Effect of center to limb brightness variations on high resolution solar observations

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- Mainly focused on ALMA observations
- Eclipsing binary stars center to limb brightness variations are usually called limb darkening
- Limb brightening is also possible
- Related to optical depth
- In center always deeper

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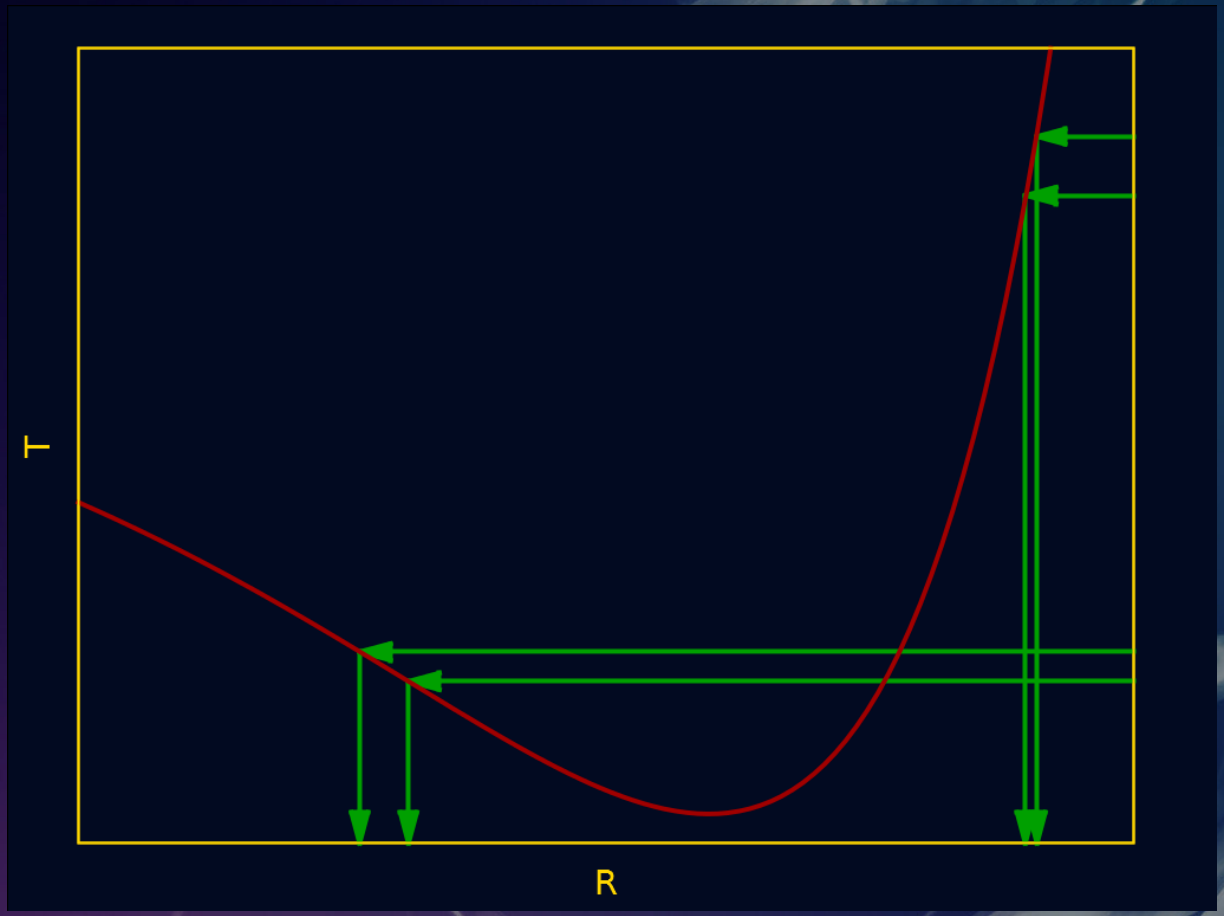
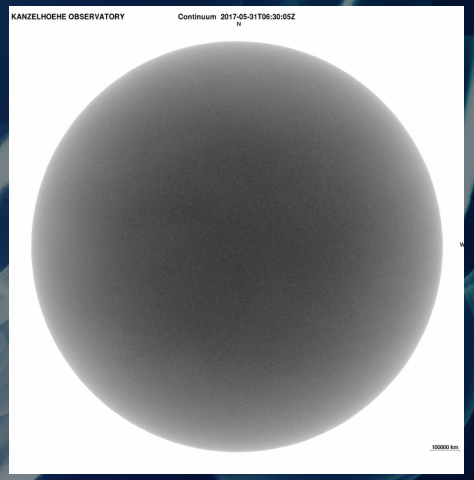
Schematic view of center to limb variations





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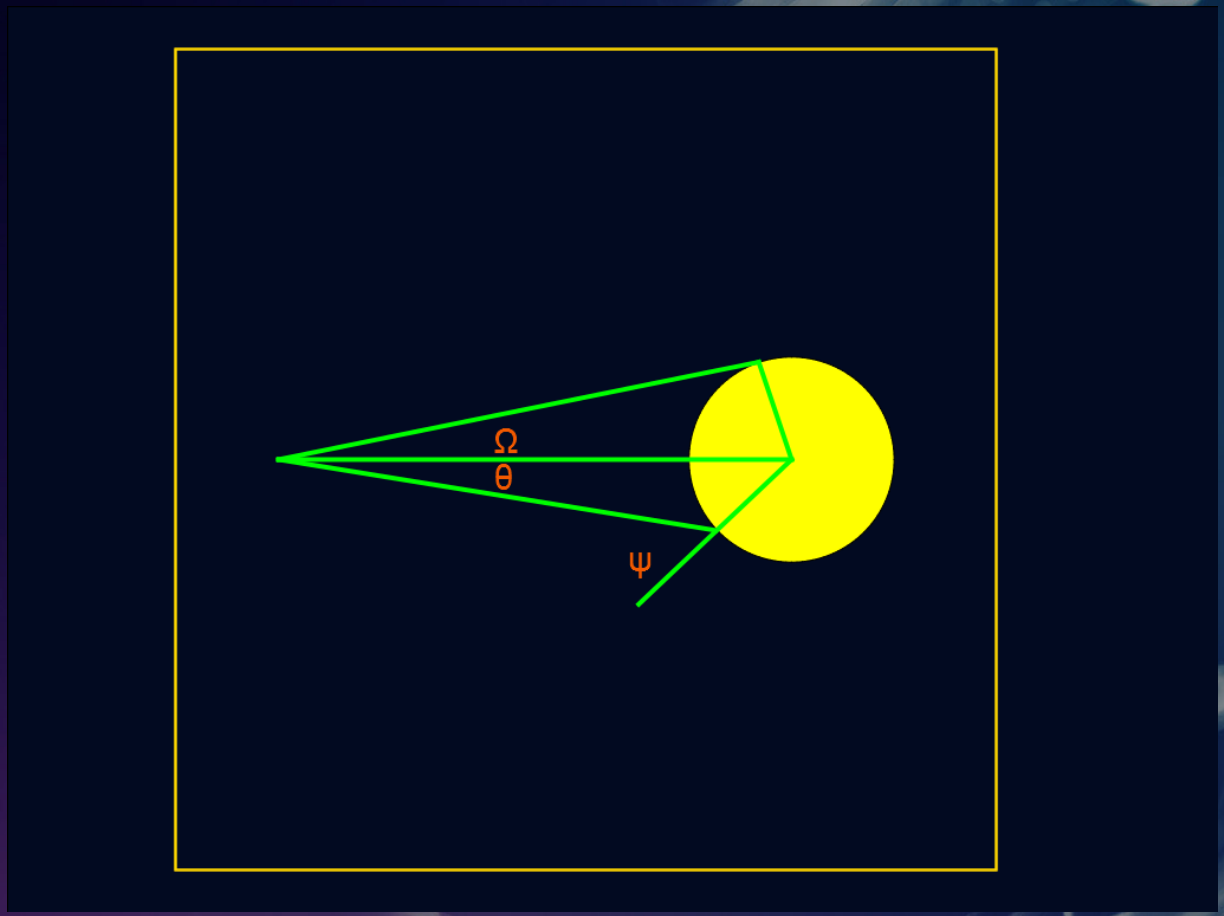
Geometry and equation



$$\frac{I(\psi)}{I(0)} = \sum_{k=0}^{N} a_k \cos^k(\psi)$$

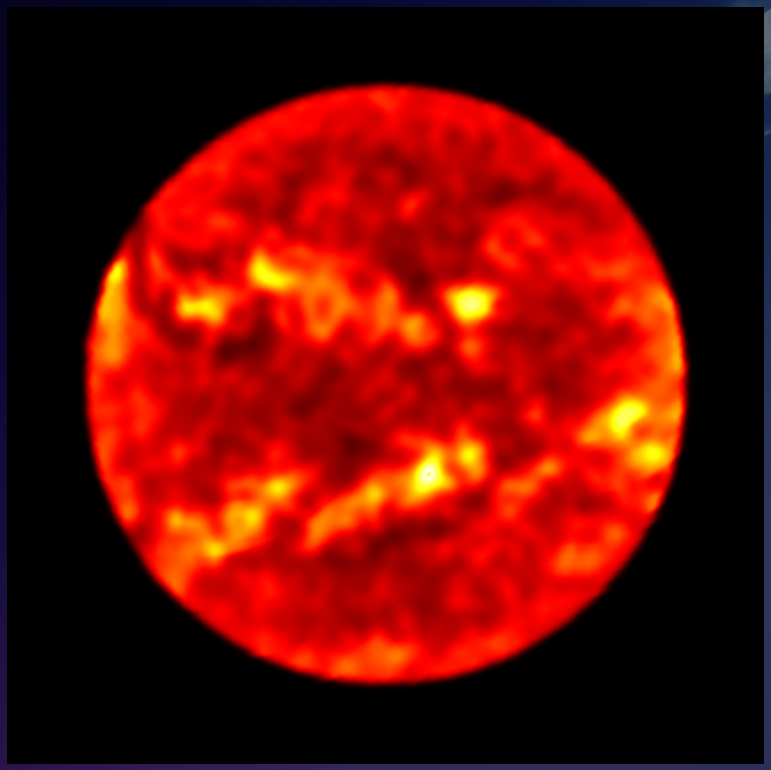
$$\cos(\psi) \approx \sqrt{1 - \left(\frac{\theta}{\sin(\Omega)}\right)^2}$$

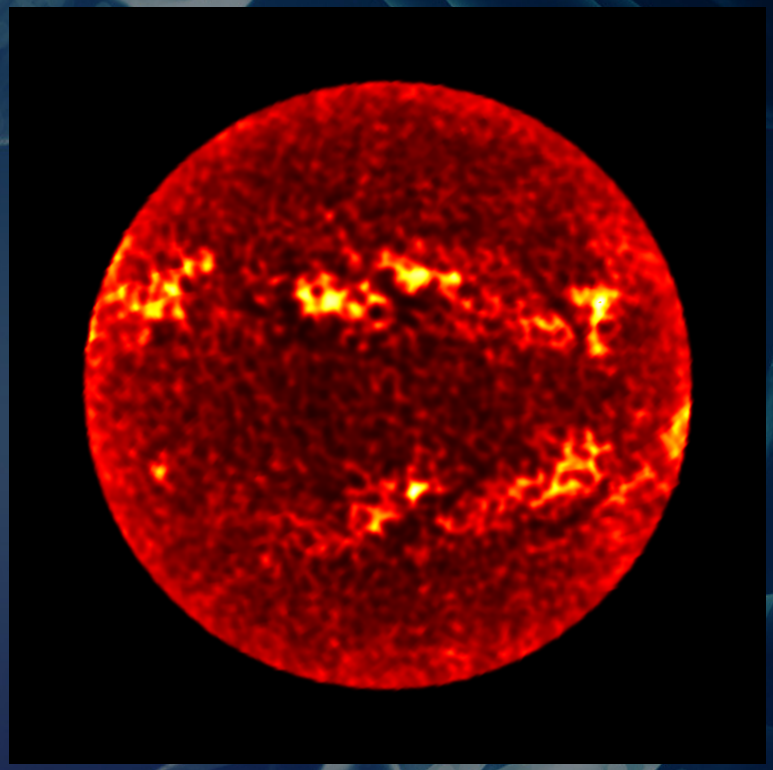
$$\cos(\psi) \approx \sqrt{1 - \left(\frac{x}{R_{Sun}}\right)^2}$$

in pixels

$$T_b(\psi) = A_0 + A_1 \cos(\psi) + A_2 \cos^2(\psi)$$

Data (December 2015)





B3 band (6 images)
f = 107 GHz, λ = 2.8 mm
Resolution = 6 arcsec/pixel
Image 400x400 pixels

B6 band (3 images)
f = 248 GHz, λ = 1.2 mm
Resolution = 3 arcsec/pixel
Image 800x800 pixels

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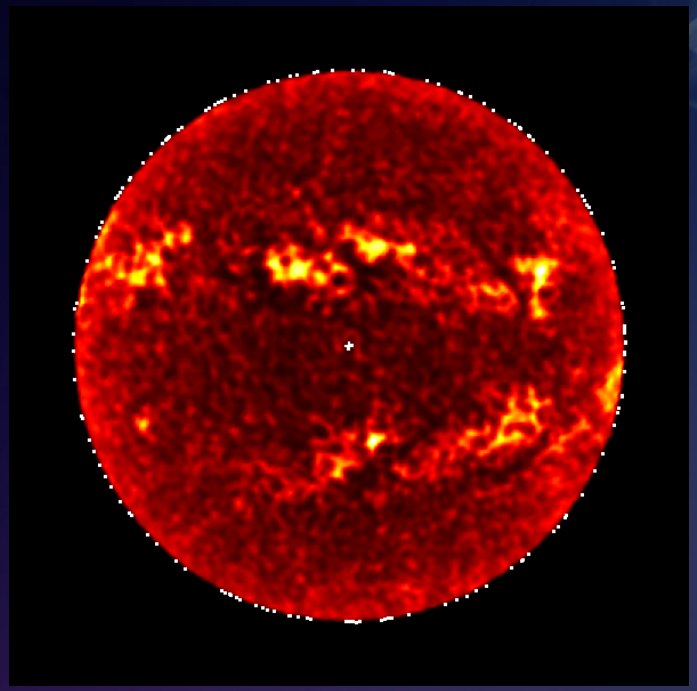
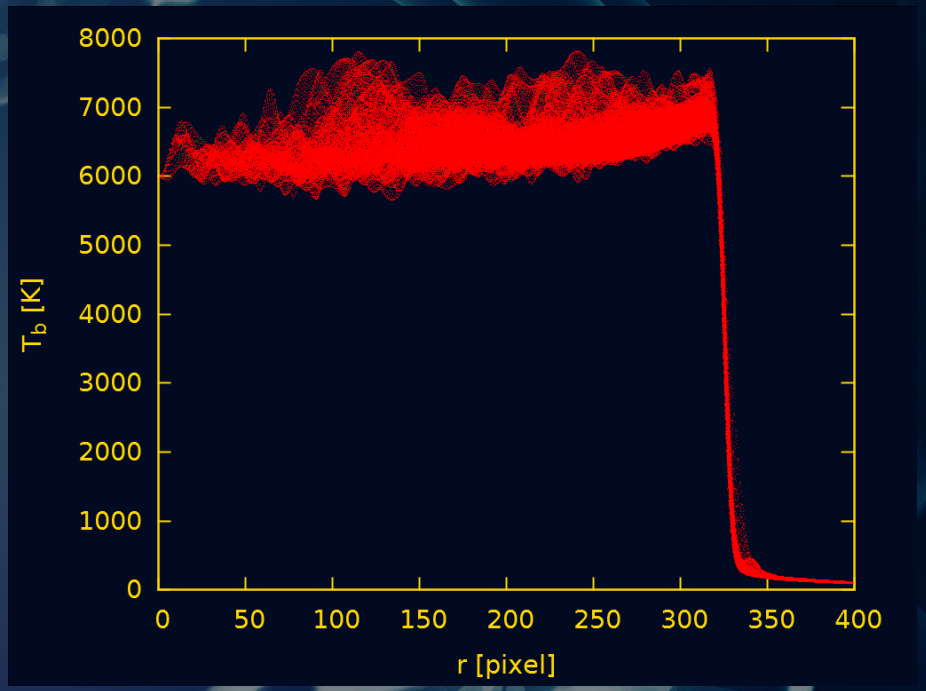
Find the center and plot $T_b(r)$





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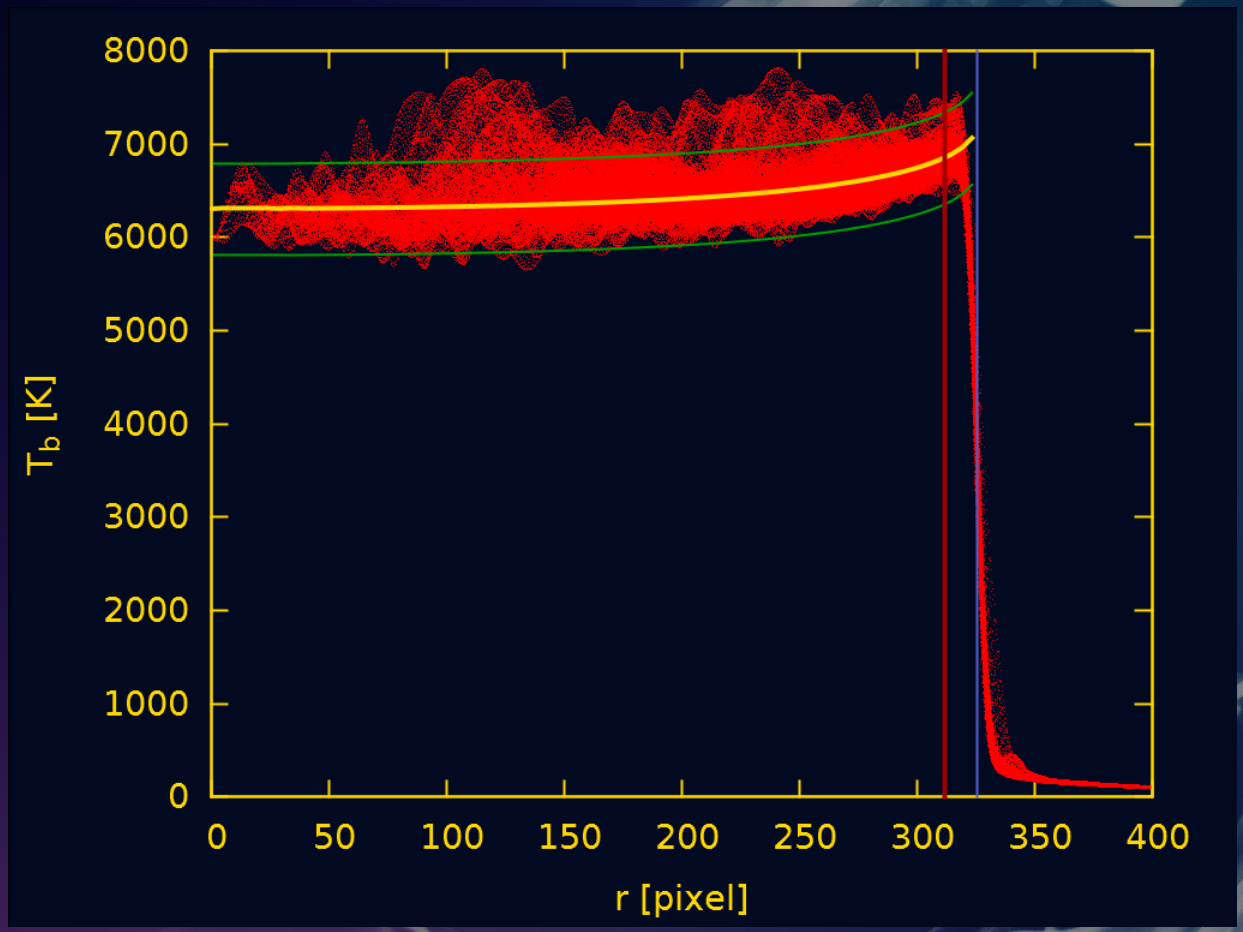
Fitting algorithm

- Find R_{Sun} in pixels
- JPL Horizons: photospheric $2R_{Sun} \approx 1950''$ (in Dec 2015)
- B3: R_{Sun} = 162.8 pixels (photosphere + 1000 km)
- B6: R_{Sun} = 325.6 pixels (photosphere + 1000 km)
- Polynomial fit - $T_b(r)$
- Interquartile range, removal of outliers, use fast sort algorithm
- Iterate until no outliers (<10)

Results B6



Band 6:

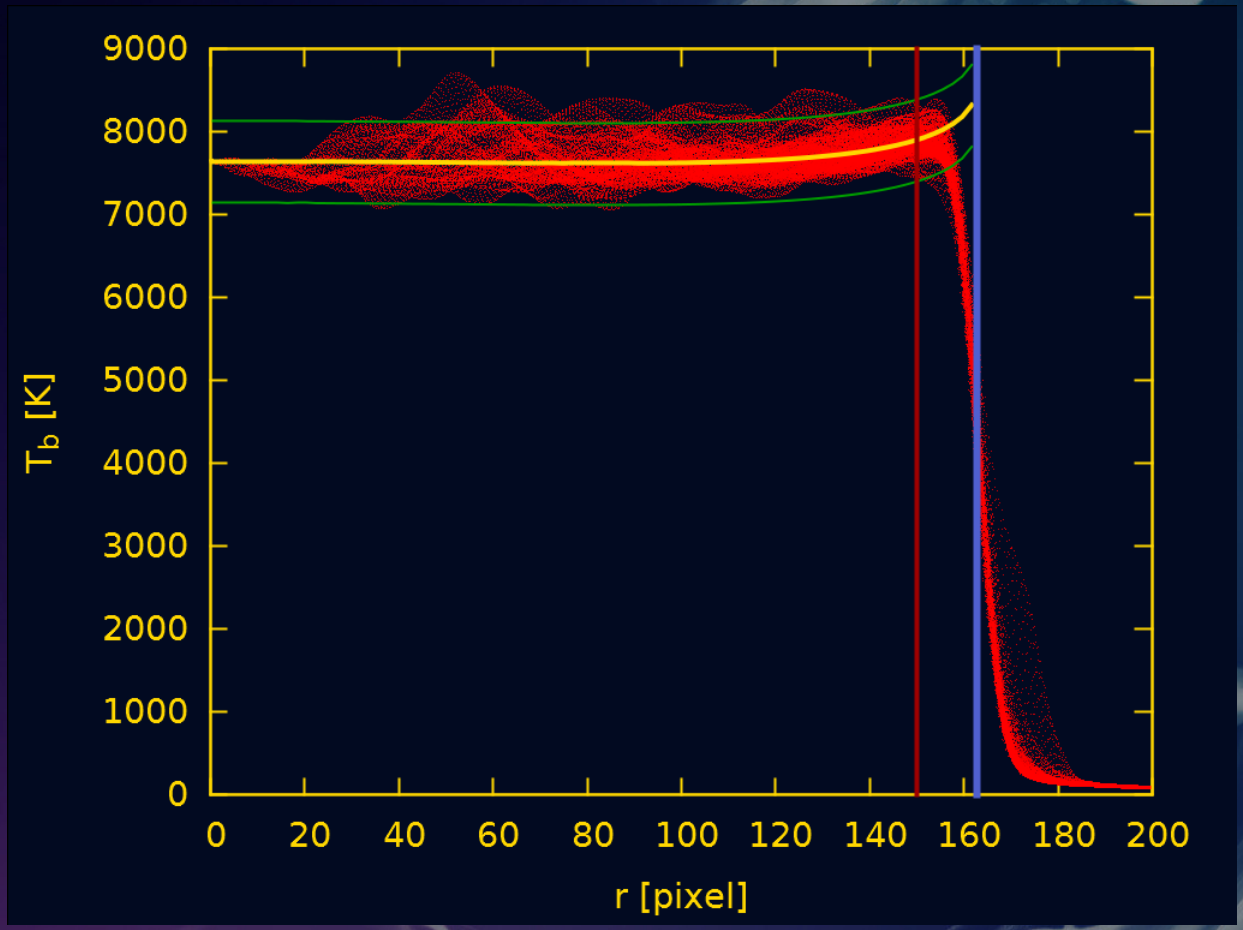
$A_0 = 7229 \pm 4$ K

$A_1 = -1443 \pm 13$ K

$A_2 = 523 \pm 10$ K

$T_b(0) = A_0 + A_1 + A_2 = 6309$ K

Results B3



Band 3:

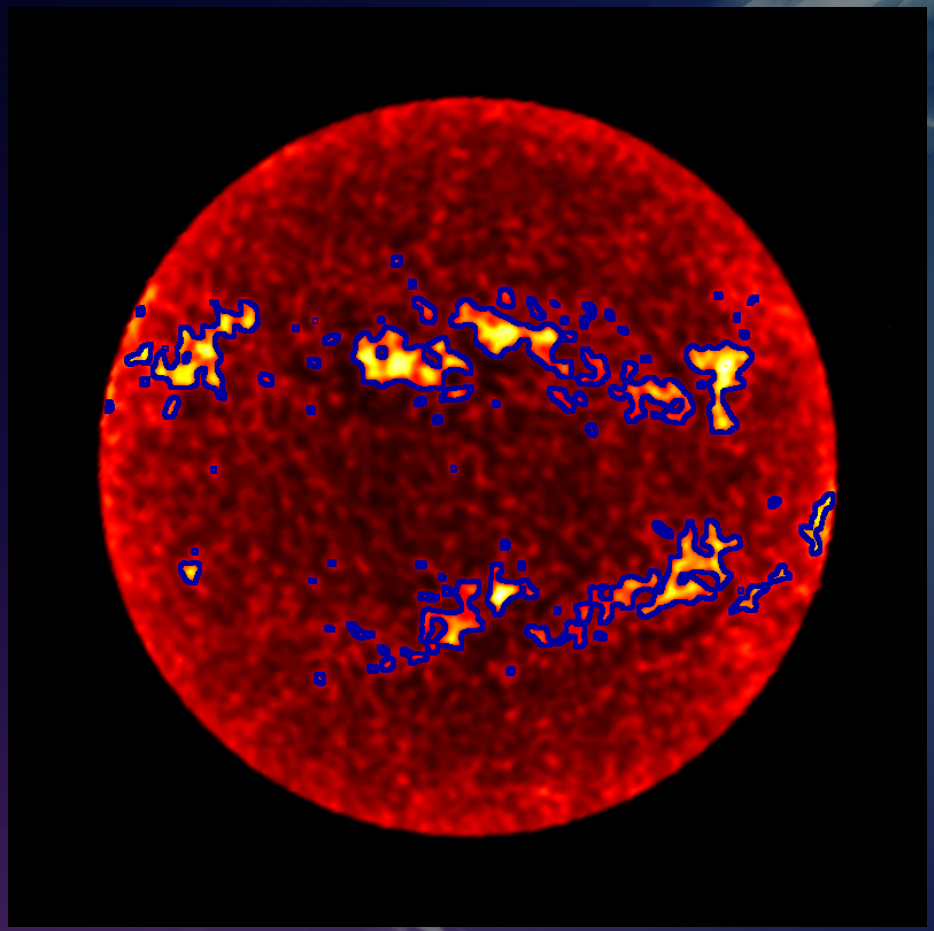
$A_0 = 8563 \pm 13$ K

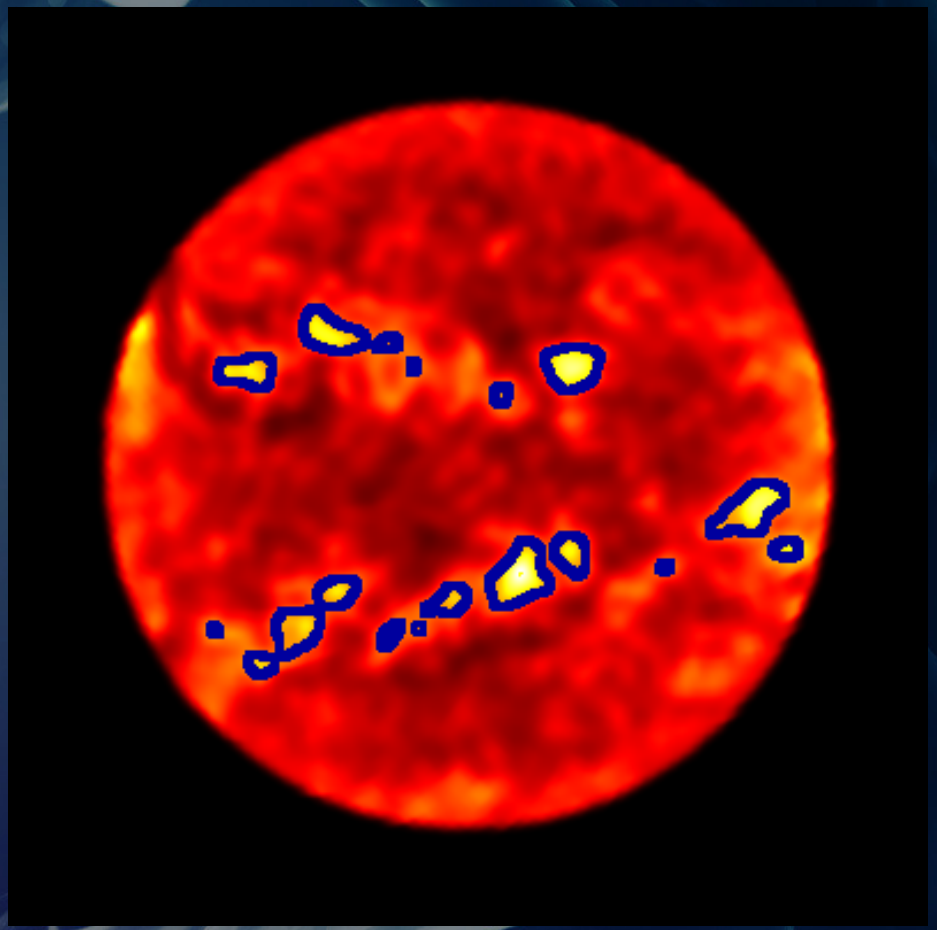
$A_1 = -2196 \pm 38$ K

$A_2 = 1278 \pm 26$ K

$T_b(0) = A_0 + A_1 + A_2$
$= 7645$ K

Outliers = Active region





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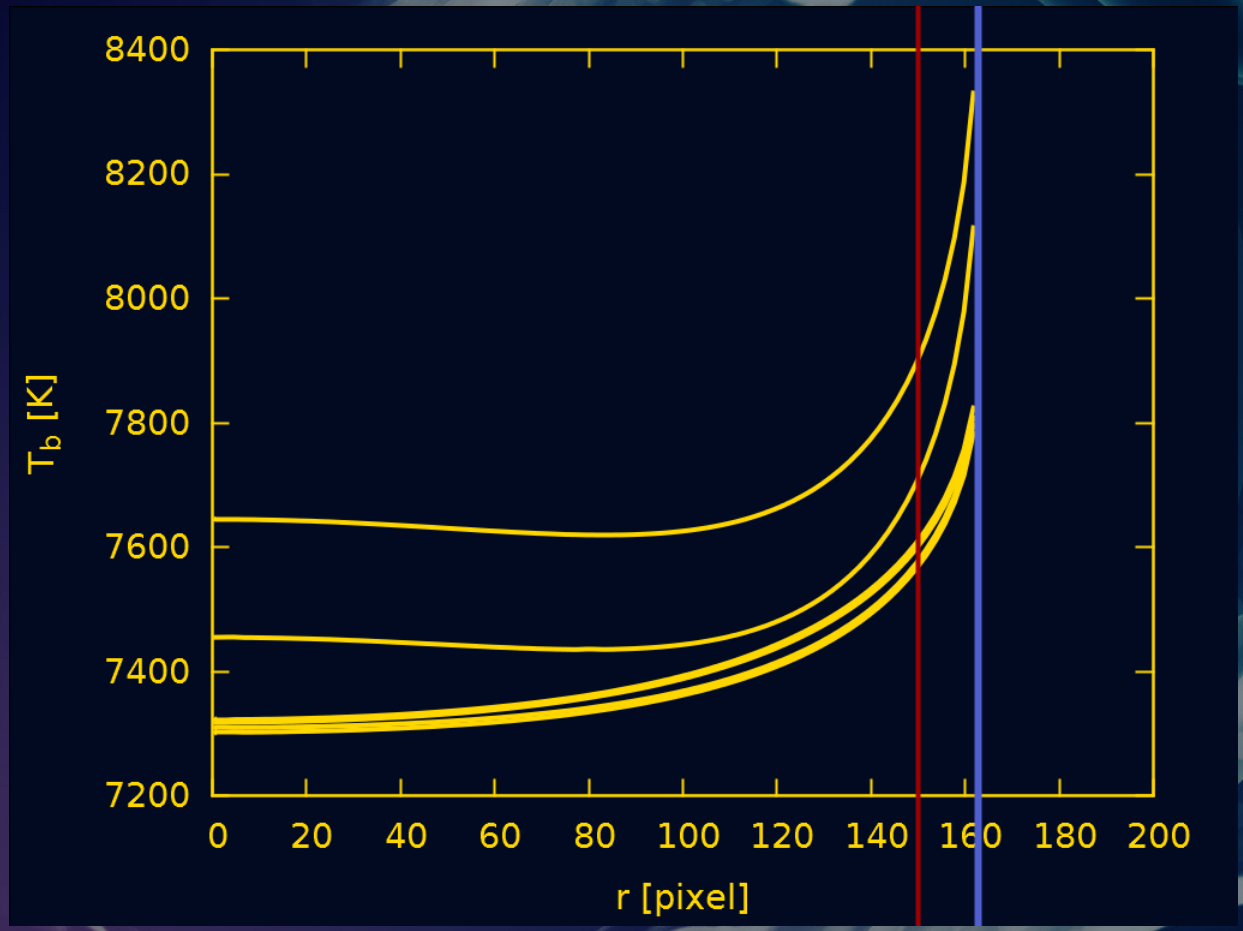
B3 Fits for 6 images



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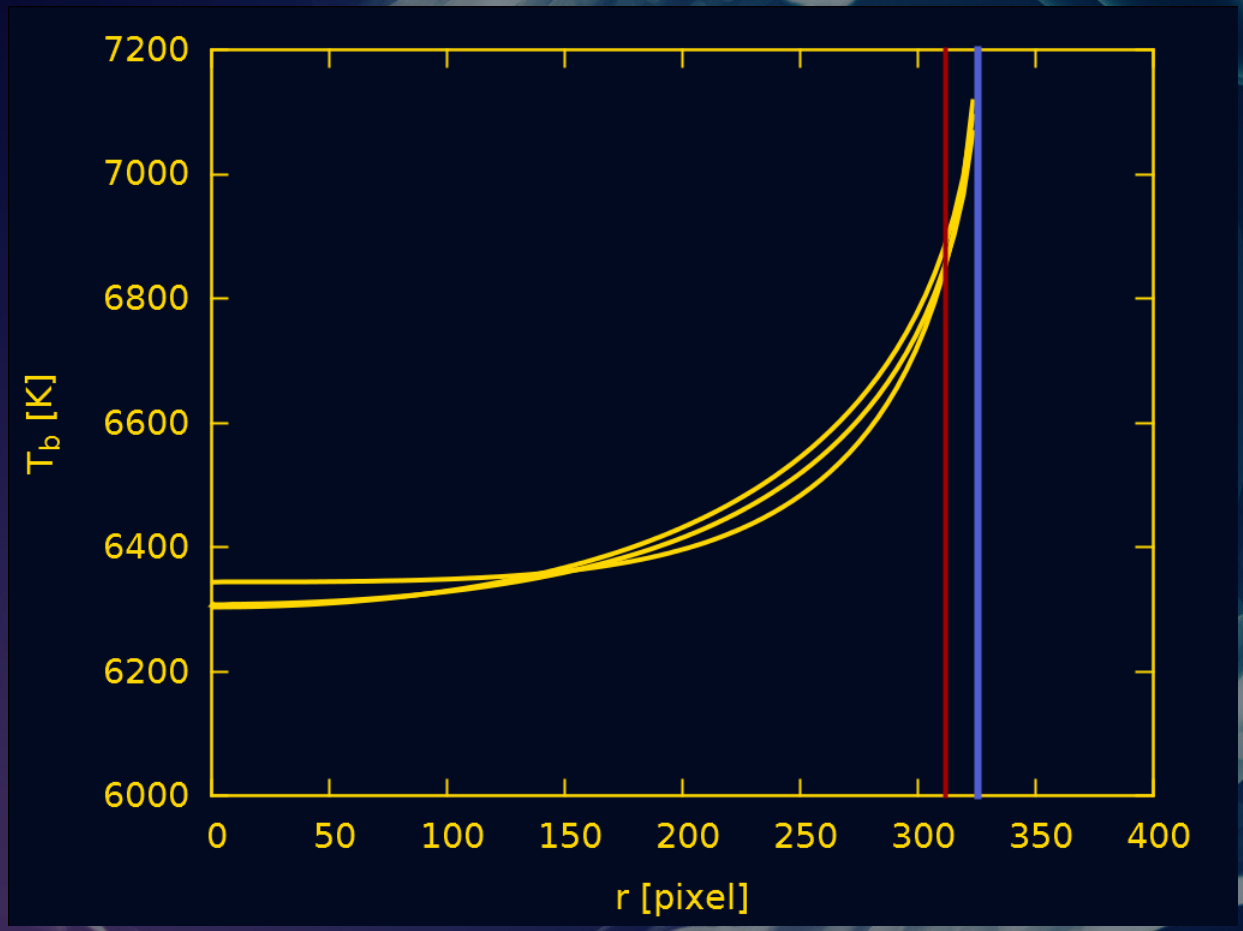
B6 Fits for 3 images



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Quiet Sun level

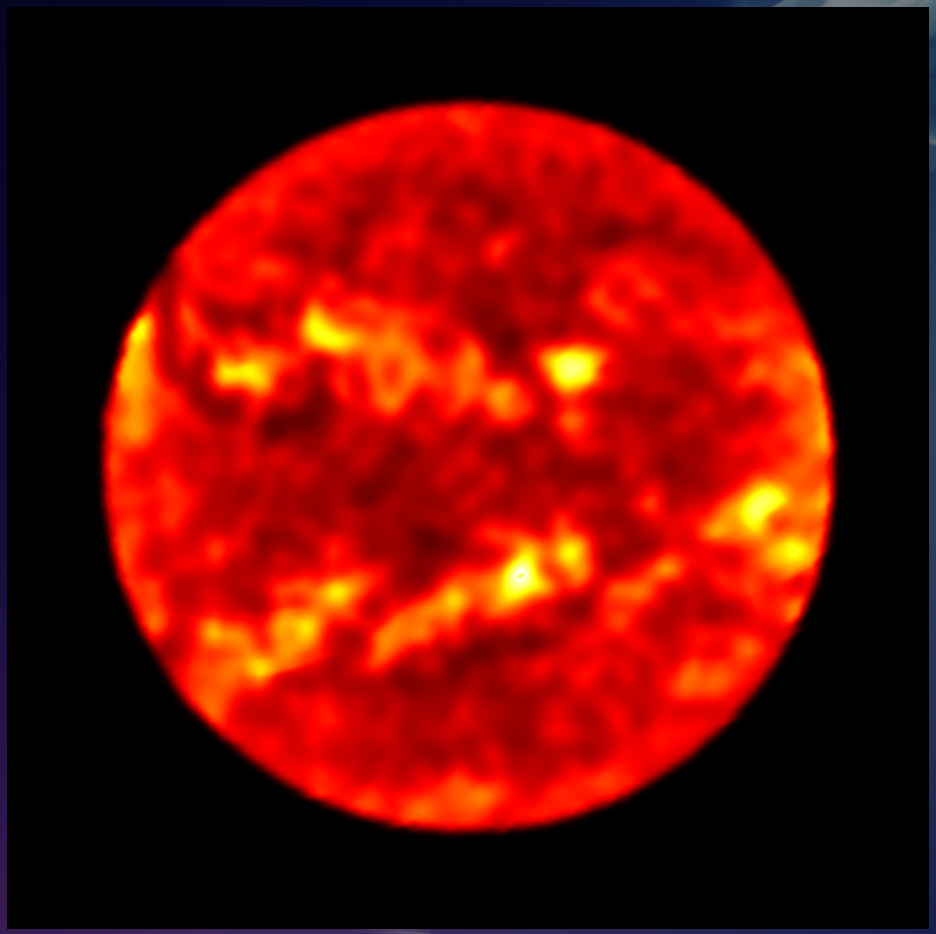
B3						
$T_b(0)$ [K]	7645	7456	7319	7310	7303	7323

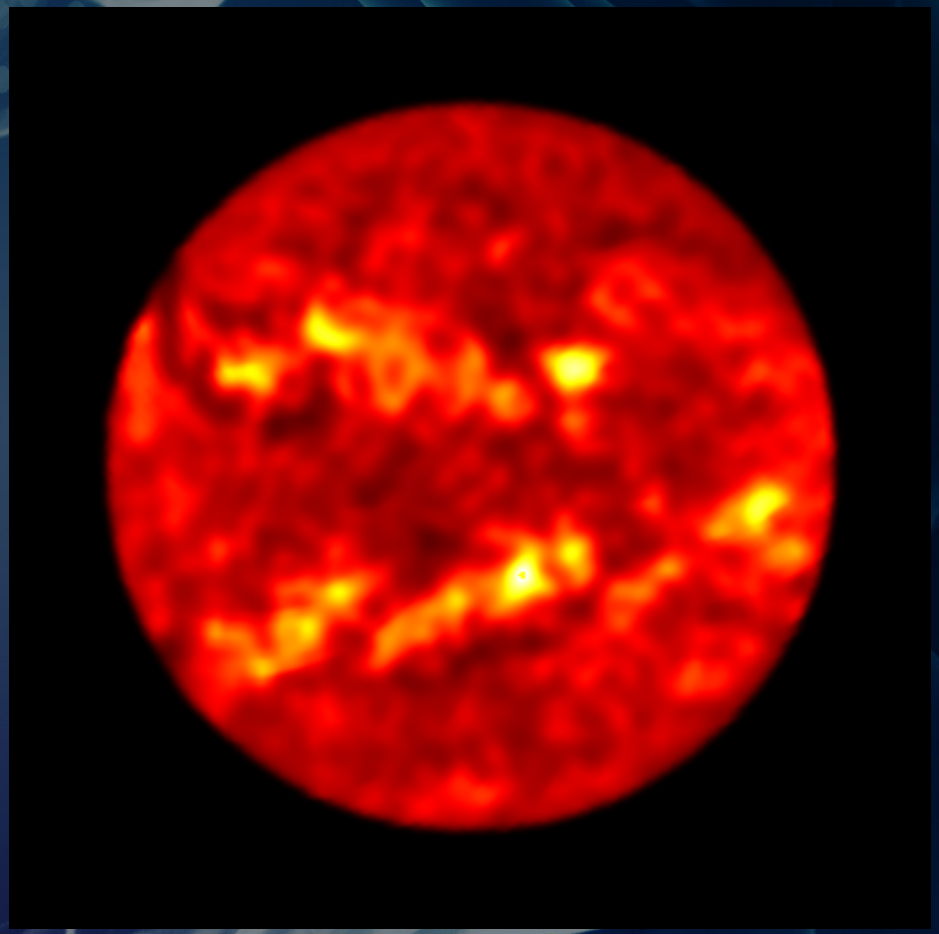
White et al. (2017): 7390 ± 220 K
$(T_b(90) - T_b(0))/T_b(0)*100\% \approx 8\%$

B6			
$T_b(0)$ [K]	6309	6344	6304

White et al. (2017): 6040 ± 250 K
$(T_b(90) - T_b(0))/T_b(0)*100\% \approx 12\%$

Flattened Images B3





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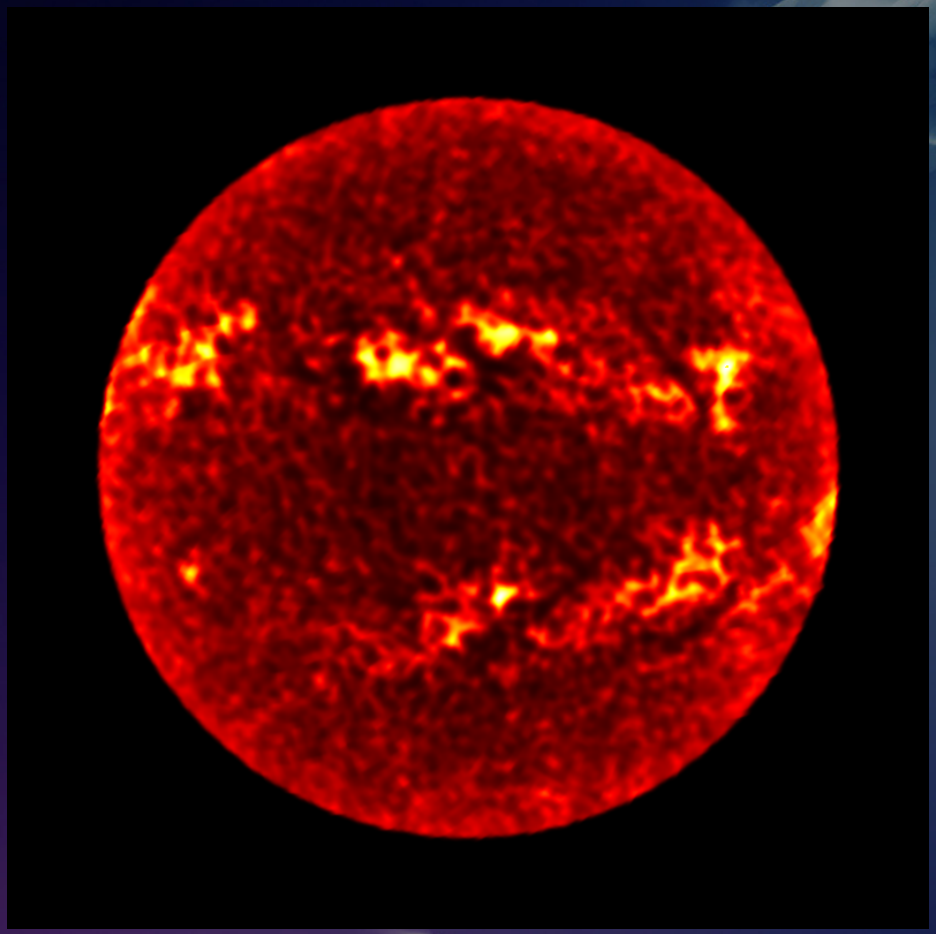
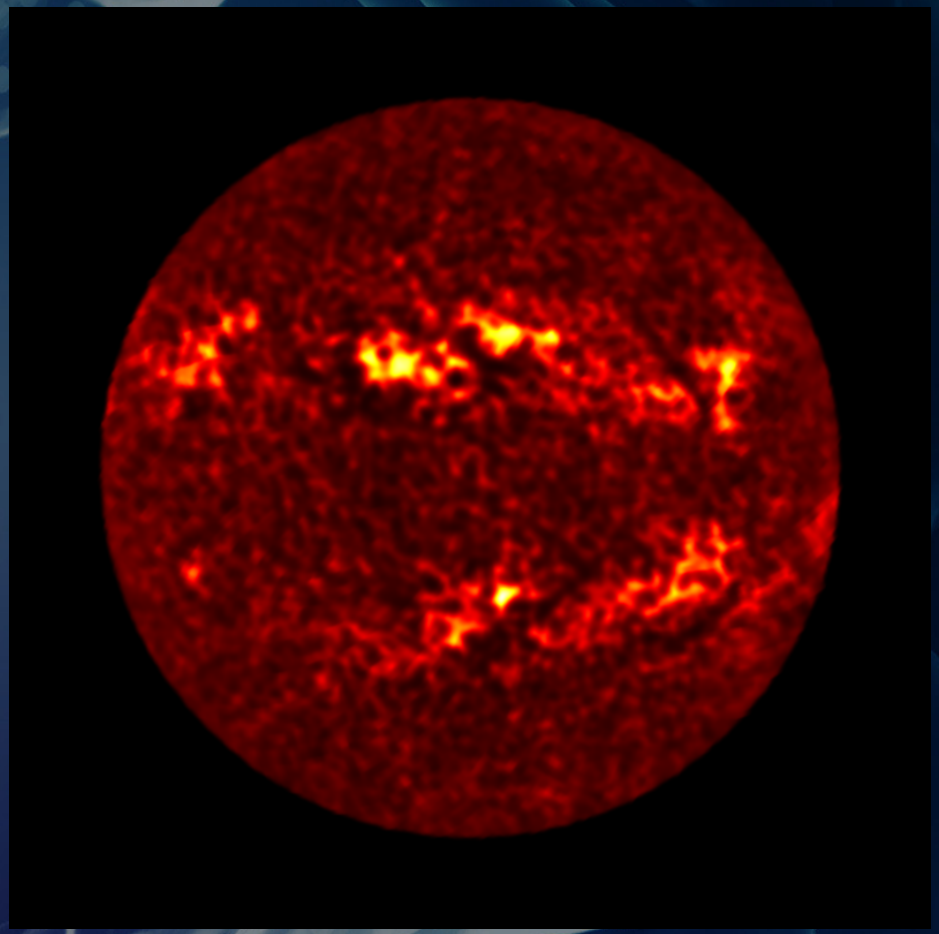
Flattened Images B6





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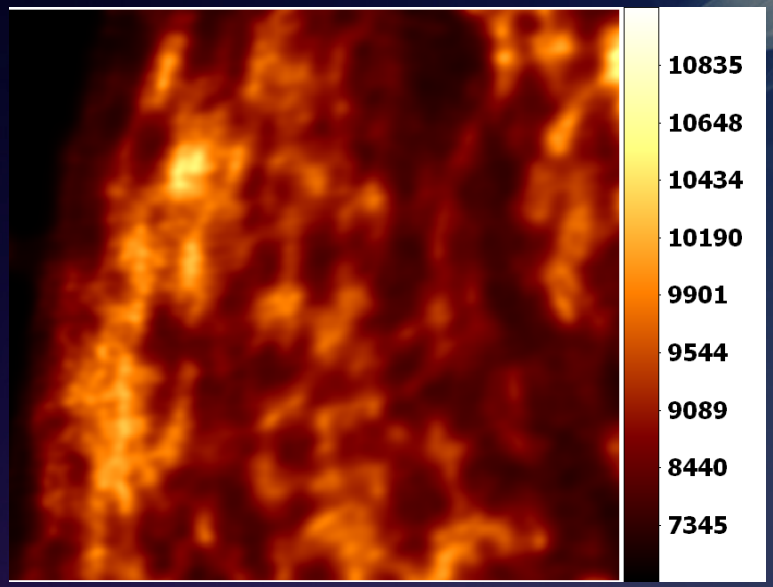
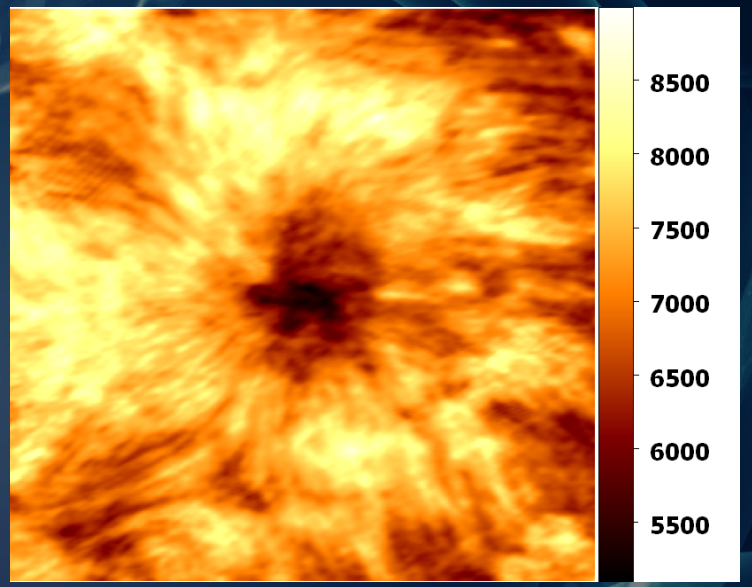
High Resolution?





Can't compare T_b directly (different position, time, band)
Applies to any telescope

Summary & Conslsion

In ALMA wavelenghts we see layers with positive temperature gradient (B3: 8% - B6: 12% increase)

For Band 3 center to limb varies in time? Need to calculate the profile for each observation. Solar cycle QS level variations?

For proper analysis, images need to be flattened with center to limb brightness function (and applied to high resolution images)

Presented procedure is not perfect, models need to take the position into account

Also applies to any other telescope (including EST)

Moral of the story: Don't lose the global picture when looking at the fine details