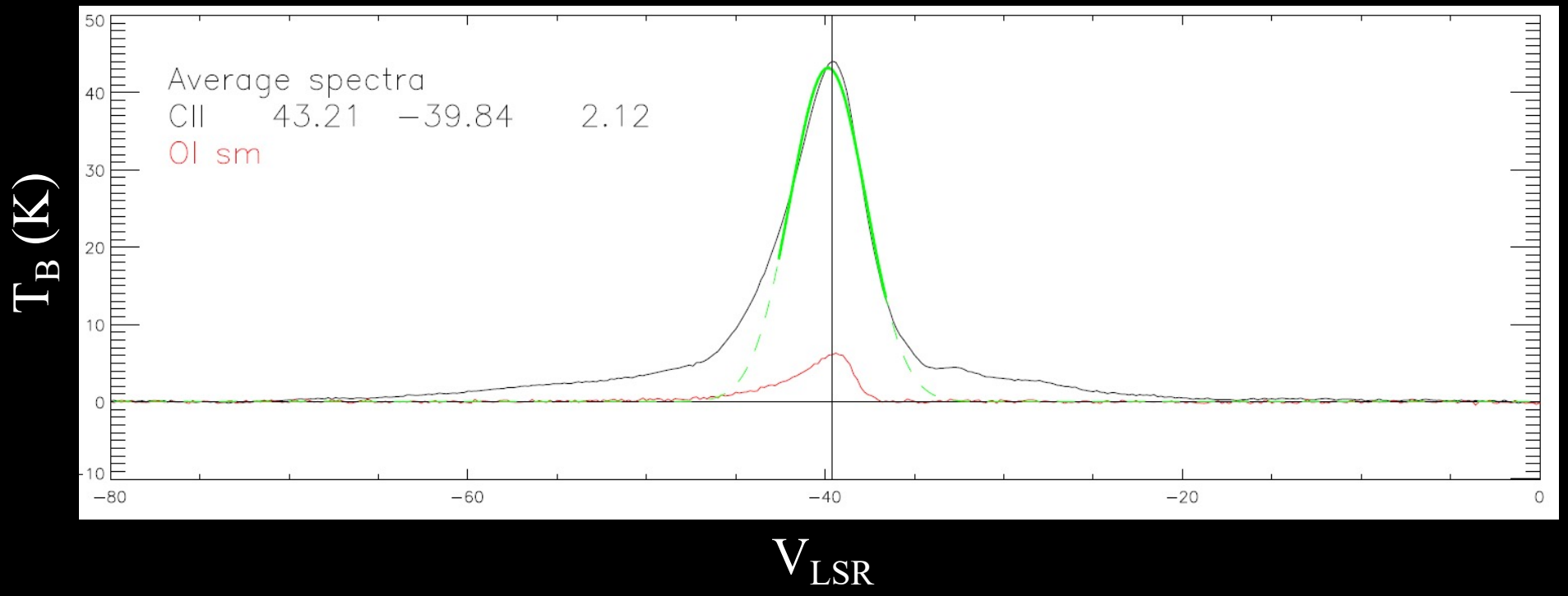


Color: [C II], cyan [O I], pink (radio continuum), red H67a, yellow NH_3 (1,1)

The “Mini-Bubble”



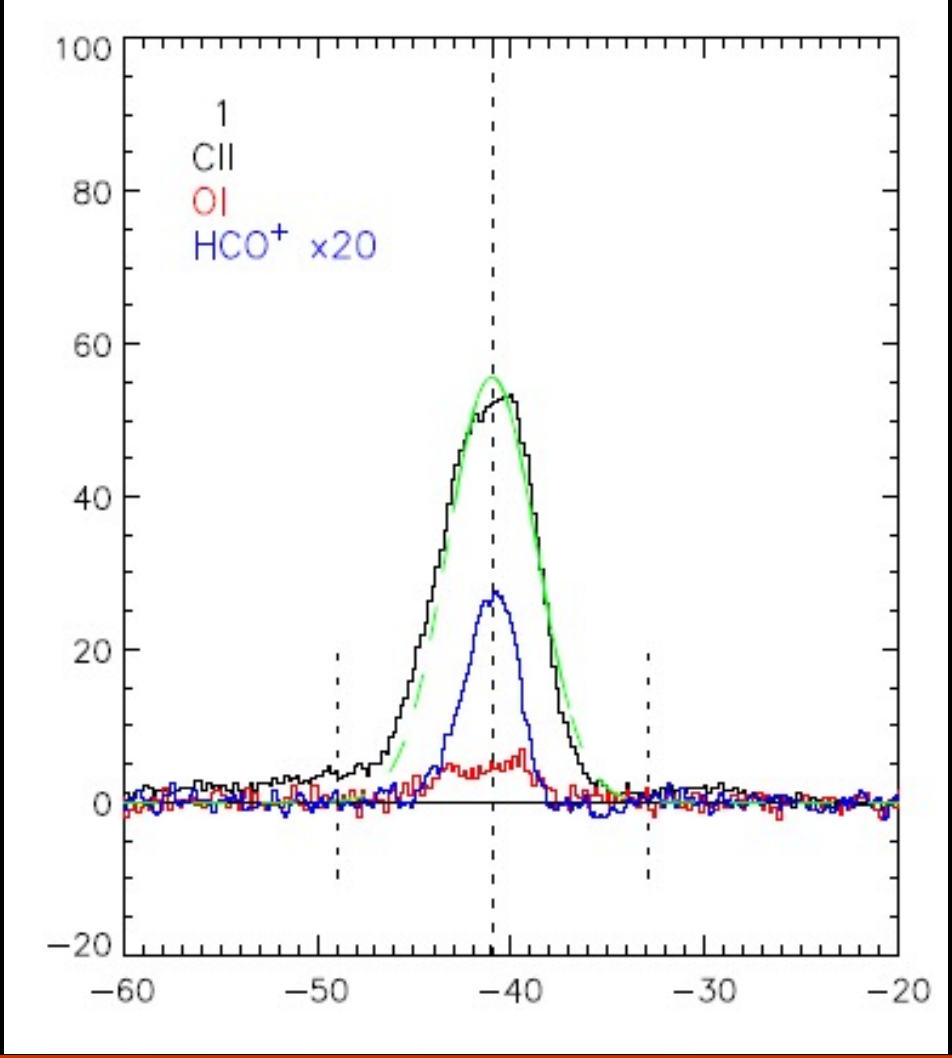
The 63 μm [O I] Line is Asymmetric

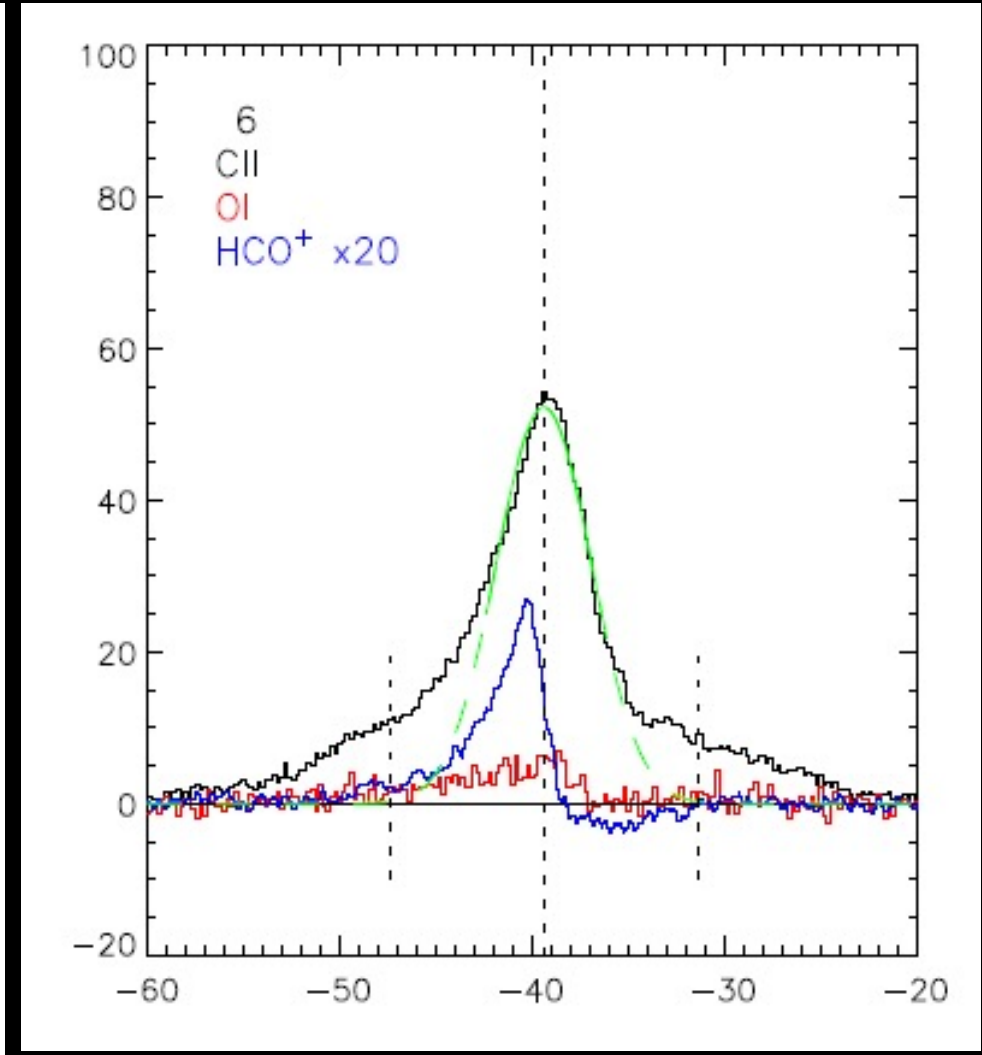


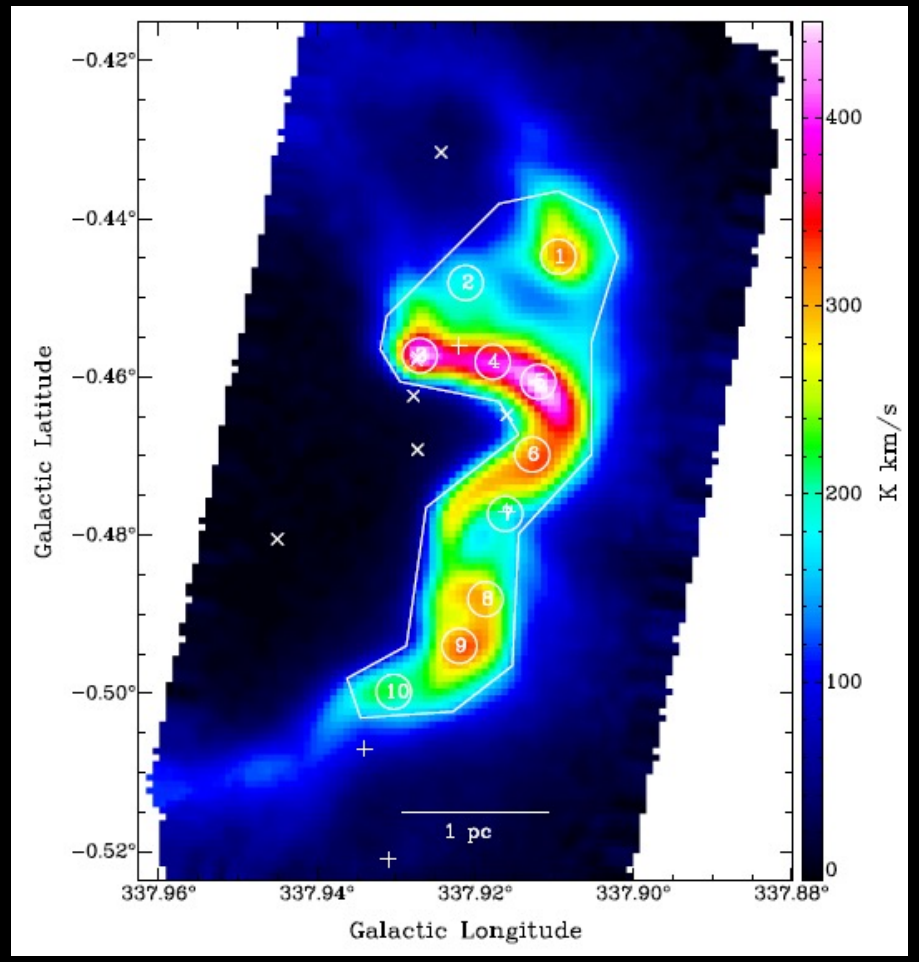
Averaged over the entire region, the [C II] line is symmetric but the [O I] line is asymmetric, with stronger blueshifted emission.

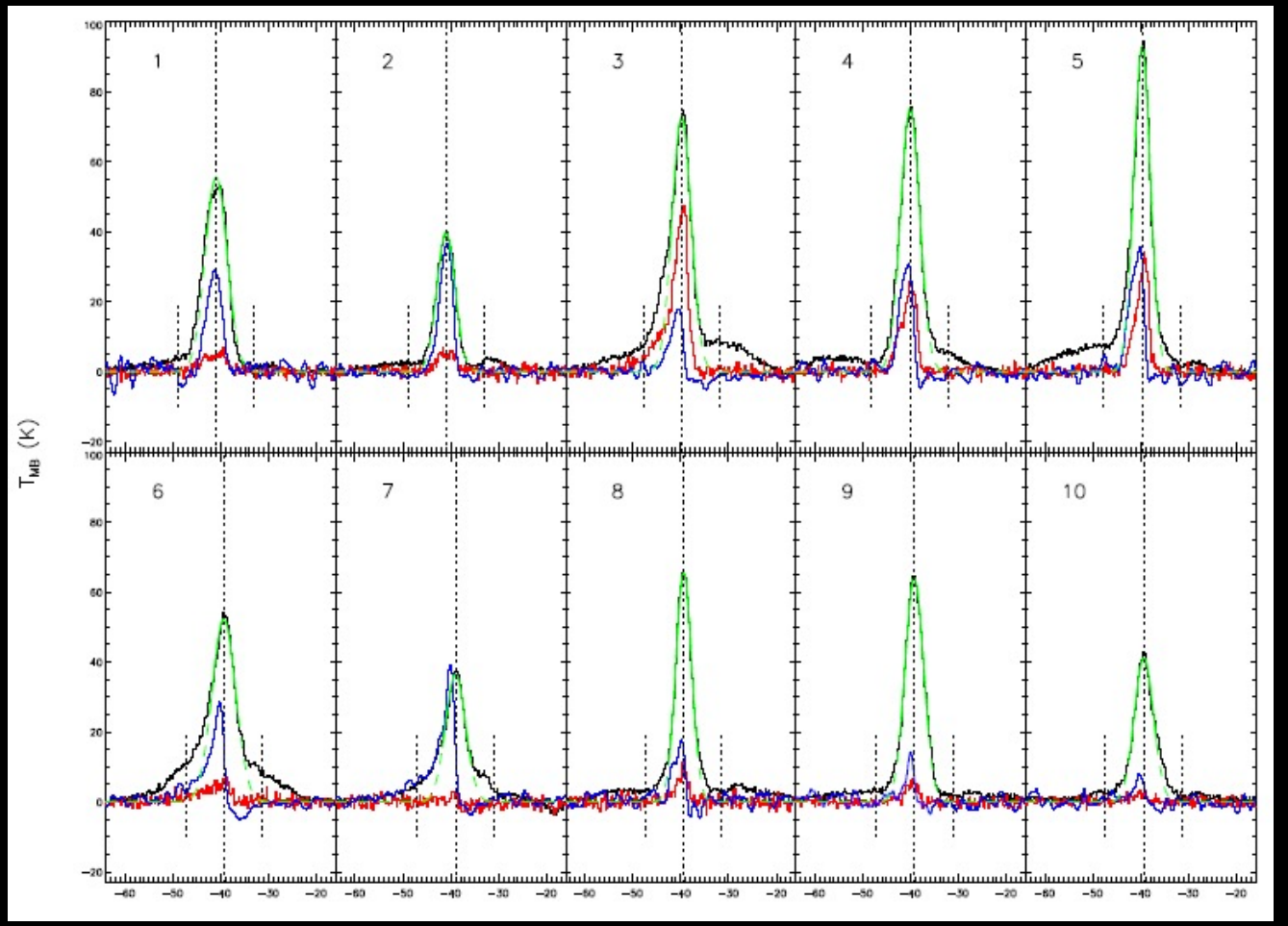
Self-absorption alters the [O I] line shape.

The [O I] line is often flat-topped (saturated) and asymmetric. [O I] is self-absorbed throughout the region



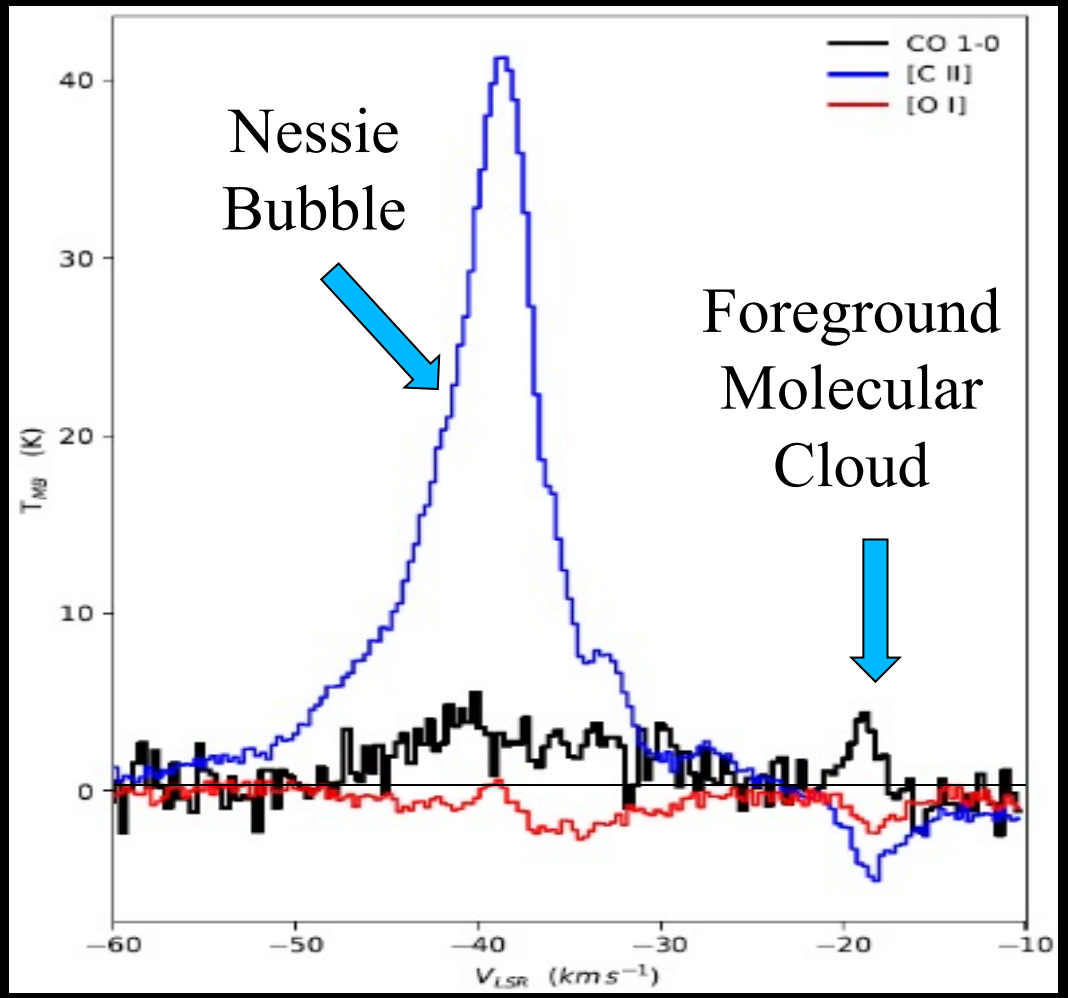






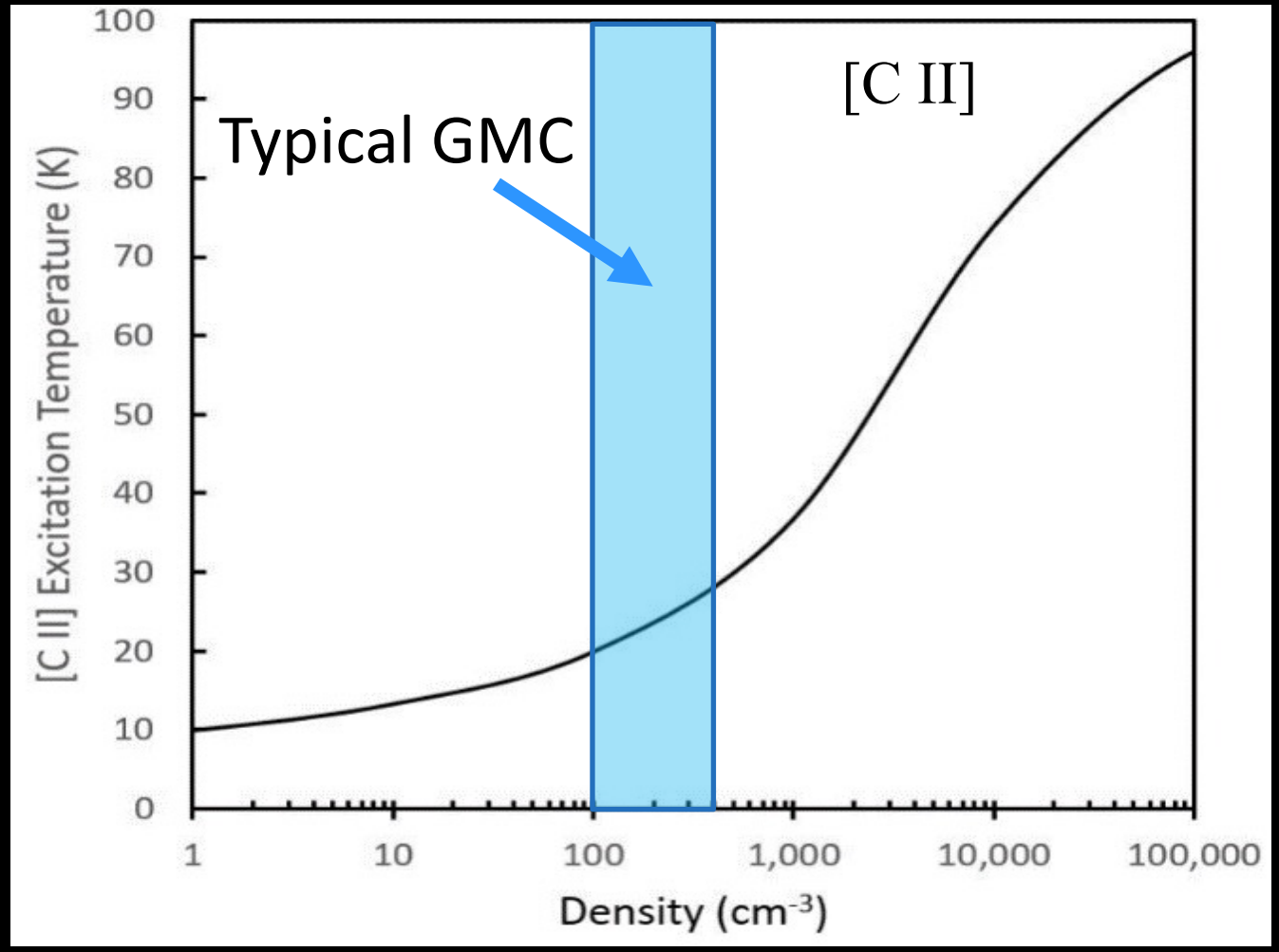
Black: [C II], Green: [C II] Gaussian fit, Red: [O I], Blue: HCO^+ 1-0

Absorption toward the Luminous Protostar: Coincident with a Foreground Molecular Cloud



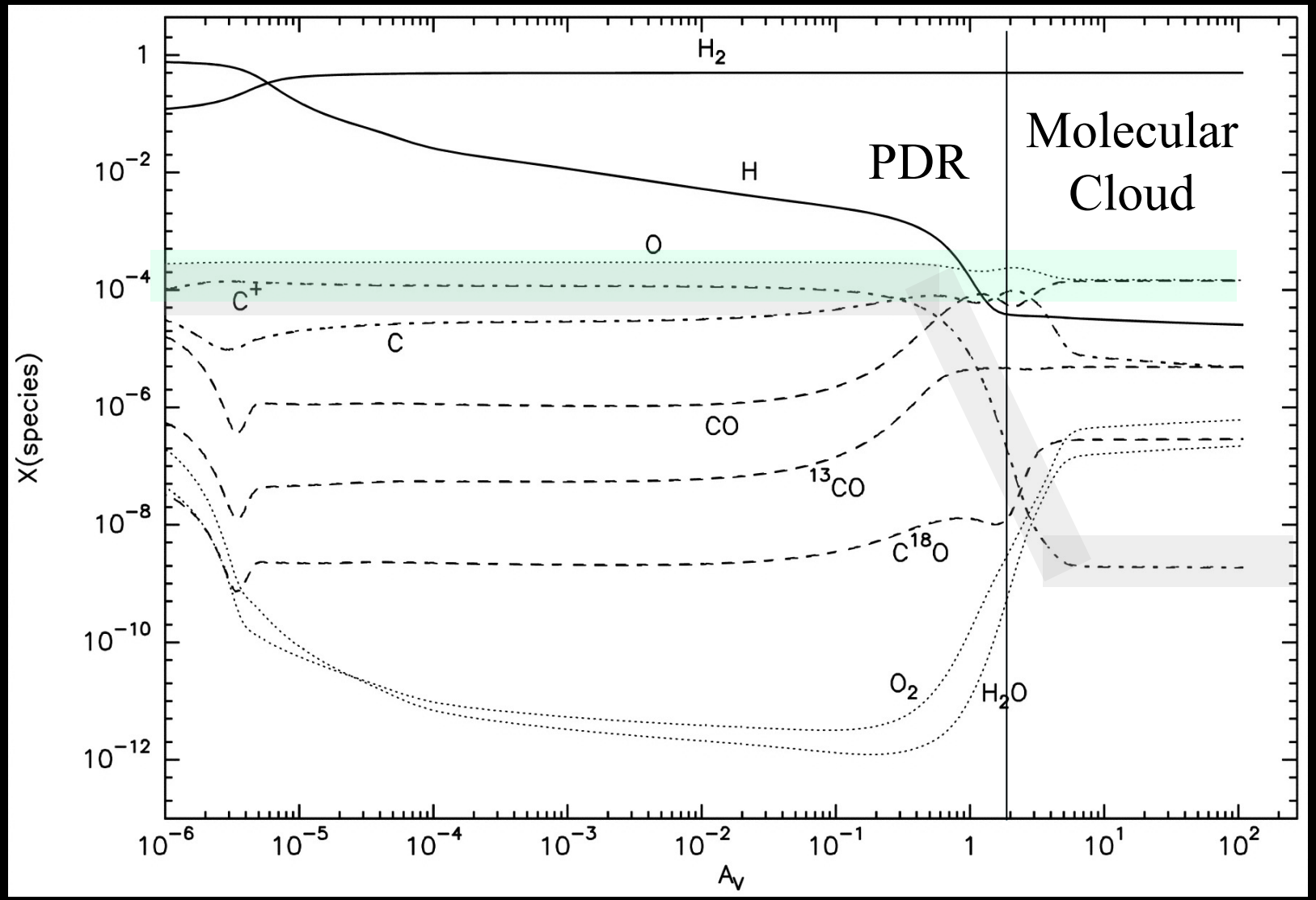
- Both [C II] and [O I] show absorption features against the continuum from the luminous protostar.
- These features are coincident in velocity with an unrelated foreground molecular cloud.

If the gas density *n* is well below the critical density, the excitation temperature is much smaller than T_{gas}



- The absorption features must arise from C^+ in warm gas (T_k>~100 K) yet the excitation temperature must be low.
- **Subthermally excited** gas with $n << n_{crit}$ of [C II] (~3300 cm^{-3}) will have low T_{ex} ~ 25 K

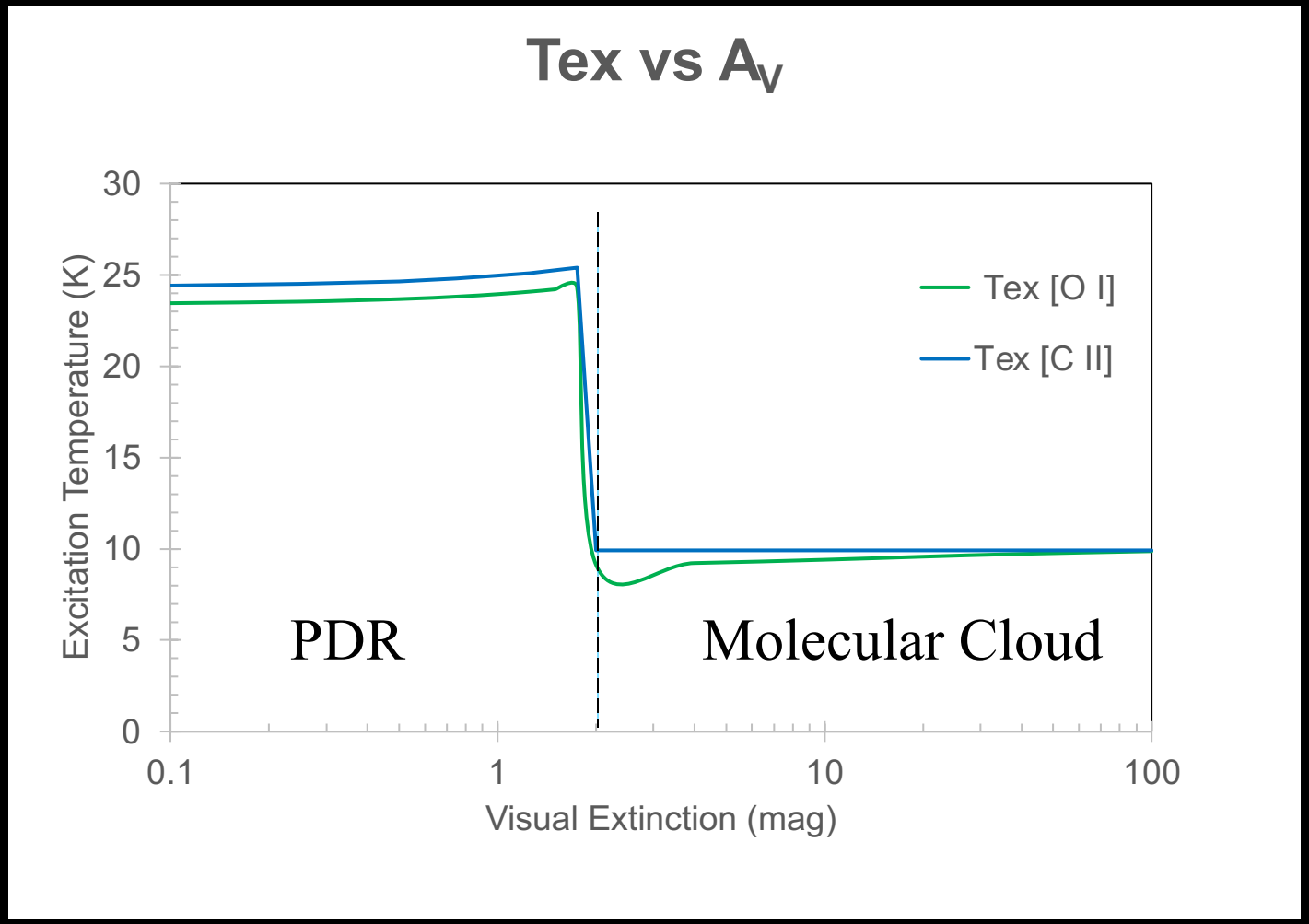
C^+ and O^0 Abundances in PDR and molecular cloud



$X(O^0)$ is ~constant from PDR into molecular cloud

$X(C^+)$ drops precipitously from PDR into molecular cloud (A_V~2)

For [C II] and [O I] the excitation temperature is low in both the low density skin and the molecular cloud



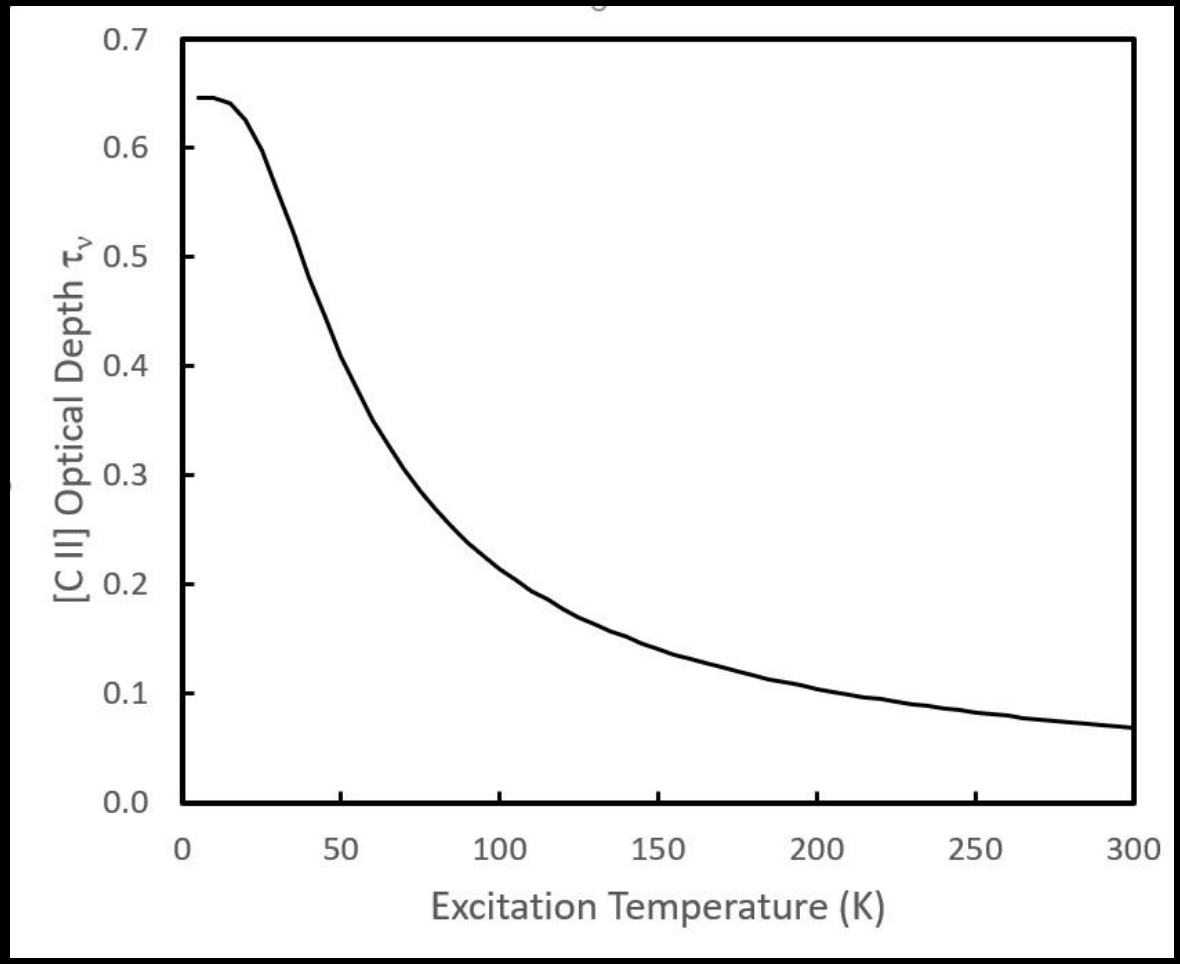
RADEX model
Two Zones:

PDR zone
T=100 K, n=300 cm^{-3}

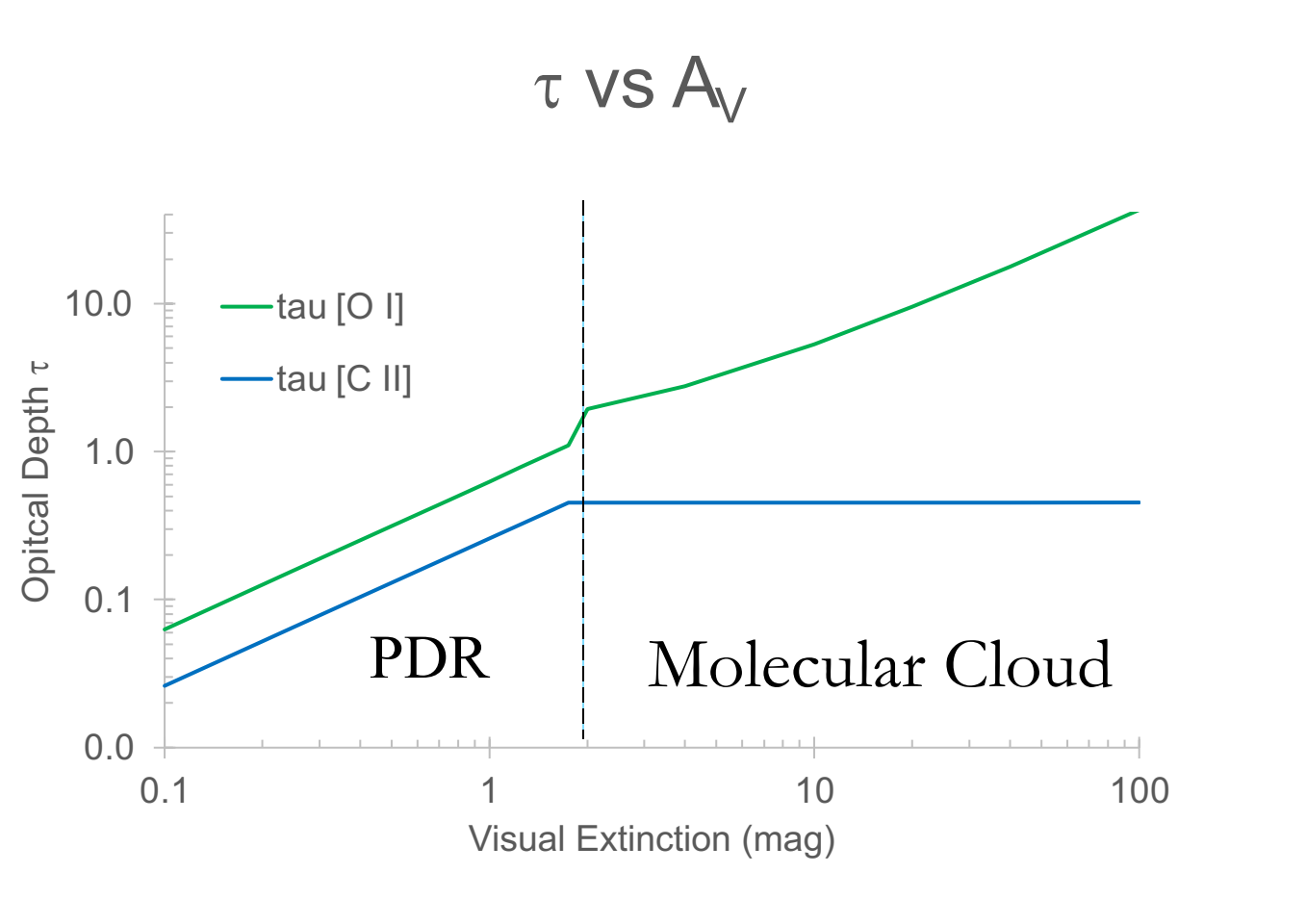
Molecular Cloud zone
T=10 K, n = 3,000 cm^{-3}

T_{ex} ~20 to 25 K in PDR zone even for T_{gas} = 100 K.

A molecular cloud "skin" (A_V ~2) has τ~0.6 for [C II]



For [C II] the optical depth is dominated by the PDR
For [O I] the optical depth is dominated by the MC

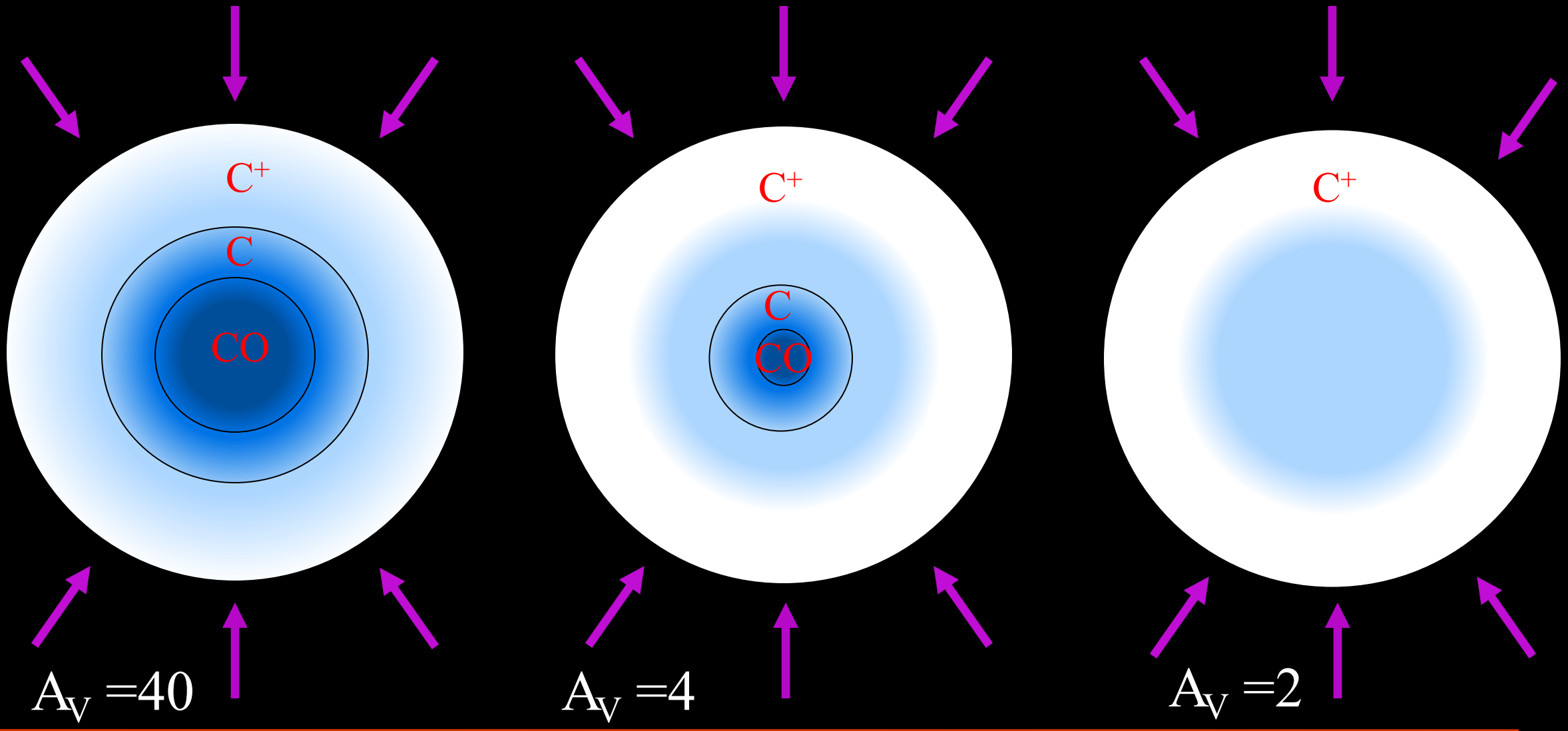


<u>RADEX model</u>
Two Zones:
PDR zone and
Molecular Cloud zone

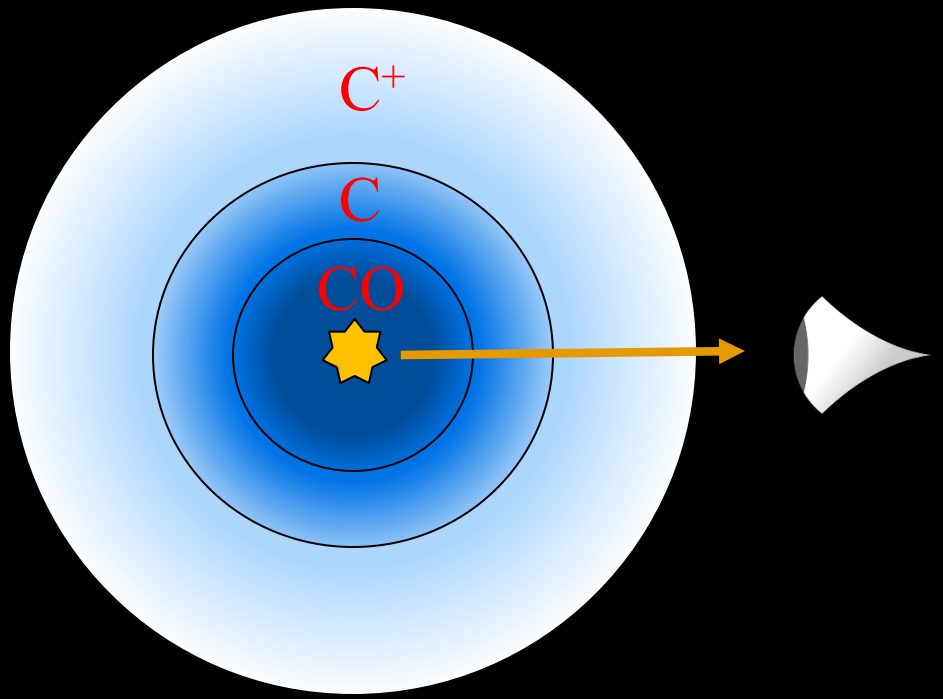
PDR: T=100 K, n=300 cm^{-3}

MC: T=10 K, n = 3,000 cm^{-3}

Externally Illuminated Clouds: All have a C^+ skin



For embedded sources, the line of sight always passes through the "skin" of the molecular cloud



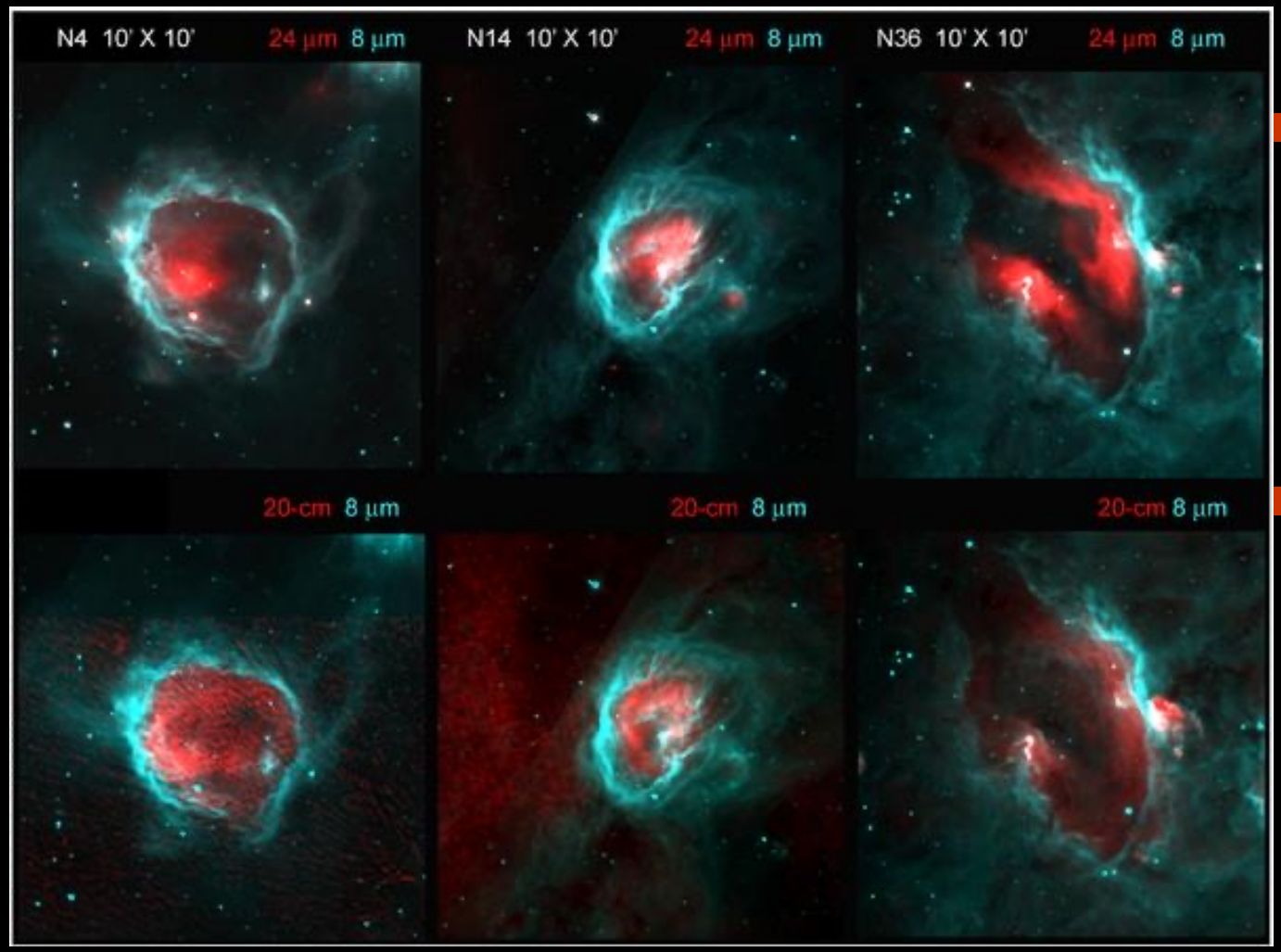
If the embedded source is a PDR self-absorption at the cloud velocity should occur.

If the embedded source is a continuum source, absorption at the cloud velocity should occur.

Hypotheses

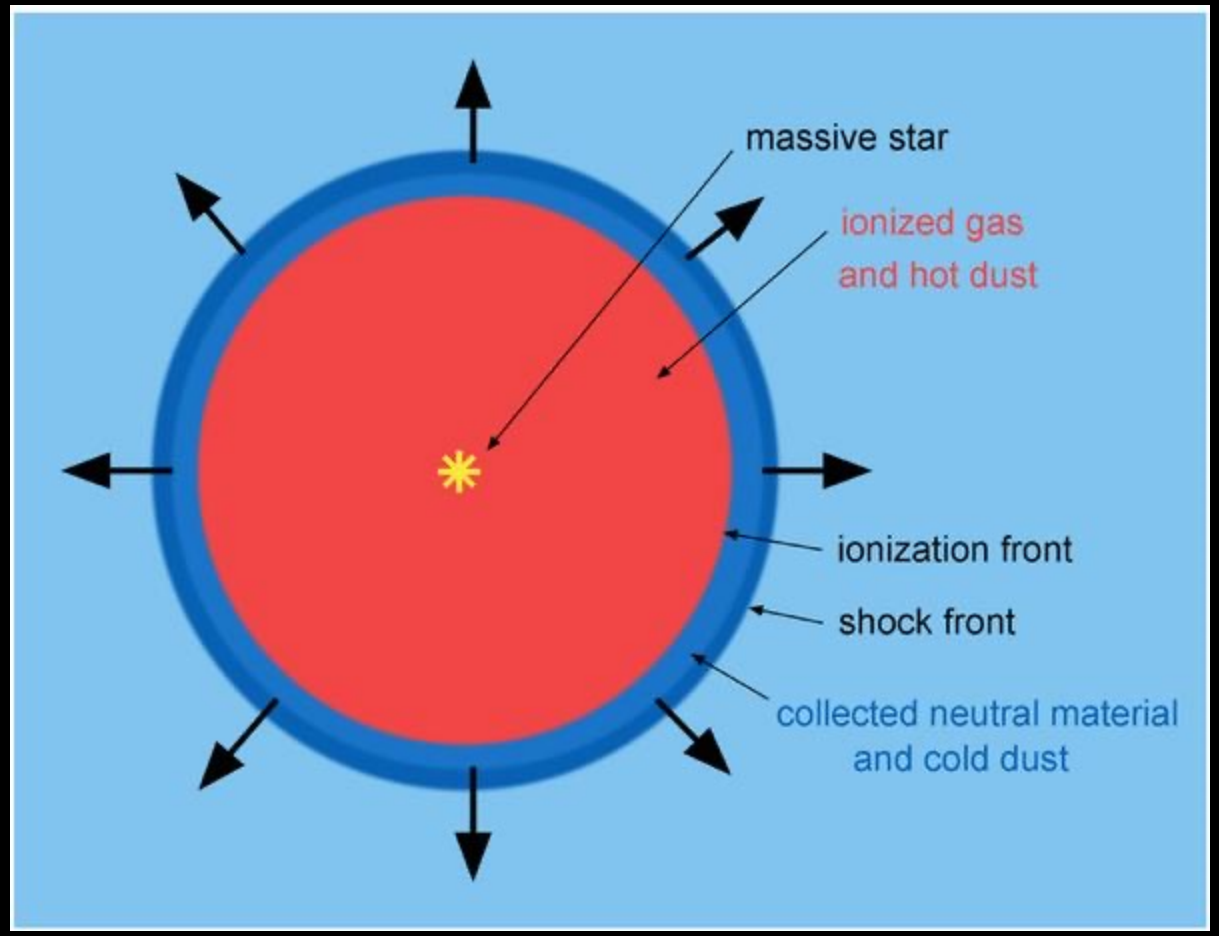
- [C II] absorption and self-absorption arises from the subthermally excited “skins” of molecular clouds or “CO dark clouds”.
- [O I] absorption and self-absorption is dominated by molecular gas.
- Radiation from embedded star forming regions typically pass through the “skin” of their own cloud, and thus should show [C II] absorption at the cloud velocity.
- In addition this radiation may happen to pass through foreground clouds, leading to [C II] and [O I] absorption at other velocities.

Expanding H II region bubbles



- Expanding H II regions contain a central region of ionized gas and hot dust.
- At their periphery, there is often a shell of collected neutral material and cold dust

Expanding H II region bubbles



- Stars can and do form in this dense shell
- “Triggered” star formation

Deharveng et al. (2010)

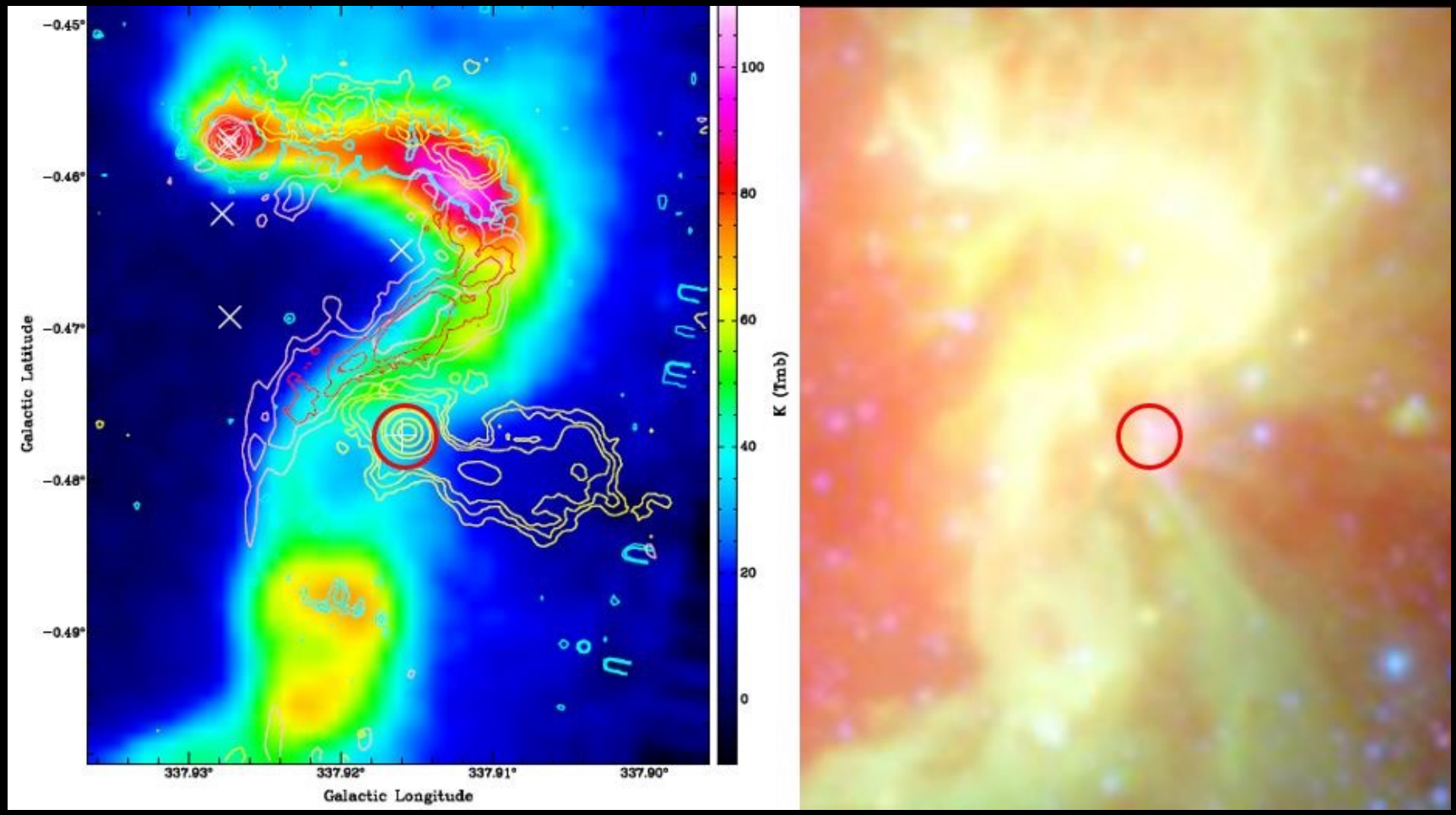
H II bubbles expanding into a filament

- The interaction with the densest gas occurs where the H II bubble interacts with the filament
- Since IRDCs are filamentary, bubble/filament interactions are likely important.
- Is there evidence for triggered star formation and bubble/filament interaction in Nessie?

Mid-IR Spitzer

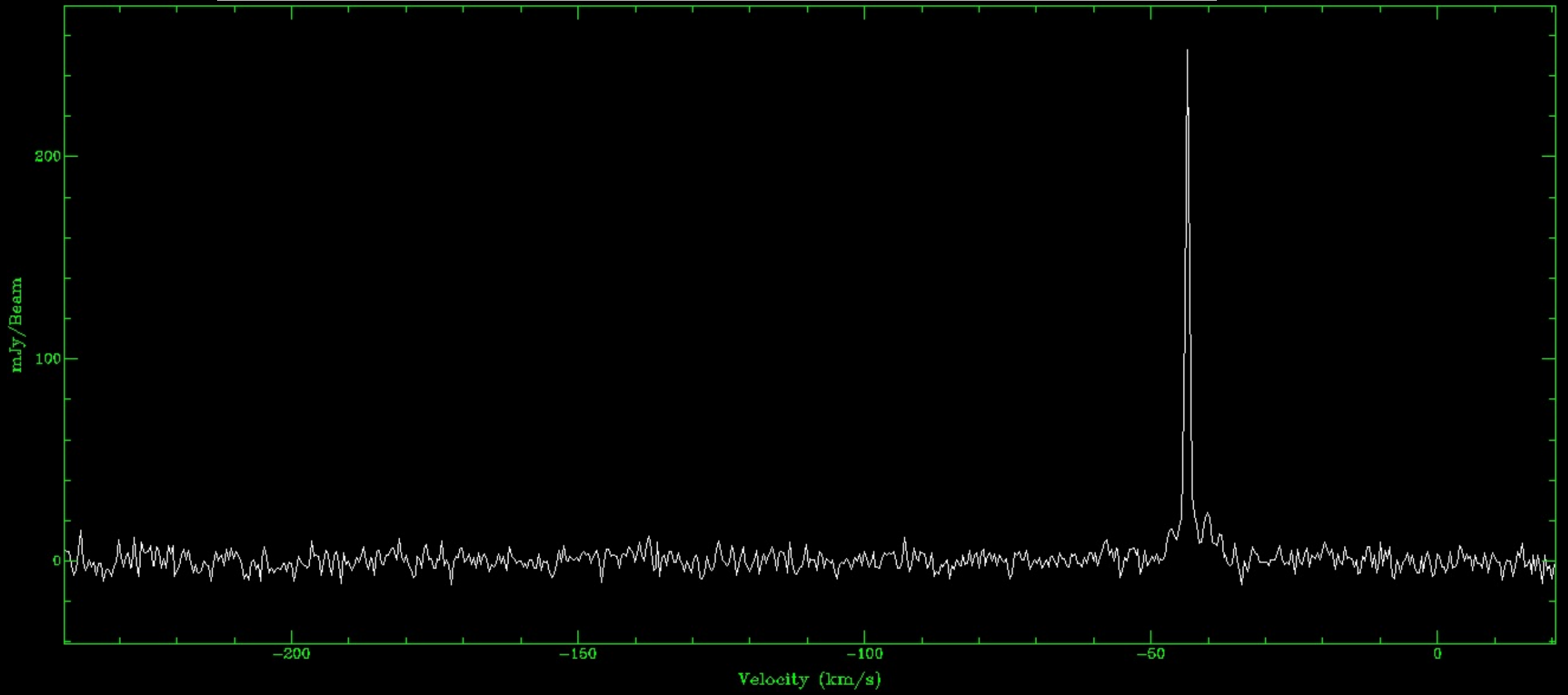
Near-IR 2MASS JHK:
Star cluster has formed that ionizes the mini-bubble

The luminous protostar: Forming where the bubble hits the filament

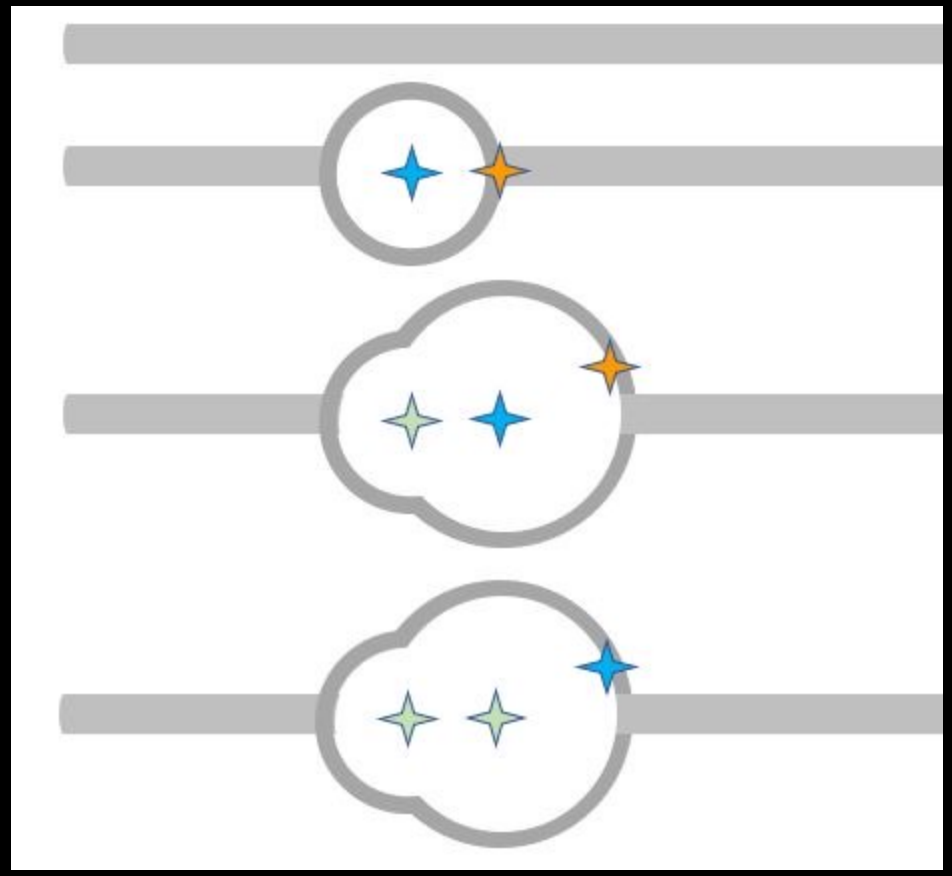


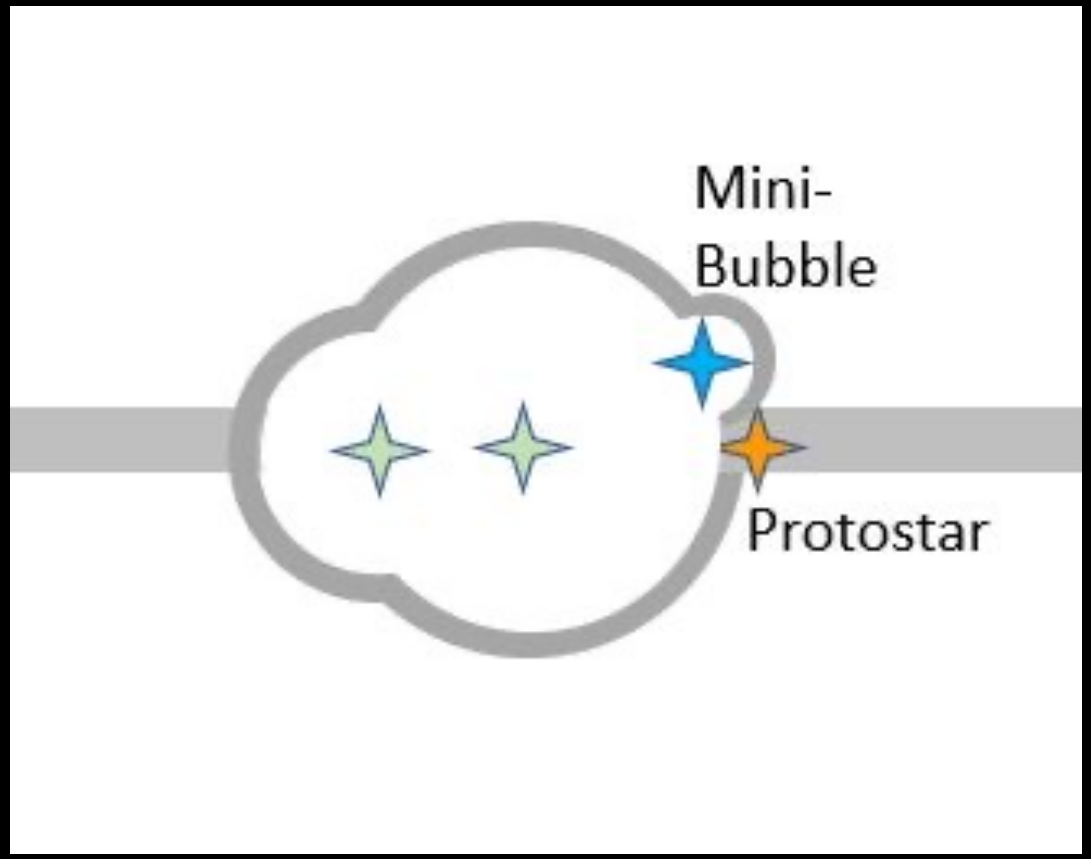
Color: [C II], cyan [O I], pink (radio continuum), red H67a, yellow NH_3 (1,1)

Shock at the Interaction Site: NH_3 (3,3) maser



A possible evolutionary scenario





Summary

- Blue asymmetries are found throughout Nessie in HCO+, indicating widespread collapse motions.
- The [O I] 63 μm shows self-absorption throughout the Bubble.
- Both [C II] and [O I] show absorption of continuum emission from the protostar due to an unrelated foreground molecular cloud.
- [C II] absorption probably arises from the photodissociated skins of molecular clouds or “CO dark” clouds.
- [O I] 63 μm absorption is much stronger in molecular gas.
- PDR models yield incorrect (often nonsensical) results if the lines are self-absorbed. Future work should take this absorption into account.