Electron-Ion Equilibration in the Merging Galaxy Cluster Abell 665

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Background

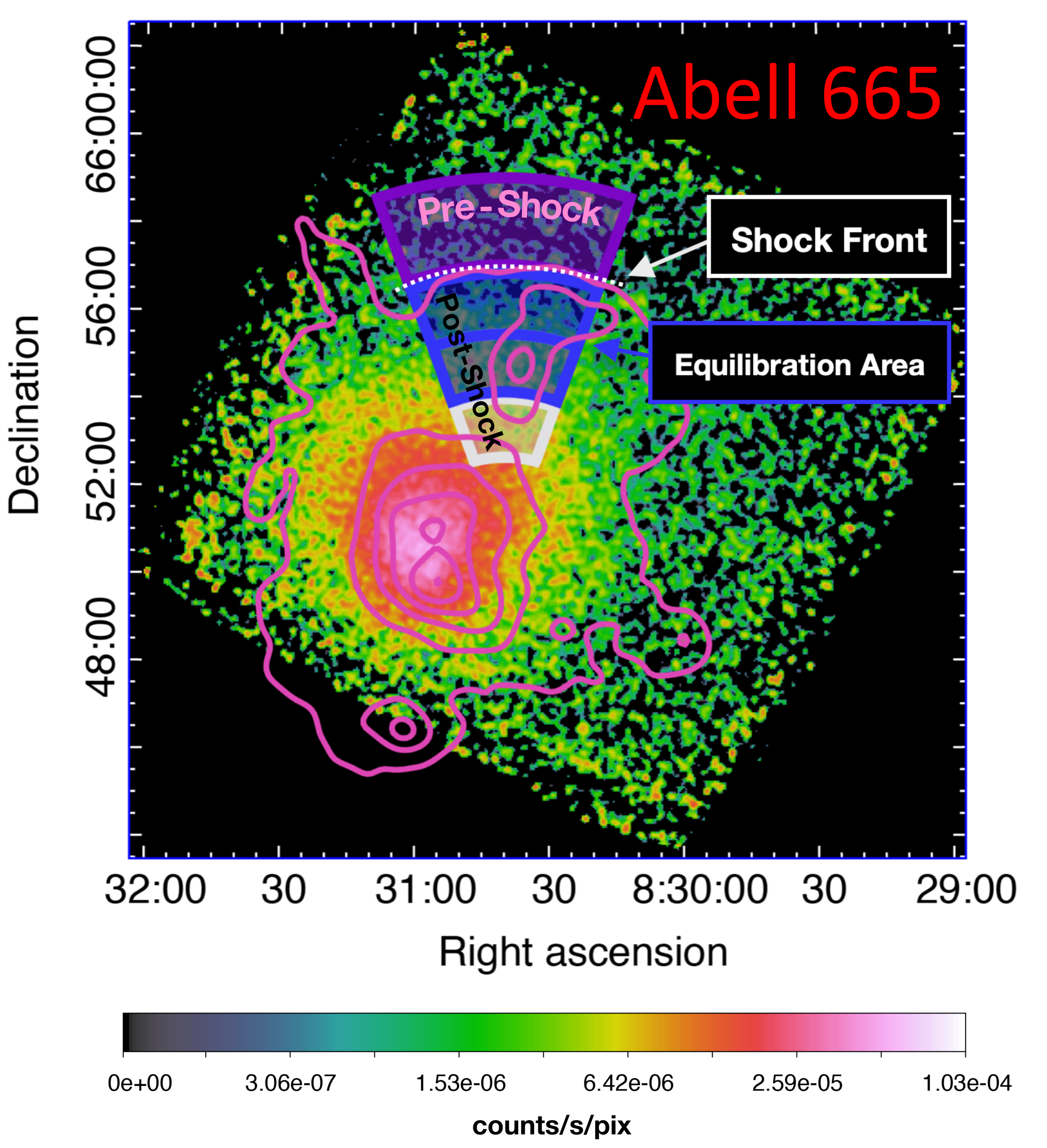


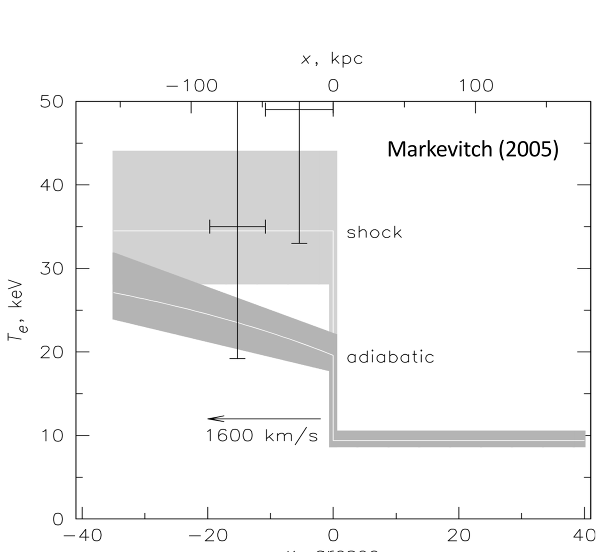
Fig 1: Exposure corrected, background subtracted NuSTAR image of **Abell 665, a merging cluster in the plane of the sky**. The **powerful shock front (M~3)** is located in-between the purple pre-shock region and the blue post-shock, equilibration regions. LOFAR radio contours are overlaid in pink.

Open Question:

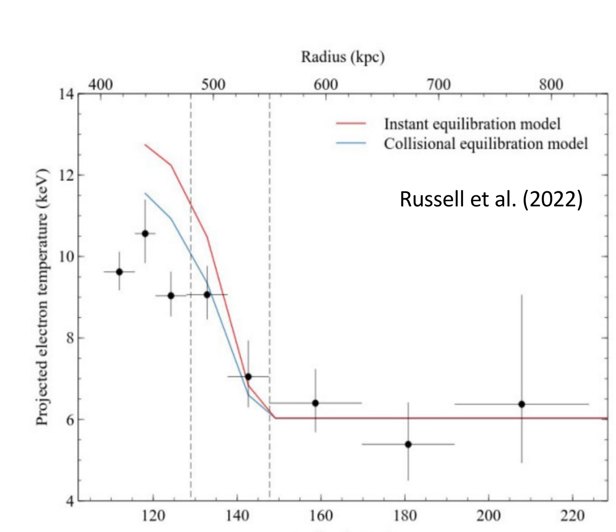
When two galaxy clusters merge, an enormous amount of energy (~10^{64} erg) is released through shocks. The electron and ion populations in the hot (~10^{8} K) Intra-Cluster Medium (ICM) are either:

- Both strongly heated by the shock front and **"instantly" equilibrate**. OR
- The ions are initially heated and **collisionally equilibrate** with the adiabatically compressed electrons over ~100 Myr.

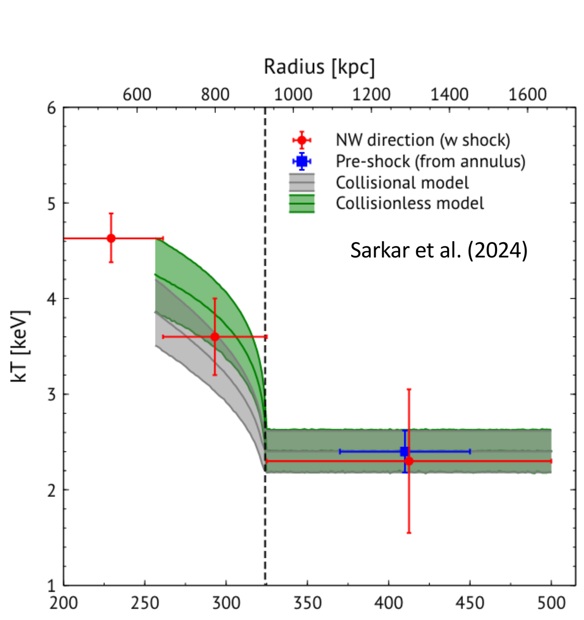
Previous post-shock electron temperature measurements:



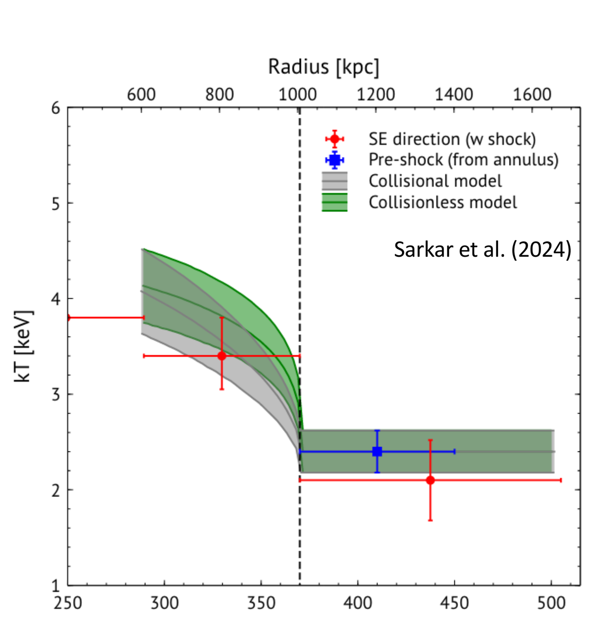
Bullet Bow Shock (M=3.0 += 0.4)



Abell 2146 Bow Shock (M=2.3 +- 0.2)



Abell 1240 NW Shock (M=1.41 +0.17-0.19)



Abell 1240 SE Shock (M=1.49 +0.22-0.24)

Analysis

Accounting For NuSTAR's PSF

NuSTAR has a large PSF that scatters light into regions of interest. We can use *NuCrossARF* to generate "Cross-ARFs" to account for how light is scattered into a region of interest from every other region.

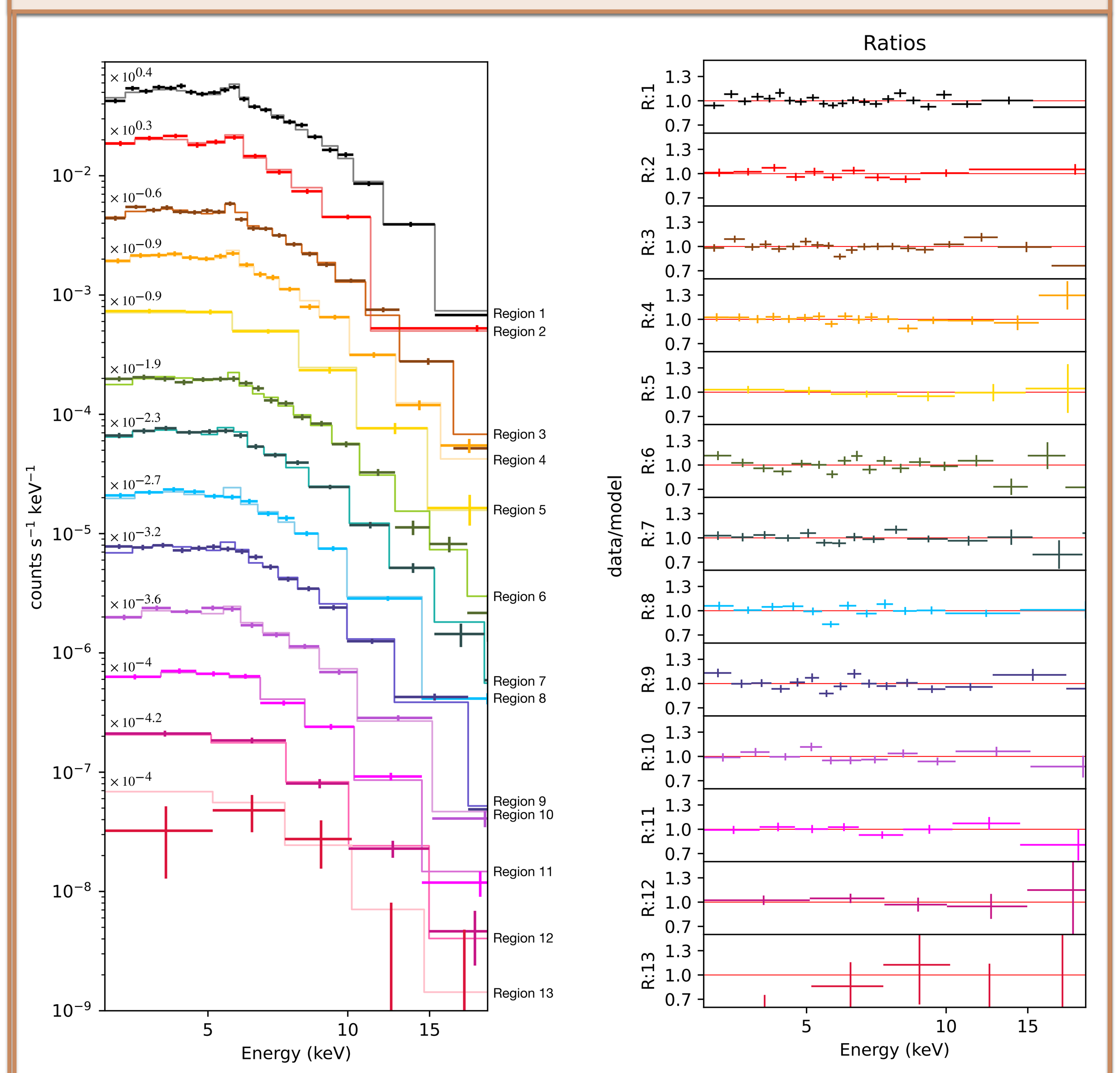


Fig 3: Spectral fitting in the NuCrossARF analysis. Left – spectra fit to *apec* models for each region. Right – corresponding ratios for each region. **Note how well each region's spectra is constrained.**

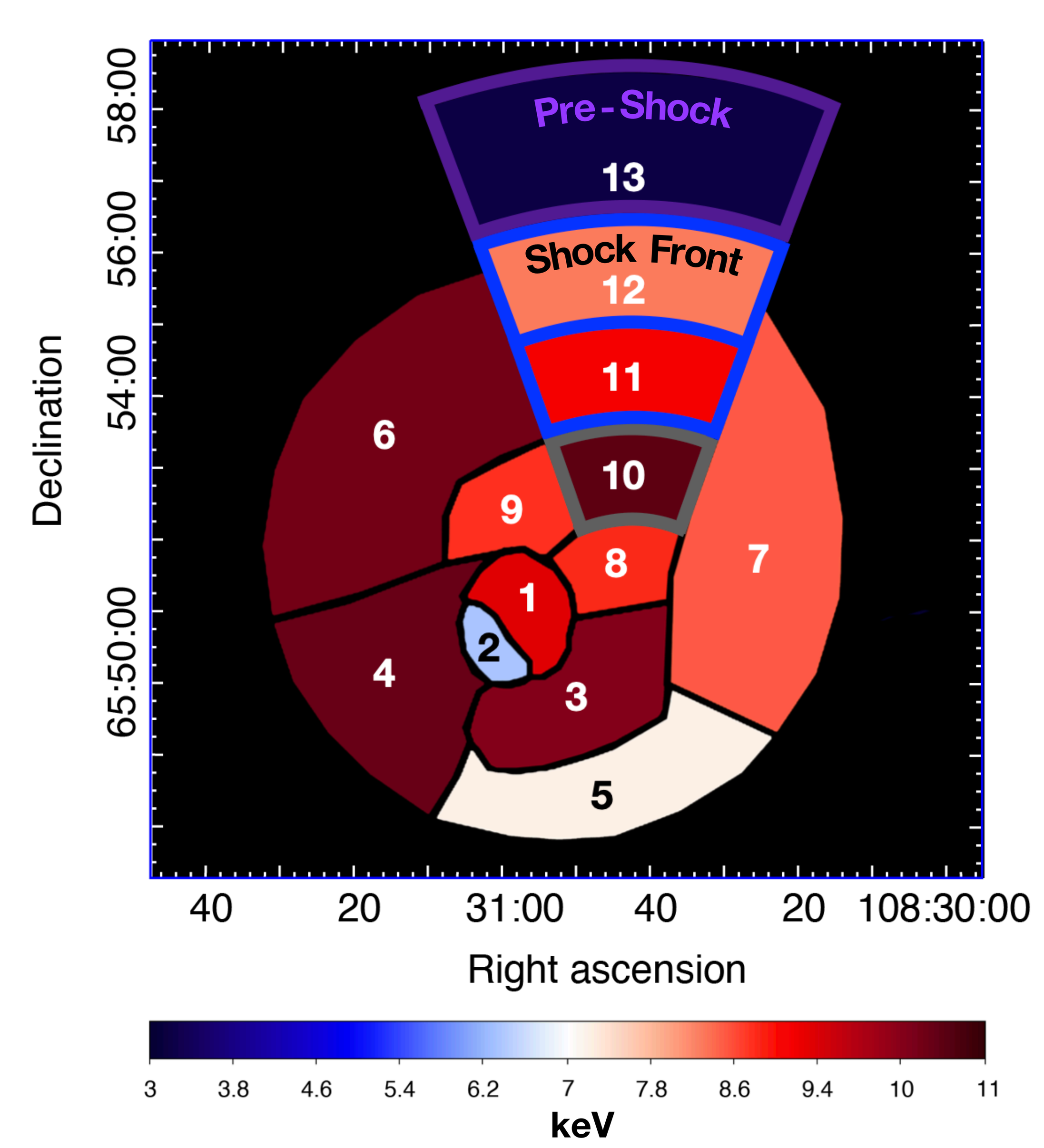


Fig 4: Temperature map from the NuCrossARF Analysis.

Region	kT (keV)	Norm^{b} (10^{-3} cm^{-3})
1	$9.33^{+0.70}_{-0.60}$	$2.33^{+0.12}_{-0.12}$
2	$6.32^{+0.62}_{-0.62}$	$1.90^{+0.20}_{-0.16}$
3	$10.20^{+1.02}_{-0.92}$	$1.34^{+0.09}_{-0.08}$
4	$10.46^{+1.66}_{-1.55}$	$0.91^{+0.10}_{-0.08}$
5	$7.19^{+5.44}_{-2.58}$	$0.24^{+0.11}_{-0.08}$
6	$10.39^{+1.26}_{-1.00}$	$1.25^{+0.08}_{-0.08}$
7	$8.49^{+0.92}_{-0.76}$	$1.14^{+0.08}_{-0.08}$
8	$8.83^{+1.14}_{-0.89}$	$0.94^{+0.08}_{-0.08}$
9	$8.74^{+0.93}_{-0.76}$	$1.17^{+0.09}_{-0.08}$
10	$10.60^{+1.39}_{-1.25}$	$0.71^{+0.06}_{-0.05}$
11	$9.14^{+1.57}_{-1.29}$	$0.52^{+0.06}_{-0.05}$
12	$8.28^{+3.29}_{-2.06}$	$0.25^{+0.06}_{-0.05}$
13	3.20^{c}	0.01^{c}

Table 1: Temperature values from the NuCrossARF analysis, matching the kT values in the above kT map.

Note that the pre-shock temperature (Region 13) is fixed to a Chandra measured value (Desadia+2016).

Results

Equilibration Models

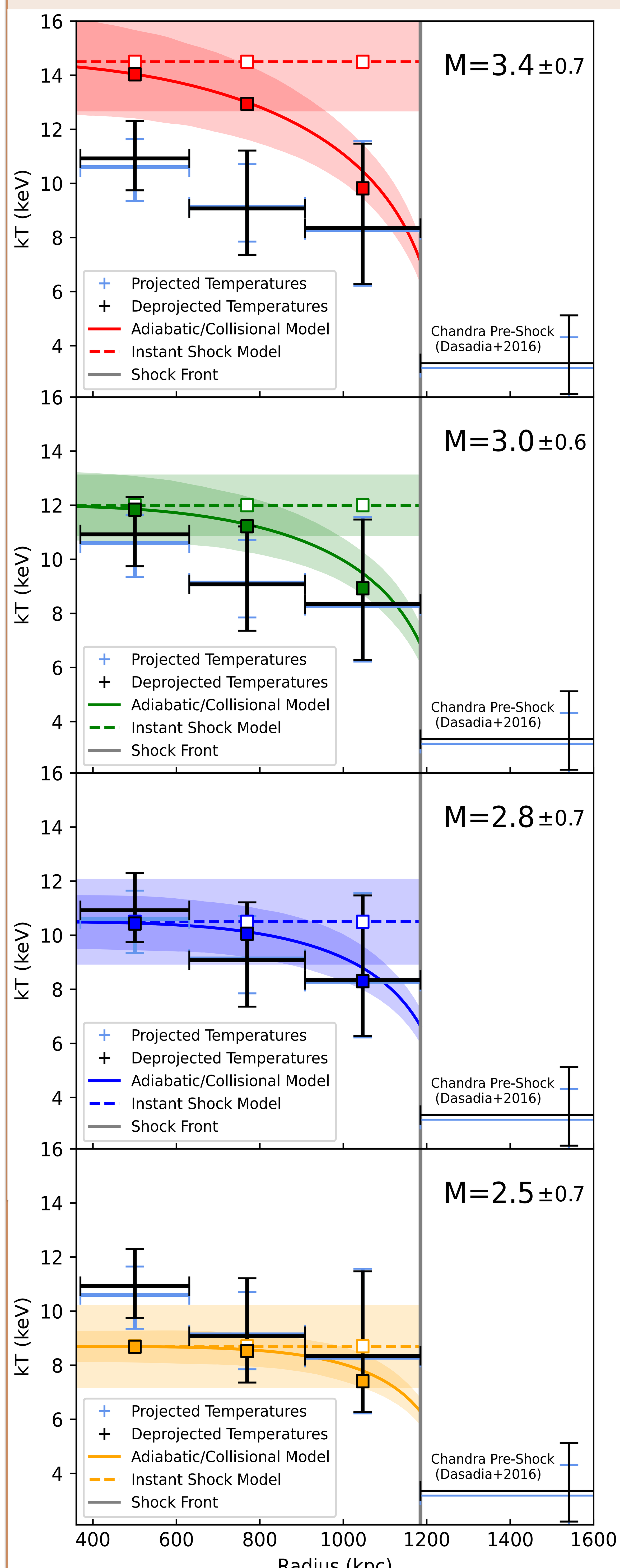


Fig 5: **Post-Shock Electron Temperatures compared to equilibration models for different shock strengths in Abell 665**.

The Mach number (shock strength) can be calculated multiple ways, including from multiple measurements. The Mach numbers presented here represent possible, derived values.

Delayed equilibration is favored when the Mach number is high (M~3), which is supported by Chandra density jump measurements.

For more details, please see the **Accepted Paper in ApJ**, link to ArXiv ->

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