Radio Interferometric Studies of Cool Evolved Stellar Winds

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Trinity College Dublin
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Supervisor: Prof. Graham Harper

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

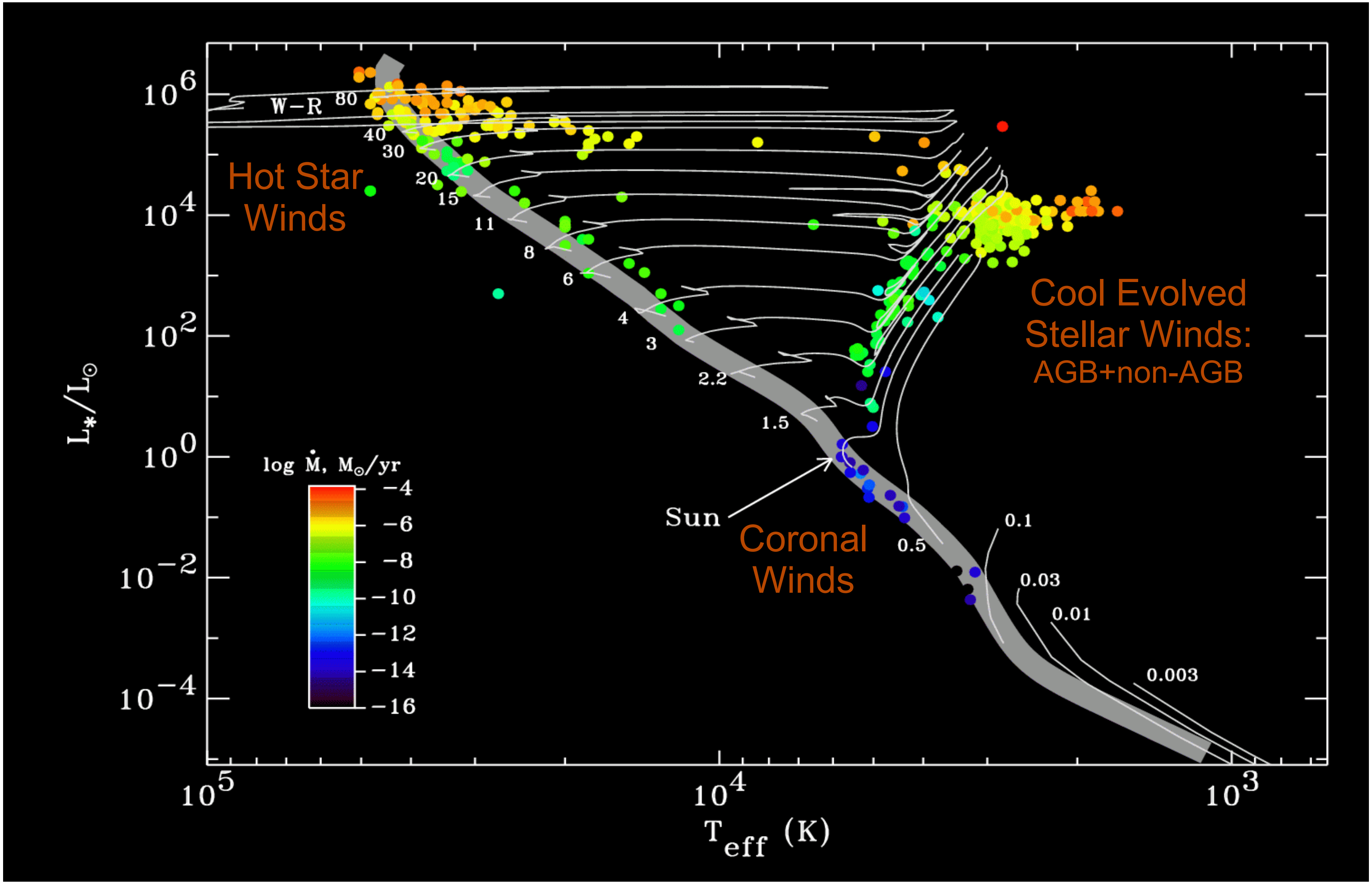

Image Credit: S. R. Cranmer

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	~ 5×10^5
dM/dt ($M_\odot$ yr^{-1})	~ 10^{-10}	~ 10^{-5}

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$$\underbrace{\qquad\qquad}$$

- $H_P/R_* \sim 10^{-2}$
- $V_\infty < V_{escape}(R_*)$
- $T_{wind} < 10^4$ K

Red Supergiants & Red Giants

- No coronae
- Radiation field peaks in the IR
- Small pulsation amplitudes and little dust
- Unknown mass-loss mechanism

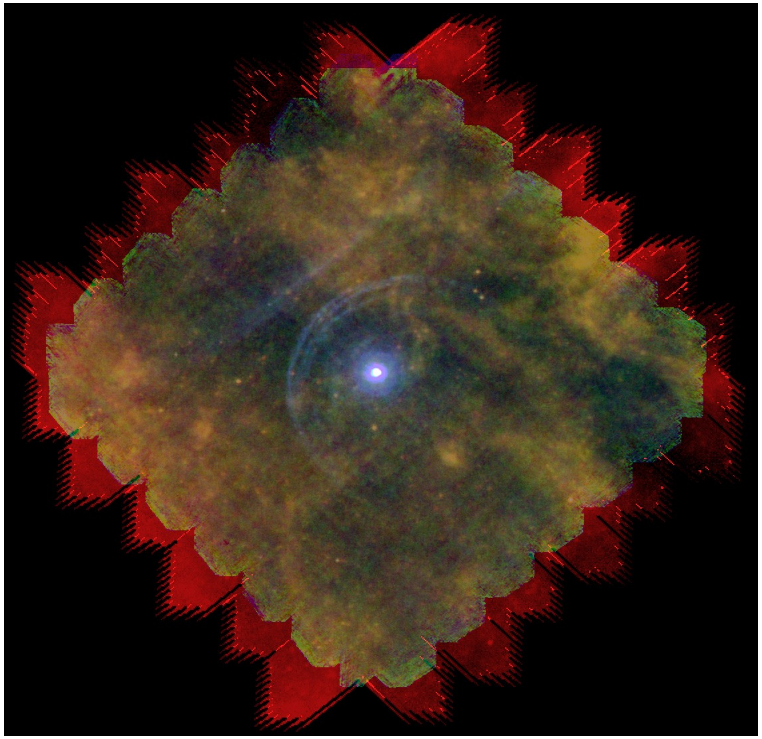

Image Credit: L. Decin

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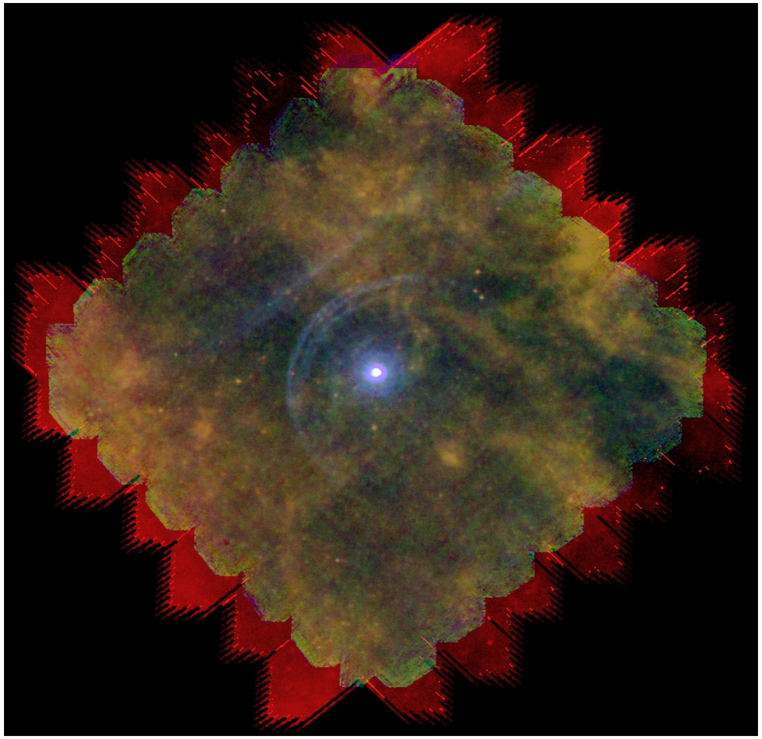
  r, v(r), T(r)
  - Disk averaged observations
  - No wind emission features at UV or optical λ.



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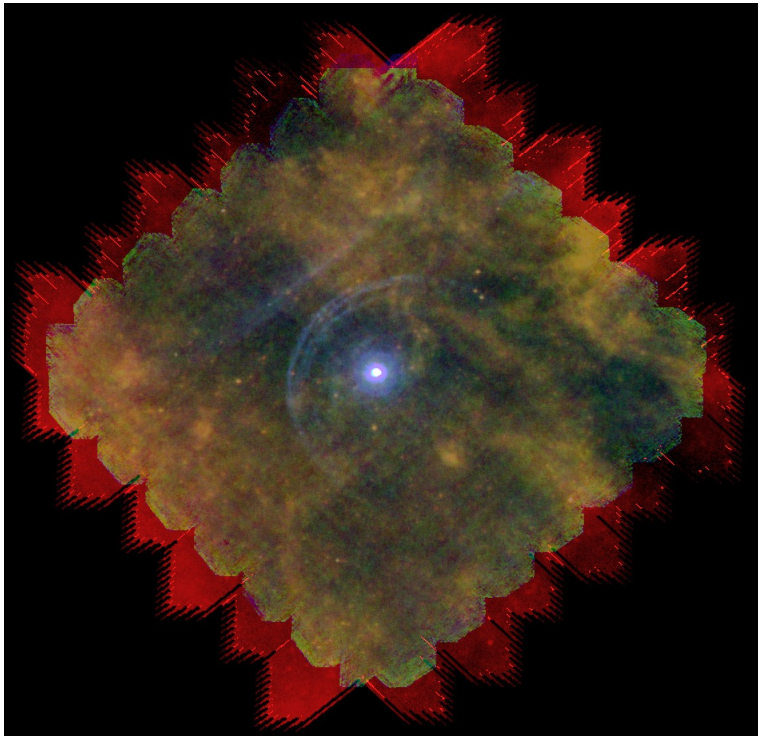

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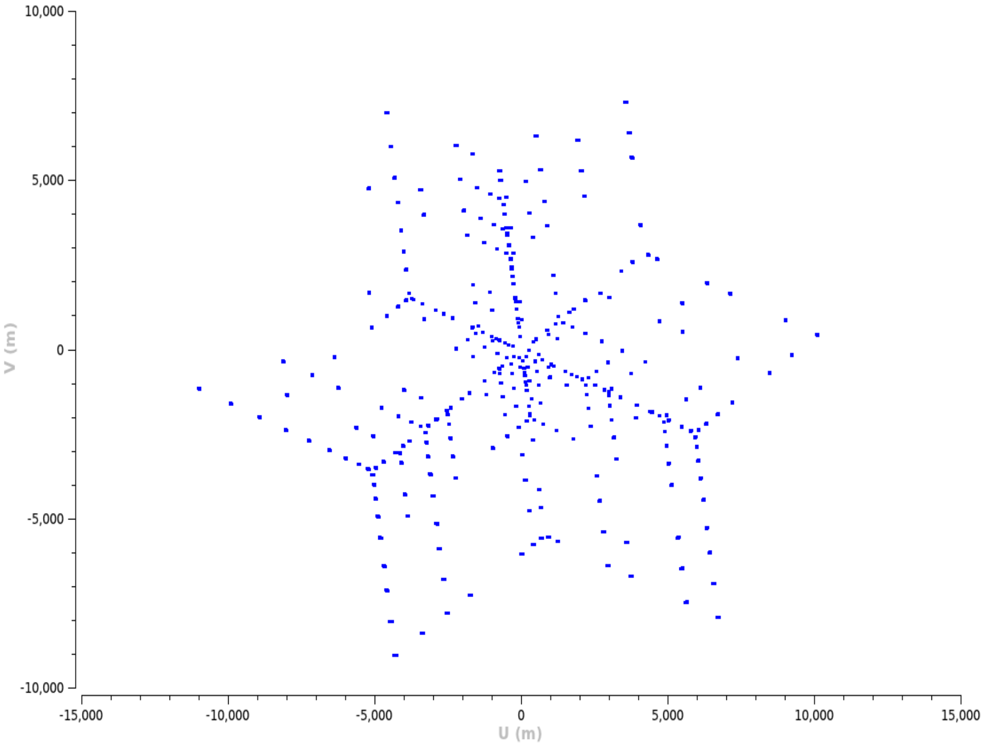
Thesis Goal: Improve understanding of outflow conditions to gain insight into mass-loss mechanism. → Radio

Aperture Synthesis



- No need to measure all the incoming rays at one time.
- Break aperture into N sub-apertures: N(N-1)/2 pairs
- FT of each measurement is a sinusoid with spacing λ/B between successive peaks.
- Build up image of sky by summing many such sinusoids.

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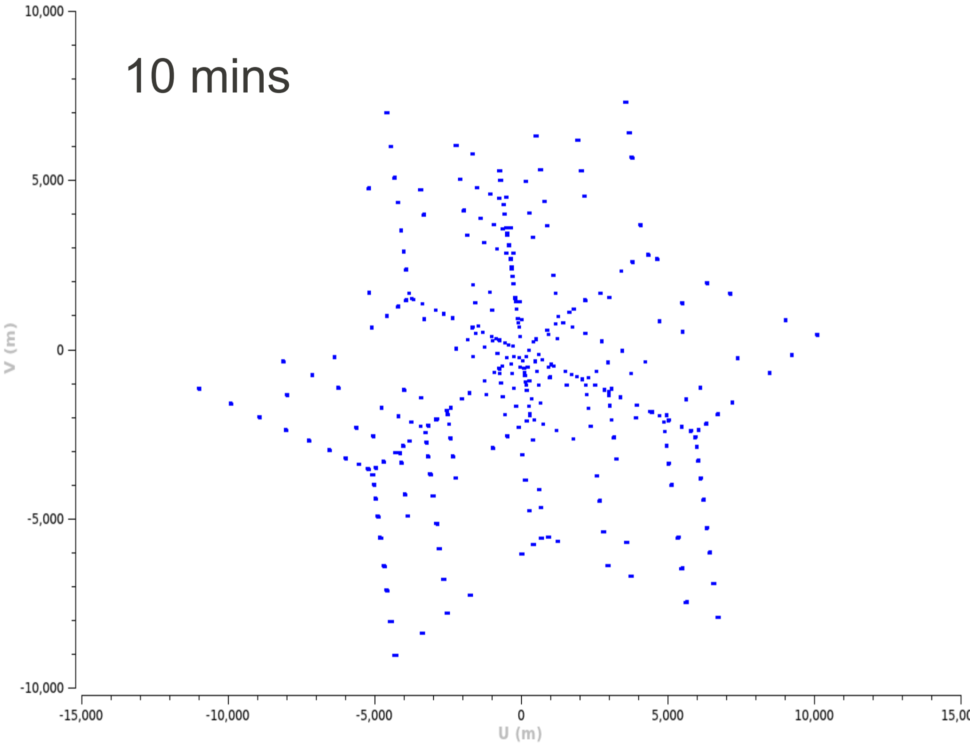

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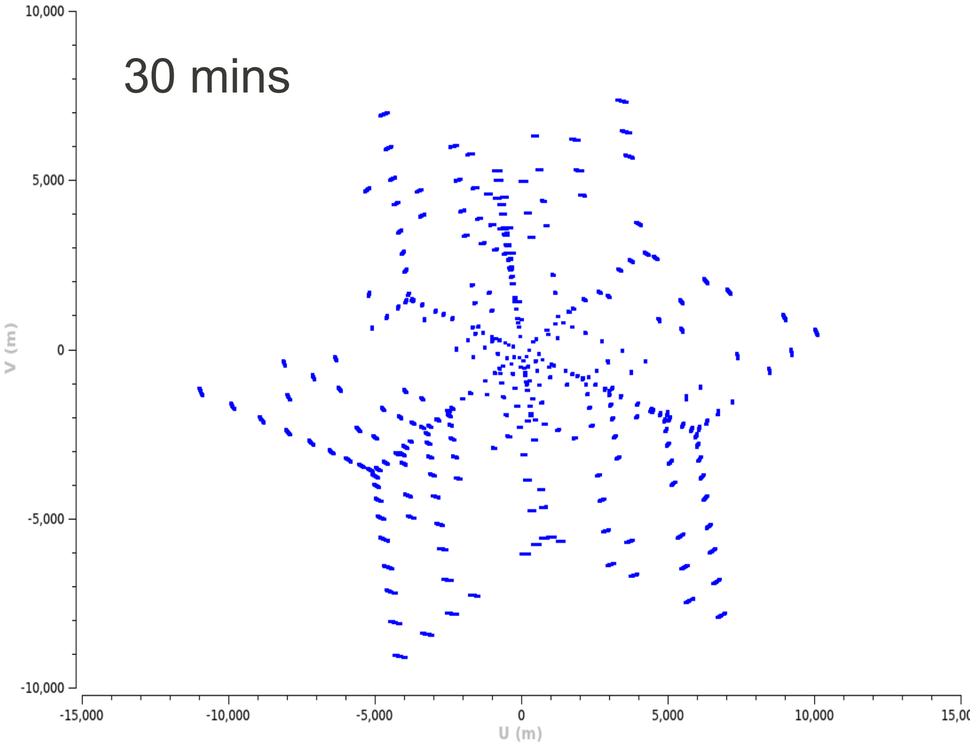

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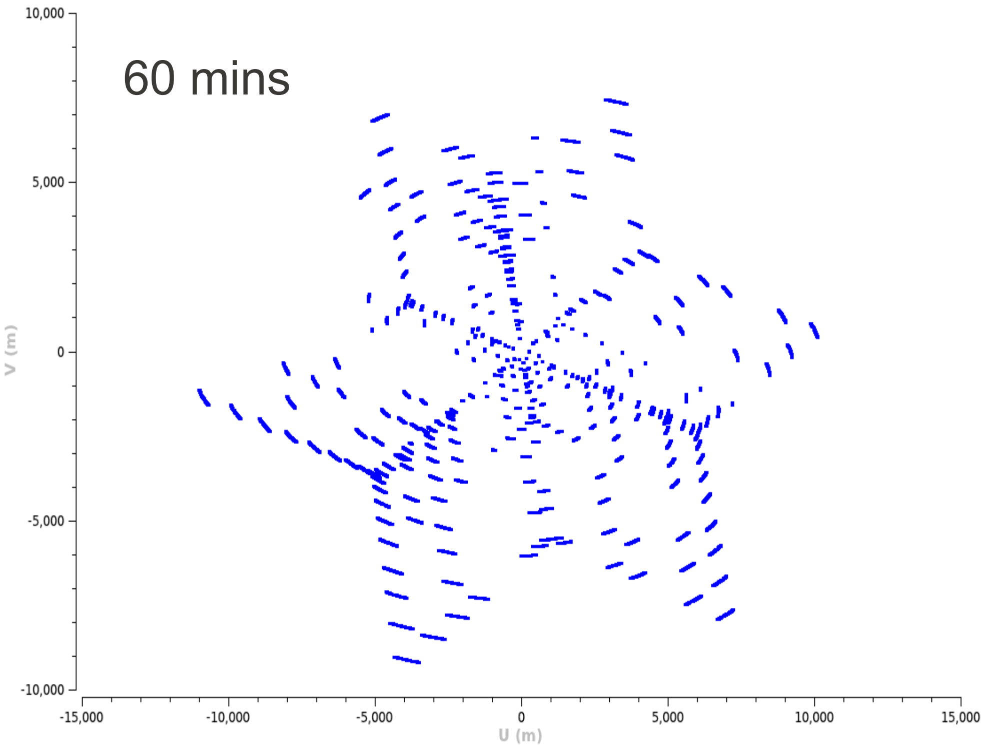

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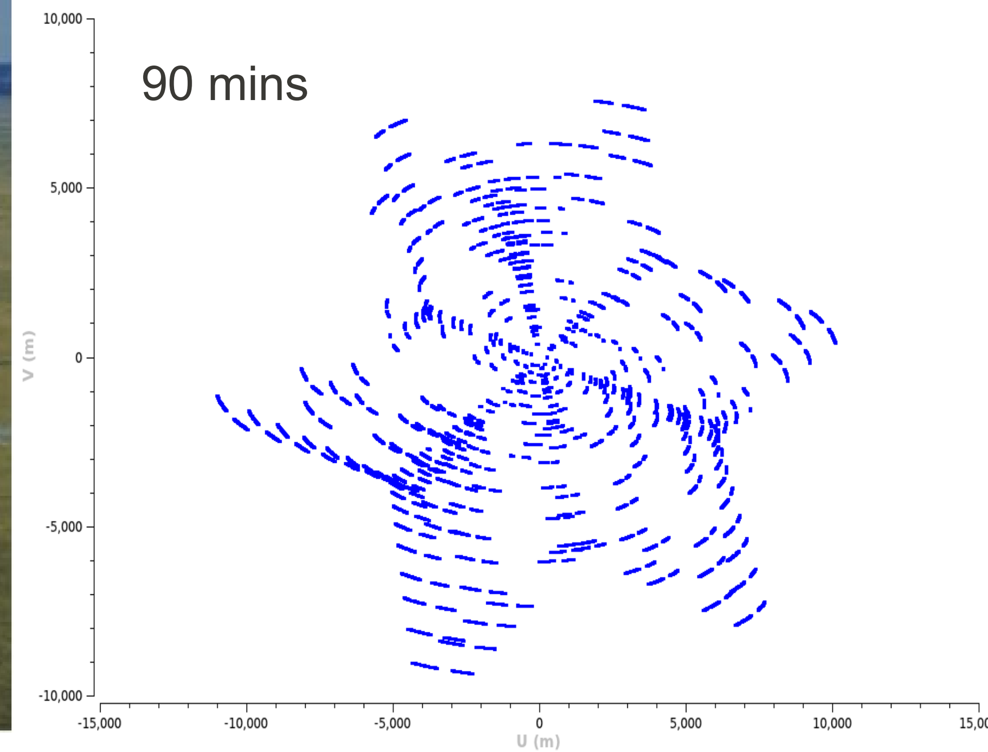

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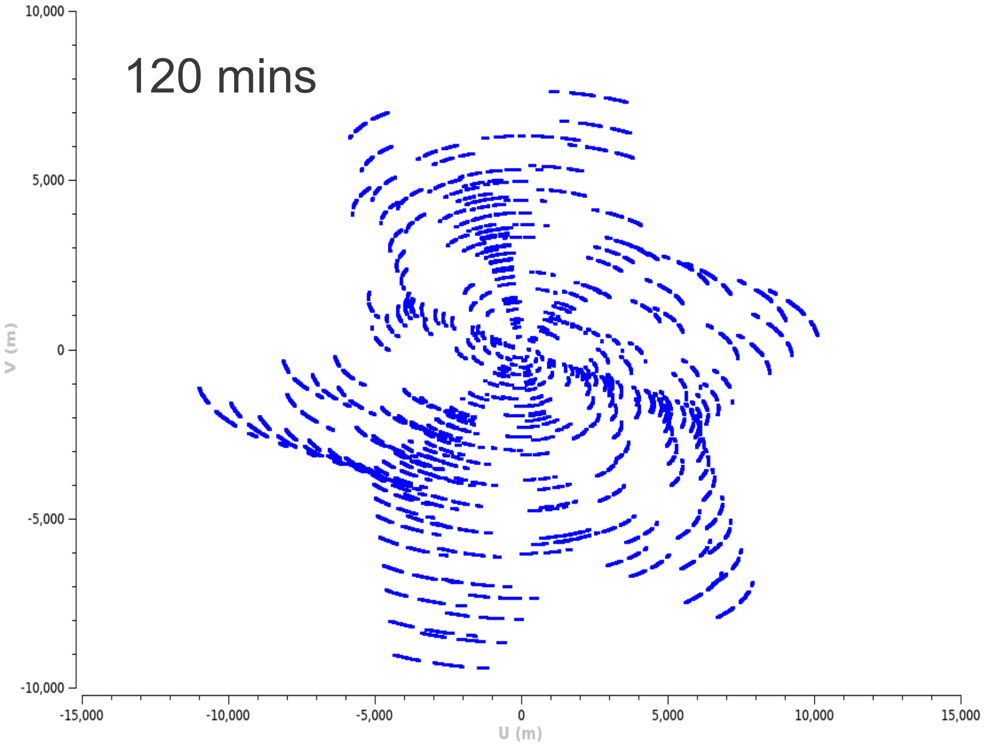

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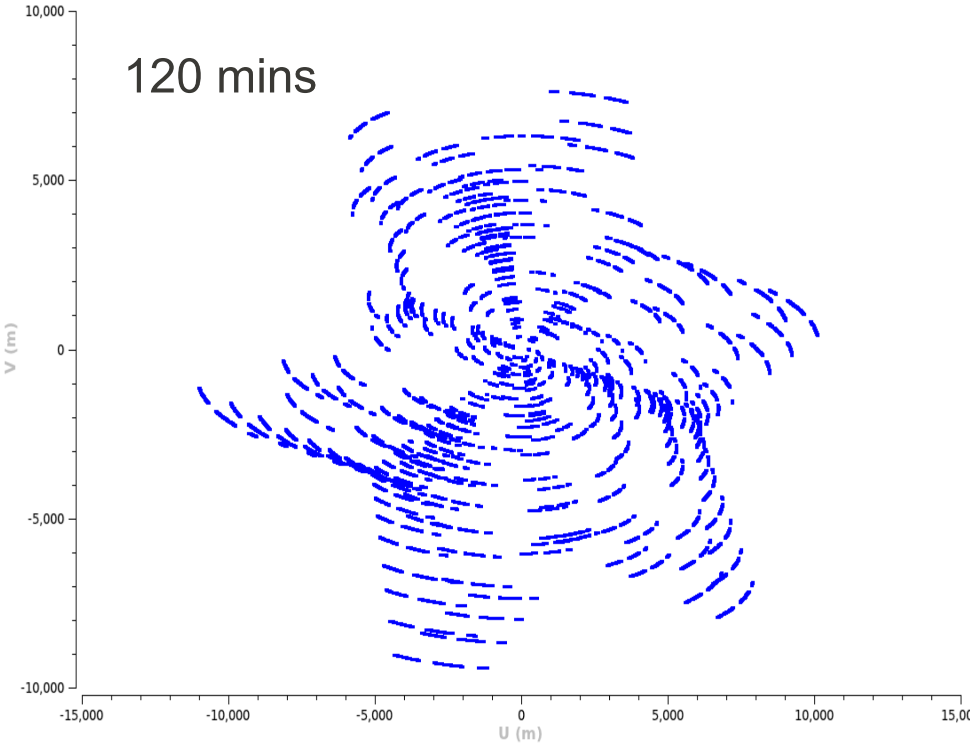

1) Field of View: λ/D (D = antenna diameter)

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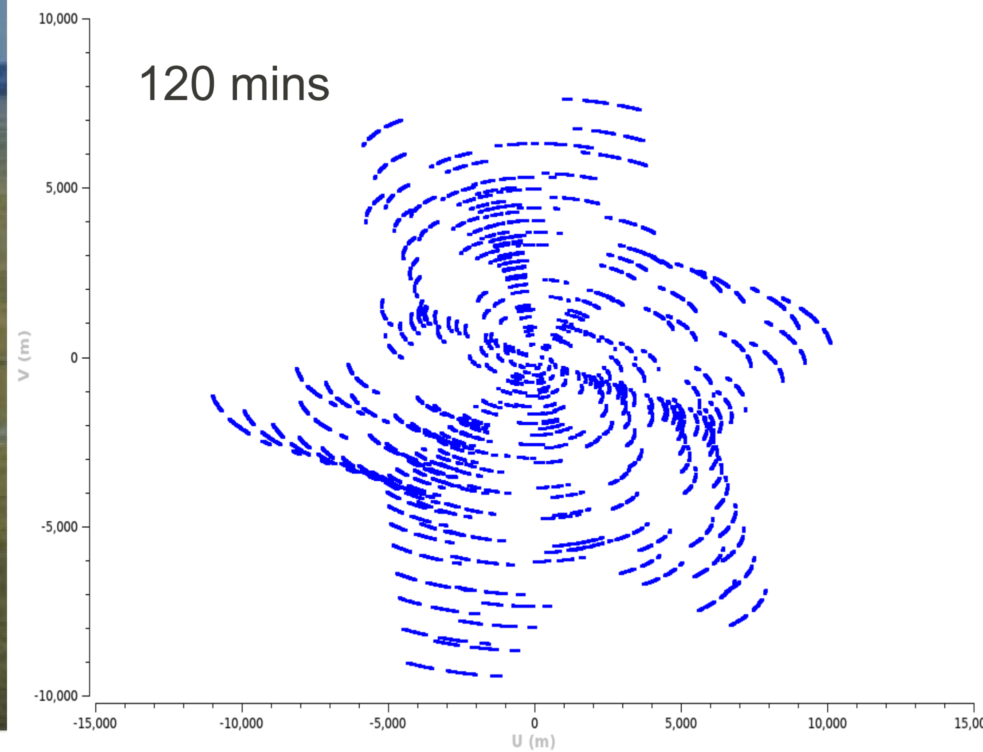

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2) Resolution: λ/B_{max} (B_{max} = longest projected baseline)

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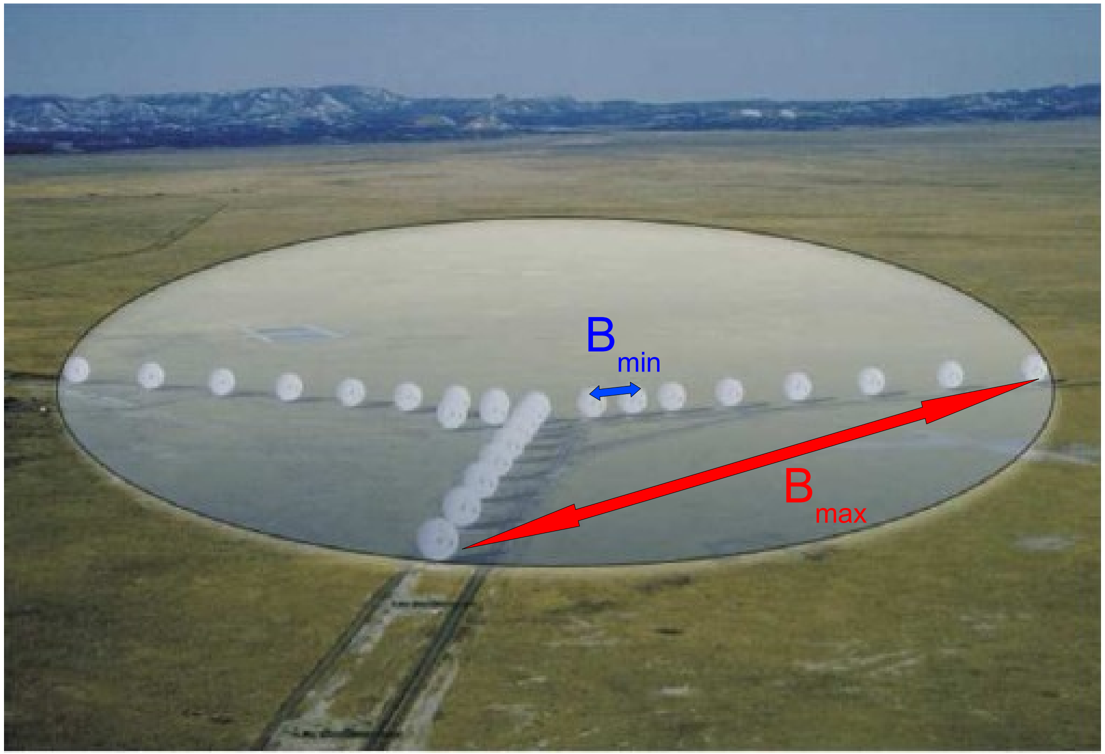

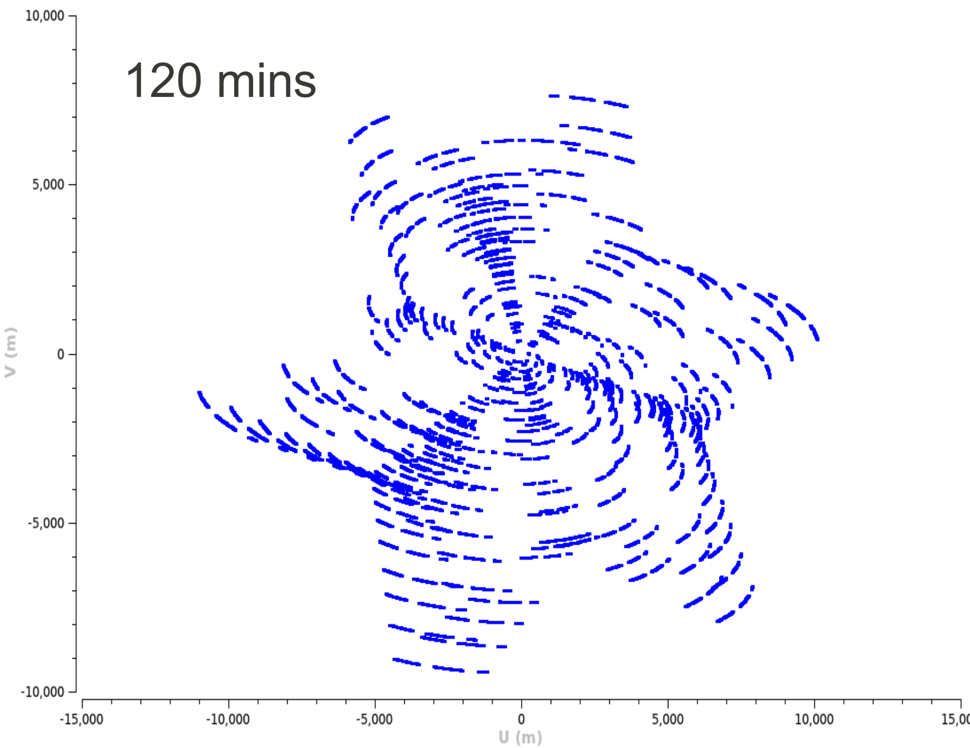

1) Field of View: λ/D (D = antenna diameter)

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

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

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

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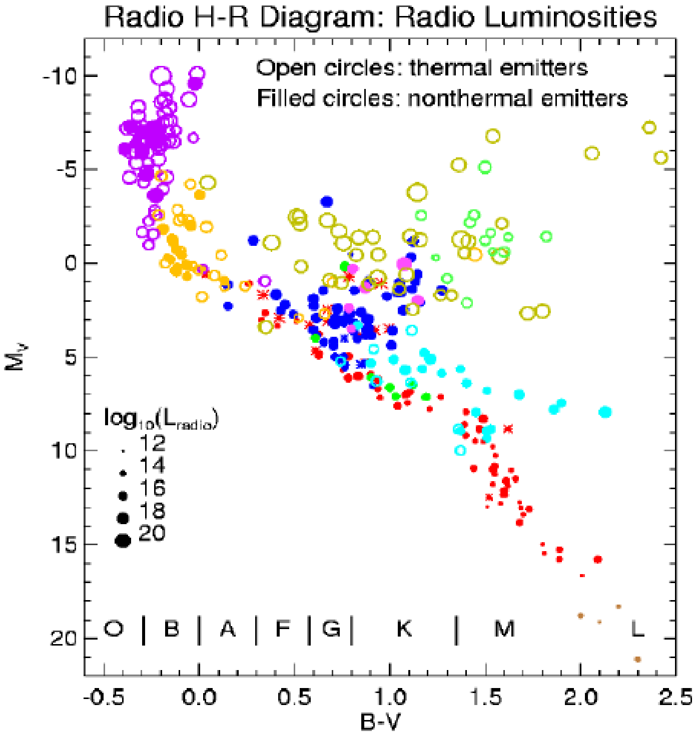
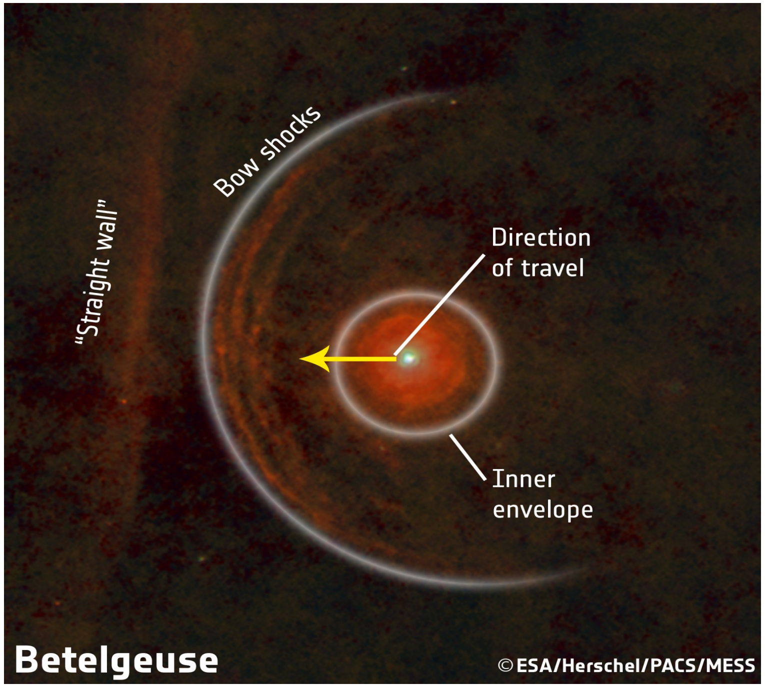


White (2000)

1) Winds of Red Supergiants

Betelgeuse (M2 Iab)

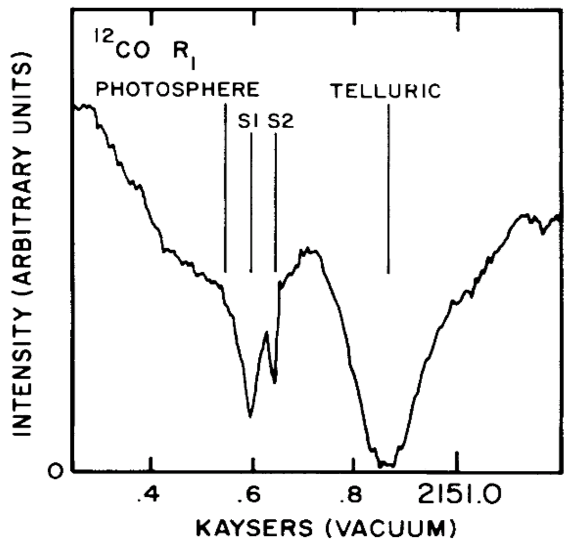


(Decin *et al.*, 2013)

$\log(L/L_\odot)$	5
Distance	197 ± 45 parsec
Photospheric Radius	22.5 mas (950 $R_\odot$)
Mass	~15 $M_\odot$
Mass loss rate	3×10^{-6} $M_\odot$ yr^{-1}
Photospheric Temperature	3,600 K (cool star)
Origin	O-type main sequence
$^{12}C/^{13}C$	6 ± 1

Betelgeuse: Circumstellar Environment

(Bernat *et al.*, 1979)



- At least two *recent* mass loss phases
- Two distinct shells spectrally resolved at 4.6 µm:
  - S2, moving at 17 km s^{-1}
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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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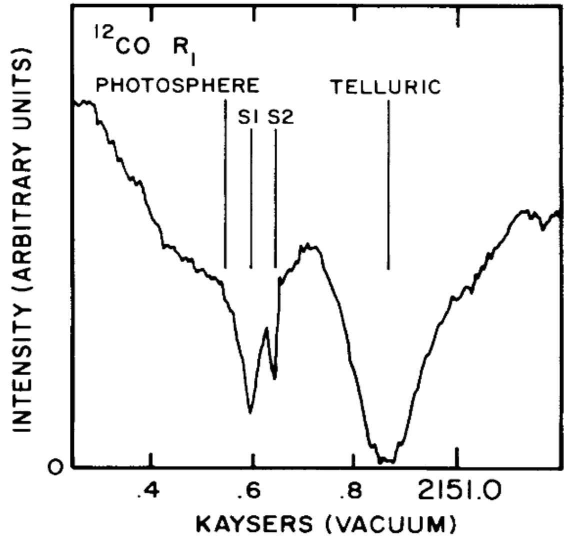

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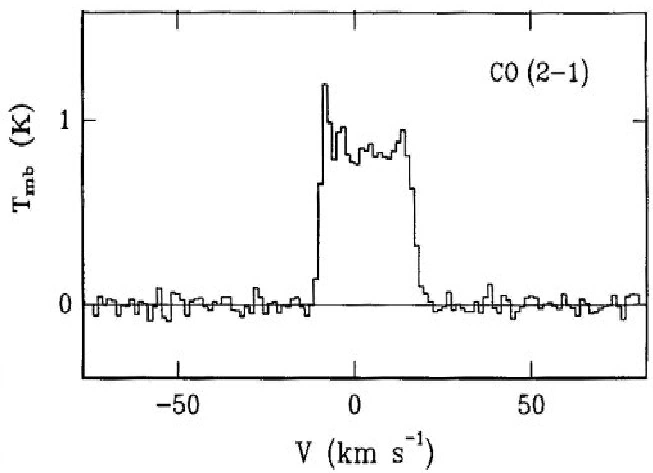

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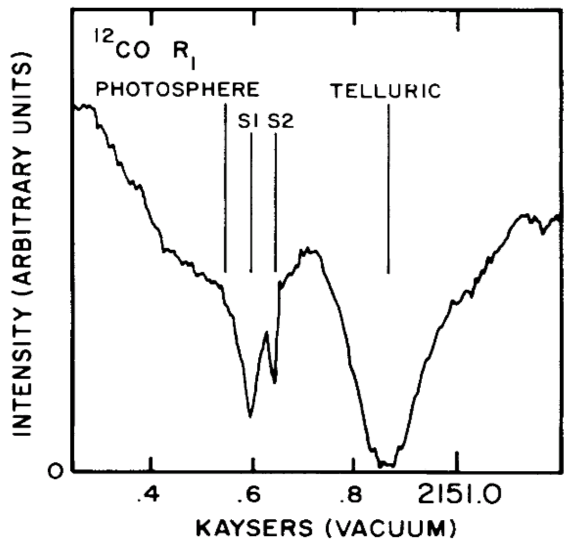
Goal: *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

(Bernat *et al.*, 1979)



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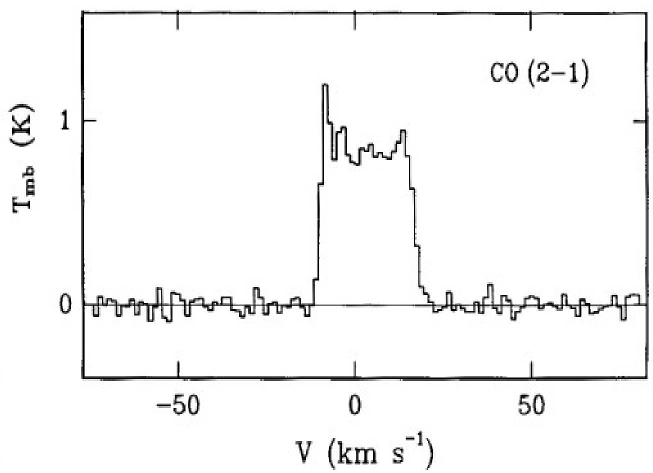


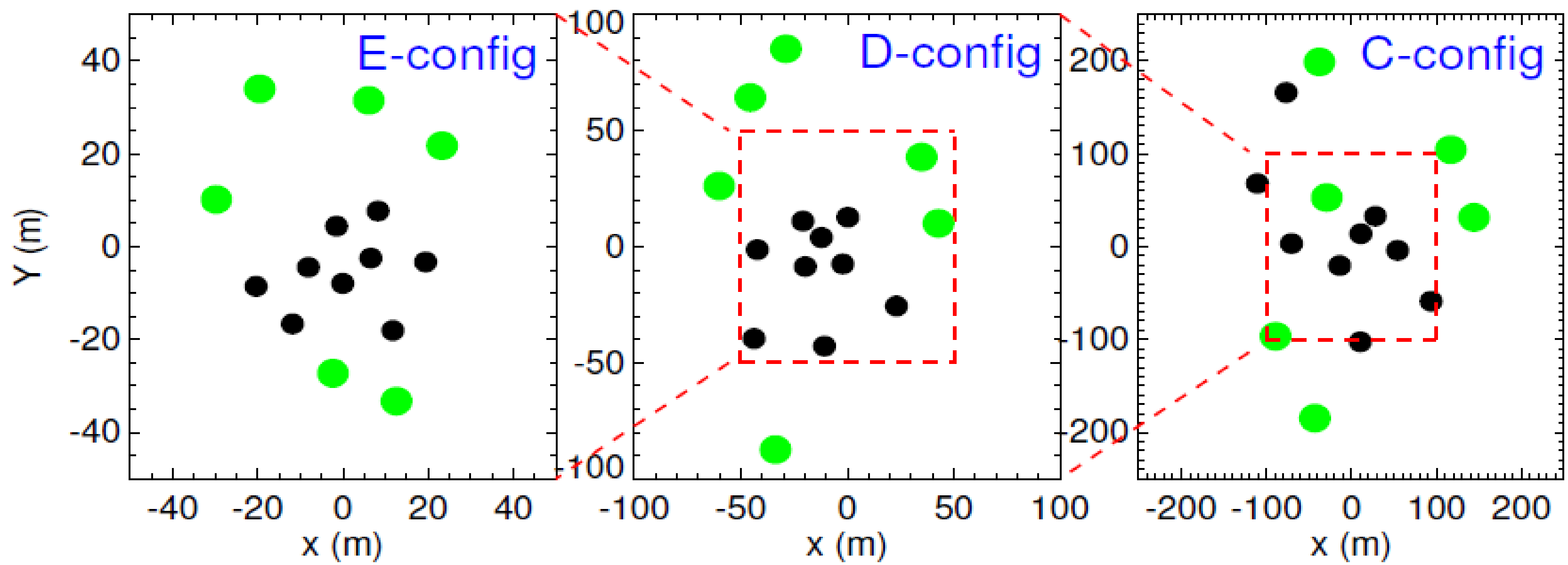
CARMA

- **C**ombined **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy
- 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

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

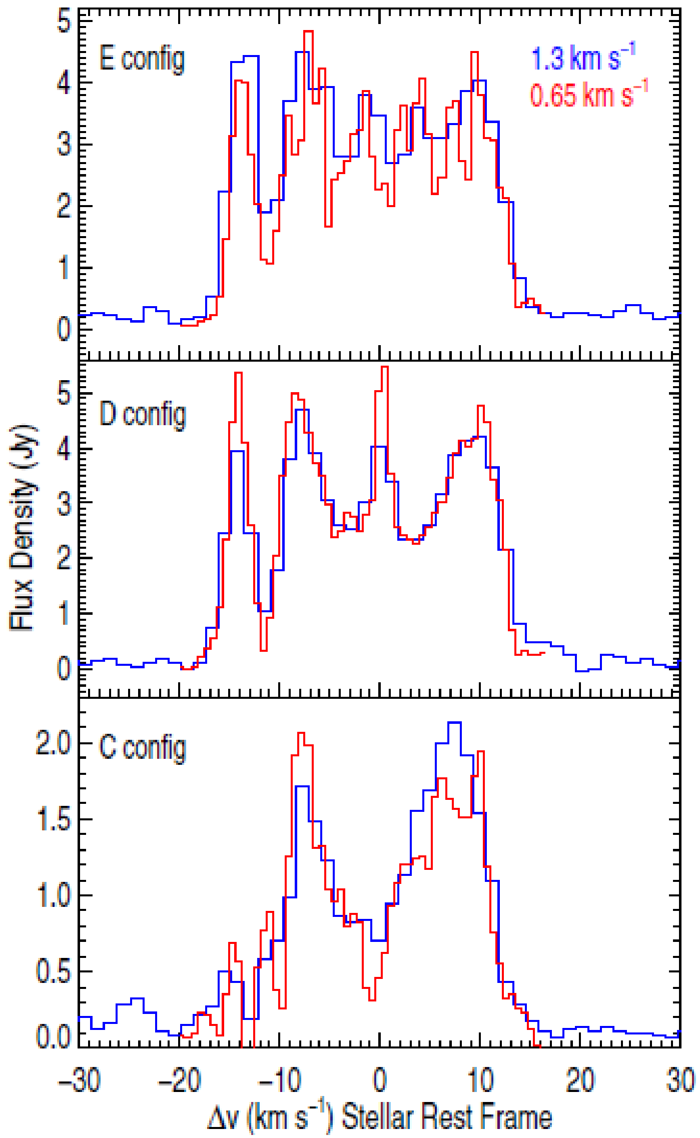


B_{min} = 8 m, B_{max} = 66 m

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

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

Individual Configurations



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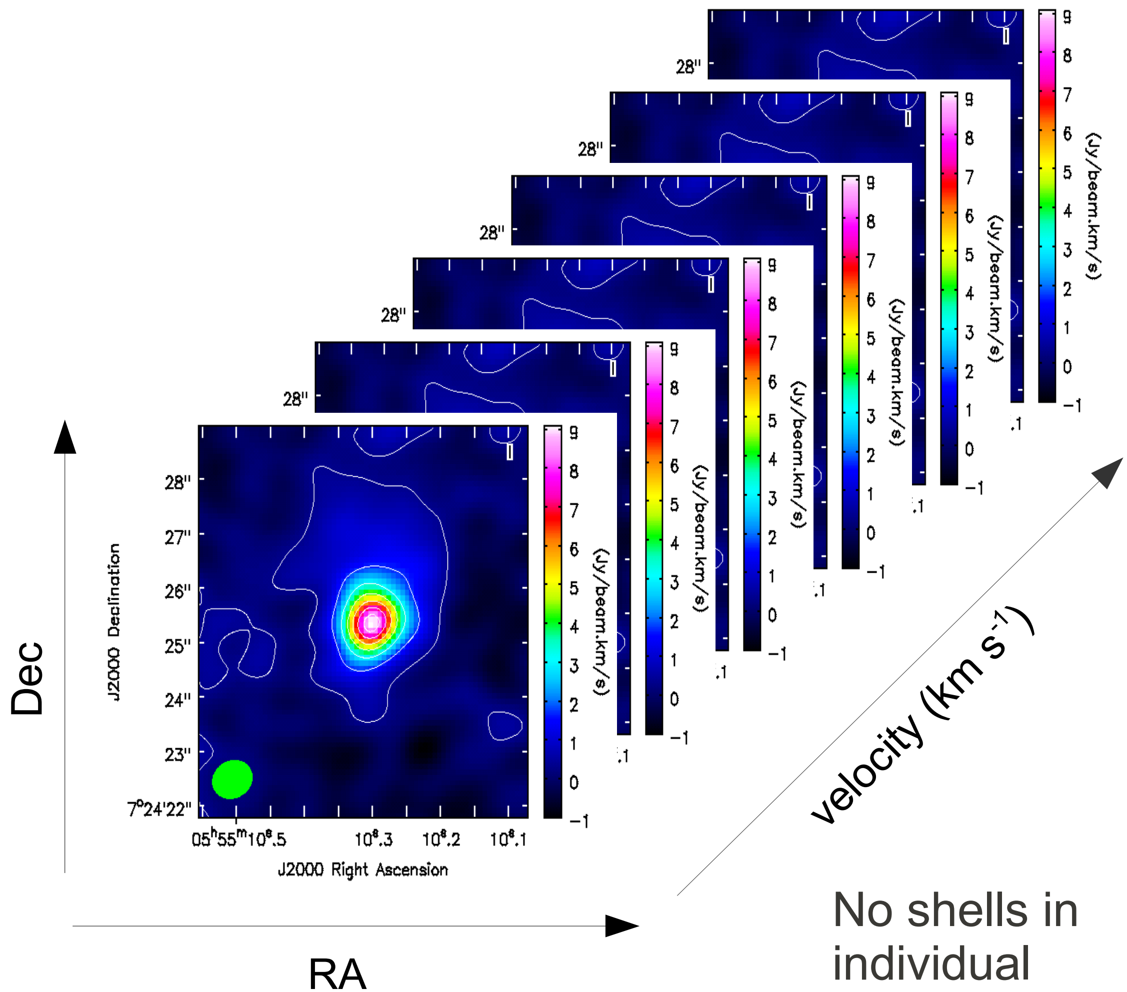
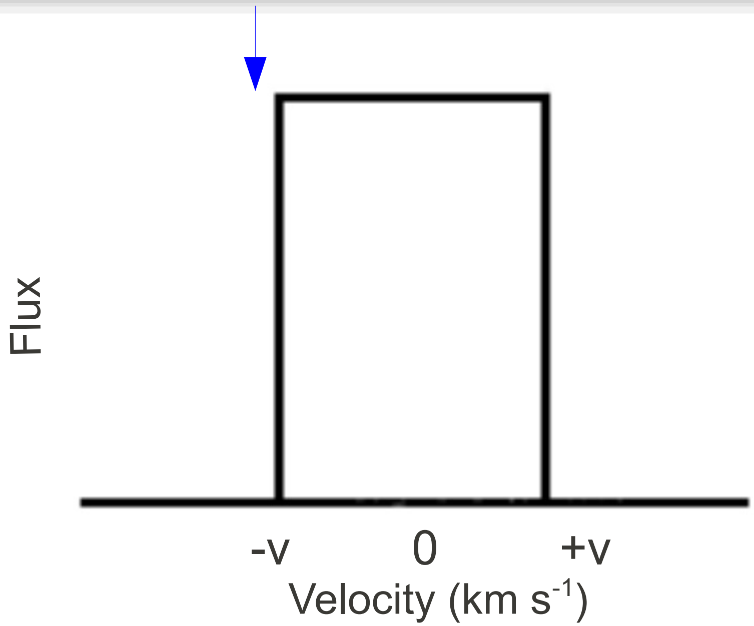
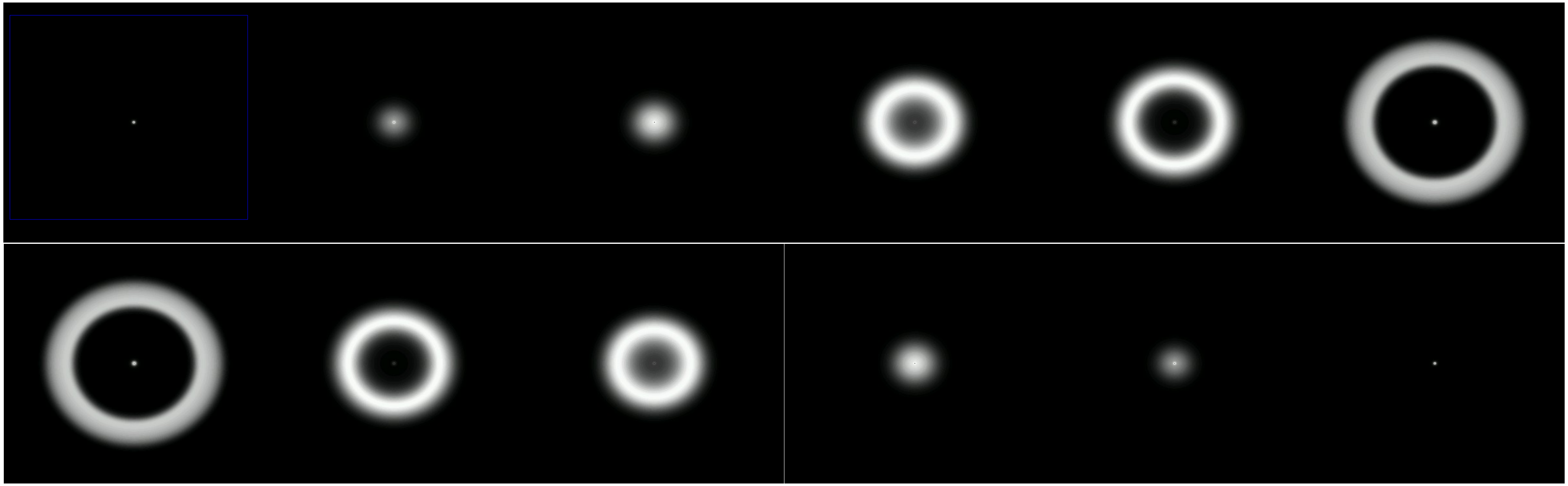


No shells in individual configuration image cubes.

Spherically Symmetric Shell





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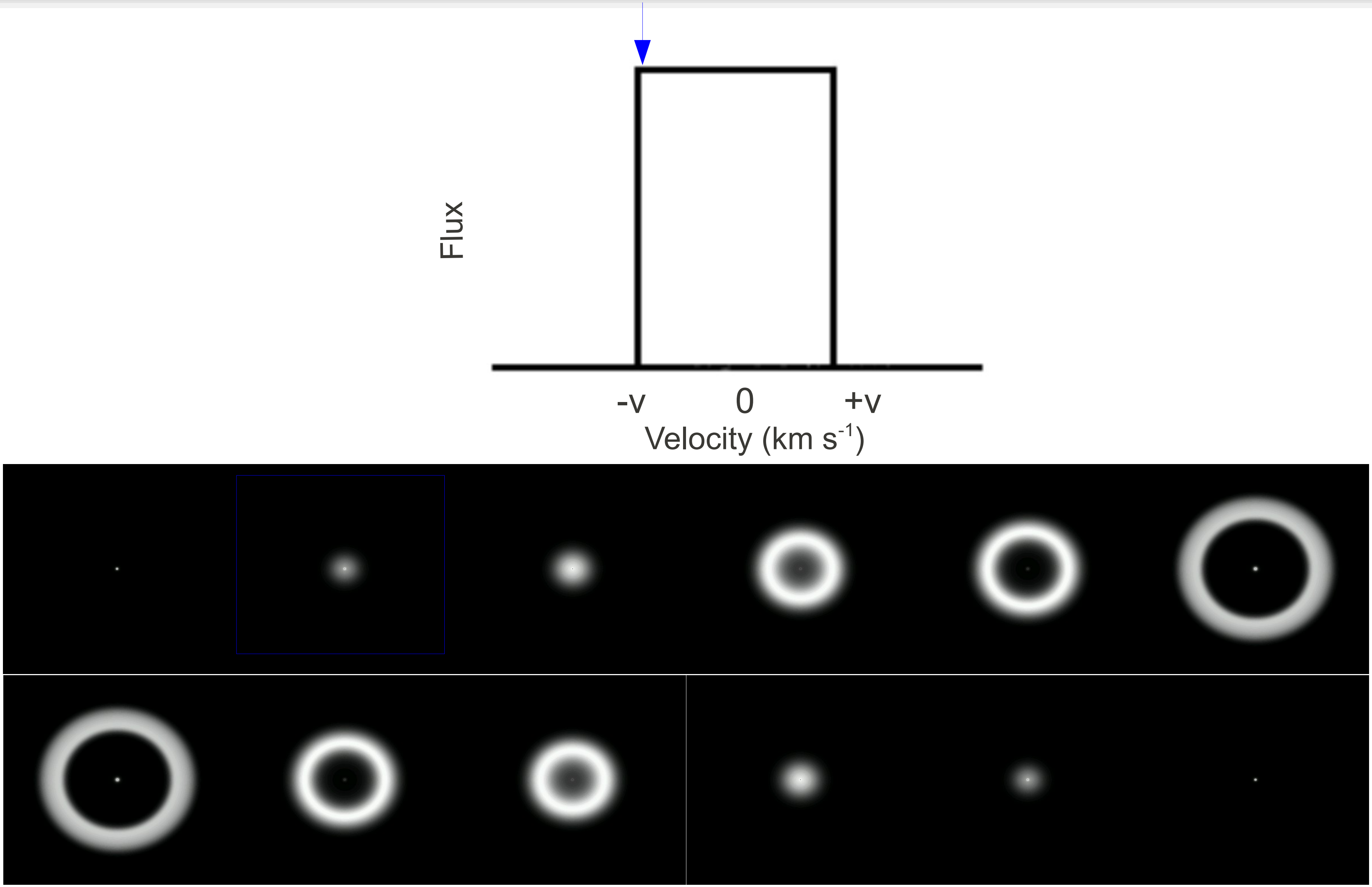

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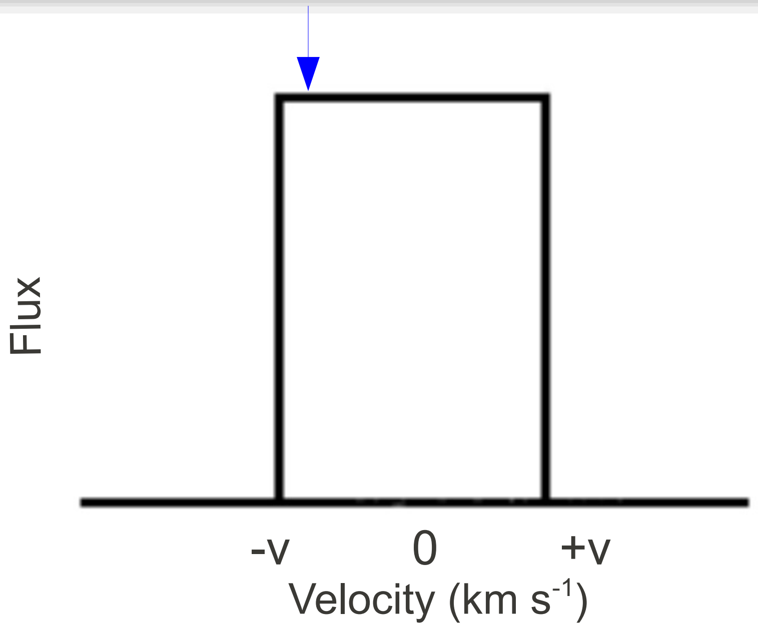

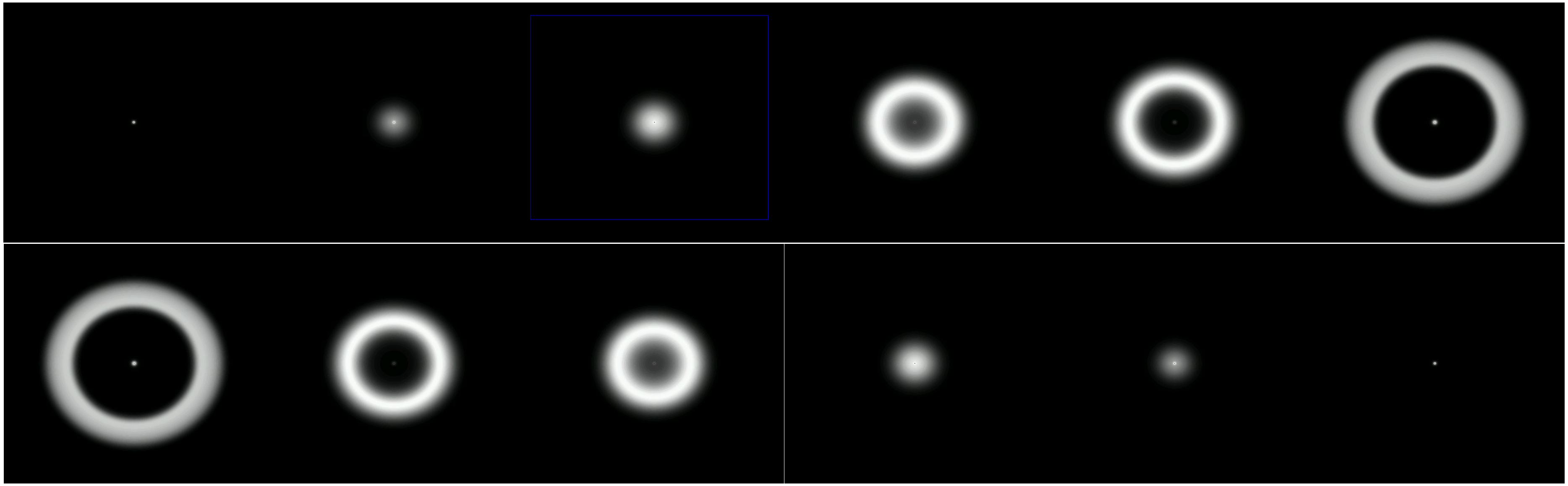

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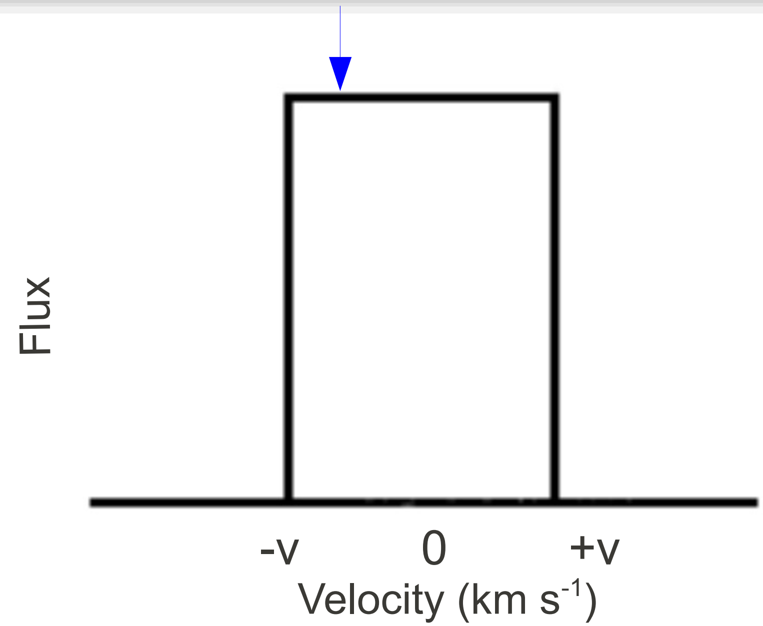

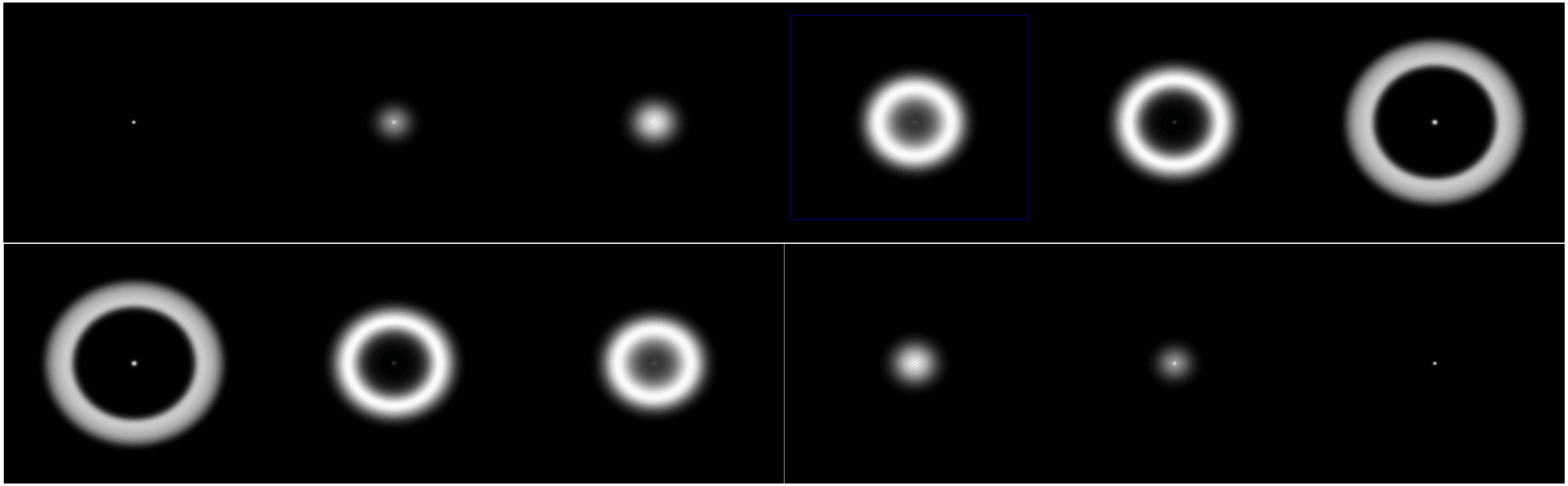

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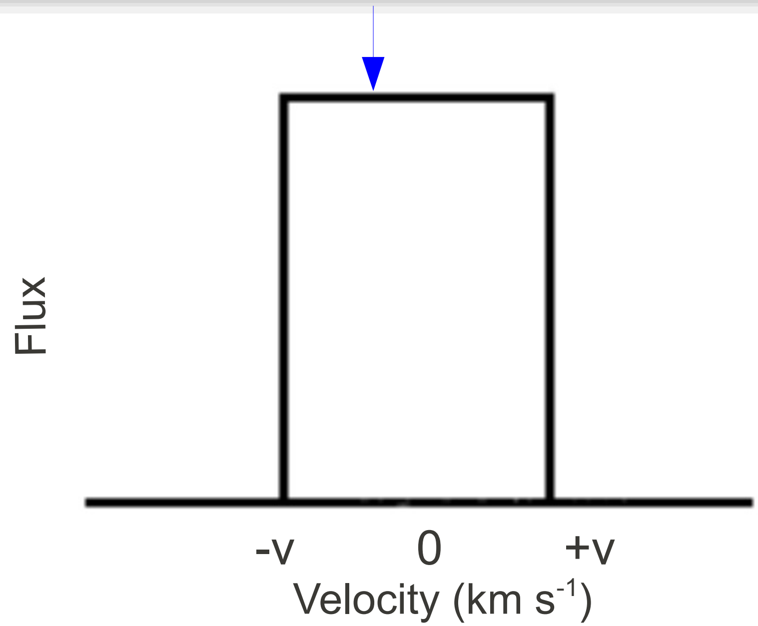

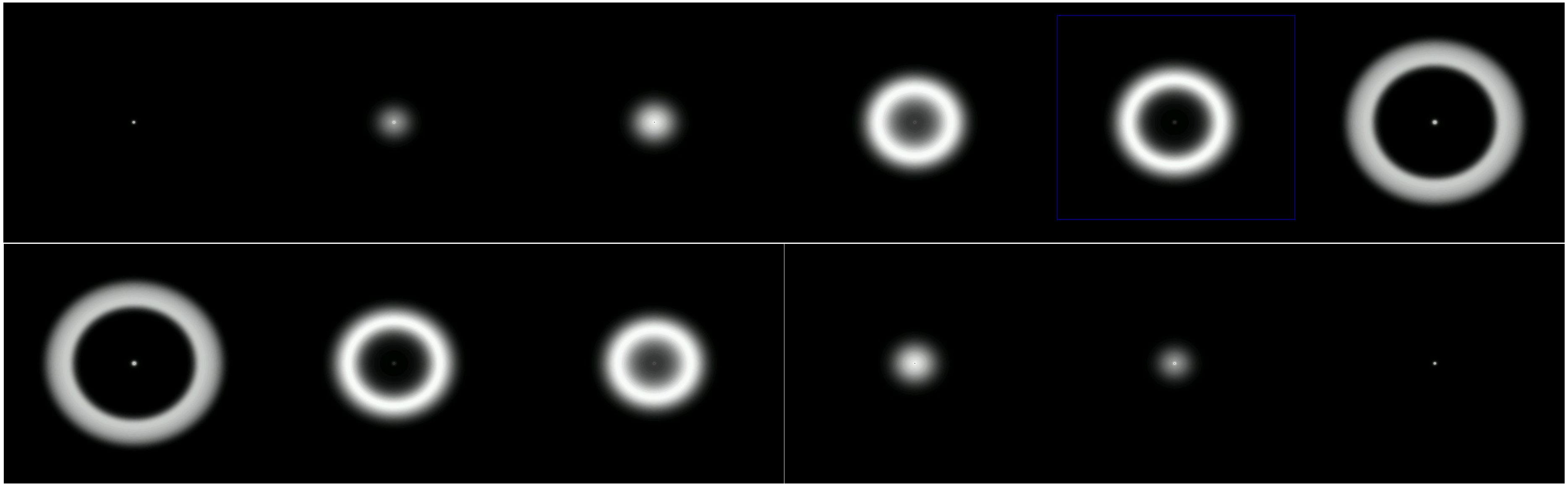

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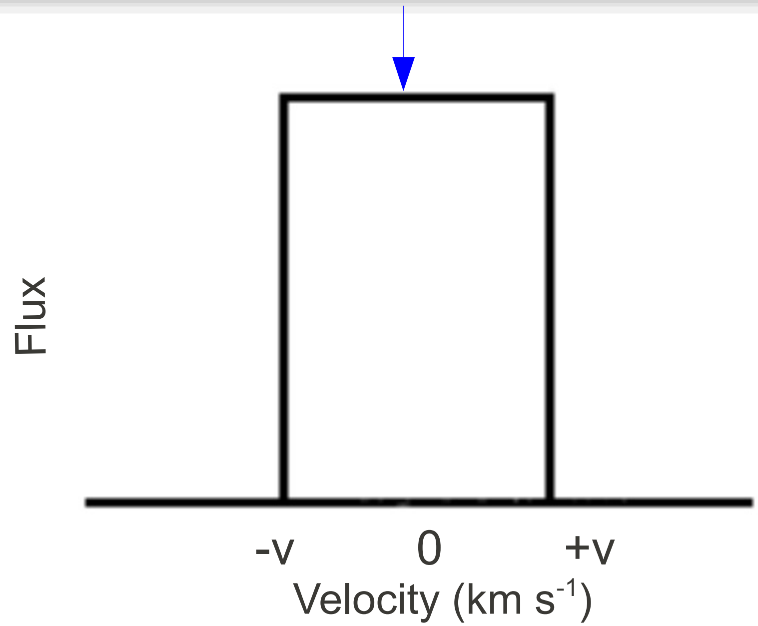

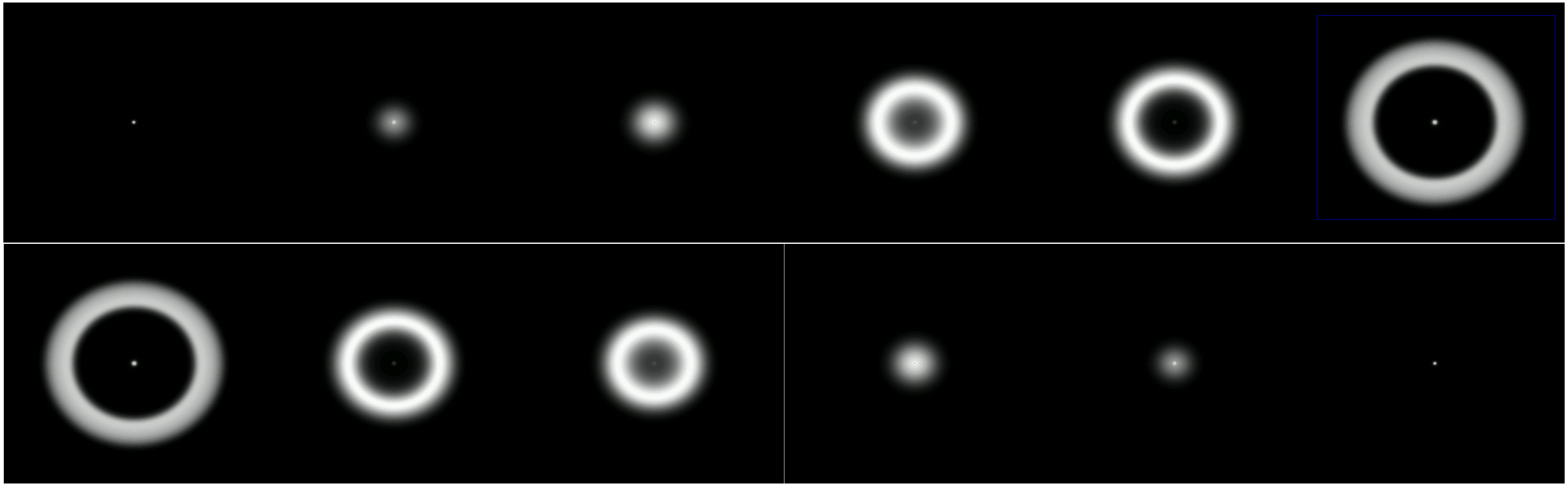

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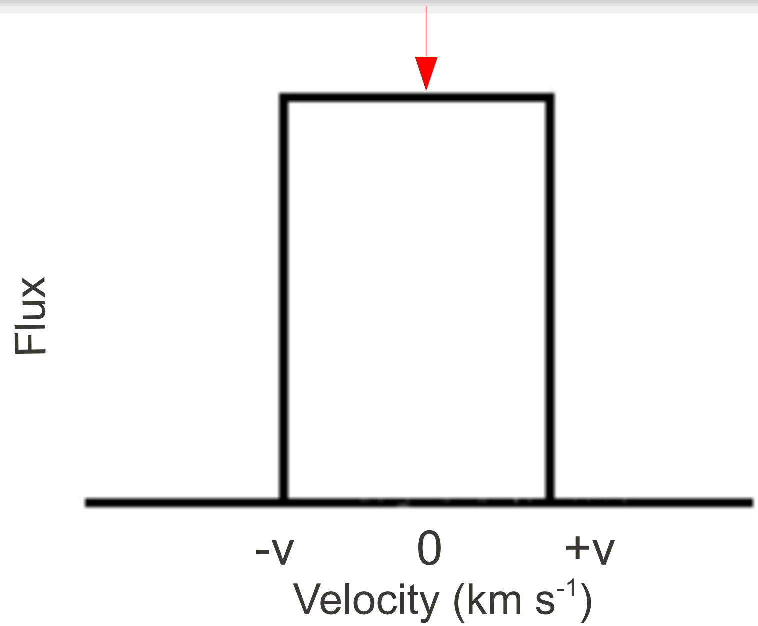

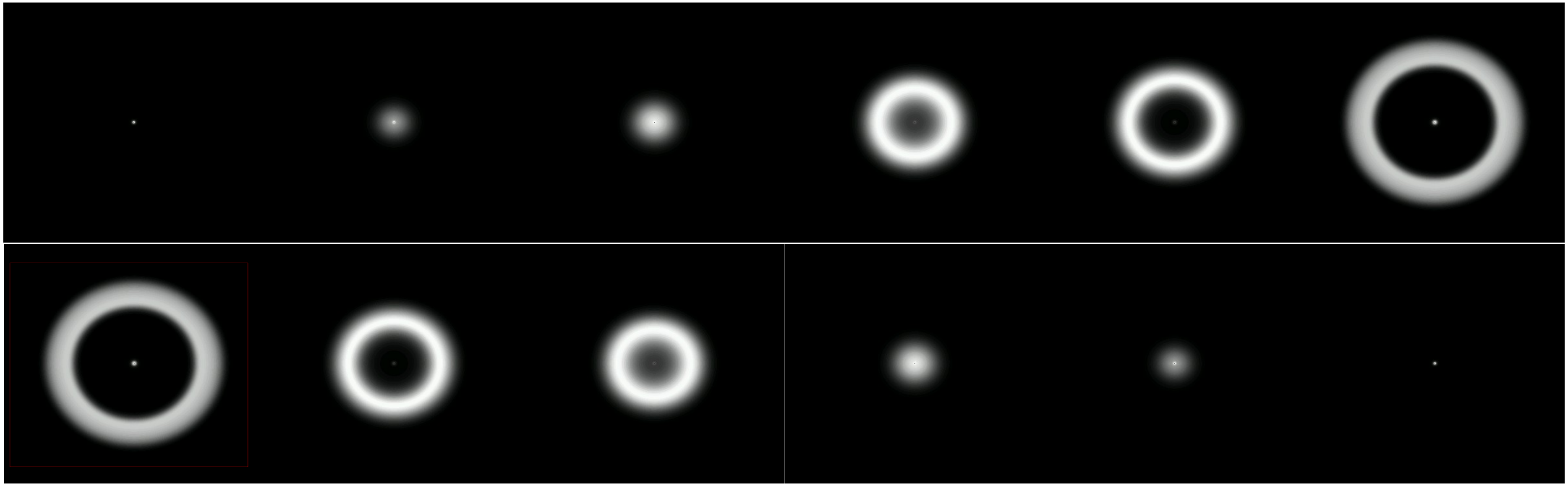

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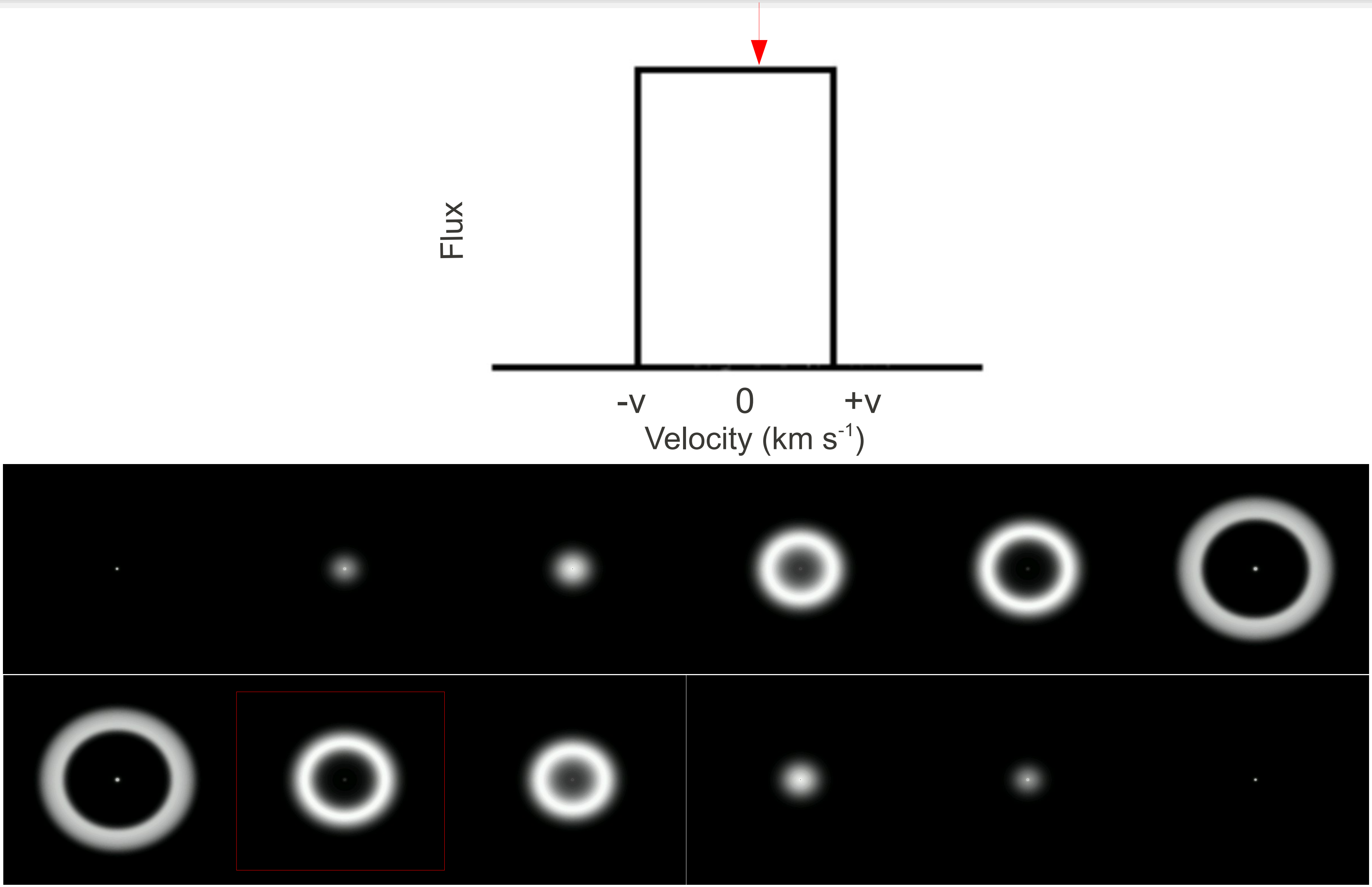

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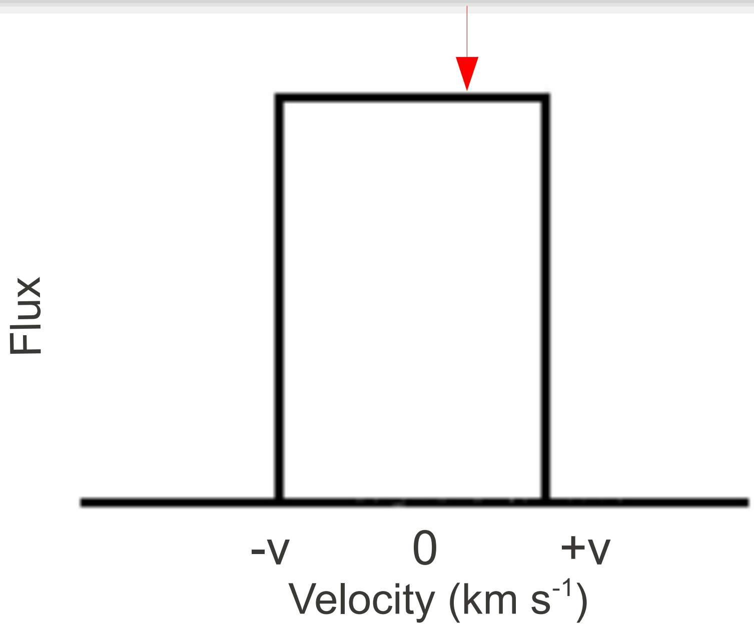

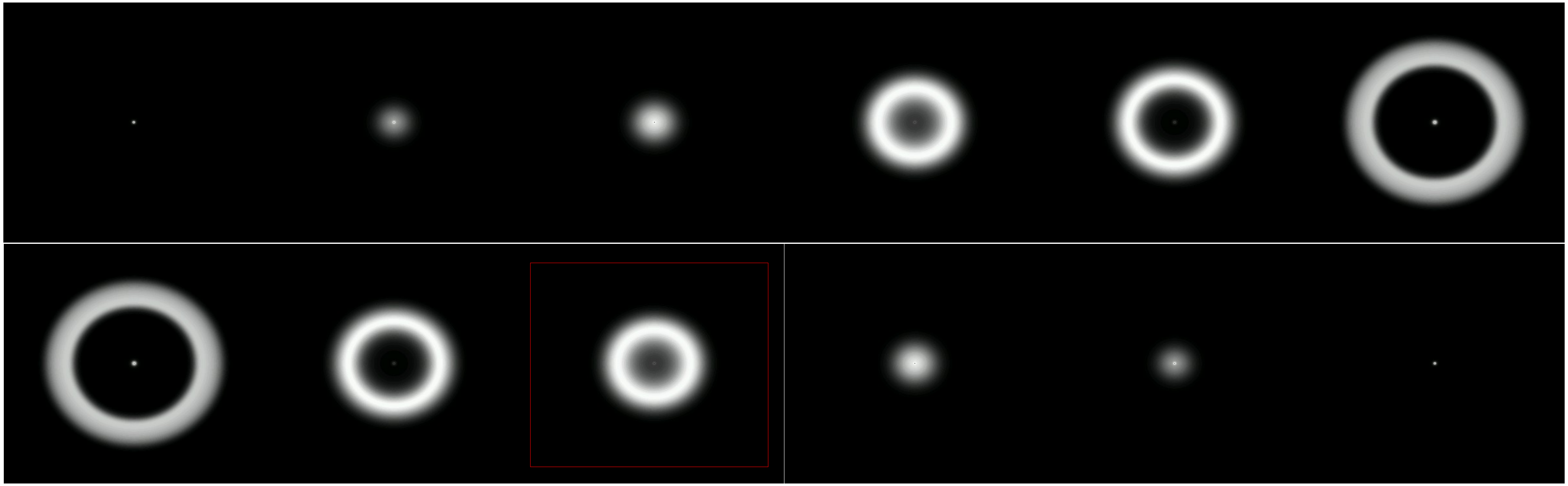

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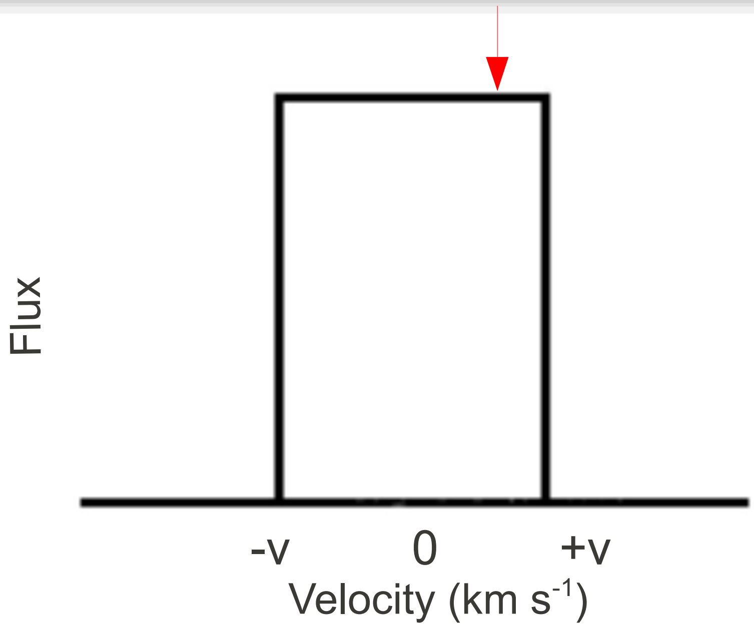

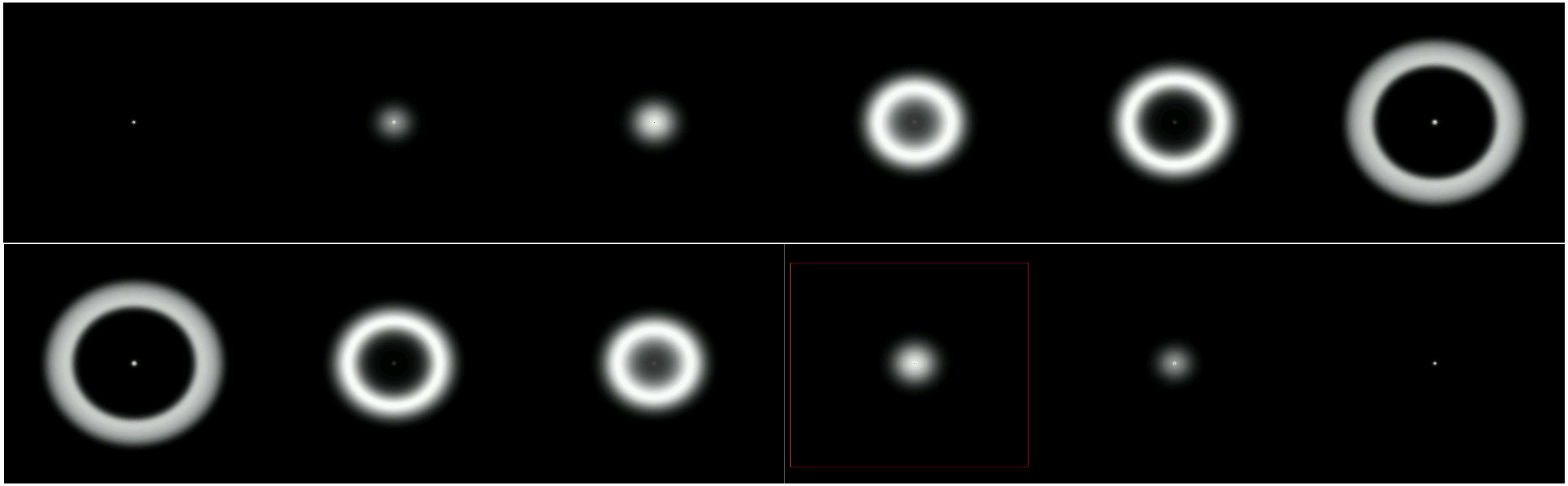

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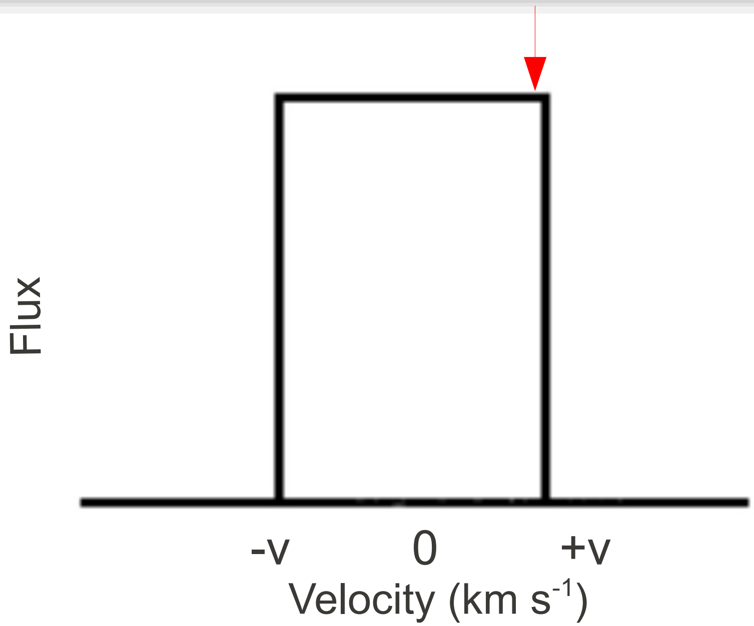

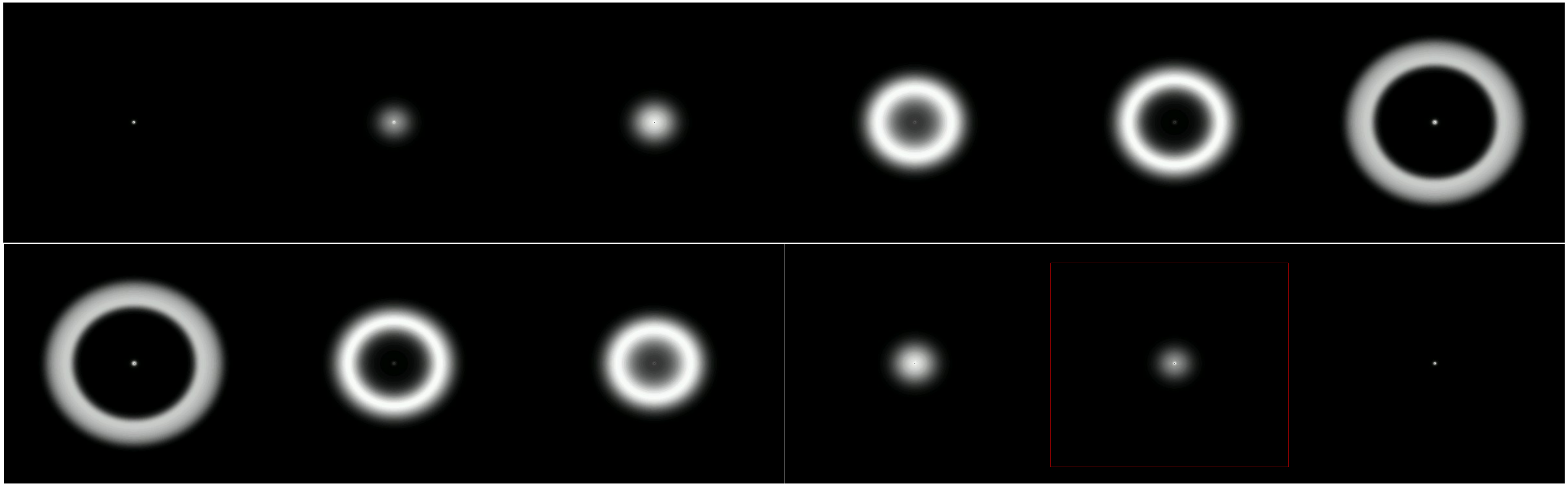

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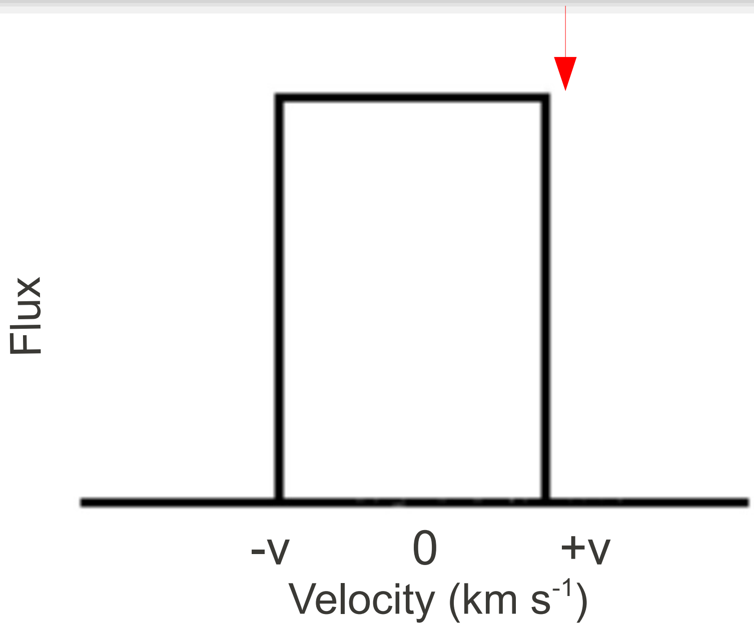
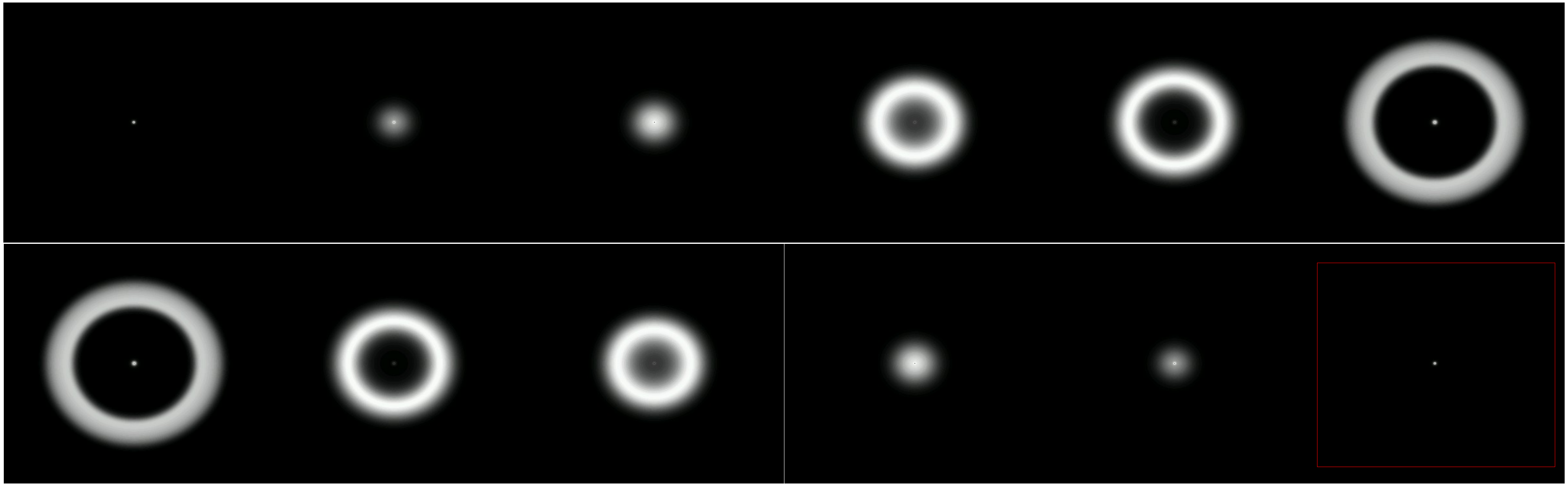
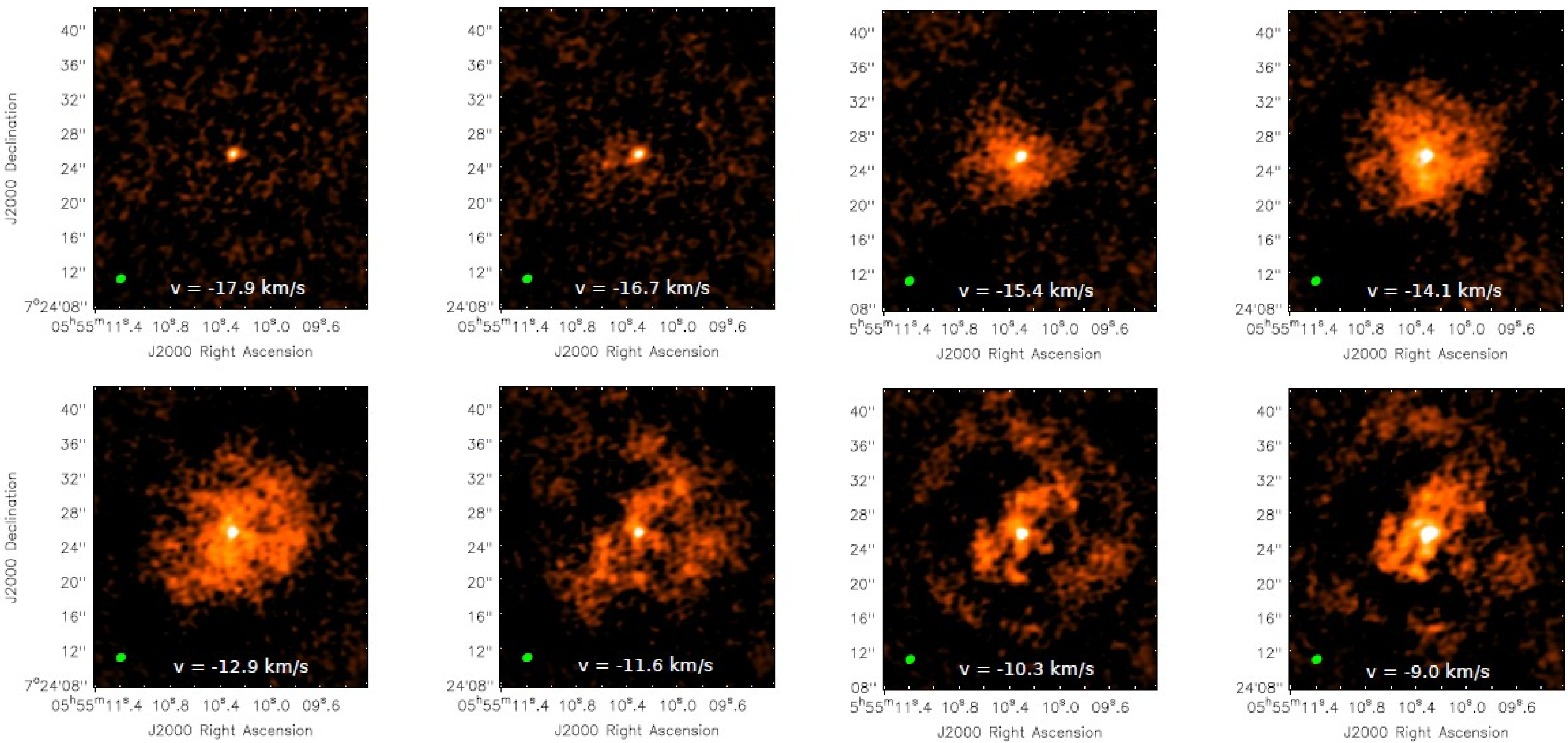
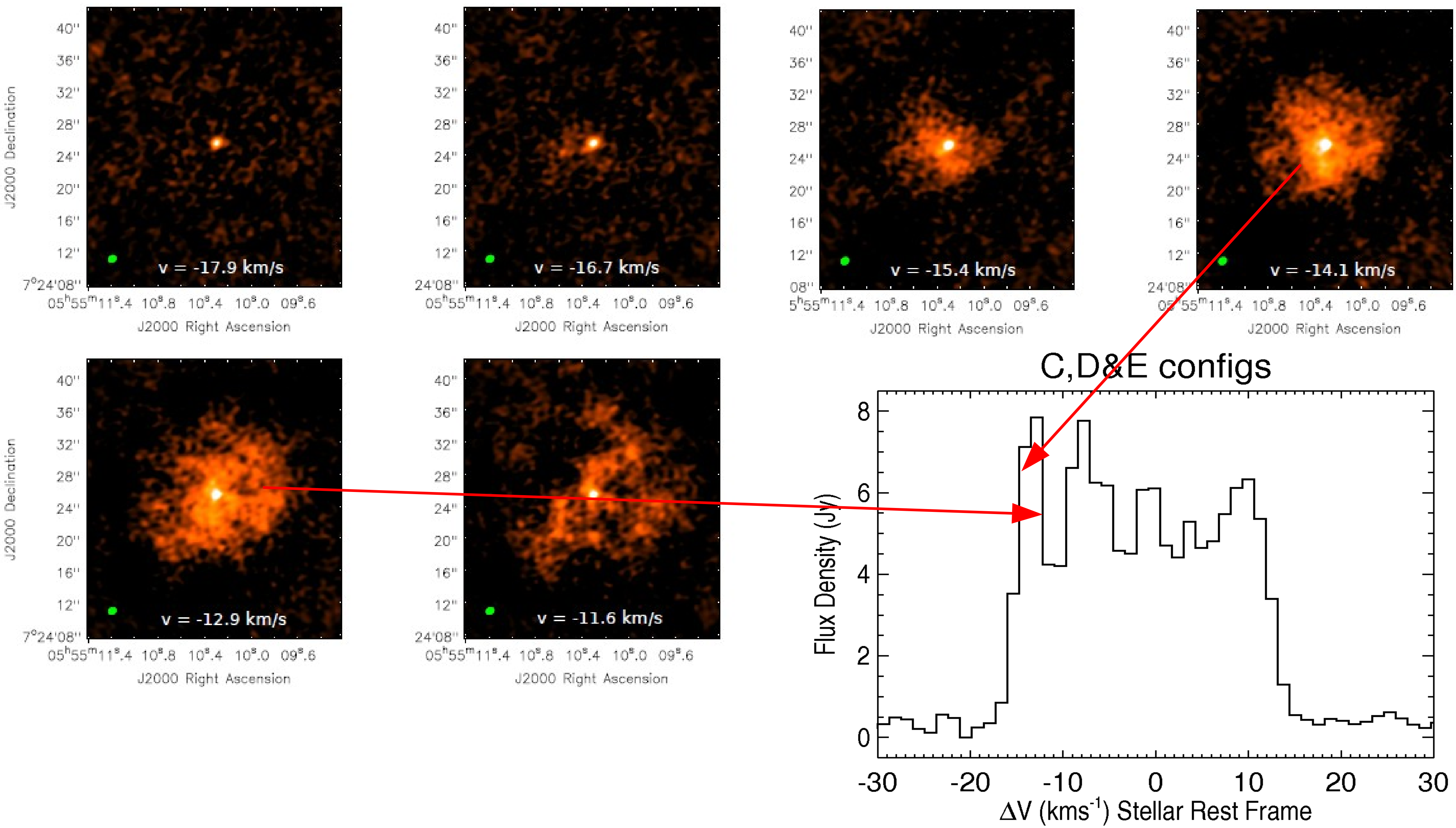




Combined Configuration

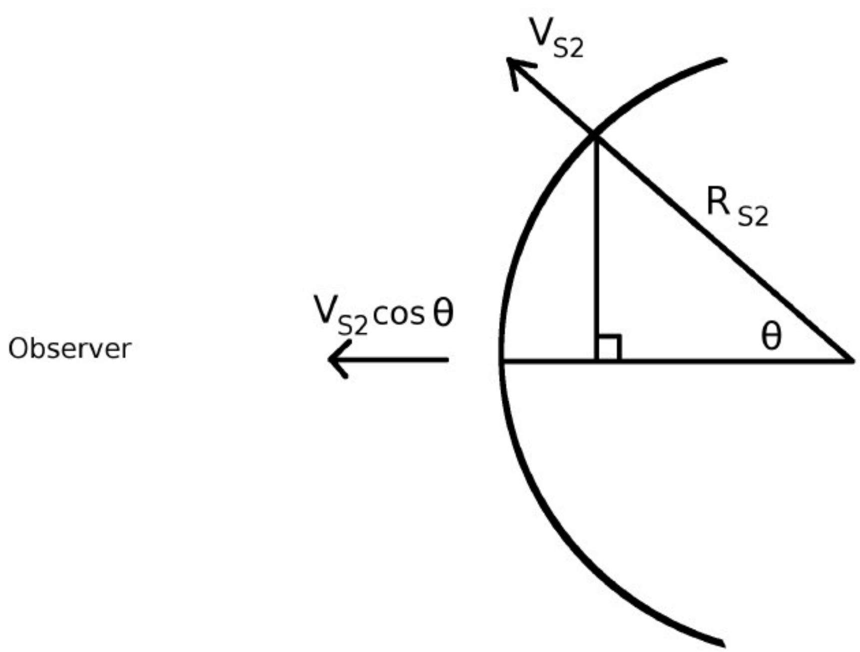


Combined Configurations

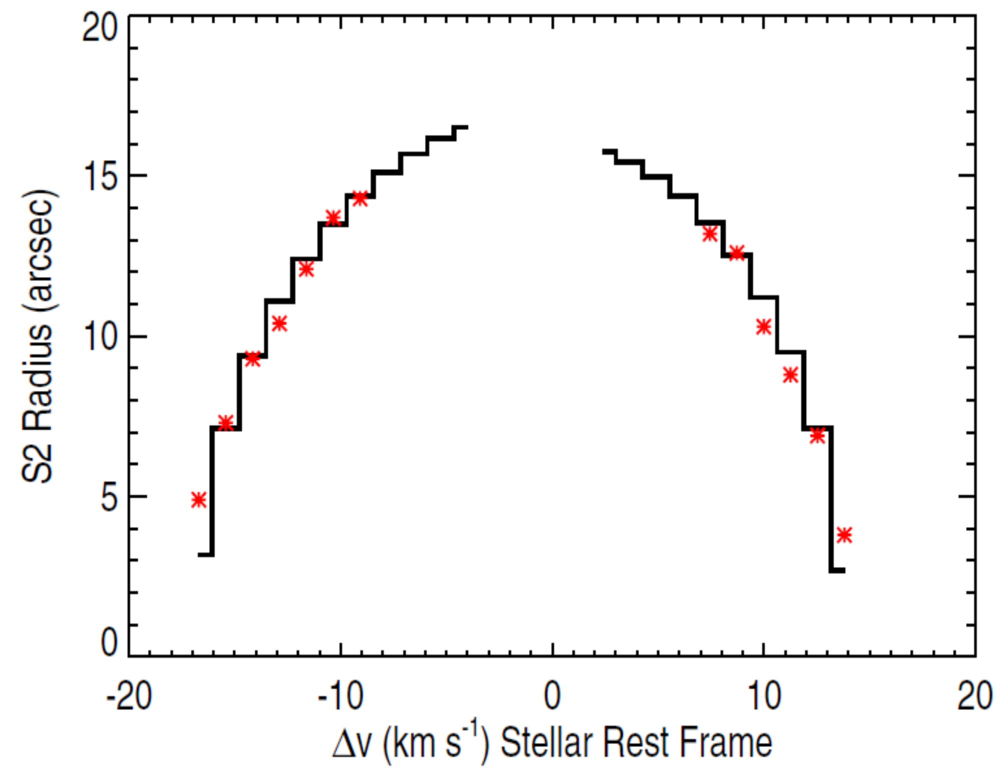


S2 Flow

S2 flow not present at low absolute velocities.

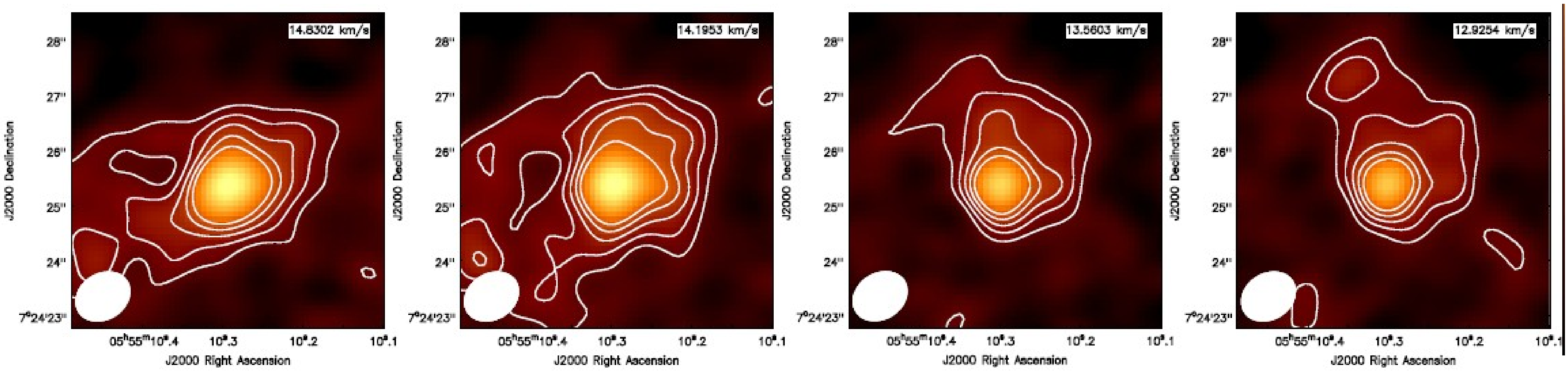


(O'Gorman *et al.*, 2012)



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

S1 Flow



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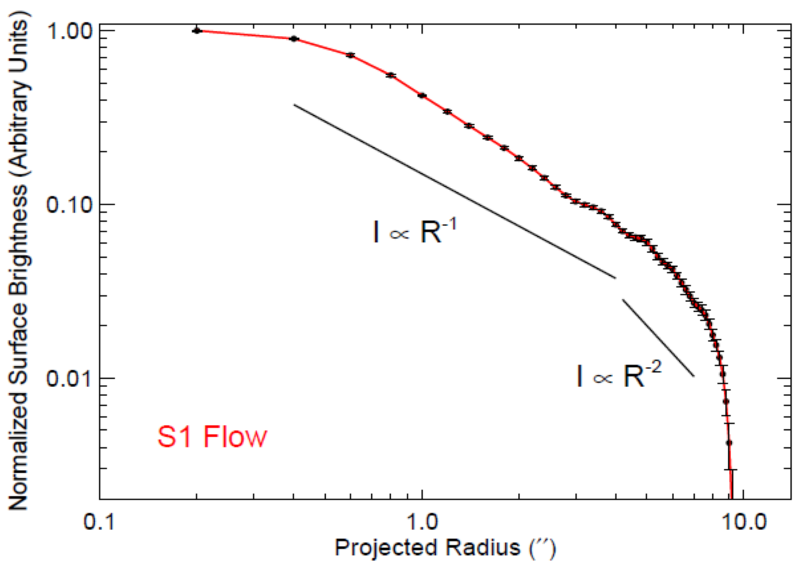


Conclusions

- 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.

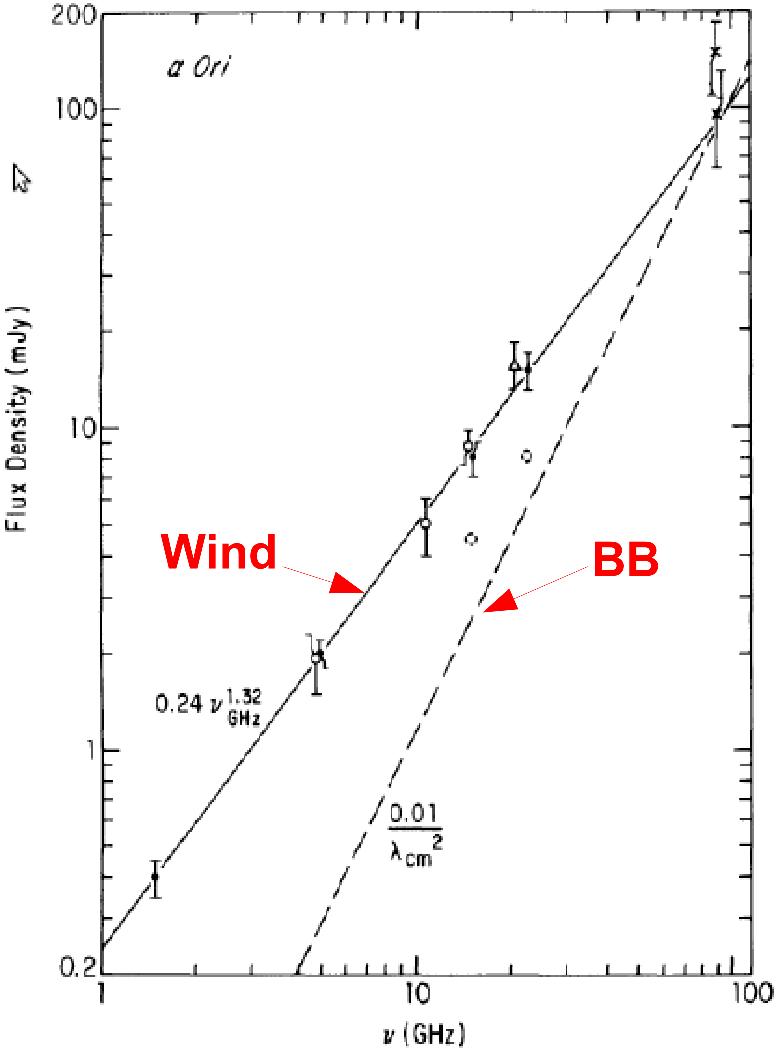
-

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

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

Betelgeuse's Wind Acceleration Region

(Newell & Hjellming, 1982)



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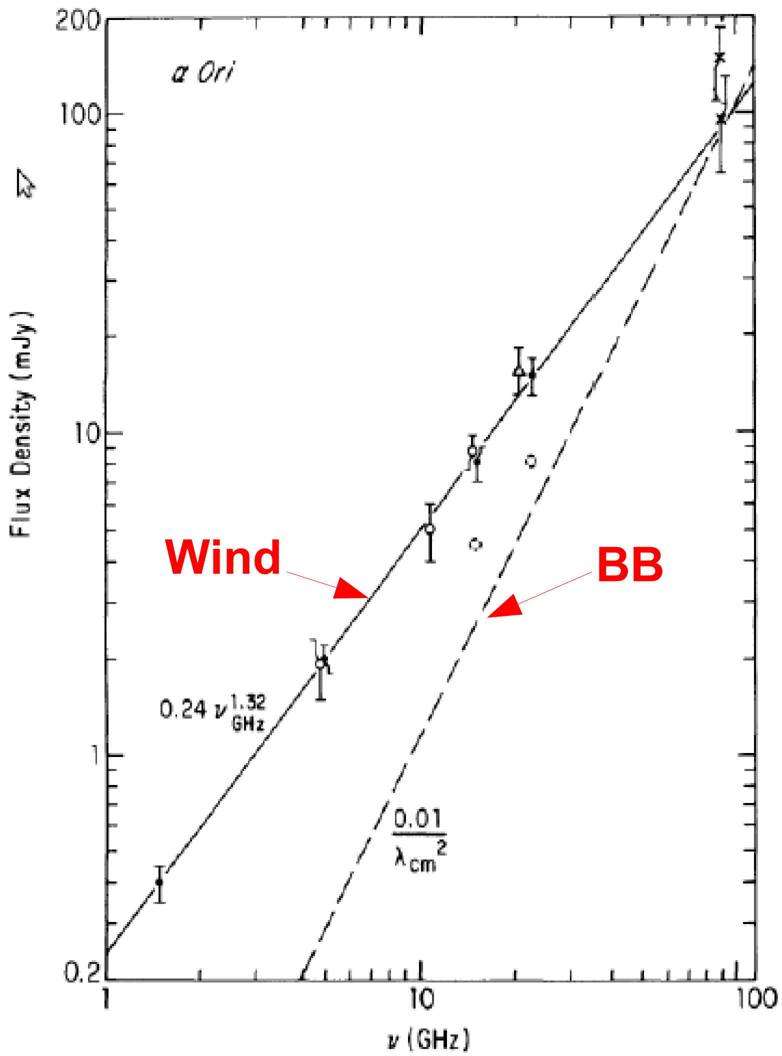
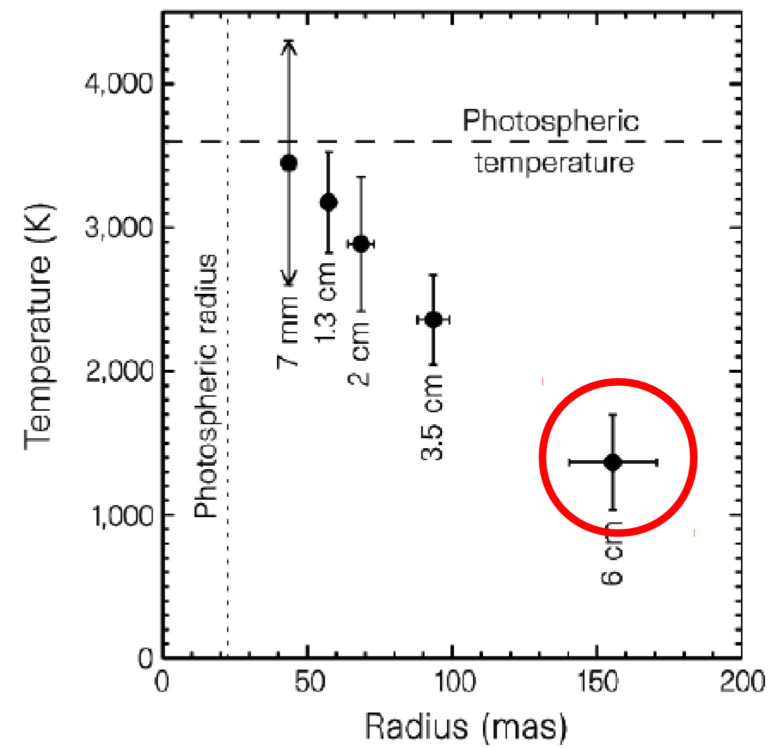


(Lim *et al.*, 1998)

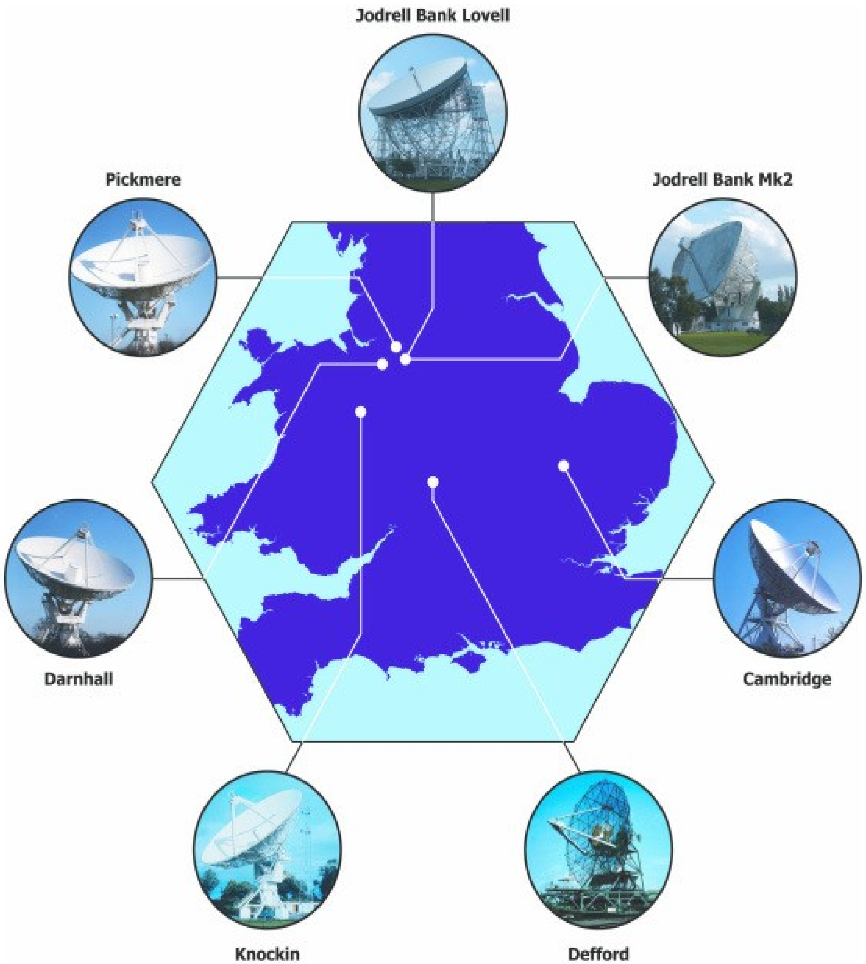


$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$

Brightness Temperature

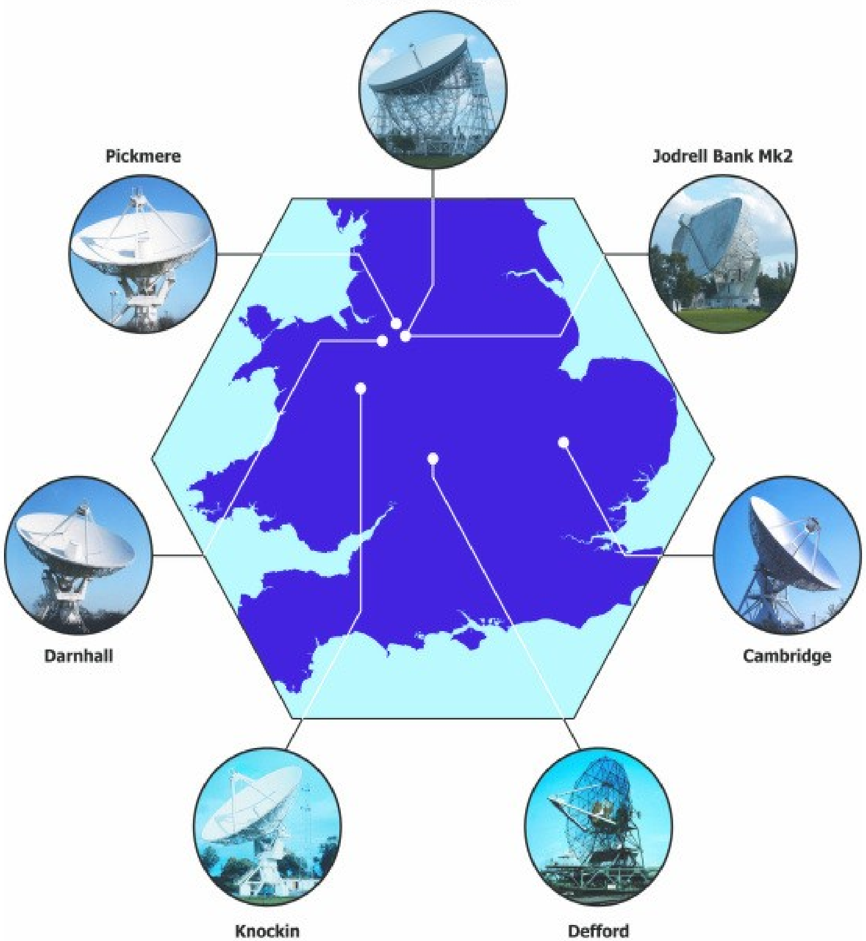
Size

Betelgeuse with e-MERLIN (5.2 cm)



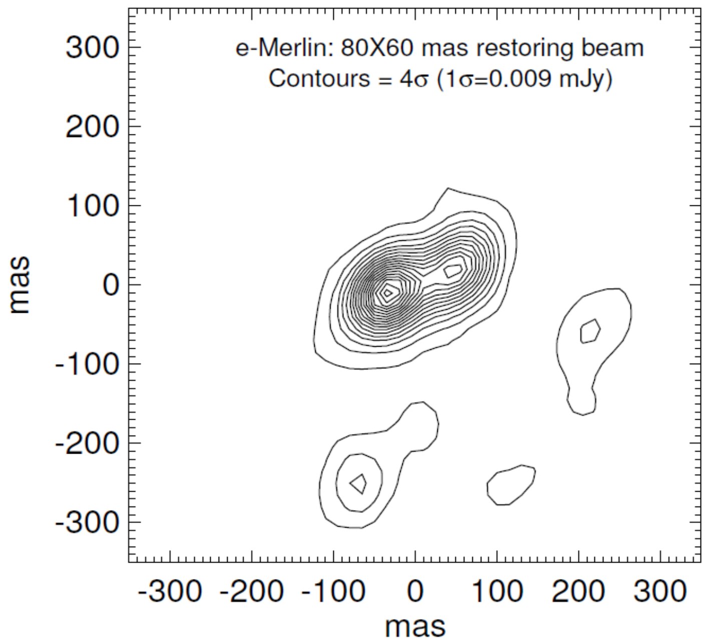
(Credit: MERLIN/VLBI national facility)

Betelgeuse with e-MERLIN (5.2 cm)



(Credit: MERLIN/VLBI national facility)

Richards *et al.* (2013)



Two unresolved *hot spots:*

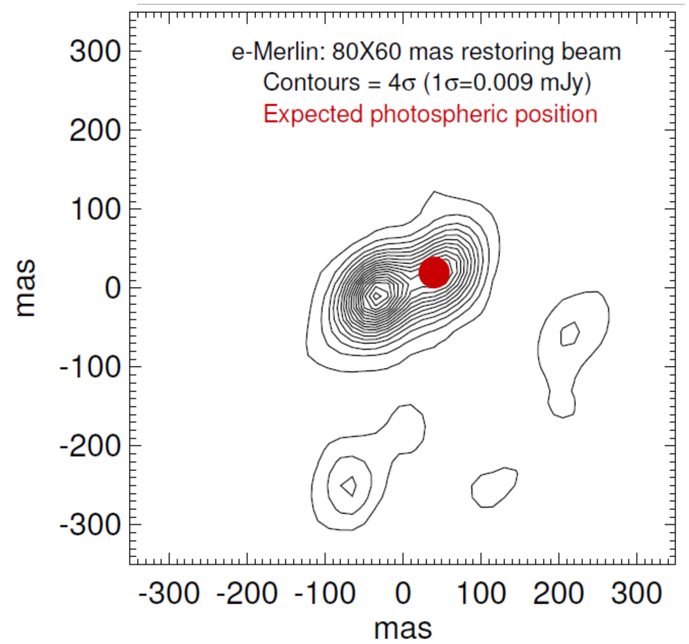
T_e > 3800 K

T_e > 5400 K

Where is the photosphere?

Betelgeuse with e-MERLIN (5.2 cm)

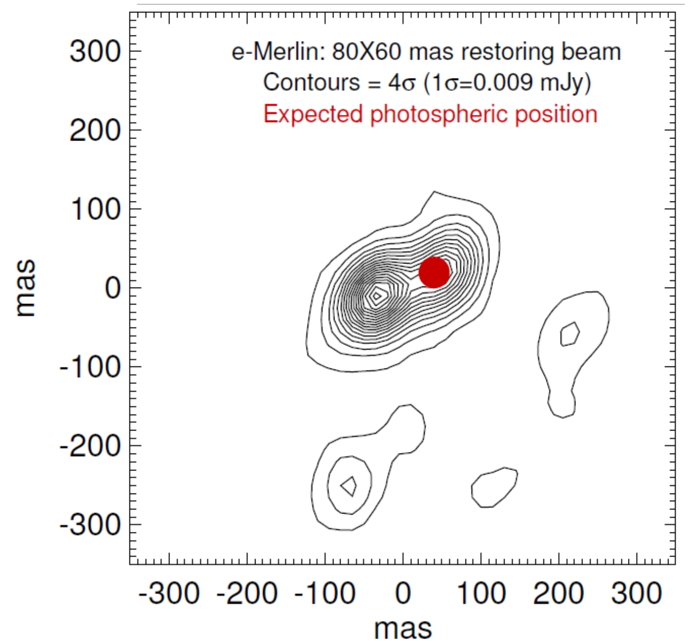
Astrometric solution of Harper *et al.*, (2008)



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

Betelgeuse with e-MERLIN (5.2 cm)

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



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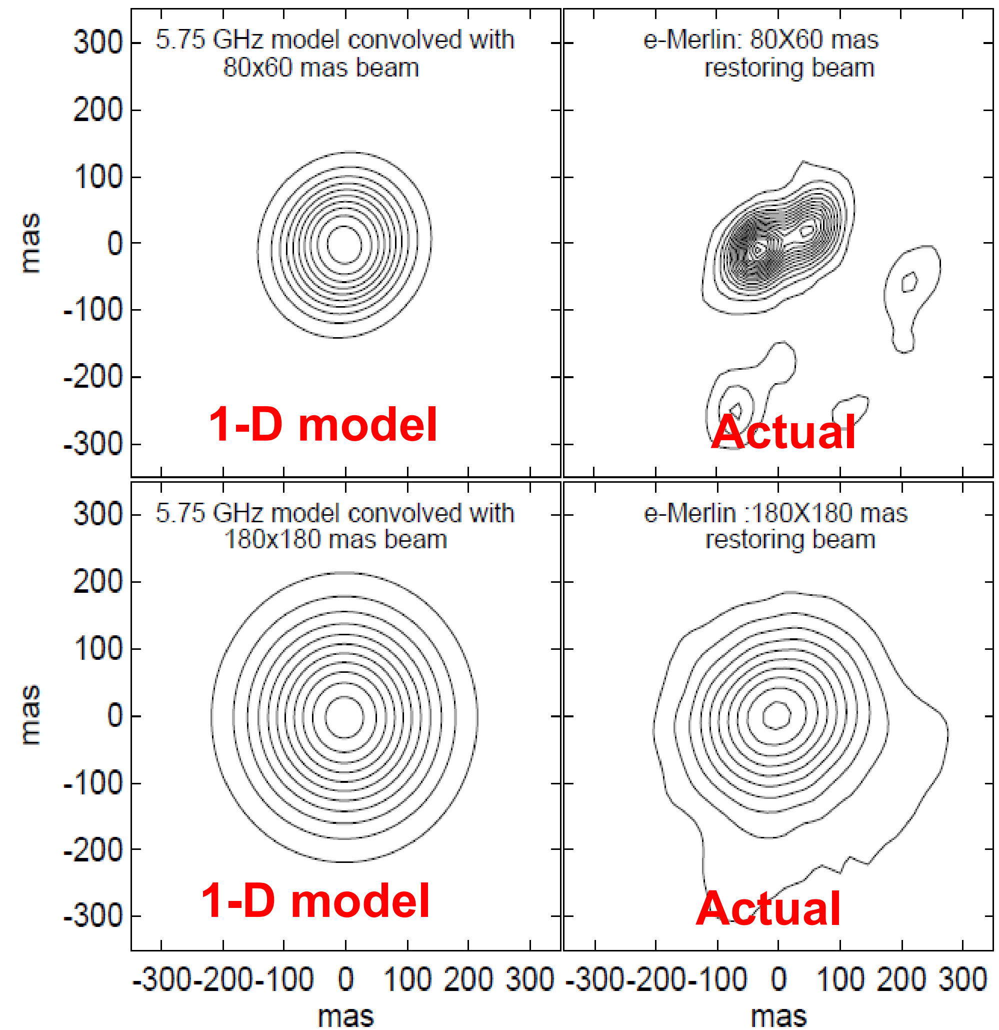
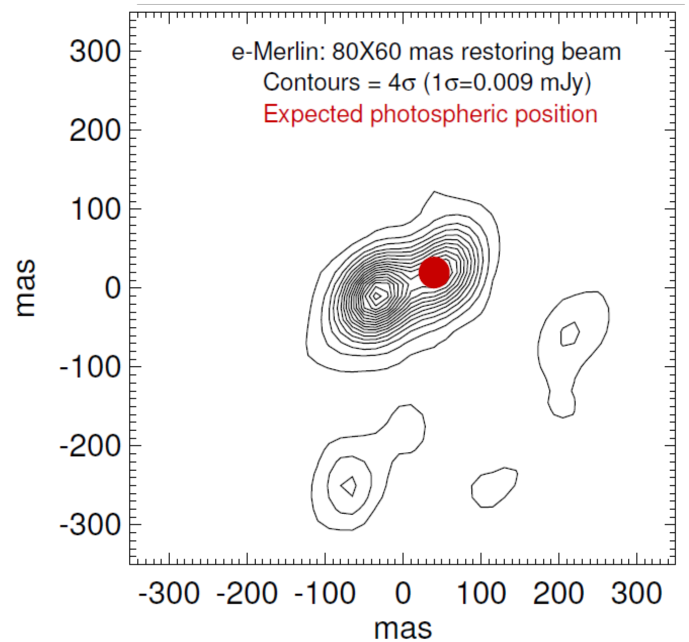


Spherically symmetric semi-empirical model of Harper *et al.*, (2001)

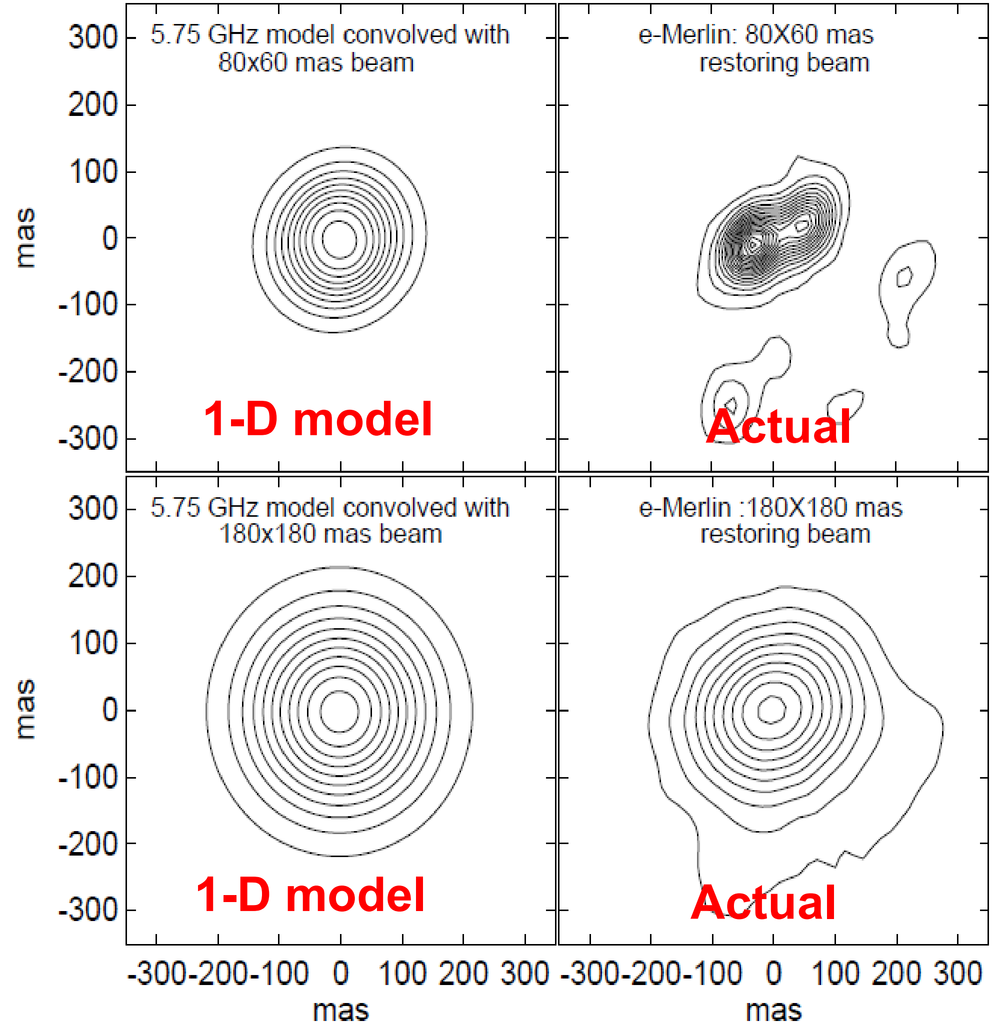
Betelgeuse with e-MERLIN (5.2 cm)

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



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

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

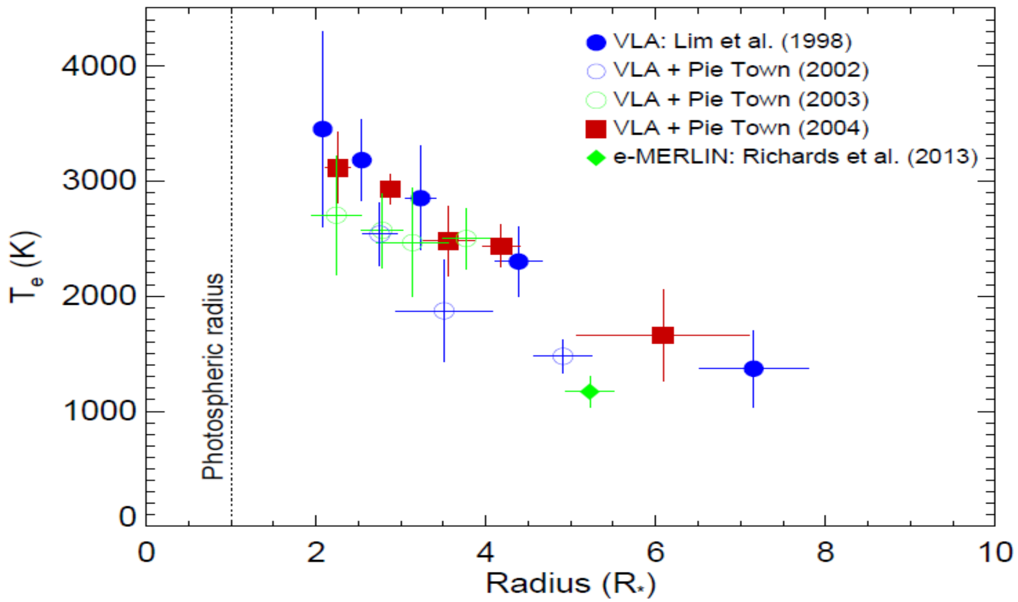
w/l (cm)	Resolution (")
0.7	40 x 25
1.3	80 x 40
2.0	120 x 90
3.5	200 x 130
6.2	380 x 270

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



Betelgeuse with VLA – Pie Town

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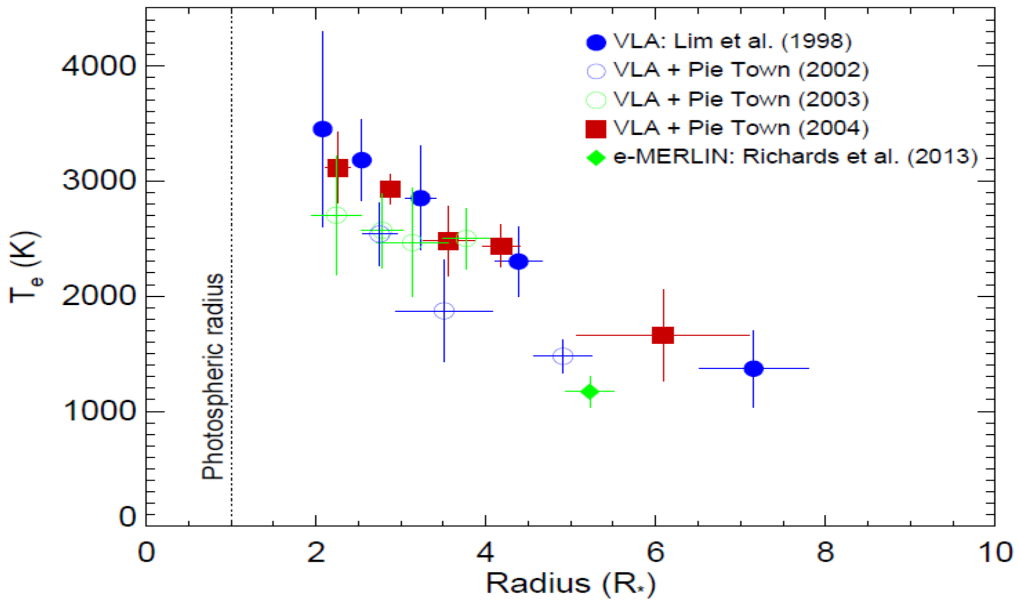
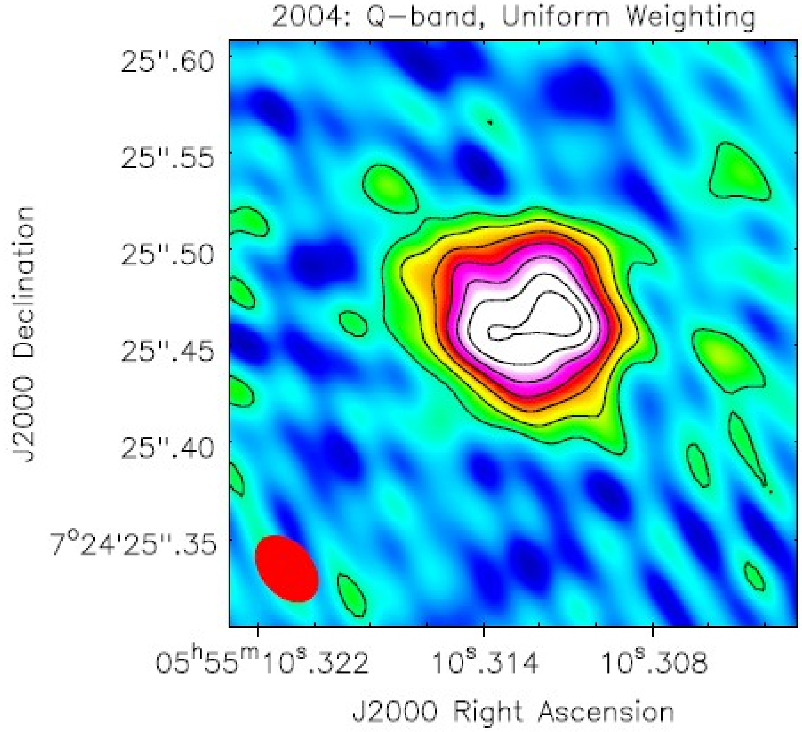


Q band (0.7 cm)



Betelgeuse with VLA – Pie Town

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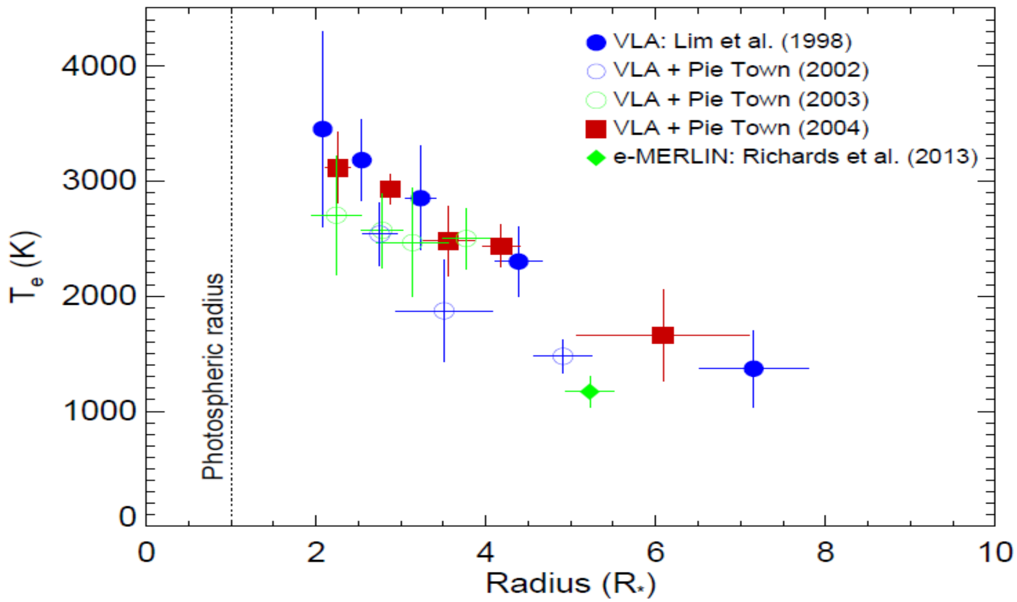
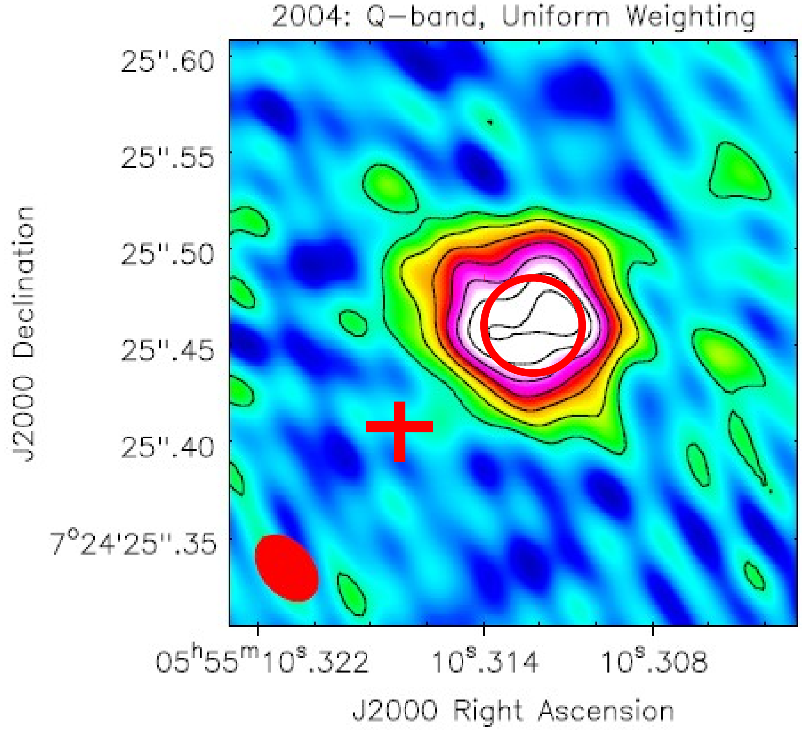
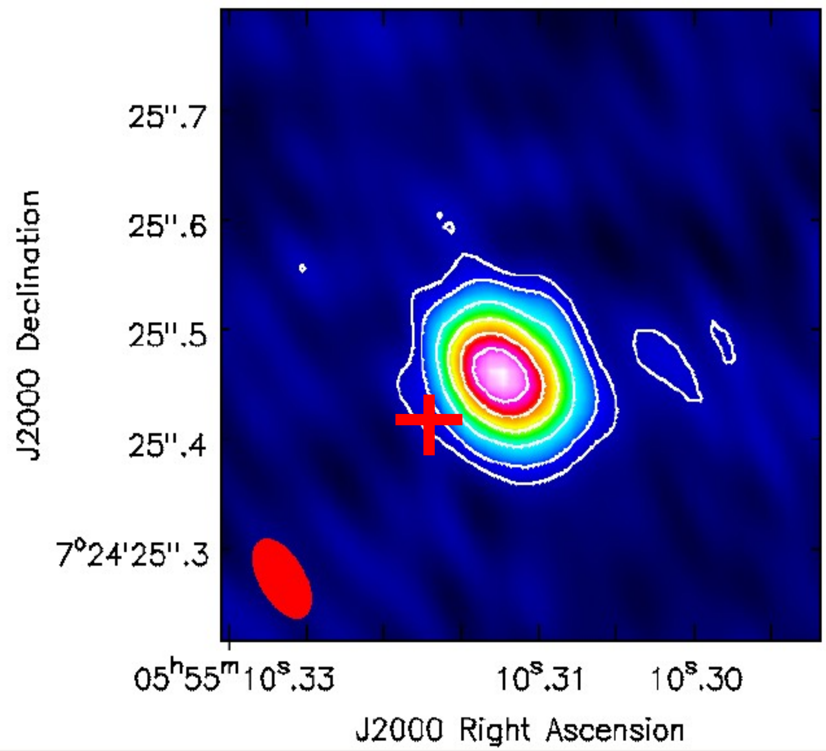


Q band (0.7 cm)



Betelgeuse with VLA – Pie Town

1.3 cm Map



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

$$\frac{\tau_{5.2\,\mathrm{cm}}}{\tau_{1.3\,\mathrm{cm}}} \simeq 20$$

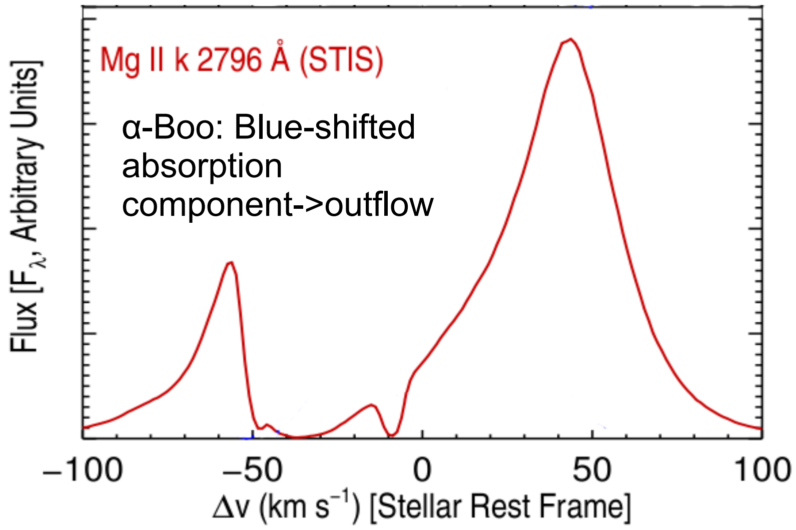
Conclusions

- 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)
- Flux and structure variability present in data
- 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}
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

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

New 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

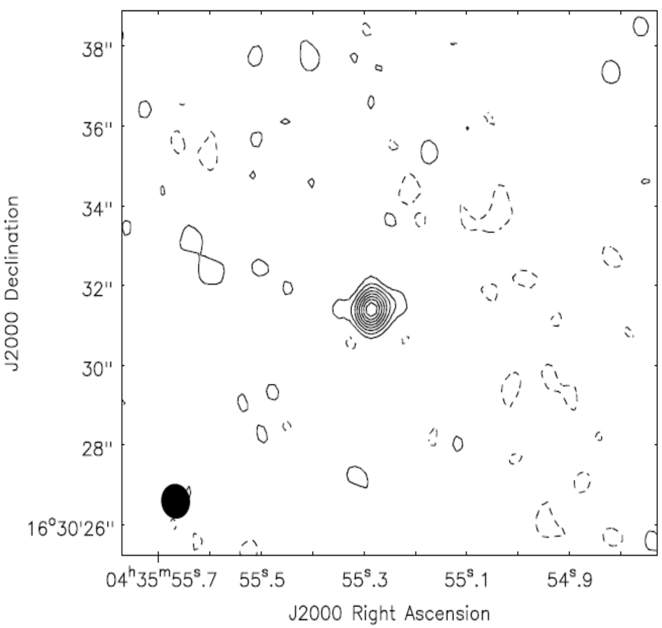
Directors Discretionary Time (DDT)

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

Red Giant Radio Maps

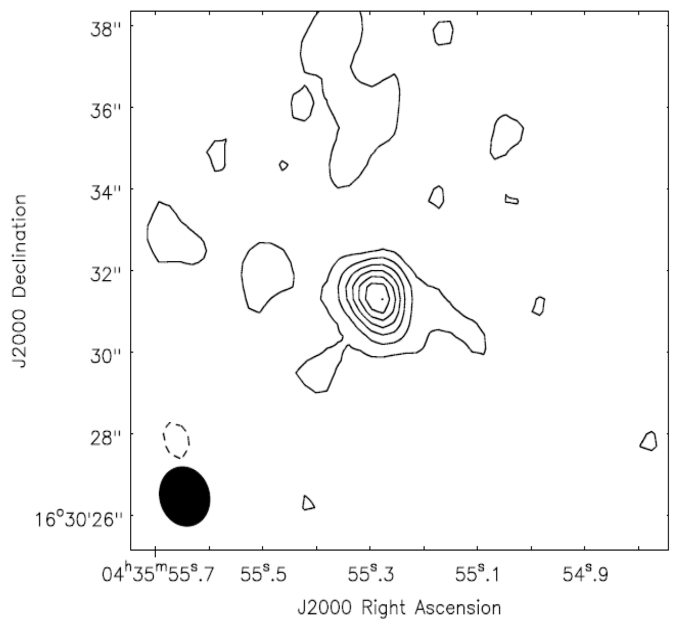
<u>Example: Aldebaran X (3 cm), C (6 cm), and S (10 cm) band</u>

X-band (8 GHz)
S_v = 0.3 mJy



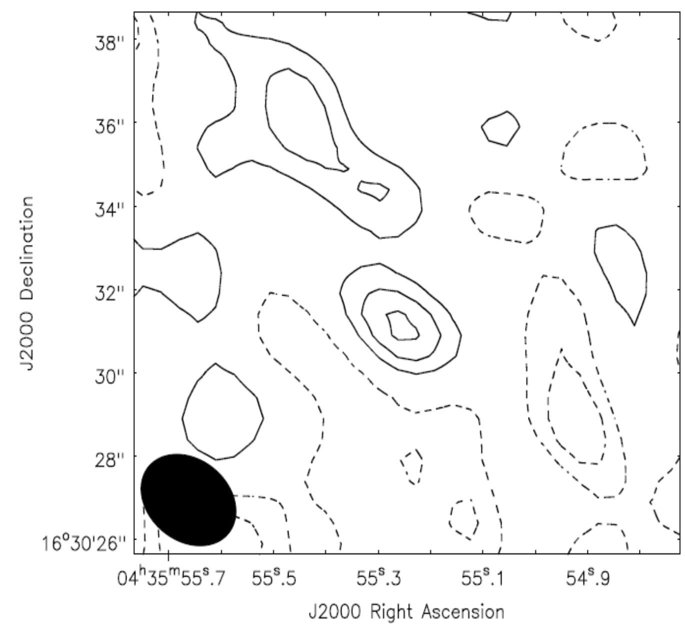
Contours = (-2,2,4......16)xσ
σ = 16 μJy

C-band (5 GHz)
S_v = 0.15 mJy



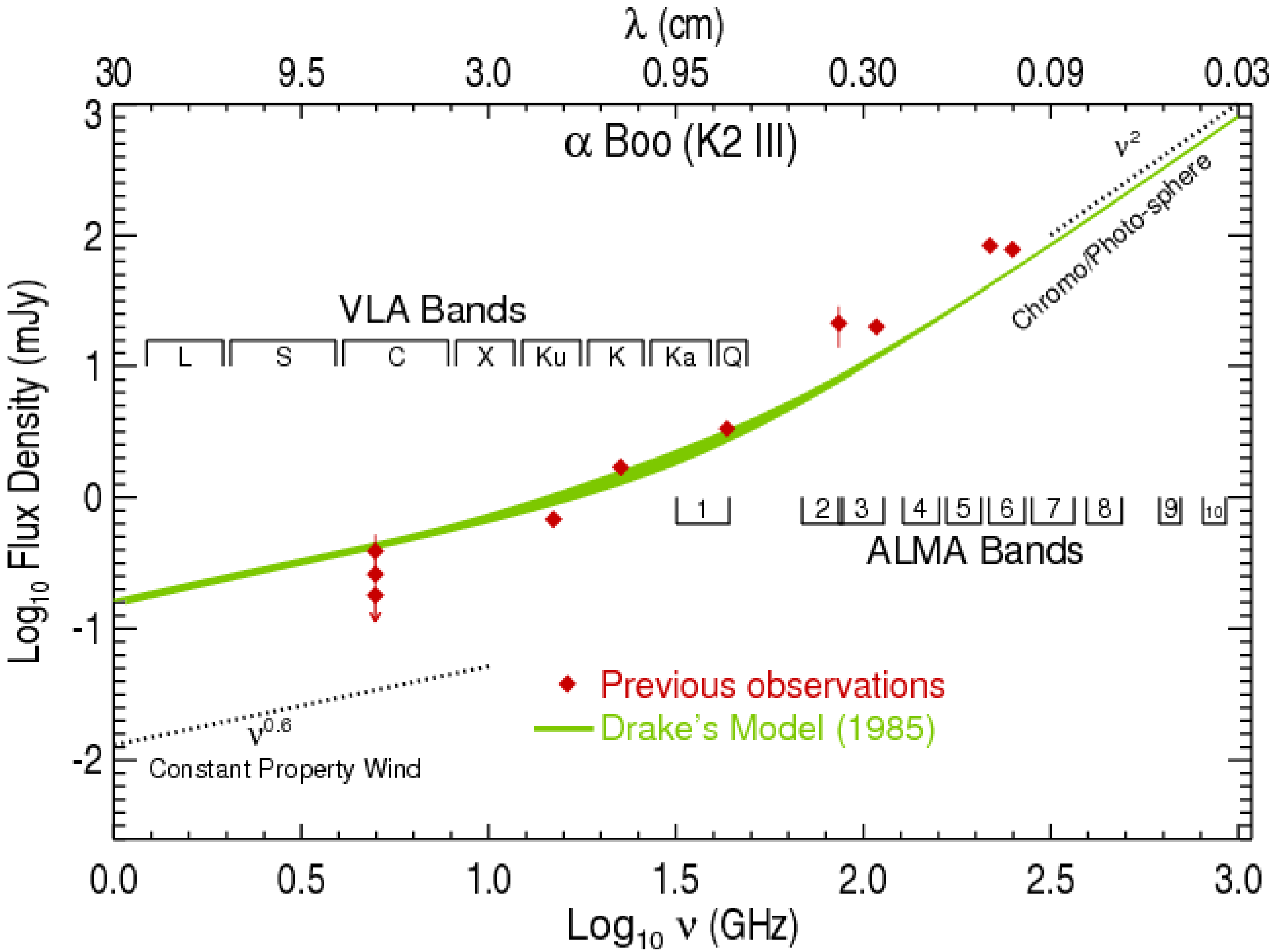
Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

S-band (3 GHz)
S_v = 0.06 mJy

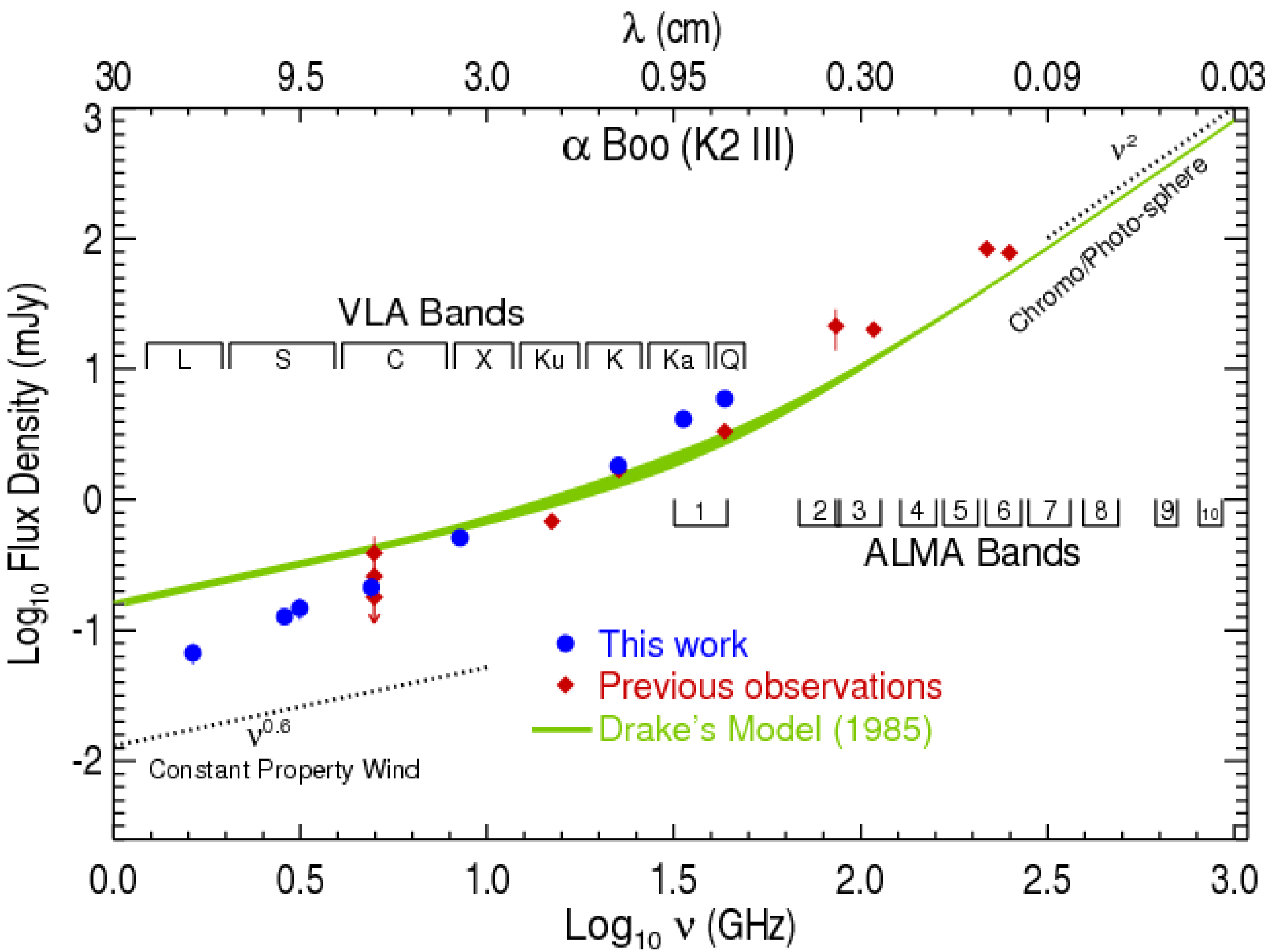


Contours = (-3,-2,-1,1,2,3)xσ
σ = 18 μJy

Spectral Energy Distribution – α Boo

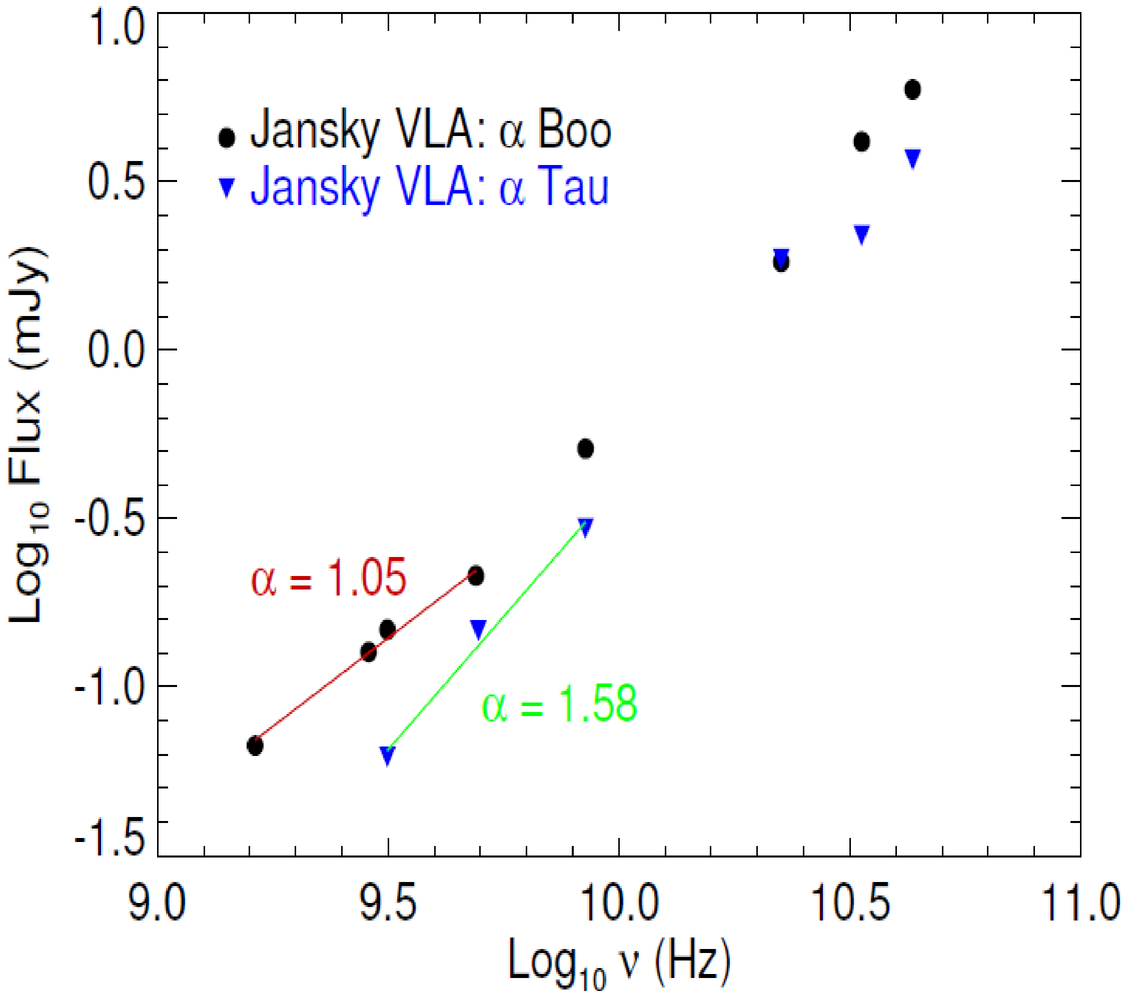


Spectral Energy Distribution – α Boo



Spectral Indices

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



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

  $T_e \propto r^{-n}$

  then,

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

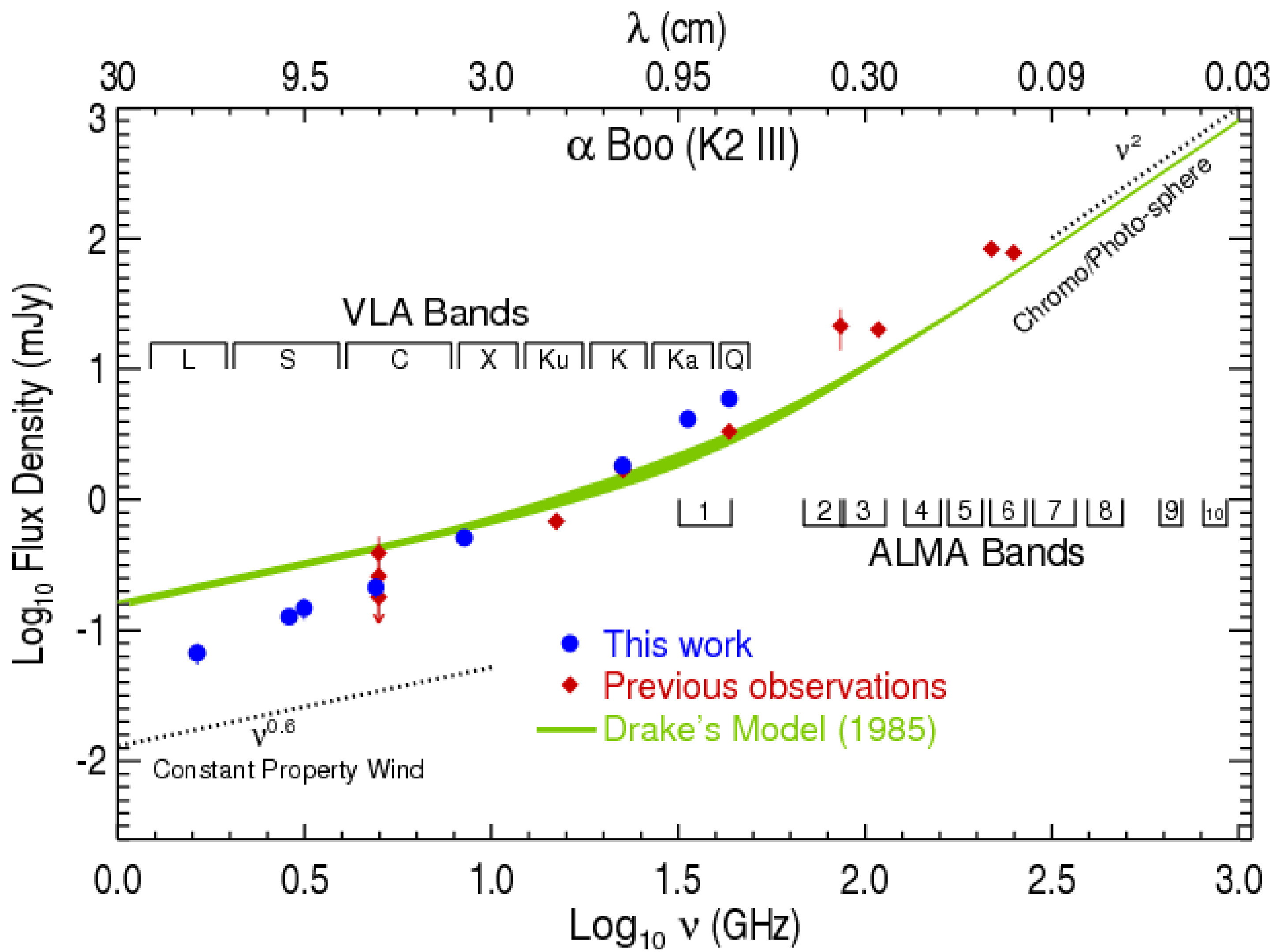
- α Tau: wind ~ wind optically thin

- α Boo:

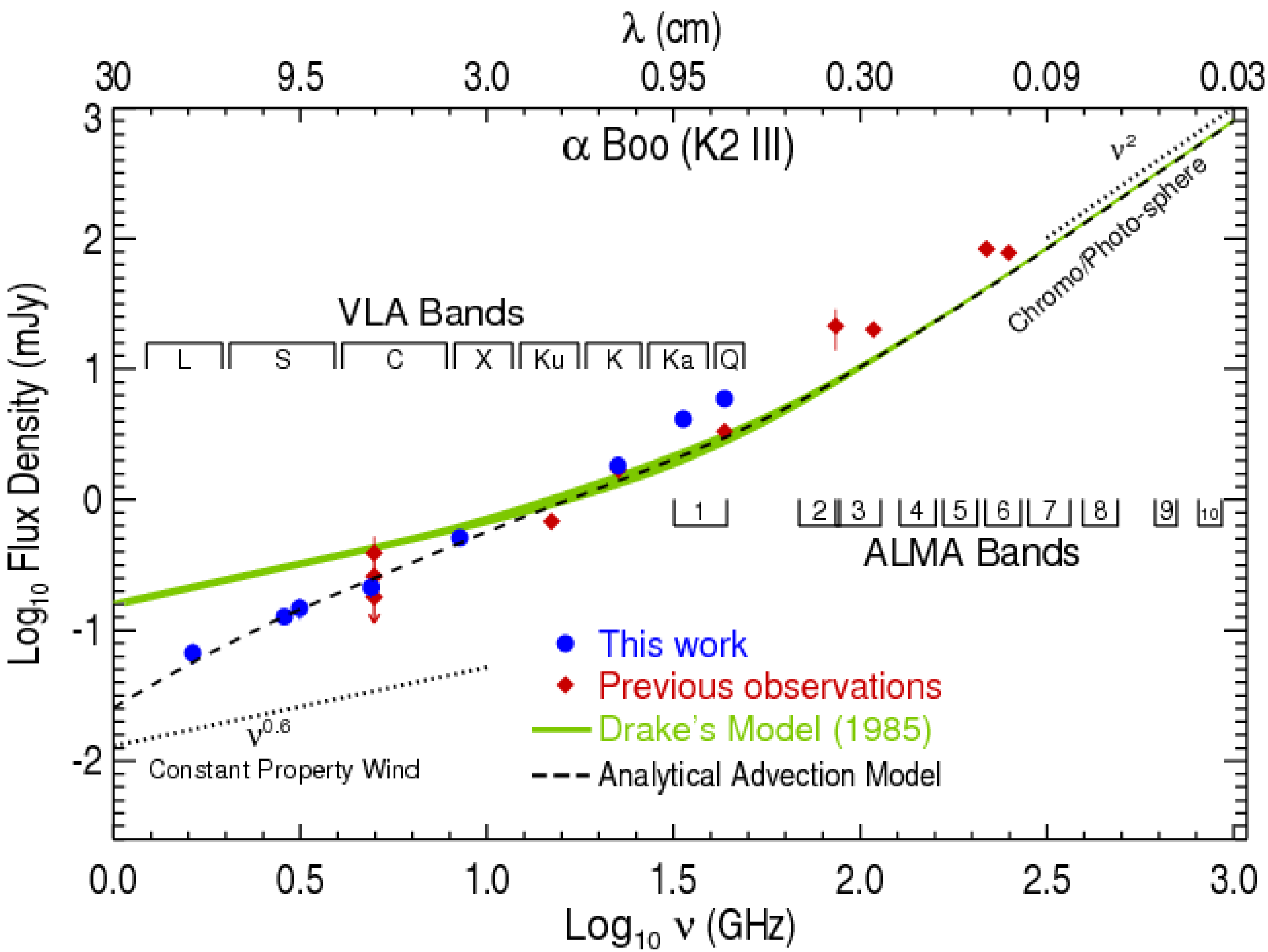
Assume constant velocity wind,

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

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
- Evidence for asymmetries in both S1 and S2 flows
- 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.

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: *Create a wind thermal energy balance to investigate possible heating mechanisms in Arcturus' inner outflow region.*

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

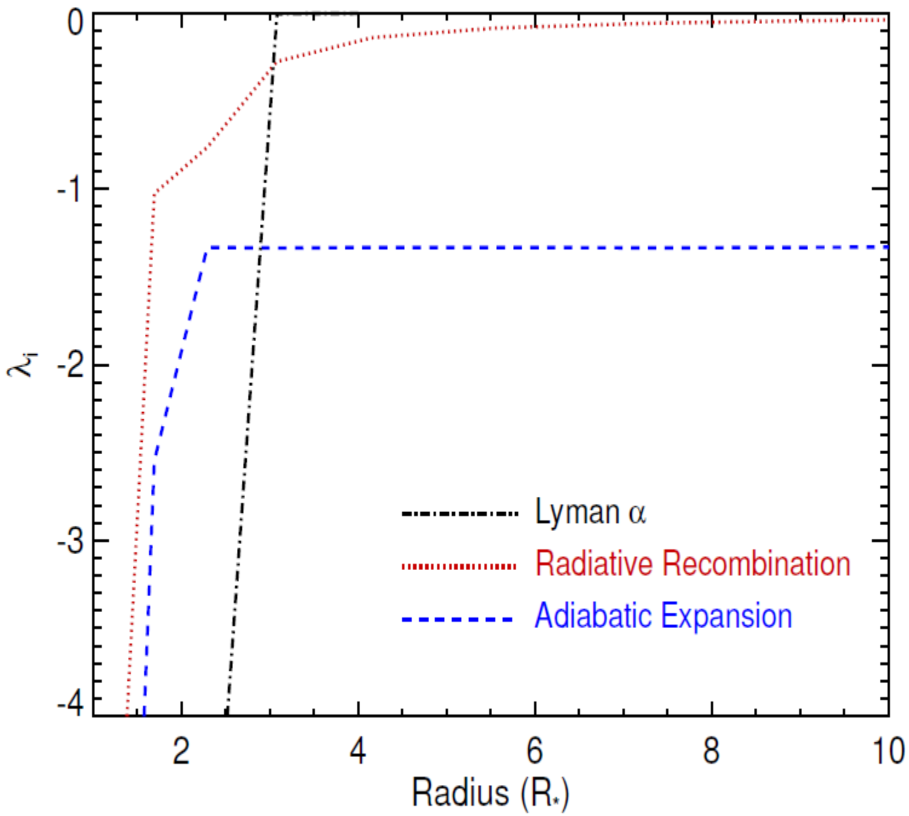
Notation:

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

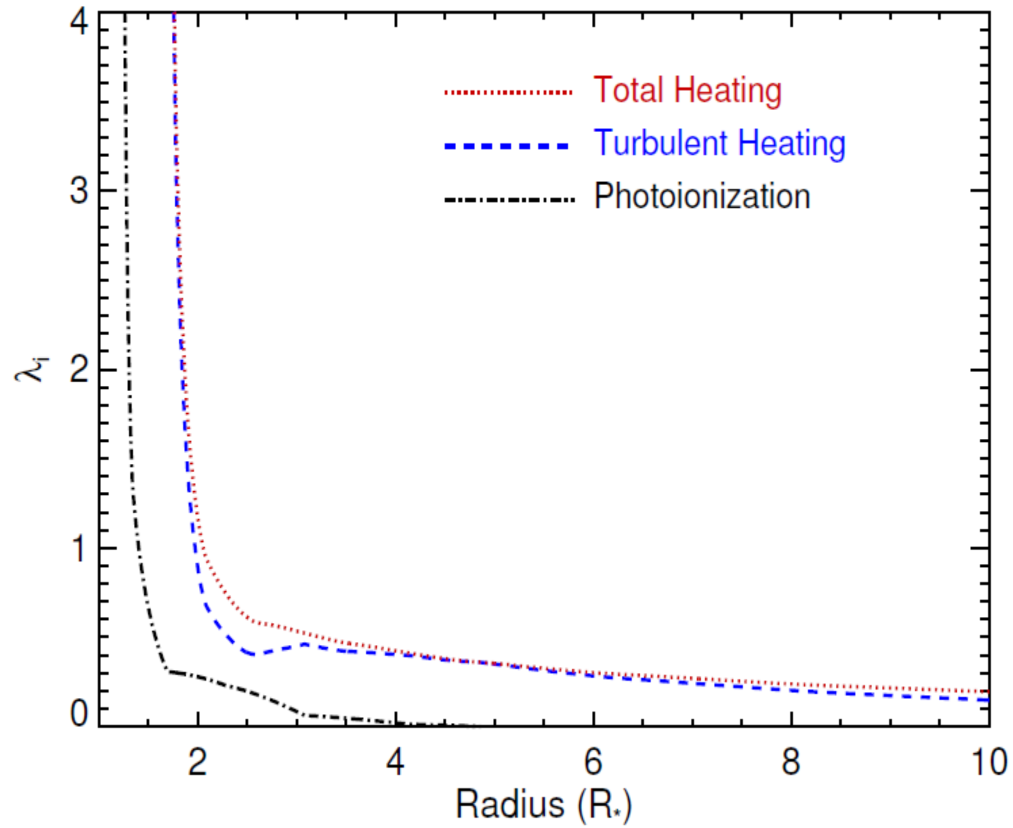
Gas kinetic power law slope

Cooling and Heating Processes

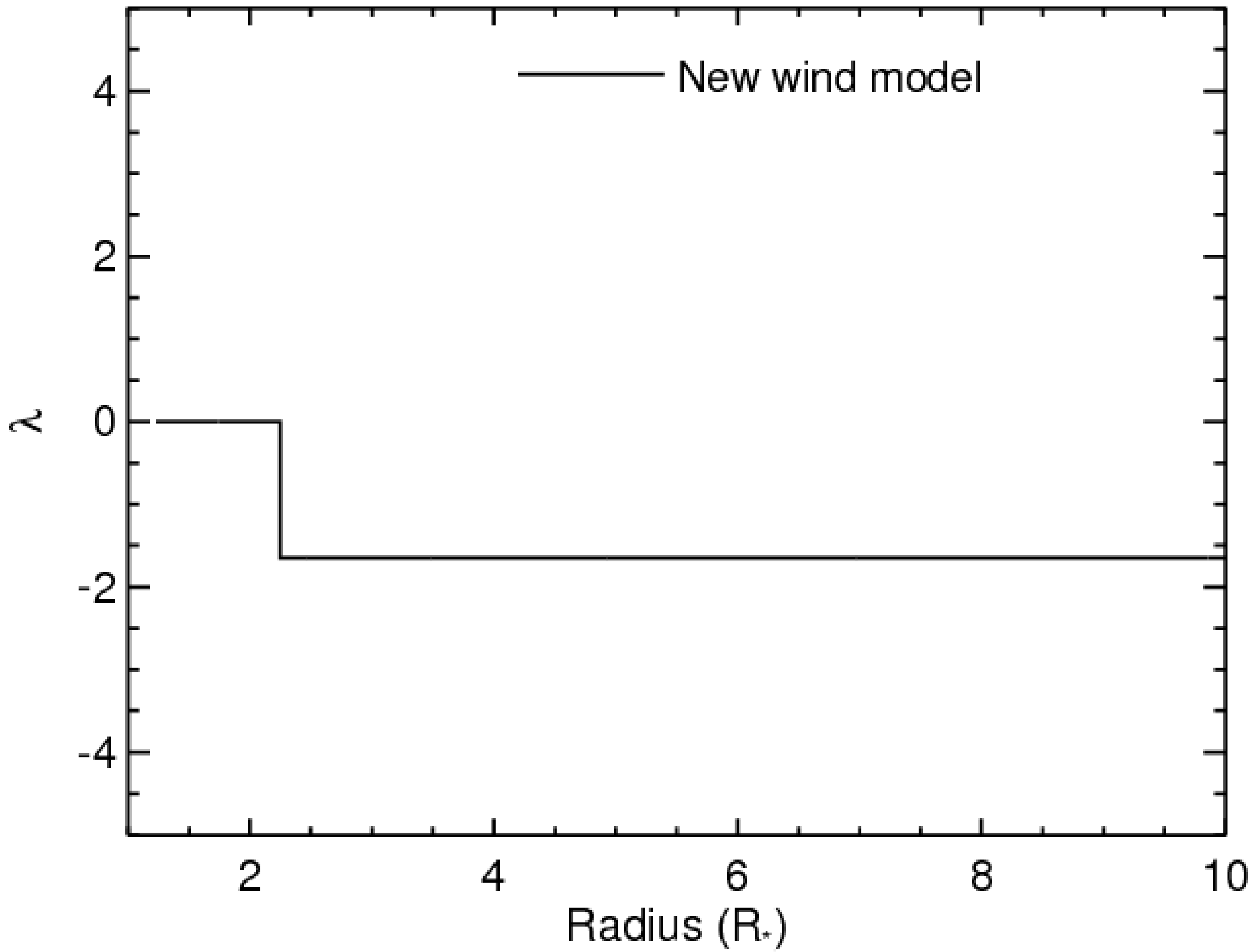
Cooling



Heating



Cooling and Heating Processes



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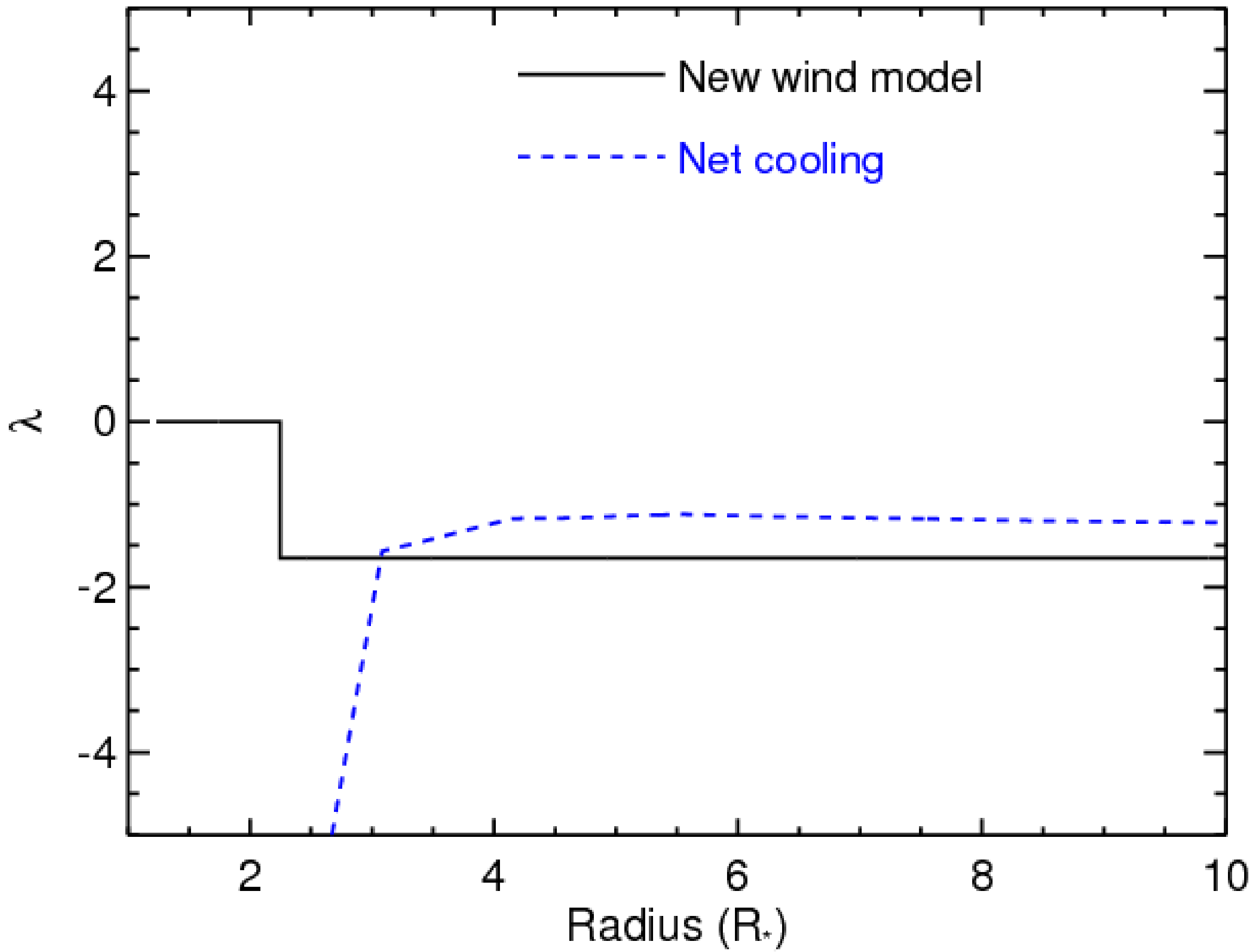

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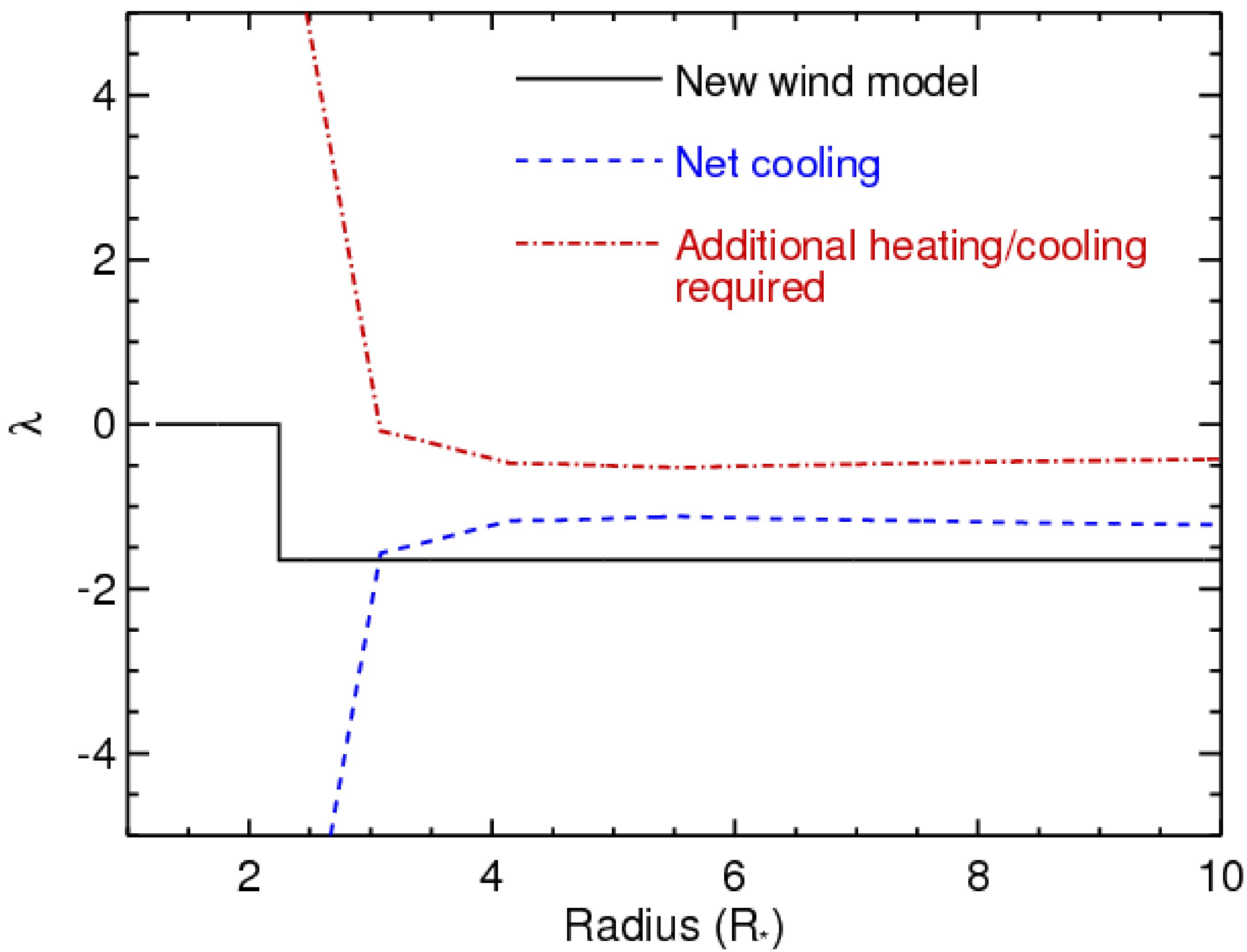


Radio Emission Mechanisms

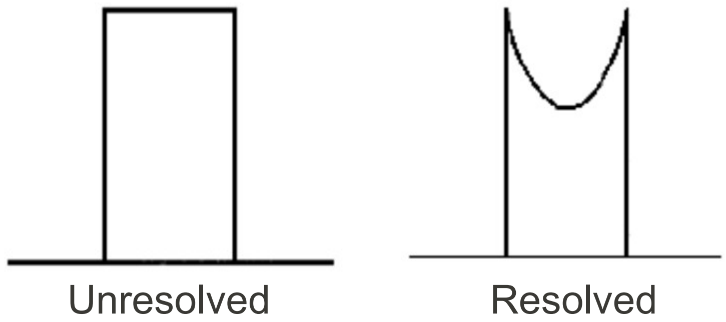
1) Molecular Emission lines

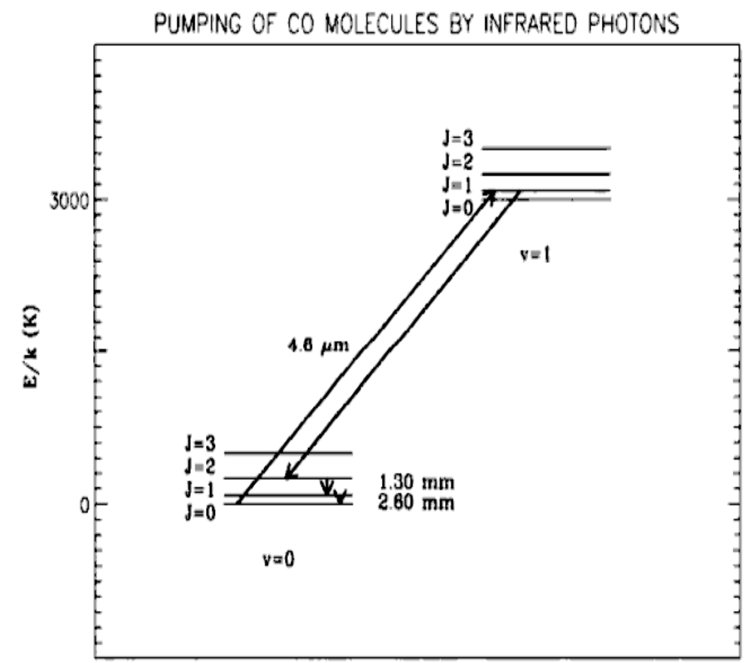
- Line profiles: flat-topped or horned shaped (optically thin)

- 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 and H_2 collisions. Photo-excitation of vibrational levels by IR photons.





1) Thermal Bremsstrahlung Emission

- Opacity is proportional to ~ $\lambda^{2.1}$

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

Source or beam size