Quantum thermodynamics of coronal heating

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`arXiv:2103.08746 [astro-ph.SR]`

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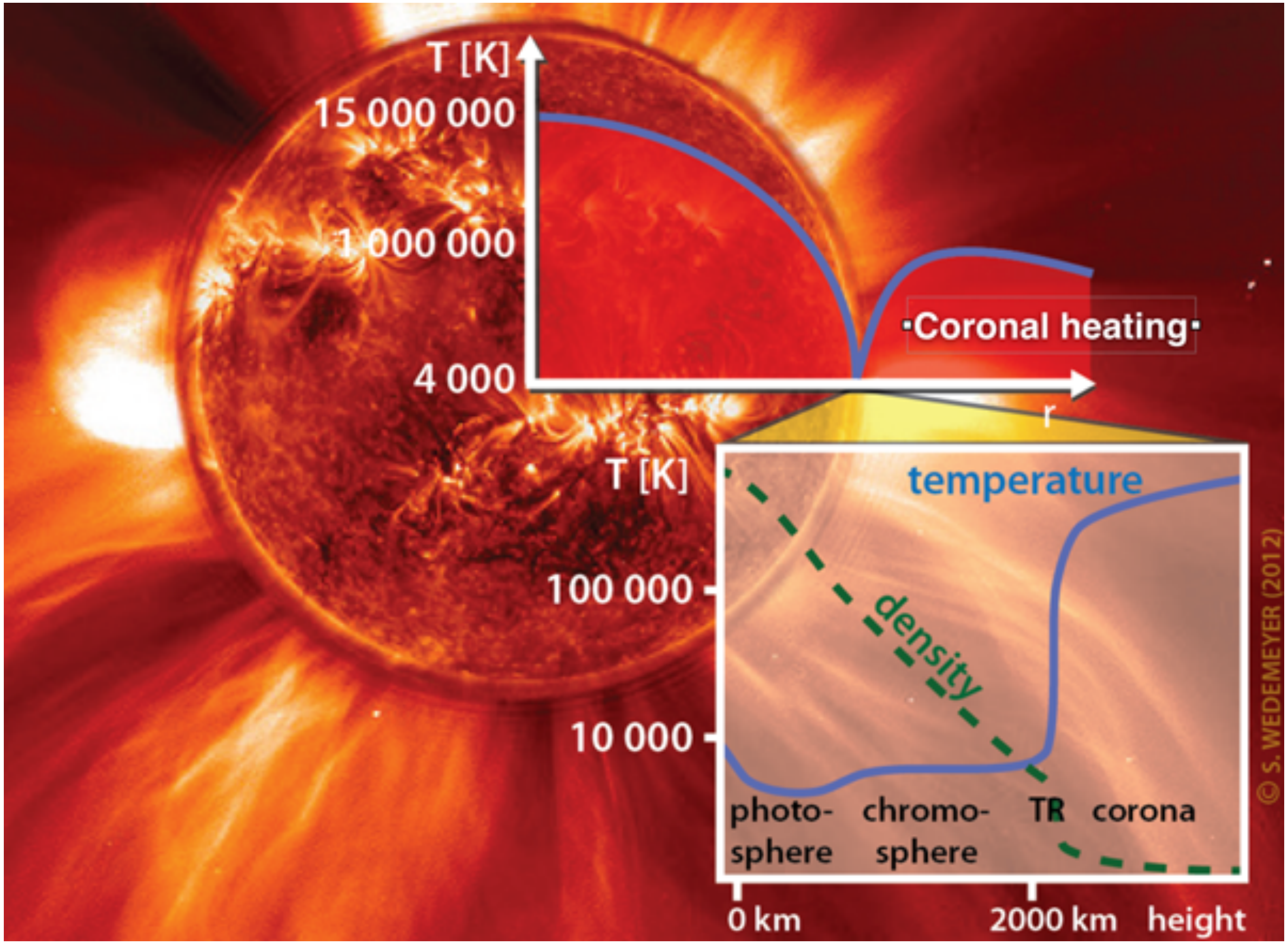
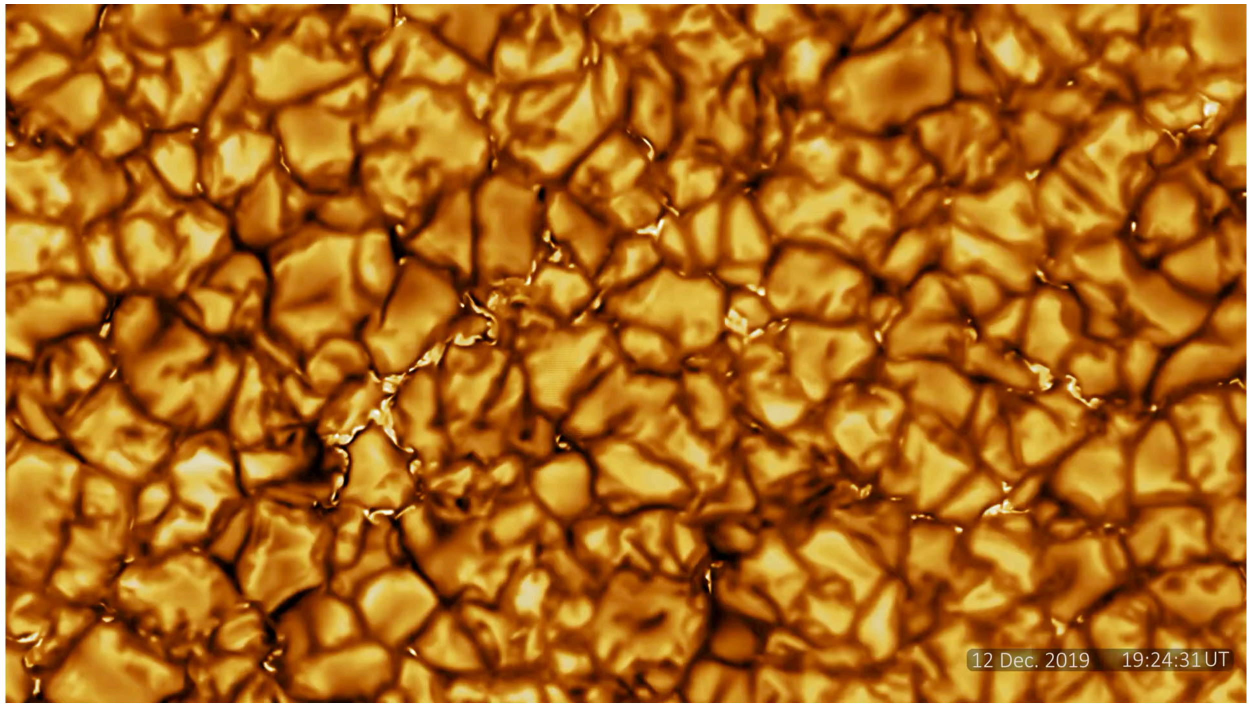
Coronal heating



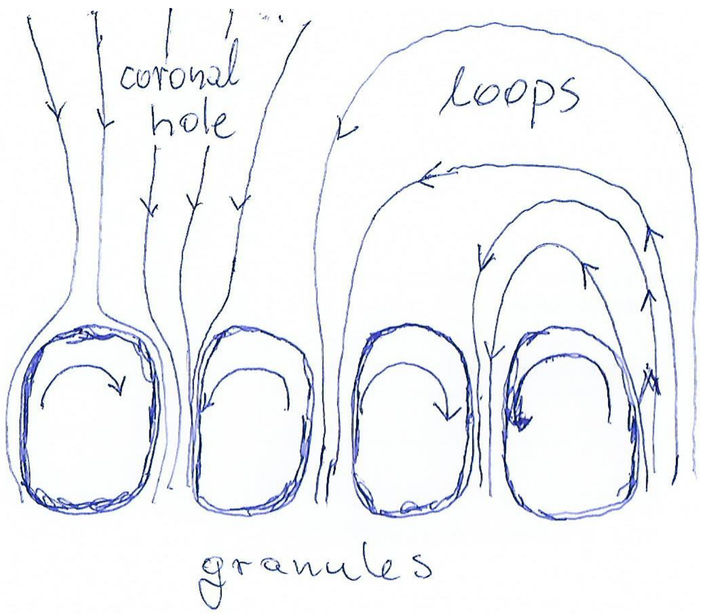
https://www.mn.uio.no/astro/english/research/research%20projects/solaralma/

Thermodynamics

- **Work** needed to pump heat from colder photosphere (~ 6,000 K) to hotter corona (~10^6 K)
- May come from **convection cells** in photosphere
- Powered by temperature & gravity gradients (Rayleigh-Bénard instability)
- Alfvén (1947) proposed that this 'granulation' makes plasma waves that travel upwards to corona



Credit: NSO, NSF, AURA, Inouye Solar Telescope
https://youtu.be/CCzl0quTDHw



Alfvén waves

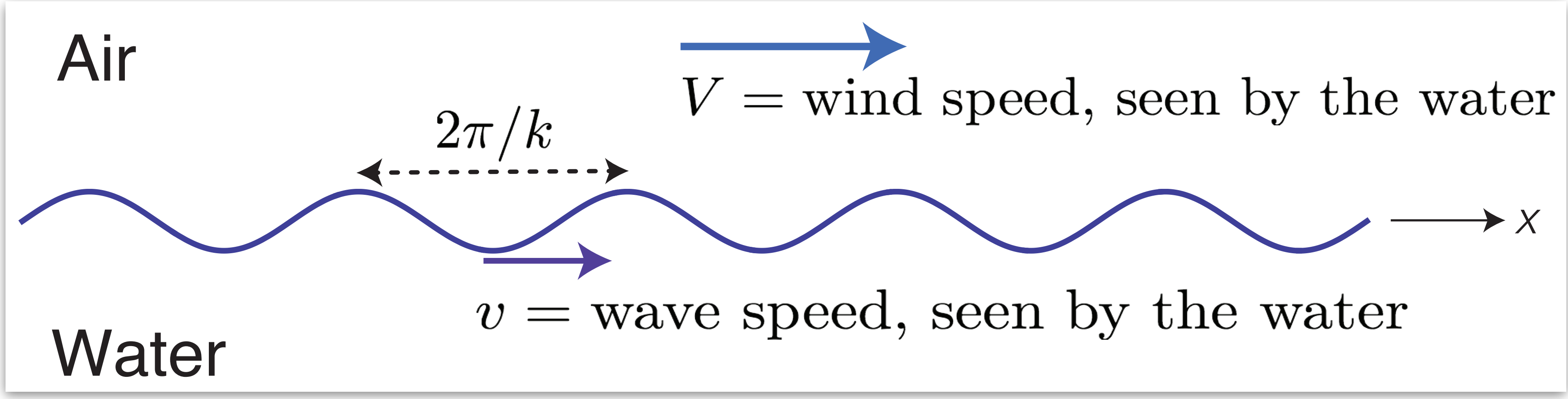
- Electrically charged fluid in external magnetic field **B** exhibits **magnetohydrodynamic** (MHD) transverse waves

- Lorentz force $\propto \mathbf{v} \times \mathbf{B}$ contributes to **restoring force**

- Alfvén speed: $v_A = \dfrac{B}{\sqrt{\mu_0 \rho}}$

- Dispersion relation: $v_A(\mathbf{k}) = v_A \left|\cos\theta(\mathbf{k})\right|$

“What Zel’dovich knew”*



Air

V = wind speed, seen by the water

$2\pi/k$

x

v = wave speed, seen by the water

Water

Angular frequency of wave: $\omega = v\,k$

Momentum conservation: $\dot{\mathbf{p}}_{\rm wind} = -\dot{\mathbf{p}}_{\rm wave}$

Kinetic energy of wind (*non-relativistic*): $E_{\rm wind} = \frac{p_{\rm wind}^2}{2m}$

$$\dot{E}_{\rm wind} = \frac{\mathbf{p}_{\rm wind}}{m}\cdot\dot{\mathbf{p}}_{\rm wind} \quad = -\mathbf{V}\cdot\dot{\mathbf{p}}_{\rm wave} \quad = -\mathbf{V}\cdot(f\hbar\mathbf{k})$$

$$\dot{E}_{\rm wave} = f\hbar\omega = f\hbar v k \;\; ; \qquad V > v \;\; \Leftrightarrow \;\; \left|\dot{E}_{\rm wind}\right| > \dot{E}_{\rm wave}$$

*** Thorne, 2013**

Zel’dovich, JETP Lett. **14**, 180 (1971);
Sov. Phys. JETP **35**, 1085 (1971)

Superradiance

$\left|\dot{E}_{\mathrm{wind}}\right| - \dot{E}_{\mathrm{wave}} > 0$ available for **dissipation in air**

- Similar to Landau criterion for critical velocity of superfluid
- Used by Zel’dovich in 1971 to predict radiation from rotating black hole (BH)
- Motivated Hawking’s discovery of thermal radiation from static BHs in 1974
- “Quantum mechanics helps understand classical mechanics”

  — ‘Paradoksov’, *Sov. Phys. Uspekhi* **9**, 618 (1967)

Solar parameters

- In Sun's **quiet** photosphere: $B \simeq 1$ G; $N_H = 1.2 \times 10^{17}$ cm^{-3}; $N_I = 6.4 \times 10^{13}$ cm^{-3}; $\nu_{\mathrm{in}} = 1.2 \times 10^9$ Hz

- $v_A \simeq 6$ m/s; compare to sound speed $v_s \simeq 10$ km/s, convective flow $v \simeq 1$ km/s

- thus: $\boldsymbol{v_A \ll v < v_s \ll c}$

- First inequality violated in active regions ($B \simeq 10^3$ G $\Rightarrow v_A \simeq v_s$)

- **UV cutoff** for Alfvén waves $\Omega_A \simeq v_A N_I^{1/3} \simeq 10^7$ Hz

Alfvenon superradiance

- Only superradiant modes (<u>negative effective temp.</u>) can transport energy towards corona B-field **vertical** (*z*-axis)

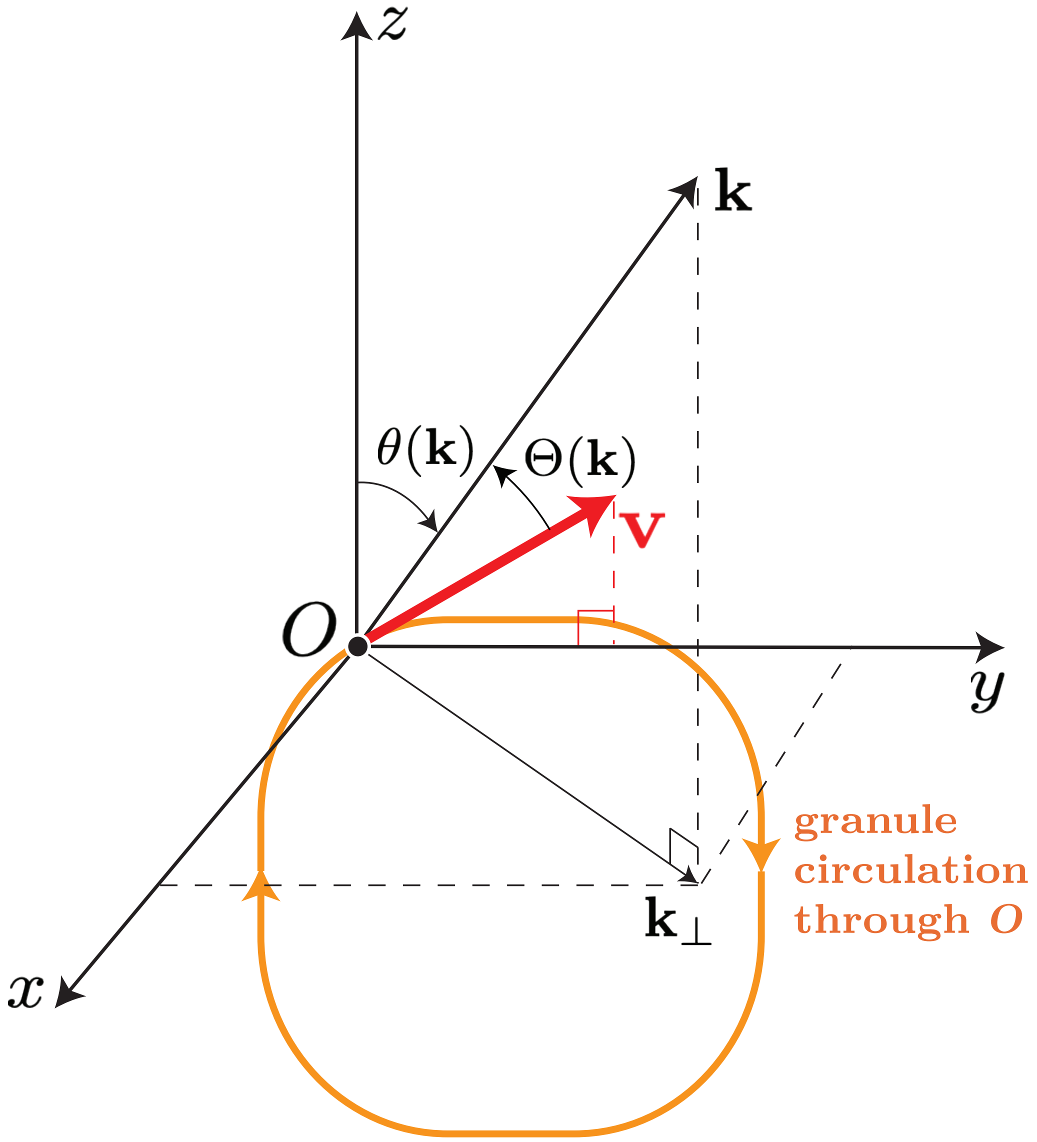
- Superradiant condition $\omega(\mathbf{k}) \leq \mathbf{k} \cdot \mathbf{v}$ becomes

$$\Theta(\mathbf{k}) \in [0, \pi/2], \quad \cos\Theta(\mathbf{k}) \geq \frac{v_A}{v} |\cos\theta(\mathbf{k})|$$

- For $v_A/v \ll 1$ this implies nearly all Alfvén modes with cos Θ(k) ≥ 0 and cos θ(k) ≥ 0 superradiate

- May compute superradiant power by treating Alfvenon field as **open system coupled to moving heat bath**;

see also R. Alicki & AJ, *Ann. Phys.* (NY) **395**, 69 (2018) [`arXiv:1702.06231`]



Power flux budget

$$J_A = \kappa\, v\, N_I\, k_B\, T$$

- Insensitive to large variations in local B-field
- (as long as $v_A \ll v < v_s \ll c$)
- Geometric factor given by $\kappa = \dfrac{\langle\cos\Theta\rangle\langle\cos^2\theta\rangle}{\langle\cos\theta\rangle}$
- bounded as $1/3 < \kappa < 1$, with lower bound corresponding to uncorrelated **k** and **v**
- For Sun, we get $J_A \sim 10^4$ W/m^2
- consistent with $10^3 - 10^4$ W/m^2 needed for coronal heating

Scattering

- mHz Alfvén waves considered in solar MHD models propagate along magnetic flux tubes
- hard to dissipate (main objection to “wave heating”)
- In our theory, heating depends on **superradiant MHz modes**
- Much stronger elastic scattering in nonuniform medium
- Expect alfvenons to *diffuse* upwards in solar atmosphere, giving <u>decoherence without dissipation</u>

Mode conversion

- Transition between alfvenon and phonon, satisfying energy-momentum conservation

$$E = \hbar\omega_1 = \hbar\omega_2; \quad \mathbf{p} = \hbar\mathbf{k}_1 = \hbar\mathbf{k}_2$$

- possible only if local phase speeds ($v_{\rm ph} = \omega\, /\, |\mathbf{k}|$) match

- In quiet regions of Sun’s photosphere:

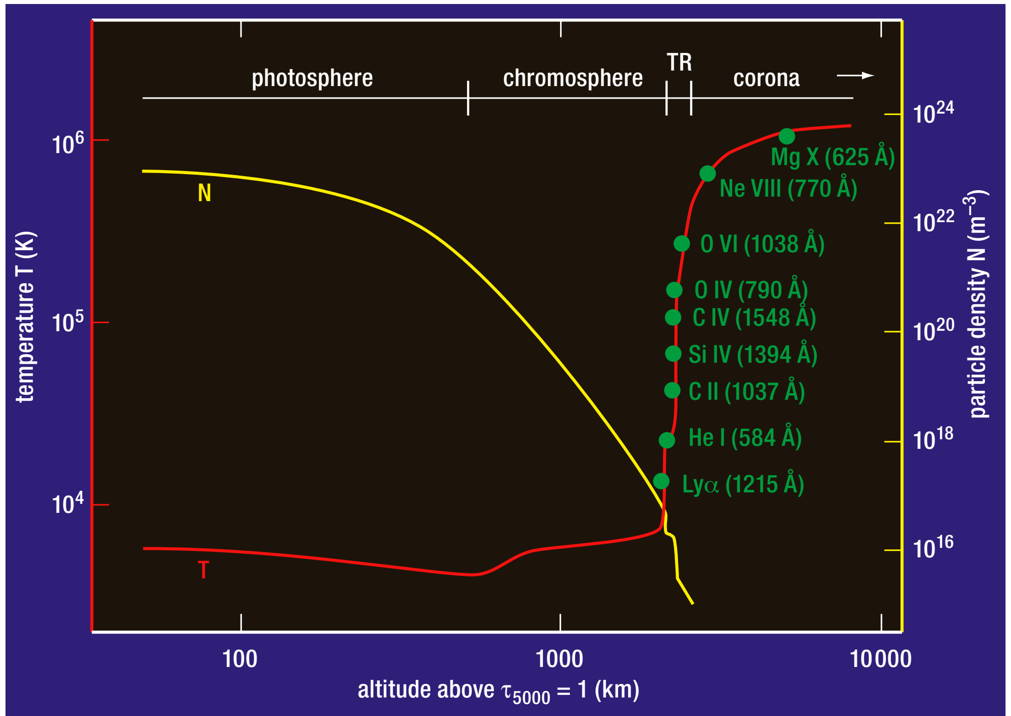
$$v_A \simeq 6\ \text{m/s} \ll v_s \simeq 10\ \text{km/s}$$

- In the corona:

$$v_A \simeq 10^3\ \text{km/s} > v_s \simeq 10^2\ \text{km/s}$$

- Speeds must match at <u>intermediate height</u> z

- Once converted to phonons, superradiant energy will quickly thermalize



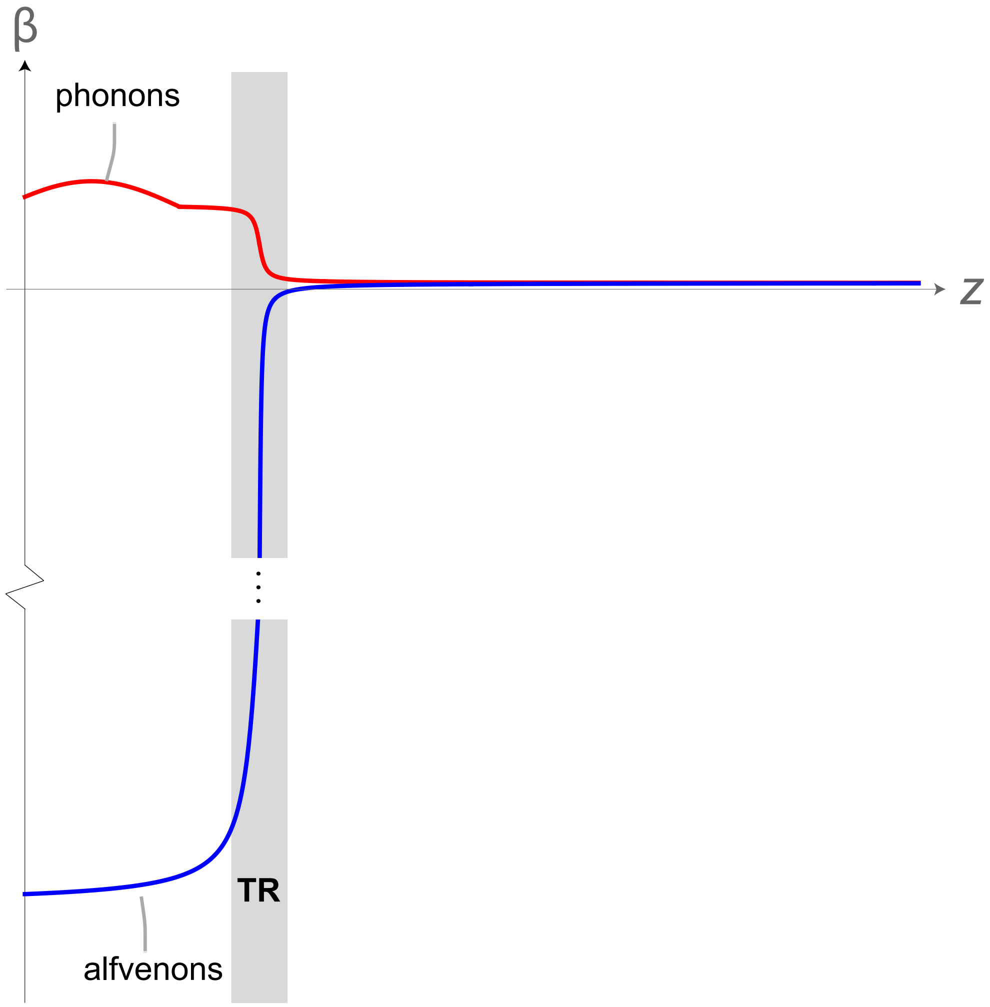
2: Temperature (red line) and density (yellow line) distributions as a function of the height measure in km in the solar atmosphere. The formation of popular lines for observations is indicated by green. Note the logarithmic scales. (Courtesy H Peter.)

R. Erdély, *Astron. & Geophys.* **45**(4), 34 (2004)

Chromospheric evaporation

- May explain abrupt temperature rise in **Transition Region (TR)** between chromosphere & corona, at $z \simeq 2{,}100$ km
- Superradiance can ***boil*** plasma in upper chromosphere
- Not in contradiction with evidence of impulsive heating (nanoflares) and other activity
- Magnetic flux tubes get filled with plasma **<u>heated from below</u>**

see Aschwanden, Winebarger, Tsiklauri & Peter, "The Coronal Heating Paradox", *Ap. J.* **659**, 1673 (2007)



Outlook

- Quantum physics needed to describe irreversible processes involving production or absorption of waves fully; see Alicki, arXiv:1904.06170
- Our results didn't depend on Planck's constant $\hbar$, but quantum thermodynamic analysis is simpler and better posed than classical MHD treatments (flux-tube shaking, shocks, wave turbulence, etc.)
- Theory transcends dichotomy between "wave heating" and "impulsive heating" in solar physics
- Active regions result, rather than cause, of coronal heating
- Approach may be useful in the theory of **turbulence**, defined as "out-of-equilibrium statistical mechanics of random nonlinear waves" (Nazarenko)