Radio Interferometric Studies of Cool Evolved Stellar Mass Outflows

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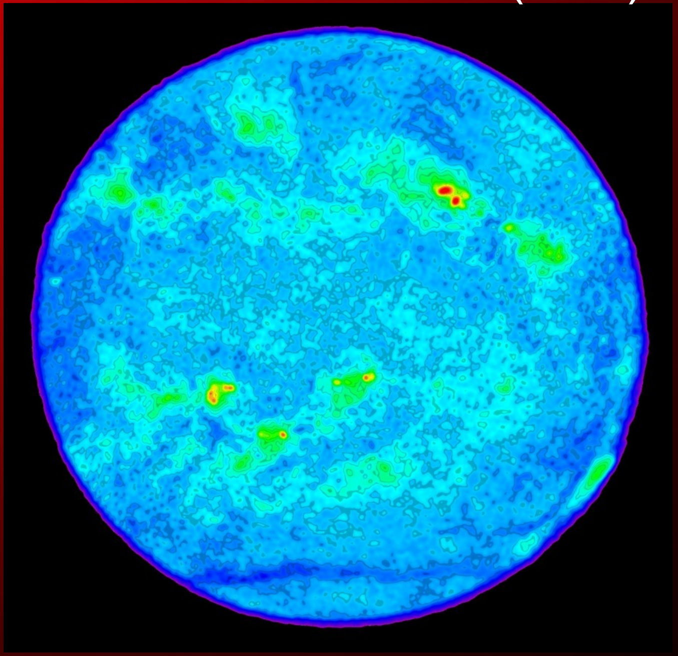
DIAS, February 1st 2013

The Radio Sky

Radio Sky at 4.85 GHz (300ft Green Bank)

Credit: NRAO/AUI

The sun at 4.6 GHz (VLA)

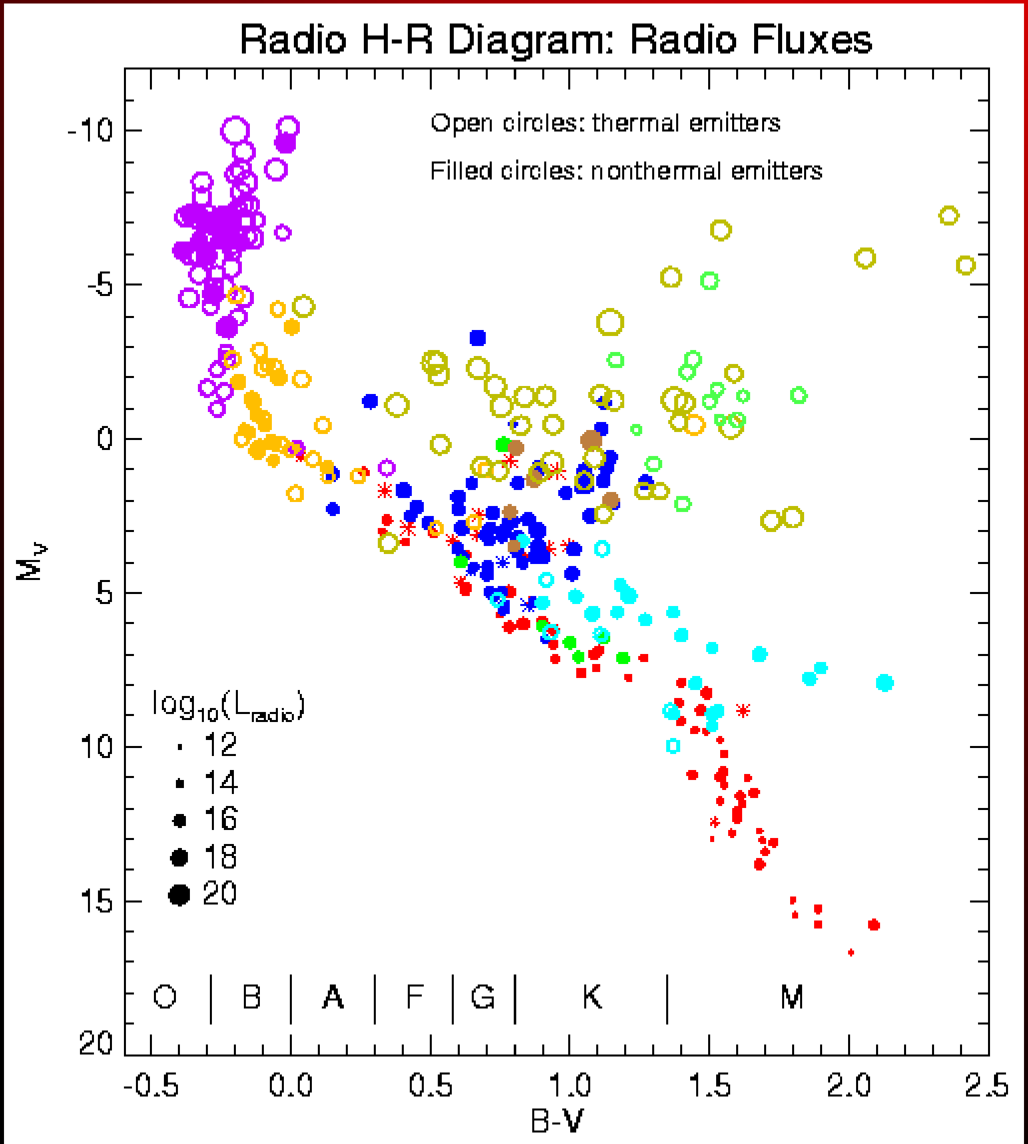


Credit: NRAO/AUI

$(P_{radio}/P_{optical})_{\odot} \sim 10^{-15}$

$S_{\upsilon} \sim 40\ \mu$Jy at α Cen
(not detectable with 'old' VLA!)

Radio Stars

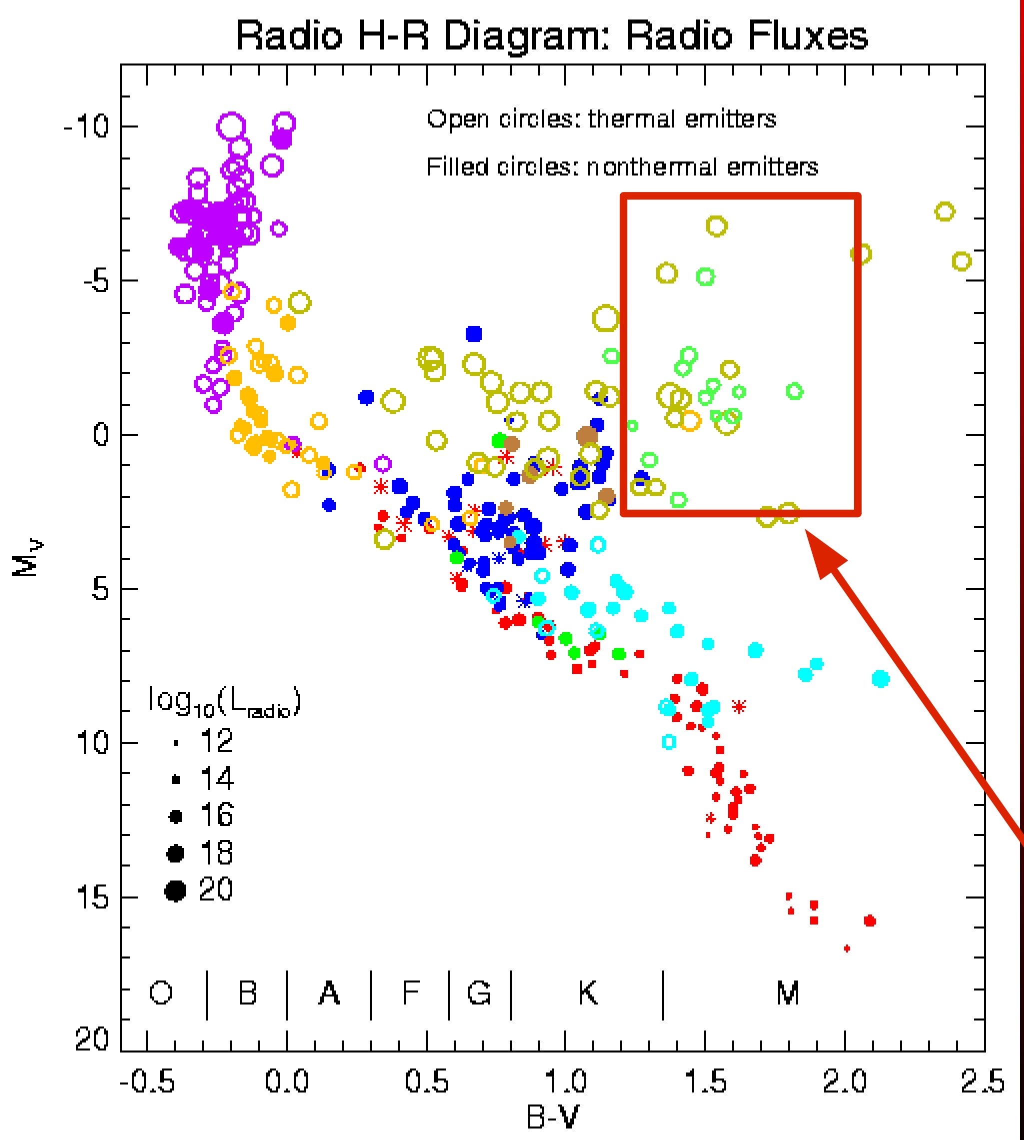


Radio H-R Diagram

Majority: Non thermal emitters

A few thermal emitters
i.e. large θ_{mas}

Radio Stars



Radio H-R Diagram

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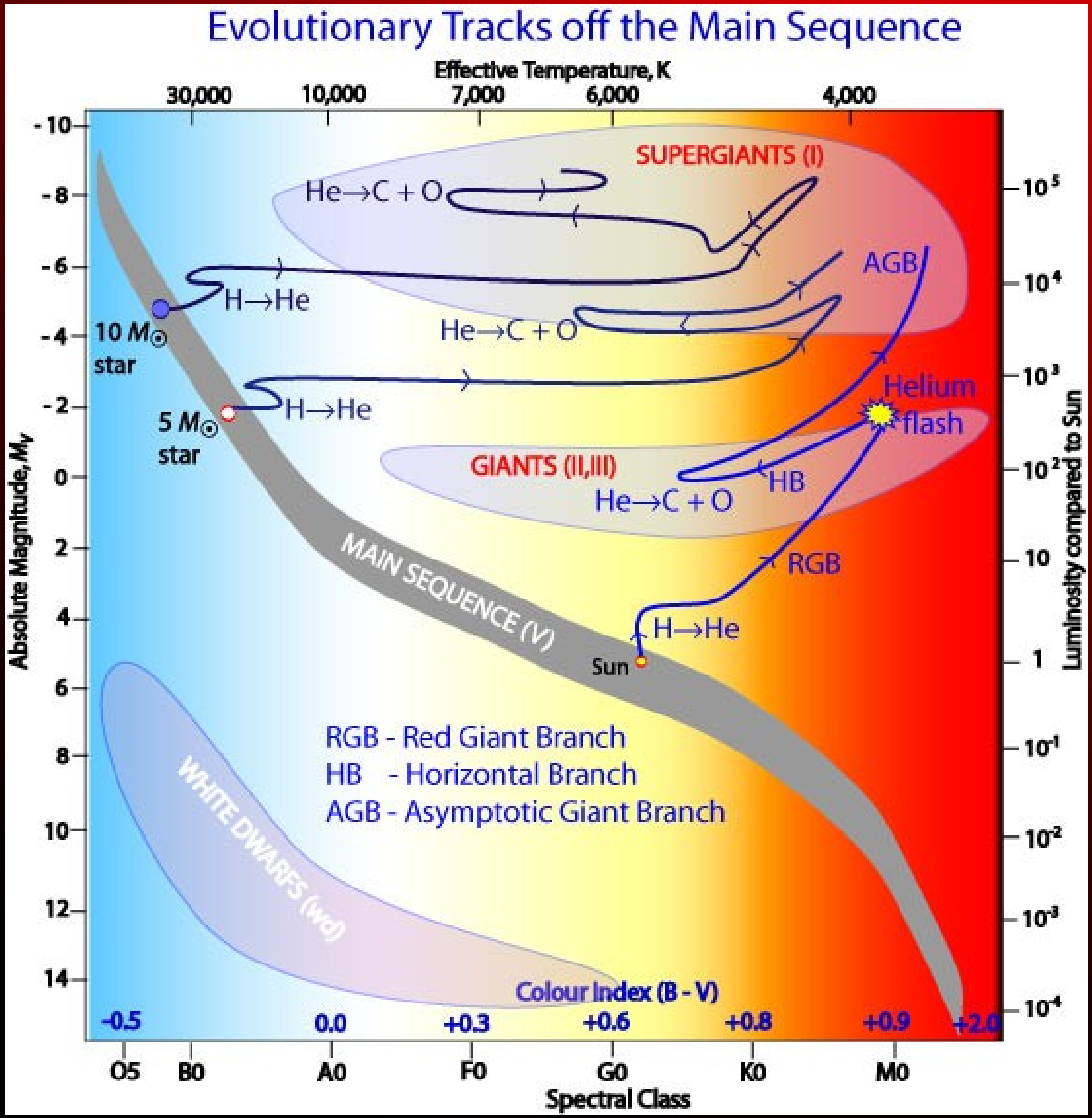
Red Giants & Red Supergiants

Red Giants and Red Supergiants



<u>Red Giants:</u>

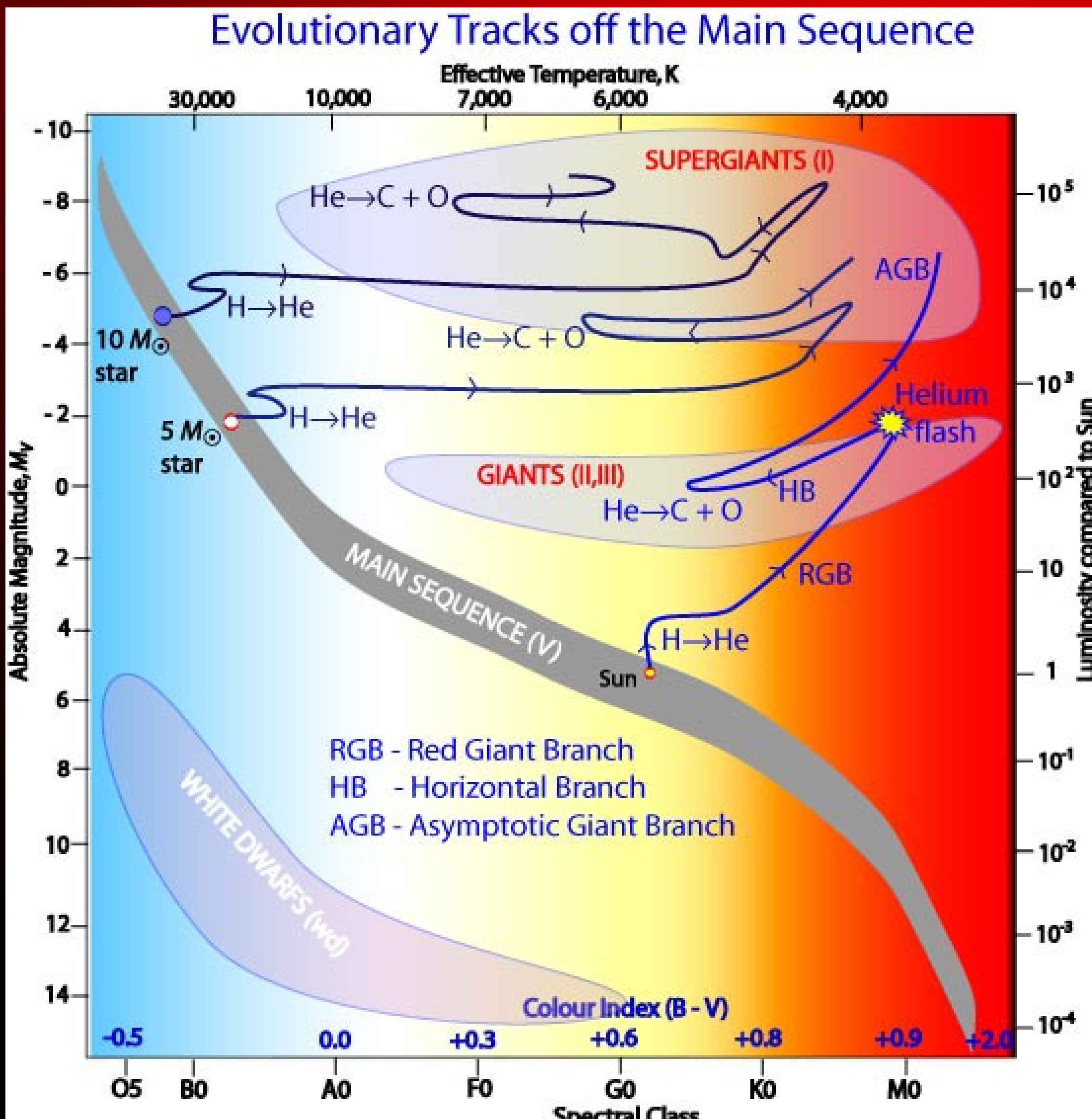
$0.35 \rightarrow \sim 8\ M_\odot$

a) RGB: Inert He Core
H burning shell

b) HB: Core He burning
H burning shell

c) AGB: Inert C-O core
H and He burning shells

Red Giants and Red Supergiants



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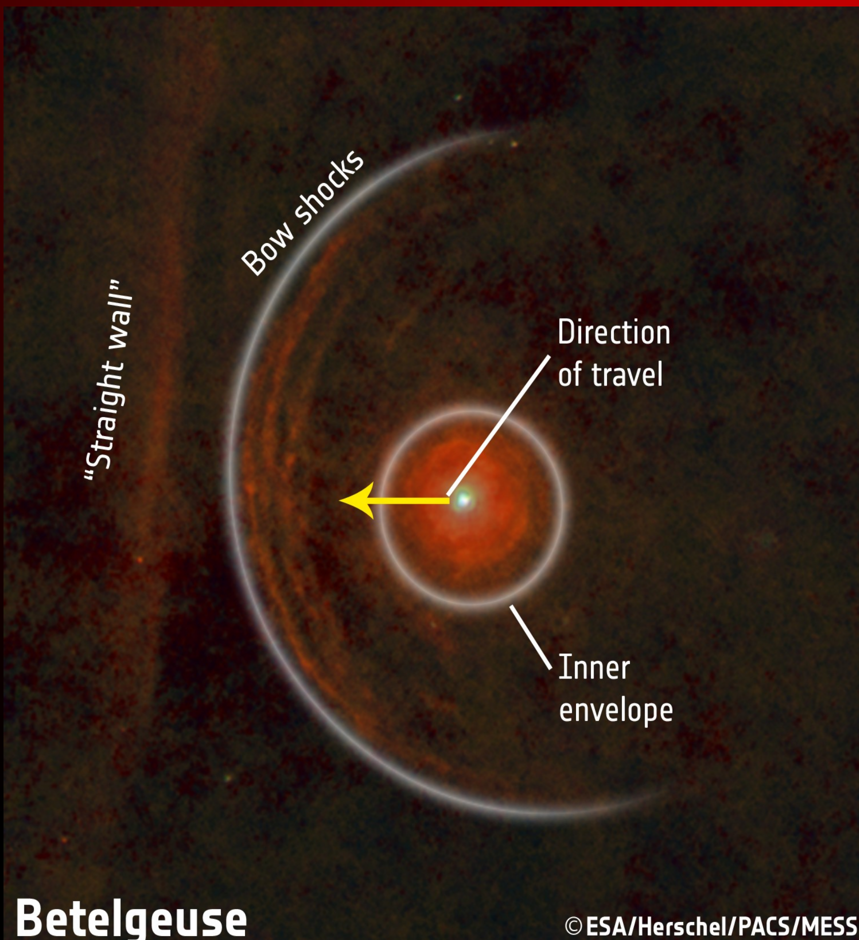
<u>Red Supergiants:</u>

- $\sim 8\ M_\odot \leq M \leq 40\ M_\odot$.
- $3{,}450\ K \leq T_e \leq 4{,}100\ K$ (i.e. M5 -> K1)
- Radii up to $1500\ R_\odot$!

a) Short lifetimes
b) Onion-like internal structure
c) Die in a spectacular fashion
d) $dM/dt \sim 10^{-4} - 10^{-6}\ M_\odot\ yr^{-1}$

e.g. α Sco, α Ori

1. Betelgeuse



(Decin et al., 2013)

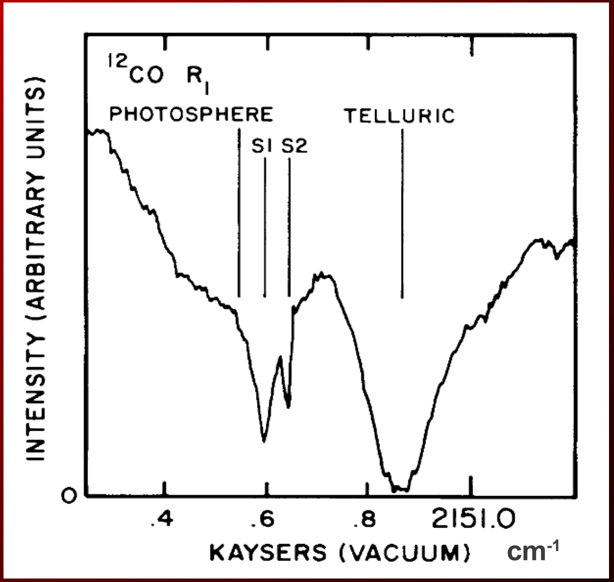
Spectral Type	M2 Iab
Radial Velocity	20.7 km s^{-1}
$Log(L/L_{\odot})$	5.12
Distance	197 ± 45 parsec
Mass (birth)	~20 $M_{\odot}$
Mass (current)	~18 $M_{\odot}$
Mass loss rate	3 x 10^{-6} $M_{\odot}$ yr^{-1}
Rotational Period	17 years
Photospheric Radius	22.5 mas (645 $R_{\odot}$)
Photospheric Temperature	3,600 K (cool star)
Origin	O-type main sequence
Fate	Supernova Type II

Betelgeuse: Circumstellar Environment

- At least two different mass loss phase in the last ~100's yr.

- Two distinct shells spectrally resolved in 4.6 µm $^{12}C^{16}O$ absorption spectra (Bernat et al., 1979):
    - A fast, low column outer shell, S2, moving at 17 km s^{-1}
    - A slower, high column inner shell, S1, moving at 10 km s^{-1}
    - Spatial extent not directly determined

- Plez & Lambert (2002) appear to detect S2 shell at 50 arcsec in K I spectra.



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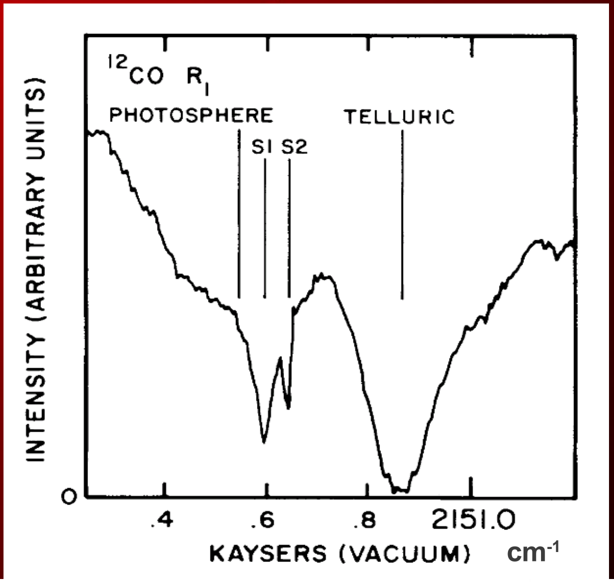
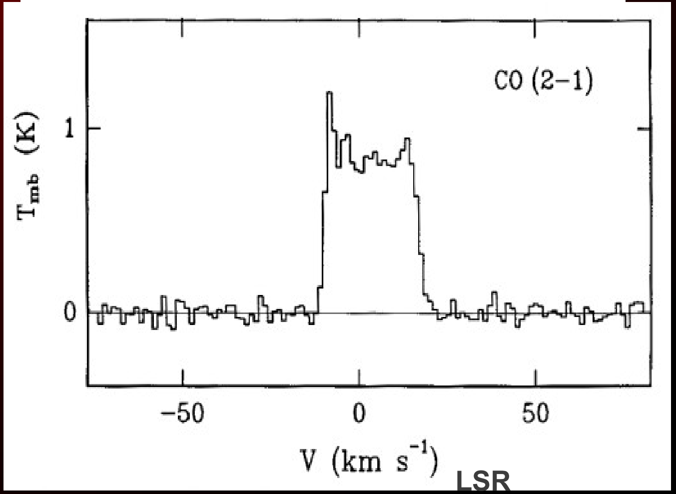
- IRAM 30 m telescope (beam size ~12") fails to resolve S2 shell (Cernicharo & Bachiller, 1993) at 1.3 mm (i.e. $^{12}C^{16}O$).

- Single dish $^{12}C^{16}O$ mm-observations reveal only high velocity S2 shell.

- Signature of S1 shell not obvious at millimeter wavelengths.





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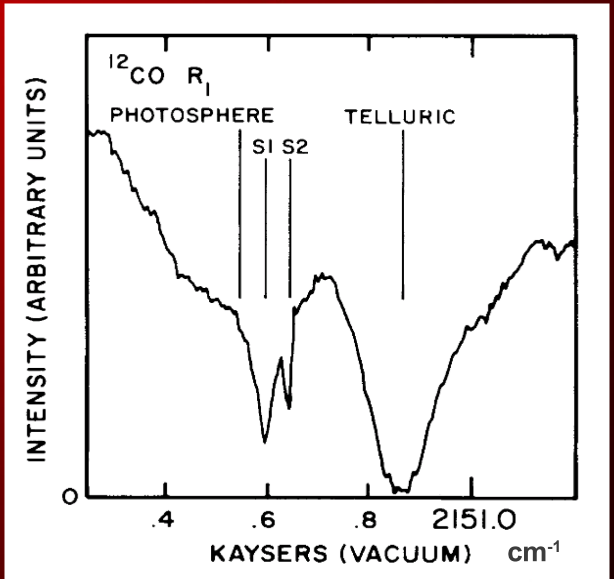
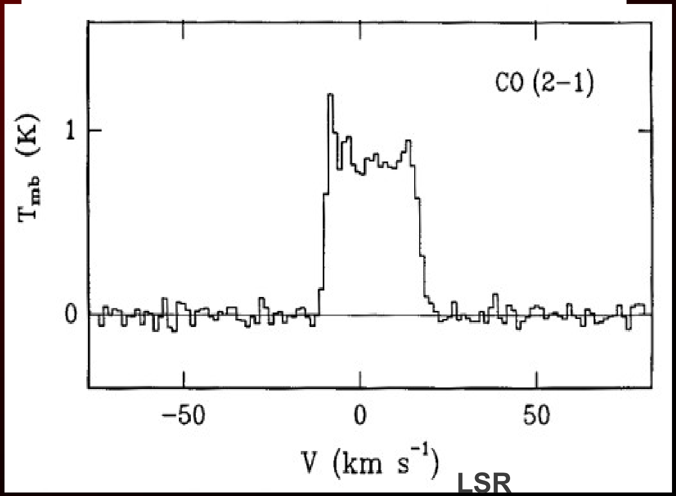




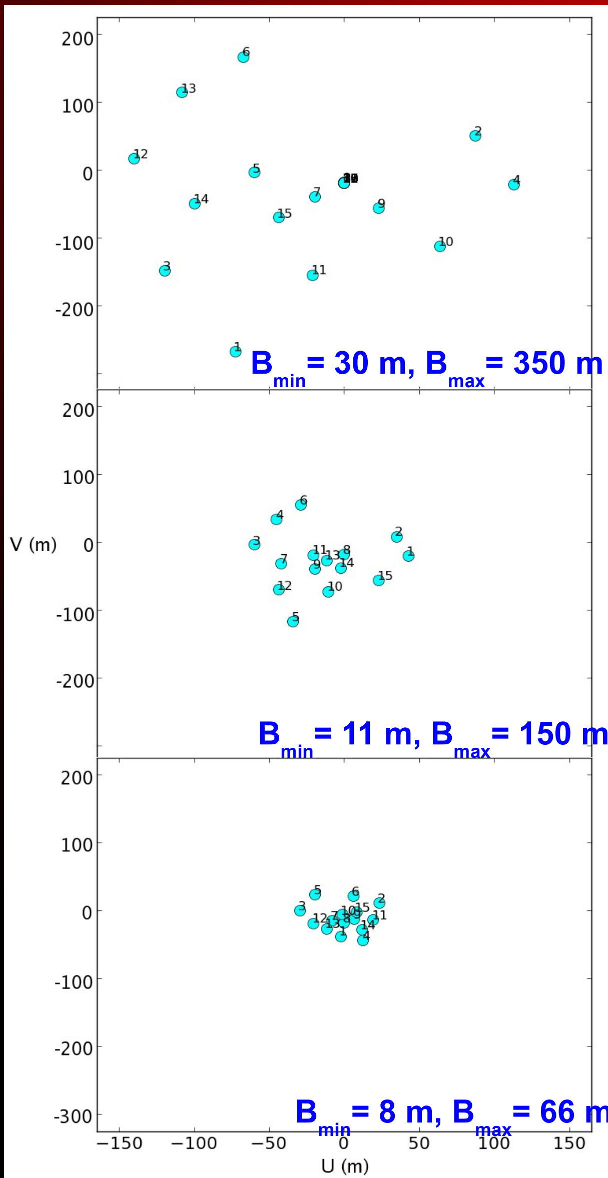
Goal: *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

CARMA

- **C**ombined **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy
- 15 element interferometer (9 x 6.1 m + 6 x 10.4 m antennas)
- Cedar Flat, eastern California (~ 2,200 m)
- Merger of two independent arrays: BIMA + OVRO (2007)
- 105 baselines (n(n-1)/2) with 5 configurations (B_{min} = 8 m and B_{max} = 2 km)
- Three bands: 7 mm, 3 mm and 1.3 mm

Credit: 2009 John Carlstrom

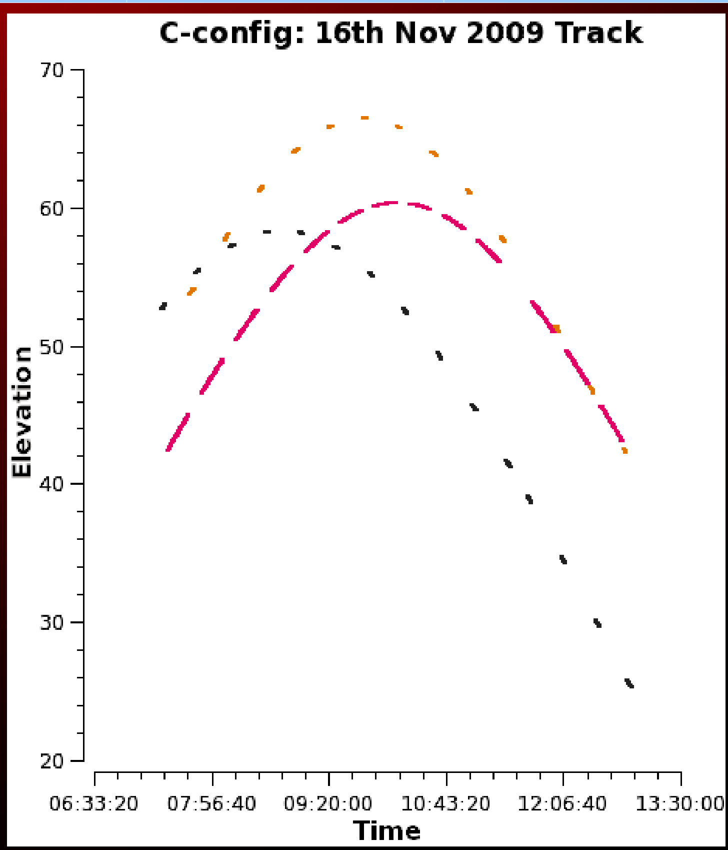
CARMA Observations



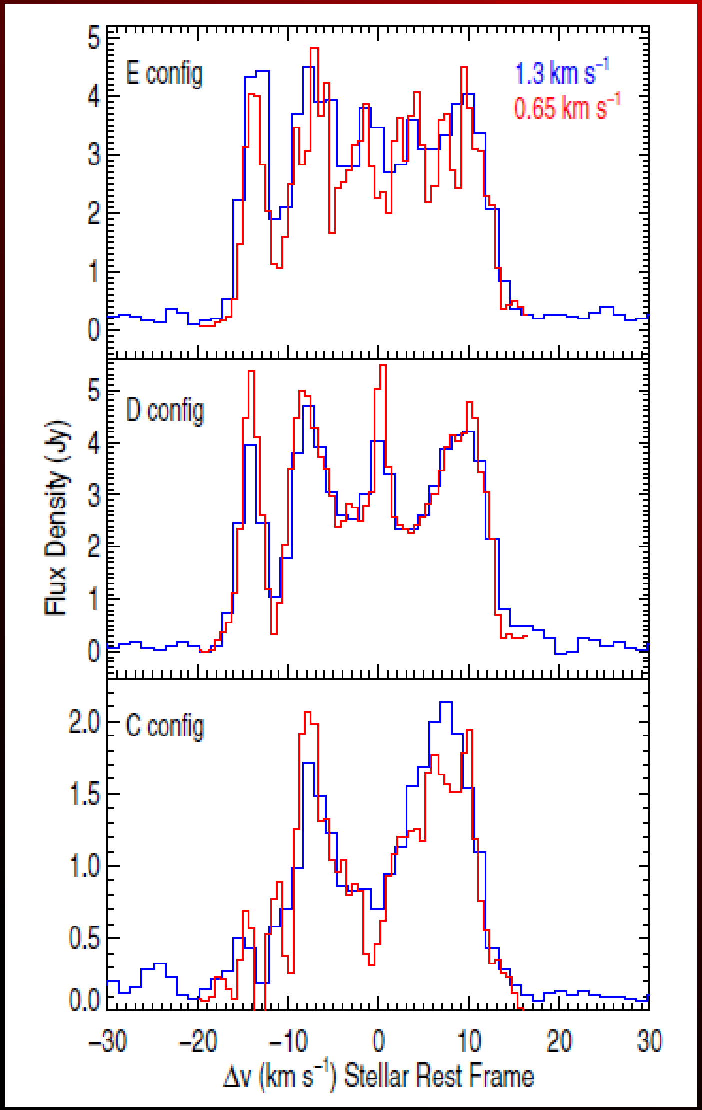
Date	Config	Tracks	Time (hr)	Resolution (")	Max Scale (")
Jun 07	D	5	9.5	1.8	24.4
Jul 09	E	1	3.25	4.0	33.5
Nov 09	C	5	8.75	0.8	8.9

3 separate bands: All centered on line

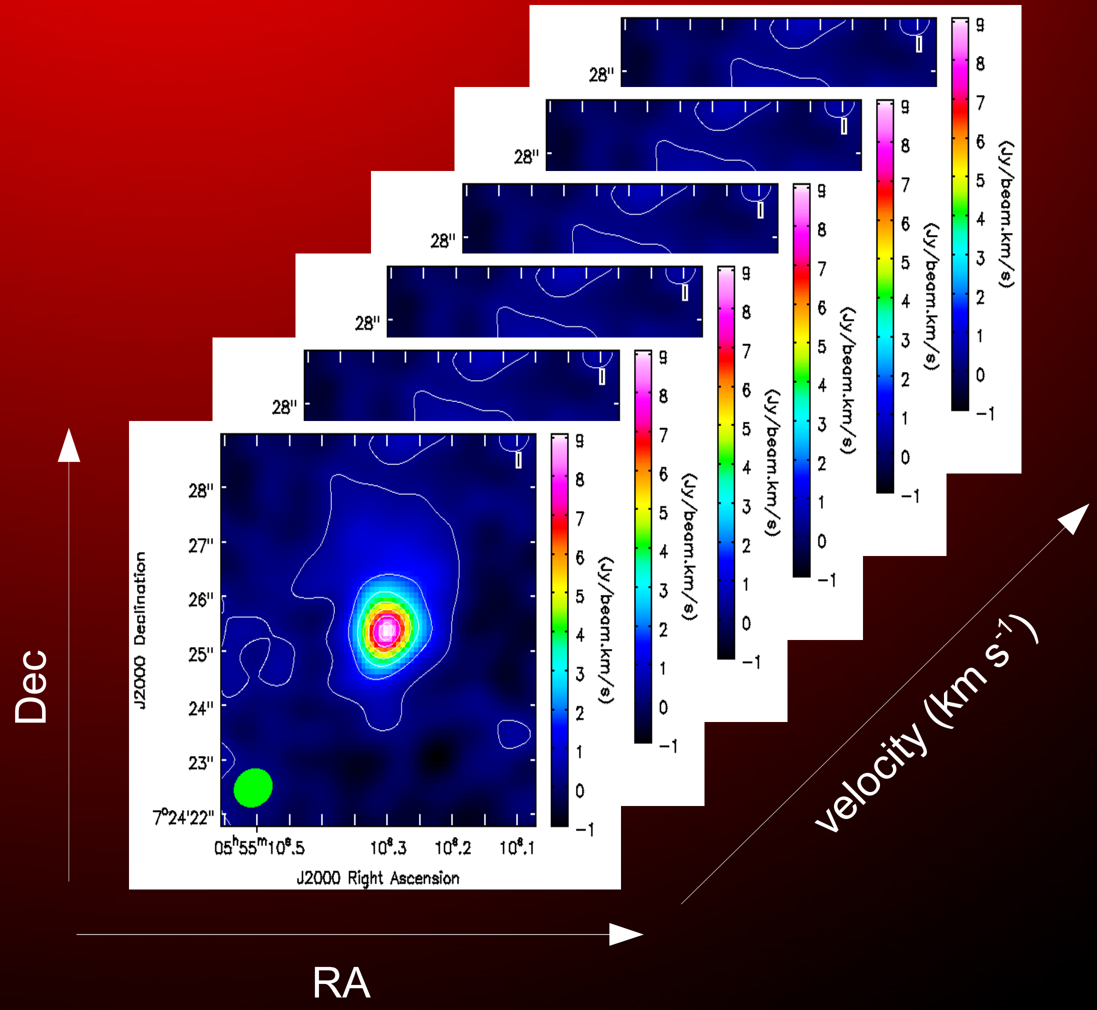
- Maximum bandwidth of 468 MHz (15 channels)
- 62 MHz of bandwidth across 63 channels (1 MHz or 1.3 km s^{-1} resolution)
- 31 MHz of bandwidth across 63 channels (0.5 MHz or 0.65 km s^{-1} resolution)



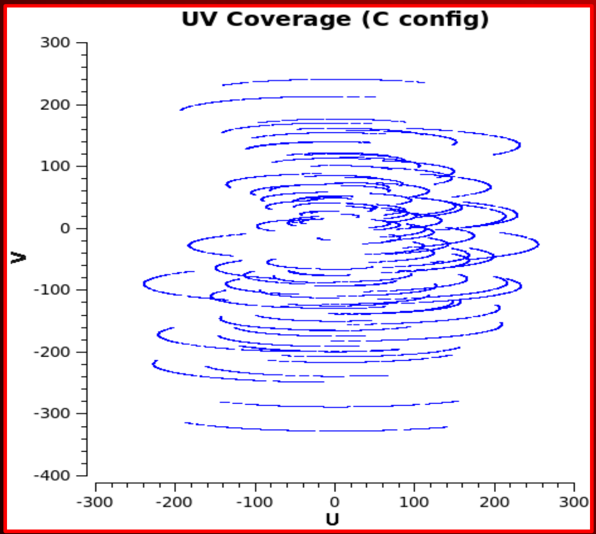
Individual Configurations

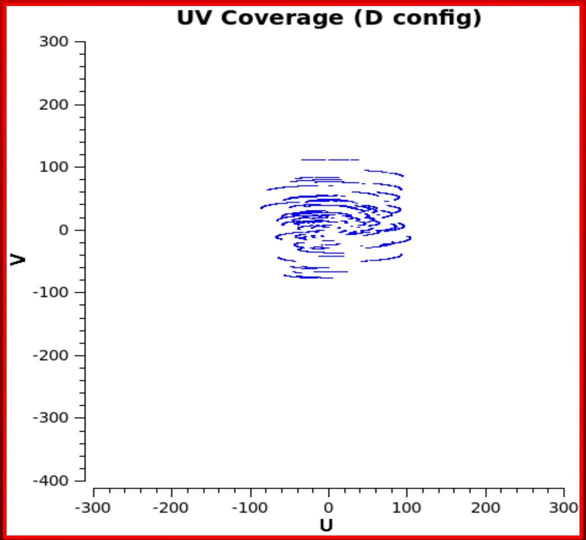


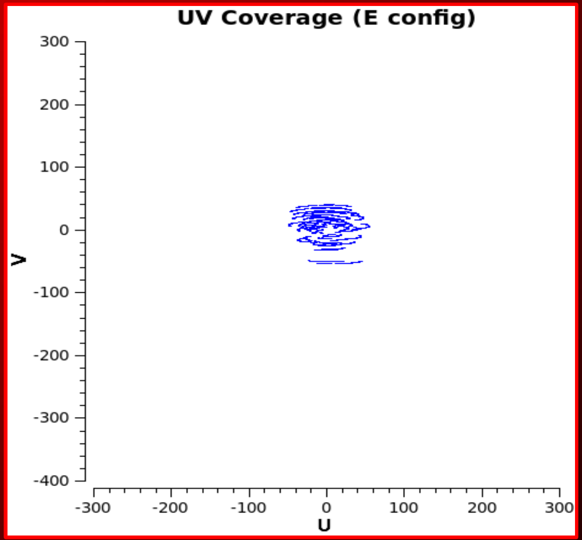
(O'Gorman et al., 2012)

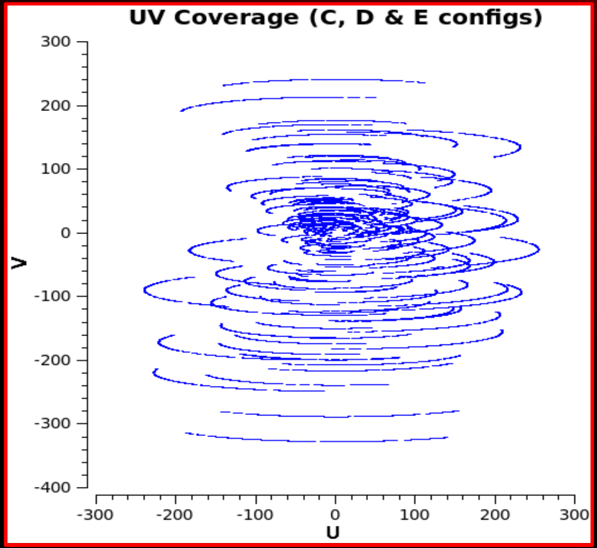


Combining Configurations





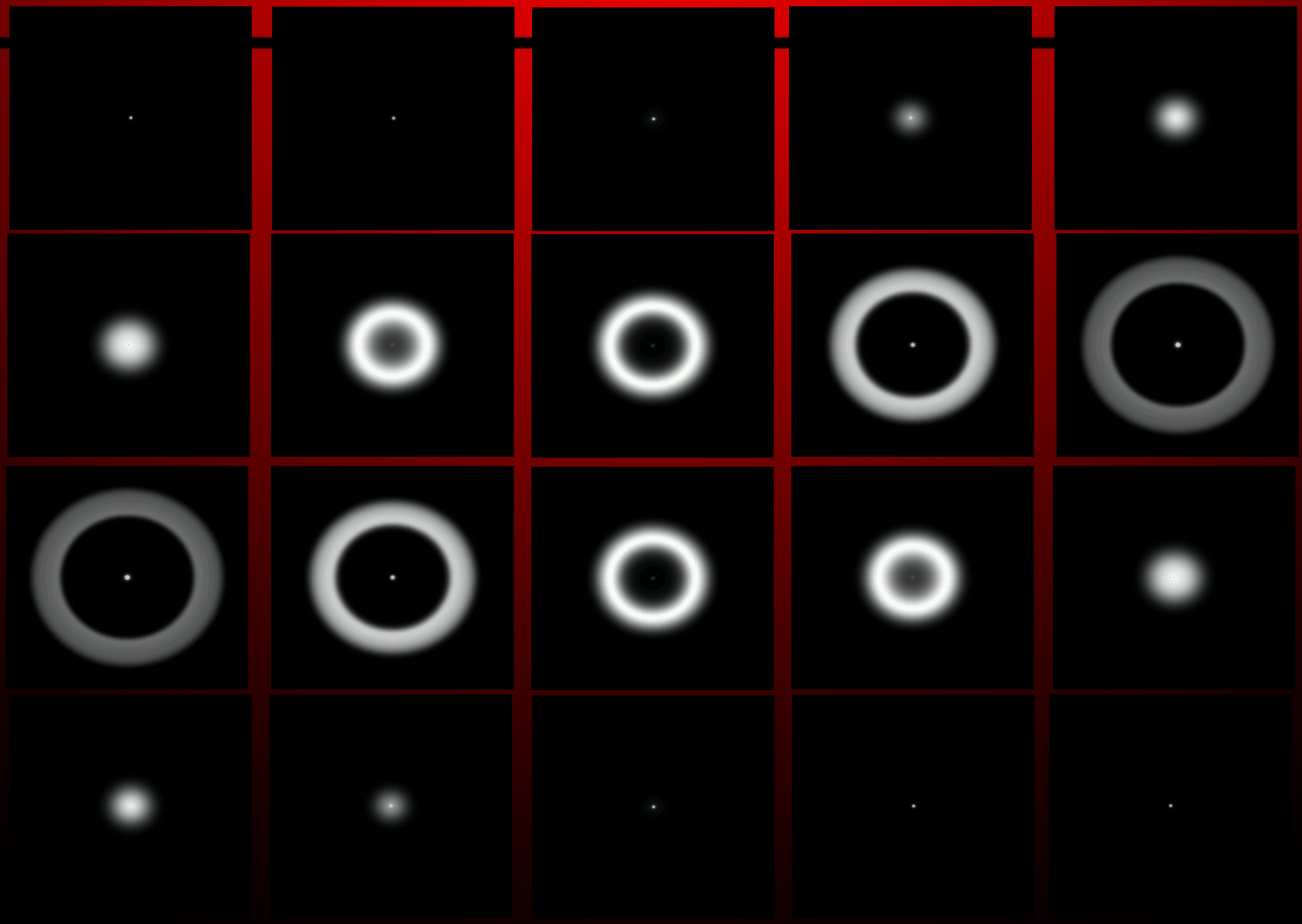




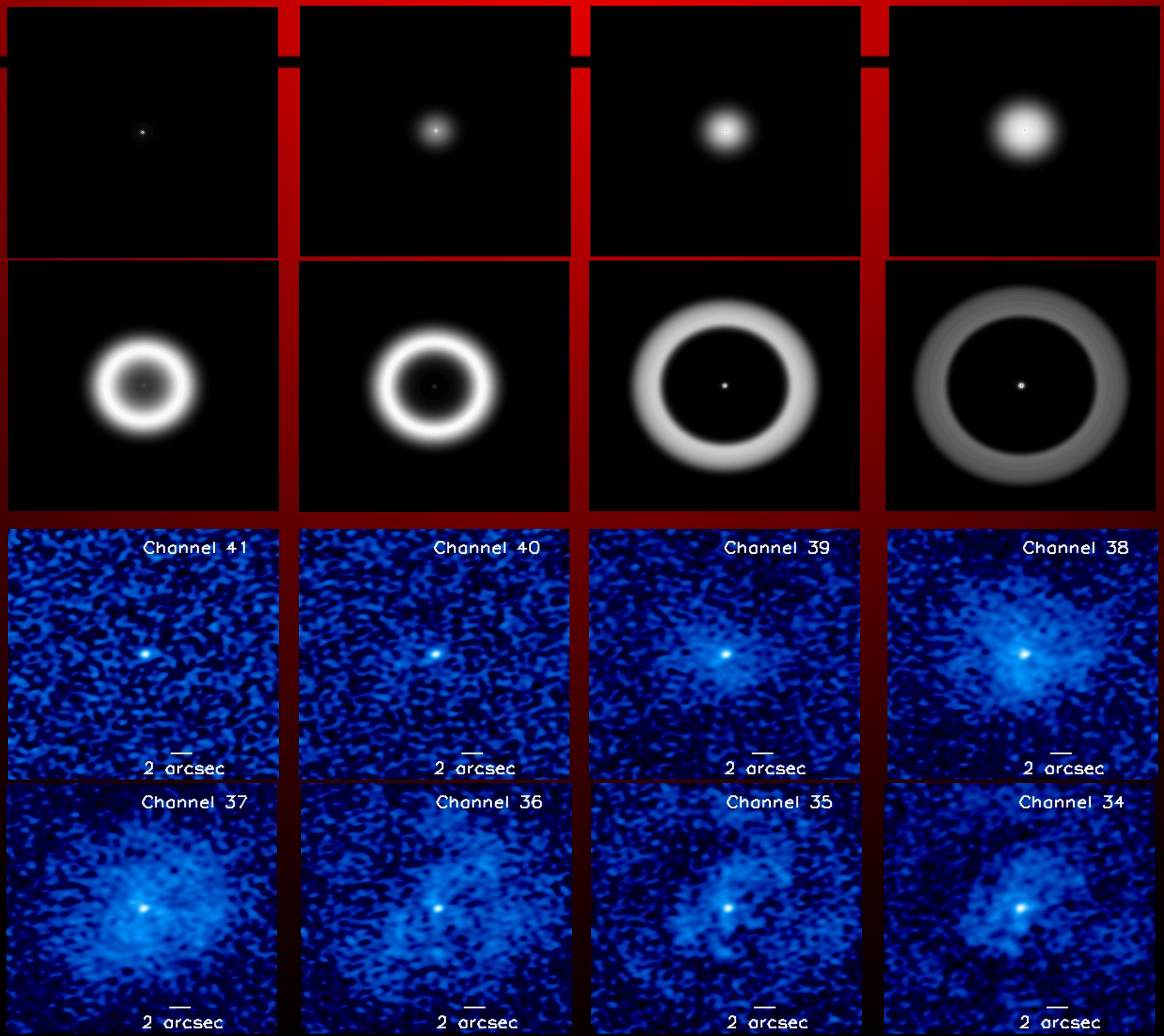
Increase uv-coverage
→ Increase sensitivity to different scales
→ Increase S/N

Config	S/N (1.3 km s^{-1})	S/N (0.65 km s^{-1})
C	24	18
D	23.5	21.5
E	21.5	13.5
Combined	33	24

Image Cube Simulation



Simulation vs Actual



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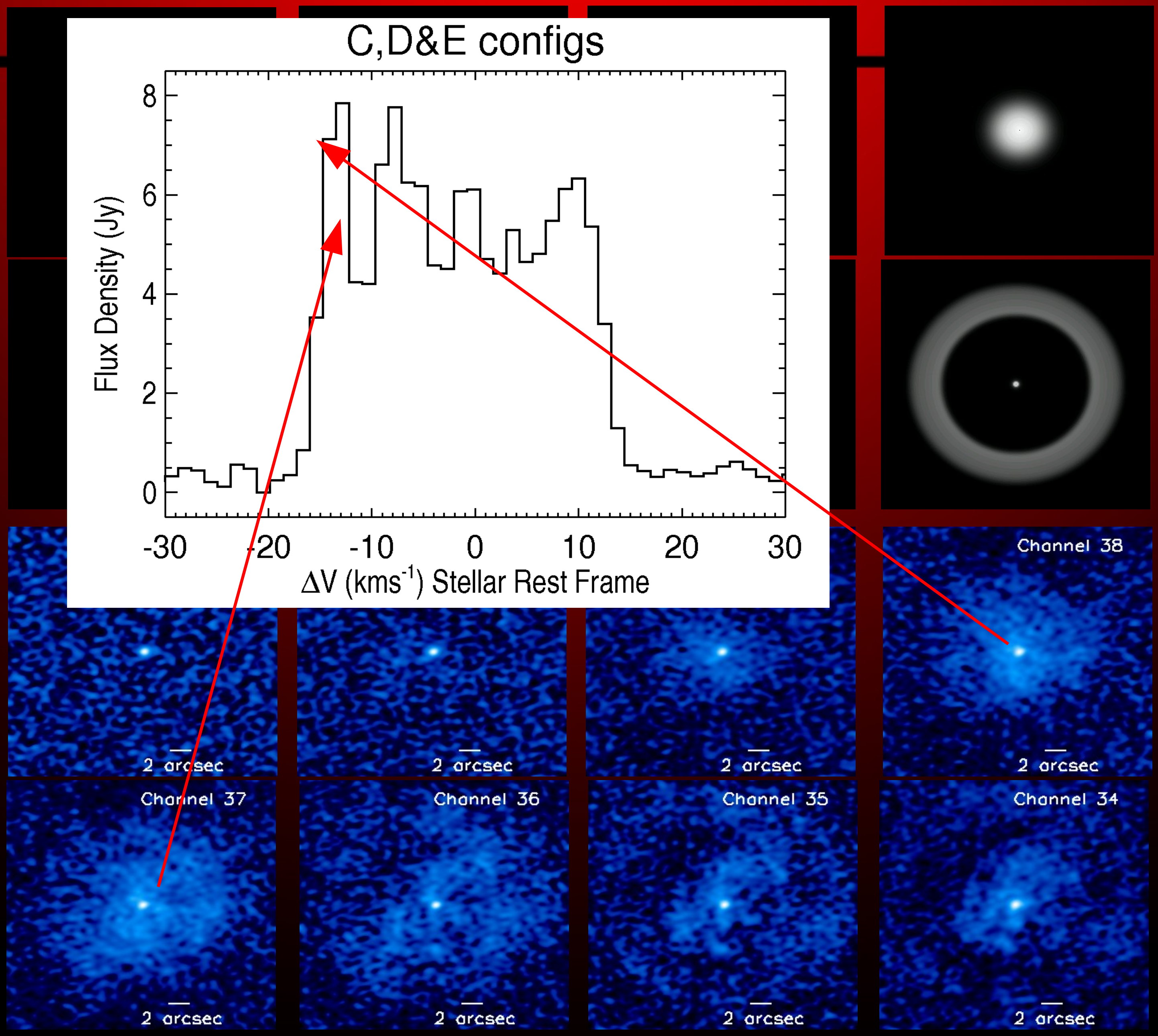
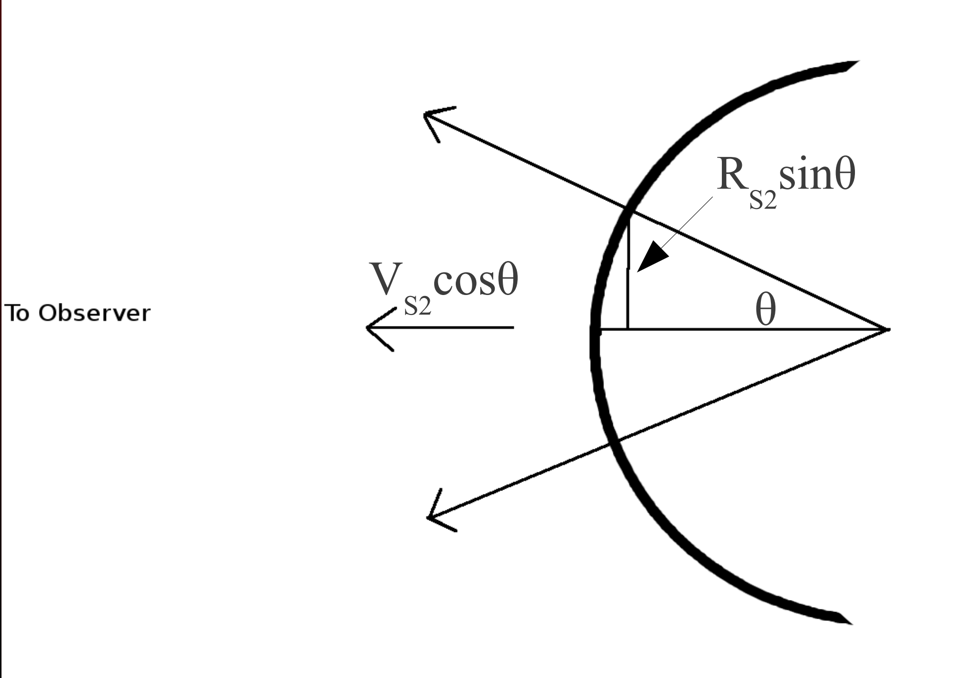
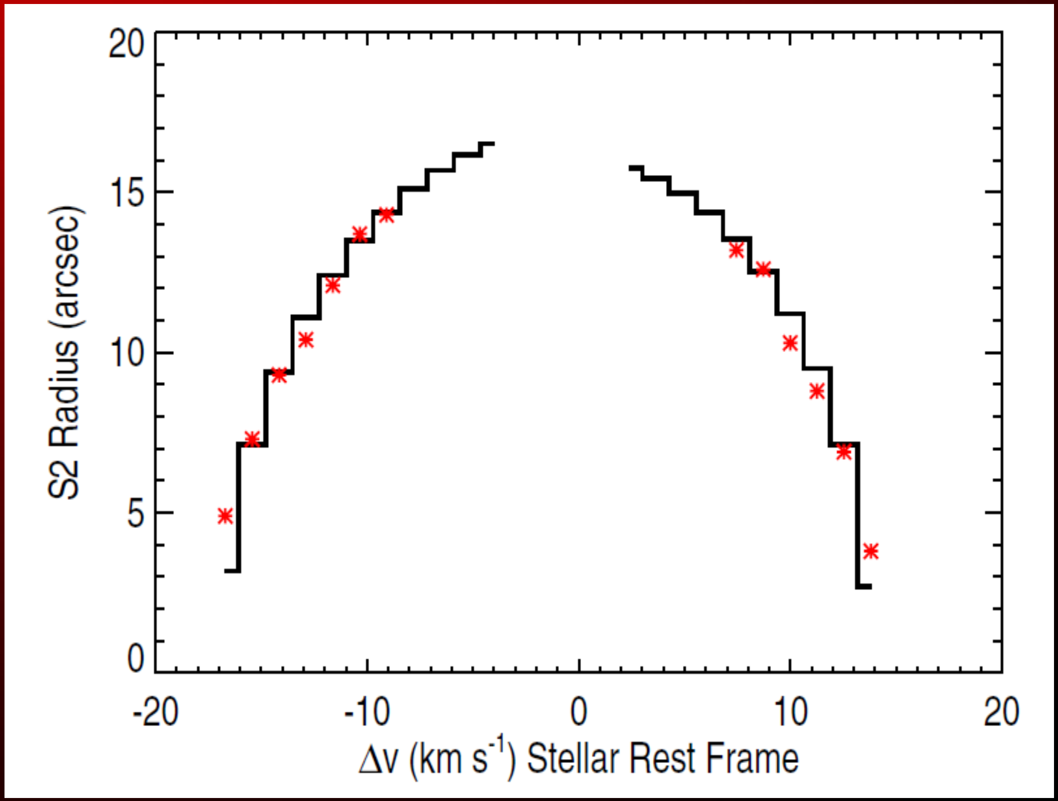
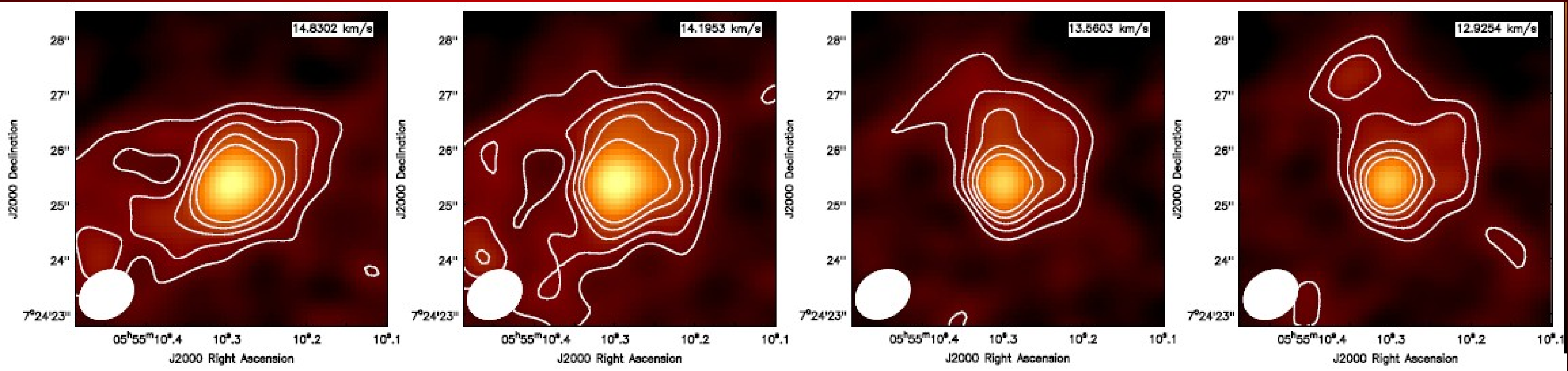


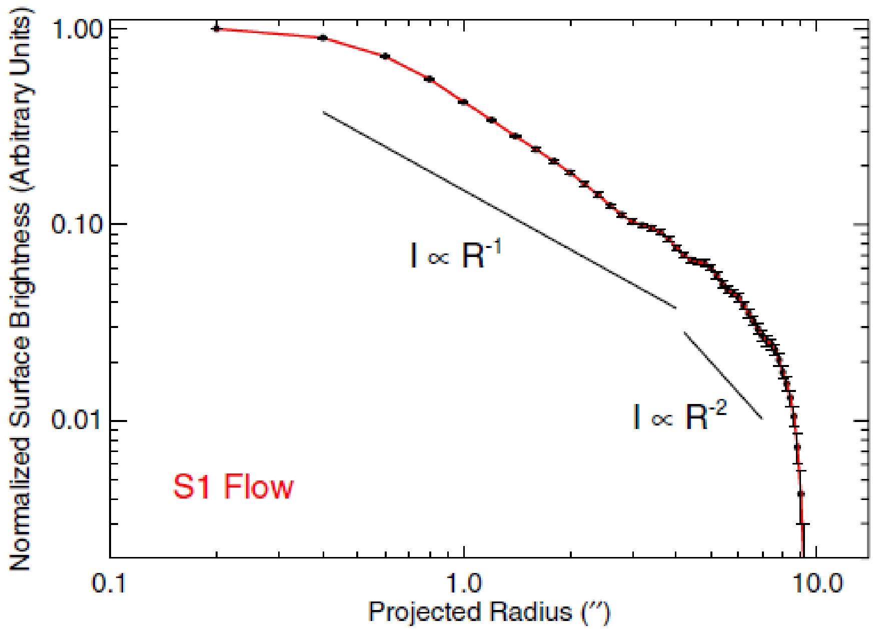
S2 Flow

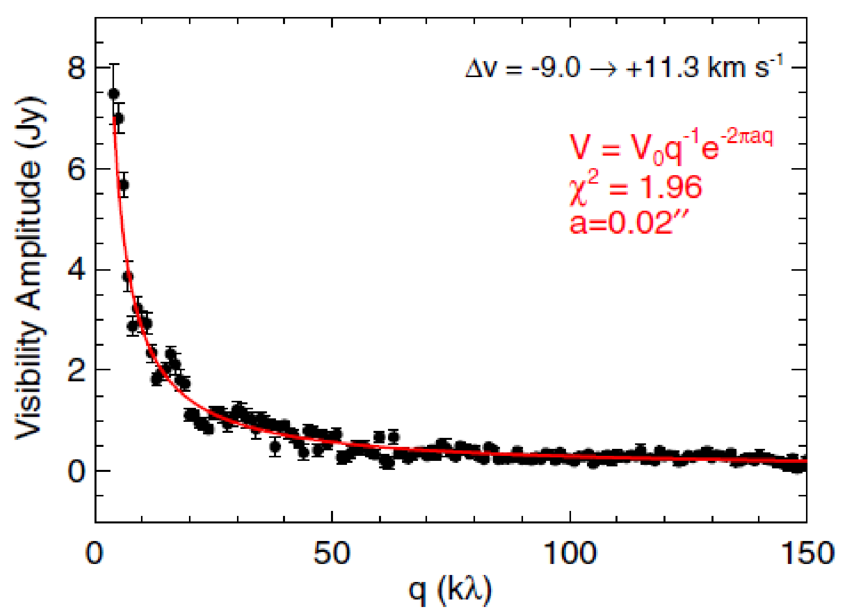


$$r_{\rm chan} = R_{S2} \sin\left[\cos^{-1}\left(\frac{v_{\rm chan}}{V_{S2}}\right)\right]$$



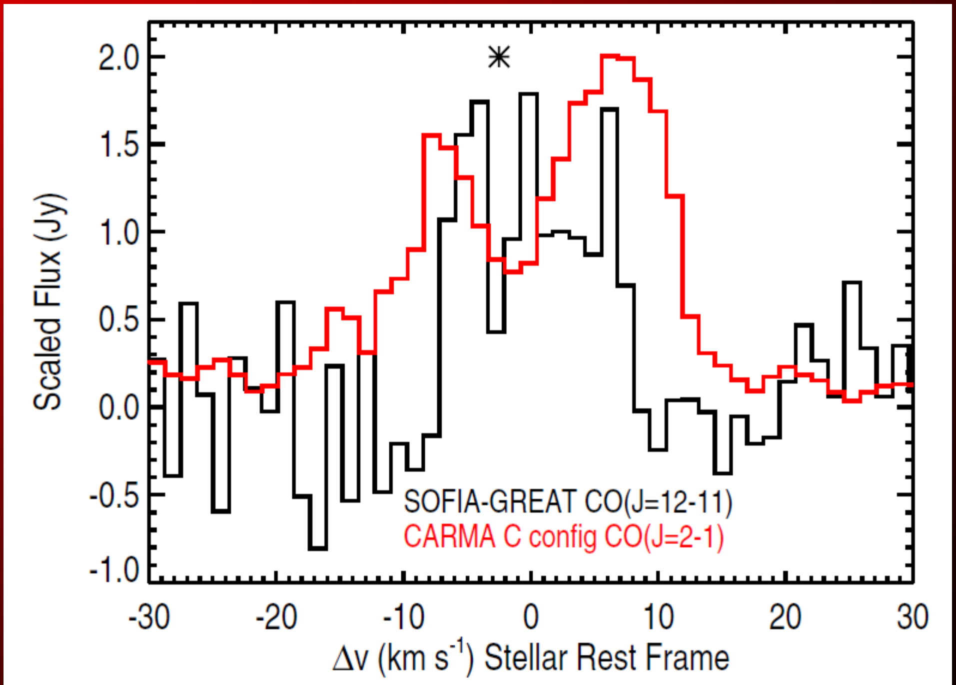

14.8302 km/s
14.1953 km/s
13.5603 km/s
12.9254 km/s
J2000 Declination
J2000 Right Ascension


Normalized Surface Brightness (Arbitrary Units)
Projected Radius (″)
I ∝ R^-1
I ∝ R^-2
S1 Flow


Δv = -9.0 → +11.3 km s^-1
V = V_0q^-1e^-2πaq
χ^2 = 1.96
a=0.02″
Visibility Amplitude (Jy)
q (kλ)

Inner Circumstellar Environment

Credit: NASA/Jim Ross.



$J_{mp} = (T_{ex}/5.53)^{1/2}$ (Rodgers & Glassgold, 1991):

S1 @ 200 K J_{mp} = 6 (i.e. J=6->5 691 GHz ALMA band 9)

S2 @ 70 K J_{mp} = 3 (i.e. J=3->2 245 GHz ALMA band 6)

ALMA Early Science 1 → 0.1" resolution of J=6-5 transition

1. Conclusions

1) Multiple CARMA configurations provide the high spatial resolution needed to study the inner S1 shell while also ensuring that larger structures (i.e. S2 shell) are not resolved out.

2) The high spatial resolution C configuration resolves out almost all material moving with a velocity < -9 km s-1 leaving us with S1 emission.

3) Image cube of total combined data reveal shell structure in channels corresponding to S2 shell in spectra.

4) Final Image Cube suggests:
R_{s1} ~ 4 arcsec
R_{s2} ~ 17 arcsec

2. Red Giant Outflows

Late-type red giants:

- chromosphere is always present
- coronal emission diminishes
- cool massive wind kicks in
  (e.g. Linsky & Haisch, 1981; Ayres et al., 1997)
- Relatively dense and slow moving winds

$$V_{terminal} < V_{escape}$$

Solar Eclipse

Importance:

- Enrich the interstellar medium with material required for the next generation of stars and planets
- Mass loss can alter the evolutionary fate of a star

Wind Driving Mechanism:

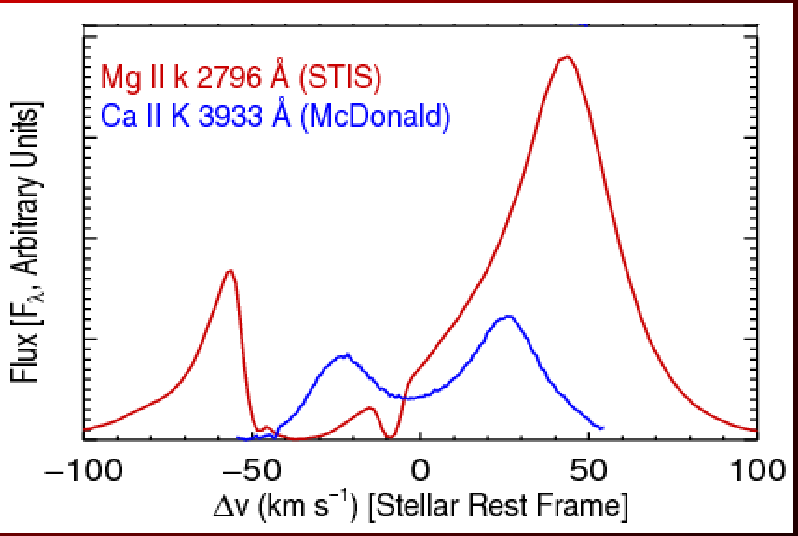
- An enduring mystery! (Holzer & MacGregor, 1985)
- Insufficient molecular or dust opacity
- Mass-loss rates too large for acoustic/pulsation models (Sutmann & Cuntz, 1995)
- Absence of hot wind plasma in optical & UV data – too cool to be Parker type flows

Red Giant Radio Emission

- Wind & chromospheric properties (dM/dt, v_{ter}) generally determined by analysing strong chromospheric resonance lines.

- Thermal structure poorly constrained. Very sensitive to T ($h\nu/kT >> 1$).

- At cm/mm the thermal continuum (Planck) function depends linearly on T.



α-Boo: Blue-shifted absorption component->outflow

- Continuum flux measurements at cm/mm wavelengths can probe different different layers in the atmosphere as radio opacity is proportional to ~ $\lambda^{2.1} n_e n_{ion}$.

- Multi-frequency observations at cm/mm wavelengths allow us to get spatial information from point sources!

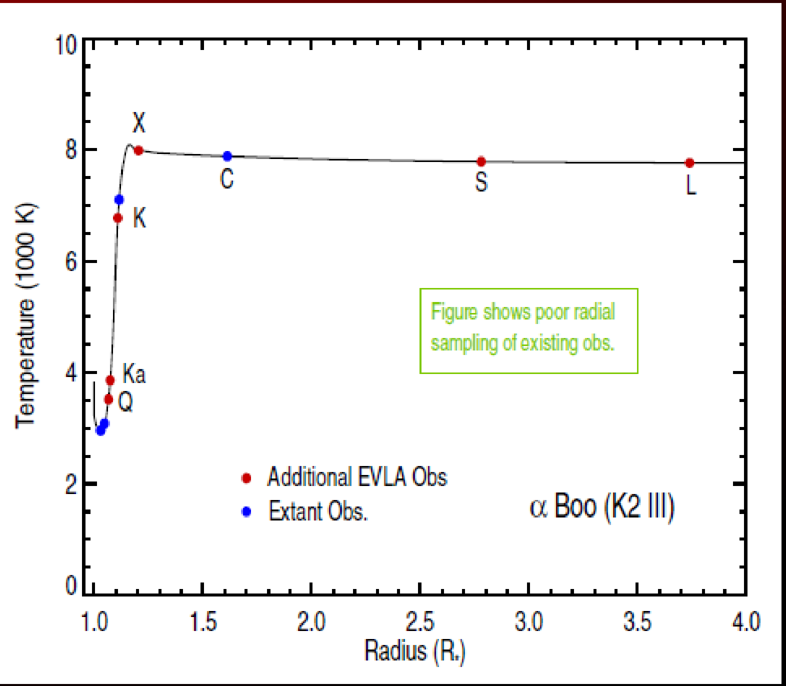
- Importance: T controls the level populations & ionization balance. Required for a detailed analysis of the wind thermal balance. Clues to mass-loss mechanism.

Sample Selection

Goal: *Observe two 'standard' red giants at all possible JVLA frequencies allowing the temperature to be probed throughout the wind acceleration zone (~1 – 4 R_*) in each.*

Arcturus (α Boo: K2 III) and Aldebaran (α Tau: K5 III)

- Single, non-dusty and non-pulsating
- Nearby (~ 11 pc and 20 pc)
- Well known stellar parameters
- Semi-empirical 1-D chromospheric and wind models that can be directly tested



The Karl G. Jansky Very Large Array

- 27 25 m antennas, New Mexico. Max baseline ~ 36 km
- Full frequency coverage between 1.0 and 50 GHz
- Continuum sensitivity improvement over the VLA by factors of 5 to 20
- Spectral Capability: A minimum of 16,384 and a maximum of 4,194,304 channels

JVLA Observations

Open Shared Risk Observing (OSRO)
B configuration – February 2011
Bandwidth = 256 MHz (2 spw's @ 64 x 2 MHz); Full Polarization

α Boo: S – Q-band in ~9 days (13^{th} Feb 2011 - 22^{nd} Feb 2011)
α Tau: S – Q-band in ~2 days (11^{th} Feb 2011 - 13^{th} Feb 2011)

A unique Data Set
α Boo: L-band not commissioned
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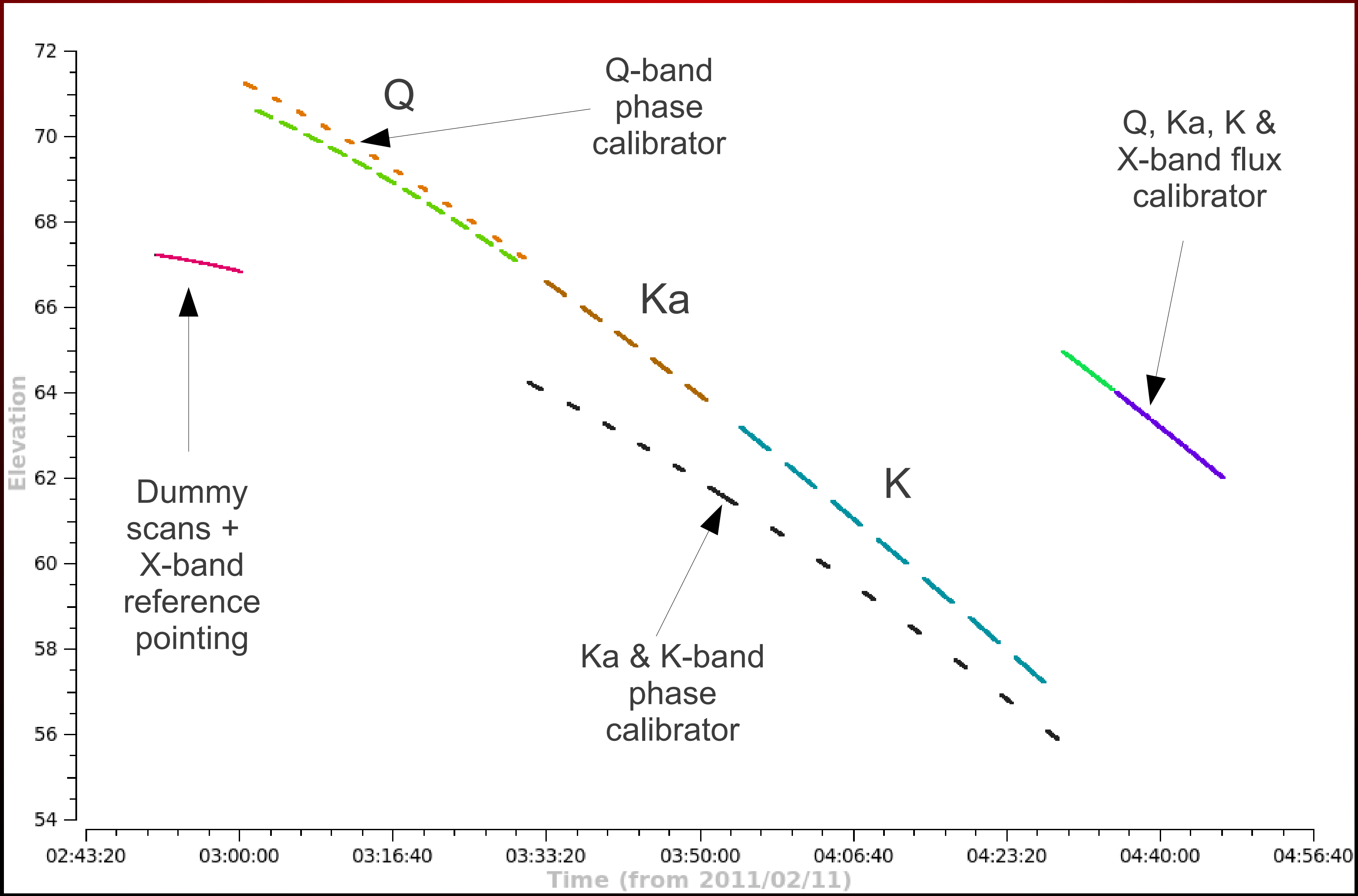
Directors Discretionary Time (DDT)
B configuration – July 2012
α Boo
L Band: Bandwidth = 1 GHz (16 spw's @ 64 x 1 MHz); Full Polarization
S Band: Bandwidth = 2 GHz (16 spw's @ 64 x 2 MHz); Full Polarization

Observing Strategy *– High Frequencies*

11 Feb 2011: Alpha Tau: K,Ka & Q-bands: 2 Hr Track: Fast Switching

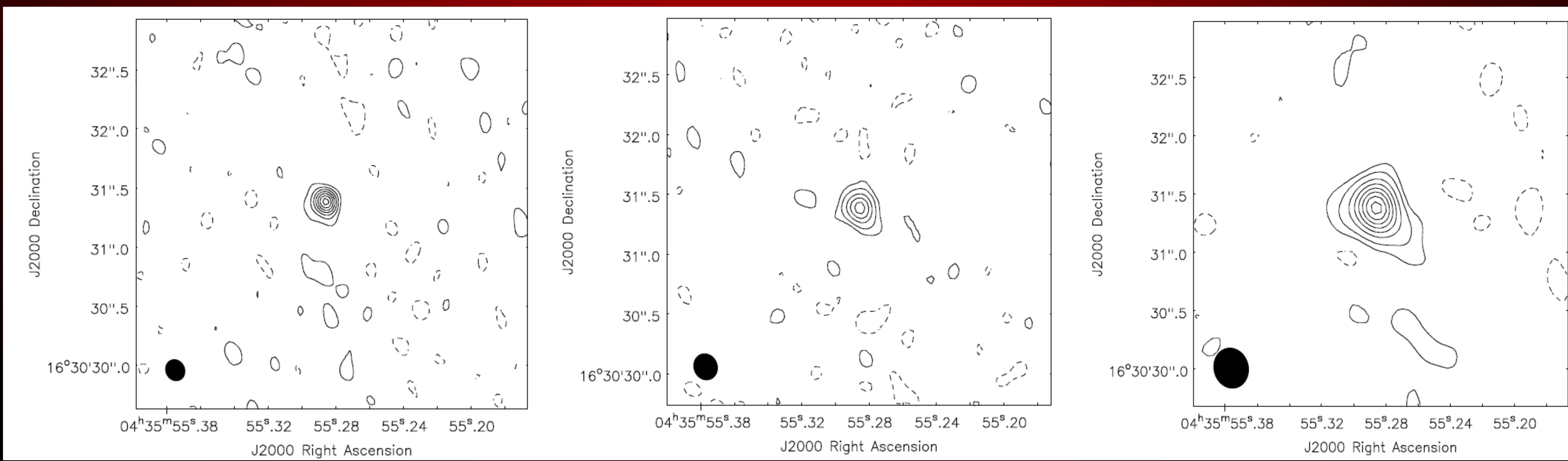


Results: α Tau – *High Frequencies*

Q-band (43 GHz)
S_ν = 3.67 mJy

Ka-band (34 GHz)
S_ν = 2.19 mJy

K-band (22 GHz)
S_ν = 1.86 mJy



Contours = (-2,2,4......14)xσ
σ = 240 μJy

Contours = (-2,2,5,10,15,20)xσ
σ = 96 μJy

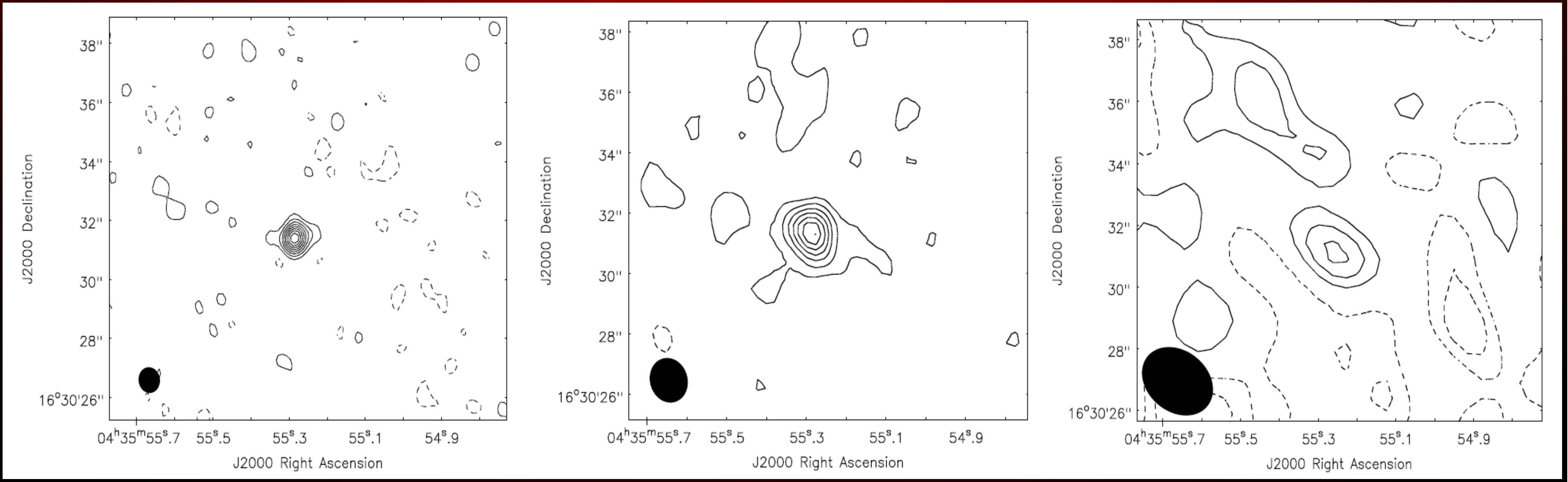
Contours = (-2,2,5,10,....35)xσ
σ = 50 μJy

Results: α Tau – *Low Frequencies*

X-band (8 GHz)
S_ν = 0.3 mJy

C-band (5 GHz)
S_ν = 0.15 mJy

S-band (3 GHz)
S_ν = 0.06 mJy

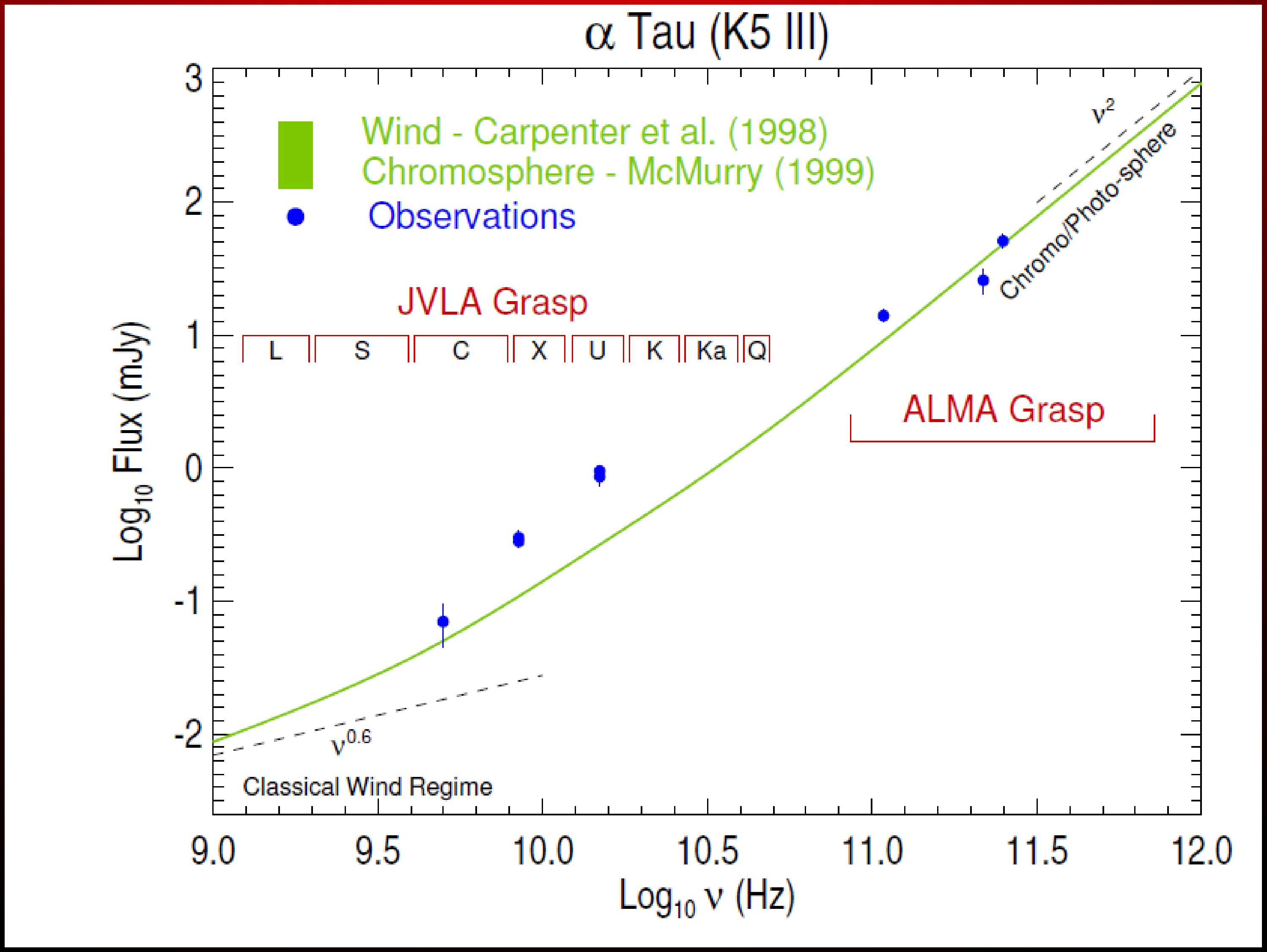


Contours = (-2,2,4......16)xσ
σ = 16 μJy

Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

Contours = (-3,-2,-1,1,2,3)xσ
σ = 18 μJy

Spectral Energy Distribution - *α Tau*



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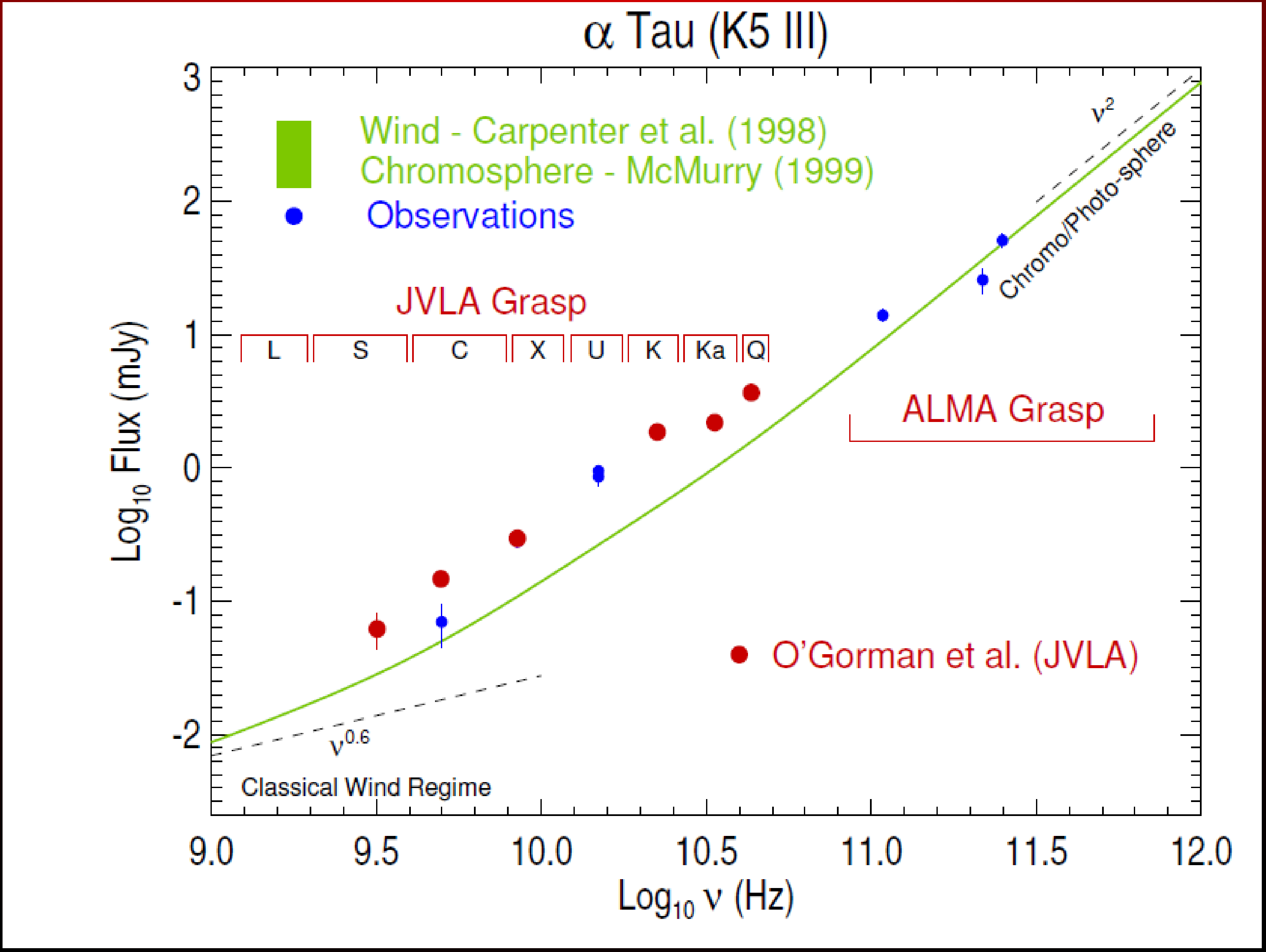
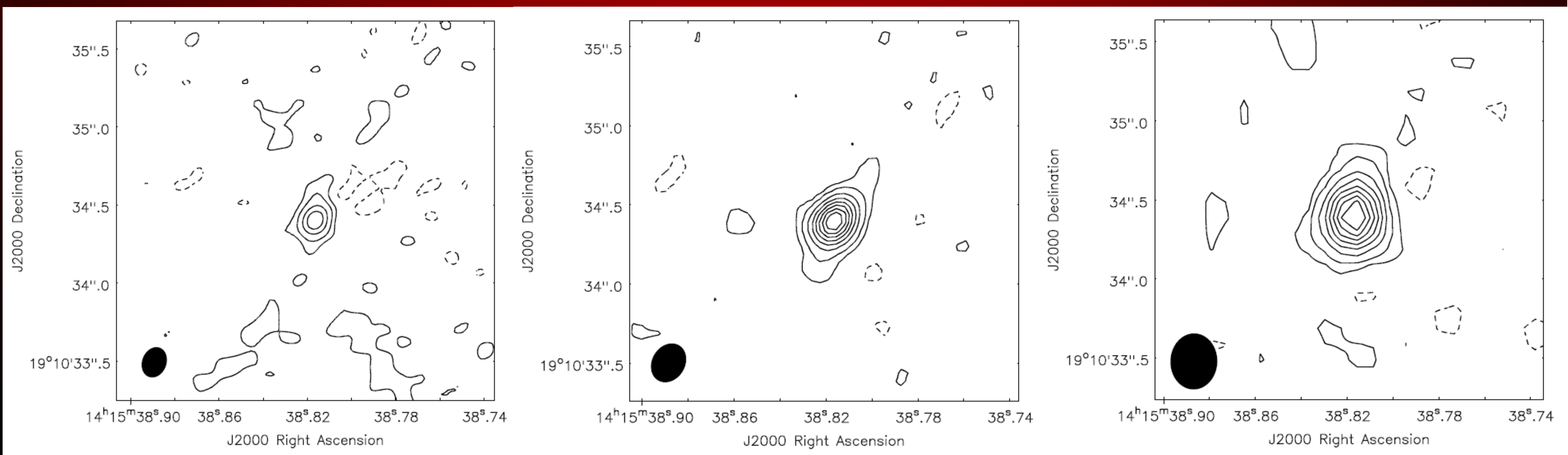


Results: α Boo – *High Frequencies*

Q-band (43 GHz)
S_ν = 5.96 mJy

Ka-band (34 GHz)
S_ν = 4.16 mJy

K-band (22 GHz)
S_ν = 1.80 mJy



Contours = (-2,2,5,.....15)xσ
σ = 276 μJy

Contours = (-2,2,5,10,....35)xσ
σ = 100 μJy

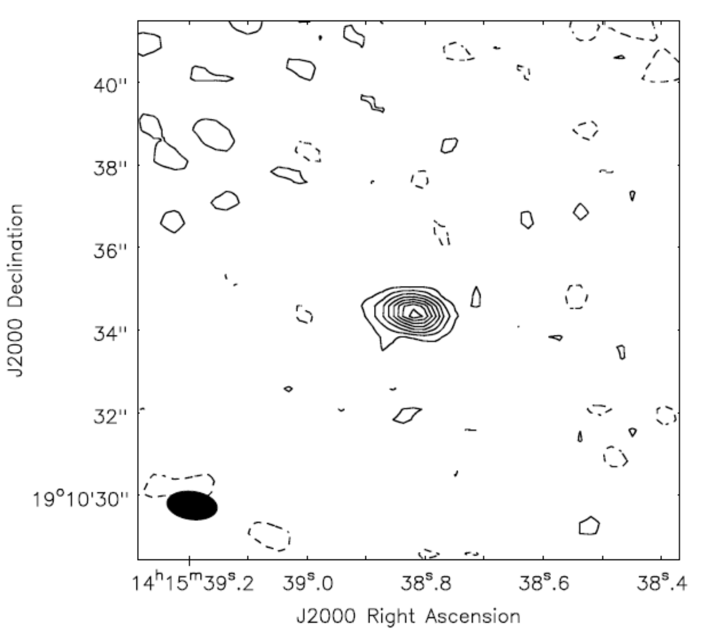
Contours = (-2,2,5,10,....35)xσ
σ = 40 μJy

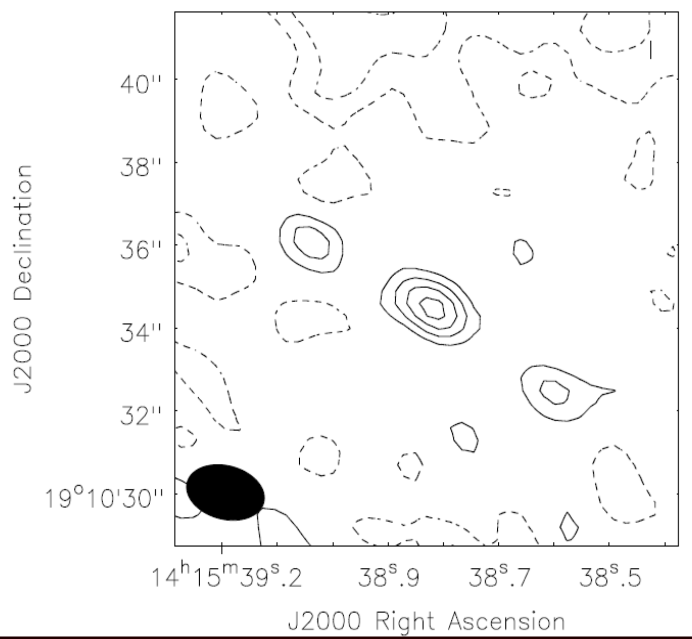
Results: α Boo – *Low Frequencies*

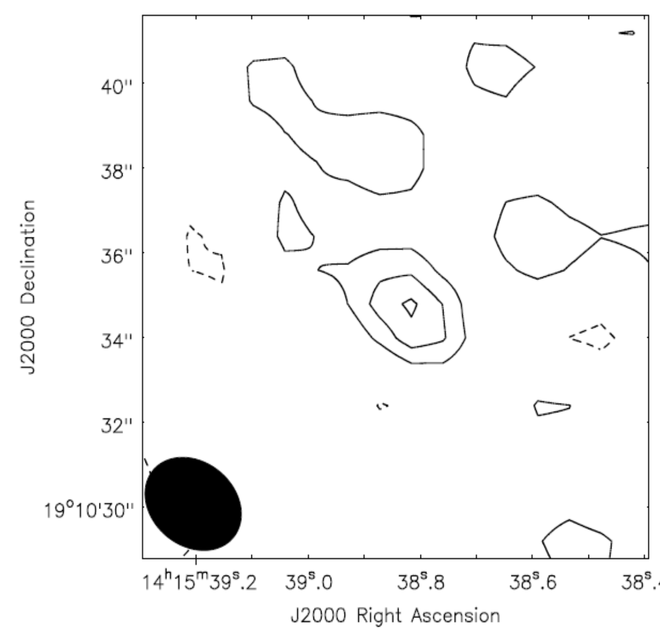
X-band (8 GHz)
S_ν = 0.49 mJy

C-band (5 GHz)
S_ν = 0.21 mJy

S-band (3 GHz)
S_ν = 0.11 mJy







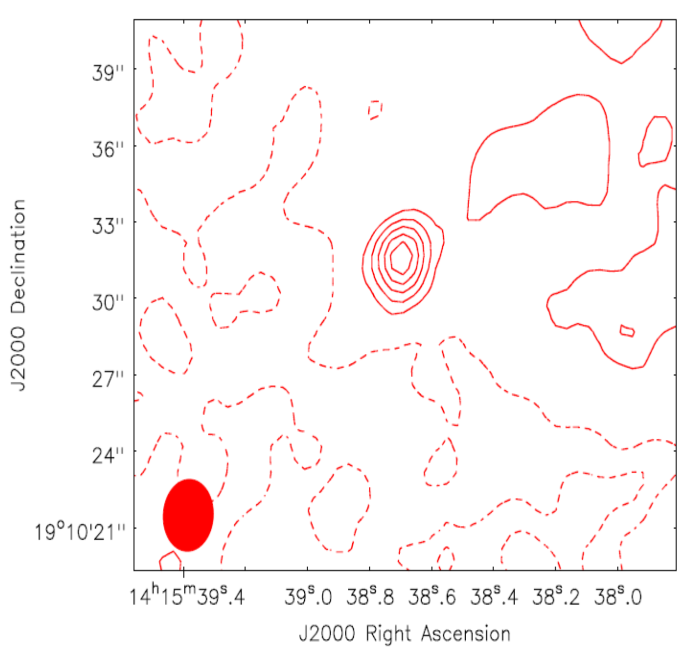
Contours = (-2,2,4......16)xσ
σ = 28 μJy

Contours = (-2,-1,1,2,3,4)xσ
σ = 46 μJy

Contours = (-2-1,1,2,3)xσ
σ = 35 μJy

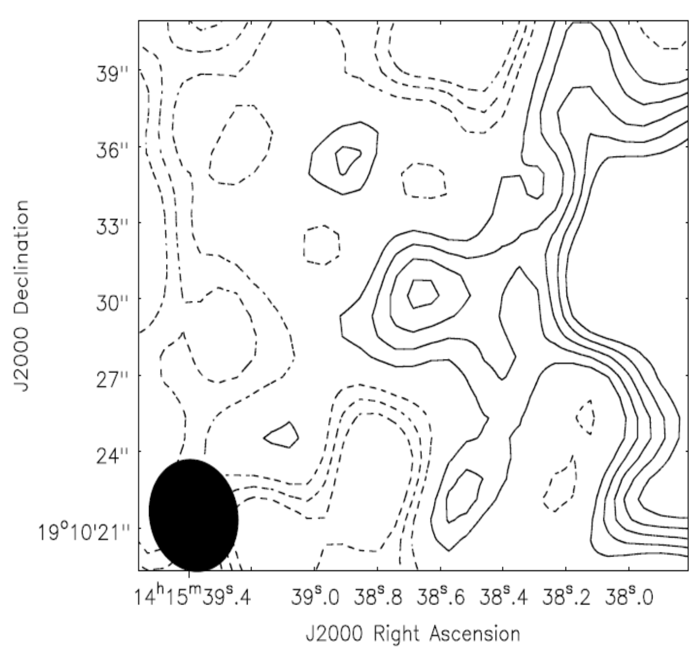
Results: α Boo – *Low Frequencies (DDT)*

S-band (2 - 4 GHz)
S_ν = 0.12 mJy



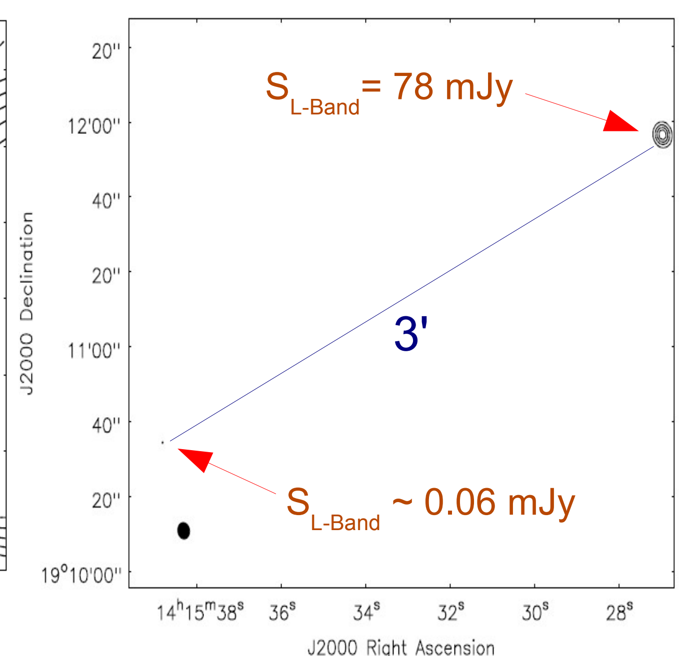
Contours = (-2,-1,1,2,3,4,5)xσ
σ = 22 μJy

L-band (1-2 GHz)
S_ν = 0.065 mJy



Contours = (-2,2,1,2,3,4,5)xσ
σ = 15 μJy

Strong 2nd Source @ C,S,L-band

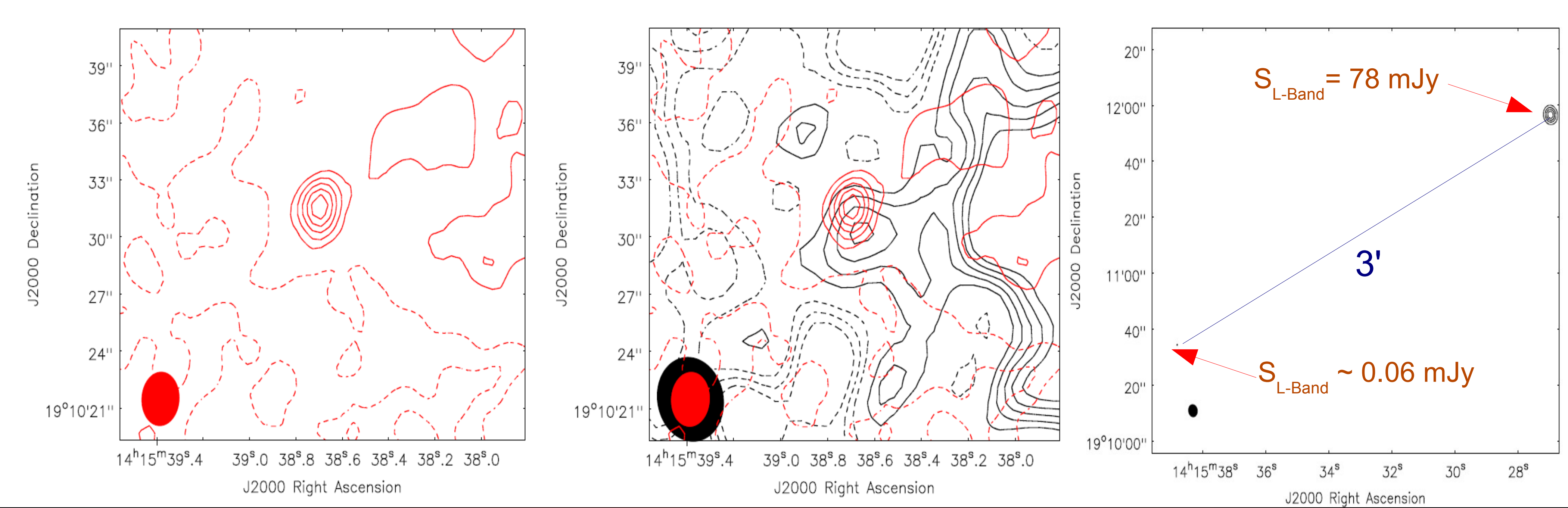


Results: α Boo – *Low Frequencies (DDT)*

S-band (2 - 4 GHz)
S_ν = 0.12 mJy

L-band (1-2 GHz)
S_ν = 0.065 mJy

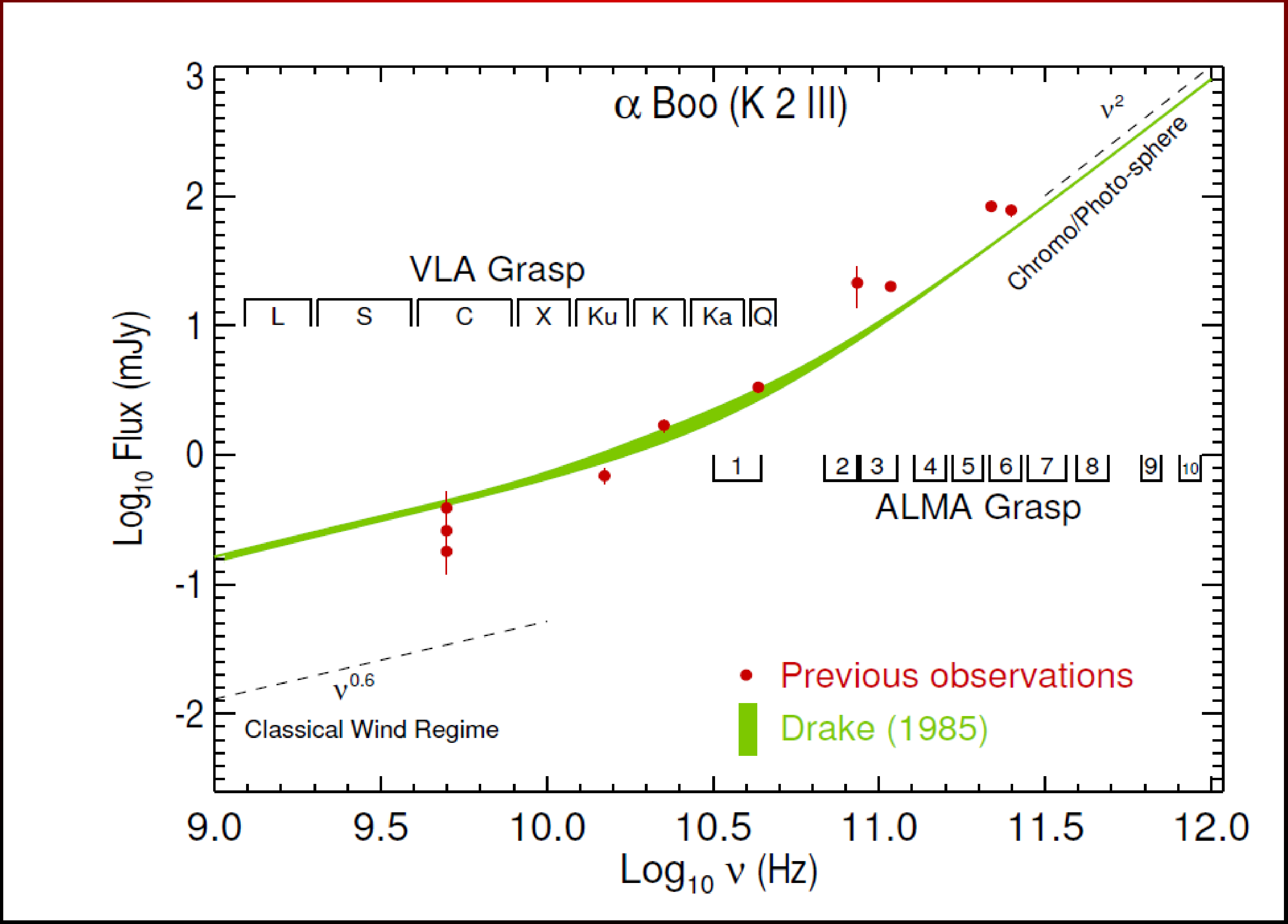
Strong 2[nd] Source @ C,S,L-band



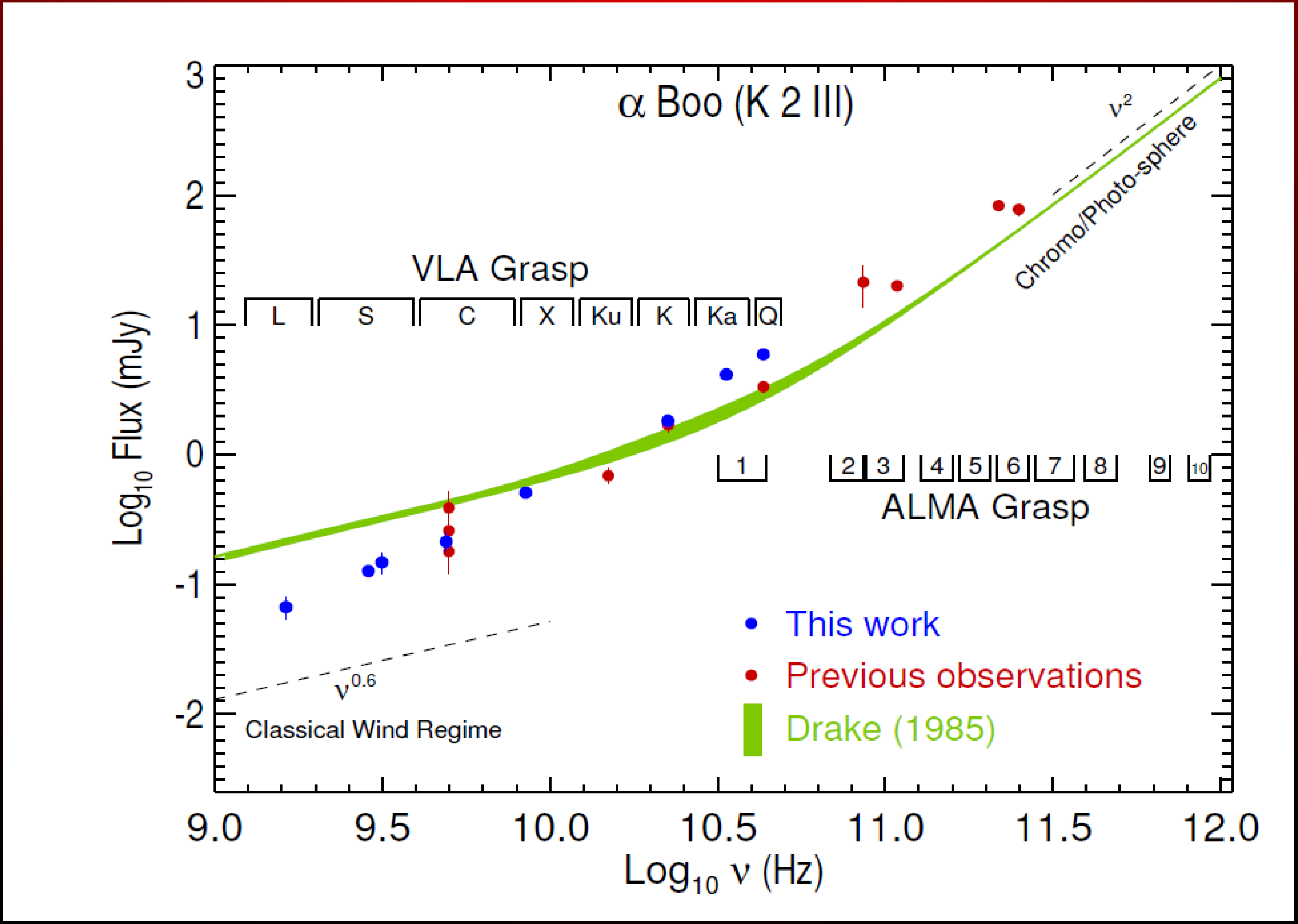
Contours = (-2,-1,1,2,3,4,5)xσ
σ = 22 μJy

Contours = (-2,2,1,2,3,4,5)xσ
σ = 15 μJy

Spectral Energy Distribution *- α Boo*



Spectral Energy Distribution *- α Boo*



Spectral Indices

$\alpha = d \log S_\nu / d \log \nu$

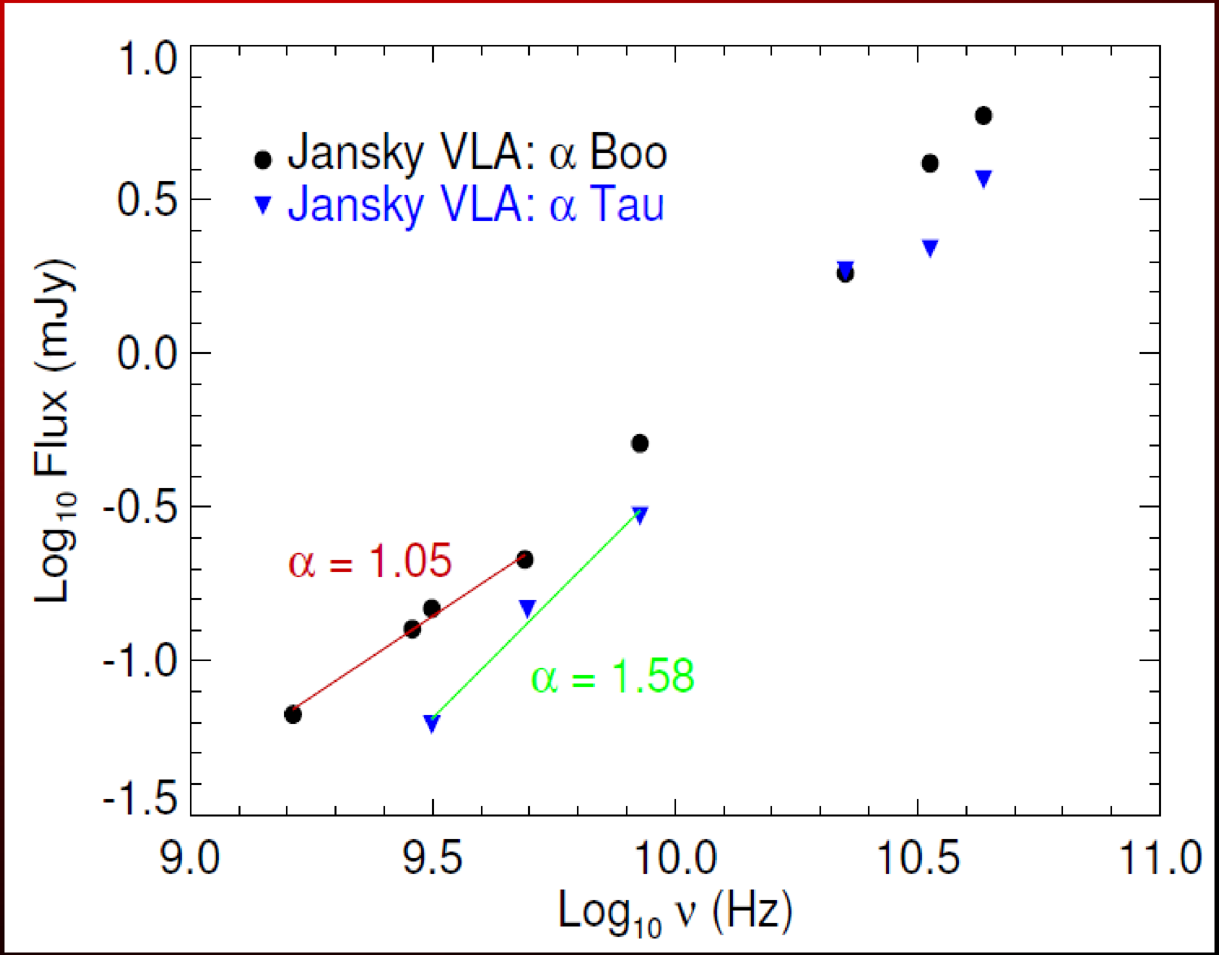
$\alpha = 2$ (thermal free-free)
Assumes homogeneous n_e

If $n_e \sim r^{-2}$ then $\alpha = 0.6$
Assumes constant v, T

If $n_e \sim r^{-p}$ & $T \sim r^{-n}$

$$\alpha = \frac{(4p-6.2-0.6n)}{(2p-1-1.35n)}$$

If p=2: $n_{\alpha\,Boo}=1.65$, $n_{\alpha\,Tau}=1.92$
If n=0: $p_{\alpha\,Boo}=2.7$, $p_{\alpha\,Tau}=5.5$



Hydrogen Ionization Code

Aim: Calculate the radio flux between 1 to 50 GHz for a grid of wind models, with different wind accelerations, mass-loss rates, and temperature profiles and see which model best fits our JVLA data.

Computes the hydrogen ionization as a function of R(z) using a 6-level model for H I (n=1 - 5 and n_K) using escape probabilities.

$$\cancel{\frac{\partial n_i}{\partial t}} + \nabla.(n_i V) = \sum_{i\neq j}^{n} n_j P_{ji} - n_i \sum_{j\neq 1}^{n} P_{ij}$$

Assume steady flow

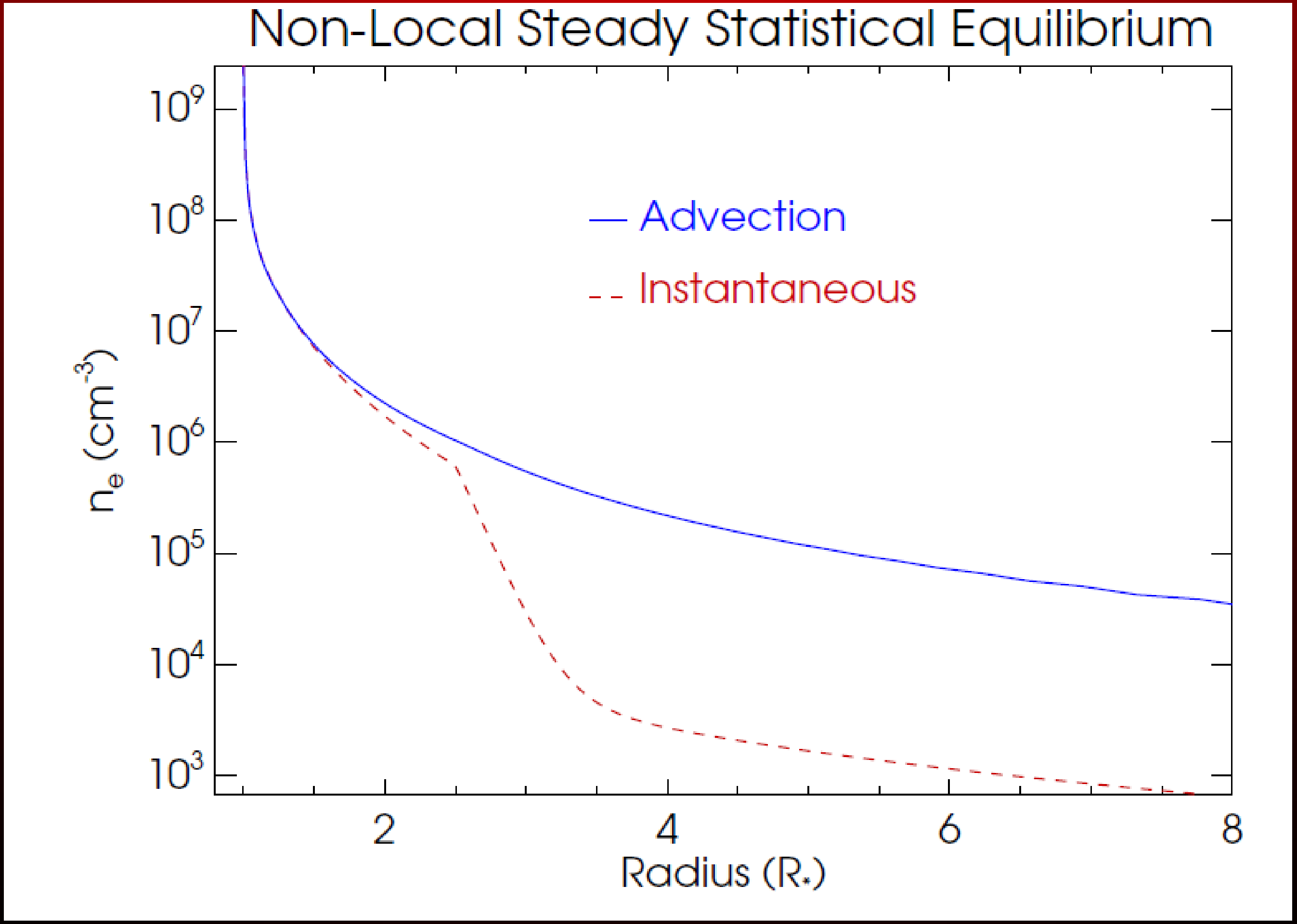
Statistical Equilibrium

Advection Term

Transition Probabilities

Hydrogen Ionization Code

Ionization state gets frozen into wind – *freezing-in of ionization balance*



Ionization state for in a stellar wind without/with advection

Conclusions & Future Work

1) Multi-frequency (L,S,C,X,K,Ka & Q-band) detections of two 'standard' red giants obtained over 11 days.

2) Proves that existing atmospheric models are outdated.

3) Don't appear to be sampling the outer wind.

a) Use our hydrogen ionization code to match our JVLA fluxes and develop an accurate thermal and density outflow model for both stars.

b) Perform a comprehensive study into the thermal energy balance -> provide clues to the wind driving mechanism(s) (e.g. O'Gorman and Harper, 2011).

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Thank you