Transient ArH^+ emission in the Crab Nebula

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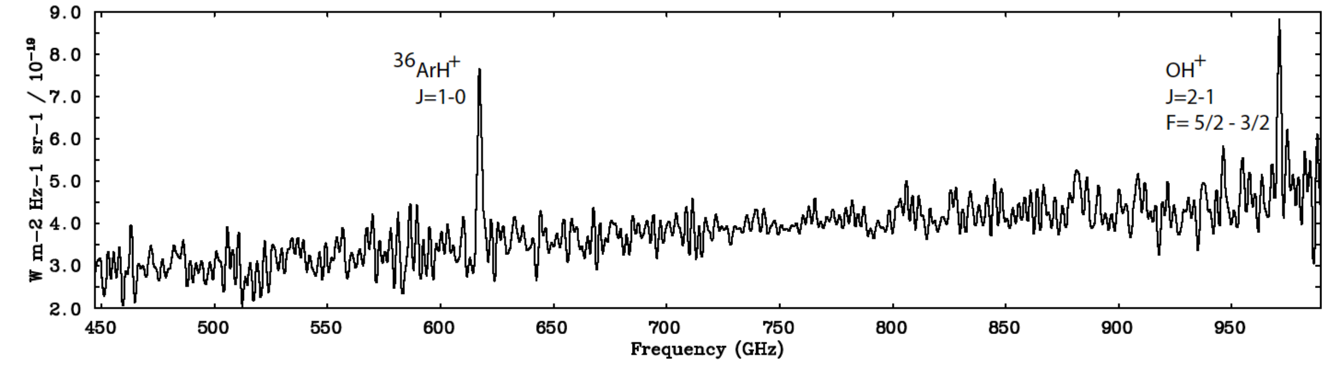
Getting ready for ALMA band 5 - synergy with APEX/SEPIA,
Garching, February 1, 2017

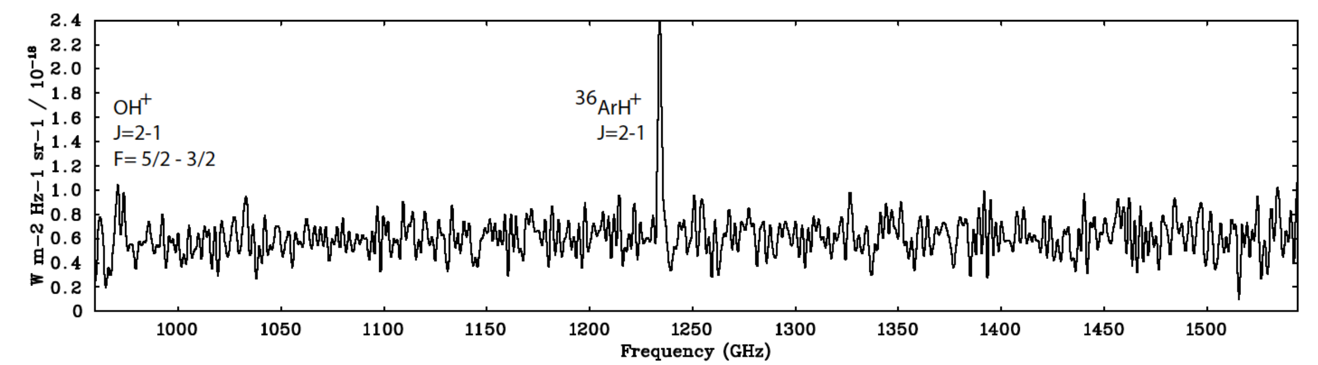
Outline

- History of ArH^+ observations
- APEX band 9 observations of the Crab Nebula
- Transient nature of ArH^+ emission!
- Modelling ArH^+ emission in the Crab Nebula
- Conclusions + future outlook

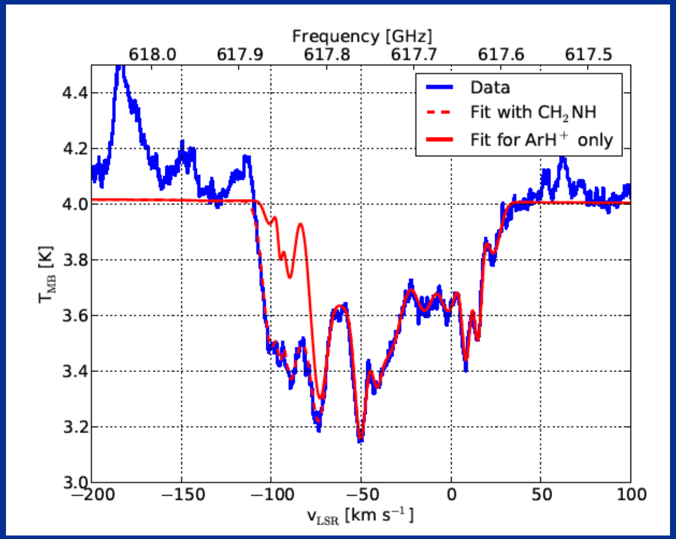
First ArH+ detection

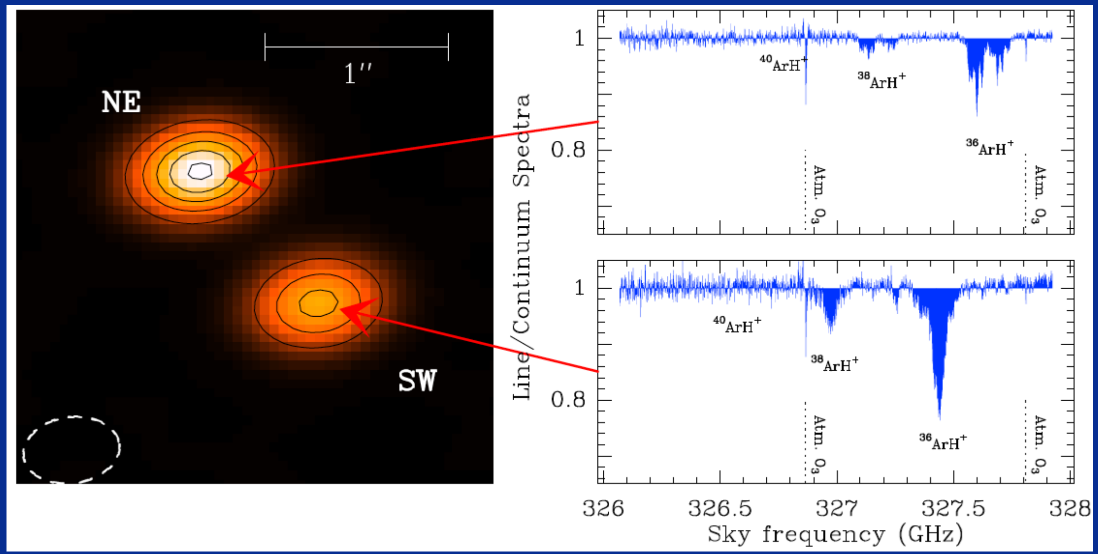
- The ArH^+ J=1-0 (617 GHz) and J=2-1 (1234 GHz) line transitions were identified *for the first time* in the SPIRE FTS observations of the **Crab Nebula** (Barlow+ 2013).





- Later detections of the ArH+ line were reported for the Galactic ISM (Schilke+ 2014) and an extragalactic source (Muller+ 2015), probing atomic hydrogen gas with H_2 fractions of 10^{-4}-10^{-3}.



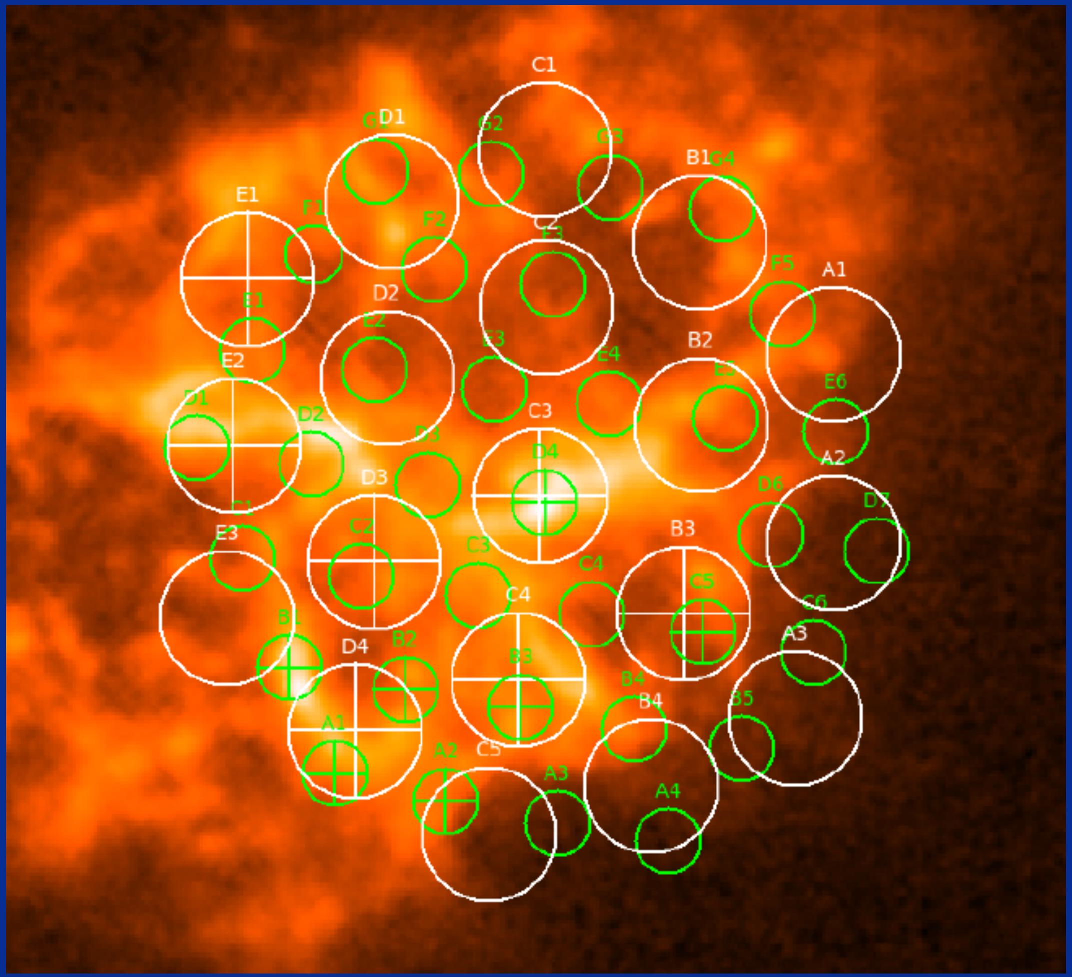


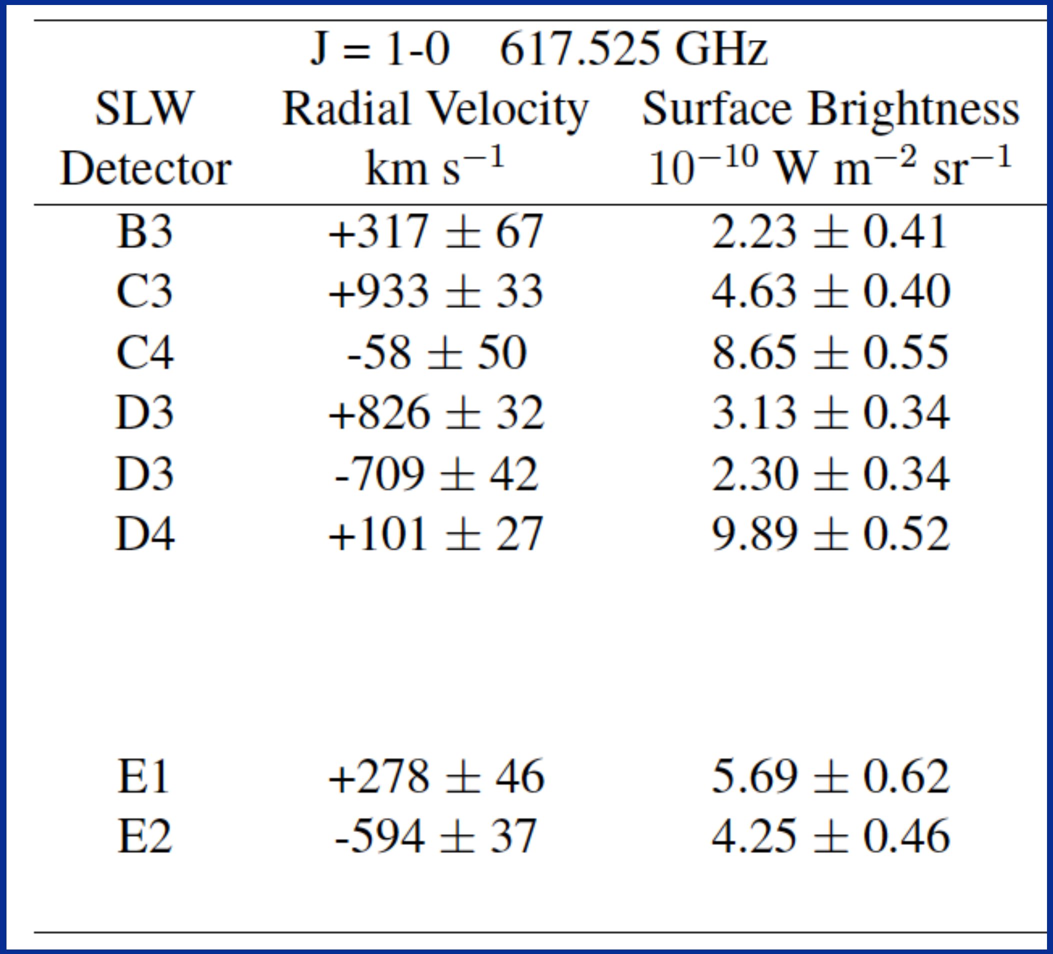
Crab Nebula

- The Crab Nebula is a Galactic supernova remnant with a central pulsar, responsible for the ionisation of most of the ejecta material.
- Most material is distributed in dense filaments
- It is the remnant of a 9-11 M_{sun} progenitor which exploded 1054 AD.
- Significant amounts of dust (0.2-0.5 M_{sun}) have also condensed in the Crab Nebula (Gomez+ 2012, Owen & Barlow 2015).

ArH⁺ in the Crab Nebula

- Bright ArH+ detections in several (mostly SE) positions in the Crab Nebula
- Radial velocities range from -1000 km/s to +1000 km/s





SLW Detector	J = 1-0 617.525 GHz Radial Velocity km s^{-1}	Surface Brightness 10^{-10} W m^{-2} sr^{-1}
B3	+317 ± 67	2.23 ± 0.41
C3	+933 ± 33	4.63 ± 0.40
C4	-58 ± 50	8.65 ± 0.55
D3	+826 ± 32	3.13 ± 0.34
D3	-709 ± 42	2.30 ± 0.34
D4	+101 ± 27	9.89 ± 0.52
E1	+278 ± 46	5.69 ± 0.62
E2	-594 ± 37	4.25 ± 0.46

Large SPIRE FTS beam (34” for ArH⁺ J=1-0, 19” for ArH⁺ J=2-1 line)
+ poor spectral resolution (~700 km/s)
—> difficult to constrain origin of ArH⁺ emission in the Crab Nebula

ArH^+ in the Crab Nebula

- The main route for ArH^+ **formation** is considered to be:

$Ar^+ + H_2 \longrightarrow ArH^+ + H$

with a reaction rate $8.4 \times 10^{-10}\ (T/300K)^{0.16}\ cm^3\ s^{-1}$ (Schilke+ 2014),
and Ar ionised by cosmic rays (CR).

- **Excitation** of ArH^+ can occur through collisions with H_2 molecules or electrons.

- With electron collisional excitation rates ~10^4 larger than for H_2, ArH^+ is believed to be mainly excited by collisions with electrons.

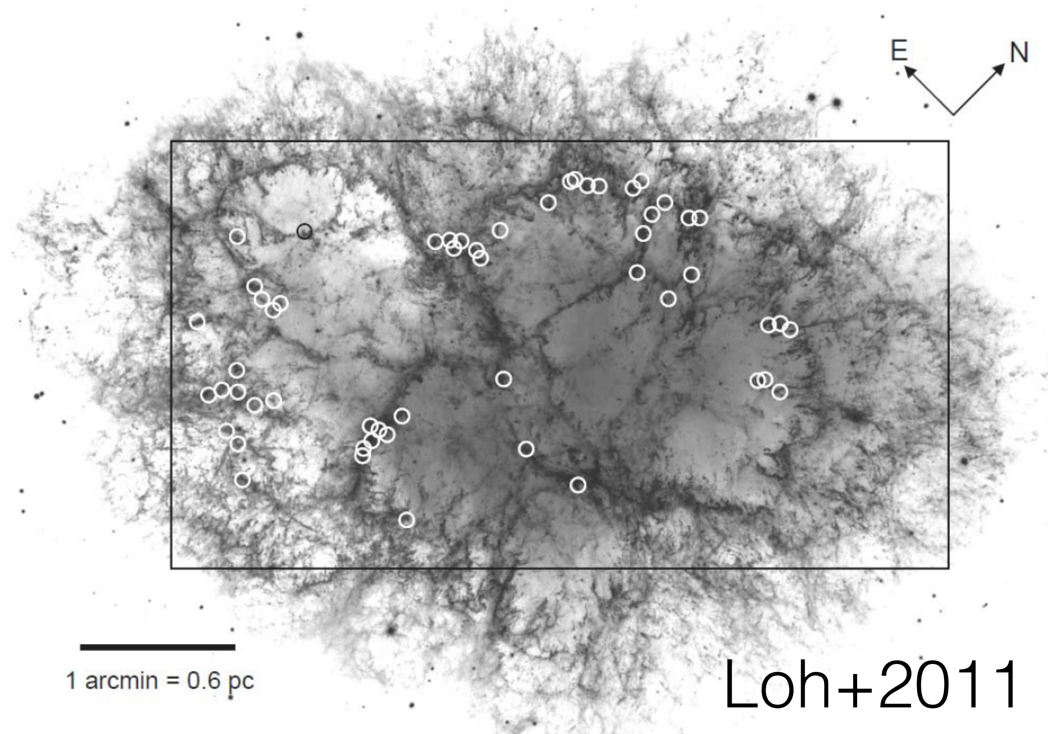
Formation of ArH^+ requires H_2 molecules + excitation through collisions with e^-
—> ArH emission must originate from partly ionised + partly neutral gas

ArH^+ in the Crab Nebula

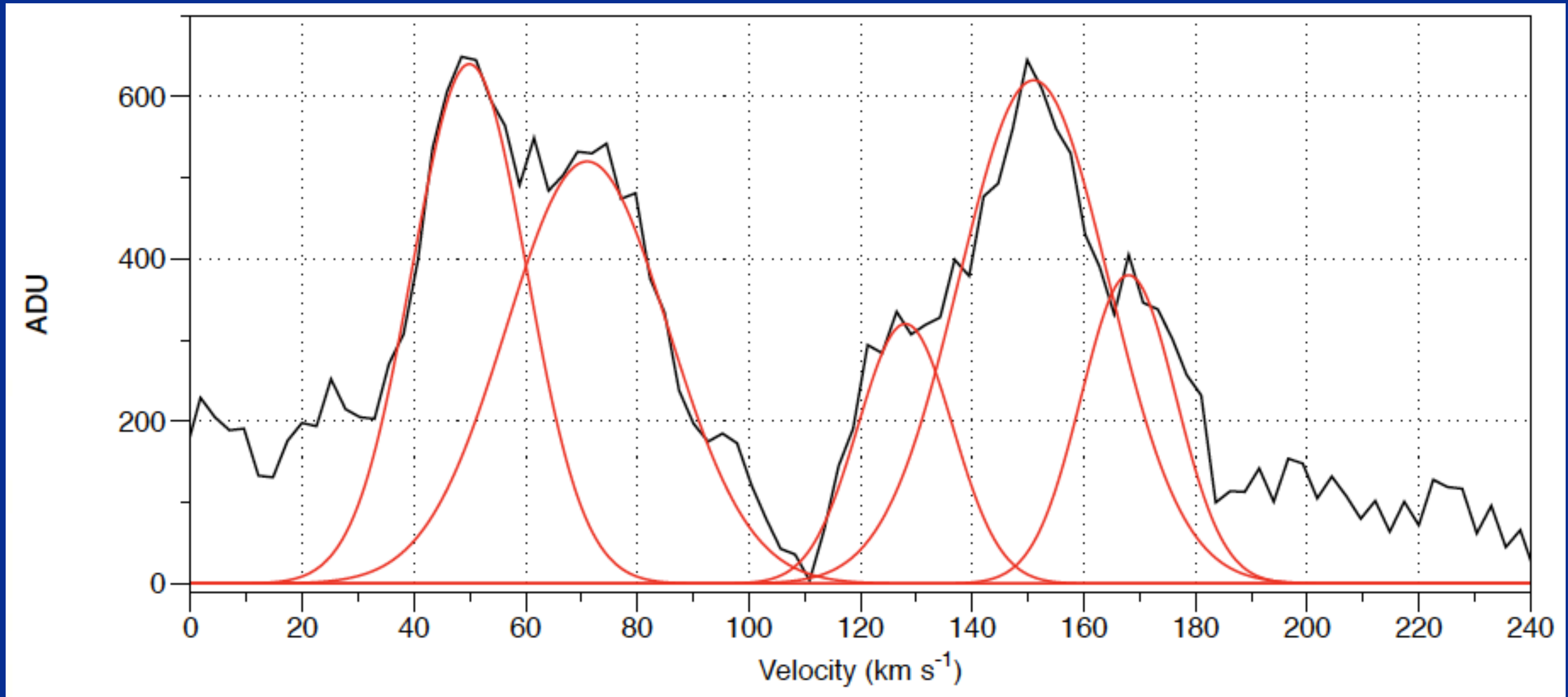
Our initial guess is that ArH^+ comes from the **surfaces of dense H_2 knots**.

- Typical sizes of H_2 knots of a few arcsec (Loh+2011,2012)
- High T_{ex}~ 2000-3000K (close to dissociation T of H_2)
- Total H_2 mass >= $2x10^{-3}$ M_{sun}

- Our high spectral resolution (R~30000 or a few km/s) follow-up IRTF CSHELL observations of H_2 2.112 μm start resolving H_2 line profiles with ~40 km/s line widths.

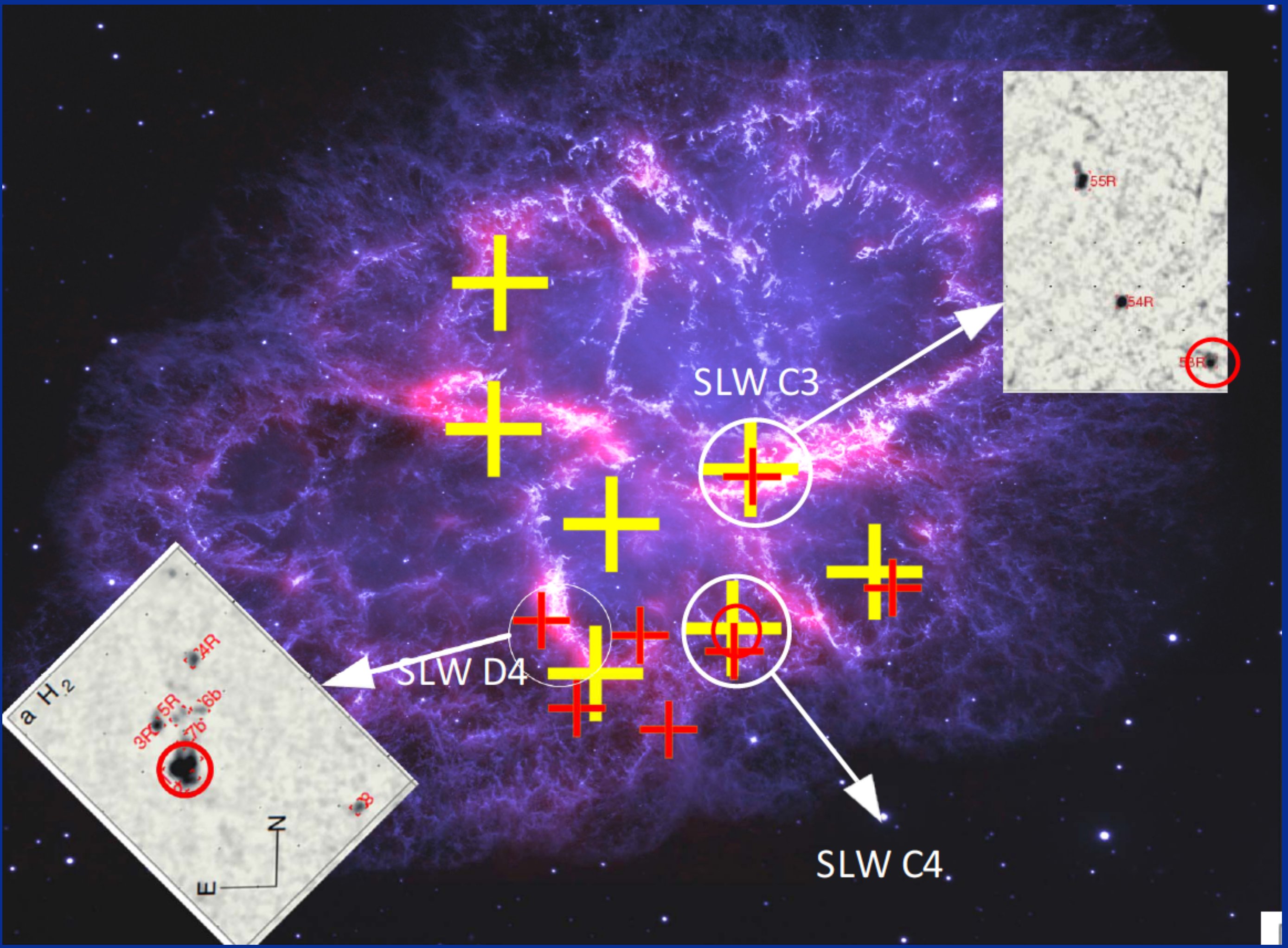


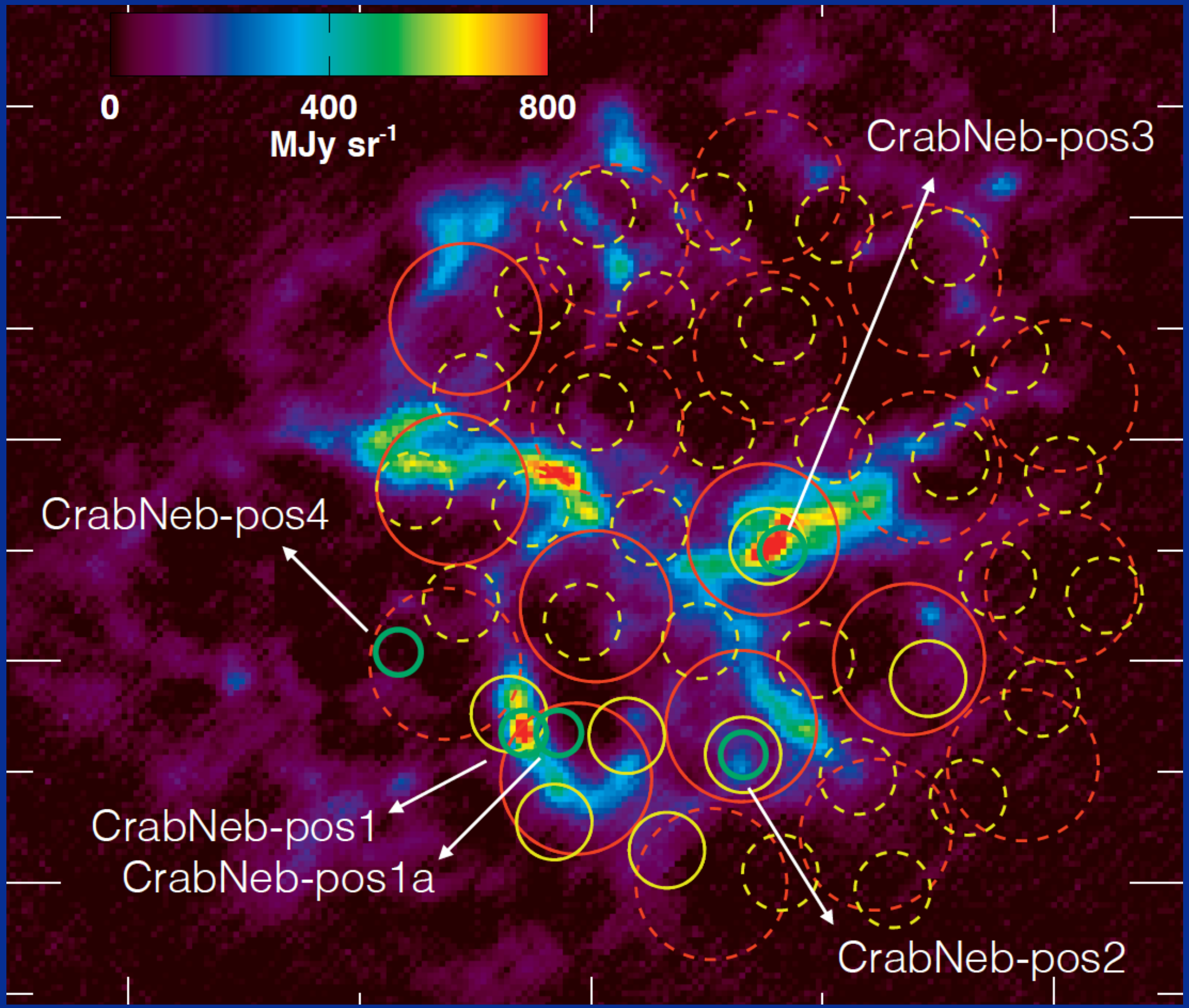
Loh+2011



APEX ArH$^+$ observations

We target dense H_2 knots (+ position offset from H_2 knot) in brightest SPIRE FTS detections of ArH$^+$ with APEX SEPIA band 9 (FWHM ~ 10.2”).



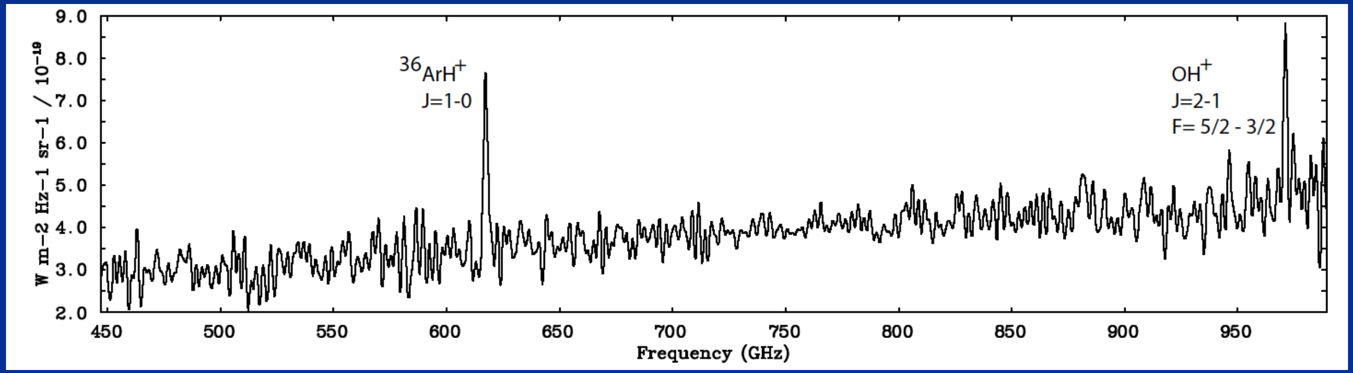


APEX ArH$^+$ observations

We detect ArH$^+$ J=1-0 in Pos1 and Pos2 (not in Pos1a, Pos3 and Pos4), but the line is surprisingly **WEAKER** and **NARROWER** compared to the SPIRE FTS detections!

Pos1

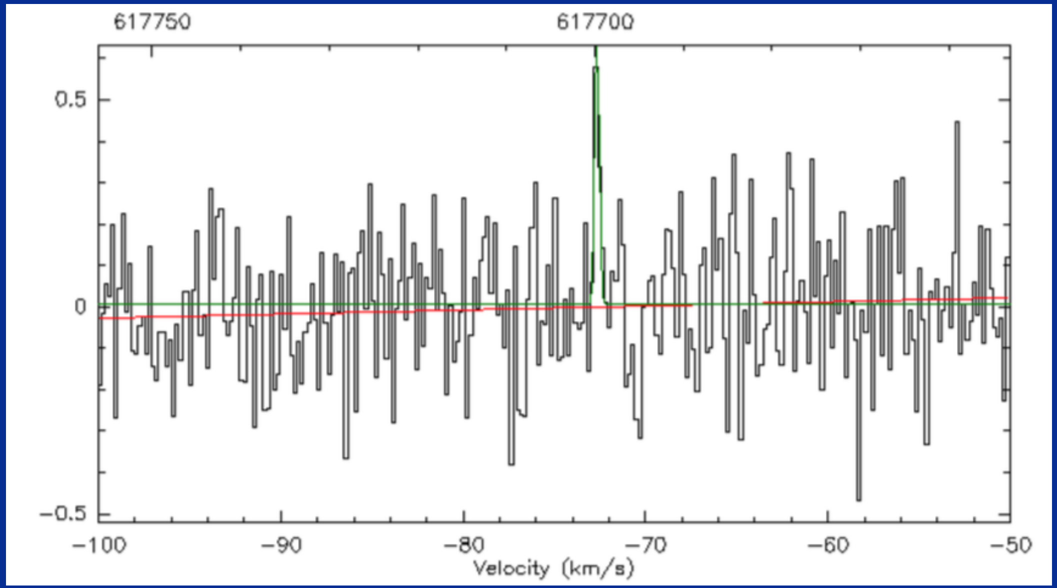
SPIRE FTS SLW-D4



FWHM ~ 34 arcsec
S_ν = 9E^{-10} W/m^2/sr

—> we expect a peak flux = 0.4 K
(for a 40 km/s line)
peak flux = >10 K
(for a <1 km/s line)

APEX SEPIA band 9



FWHM ~ 10.2 arcsec
Peak line flux ~ 0.6 K
V_{helio} = -73 km/s (agrees with SPIRE FTS)
but Δv = 0.5 km/s
—> **line = 40x weaker than expected!!!**

De Looze+2017 in prep

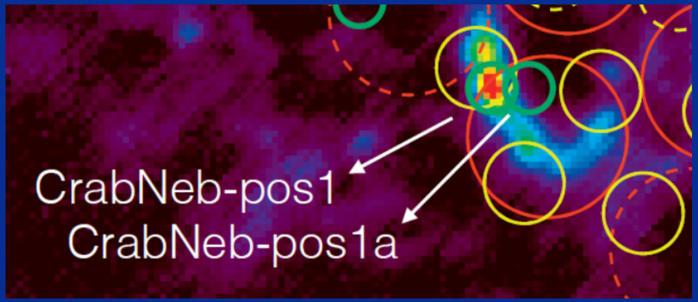
APEX ArH^+ observations

What causes ArH^+ J = 1-0 line to be 40x weaker than expected?

1. **Uniform distribution of ArH^+** ? (not just bright H_2 knots)
   + APEX beam (10.2”) < SPIRE FTS (34”)

   but $\frac{34}{10}^{2} \sim 11$ (not enough to explain huge difference)

   but no detections in adjacent pointings around Pos1



2. We are missing the brightest ArH+ emission?
   —> need to map the entire beam to rule this out!

3. **ArH^+ originates from several small clumps** (at $\neq v_{rad}$) within the beam
   —> given the current ArH^+ lines detections of 3-4σ with APEX, it is possible that we are missing fainter narrow lines at a different radial velocity (v_{rad} between -1000 km/s and 1000 km/s!)

De Looze+2017 in prep

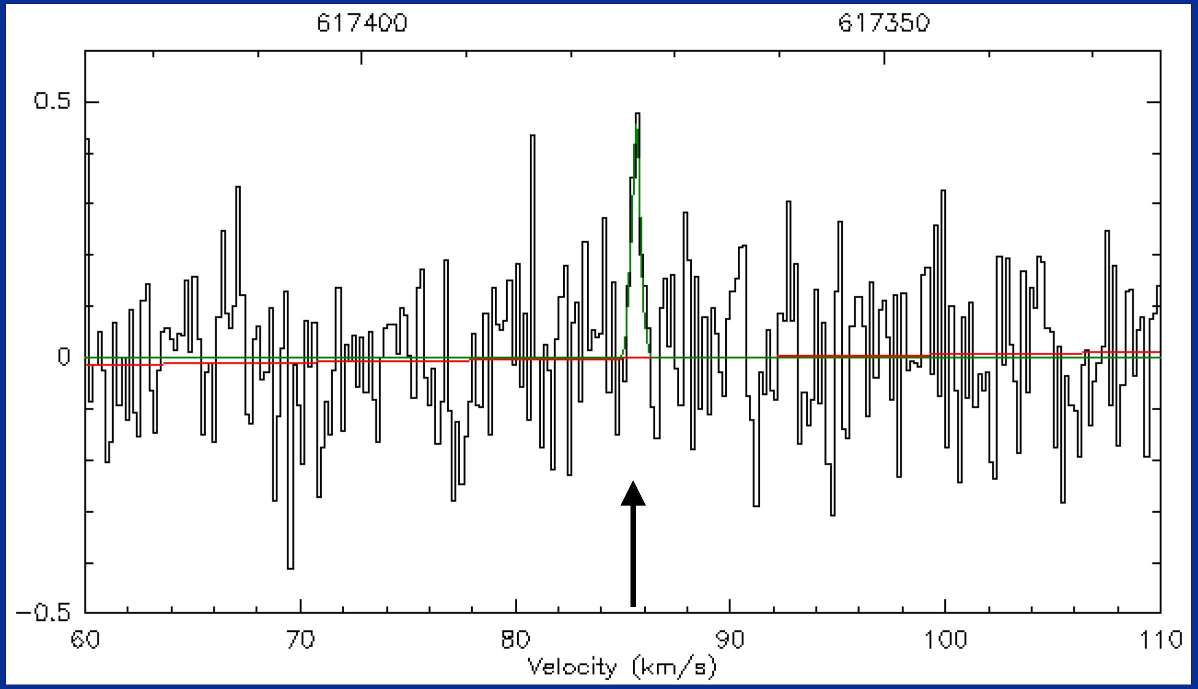
Transient ArH$^+$ emission?

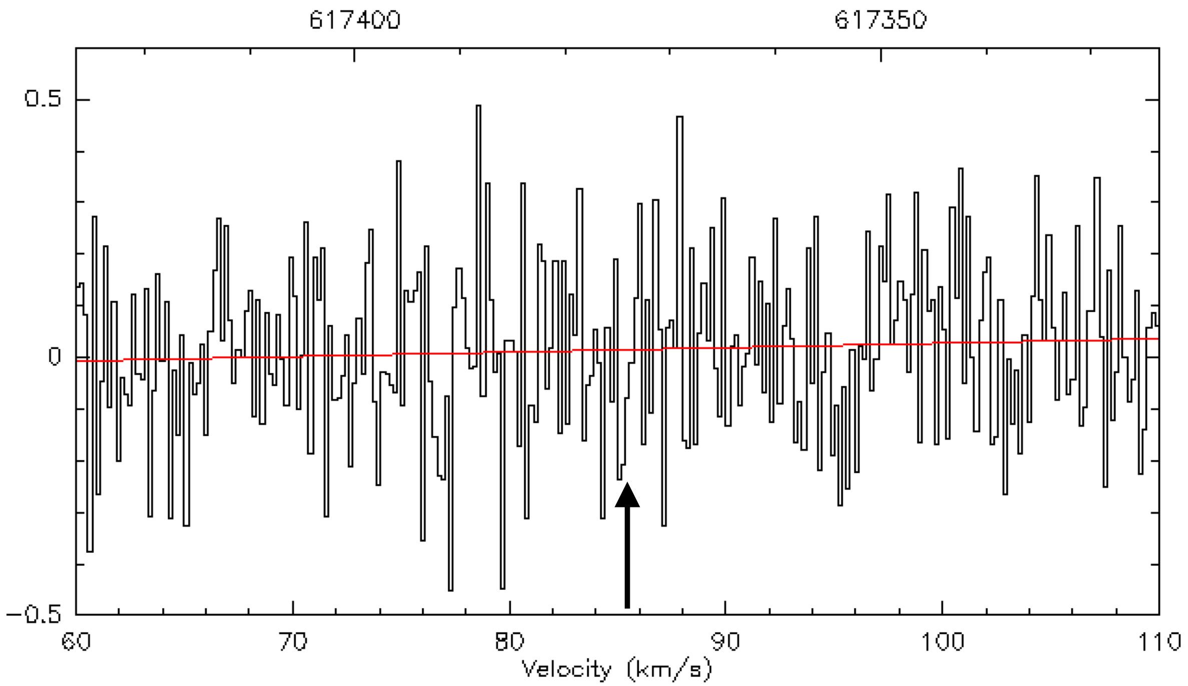
Other than the weak and narrow ArH+, the APEX SEPIA band 9 observations had another **surprising outcome**!

We detected ArH+ in Pos 1 (4σ) and Pos 2 (3.5σ) but could not recover it in subsequent visits!!!

⟶ **ArH$^+$ line emission = TRANSIENT?!?!**

Pos1





OD: July 29, 2016
rms: 0.14 K

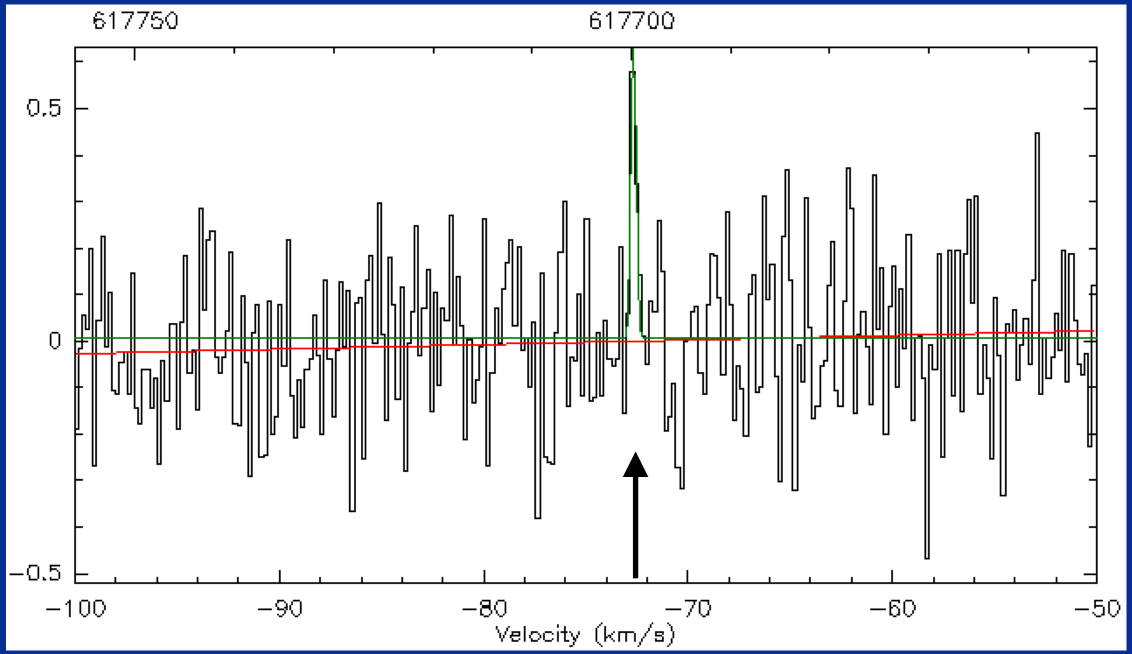
OD: Oct 4, 2016
rms: 0.16 K

De Looze+2017 in prep

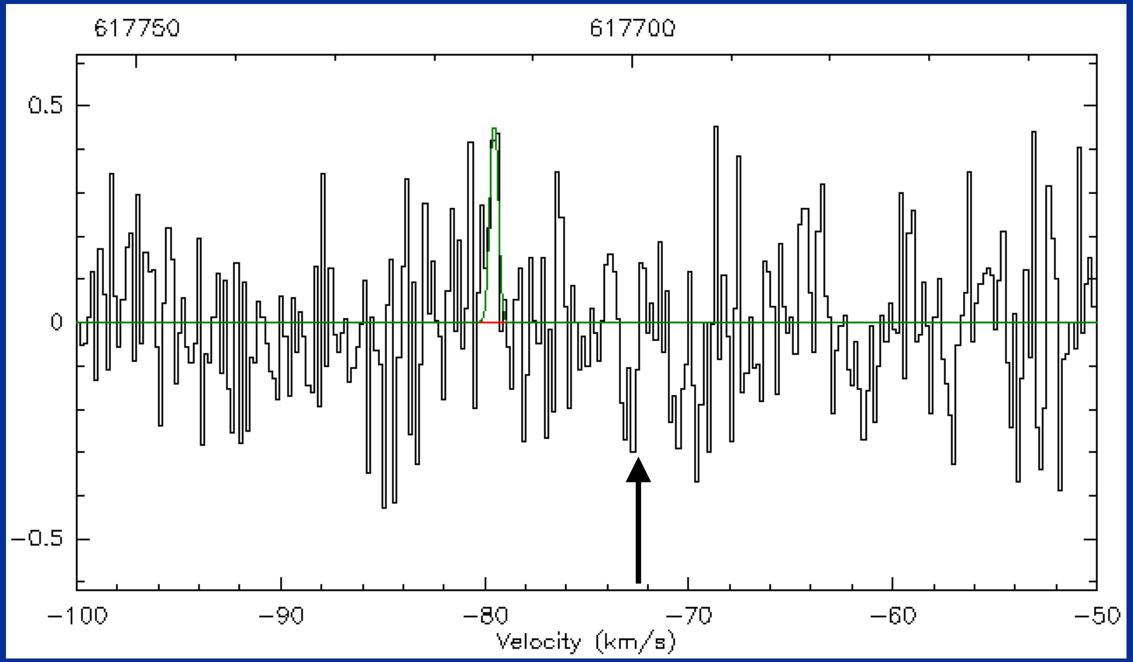
Transient ArH^+ emission?

Although detections are relatively weak (3.5-4σ):
- clear detections in several adjacent channels!
- transient nature identified in two positions!

Pos2



OD: Aug 11, 2016
rms: 0.16 K



OD: Aug 12, 2016
rms: 0.17 K

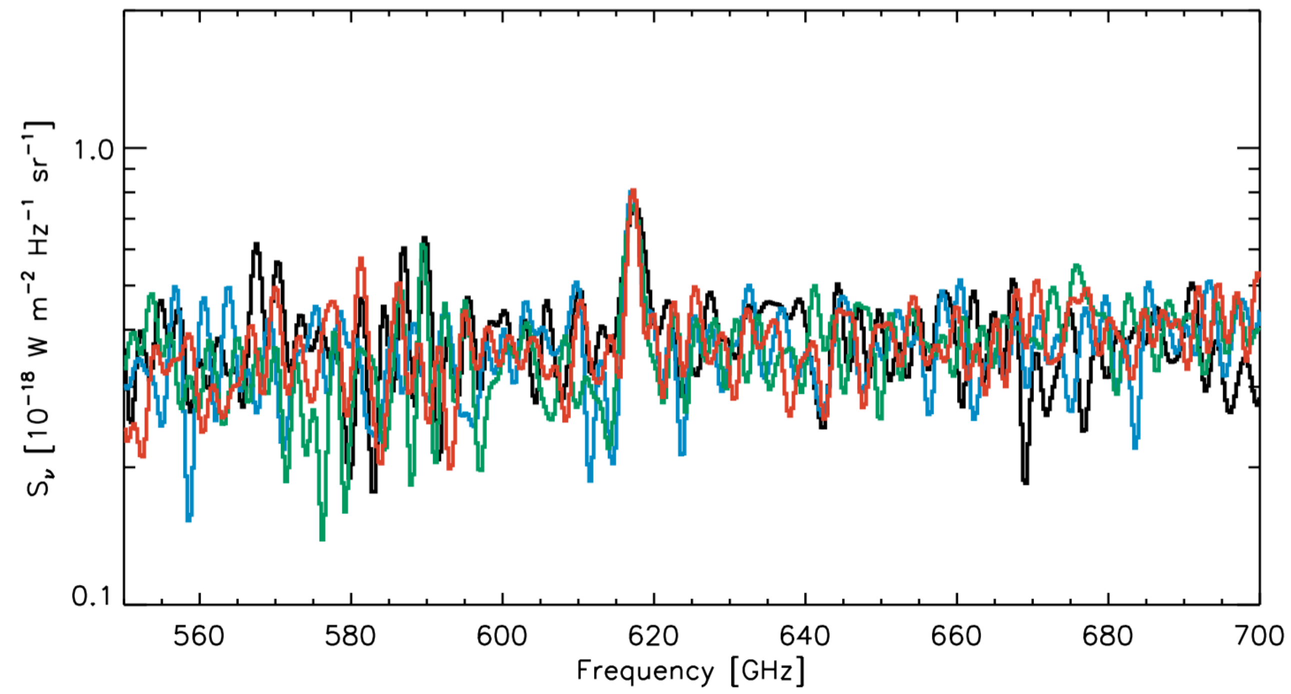
APEX observations show that ArH^+ emission in the Crab Nebula is highly variable on time scales of a few months with possible day-to-day variations!!

Transient ArH^+ emission?

Herschel SPIRE FTS observations

→ 48 FTS scans in $t_{\text{on-source}}$ = 3197s

→ splitting up in 4x 12 FTS scans, we check for variability in SPIRE FTS data



No variability within the 1-hour time frame of the SPIRE FTS observations

→ ArH^+ emission = variable on time scales of >1 day to months

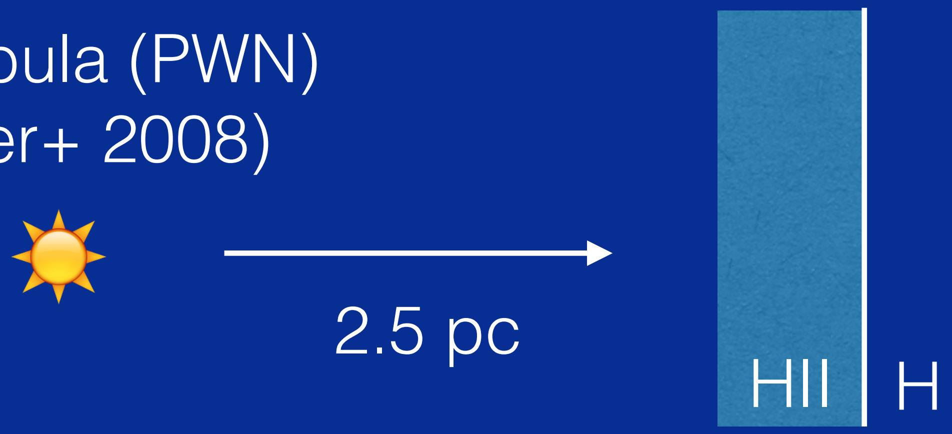
Can models explain variability of ArH^+ emission on such short time scales?!

Modelling ArH^+ in the Crab

Models constructed with ***Mocassin*** (ionised gas) + ***UCL_PDR*** (PDR+XDR) (Priestley+2017 in prep)

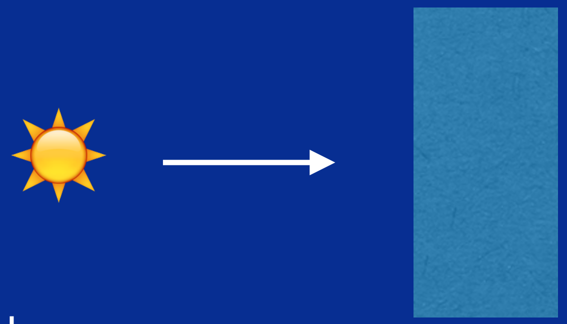
Step 1

Pulsar Wind Nebula (PWN) spectrum (Hester+ 2008)



Step 2

Output spectrum of Mocassin fed into ***UCL_PDR***



Input : el. abundances + gas-to-dust ratio (30) from Owen & Barlow (2015)

Parameters :

- **cosmic ray ionisation rate:**
  $\zeta = 1, 10^4, 10^5, 10^6, 10^7, 10^8\ \zeta_0$
  with the standard ISM $\zeta_0 = 1.3E^{-17}\ s^{-1}$

- **gas density:**
  $n_H = 2E^{+3}, 2E^{+4}, 2E^{+5}, 2E^{+6}\ cm^{-3}$
- **cloud depth A_V:**
  $A_V = 1E^{-3}, 1E^{-2}, 1$

Modelling ArH^+ in the Crab

Models need to reproduce Herschel SPIRE FTS surface brightnesses + line ratios*!

- ArH+ J=2-1 / ArH+ J=1-0 > 1
- bright OH+ 971 GHz, with weak/no detections of OH^+ 909GHz and OH^+1033 GHz
- no carbon (492, 891 GHz) or CO (J=4-3 to J=13-12) lines detected

⟶ we require:

- high CR ionisation rate!

$\zeta >= 10^7 \zeta_0$

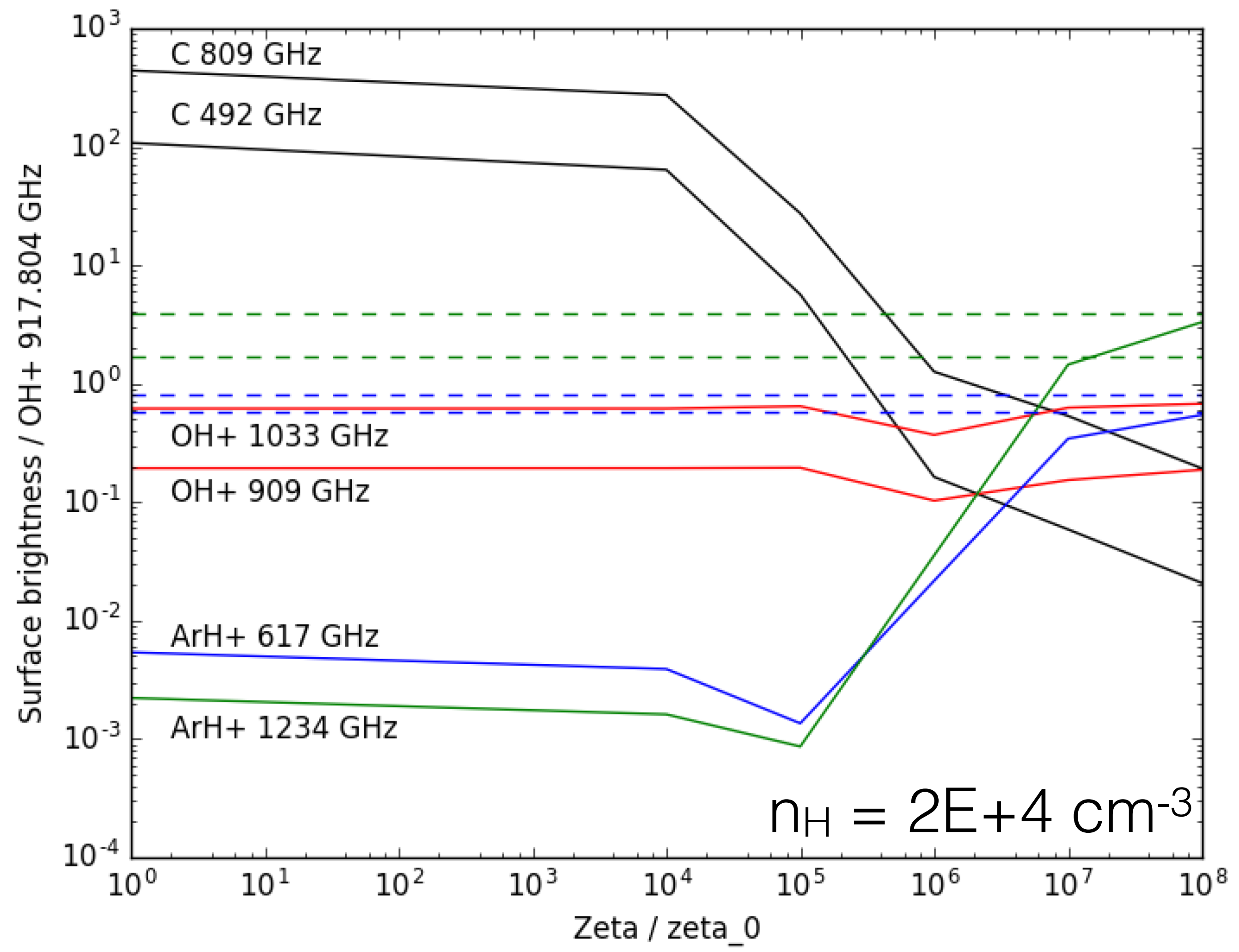
- lower densities

$n_H \sim$ 2-20E+3

- low A_V , shallow cloud depth

$A_V \sim$ 1E-3 - 1E-2

(Priestley+2017 in prep)



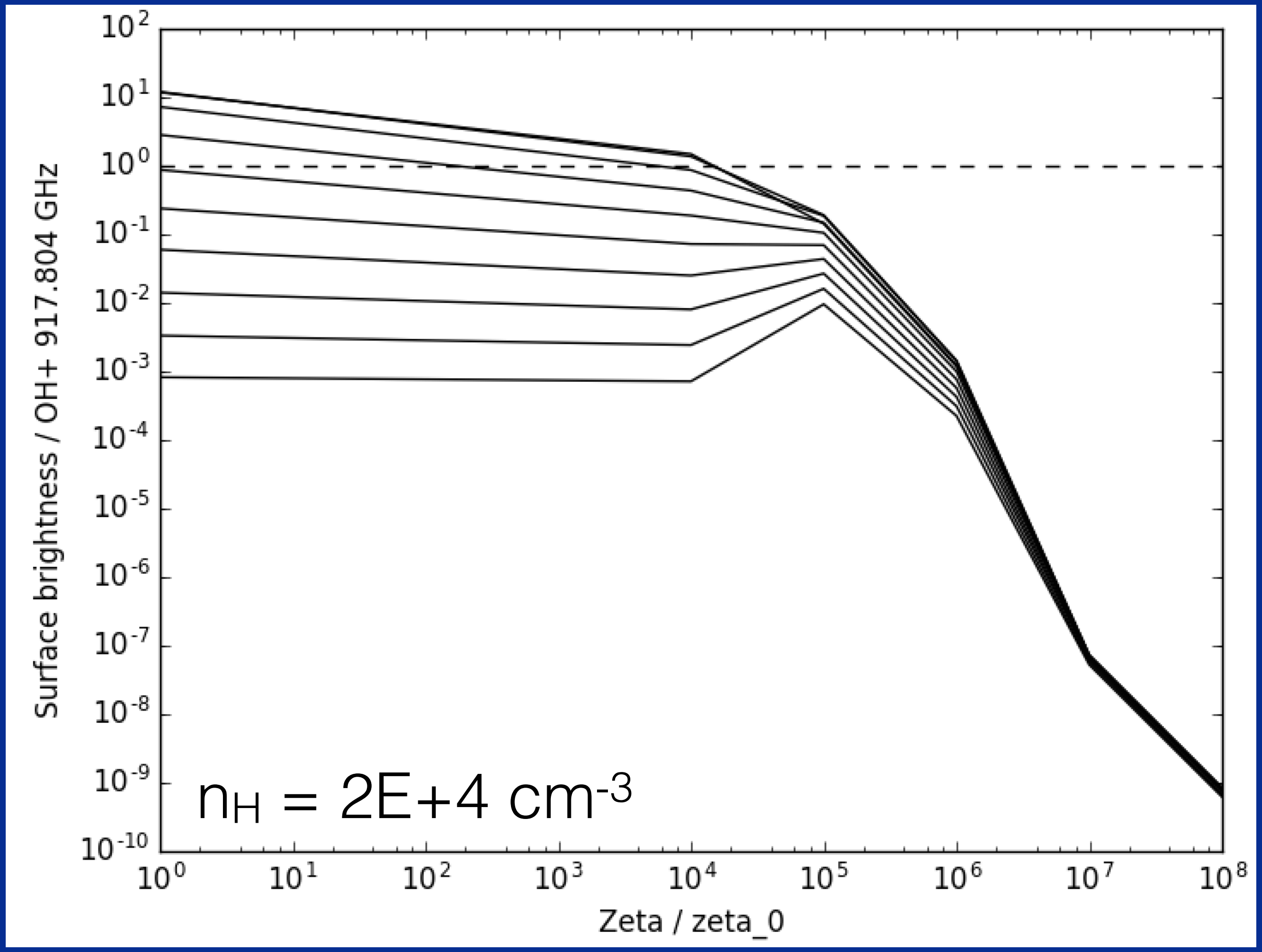
*Dissociation of ArH+ due to reaction with e^- is assumed to have reaction rate 10E-11 cm^3 s^{-1}

Modelling ArH^+ in the Crab

Non-detection of any CO line emission (J=4-3 to J=13-12) in the SPIRE FTS spectra of the Crab Nebula can only be explained by high cosmic ray ionisation rates ($\zeta >= 10^7 \zeta_0$)!! —> support results for ArH^+ and OH^+

→ we require:

- **high CR ionisation rate!**
  $\zeta >= 10^7 \zeta_0$
- **lower densities**
  $n_H \sim$ 2-20E+3
- **low A_V , shallow cloud depth**
  $A_V \sim$ 1E-3 - 1E-2



(Priestley+2017 in prep)

Modelling ArH^+ in the Crab

What do models tell us about formation/destruction mechanisms of ArH^+?

(Priestley+2017 in prep)

- Main formation route:

$Ar^+ + H_2 \longrightarrow ArH^+ + H$ **[8E-10 $cm^3\ s^{-1}$]**

Neufeld & Wolfire (2016)

- Main destruction channels:

$ArH^+ + H_2 \longrightarrow Ar + H_3^+$ **[$8.4\times10^{-10}\ (T/300K)^{0.16}\ cm^3\ s^{-1}$]**

Schilke+ (2014)

n_{H2} = 5 cm^{-3}, T = 2000K ($10^7\ \zeta_0$),

= 0.2 cm^{-3}, T = 6000K ($10^8\ \zeta_0$)

→ **τ = 2-40e8s > few yr (too high!!)**

$ArH^+ + e \longrightarrow Ar + H$ **[< 10E-9 $cm^3\ s^{-1}$]**

Mitchell+ (2015)

n_e = 2000 cm^{-3} ($10^7\ \zeta_0$)

= 8000 cm^{-3} ($10^8\ \zeta_0$)

—> **10E^{-11} $cm^3\ s^{-1}$**

reproduces line ratios

→ **τ = 1-5e7s ~ 100-500 days (!)**

for densities n_{H2} ~ 2E+4 cm^3 and high $\zeta >= 10^7\ \zeta_0$

→ destructive reactions with e- have time scales of ~10^7 s (or ~100 days)!

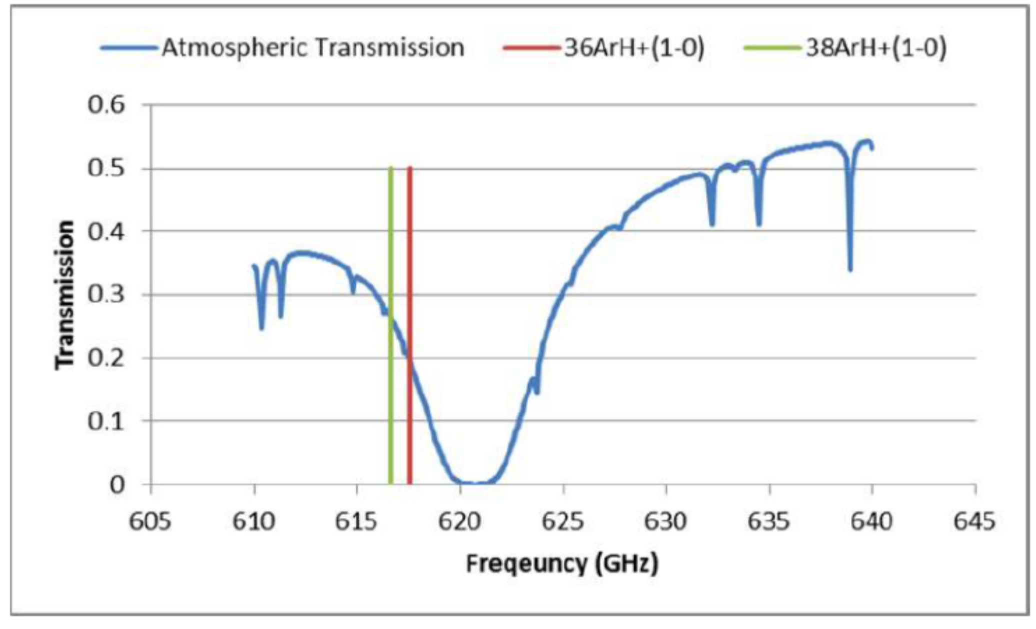
→ models show that variability of ArH^+ emission is possible

Conclusions

- First detection of the noble gas molecule, **ArH^+**, in the **Crab Nebula** with SPIRE FTS
- **APEX SEPIA band 9** observations allow us to resolve ArH^+ emission
- ArH^+ observed with APEX is **weaker + narrower** compared to Herschel detections!
—> we require ArH+ to originate from **several small clumps** within the beam
- PDR/XDR models with **high cosmic ionisation rates ($\zeta >= 10^7 \zeta_0$)** reproduce ArH^+ and OH^+ emission observed (and non-detections of C and CO lines)
—> ArH^+ emission seems to mainly originate from cloud surfaces
- ArH^+ is thought to be **transient** on timescales of months (possibly days)!
—> dissociative recombination processes with H_2 and e^- predict **destruction timescales of the order of 100 days**

Future outlook

- ArH^+ observations require excellent weather conditions !!
  (due to its location on a water vapour line)
- APEX = excellent facility for ArH^+ observations
  (need to constrain timescale of variability
  + sample other positions in the Crab)



- Follow-up with ALMA —> spatially resolving clumps within one APEX beam
- Modelling the H_2 emission in the Crab Nebula
  (H_2 formed on grains in current models, need to include H_2 gas phase processes)
- Probe the $^{38}ArH+$ isotope to constrain nucleosynthesis processes in SNe

Big thanks to the APEX staff!