Radio Interferometric Studies of Cool Evolved Stellar Winds

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Overview

- Mass-loss across the HR diagram
- Mass-loss Diagnostics
- Stellar Radio Emission Mechanisms
- Red Supergiants vs. Red Giants
- 1) Winds of Red Supergiants
  - 1(a) mm study of Betelgeuse's CSE
  - 1(b) cm study of Betelgeuse's wind acceleration region
- 2) Winds of Red Giants
  - 2 (a) Multi-wavelength cm study
  - 2 (b) Thermal energy balance
- Concluding Remarks

Mass-loss Across the H-R Diagram

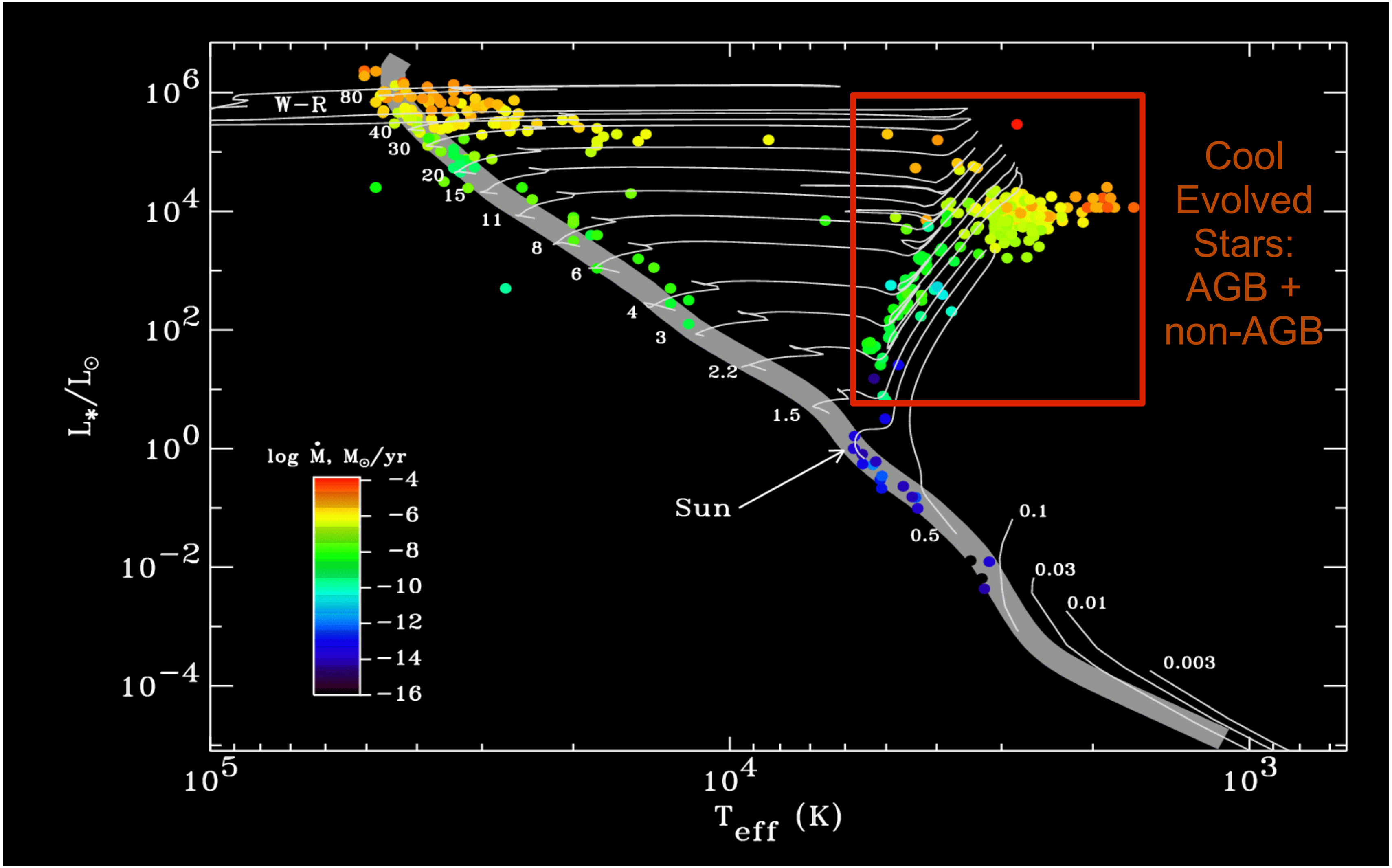
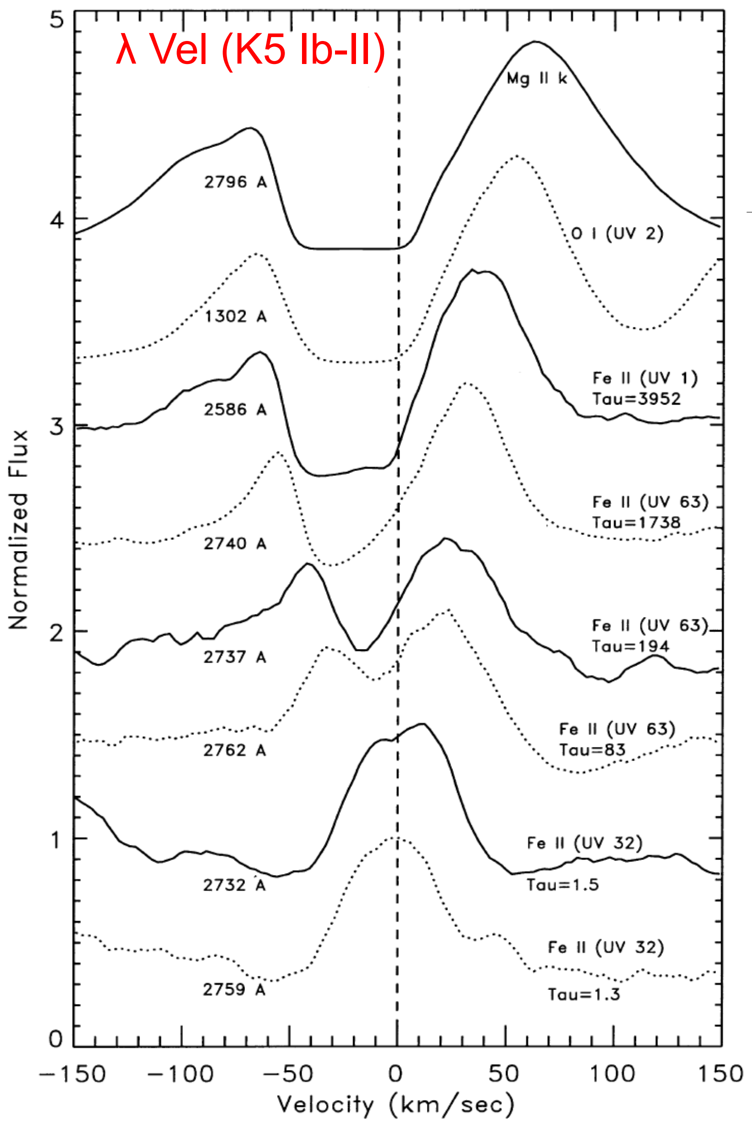
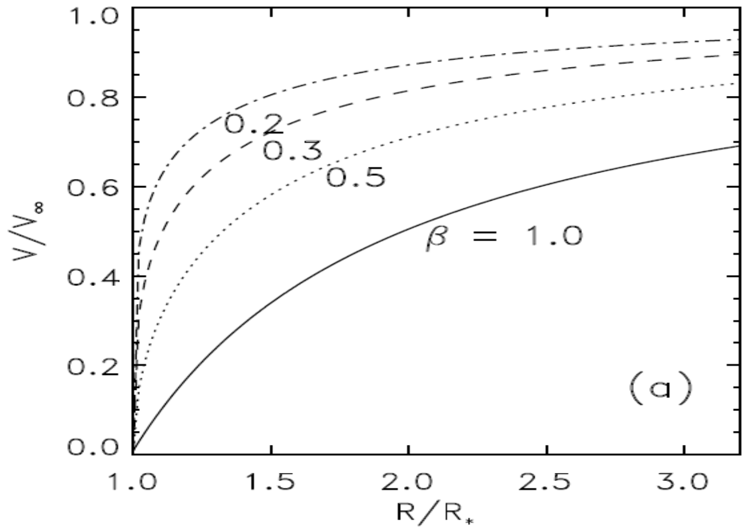


Image Credit: S. R. Cranmer

Traditional Diagnostics of Mass Loss



Carpenter *et al.*, (1999)



Robinson *et al.*, (1998)

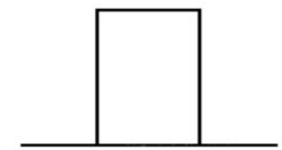
- **Optical and UV spectroscopy:**
  Full "P Cygni" profiles or blueshifted absorption
- **IR continuum:** Dust excess
- **Molecular lines:**
  mm, sub-mm (disk averaged)
- **Centimetre continuum:**
  Ionized mass rate.
  Single wavelength detections

Radio Emission Mechanisms

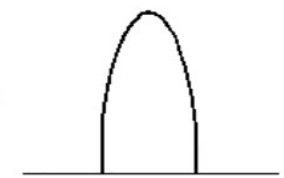
1) Molecular Emission lines

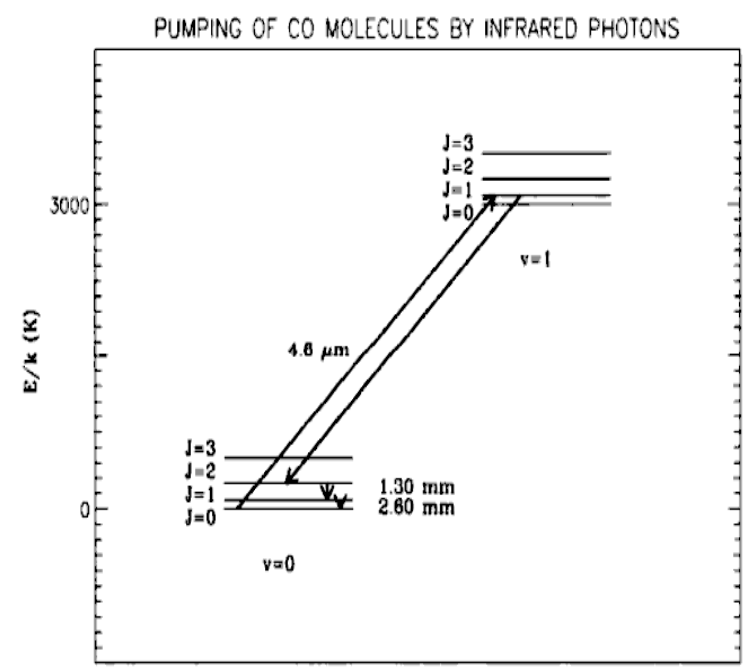
- Line profiles are either flat-topped or parabolic
- Line full widths typically between 20 and 50 km s^{-1}
- CO: Both O-rich and C-rich stars. Stable.
- Excitation processes for CO: H_2 collisions. Photo-excitation of vibrational levels by IR photons.

Optically thin emission:



Optically thick emission:





1) Thermal Bremsstrahlung Emission

- Opacity is proportional to ~ λ^2
-

$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$

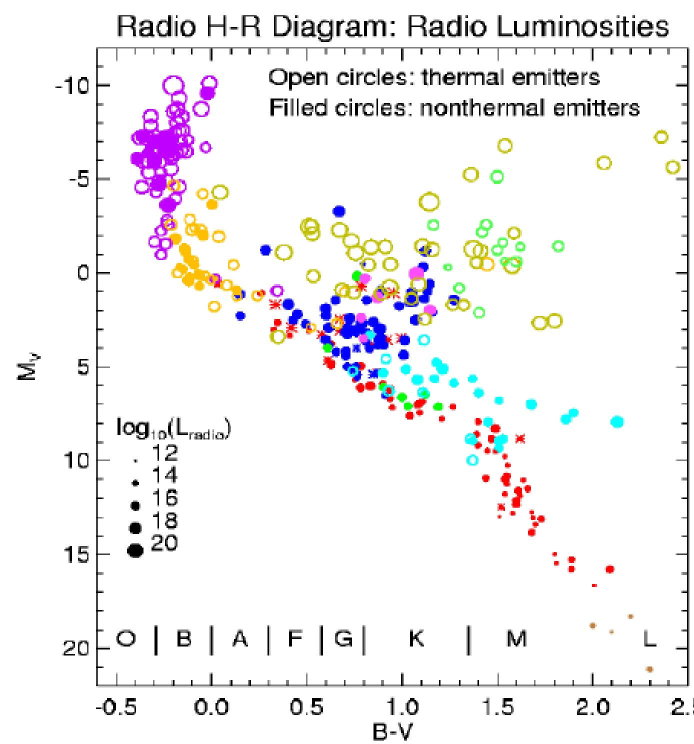
Stellar Radio Emission

Radio Sky at 4.85 GHz (300ft Green Bank)

Credit: NRAO/AUI

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

$S_{\nu=4.6\,\mathrm{GHz}} \sim 40\ \mu$Jy at α Cen
(not detectable with 'old' VLA!)



White (2000)

Red Supergiants vs. Red Giants

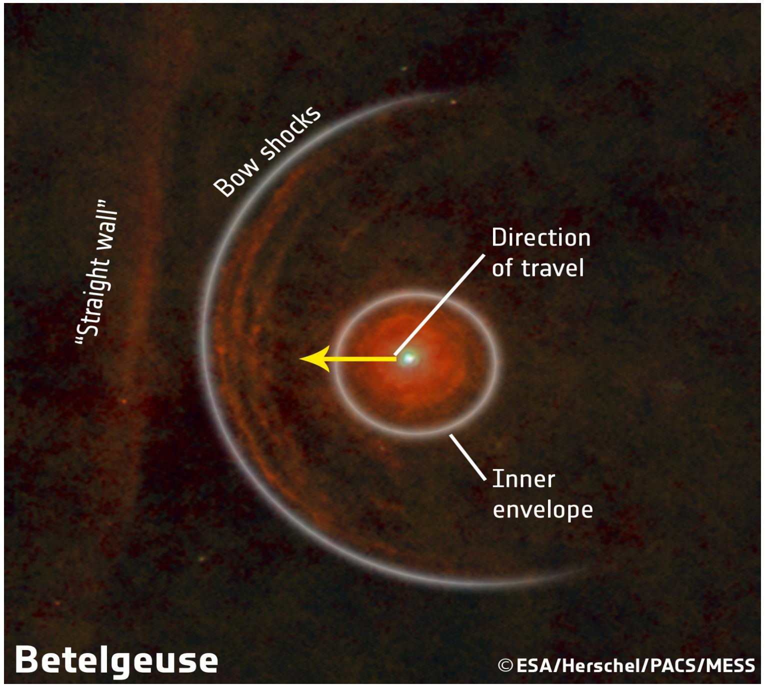
	Red Giants	Red Supergiants
Mass ($M_\odot$)	~ 0.4 → ~ 8	~8 → ~ 40
Radius ($R_\odot$)	~ 50	~ 500
Lifetime (yr)	~ 10^9	~ 5×10^5
dM/dt ($M_\odot$ yr^{-1})	~ 10^{-10}	~ 10^{-5}
Total dM/dt ($M_\odot$)	~ 0.1	~ 5

$V_{teminal} < v_{*\ escape}$
$H_P/R \sim 10^{-2}$
$T_{wind} < 10^4$ K

No coronae.
Insufficient dust opacity.
Small pulsation amplitudes.

1) Winds of Red Supergiants

Betelgeuse (M2 Iab)



(Decin *et al.*, 2013)

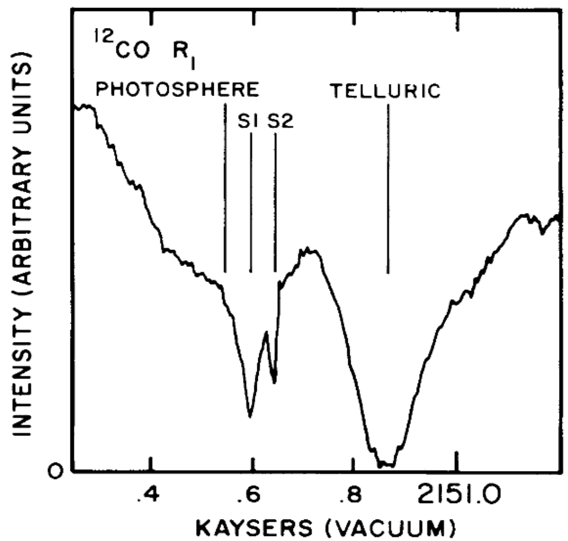
$Log(L/L_{\odot})$	5.12
Distance	197 ± 45 parsec
Photospheric Radius	22.5 mas (950 $R_{\odot}$)
Mass (current)	~15 - 18 $M_{\odot}$
Mass loss rate	$3 \times 10^{-6}\ M_{\odot}\ yr^{-1}$
Photospheric Temperature	3,600 K (cool star)
Origin	O-type main sequence
Fate	Supernova Type II
$^{12}C/^{13}C$	6 ± 1

1 (a): Betelgeuse: Circumstellar Environment

- At least two *recent* mass loss phases

- Two distinct shells spectrally resolved at 4.6 µm:
  - S2, moving at 17 km s^{-1}
  - S1, moving at 10 km s^{-1}
  - Spatial extent not directly determined

(Bernat *et al.*, 1979)



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- Plez & Lambert (2002) appear to detect S2 shell at 50"
- IRAM 30 m (θ_{HPBW} ~12") fails to resolve S2 shell at 1.3 mm
- Single dish $^{12}C^{16}O$ mm-observations reveal only high velocity S2 shell.

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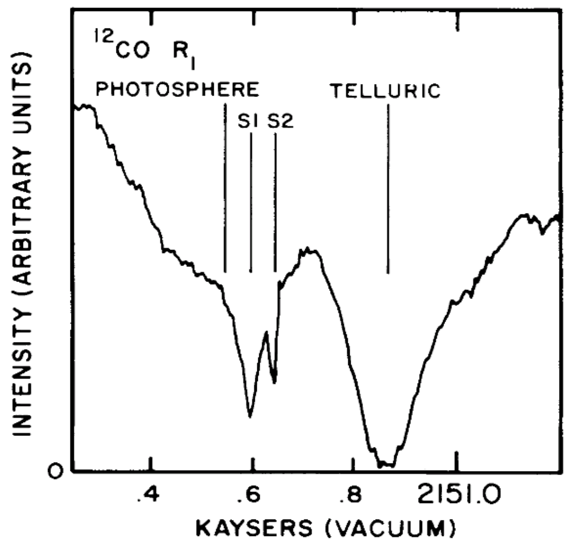
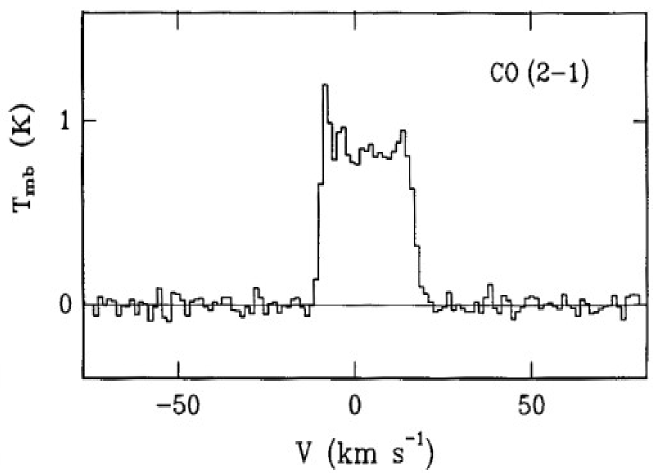


(Huggins *et al.*, 1994)



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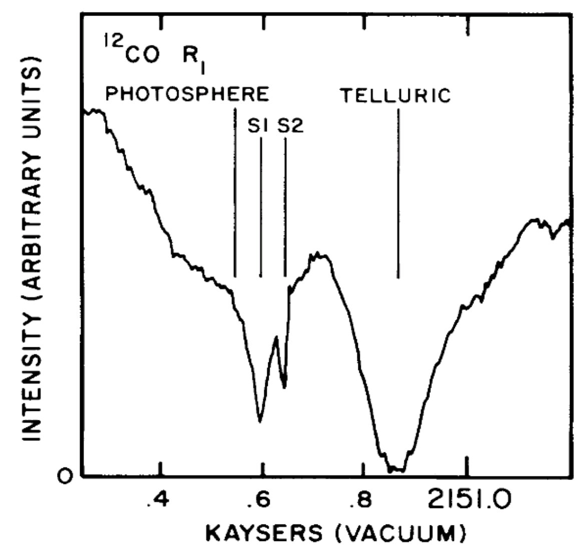
Goal 1 (a): *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

(Bernat *et al.*, 1979)



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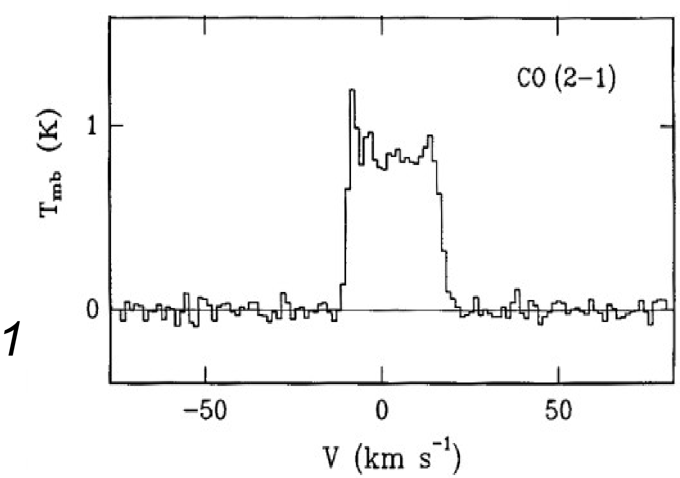


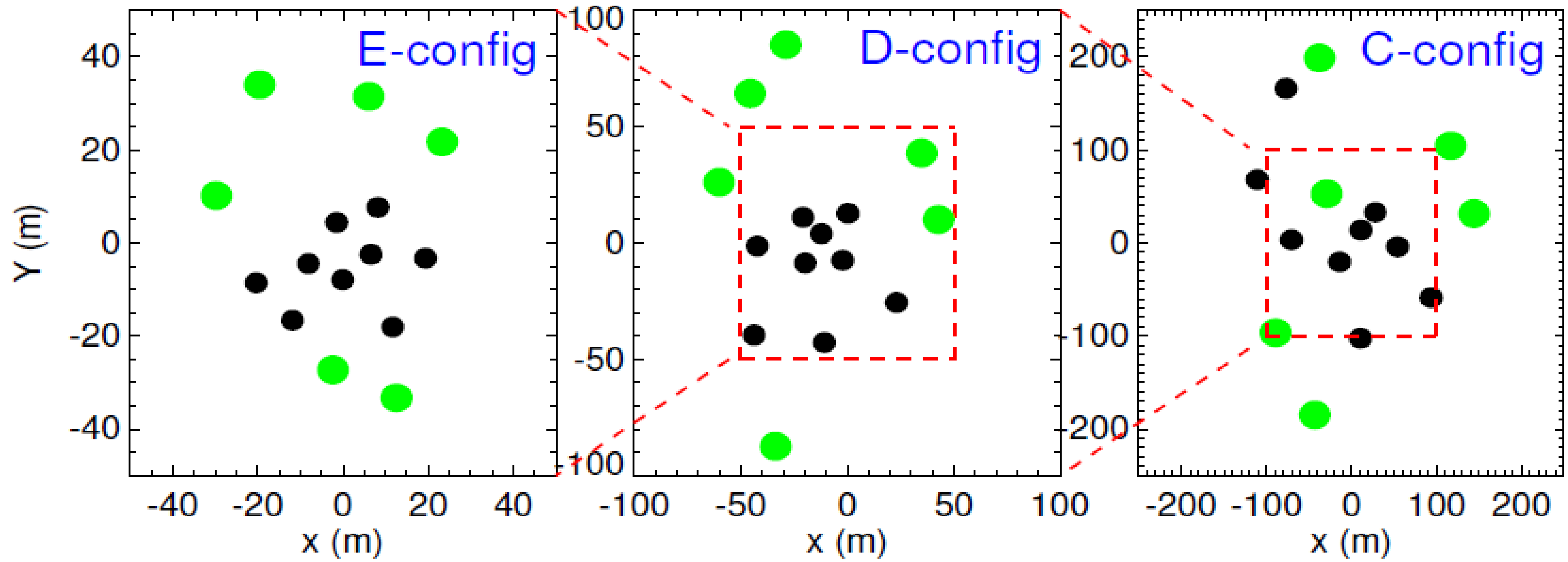
1 (a): CARMA

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

Credit: John Carlstrom

1 (a): mm Observations

Date	Config	Time (hr)	Resolution ('')	Max Scale ('')
Jun 07	D	8.4	2.1	15
Jul 09	E	3.2	4.4	19
Nov 09	C	8.4	0.9	6

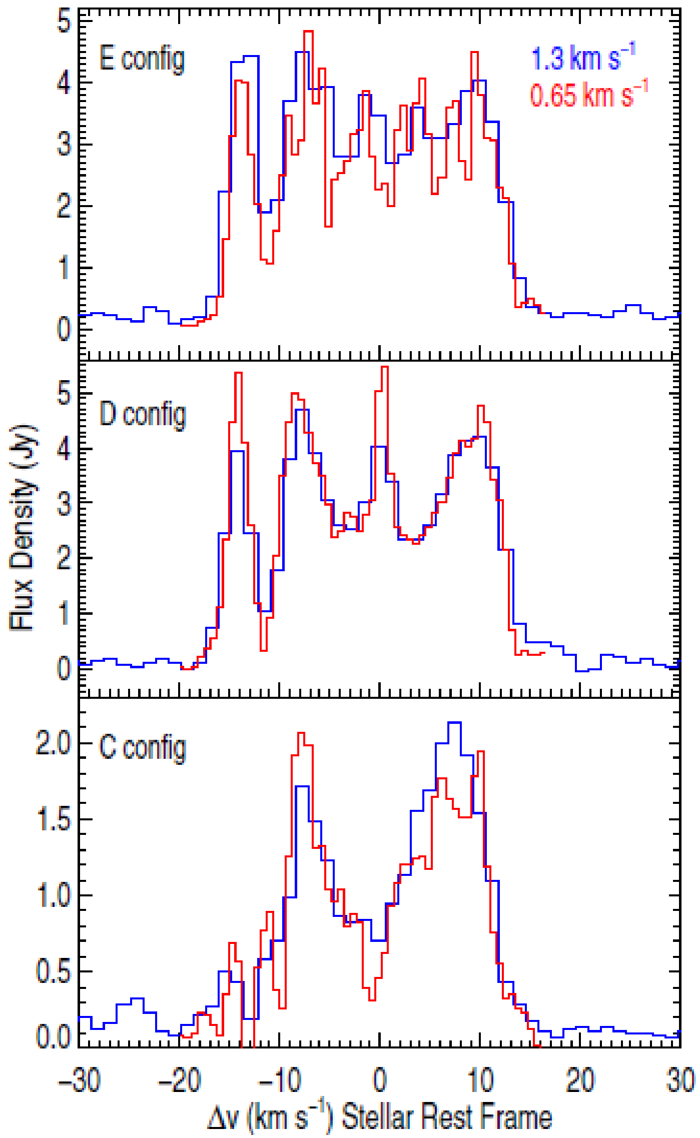


B_{min} = 8 m, B_{max} = 66 m

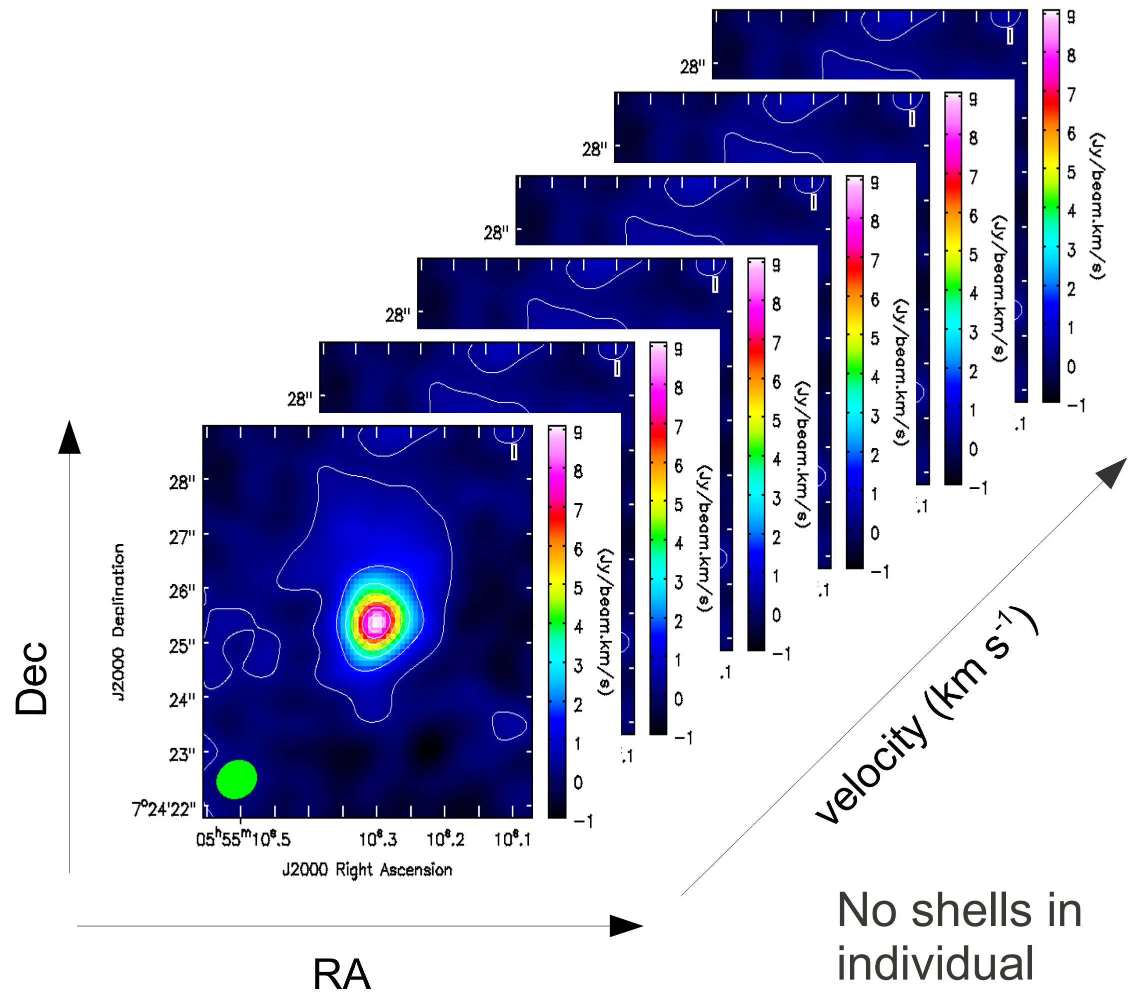
B_{min} = 11 m, B_{max} = 150 m

B_{min} = 30 m, B_{max} = 350 m

1 (a): Individual Configurations

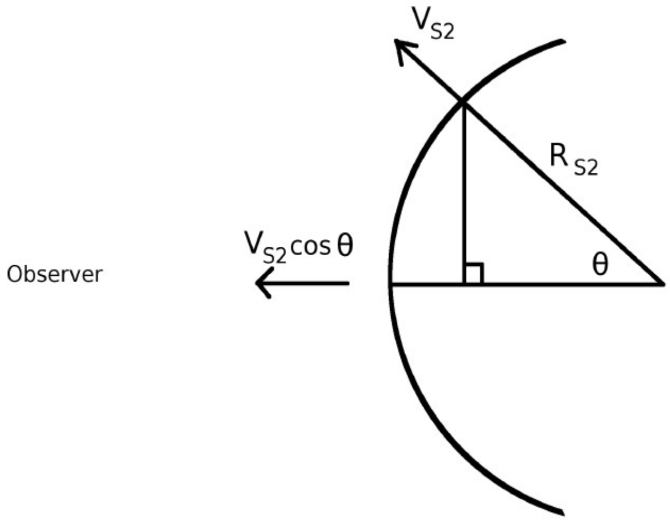


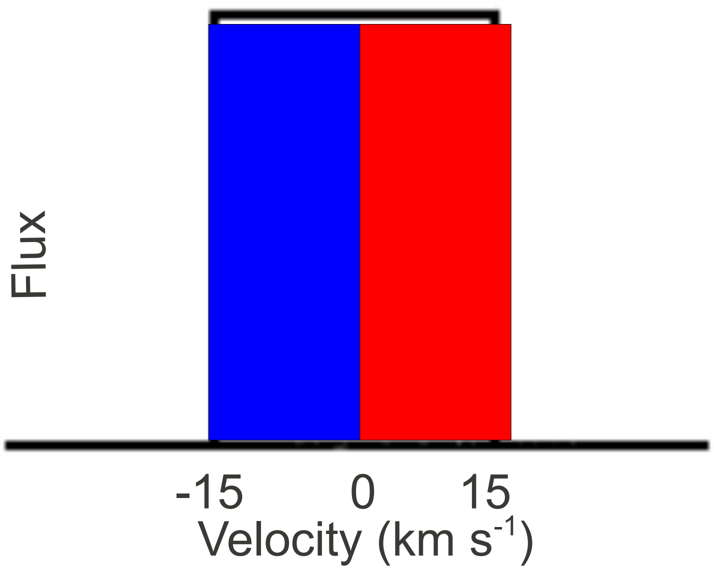
(O'Gorman *et al.*, 2012)

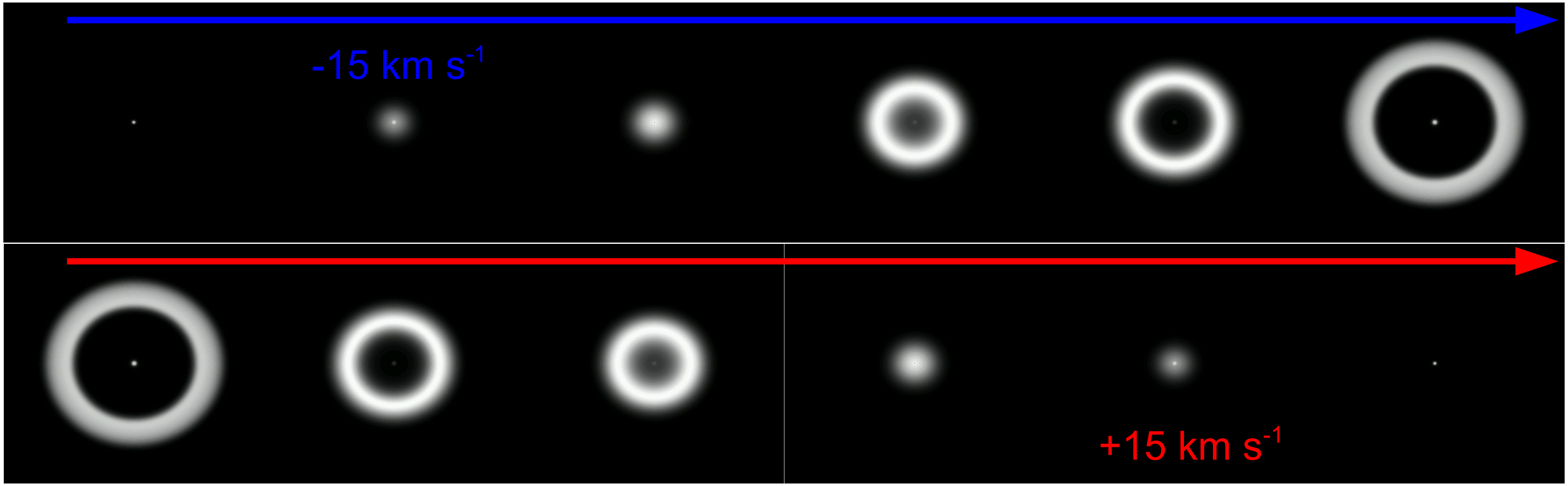


No shells in individual configuration image cubes.

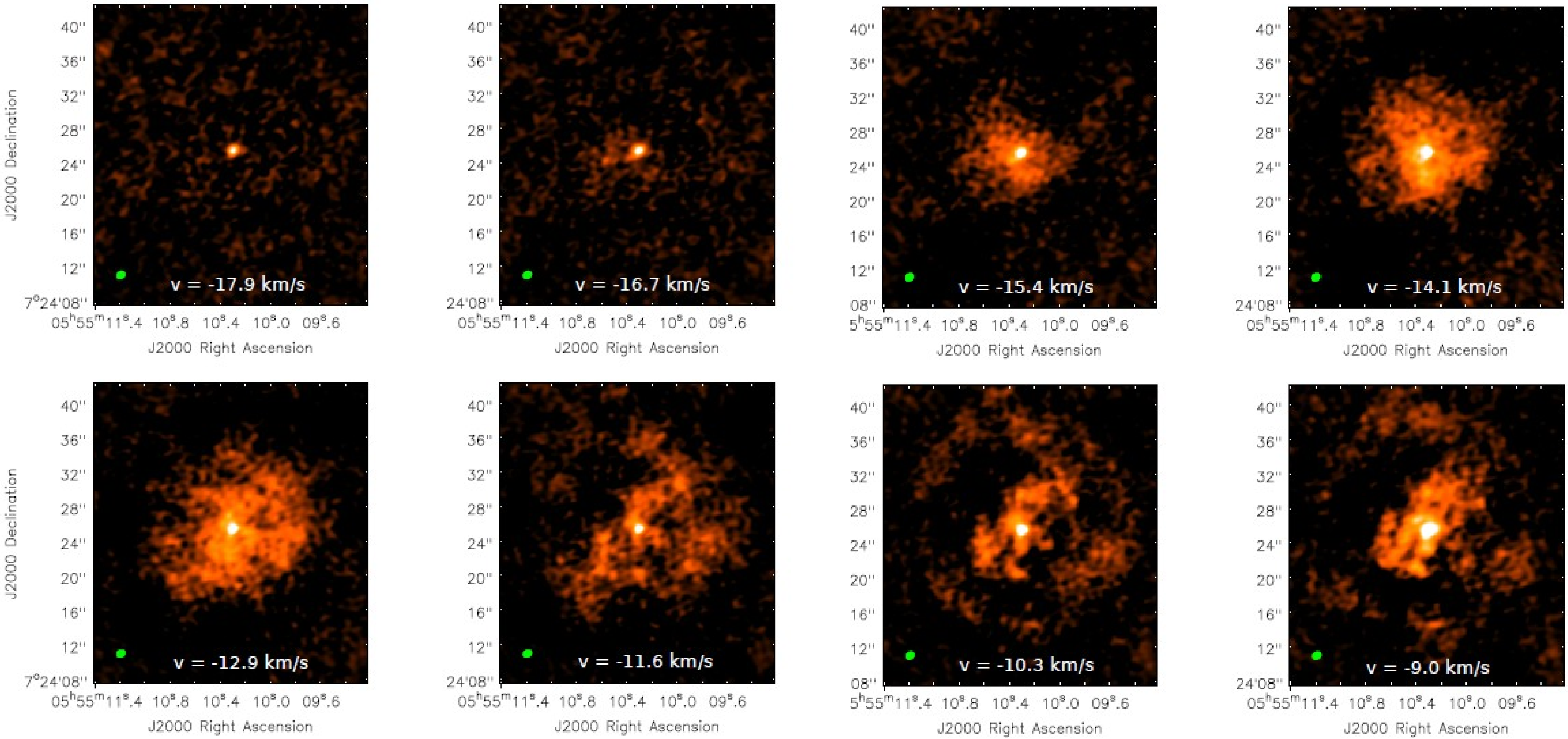
1 (a): Theoretical Shell



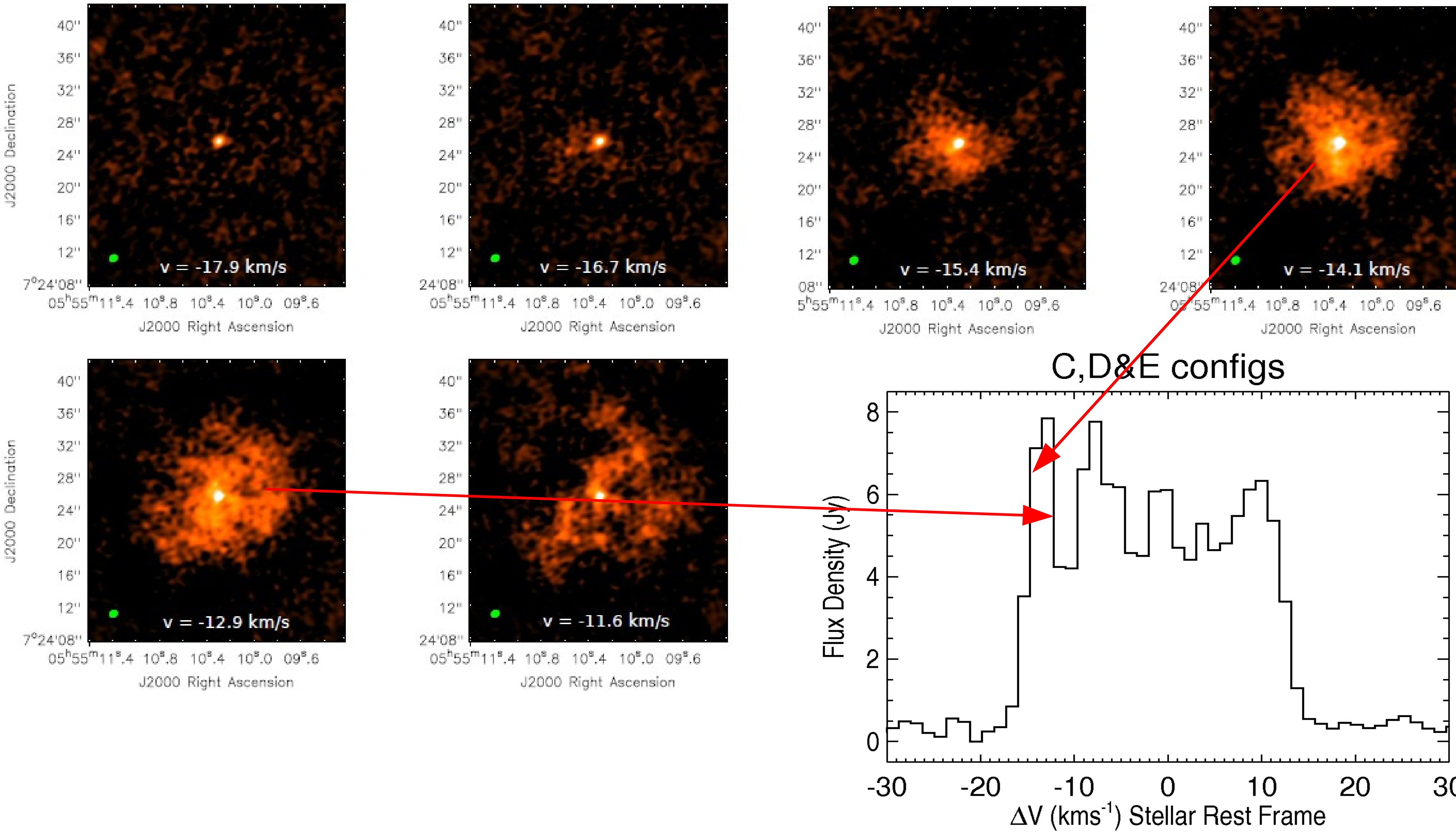




1 (a): Combined Configuration

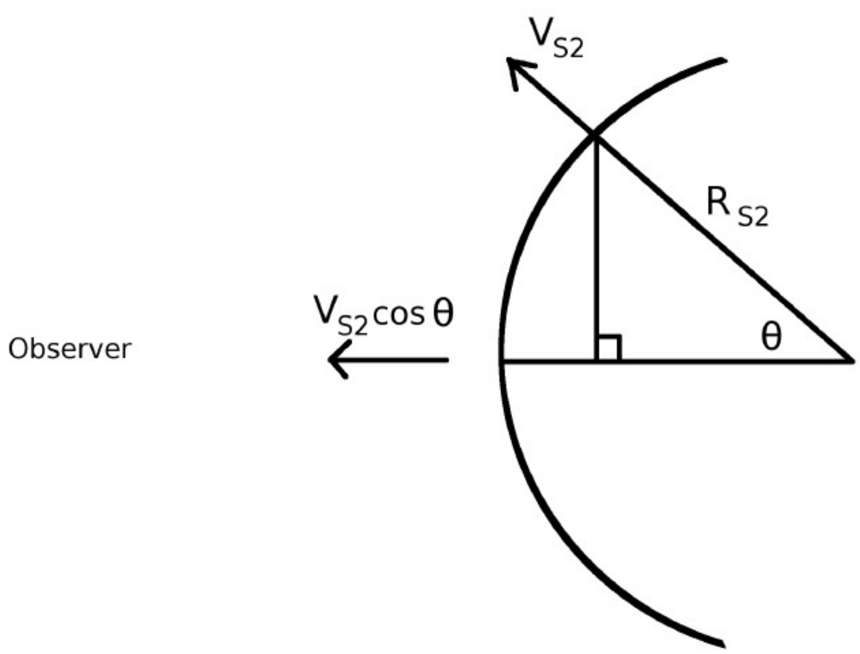


1 (a): Combined Configurations

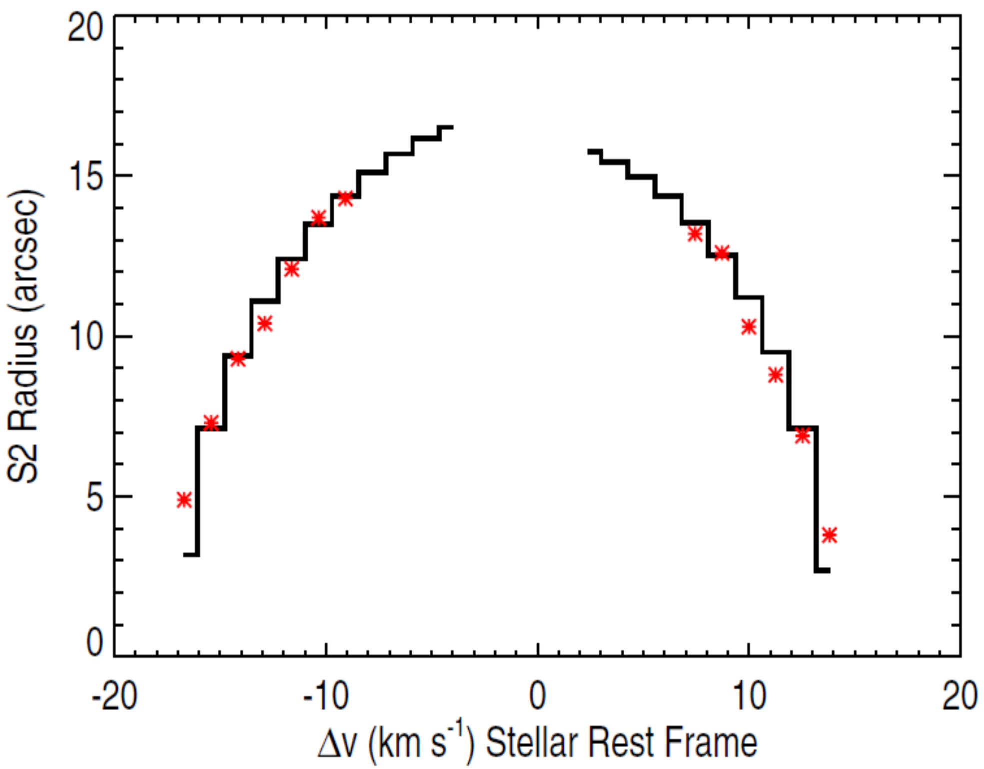


1 (a): S2 Flow

S2 flow not present at low absolute velocities.

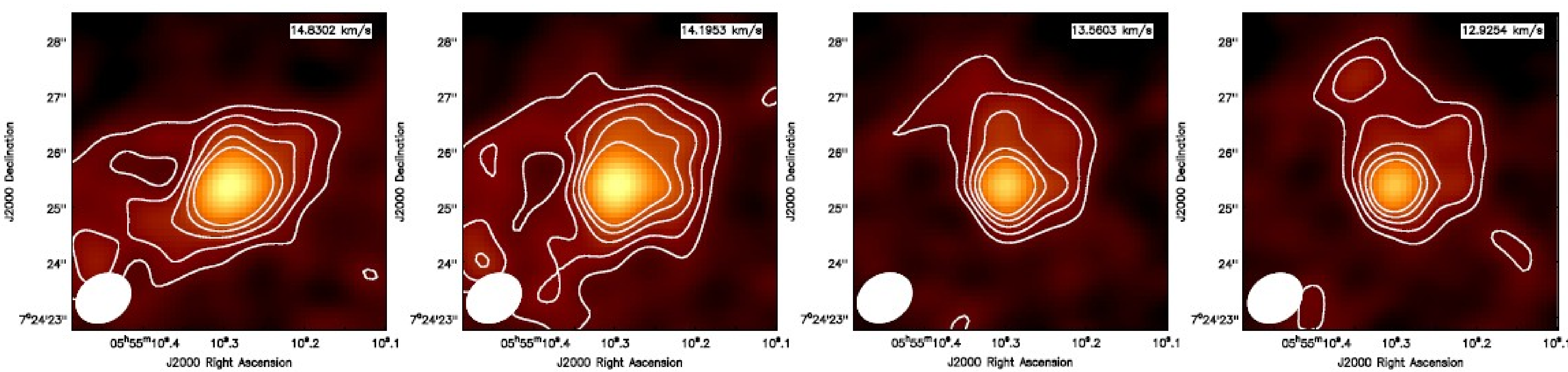


(O'Gorman *et al.*, 2012)

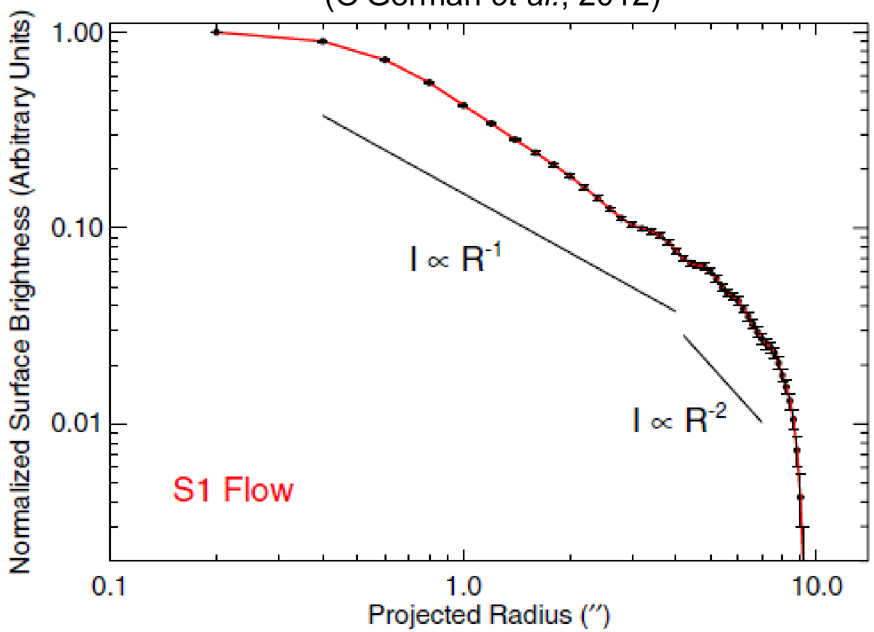


$$r_{\rm chan} = R_{\rm S2} \sin\left[\cos^{-1}\left(\frac{v_{\rm chan}}{V_{\rm S2}}\right)\right]$$

1 (a): S1 Flow



(O'Gorman *et al.*, 2012)



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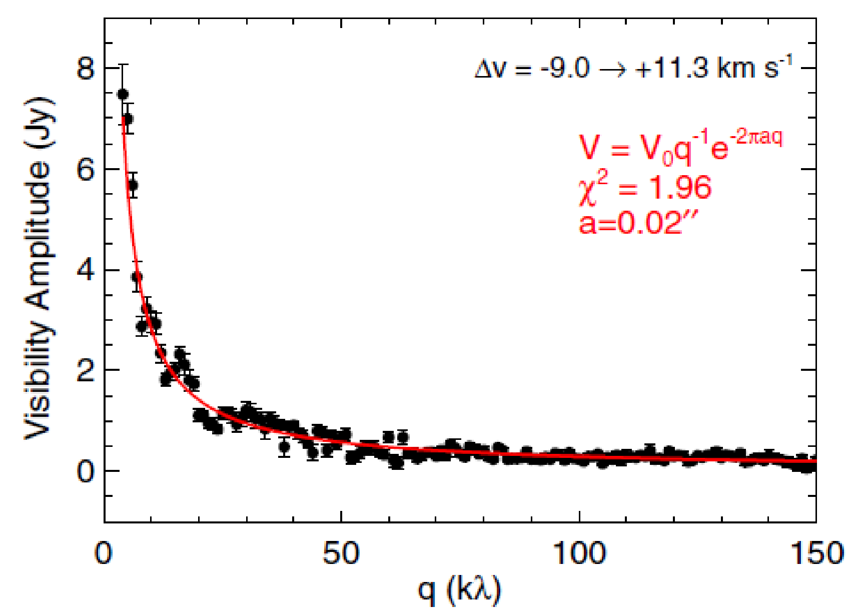


1 (a): Conclusions

- The high spatial resolution C configuration resolves out extended emission leaving us with S1 emission profile.

- 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.

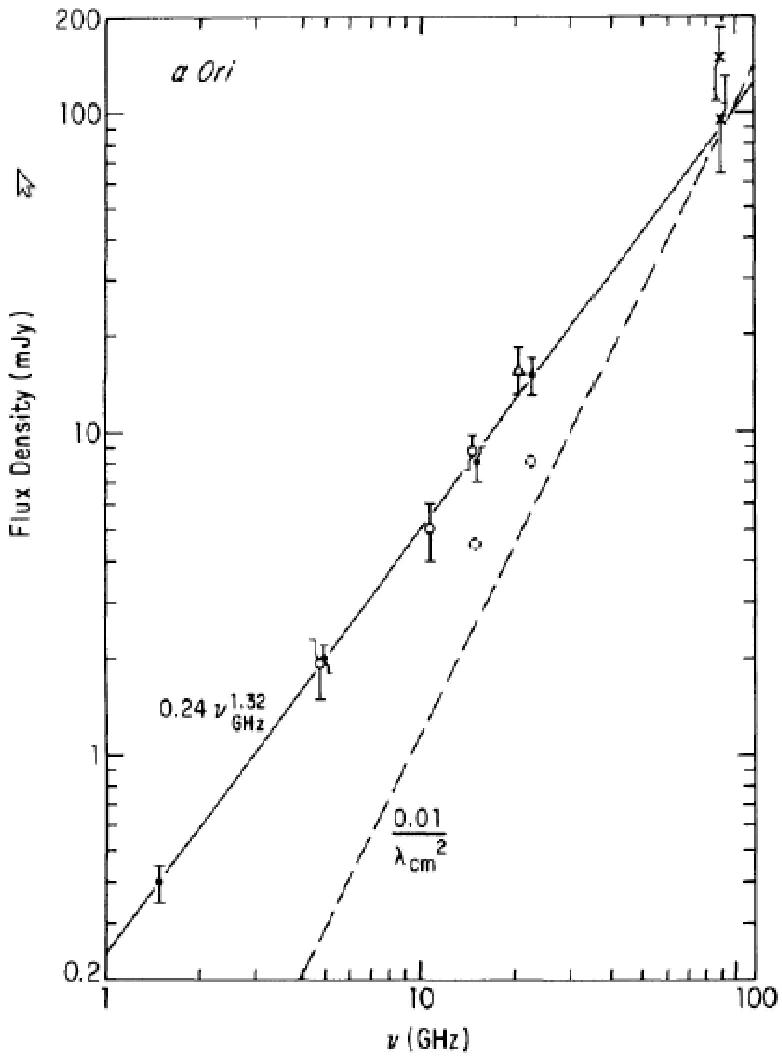
-

	S1	S2
Outflow Velocities (km s^{-1})	2.1	15
Maximum Spatial Extent ('')	4 → 6	17
Age (yr)	400 → 600	1100

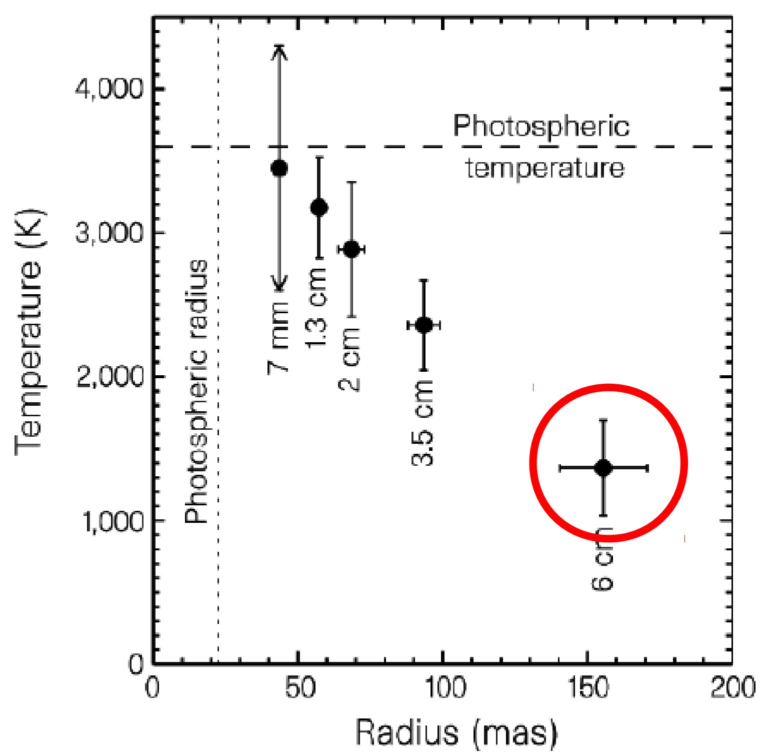
- Previous line profiles not horned shaped because:
  - S1 emission is also present
  - S2 emission weak at low absolute velocities

1 (b): Betelgeuse at cm w/ls: Wind Acceleration Region

(Newell & Hjellming, 1982)

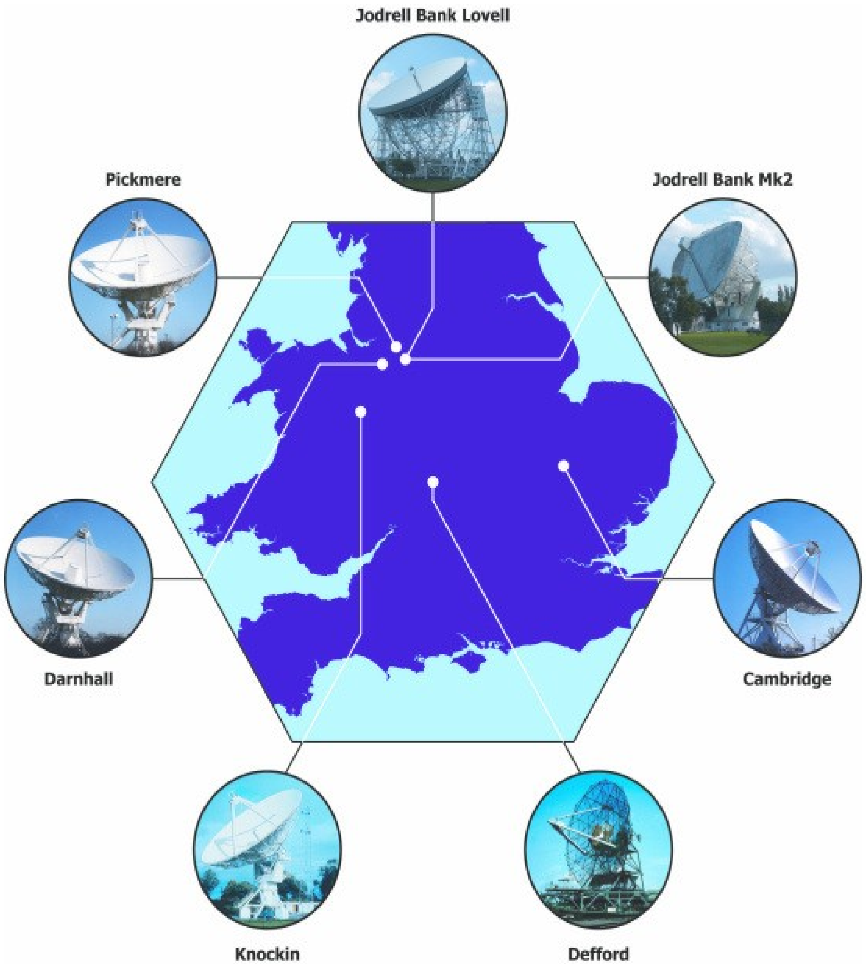


(Lim *et al.*, 1998)



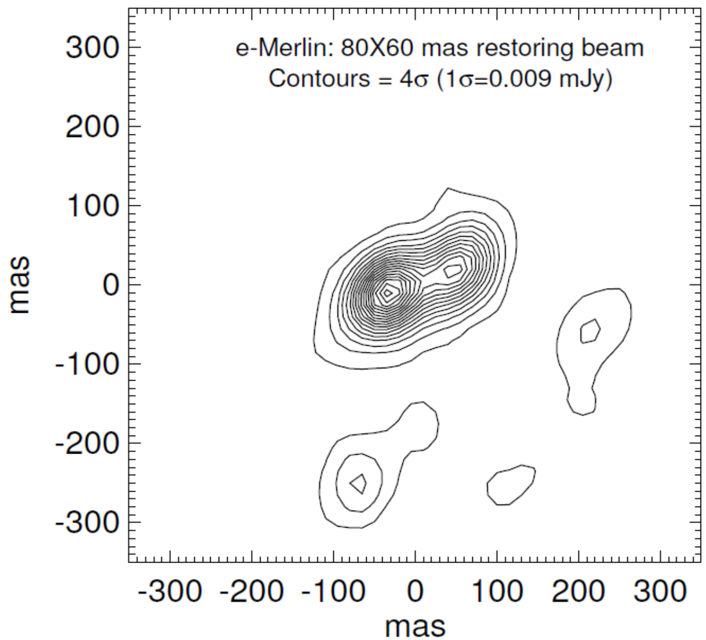
$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$

1 (b): Betelgeuse with e-MERLIN (5.2 cm)



(Credit: MERLIN/VLBI national facility)

Richards *et al*. (2013)

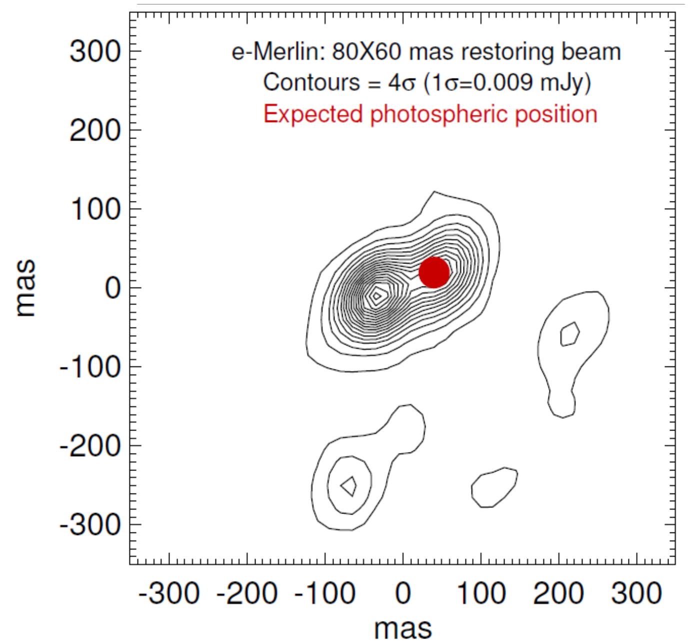


Two unresolved *hot spots:*
T_e > 3800 K
T_e > 5400 K
Where is the photosphere?

Goal 1 (b): *Analyse high resolution archival cm data to search for signatures of hotspots.*

1 (b): Betelgeuse with e-MERLIN (5.2 cm)

Astrometric solution of Harper *et al.*, (2008)



- Hottest source at 4 R_*.
- At least ~3 times the predicted T_e.

1 (b): Betelgeuse with e-MERLIN (5.2 cm)

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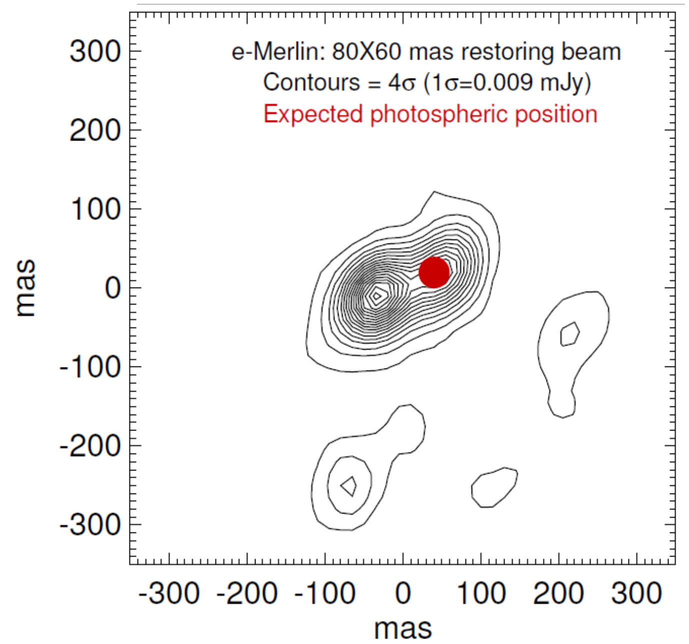

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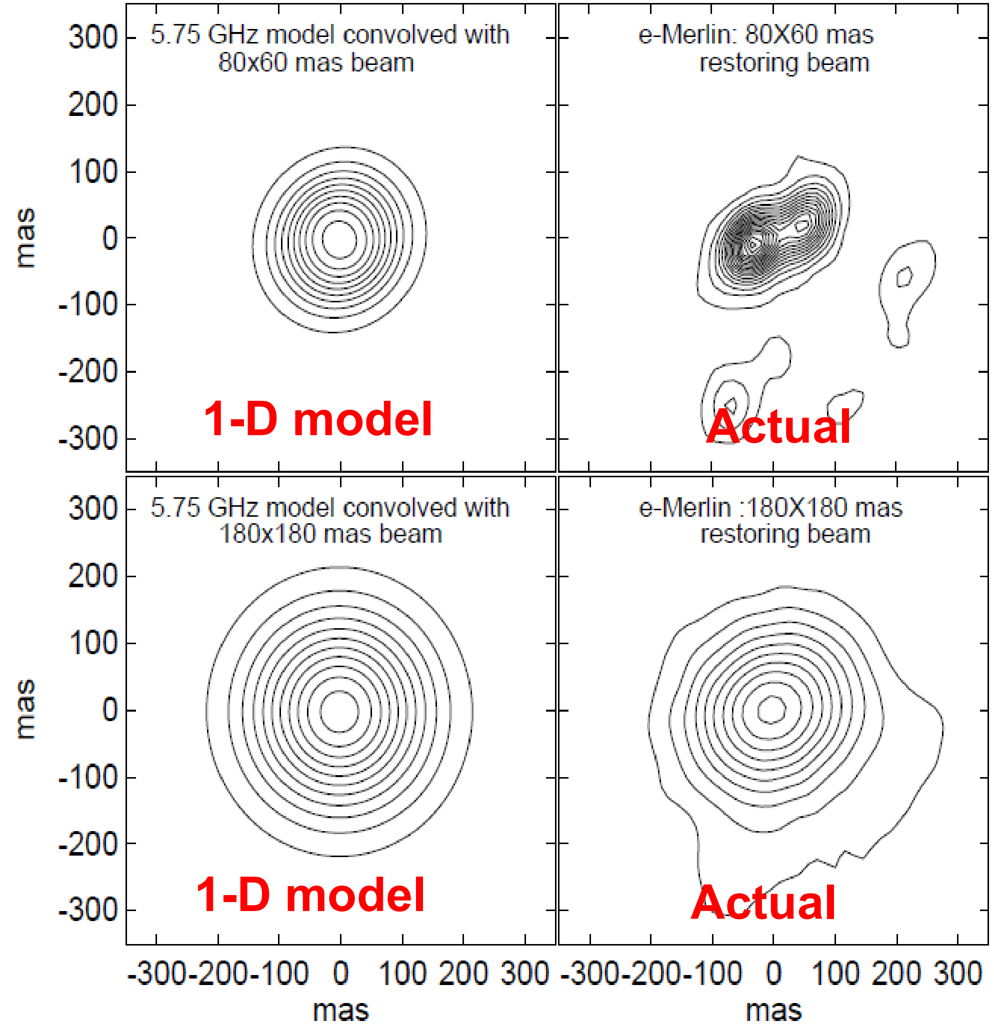


Spherically symmetric semi-empirical model of Harper *et al.*, (2001)

1 (b): Betelgeuse with VLA – Pie Town

VLA

+

Pie Town Antenna

=

e-MERLIN

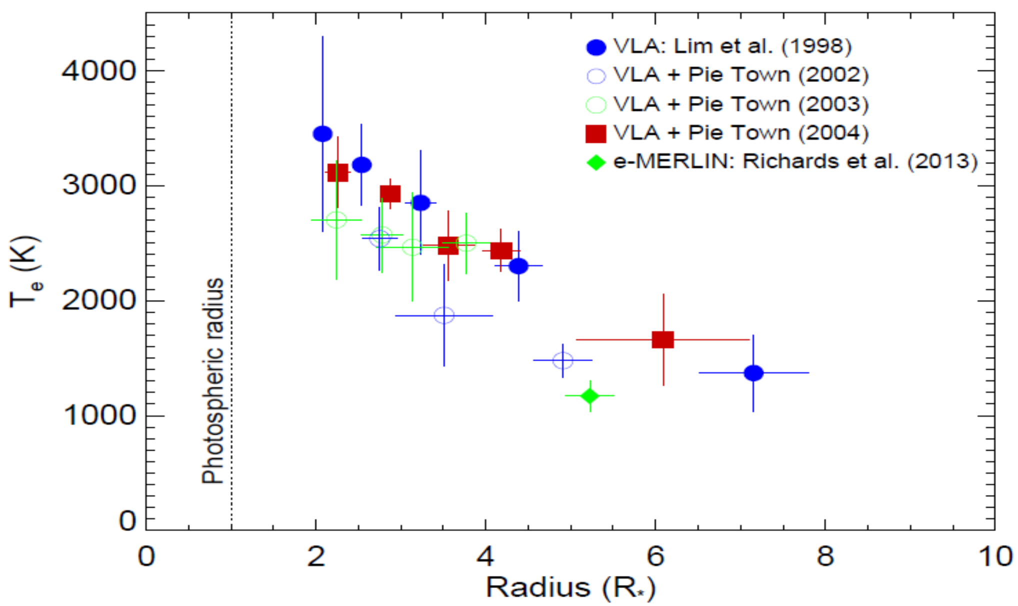
w/l (cm)	Resolution (")
5.2	80 x 60

VLA + Pie Town

w/l (cm)	Resolution (")
0.7	40 x 25
1.3	80 x 40
2.0	120 x 90
3.5	200 x 130
6.2	380 x 270

1 (b): Betelgeuse with VLA – Pie Town

Thermal Profile



Variability 1998-2004

w/l (cm)	Variability
0.7	23%
1.3	27%
2.0	32%
3.5	21%
6.2	35%

1 (b): Betelgeuse with VLA – Pie Town

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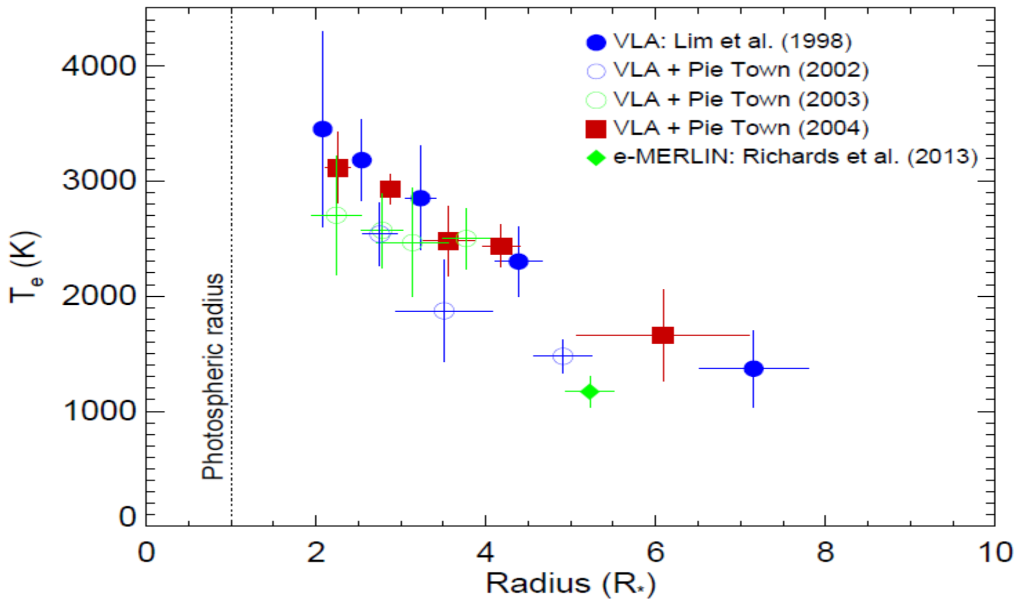
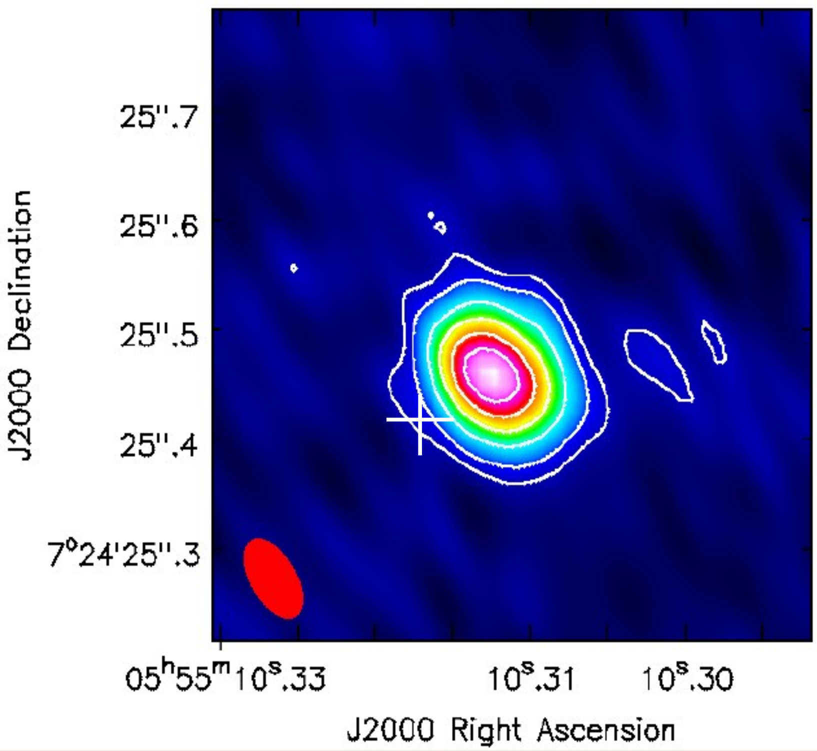


1.3 cm Map



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w/l (cm)	Variability
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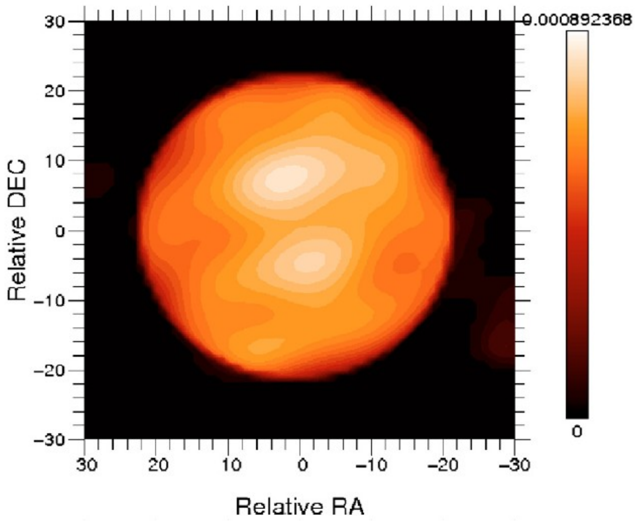
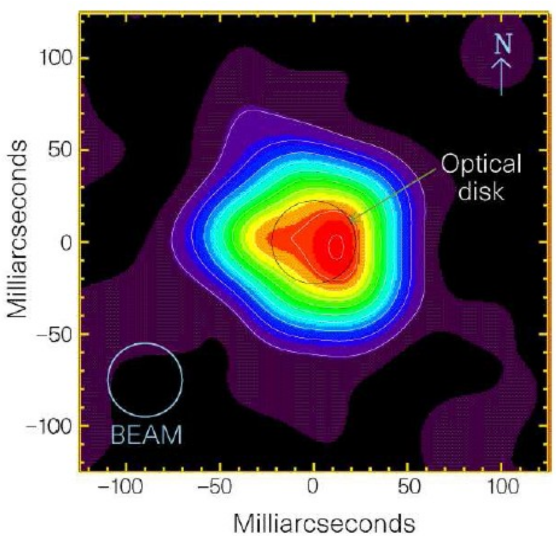
- No clear signature of hot spots any in any maps.
  - Time dependence
  - Opacity $$\frac{\tau_{5.2\,\mathrm{cm}}}{\tau_{1.3\,\mathrm{cm}}} \simeq 20$$

1 (b): Betelgeuse with VLA – Pie Town



(Haubois *et al.*, 2009)



(Lim *et al.*, 1998)

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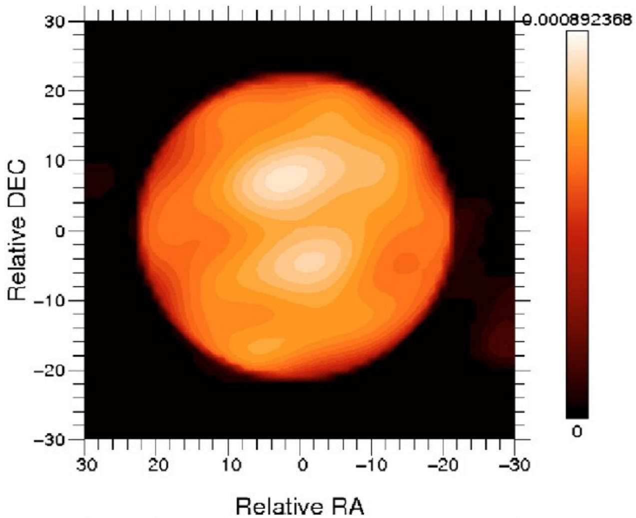

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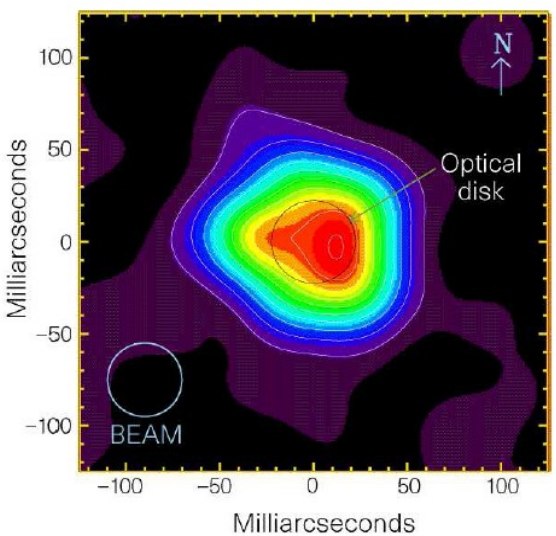
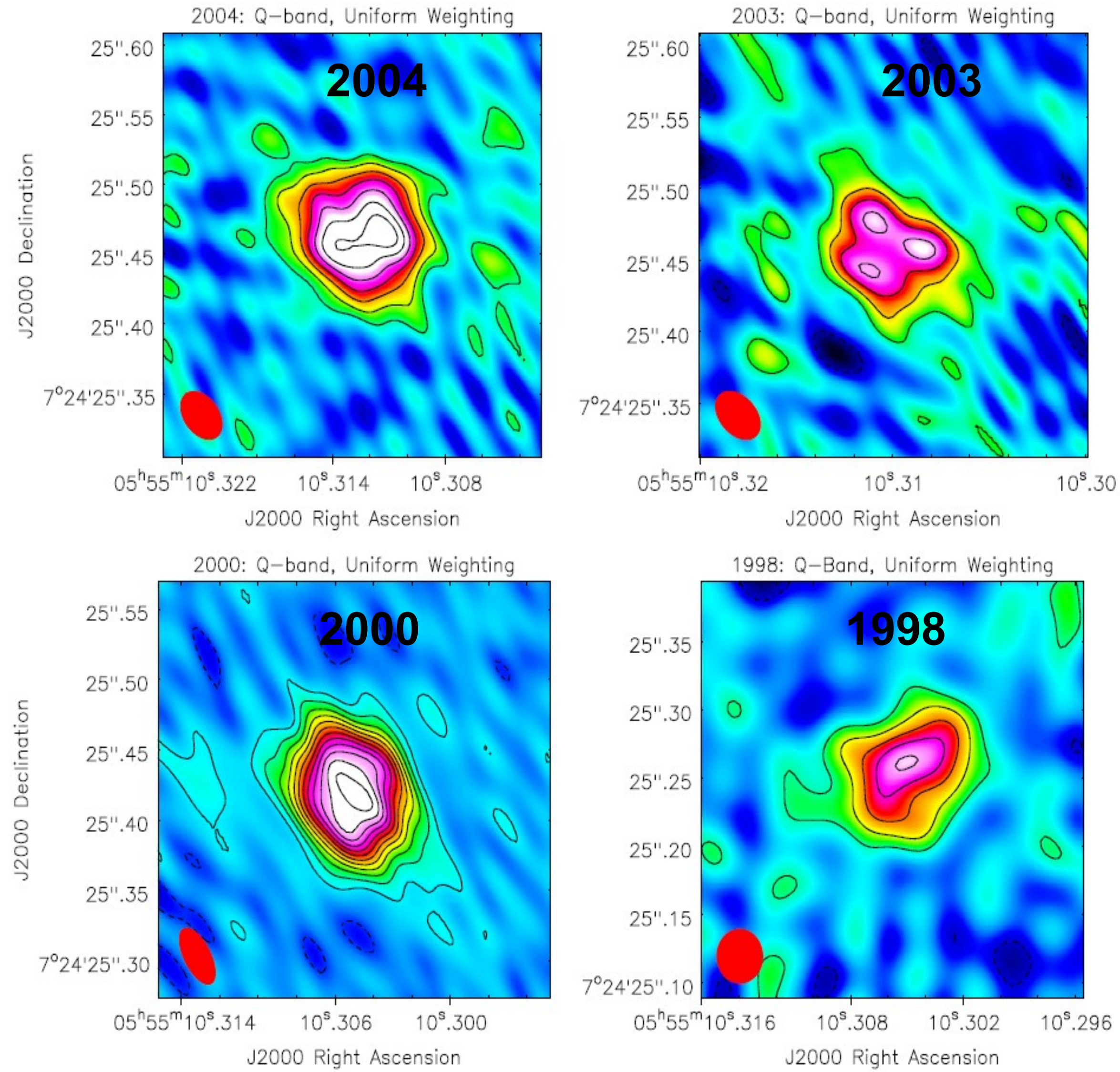


(Lim *et al.*, 1998)

Q-band (0.7 cm) maps using uniform weighting

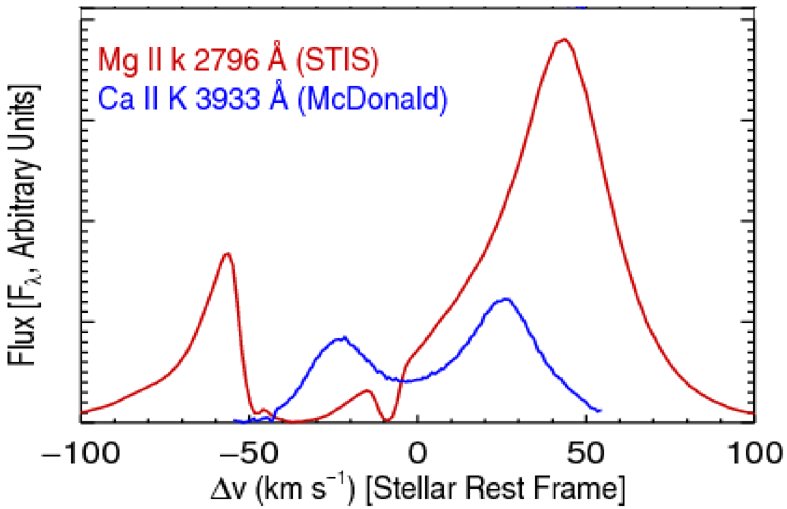


1 (b): Conclusions

- e-MERLIN has revealed two unresolved *hotspots* separated by 90 mas (i.e., 4 R_{star})
- Cooler one may be at the position of photosphere
- VLA + Pie Town data in good agreement with the findings of Lim *et al.* (1998) (i.e., mean thermal profile, asymmetries at 0.7 cm)
- No clear signature of e-MERLIN hotspots in any of the VLA + Pie Town data
  - Time dependant?
  - Opacity?

2) Winds of Red Giants

- Currently cannot be spatially resolved at radio w/ls
- Wind & chromospheric properties (dM/dt, v_{ter}) generally determined by analysing strong chromospheric resonance lines.
- At cm/mm the thermal continuum Planck function depends linearly on T, unlike the UV.



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

- Continuum flux measurements at cm/mm: opacity is proportional to ~ $\lambda^{2.1} n_e n_{ion}$.

Goal 2 (a): *Observe two 'standard' red giants at all possible cm wavelengths to test existing models and possibly develop ones.*

2a) Red Giant Targets

	Arcturus (α Boo: K2 III)	Aldebaran (α Tau: K5 III)
Distance (pc)	11.3	20.4
Photospheric Radius ($R_\odot$)	25.4	44.2
Mass ($M_\odot$)	0.8	1.3
Mass loss rate ($M_\odot$ yr^{-1})	2×10^{-10}	1.6×10^{-11}
T_{eff} (K)	4290	3970

- Single, non-dusty and non-pulsating
- Nearby, with well known stellar parameters
- Semi-empirical 1-D chromospheric and wind models that can be directly tested

2 (a): The Karl G. Jansky Very Large Array

Credit: NRAO

- 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

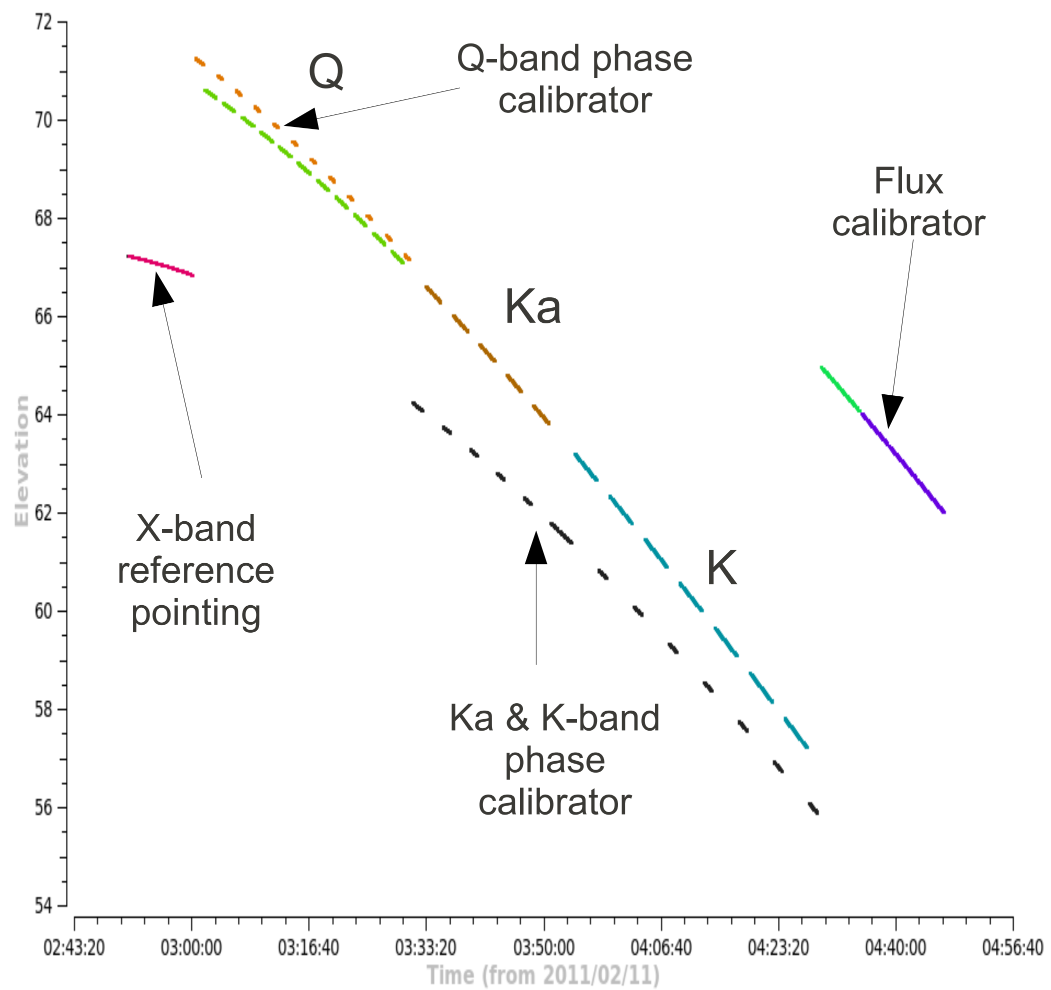
2 (a): Observations

Open Shared Risk Observing (OSRO)

- B config (128 MHz)
- α Boo: S → Q band (13th - 22nd Feb 2011)
- α Tau: S → Q band (11th - 13th Feb 2011)
- A unique dataset

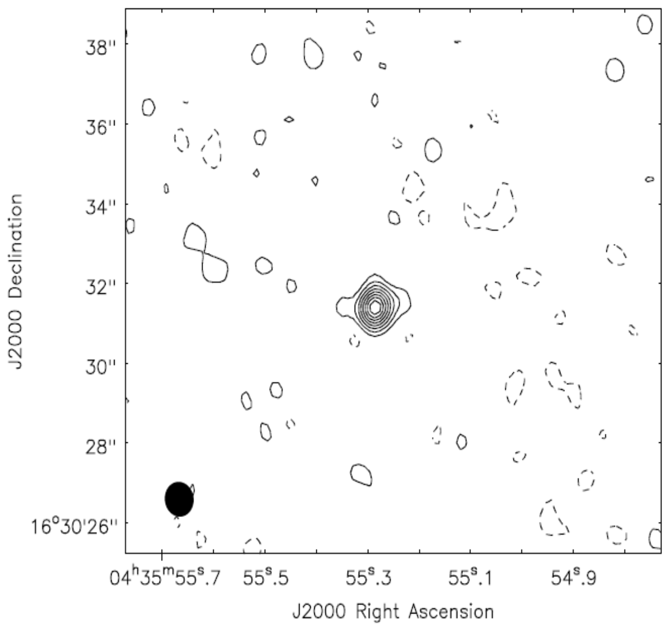
Directors Discretionary Time (DDT)

- B config (2 GHz)
- α Boo: S & L band (July 2012)



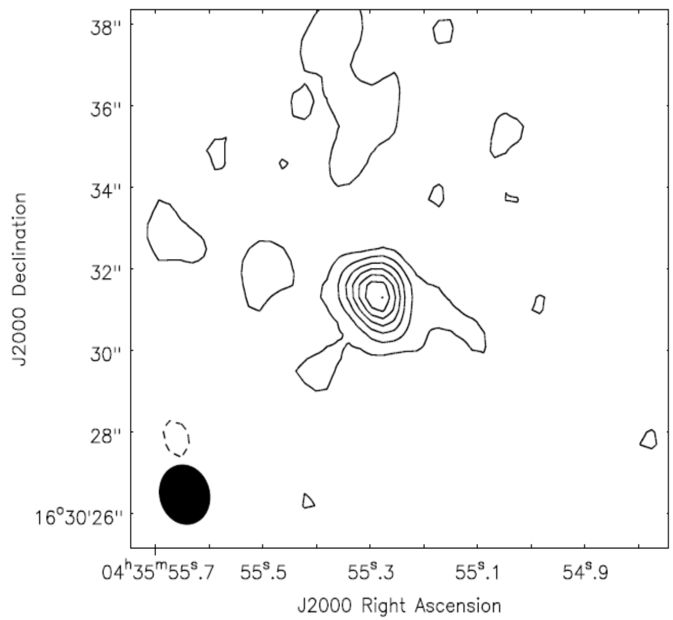
<u>Example: Aldebaran X (3 cm), C (6 cm), and S (10 cm) band</u>

X-band (8 GHz)
S_v = 0.3 mJy



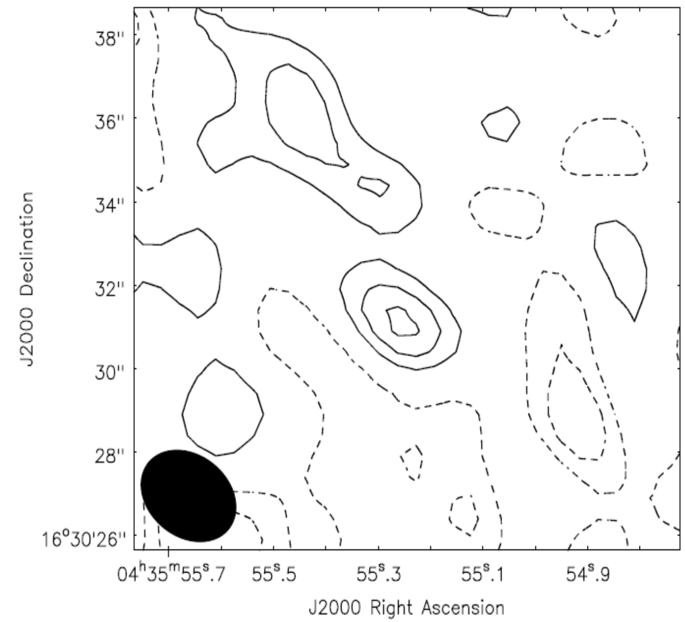
Contours = (-2,2,4......16)xσ
σ = 16 μJy

C-band (5 GHz)
S_v = 0.15 mJy



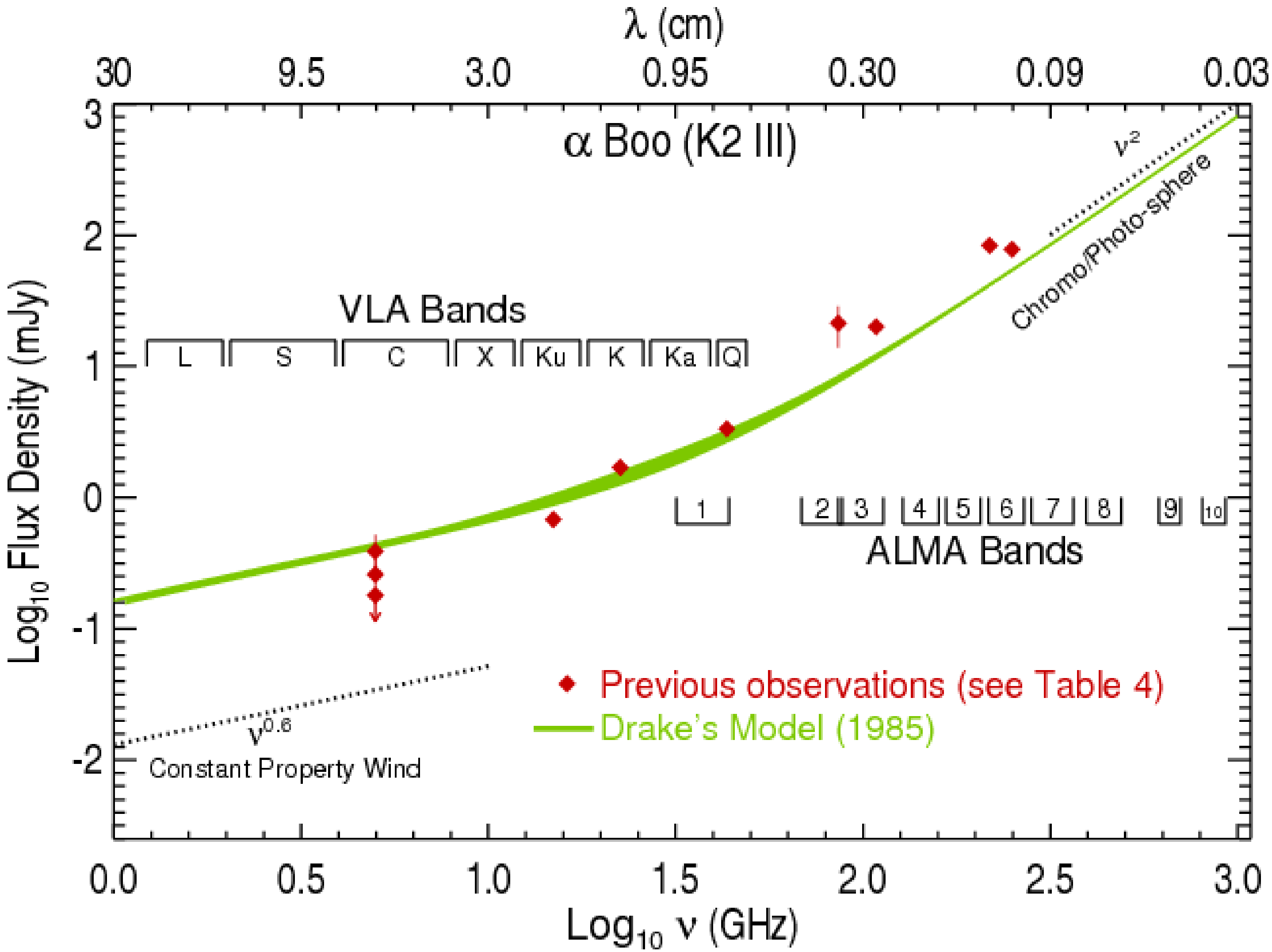
Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

S-band (3 GHz)
S_v = 0.06 mJy



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

2 (a): Spectral Energy Distribution – α Boo



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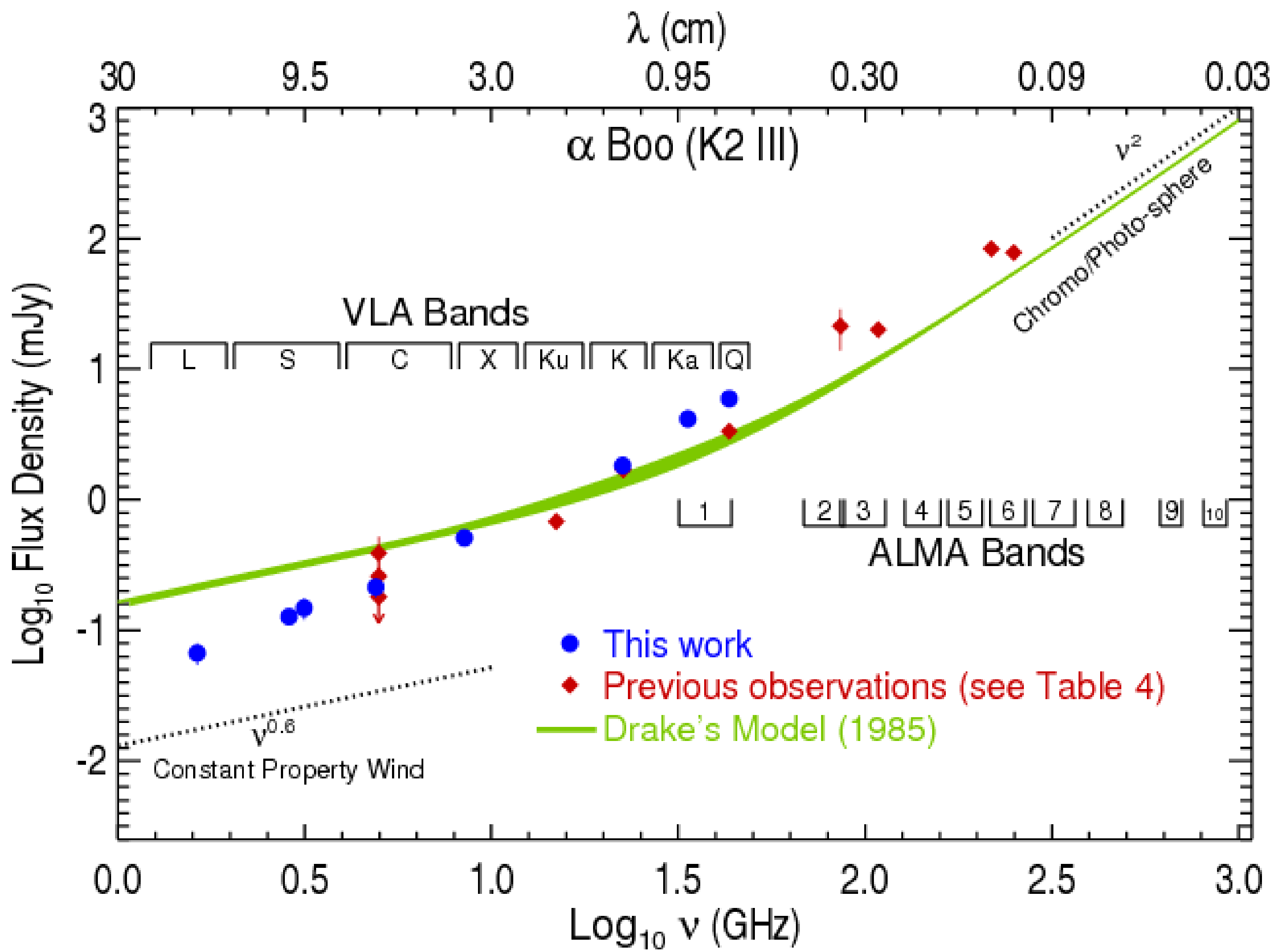
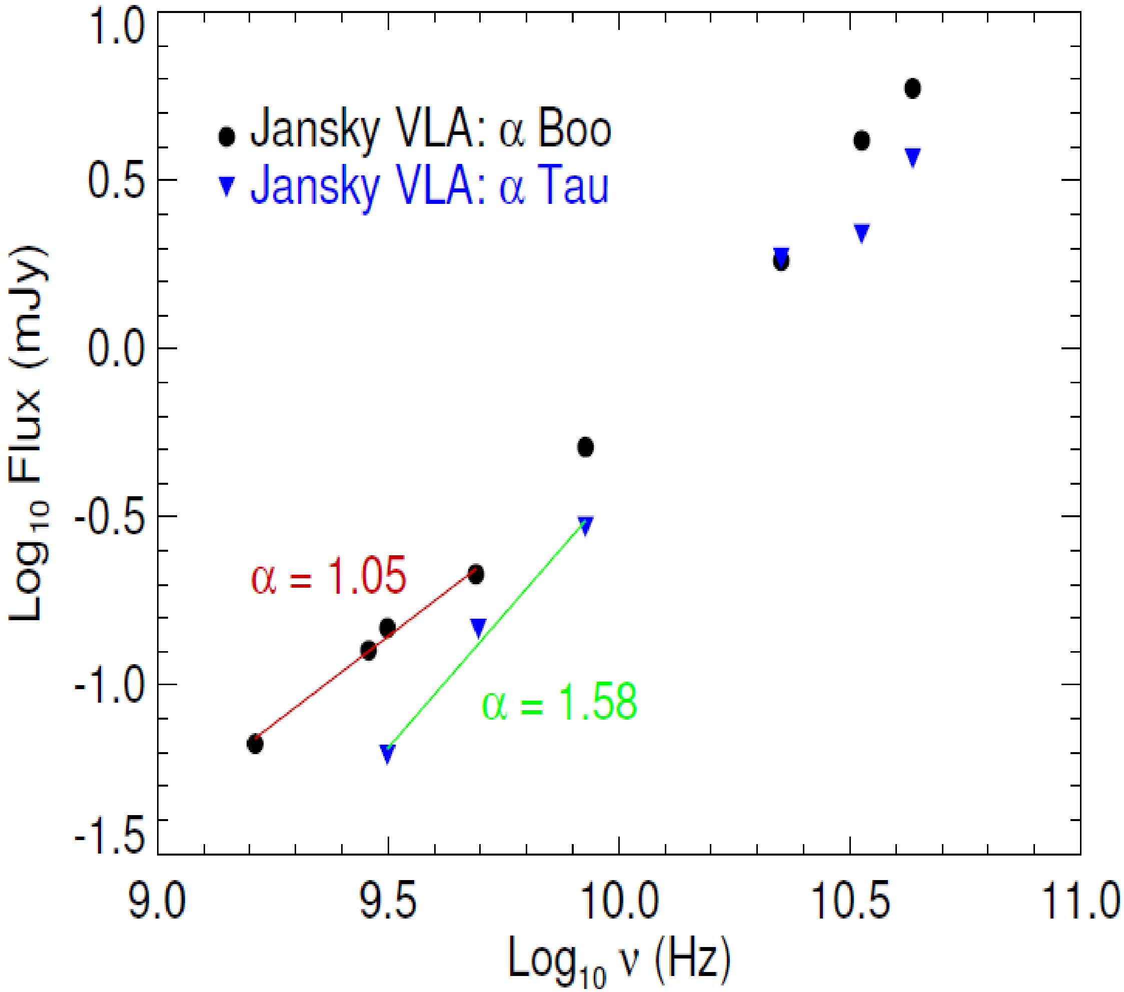


2 (a): Spectral Indices



- If, $n_e \propto r^{-p}$

  $T_e \propto r^{-n}$

Then,

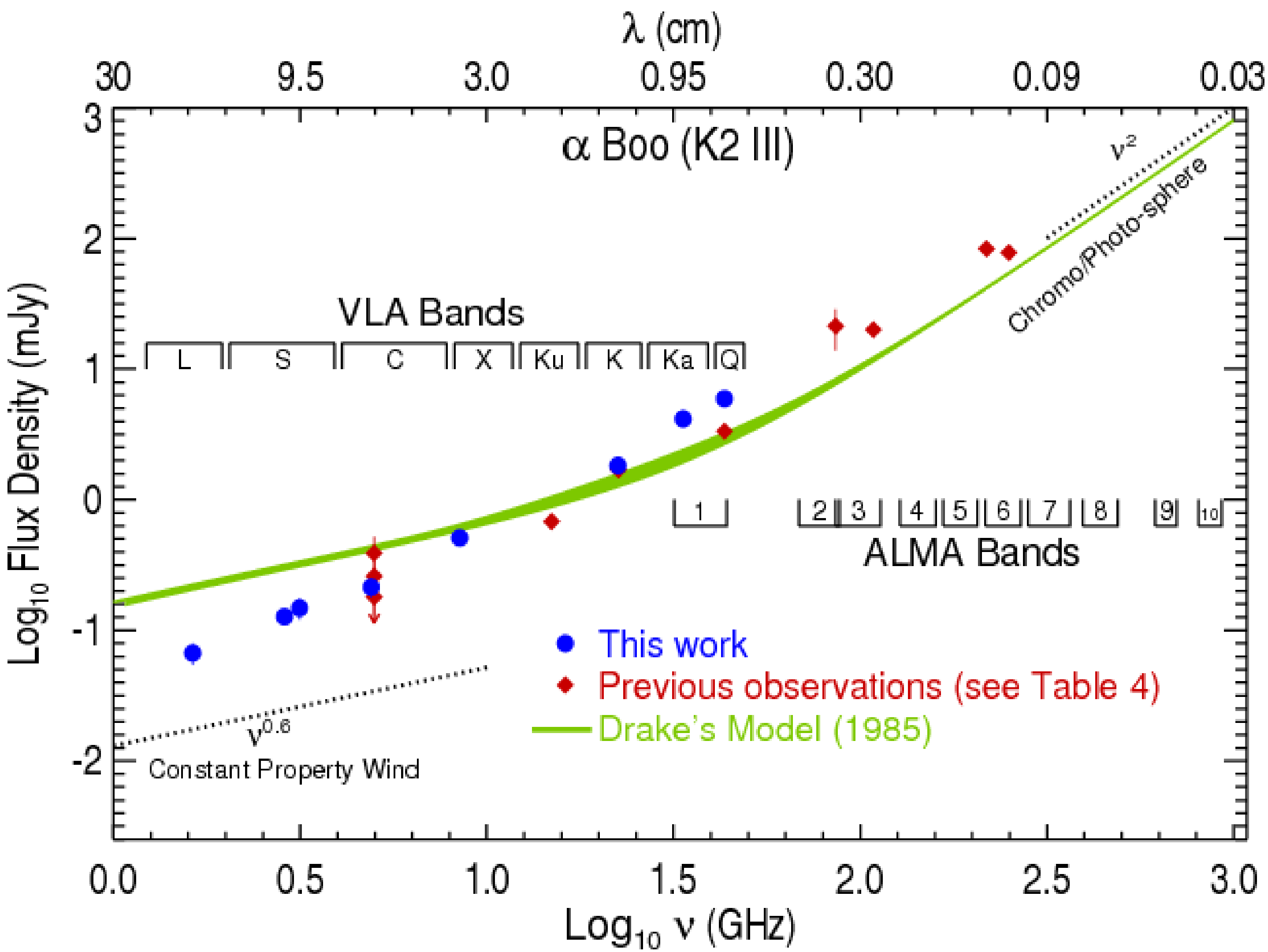
$$\alpha = f(p, n)$$

- α Tau: wind ~ wind optically thin
- α Boo:

Assume constant velocity wind,

$$T_e \propto r^{-1.65}$$

2 (a): Spectral Energy Distribution – α Boo



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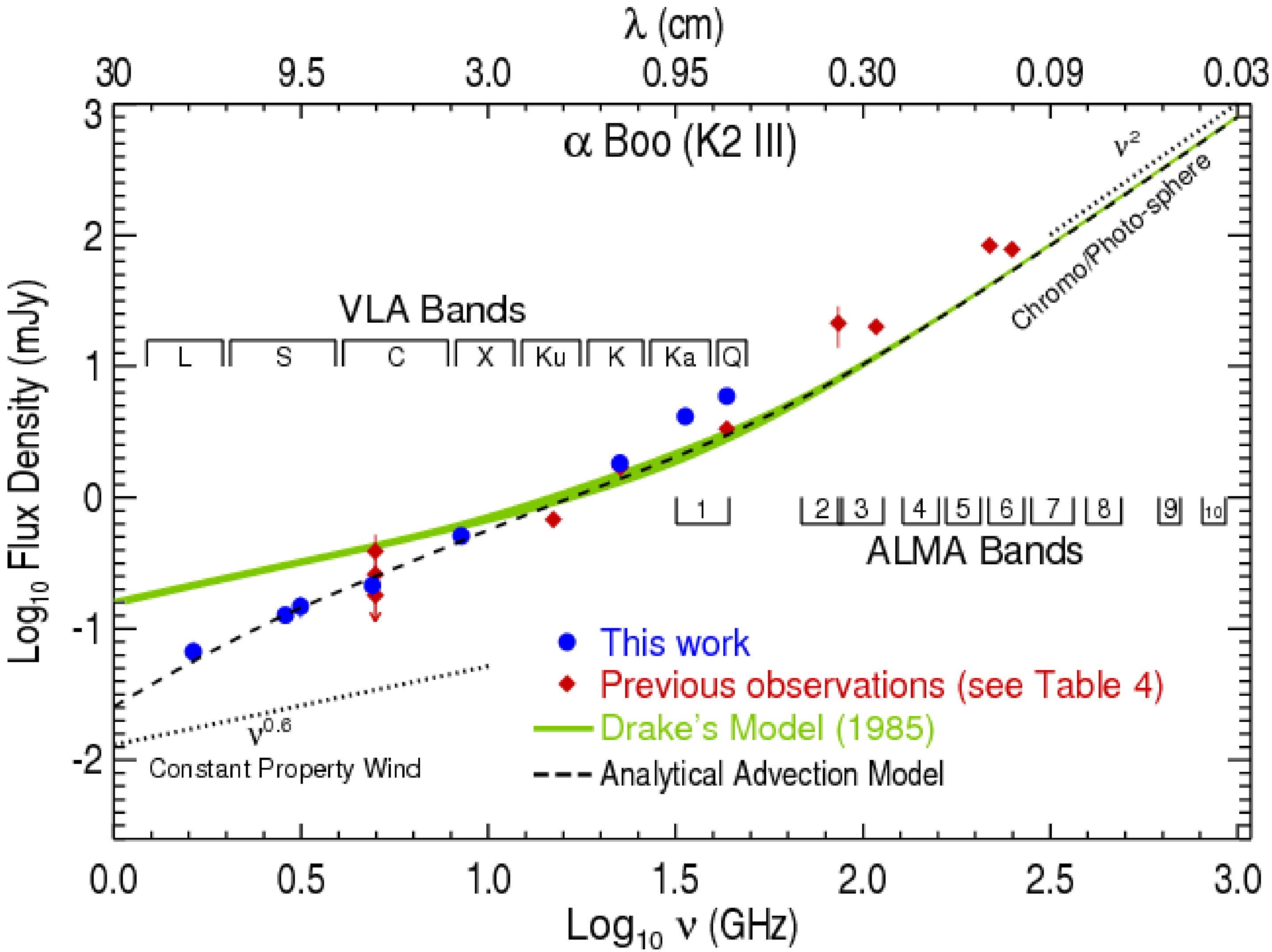

2 (b): Thermal Energy Balance

- Close to photosphere: $v^2(r) << v^2_{esc}(r)$
- To escape star: $v^2(r) > v^2_{esc}(r)$
- Energy added in the form of either heat or momentum

Goal 2 (b): *Carry out a thermal energy balance to investigate possible heating mechanisms in Arcturus' inner outflow region.*

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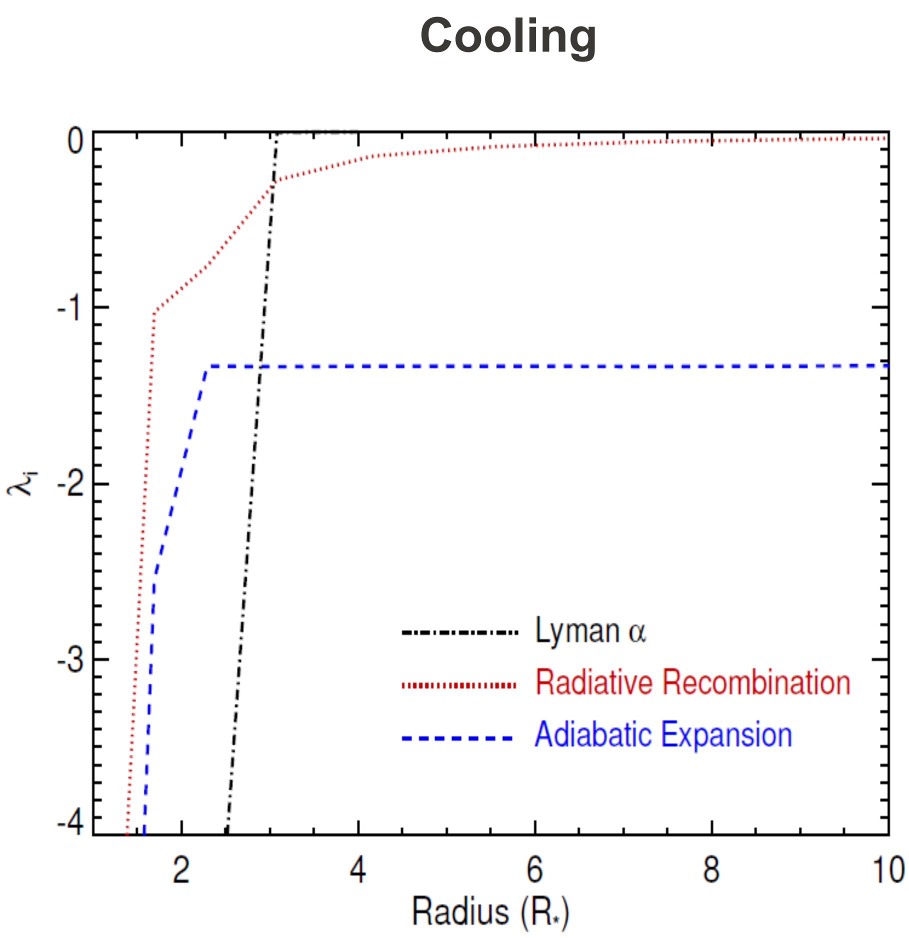
Goal 2 (b): *Carry out a thermal energy balance to investigate possible heating mechanisms in Arcturus' inner outflow region.*

Notation:

$$\sum \lambda_i = \overbrace{-\frac{4}{3} - \frac{2}{3}\frac{d(\ln v)}{d(\ln r)}}^{\text{Adiabatic Expansion}} + \overbrace{\sum_{i=1} \mathcal{H}_i}^{\text{Heating}} - \overbrace{\sum_{j=1} \mathcal{L}_j}^{\text{Cooling}}$$

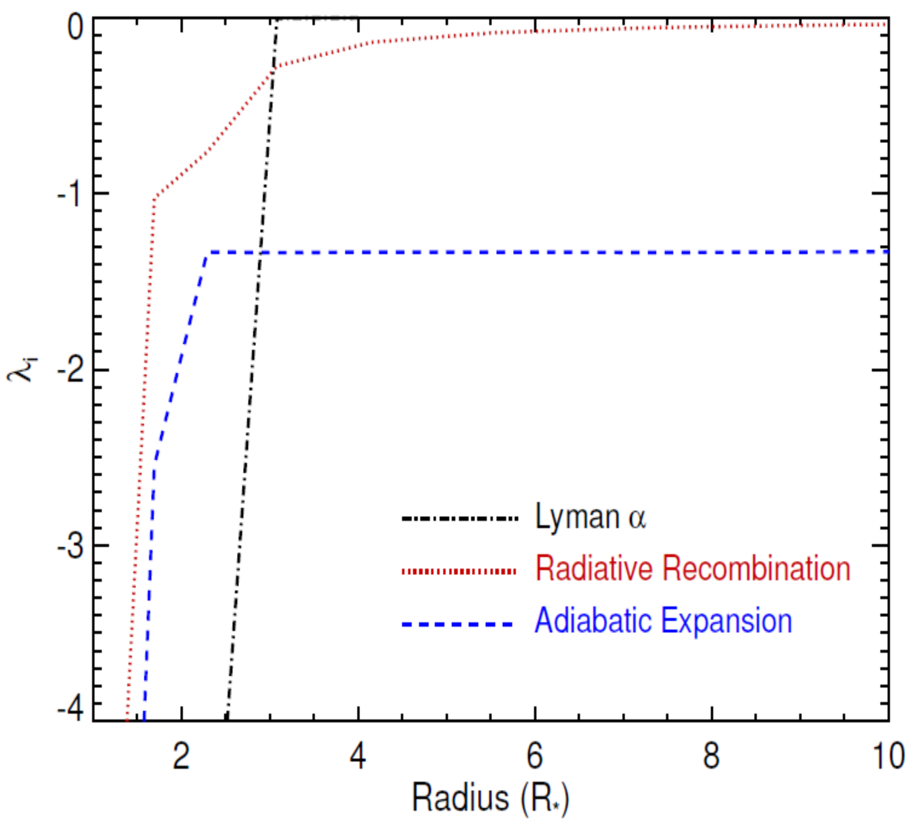
Gas kinetic power law slope

2 (b): Cooling and Heating Processes

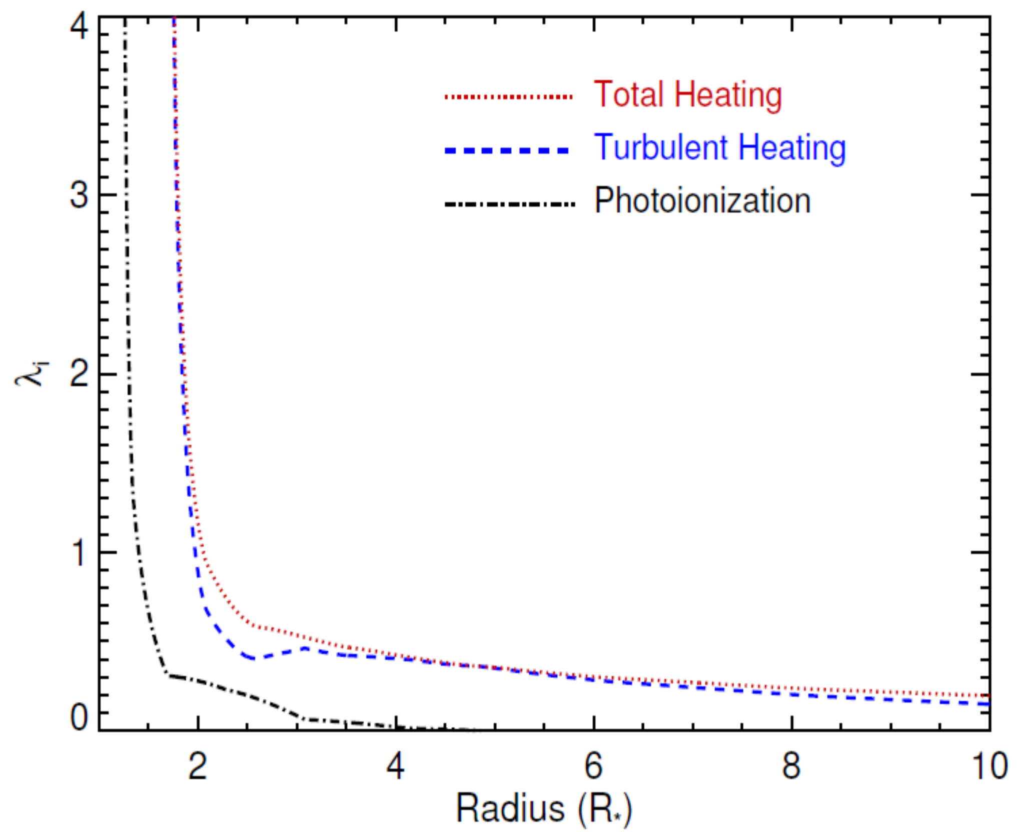


2 (b): Cooling and Heating Processes

Cooling



Heating



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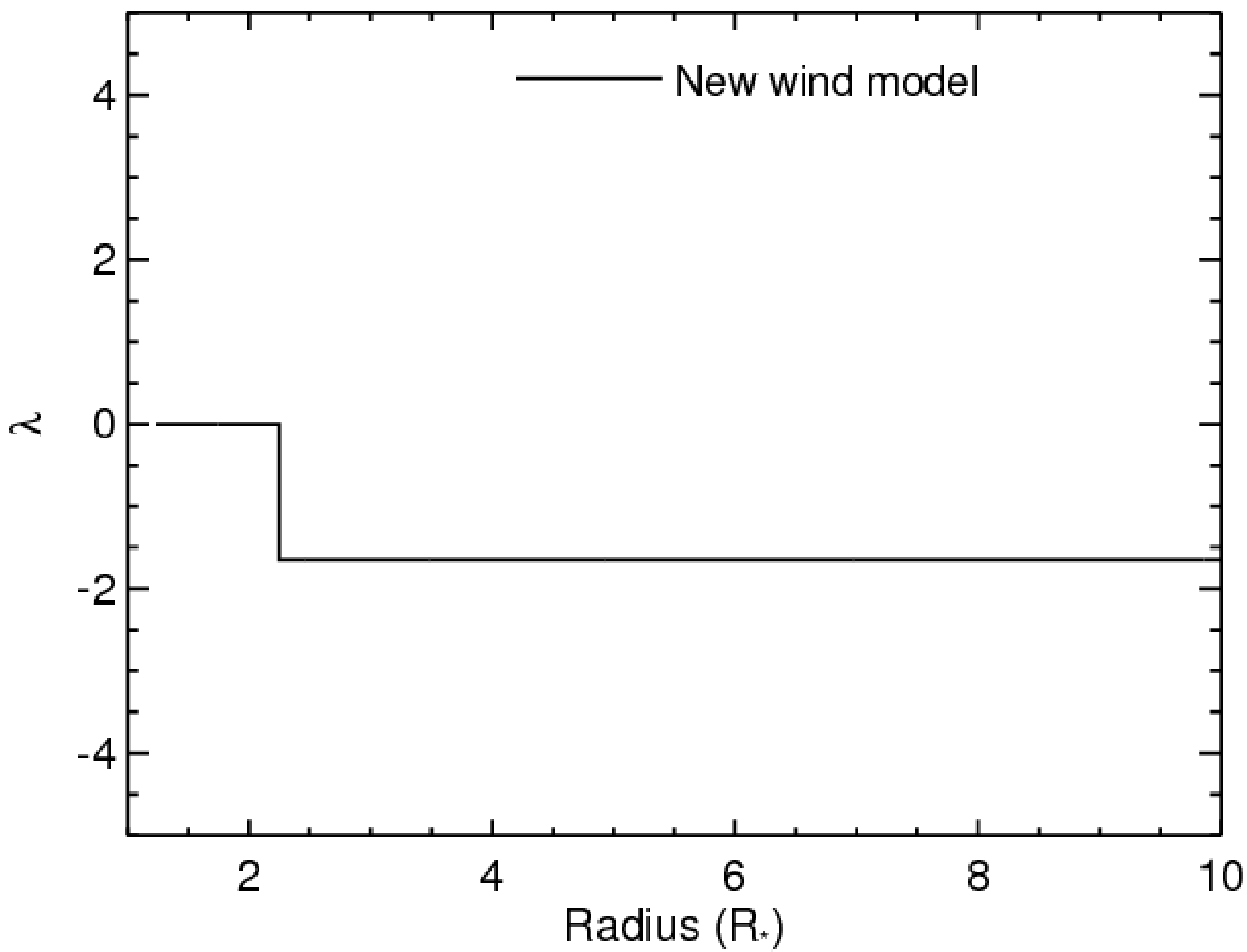

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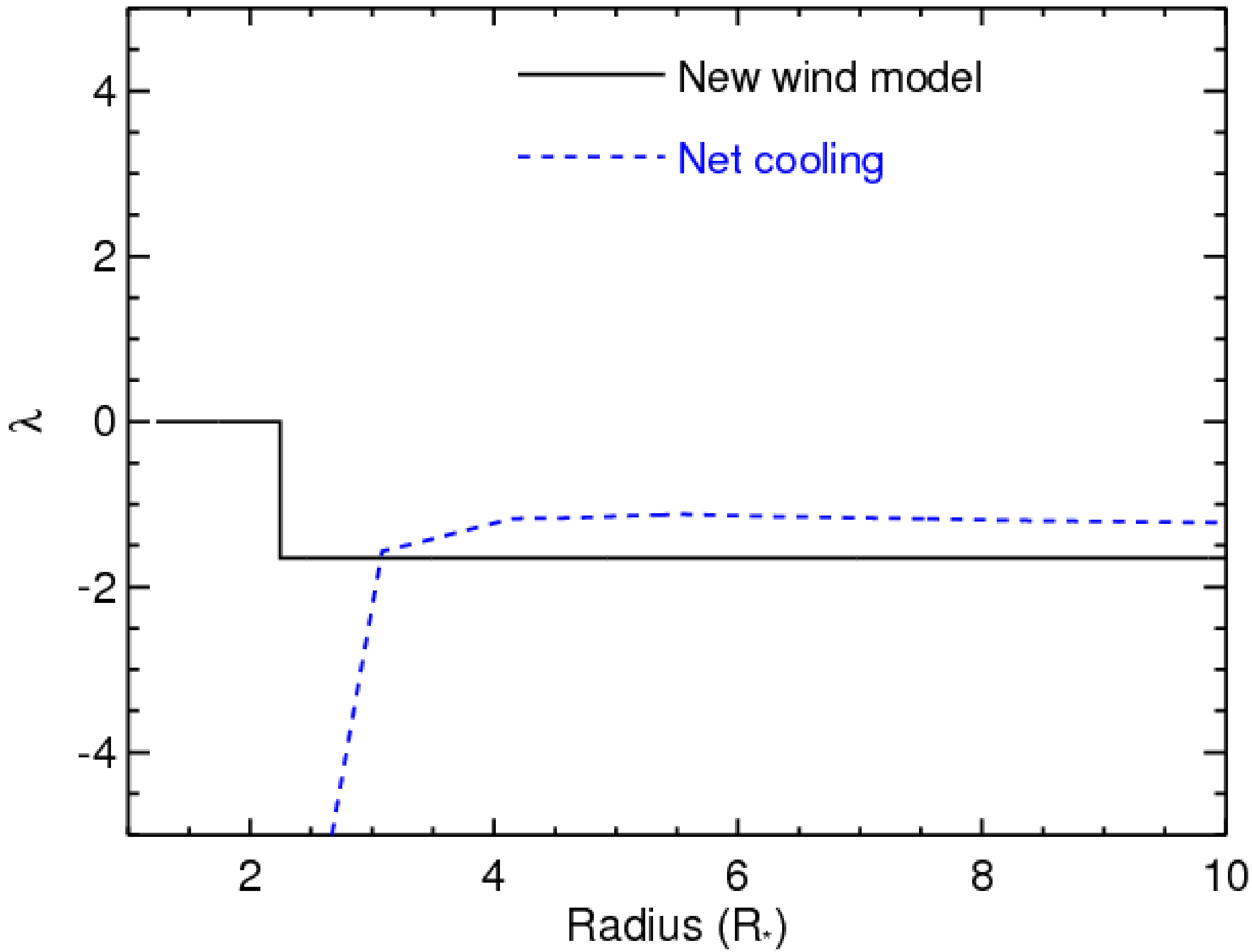

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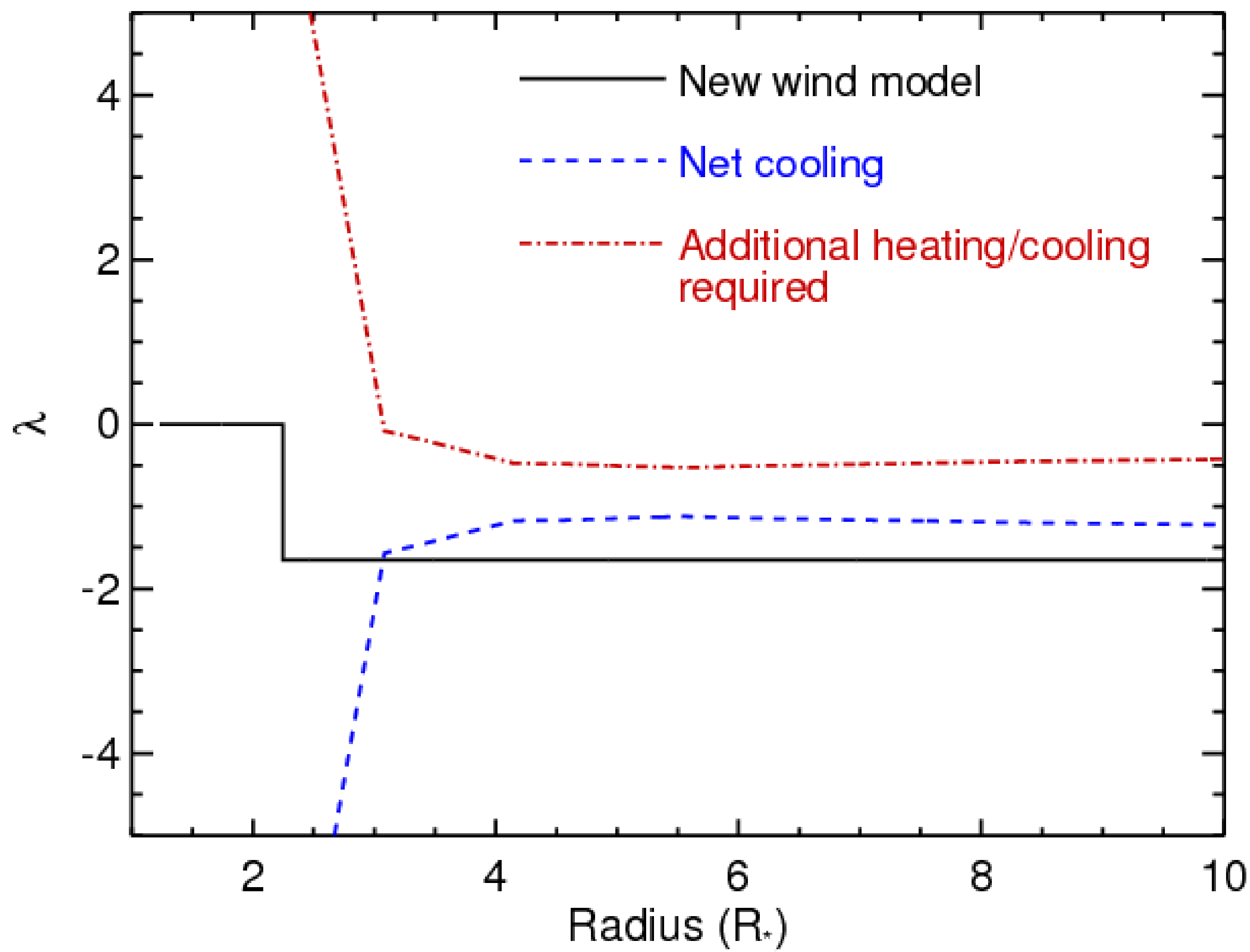

2 (a) & (b) Conclusions

- The most comprehensive set of multi-wavelength radio continuum observations of two *standard* red giants to date.

- Allows us to test theoretical and semi-empirical atmospheric models.

- Radio spectral indices allow flow properties to be investigated.
  - Optically thin wind for α Tau.
  - Rapidly cooling wind for α Boo.

- Analytical advection model used to develop new wind model for α Boo.

- Placed constraints on the heating produced by α Boo's mass-loss mechanism.

Concluding Remarks

- Betelgeuse has two unique outflows. Why?
  - Unique epochs of mass-loss in the last ~1100 years.
  - Change in outflow properties at certain distances.

- Evidence for assymetries in both S1 and S2 flows
  - Formed during outflow?
  - Or from mass-loss process?

- E-MERLIN hints at an episodic mass-loss mechanism in red supergiants. No signature in VLA data.

- Multi-wavelength radio continuum observations provide spatial information from point sources. Provide wind diagnostics and updated outflow models.

- Our understanding is improving and radio interferometry will continue to play a major role in future developments.