Radio Interferometric Studies of Cool Evolved Stellar Winds

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Trinity College Dublin
November 15, 2013

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Overview

- Stellar Winds Across the HR Diagram
- Stellar Radio Emission
- 1) Winds of Red Supergiants (CSE and inner wind)
- 2) Winds of Red Giants (inner wind)
- Summary

Stellar Winds Across the H-R Diagram

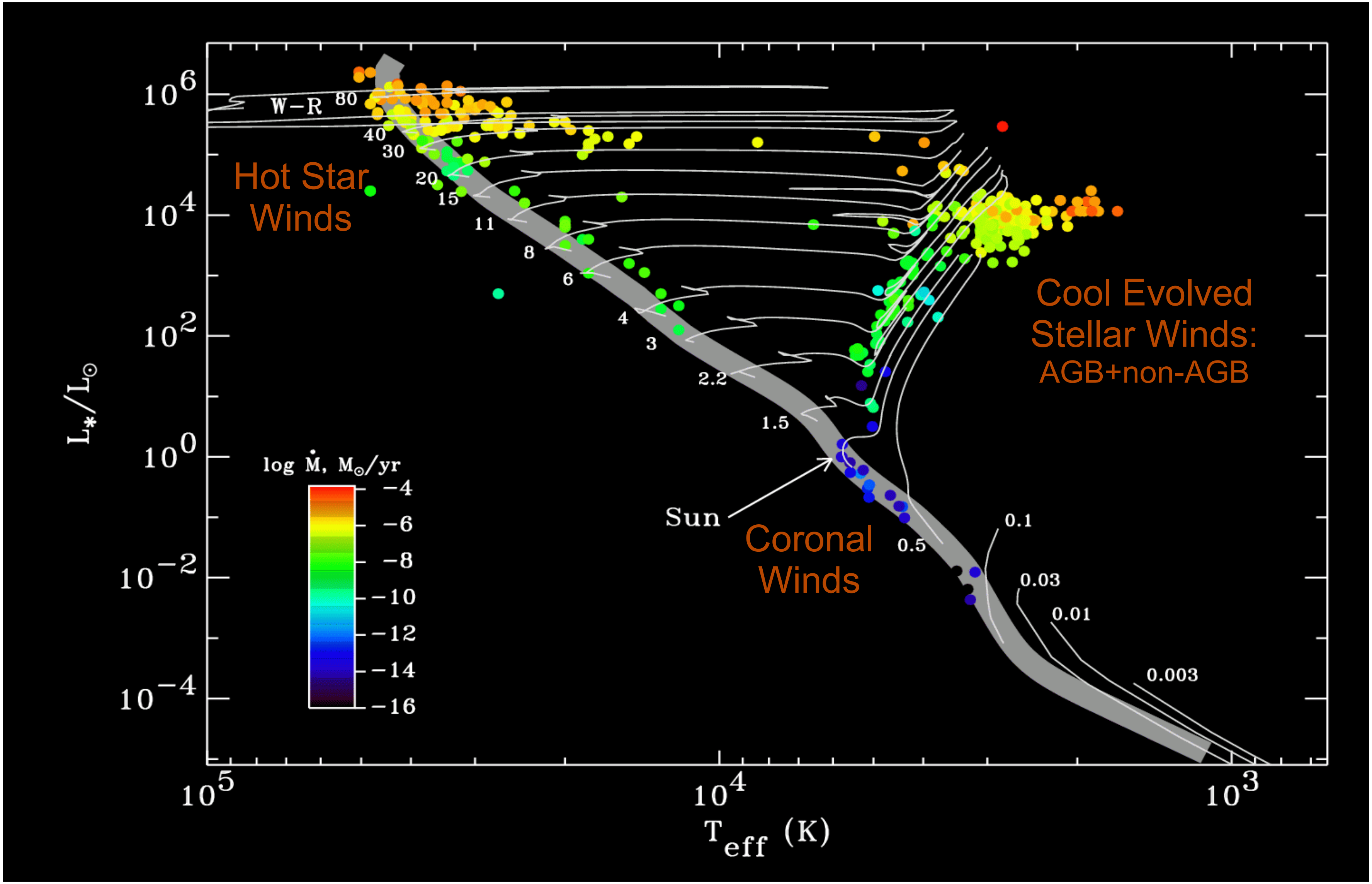

Image Credit: S. R. Cranmer

Red Supergiants & Red Giants

	Red Giants	Red Supergiants
Mass ($M_\odot$)	~ 0.4 → ~ 8	~8 → ~ 40
Radius ($R_\odot$)	~ 50	~ 500
Lifetime (yr)	~ 10^9	~ 10^6
dM/dt ($M_\odot$ yr^{-1})	~ 10^{-10}	~ 10^{-5}

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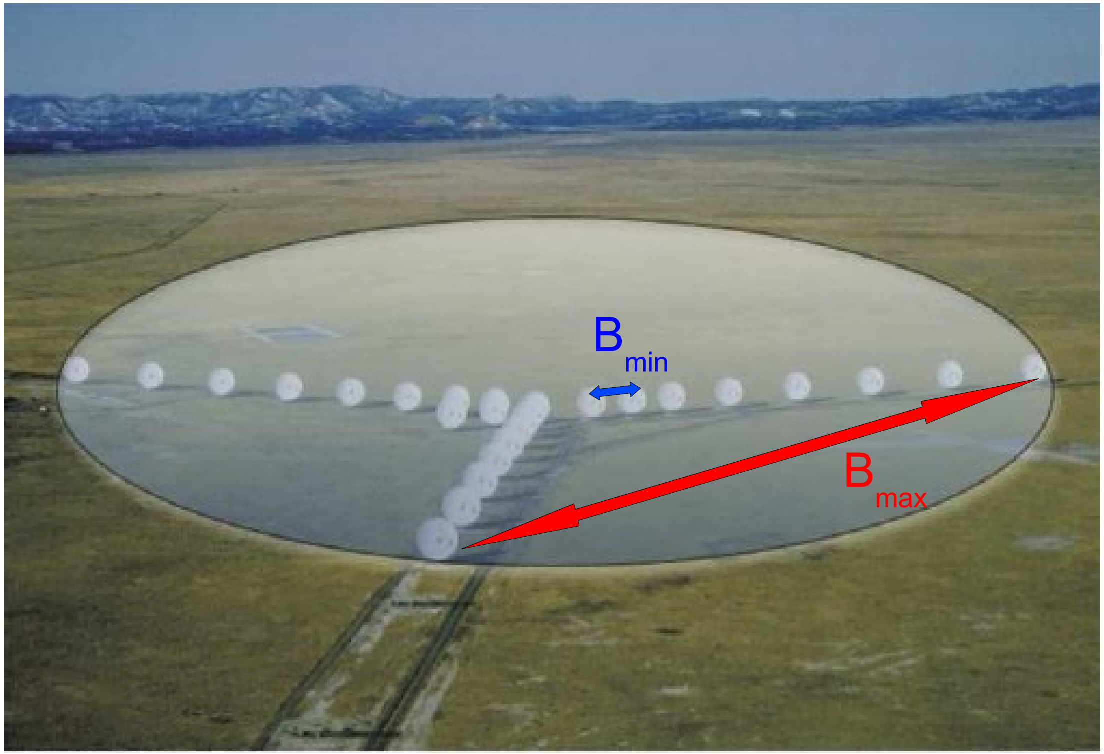
- ***Thesis Goal:*** Improve understanding of outflow conditions → Radio

Aperture Synthesis



1) Field of View: λ/D (D = antenna diameter)

2) Resolution: λ/B_{max} (B_{max} = longest projected baseline)

3) Resolving out scale: λ/B_{min} (B_{min} = shortest projected baseline)

Stellar Radio Emission

Radio Sky at 4.85 GHz (300ft Green Bank)

Credit: NRAO/AUI

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

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

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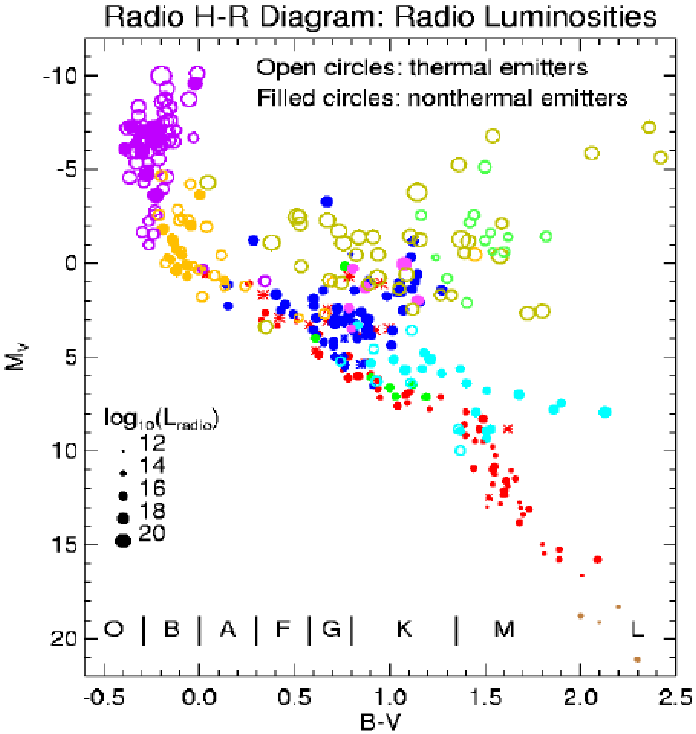
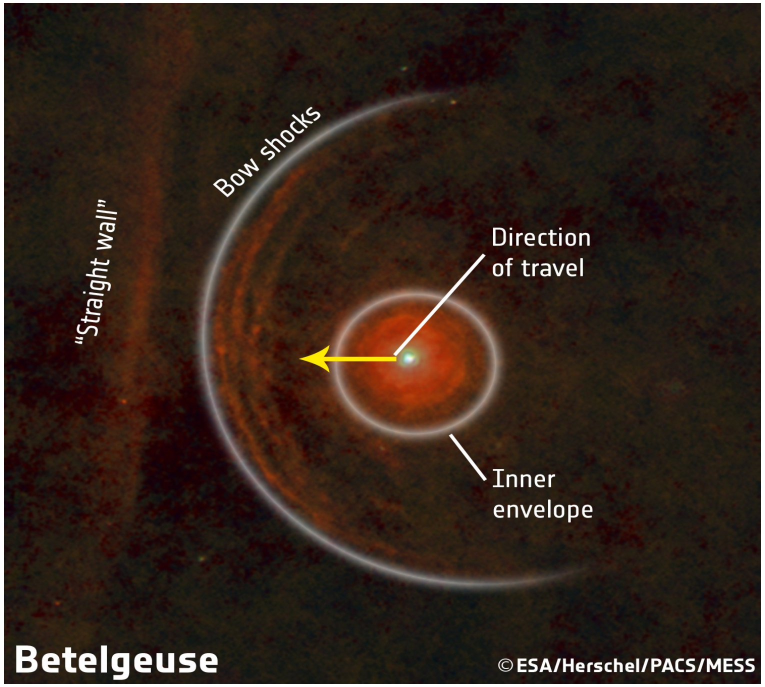


White (2000)

1) Winds of Red Supergiants

Betelgeuse (M2 Iab)



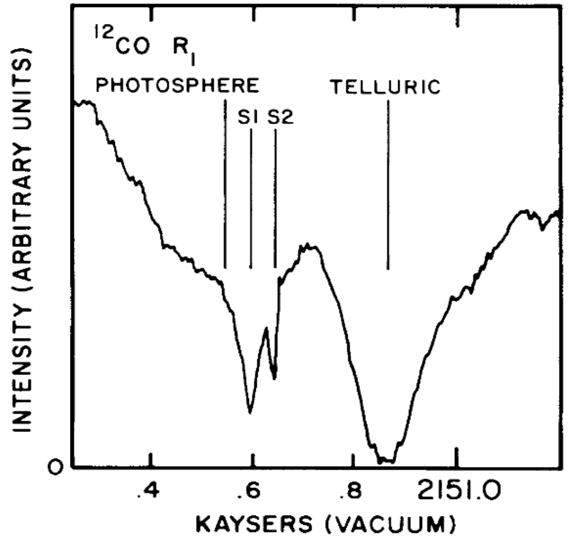
(Decin *et al.*, 2013)

Distance	197 ± 45 parsec
Photospheric Radius	22.5 mas (950 $R_{\odot}$)
Mass	~15 $M_{\odot}$
Origin	O-type main sequence
Mass loss rate	3 x 10^{-6} $M_{\odot}$ yr^{-1}
$^{12}C/^{13}C$	6 ± 1

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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- 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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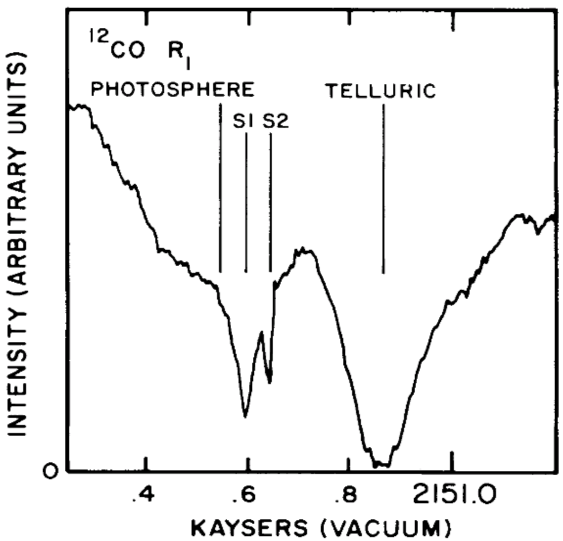

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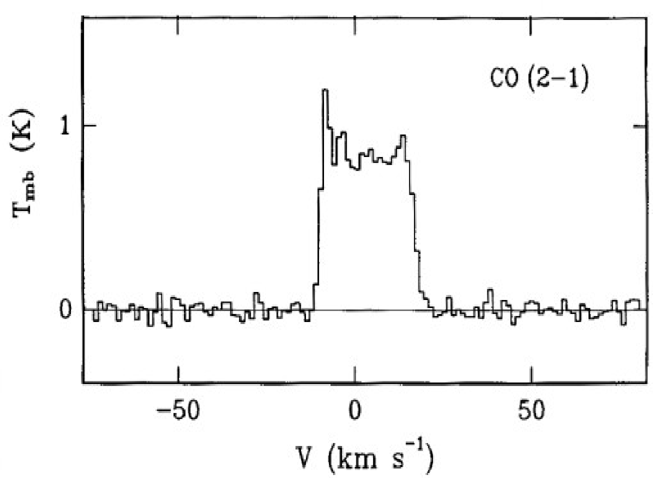

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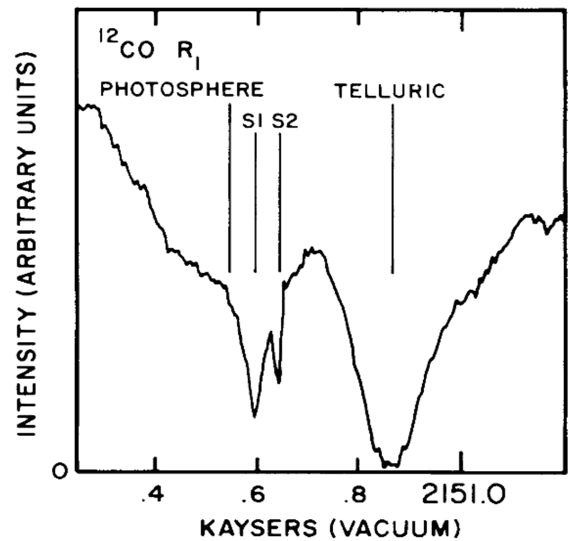
Goal: *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

(Bernat *et al.*, 1979)



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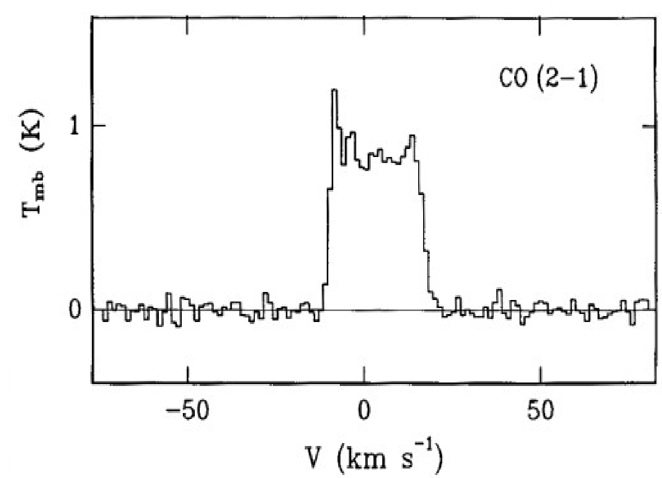
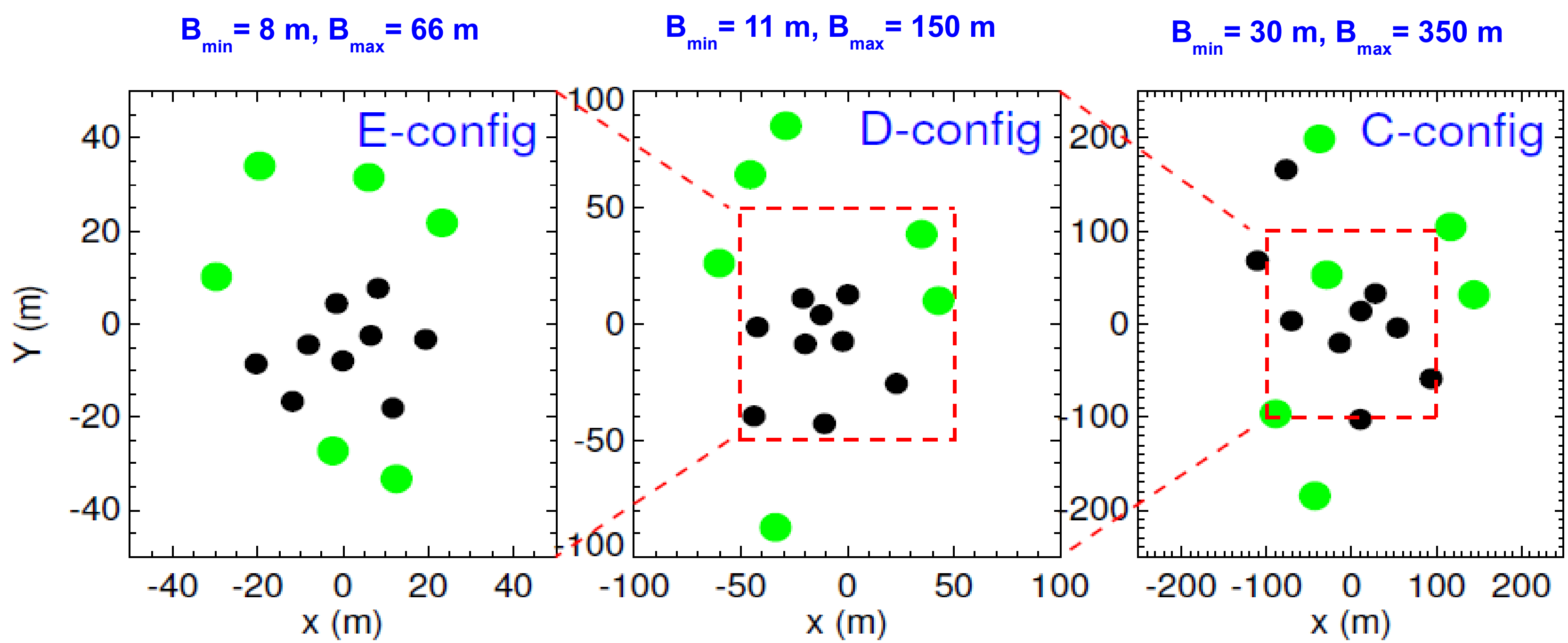


CARMA

- **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)
- 105 baselines (n(n-1)/2) with 5 configurations
- Three bands: 7 mm, 3 mm and 1.3 mm

Credit: John Carlstrom

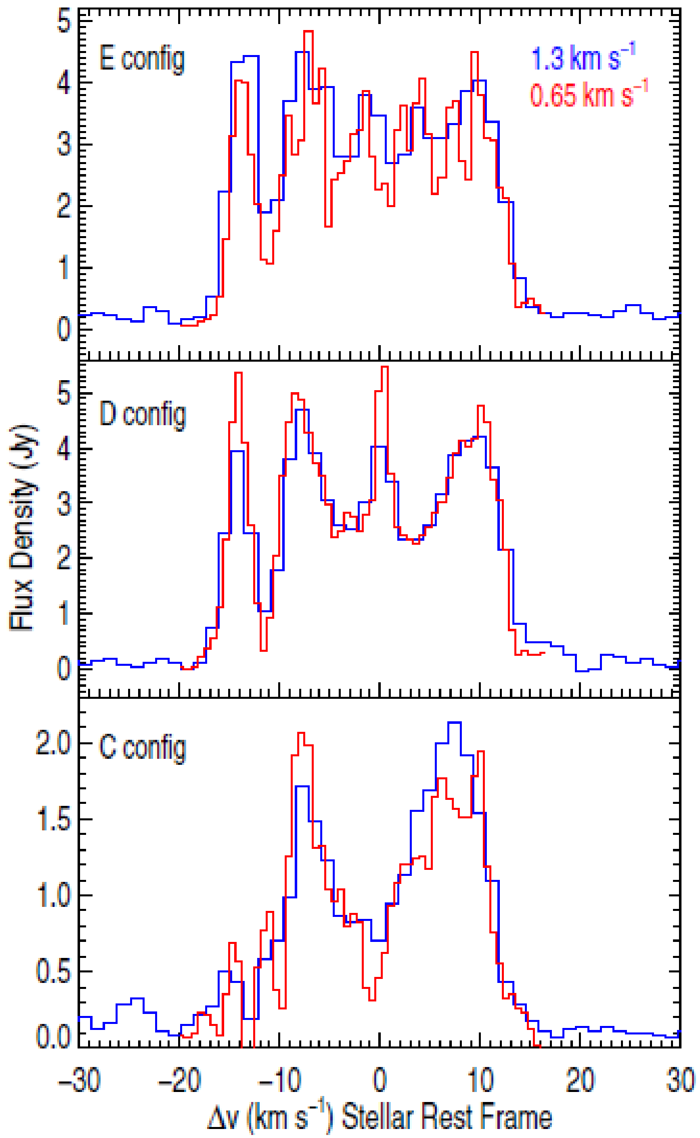
mm Observations



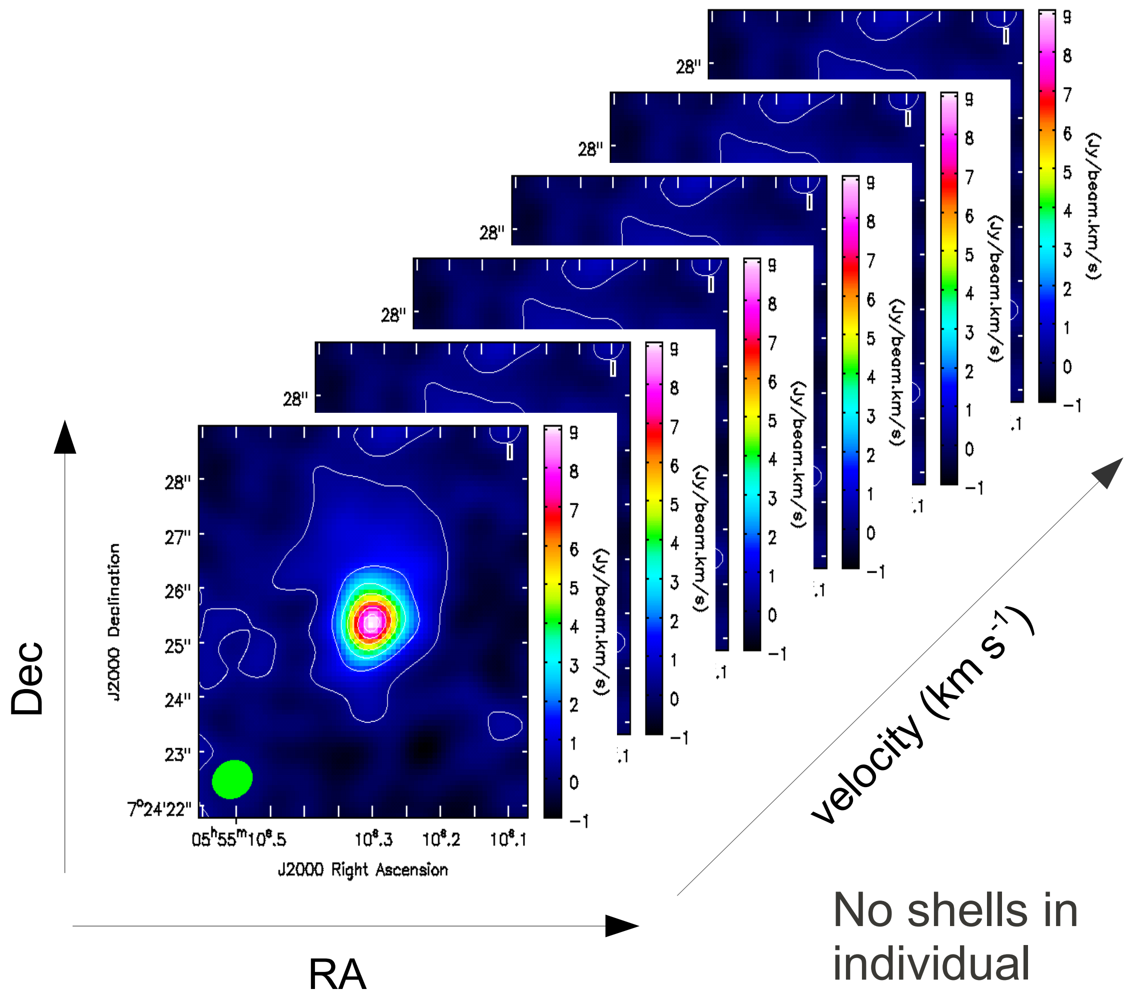
Resolution (") 0.9" → (~40 R_*)

Maximum scale (") 20" → (~800 R_*)

Individual Configurations

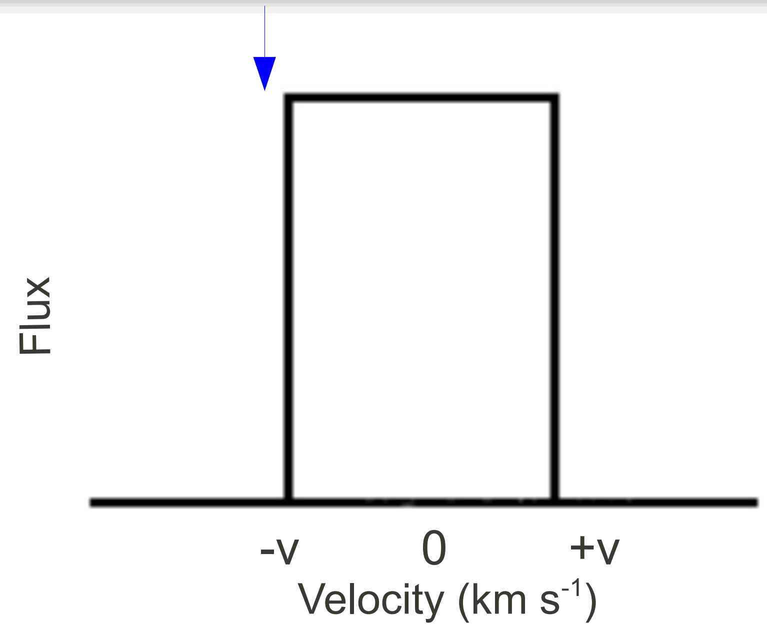


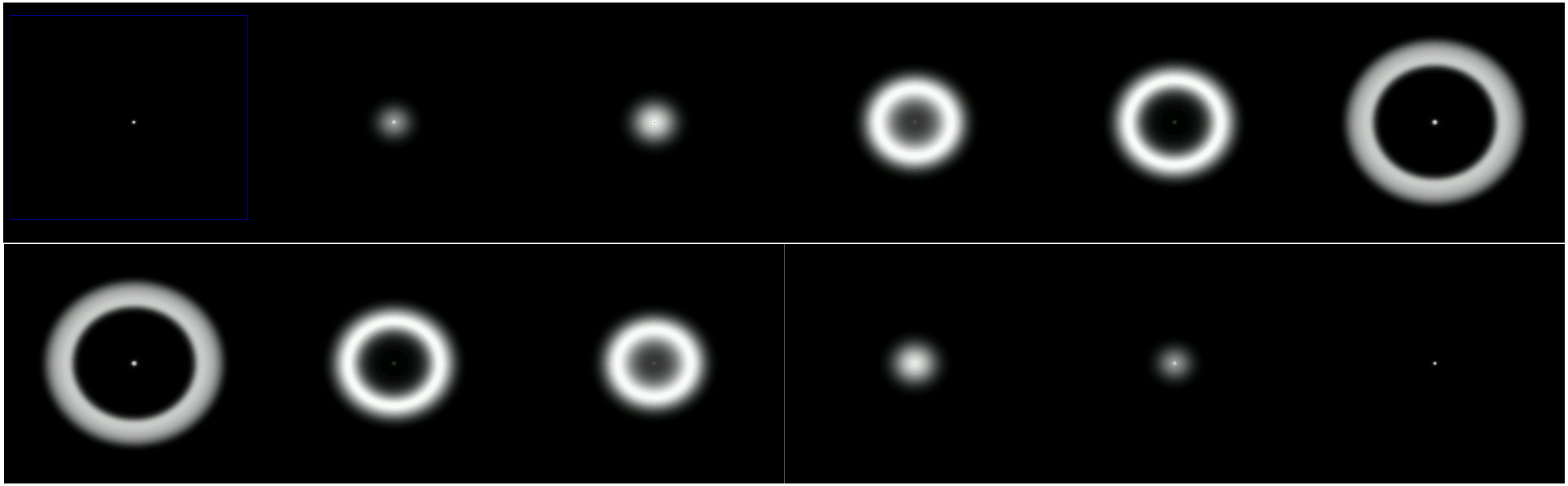
(O'Gorman *et al.*, 2012)



No shells in individual configuration image cubes.

Spherically Symmetric Shell





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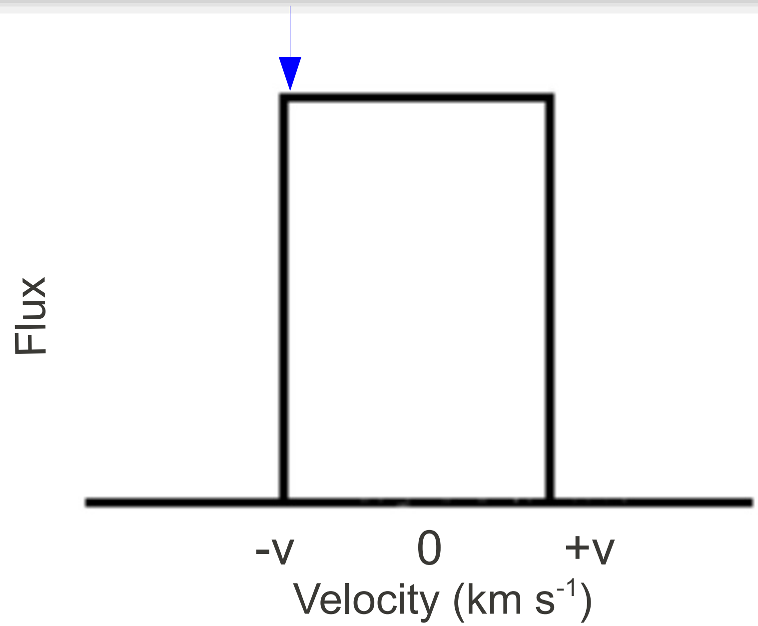

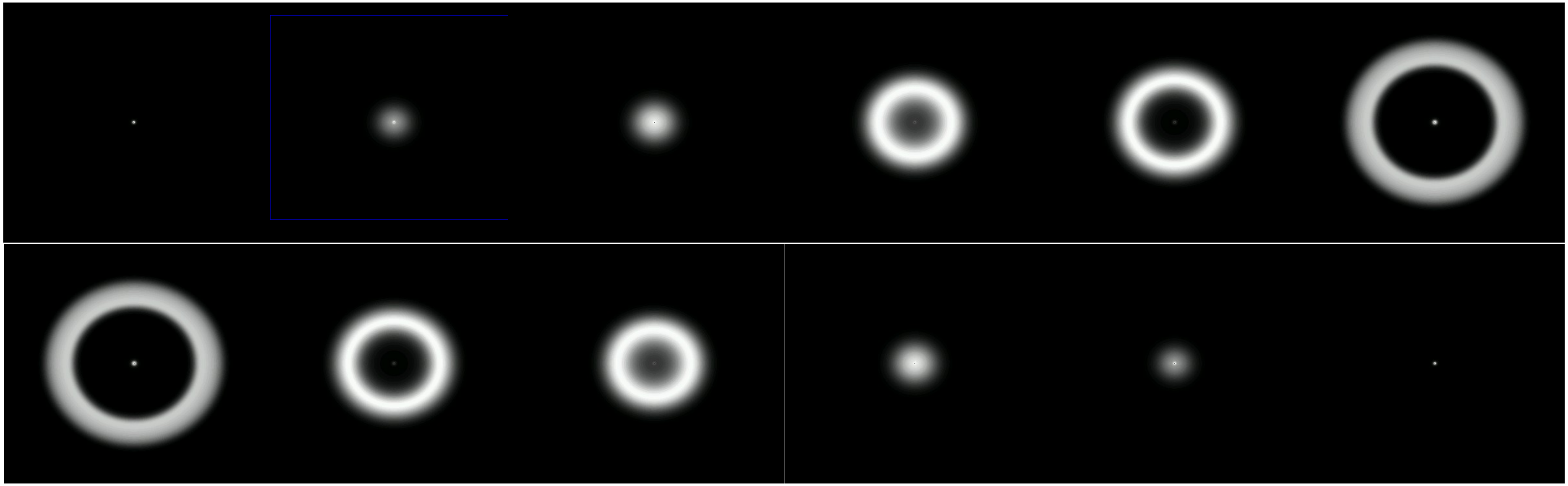

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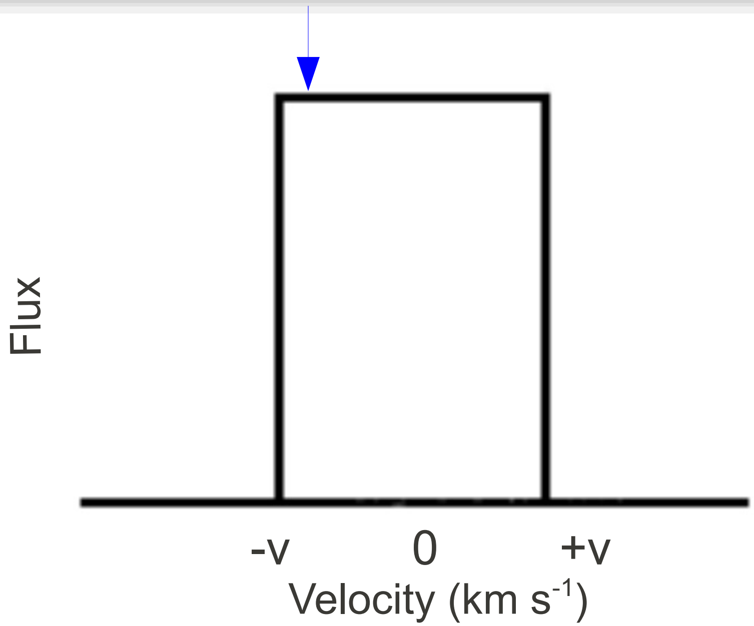

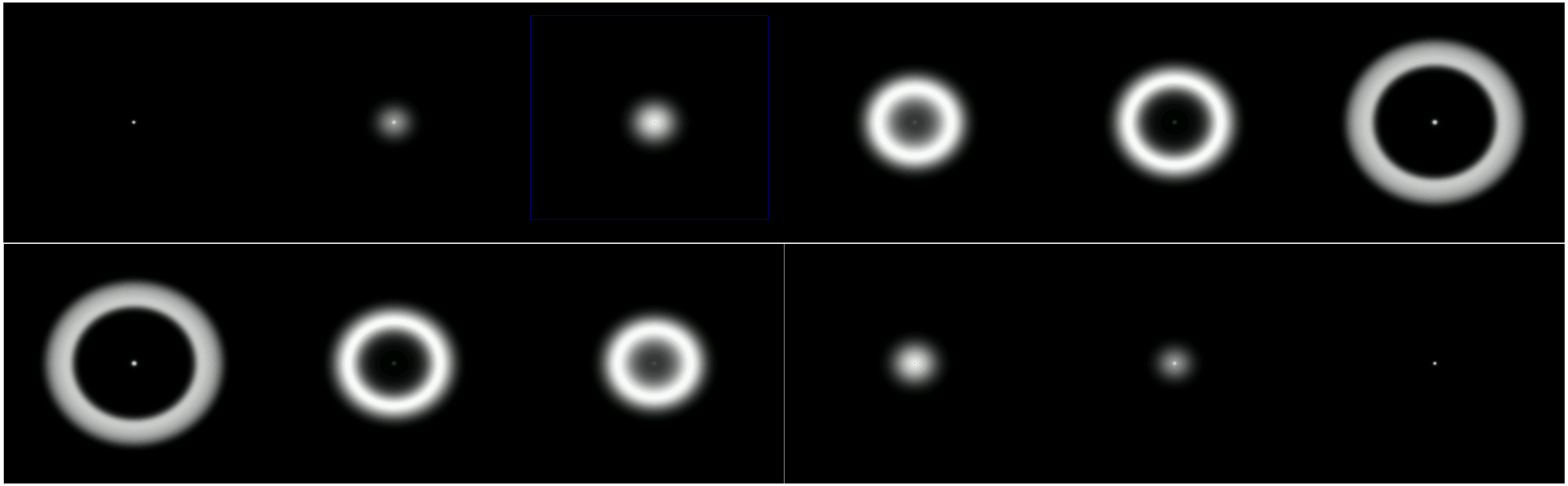

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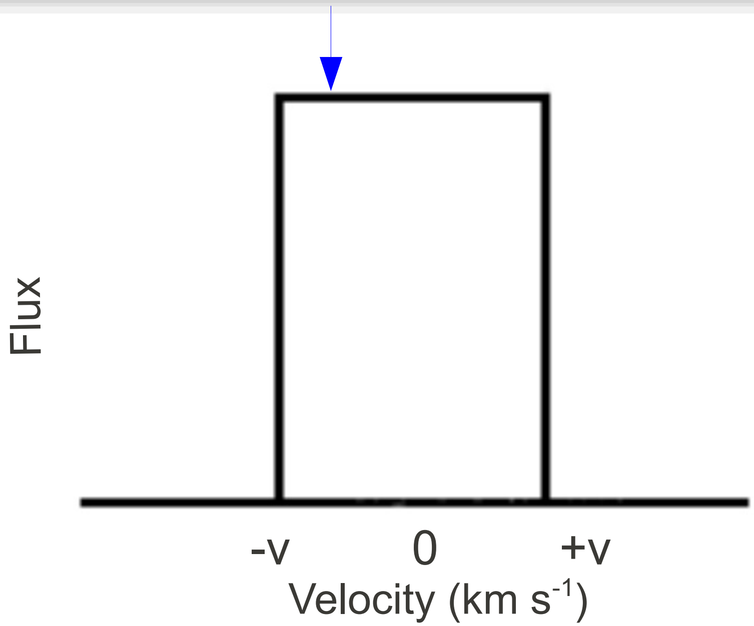

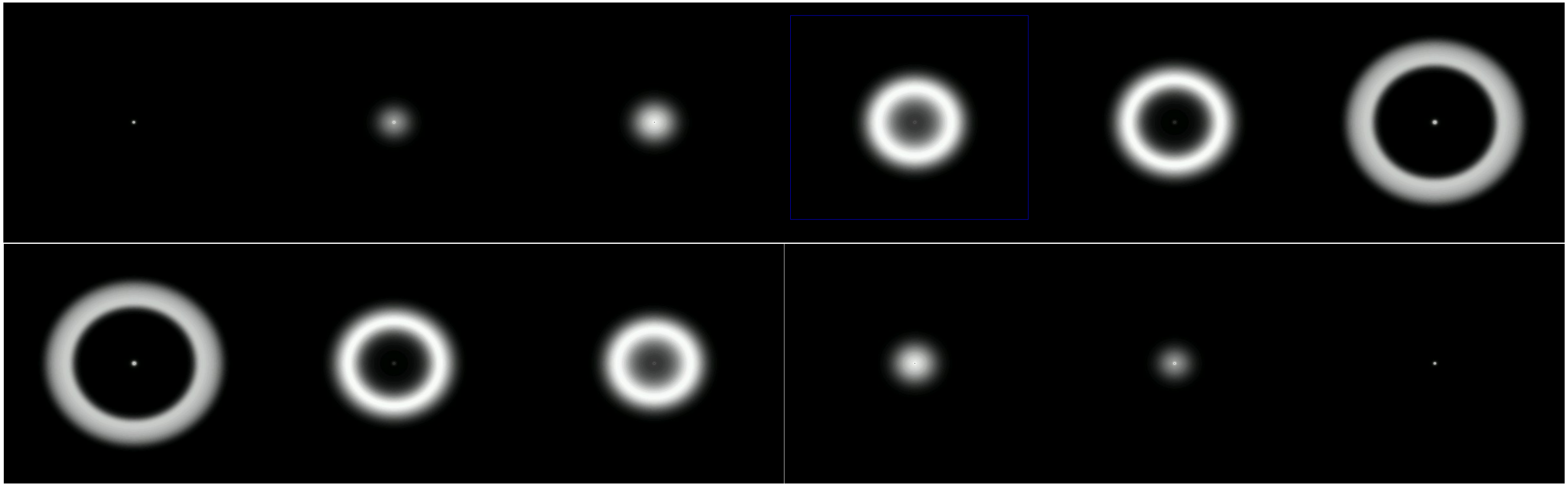

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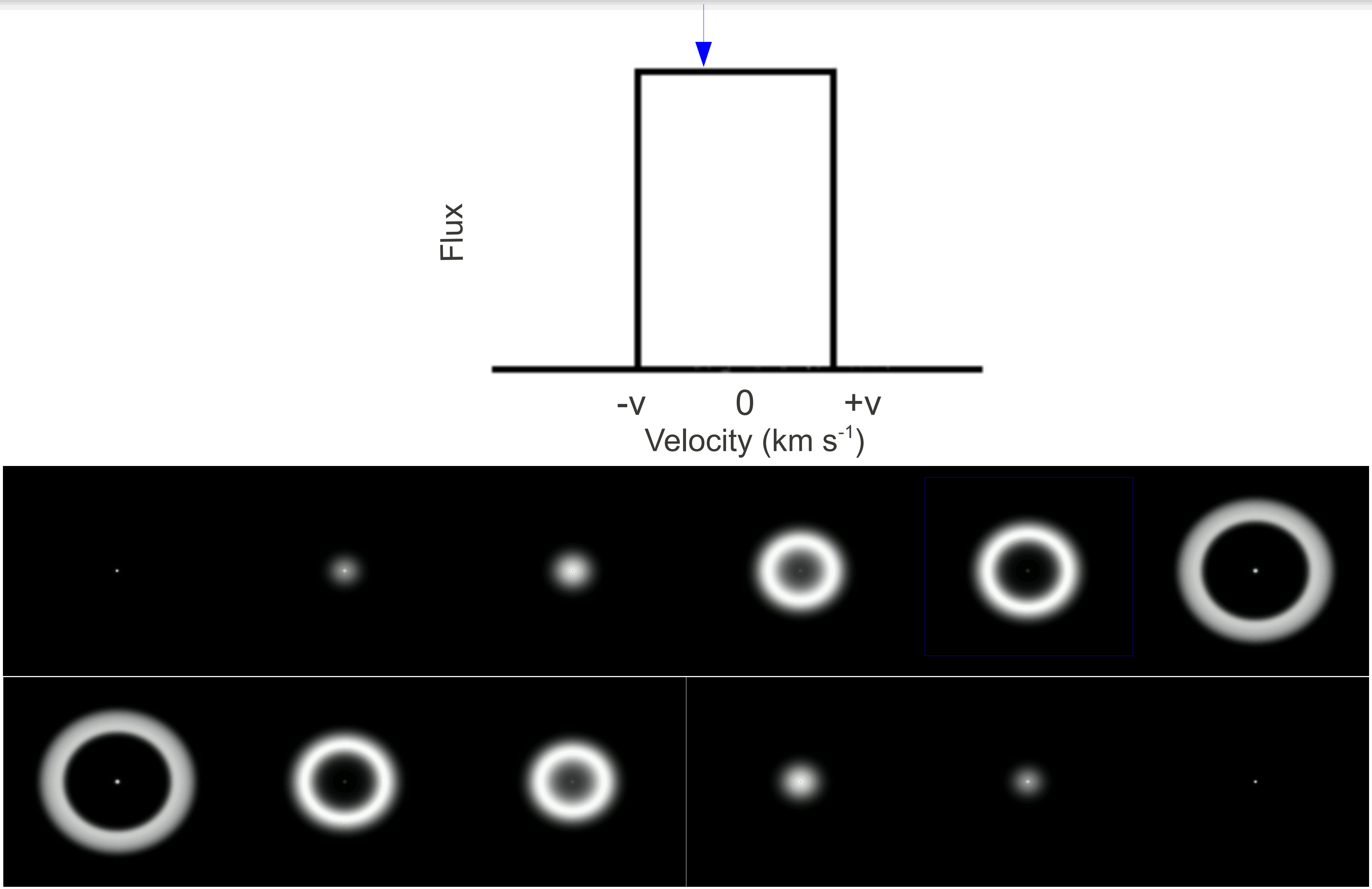

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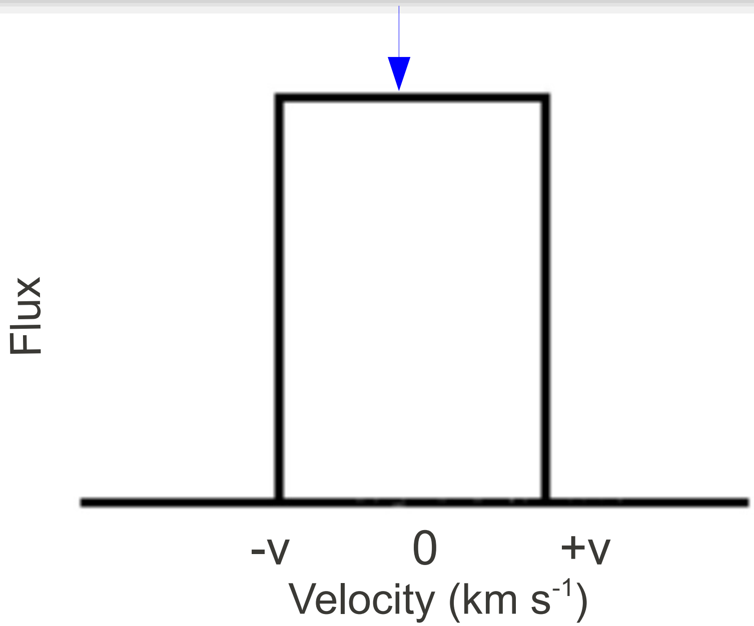

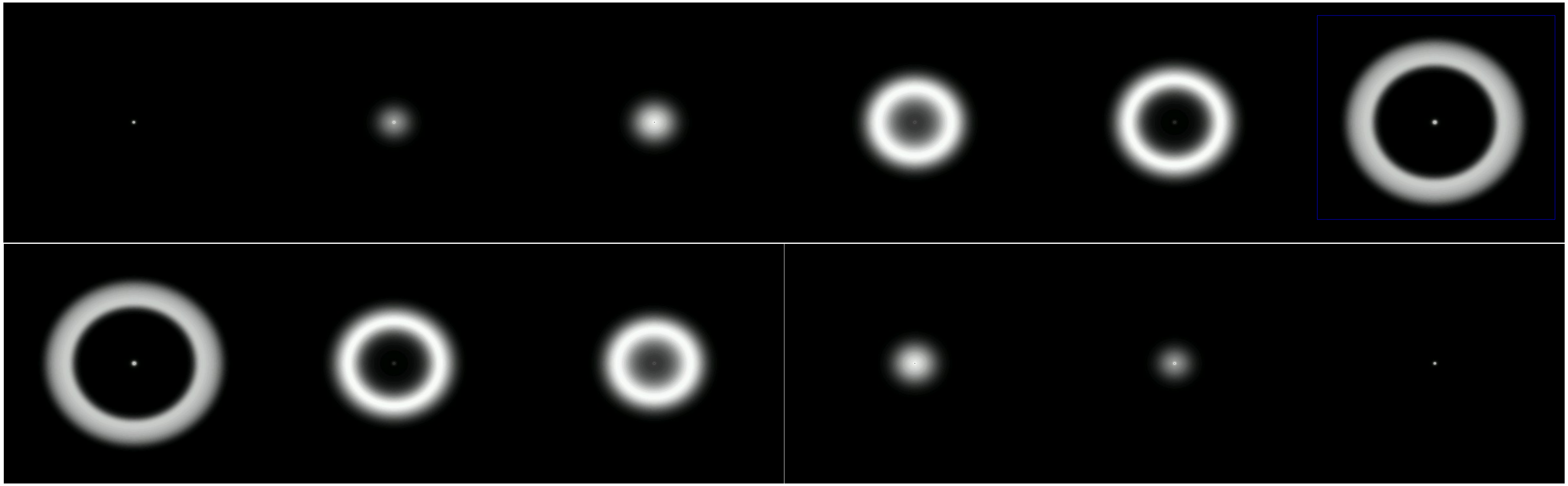

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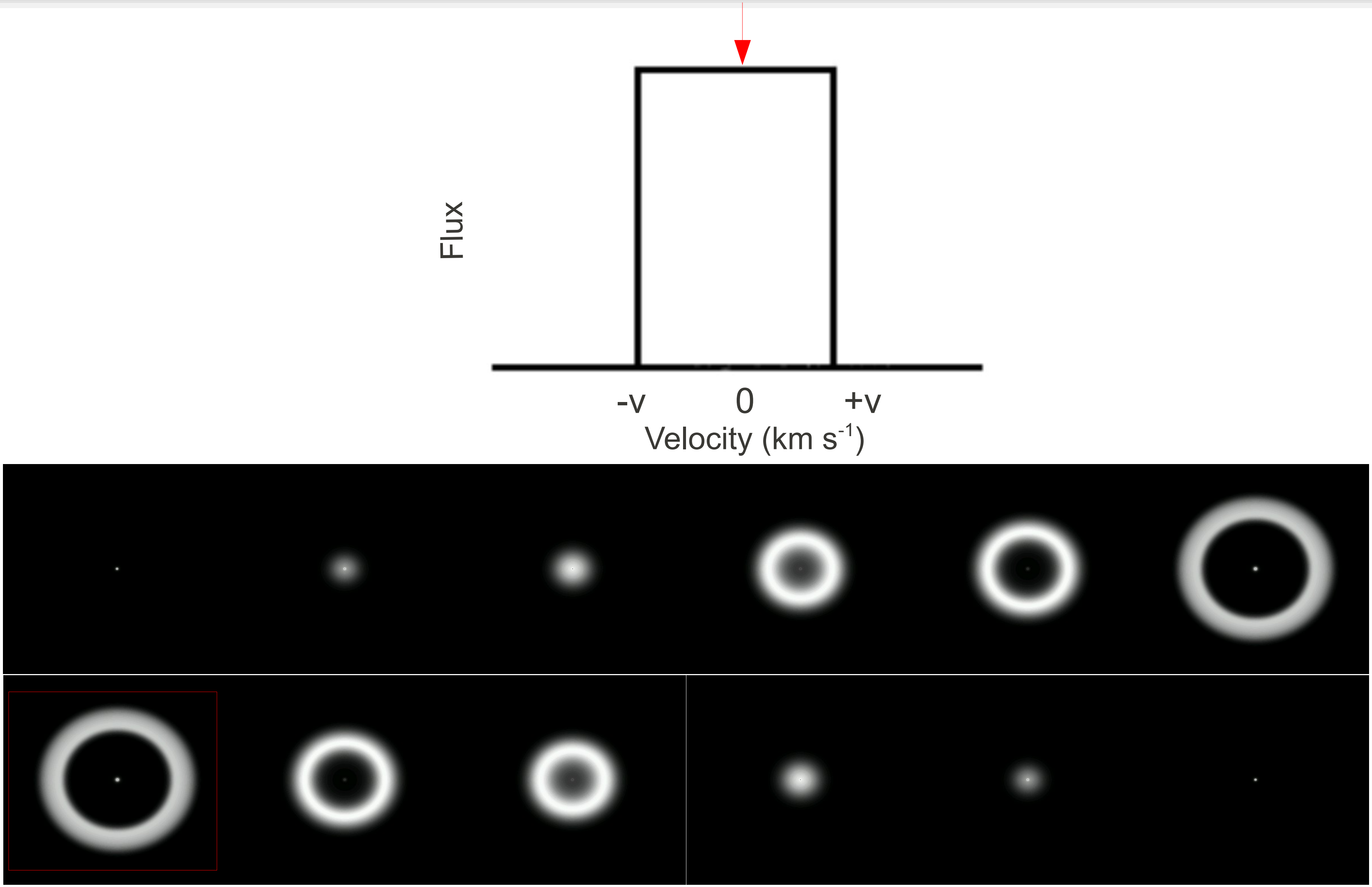

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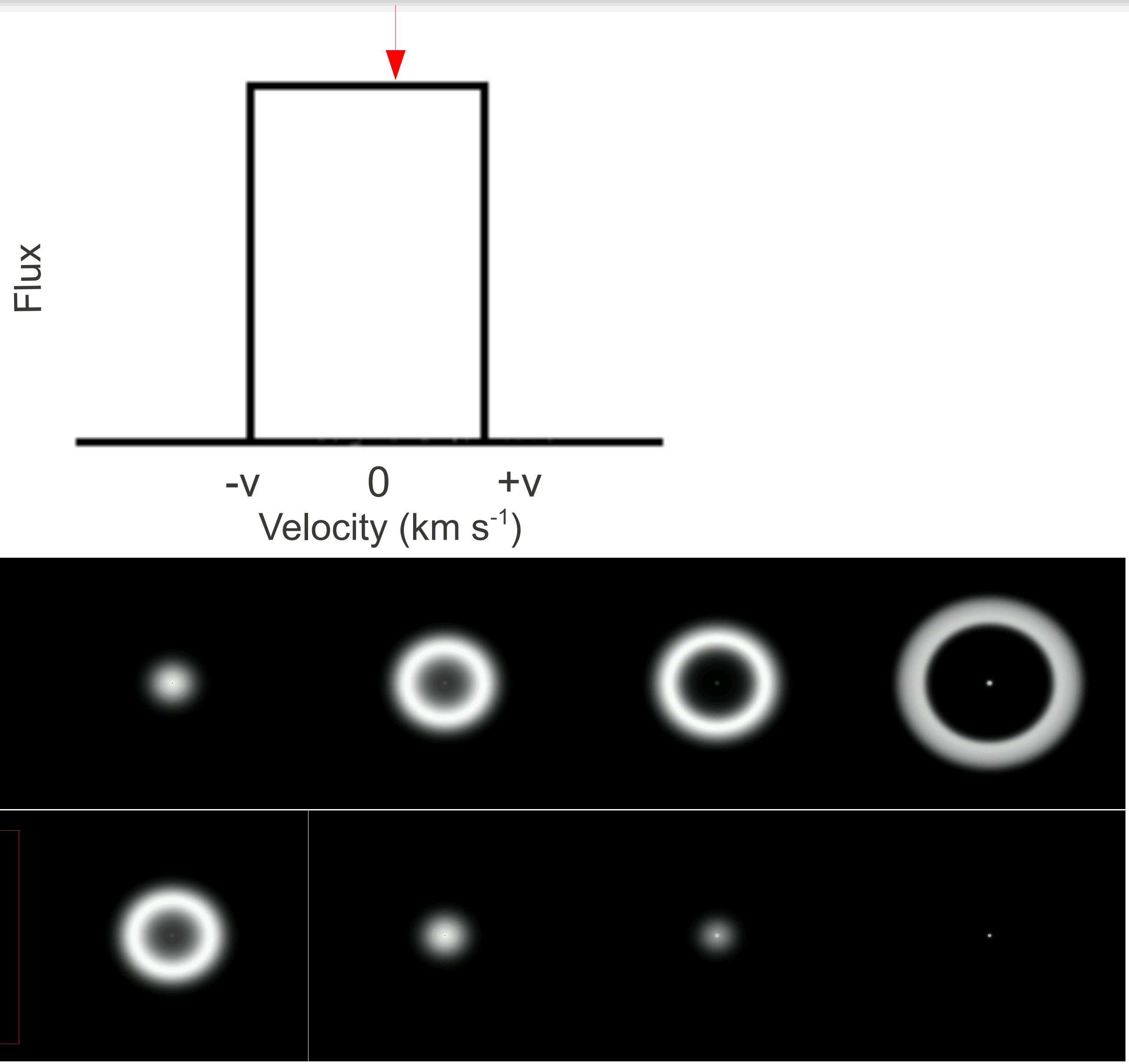

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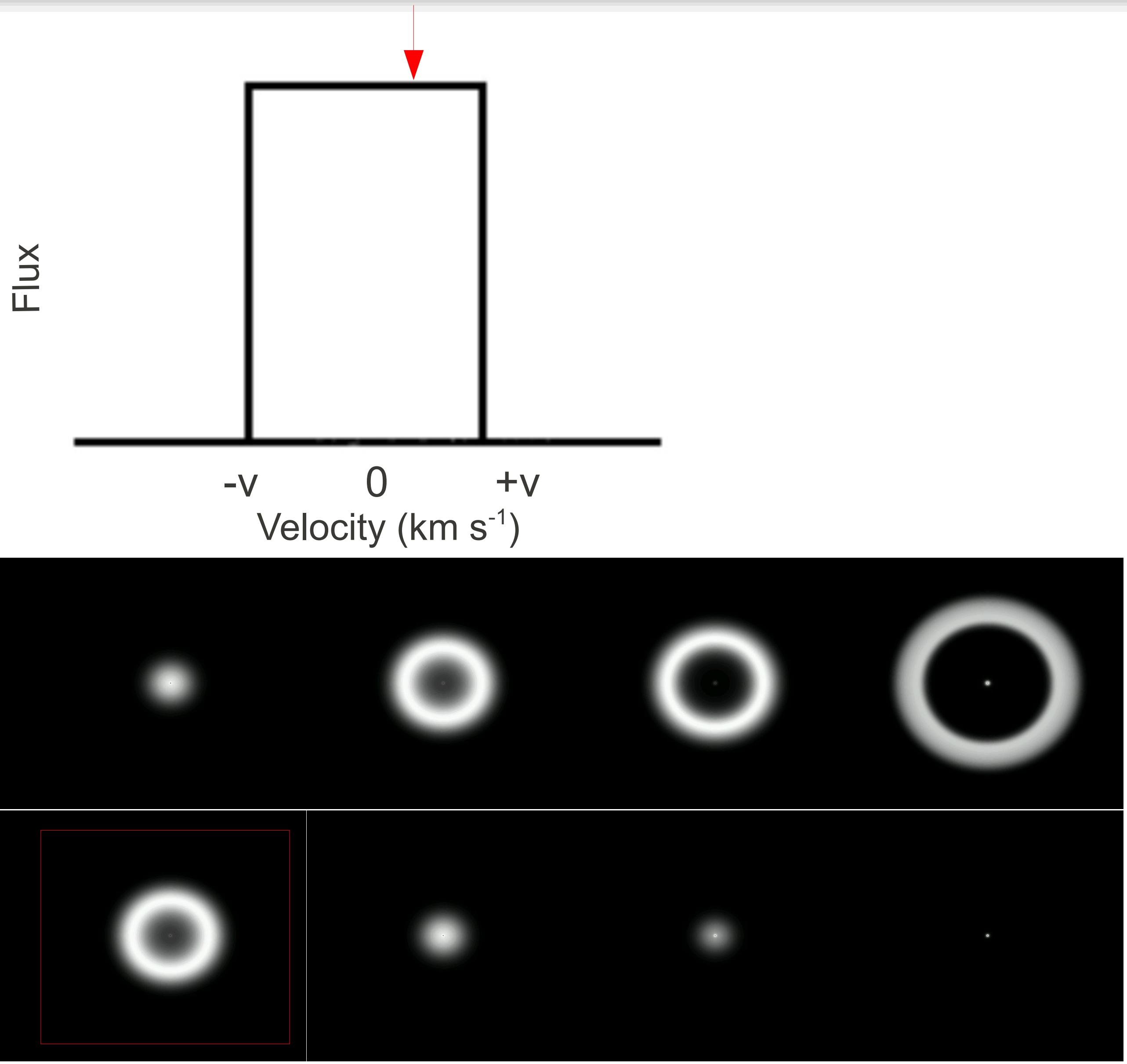

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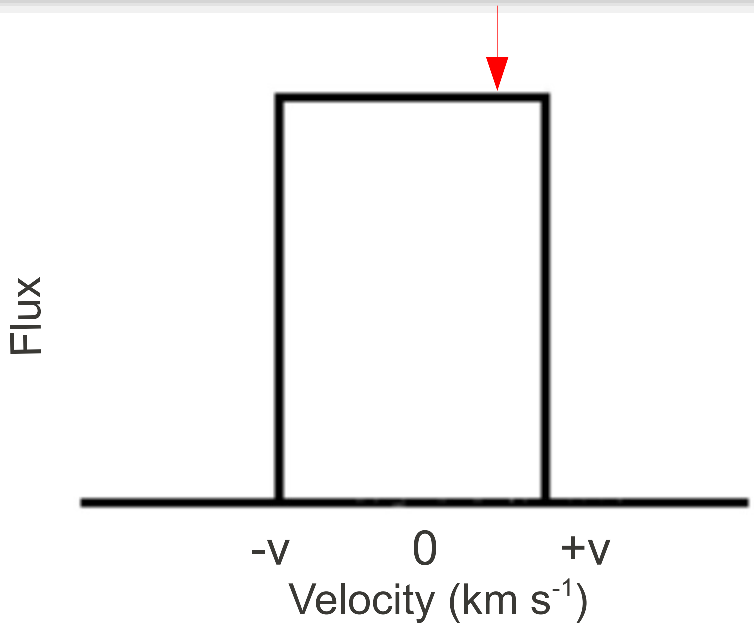

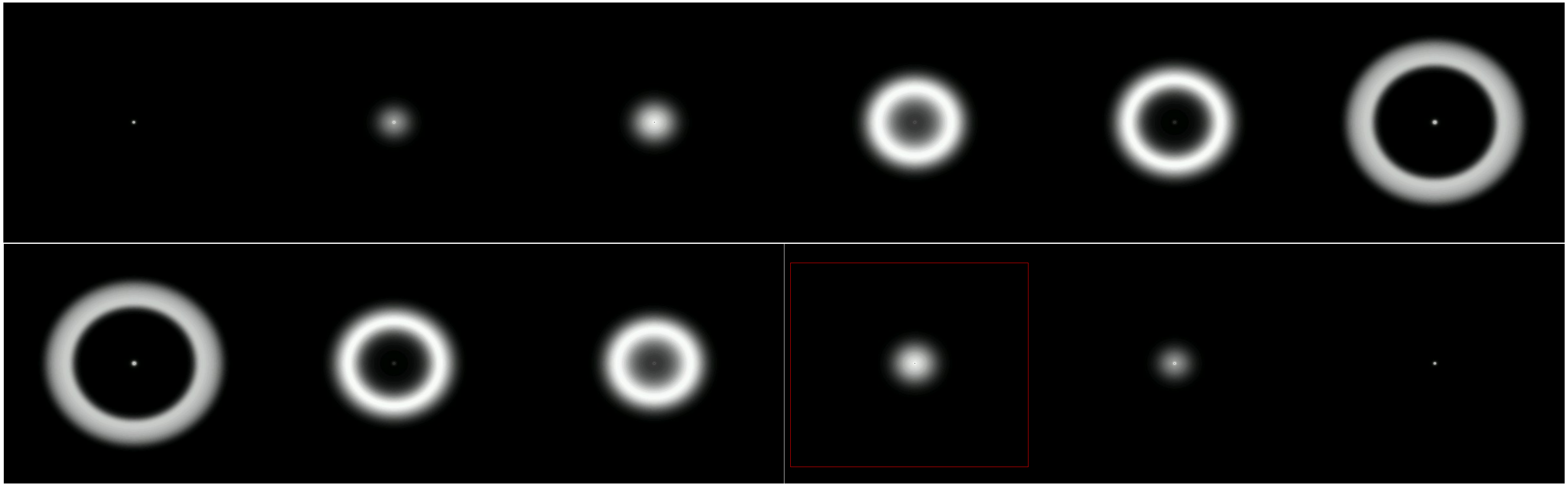

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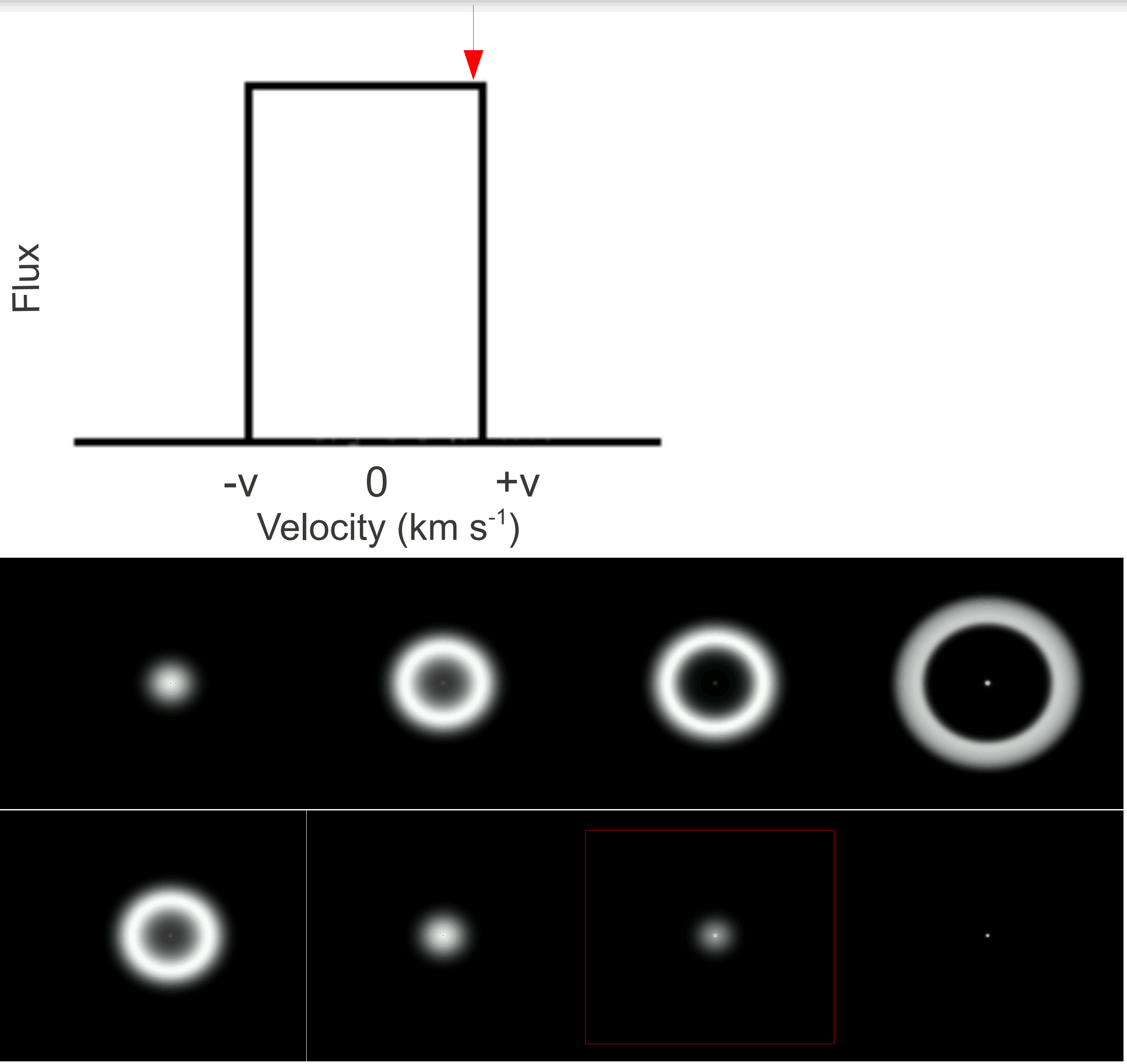

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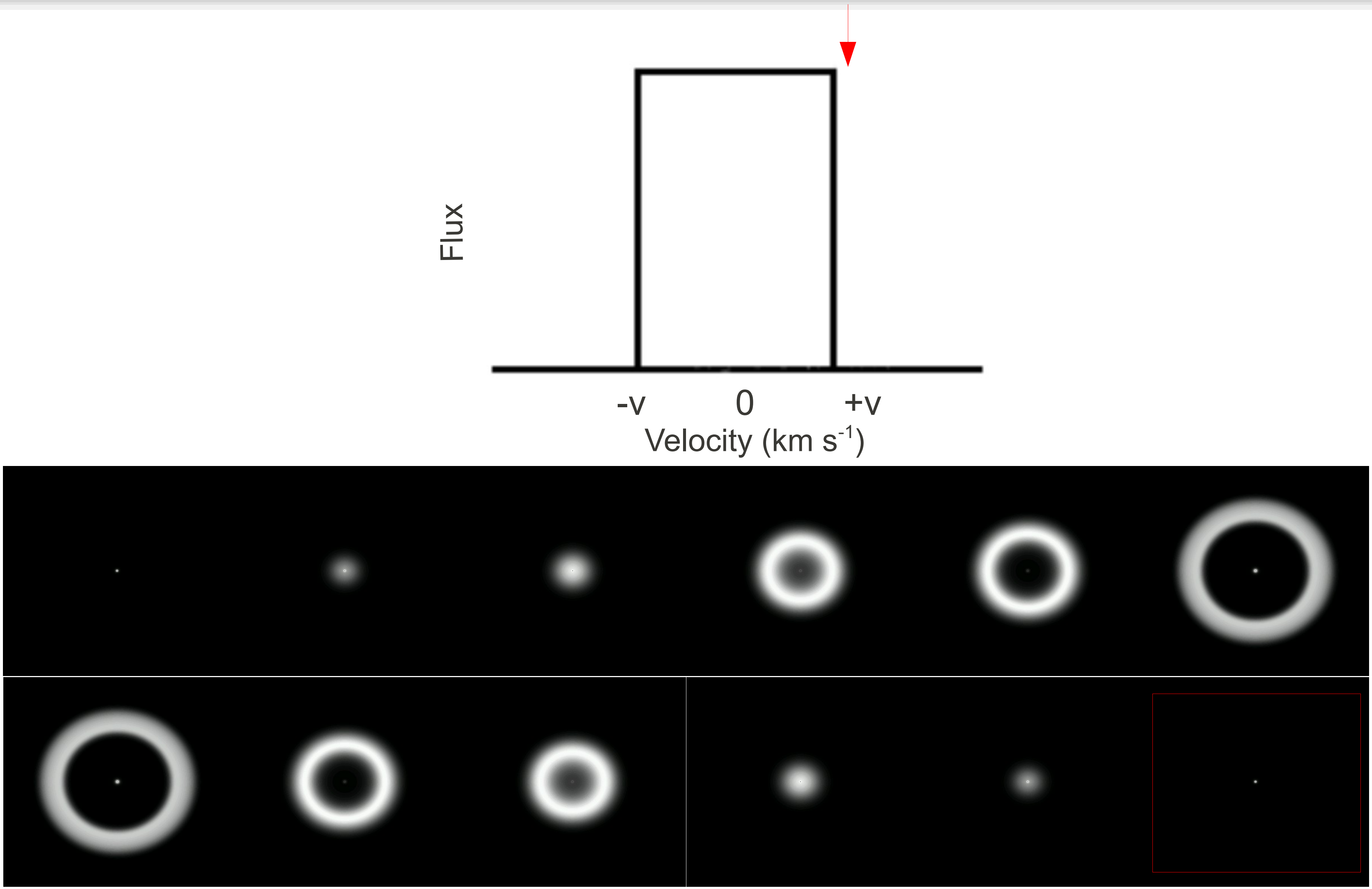
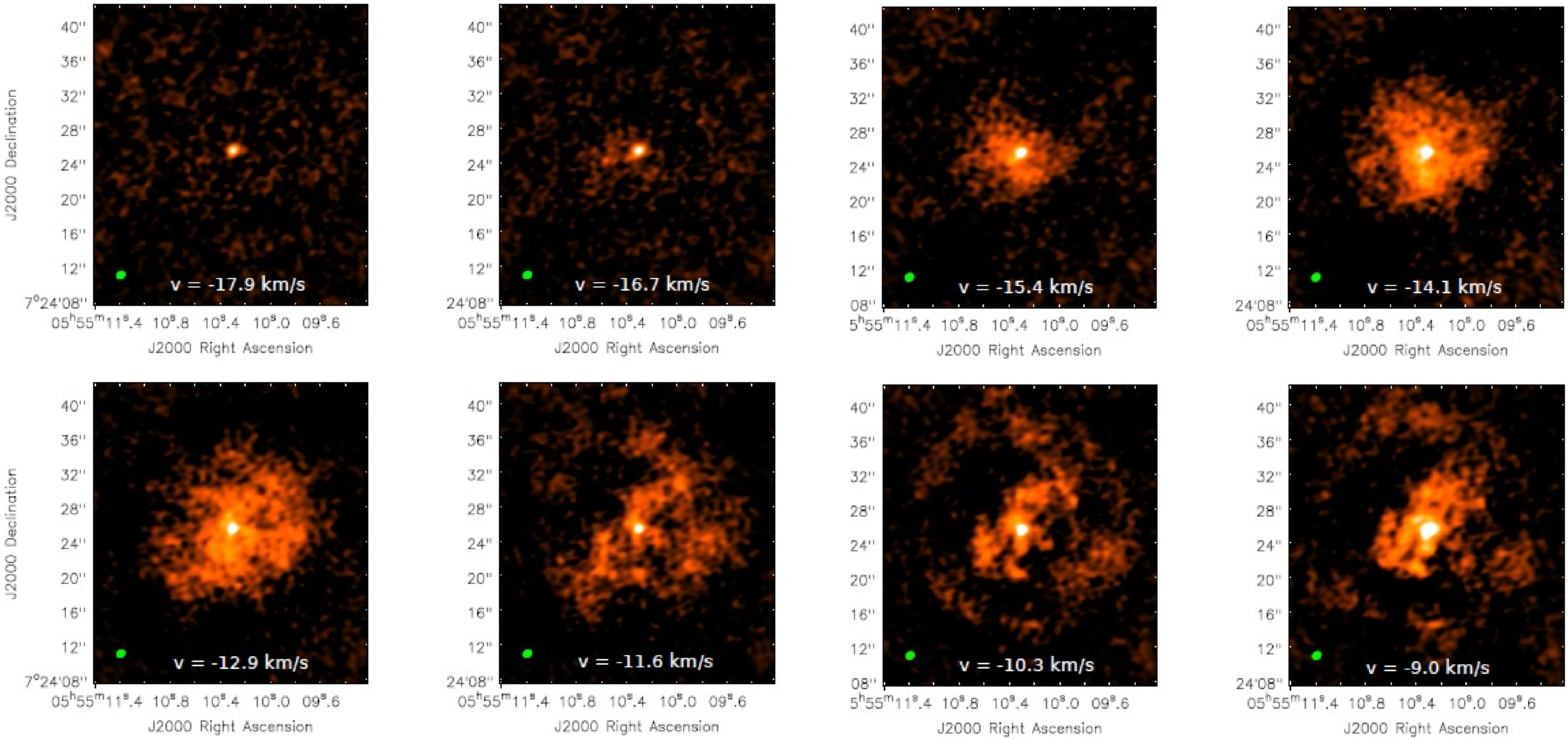


Combined Configuration



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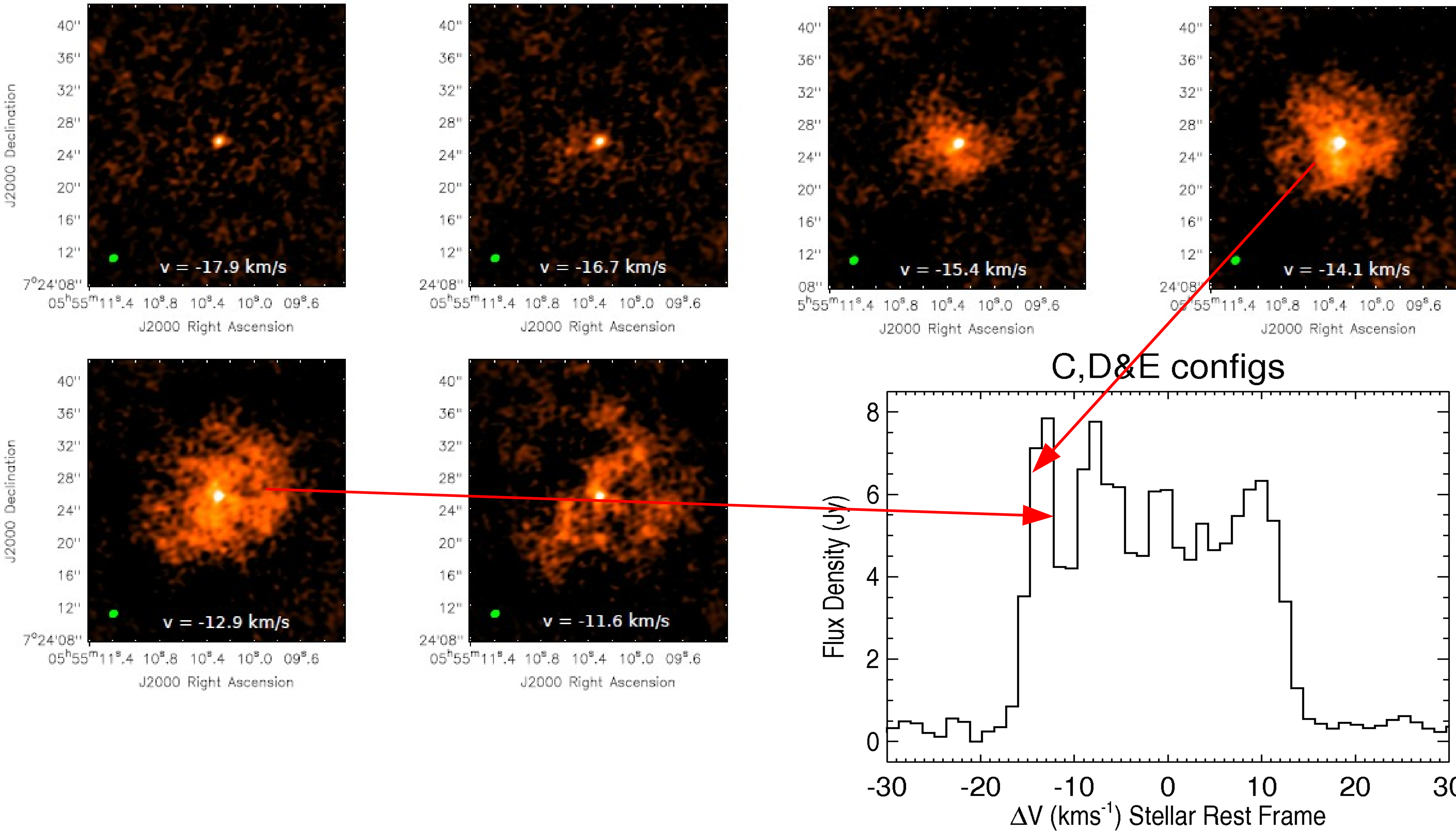
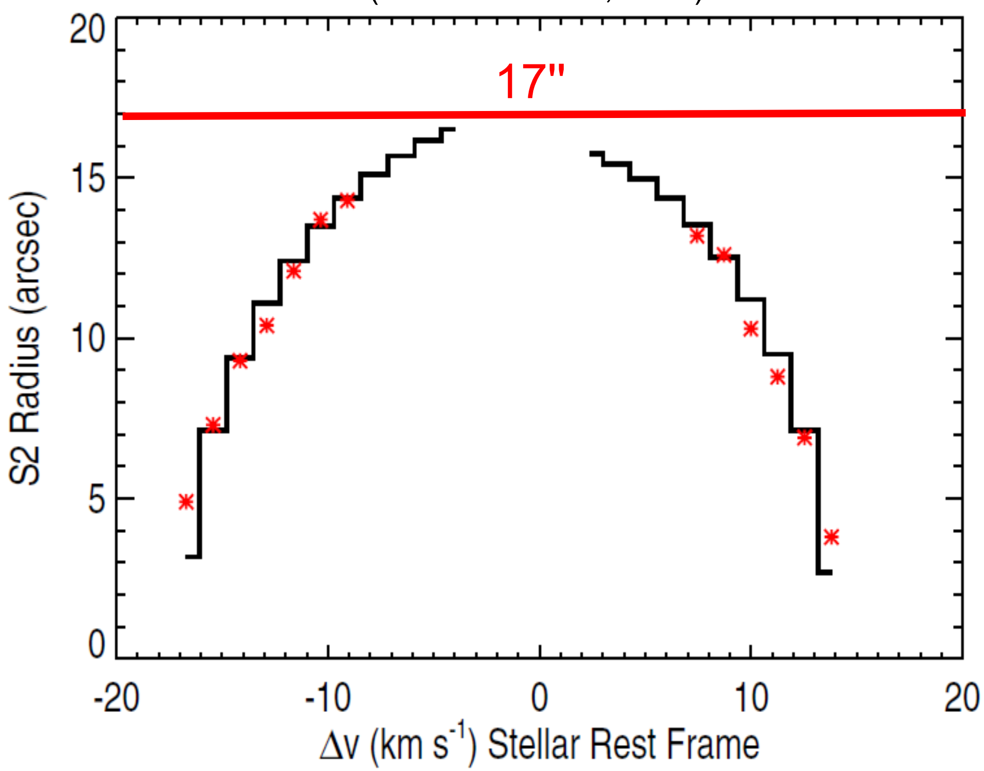


Spatial Extent of Flows

S2 flow not present at low absolute velocities.

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



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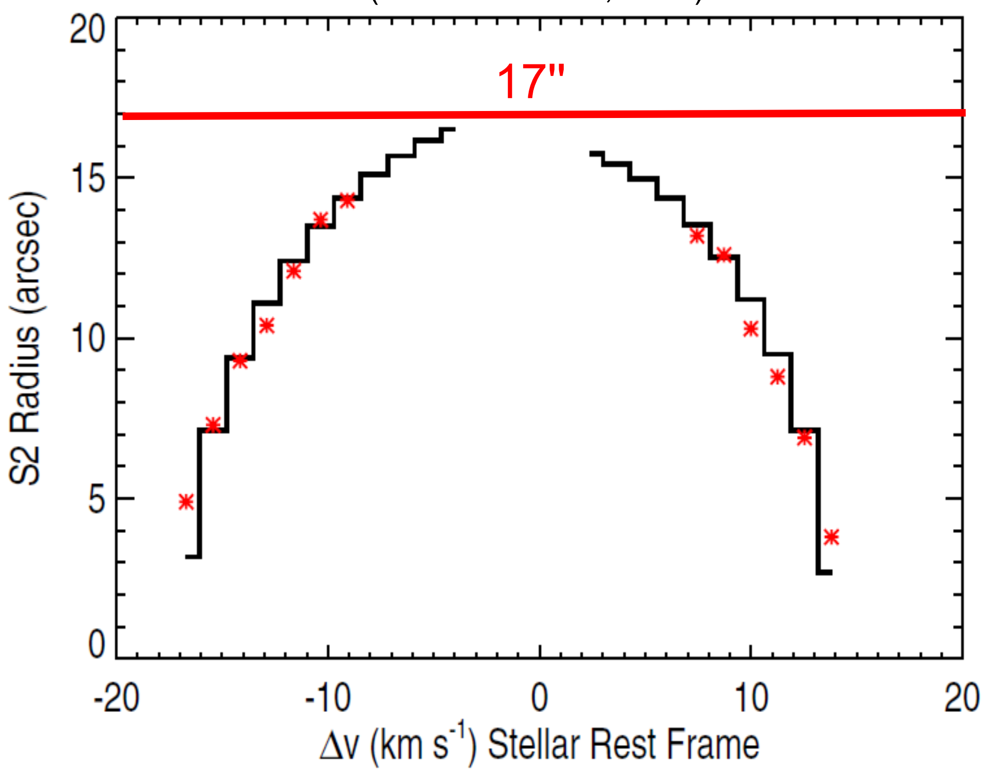

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S1 flow

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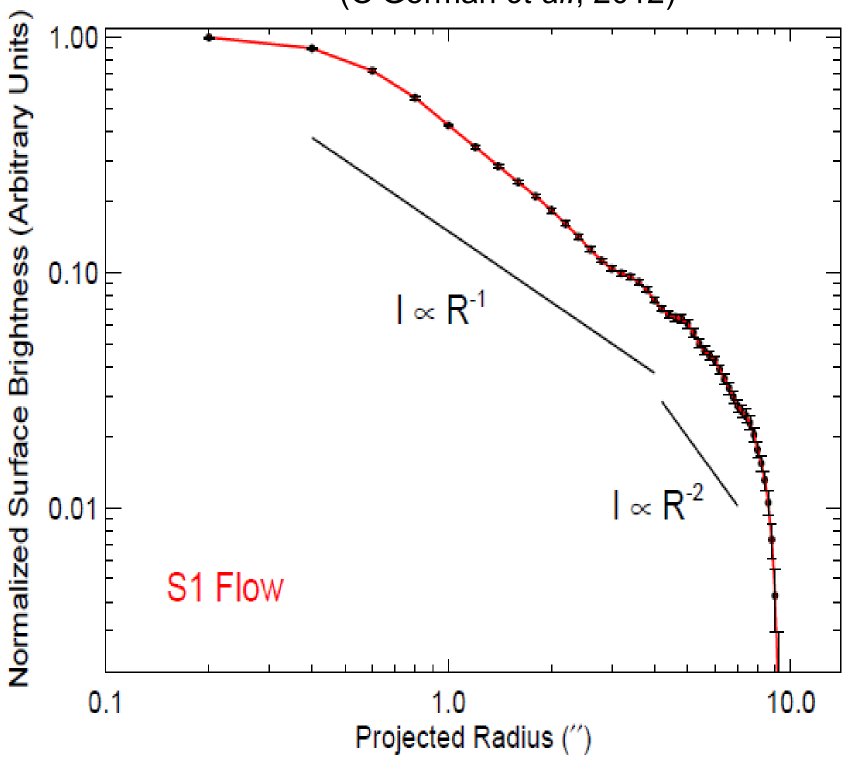


S1 flow: Density consistent with R^{-2}.
Also clumping.

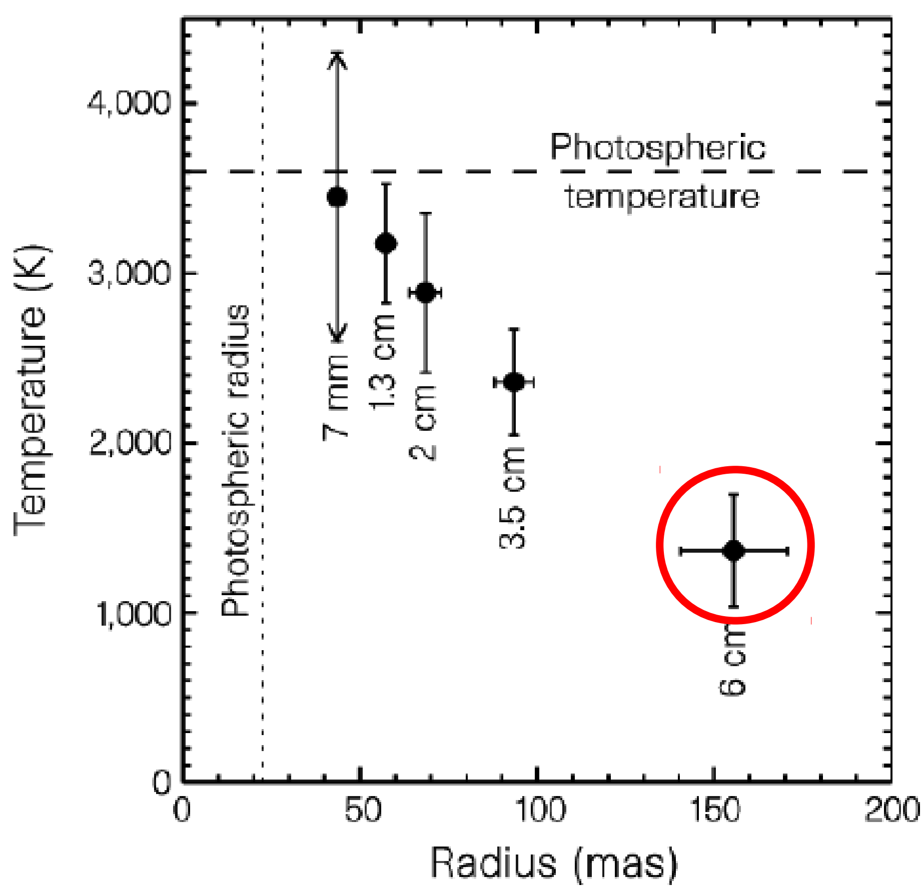
Conclusions

- High spatial resolution configuration resolves out S2 emission providing S1 profile.
- Multiple CARMA configurations provide the high spatial resolution needed to study the inner S1 flow, while ensuring the extended S2 flow is not resolved out.
-

	S1	S2
Outflow Velocities (km s^{-1})	9.8	14.3
Maximum Spatial Extent (")	4 → 6	17
Age (yr)	400 → 600	1100

Betelgeuse's Wind Acceleration Region

(Lim *et al.*, 1998)

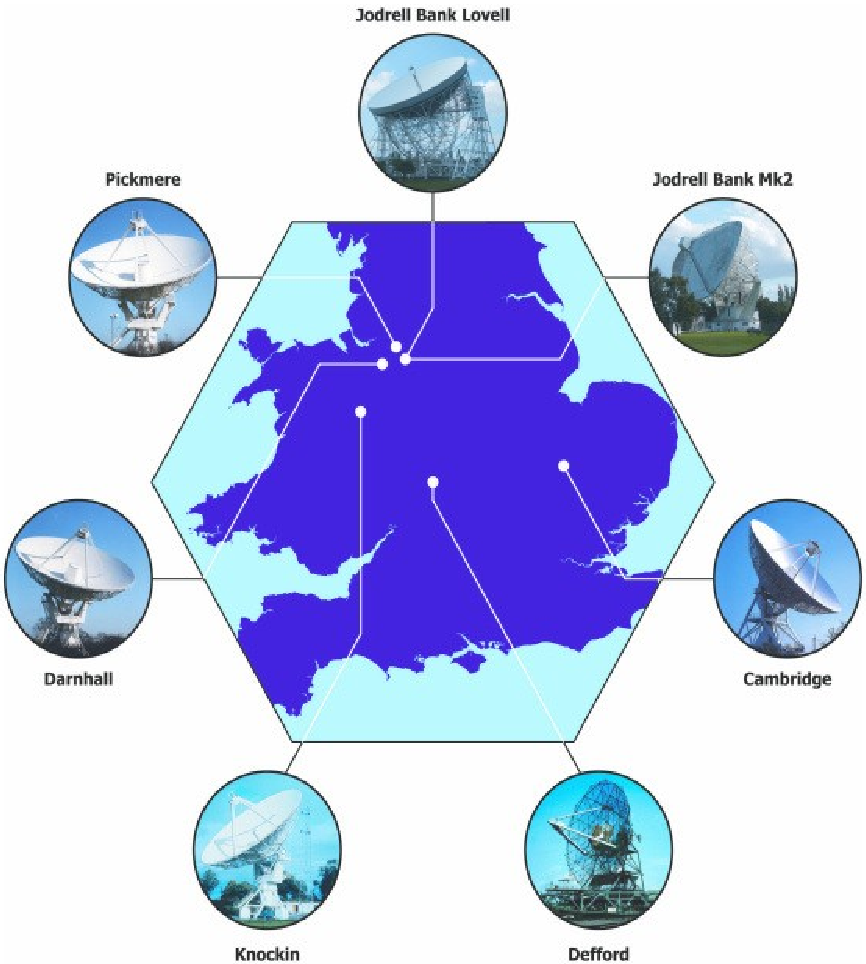


$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$

Size

Brightness Temperature

Betelgeuse with e-MERLIN (5.2 cm)



(Credit: MERLIN/VLBI national facility)

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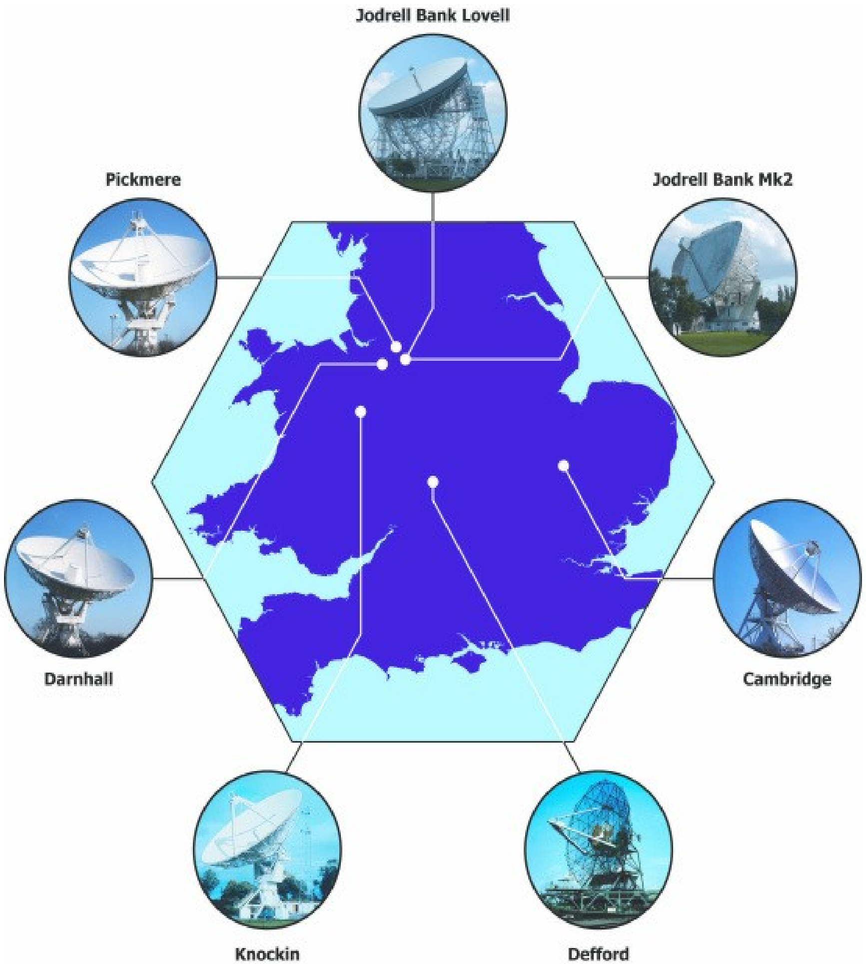

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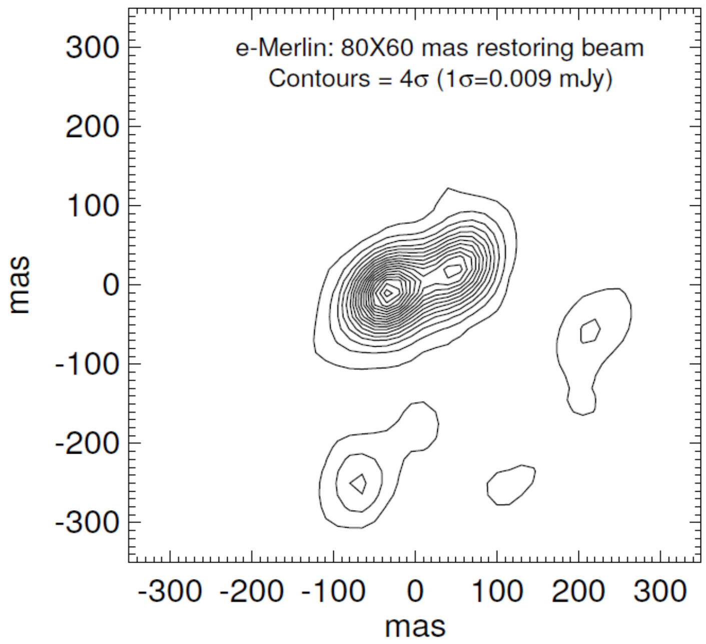
Richards *et al*. (2013)



Two unresolved *hot spots:*

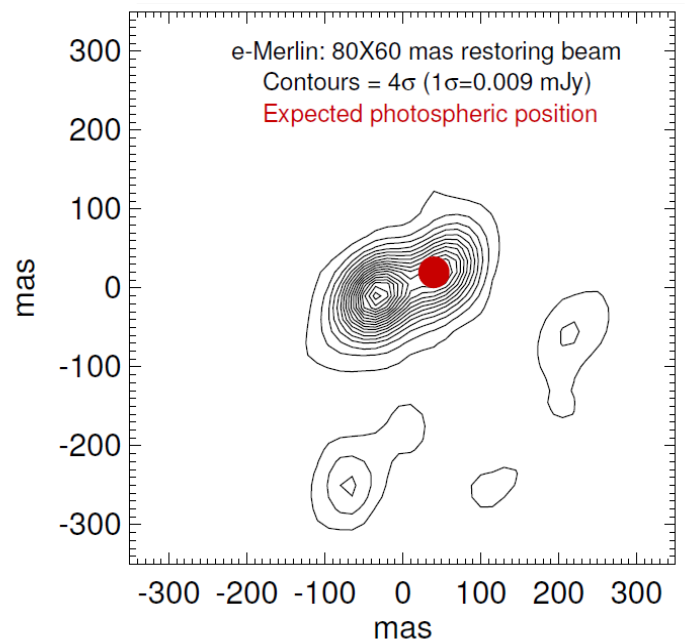
$T_e > 3800$ K

$T_e > 5400$ K

Where is the photosphere?

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.

Betelgeuse with e-MERLIN (5.2 cm)

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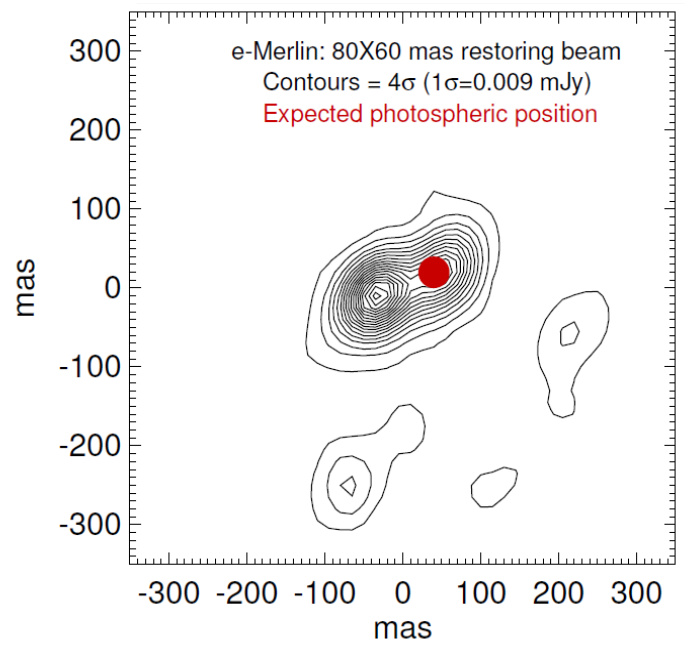

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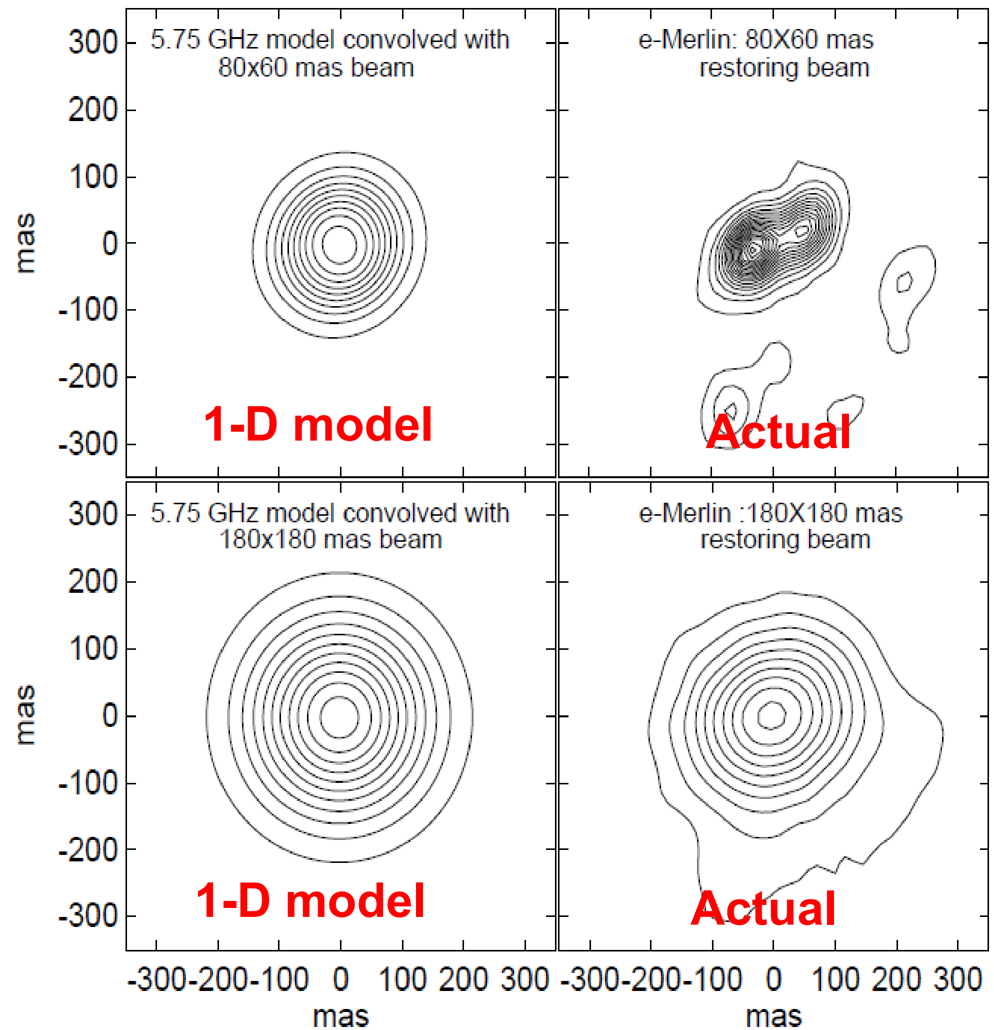

Spherically symmetric semi-empirical model of Harper *et al.*, (2001)

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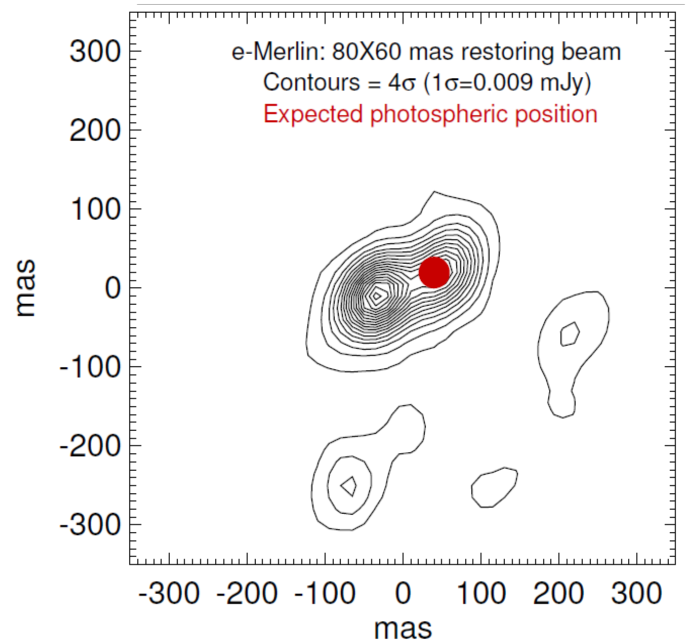

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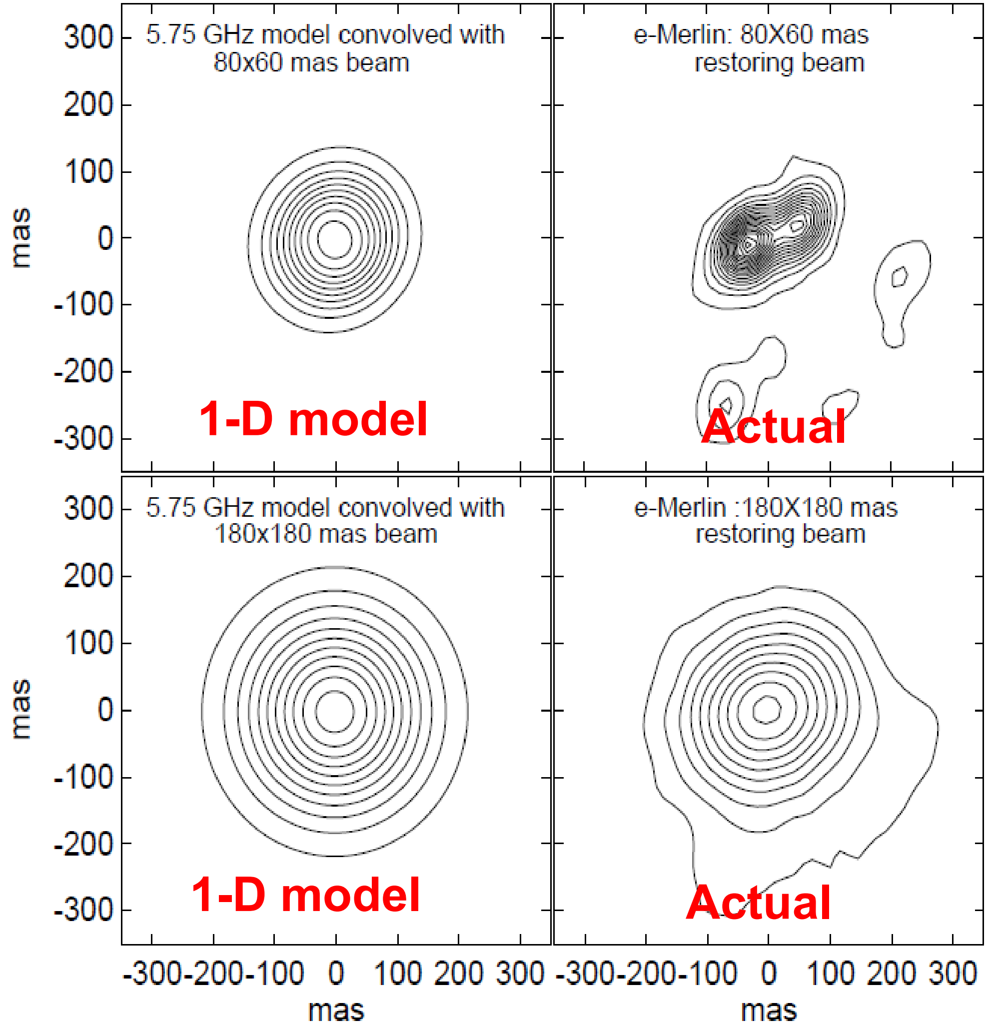
Goal: *Analyse high resolution archival cm data to search for signatures of hotspots.*



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

Betelgeuse with VLA – Pie Town

VLA

\+

Pie Town Antenna

=

e-MERLIN

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

VLA + Pie Town

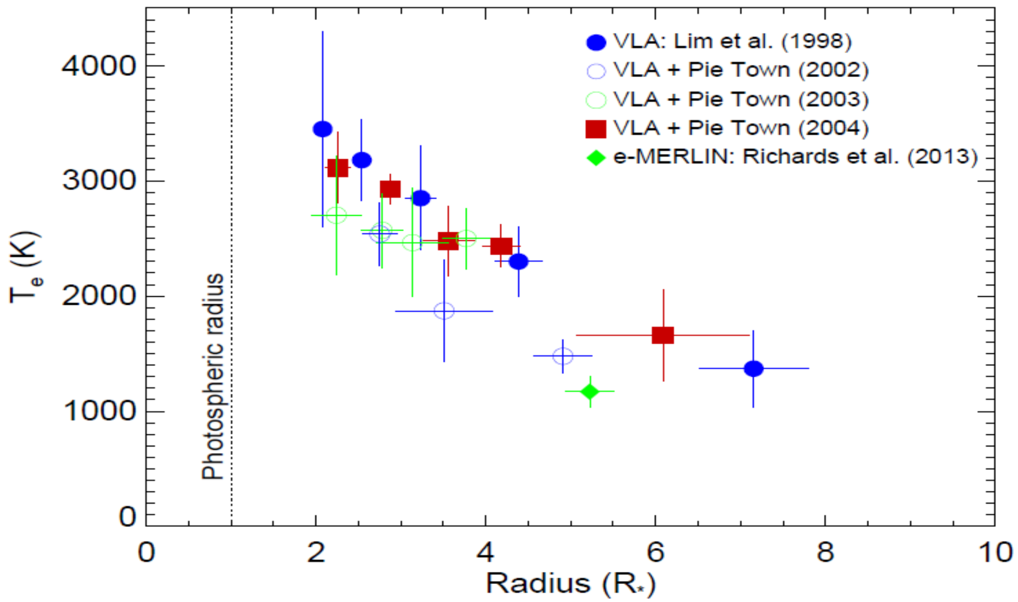
w/l (cm)	Resolution (")
0.7	40 x 25
1.3	80 x 40
2.0	120 x 90
3.5	200 x 130
6.2	380 x 270

Betelgeuse with VLA – Pie Town

Variability 1998-2004

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

Thermal Profile



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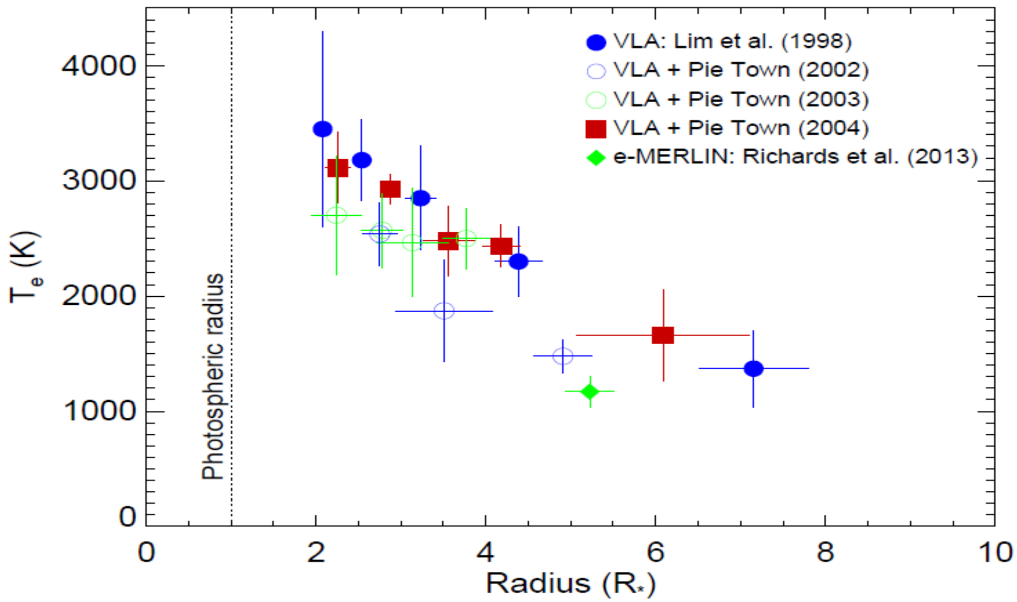
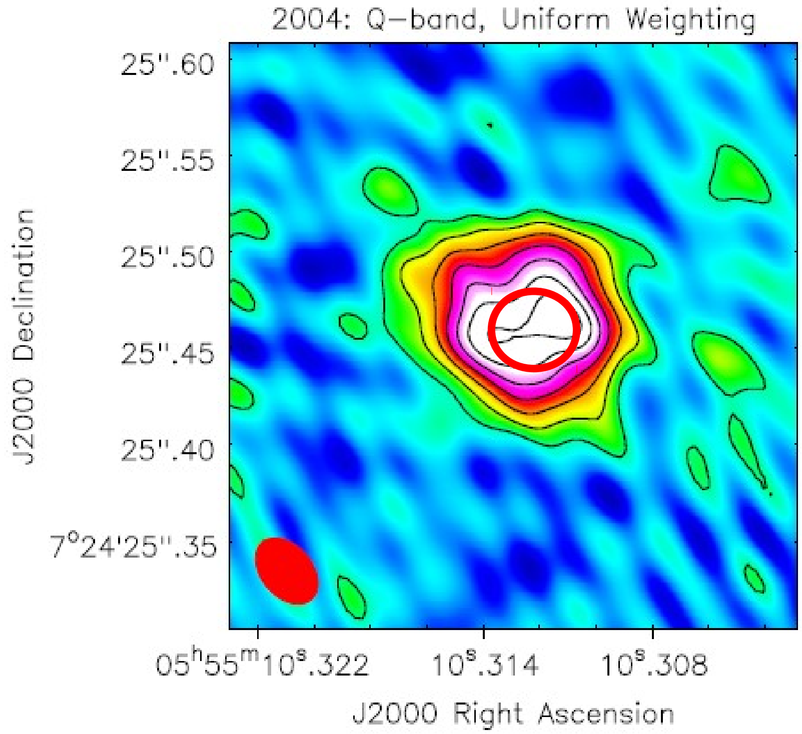


Q band (0.7 cm)



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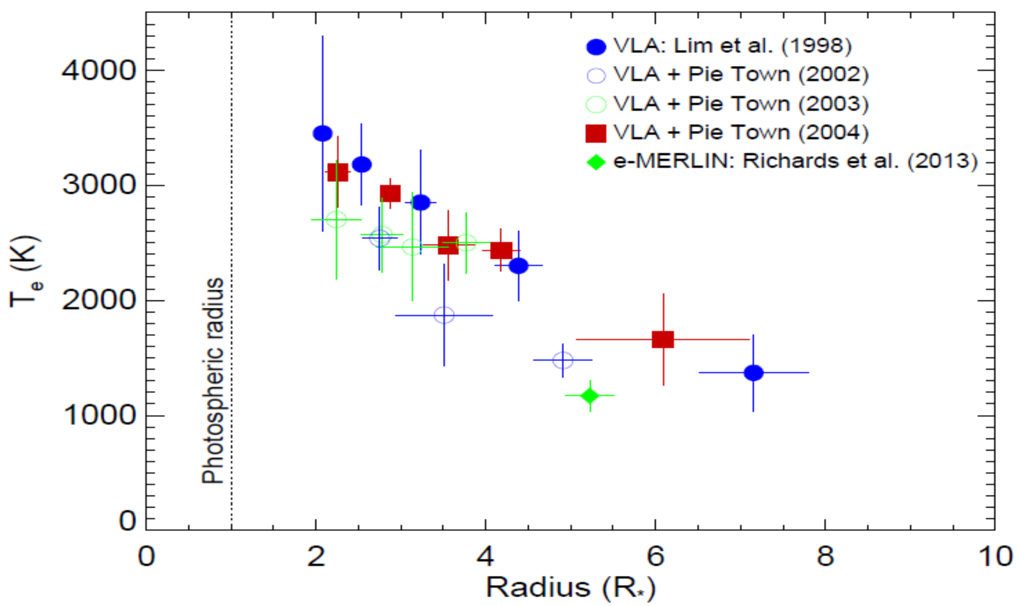
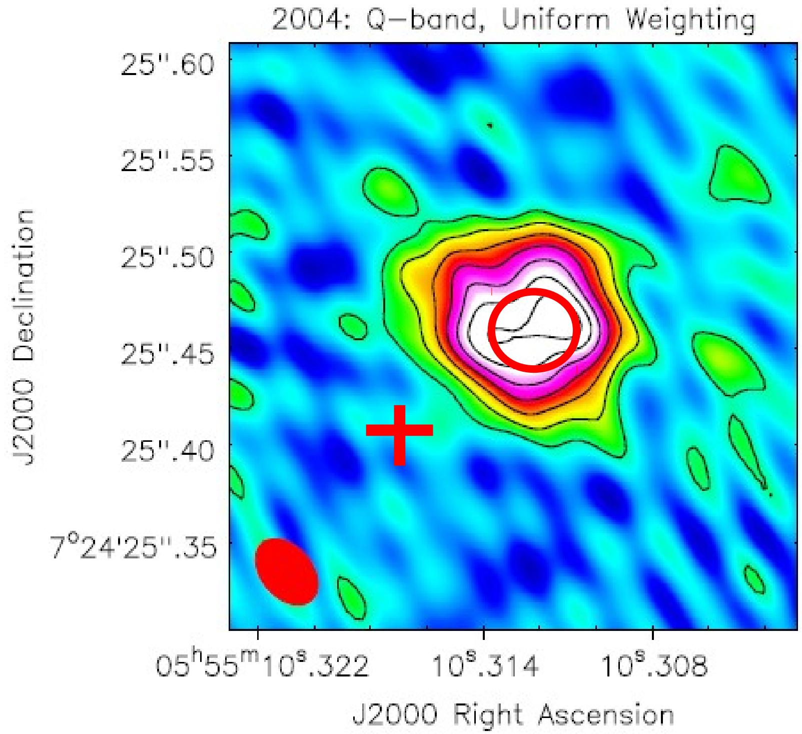
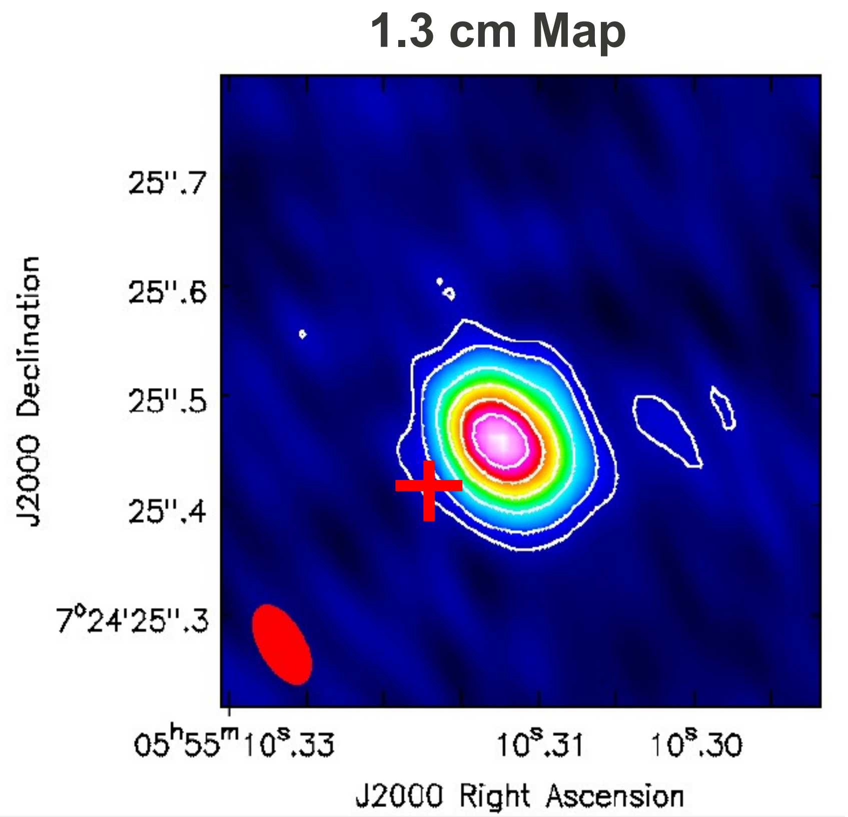
Thermal Profile



Q band (0.7 cm)



Betelgeuse with VLA – Pie Town

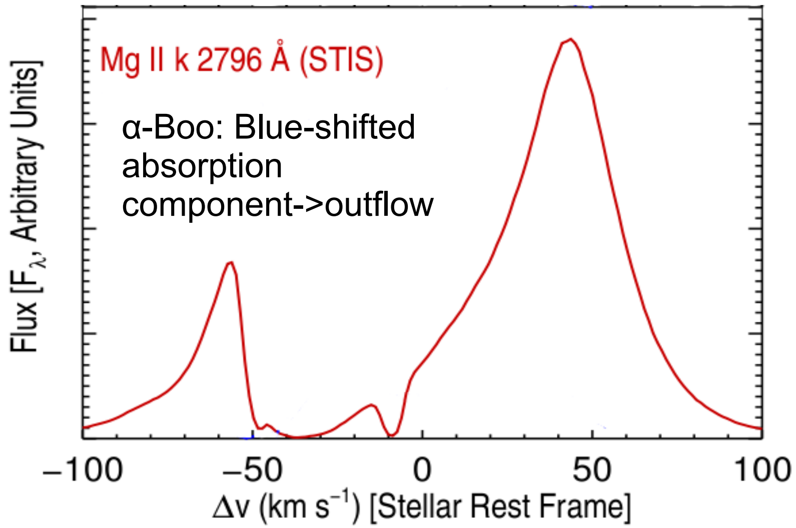


- **No clear signature of hot spots any in any maps.**
  - Time dependence?
  - Opacity?

Conclusions

- e-MERLIN has revealed two unresolved *hotspots* separated by 4 R_*
- One may be at the position of photosphere
- VLA + Pie Town data in good agreement with Lim *et al.* (1998)
- No clear signature of e-MERLIN hotspots in any of the VLA + Pie Town data

2) Winds of Red Giants



- Atmospheres cannot be spatially resolved at radio wavelengths.
- Wind properties generally traditionally determined by analysing strong UV and optical resonance lines.
- At cm/mm the thermal continuum Planck function depends linearly on T, unlike the UV.
- Continuum flux measurements at cm/mm: opacity is proportional to ~ $\lambda^{2.1} n_e n_{ion}$.

Goal: *Observe two 'standard' red giants at all possible cm wavelengths to test and improve existing models.*

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}

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

Karl G. Jansky Very Large Array

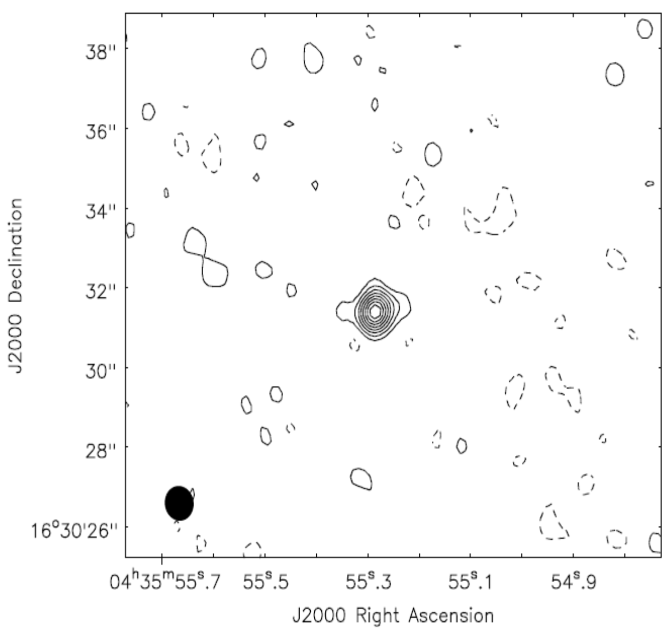
Credit: NRAO

- Full frequency coverage between 1.0 and 50 GHz
- Observations:
  - B config (128 MHz bandwidth)
  - S → Q band (13th - 22nd Feb 2011)
  - A unique data set

Red Giant Radio Maps

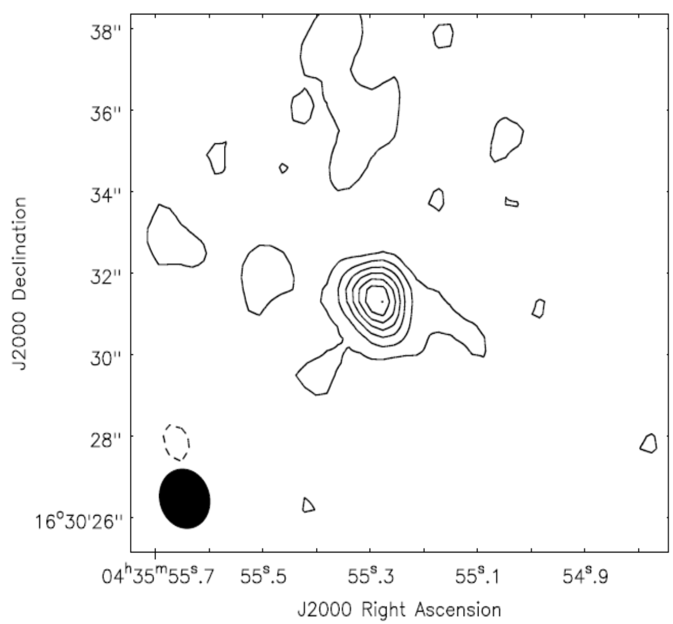
Example: Aldebaran X (3 cm), C (6 cm), and S (10 cm) band

X-band (8 GHz)
S_ν = 0.3 mJy



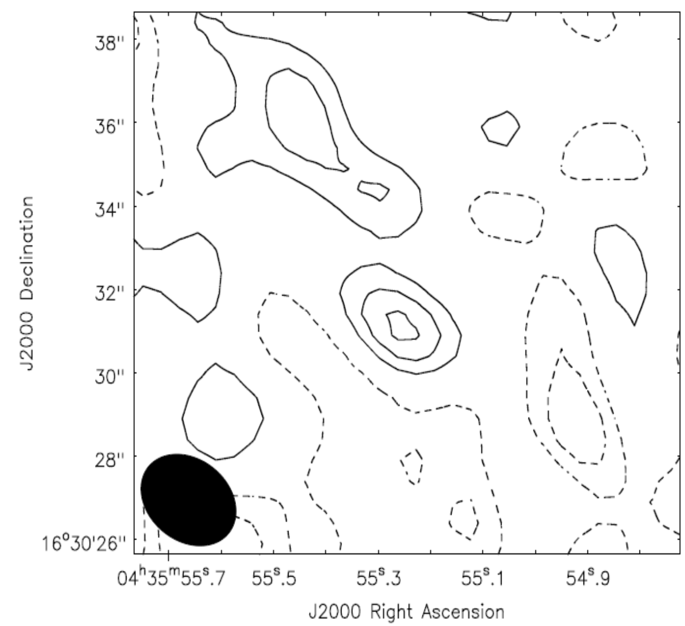
Contours = (-2,2,4......16)xσ
σ = 16 μJy

C-band (5 GHz)
S_ν = 0.15 mJy



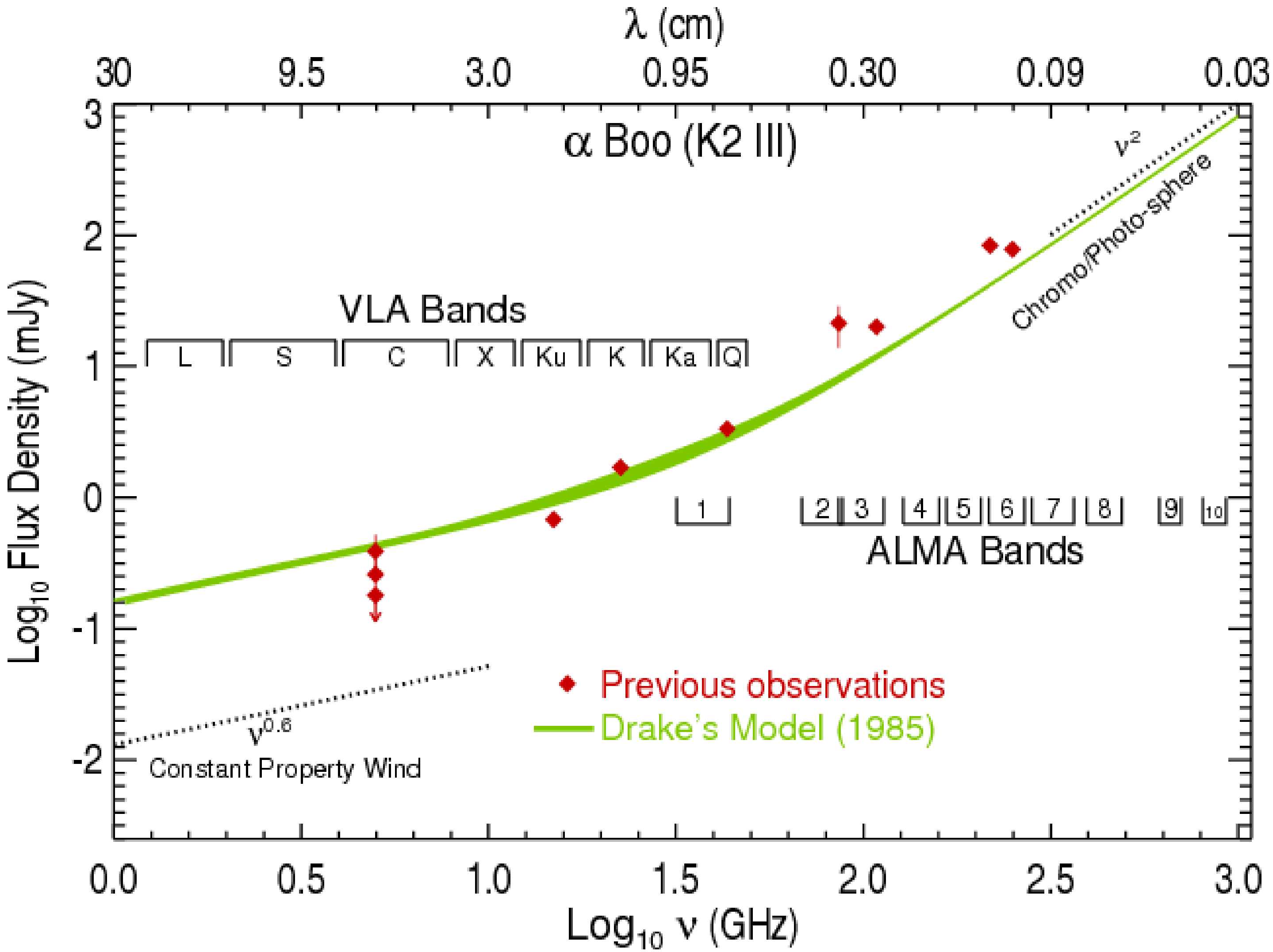
Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

S-band (3 GHz)
S_ν = 0.06 mJy

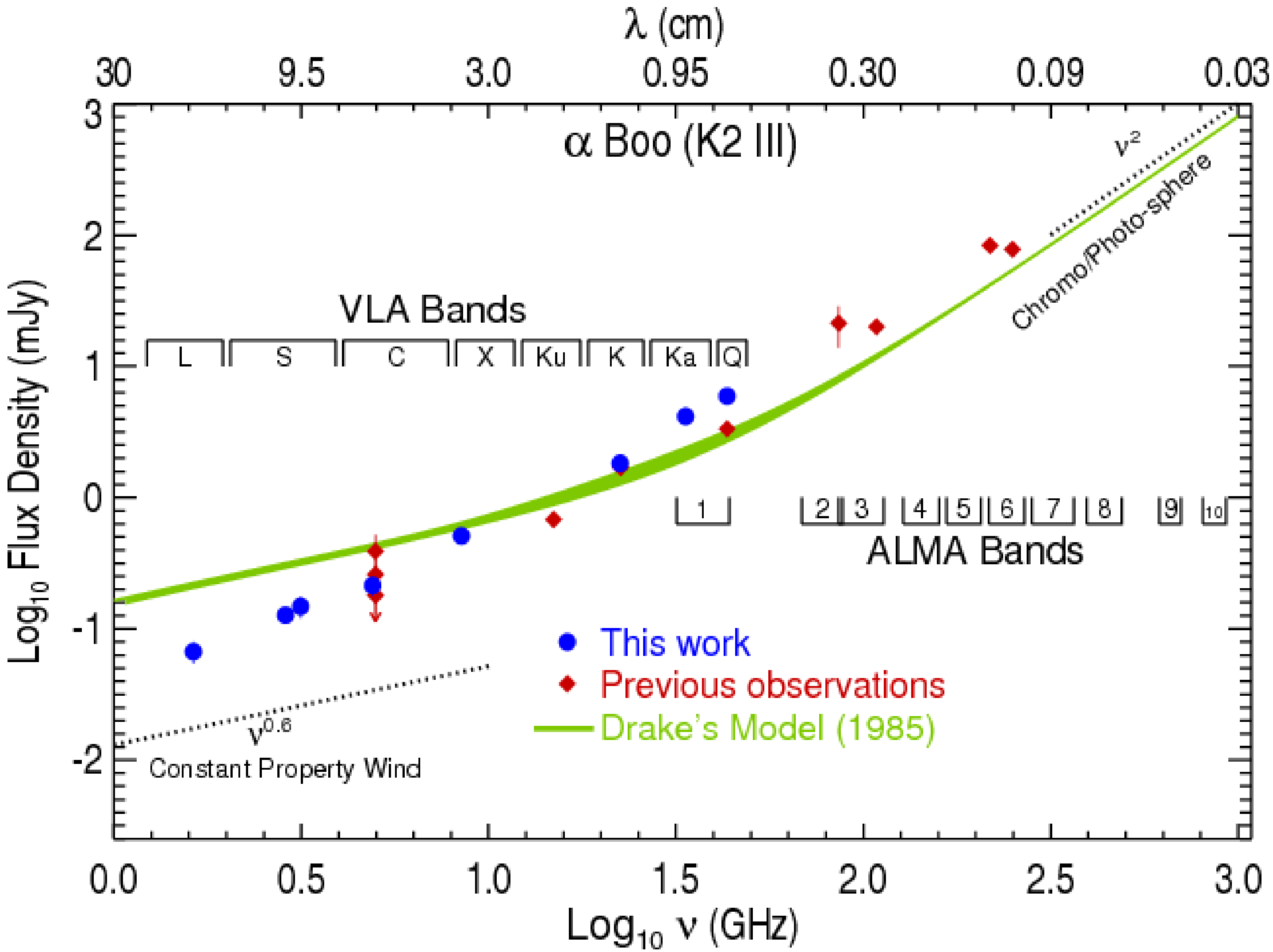


Contours = (-3,-2,-1,1,2,3)xσ
σ = 18 μJy

Spectral Energy Distribution – α Boo

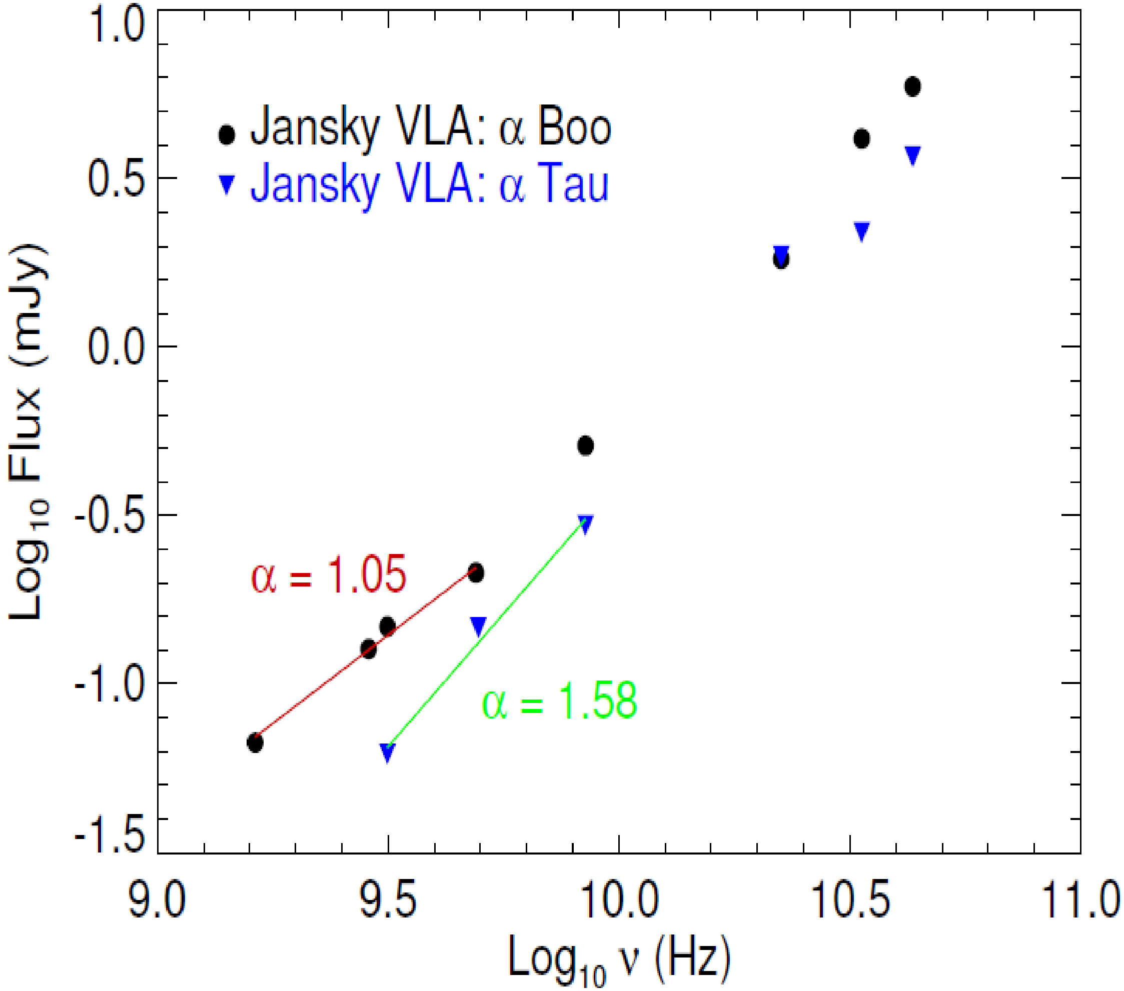


Spectral Energy Distribution – α Boo



Spectral Indices

$$F_\nu \propto \nu^\alpha$$



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

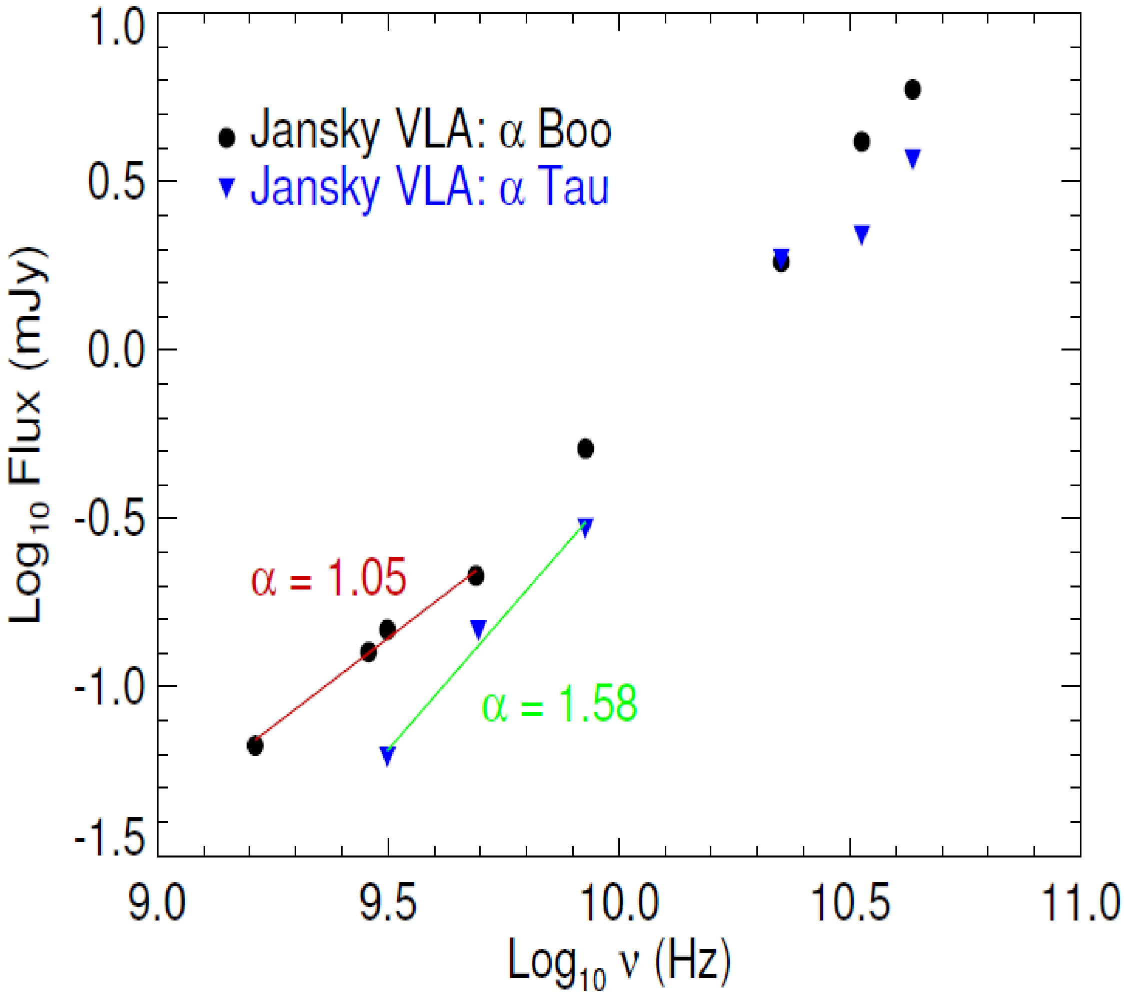
  $T_e \propto r^{-n}$

  then,

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

Spectral Indices

$$F_\nu \propto \nu^\alpha$$



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

  $T_e \propto r^{-n}$

  then,

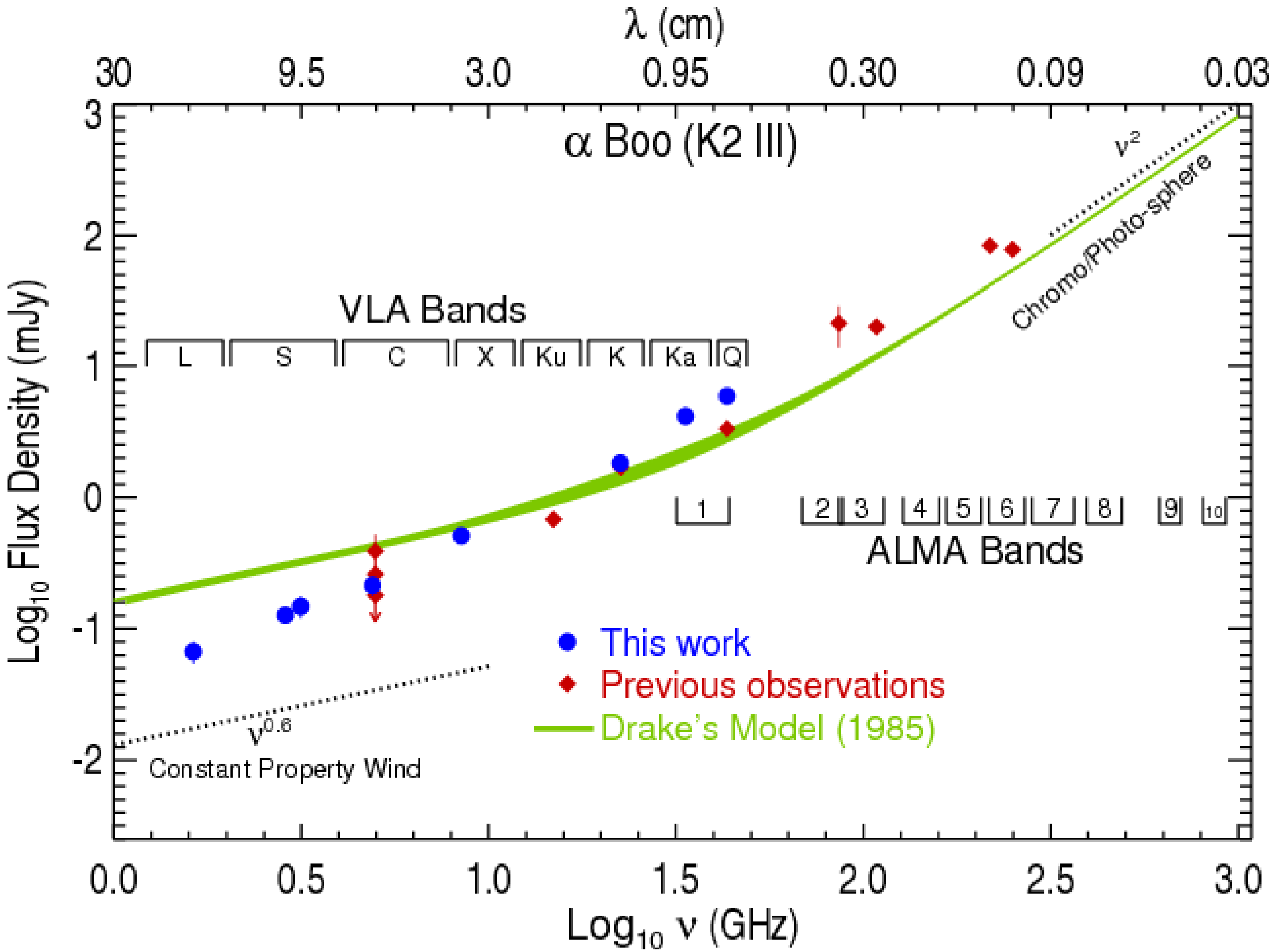
$$\alpha = f(p, n)$$

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

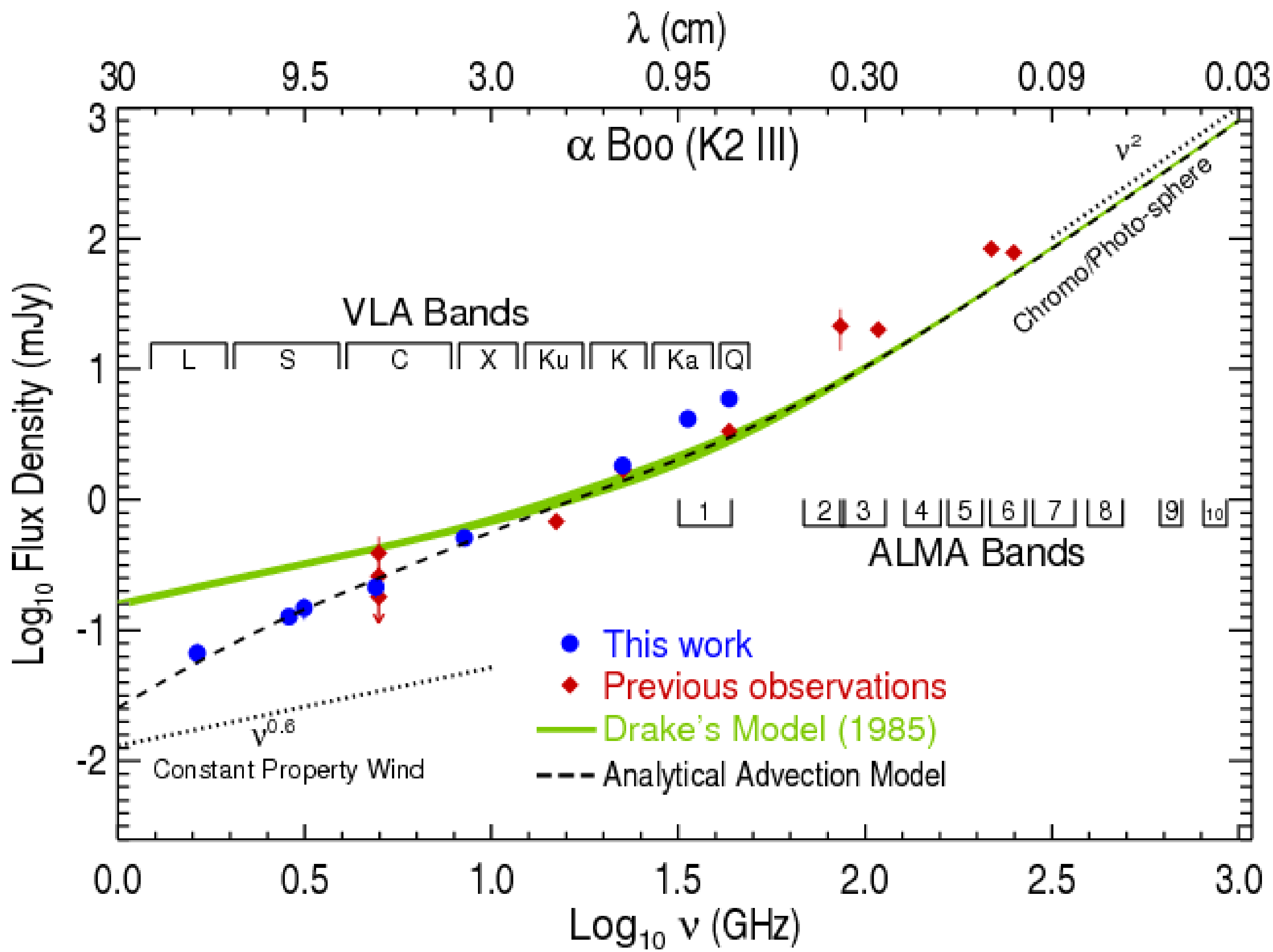
Assume constant velocity wind,

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

Spectral Energy Distribution – α Boo



Spectral Energy Distribution – α Boo



2) Conclusions

- Most comprehensive set of multi-λ radio observations of two *standard* red giants.
- Tested 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.
- New analytical advection wind model for α Boo.

Summary

- Established spatial scales for the two flows in CSE of Betelgeuse
- e-MERLIN results are surprising. Episodic mass-loss mechanism in RSGs?
- 1st multi-wavelength radio study of red giants
- Provide wind diagnostics and updated outflow models.
- Understanding of mass-loss is improving and radio interferometry will continue to play a major role in future developments.