Australian National University

Resolving Electron Temperature Discrepancies in H II regions and PNe: the Kappa-distribution

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What this talk is about

- For a long time there have been discrepancies in temperatures and metallicities in H II regions and PNe measured using different techniques.
- For example, ORL temperatures are systematically lower than CEL temperatures - there are others, too.
- It has always been assumed that the electrons in these regions are in thermal equilibrium.
- If this is not the case, the temperature and metallicity discrepancies can be naturally explained.

Genesis of the idea

- In September last year I started to find some of the apparent metallicities in my reduced data did not match photoionization models.
- Was the problem missing physics in the models, or something wrong with the assumptions underlying the “direct method” for measuring T_e?
- For over 70 years, people have assumed that the electron energy distributions in HII regions are at equilibrium.

From 1940...

We assume that the velocity distribution of the nebular electrons is Maxwellian, defined by a kinetic temperature T_ϵ, so that the fraction $f(v)$ of electrons having velocities between v and $v + dv$ is

$$f(v)dv = 4\pi \left(\frac{m}{2\pi k T_\epsilon}\right)^{3/2} v^2 e^{-\frac{1}{2}mv^2/kT_\epsilon} dv \,. \qquad (29)$$

Hebb & Menzel, 1940, ApJ, 92, 408

But are they?

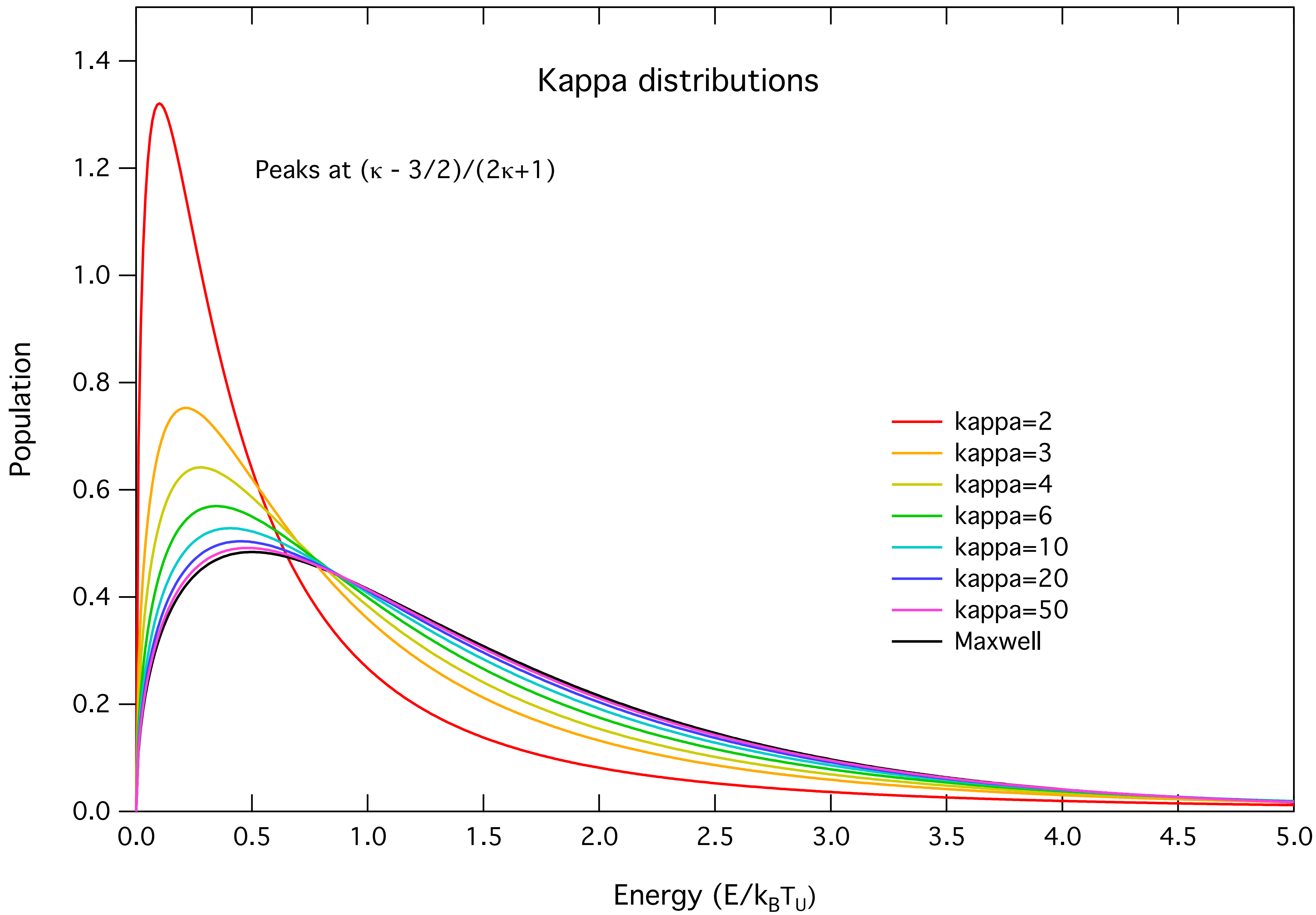
First evidence for non-equilibrium energies

- Vasyliunas (1968) found that electron energy distributions in the Earth's magnetosphere, measured using the OGO1 and 3 satellites, had a non-Maxwellian distribution.
- The high energy electrons followed a power law not an exponential.
- Vasyliunas found that the distribution was well described by a "kappa distribution".

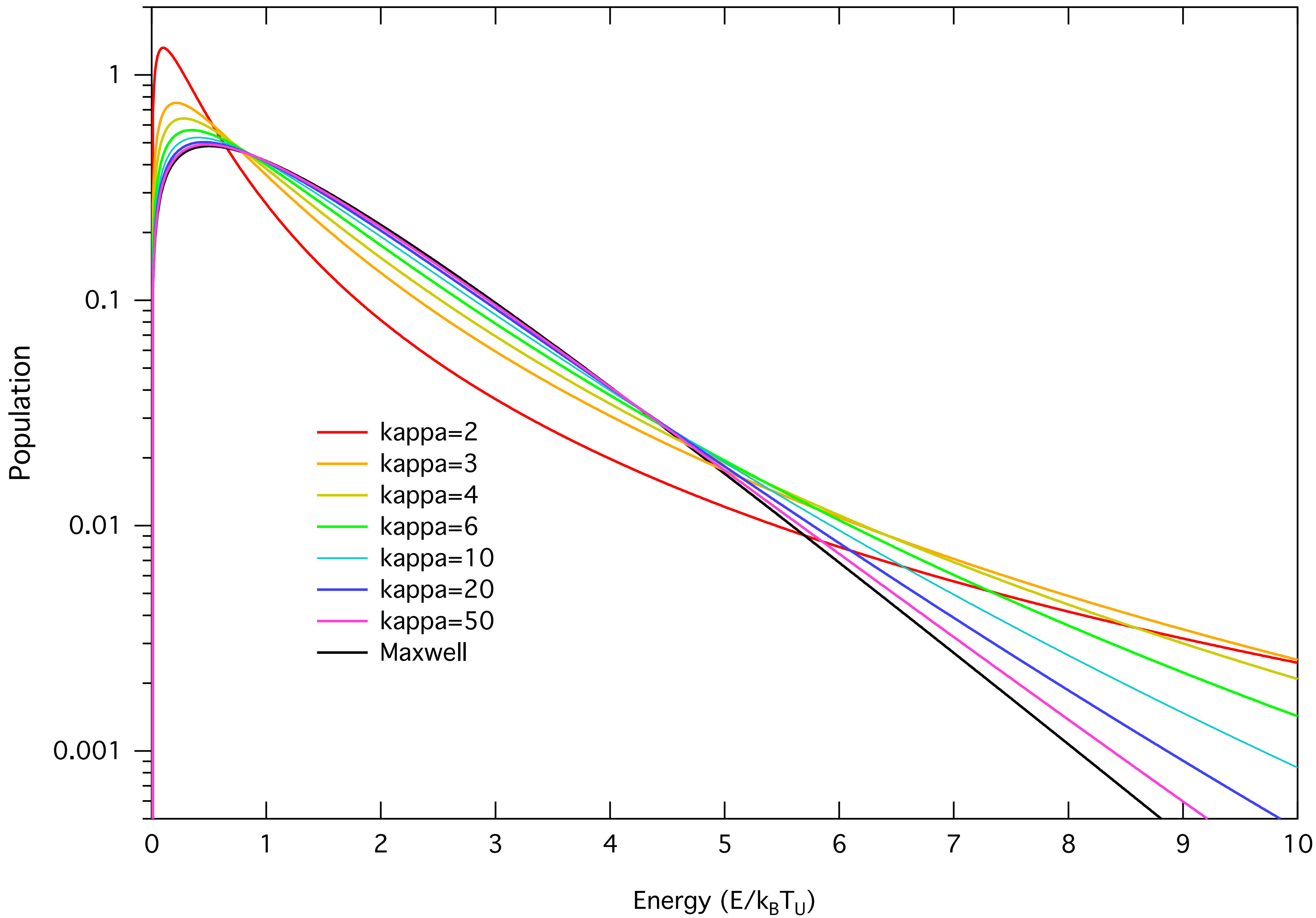
More evidence

- Since then, virtually all electron energy distributions in solar system space plasmas have been found to follow the kappa distribution:
- the magnetospheres of Neptune, Uranus, Saturn, Jupiter, Titan, Io, Mercury and the Earth, as well as the Solar Wind
- Recently the IBEX experiment data indicate extreme but stable departures from equilibrium in Energetic Neutral Atoms in the Heliosheath

What does one look like?



Easier to see on a log plot...



Characteristics...

- MB distribution is a special case, as $\kappa \rightarrow \infty$
- Power law tail, not exponential
- Distribution peak at lower energy than MB
- Excess over MB at both lower and higher temperatures, deficit in between, for same internal energy

Theoretical basis?

- Kappa distributions used as an empirical fit to observed energy distributions, criticised for not having a theoretical basis
- Until Tsallis presented the "q-nonextensive statistical mechanics"
- Derived from entropy considerations, for species with long-range interactions
- The kappa distribution is a natural consequence of the new statistical mechanics

How might a κ-distribution arise?

- There are several mechanisms that can supply the "hot" distribution tail of the electron energy distribution.
- e.g. Magnetic reconnection; inertial Alfvén waves; internal shocks; photoionisation of both ions and dust grains.
- Until now, the possibility of non-equilibrium κ energy distributions in HII regions and Planetary Nebulae appears not to have been considered.

Temperature?

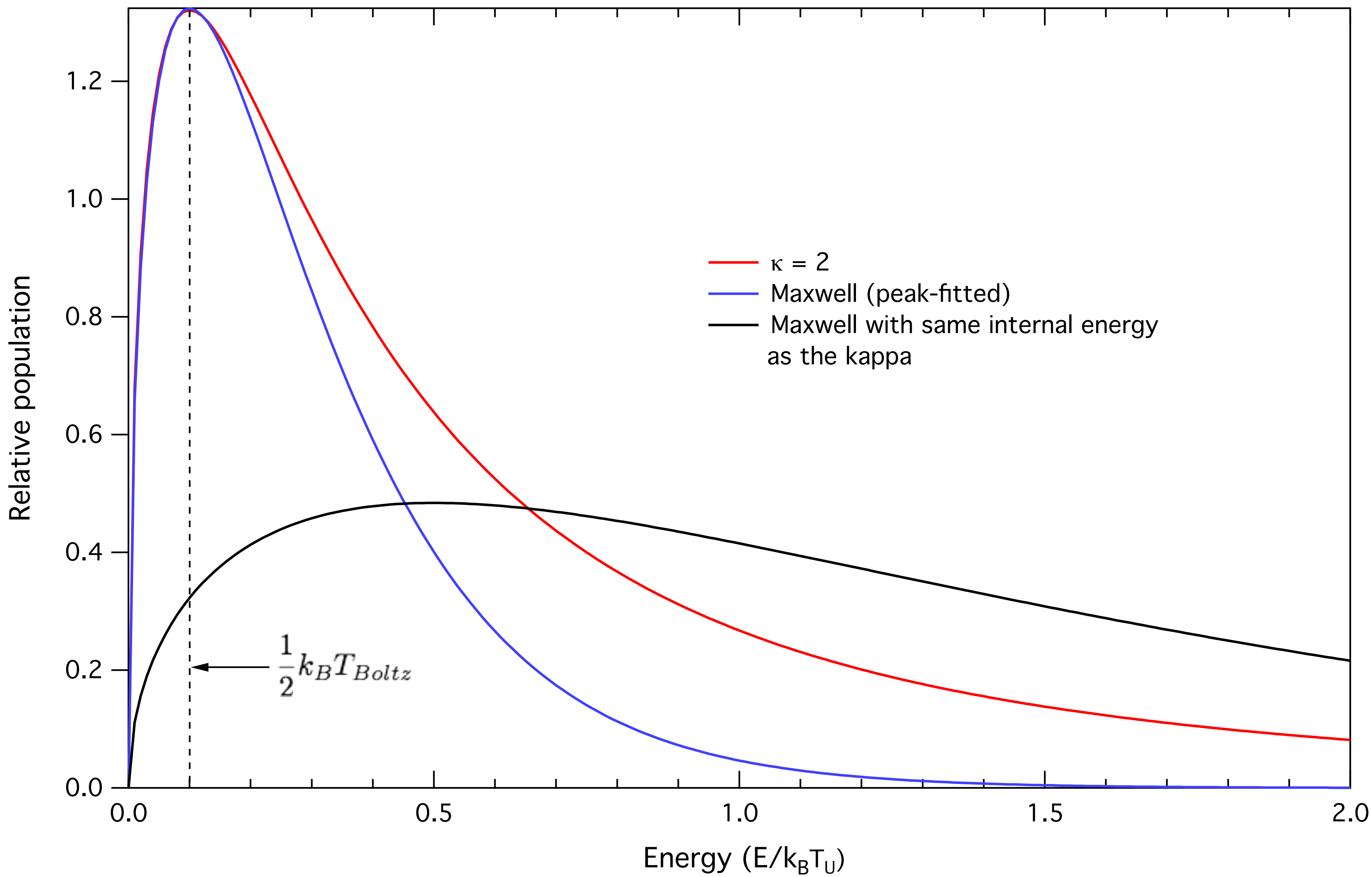
- Define a "kinetic" temperature T_U in terms of the total internal kinetic energy:

$$U = \frac{3}{2} k_B T_U$$

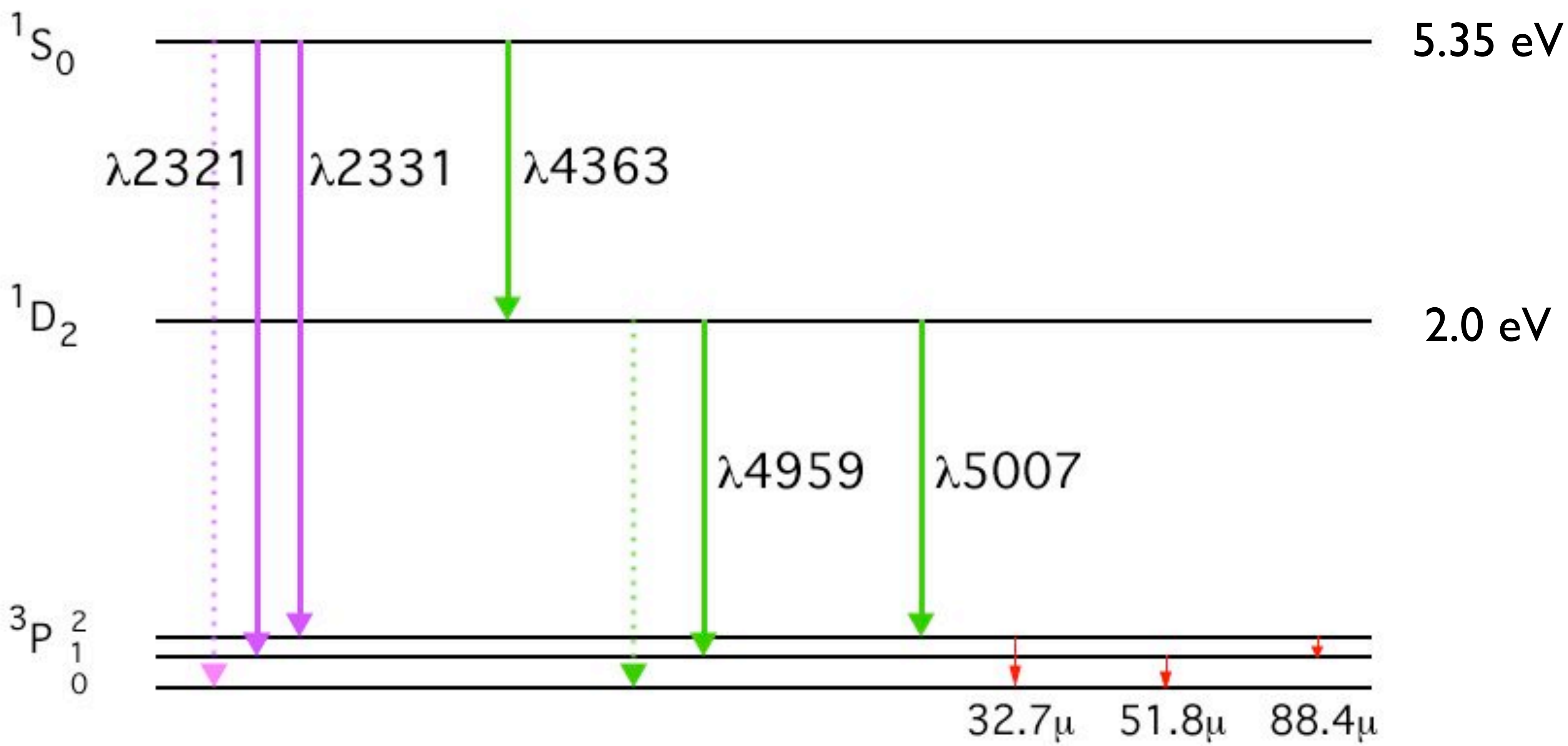
- Applies also to Boltzmann-Gibbs statistics in equilibrium, where $T_U \equiv T_{Boltzmann}$
- The general relationship between $T_{Boltzmann}$ and T_U is:

$$T_{Boltzmann} = \frac{\kappa - \frac{3}{2}}{\kappa} T_U$$

The key...


κ = 2
Maxwell (peak-fitted)
Maxwell with same internal energy as the kappa
$\frac{1}{2}k_B T_{Boltz}$
Relative population
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
Energy ($E/k_B T_U$)

[OIII] energy levels

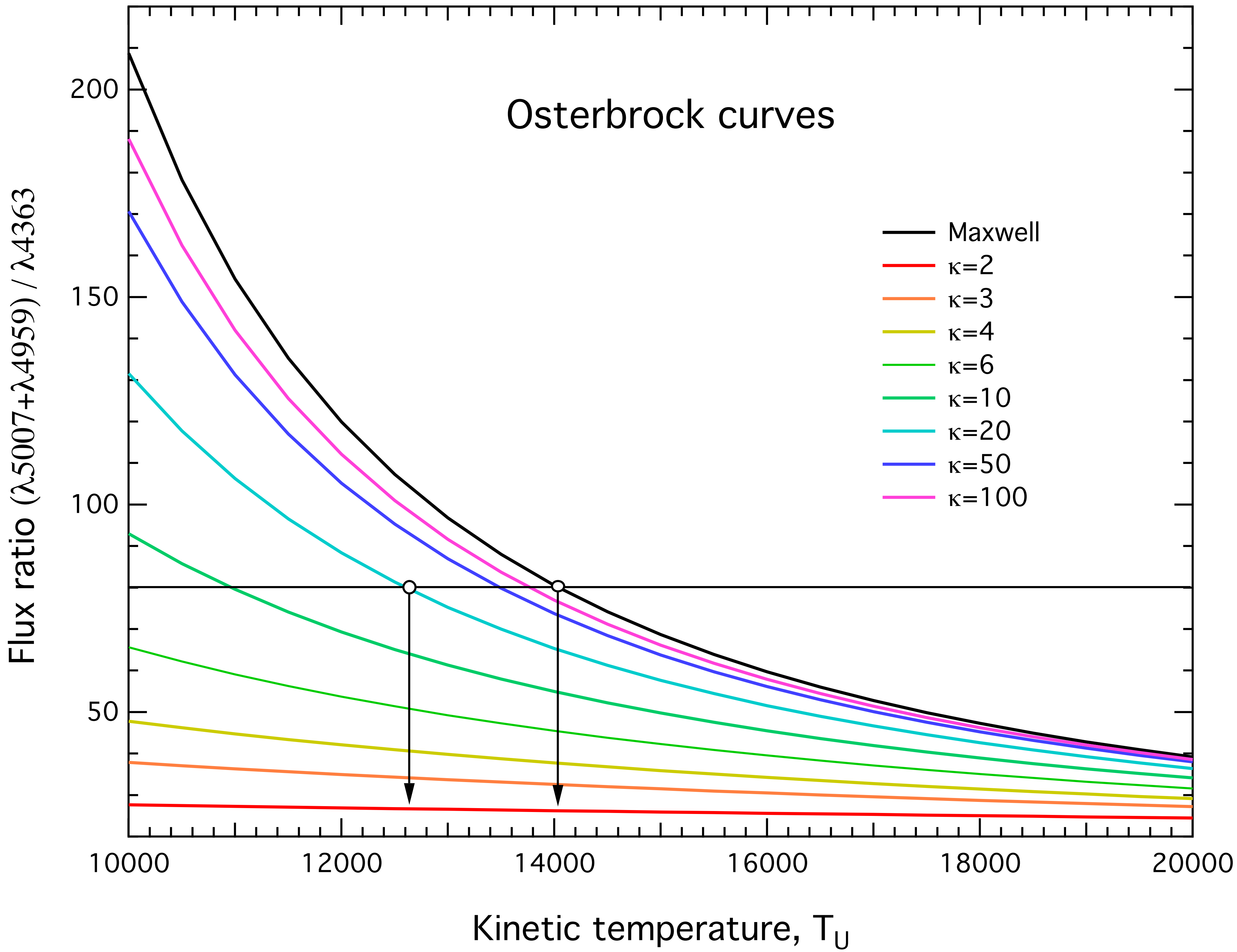


The more high energy electrons there are, the more excitations into the $^1S_0$ level will occur

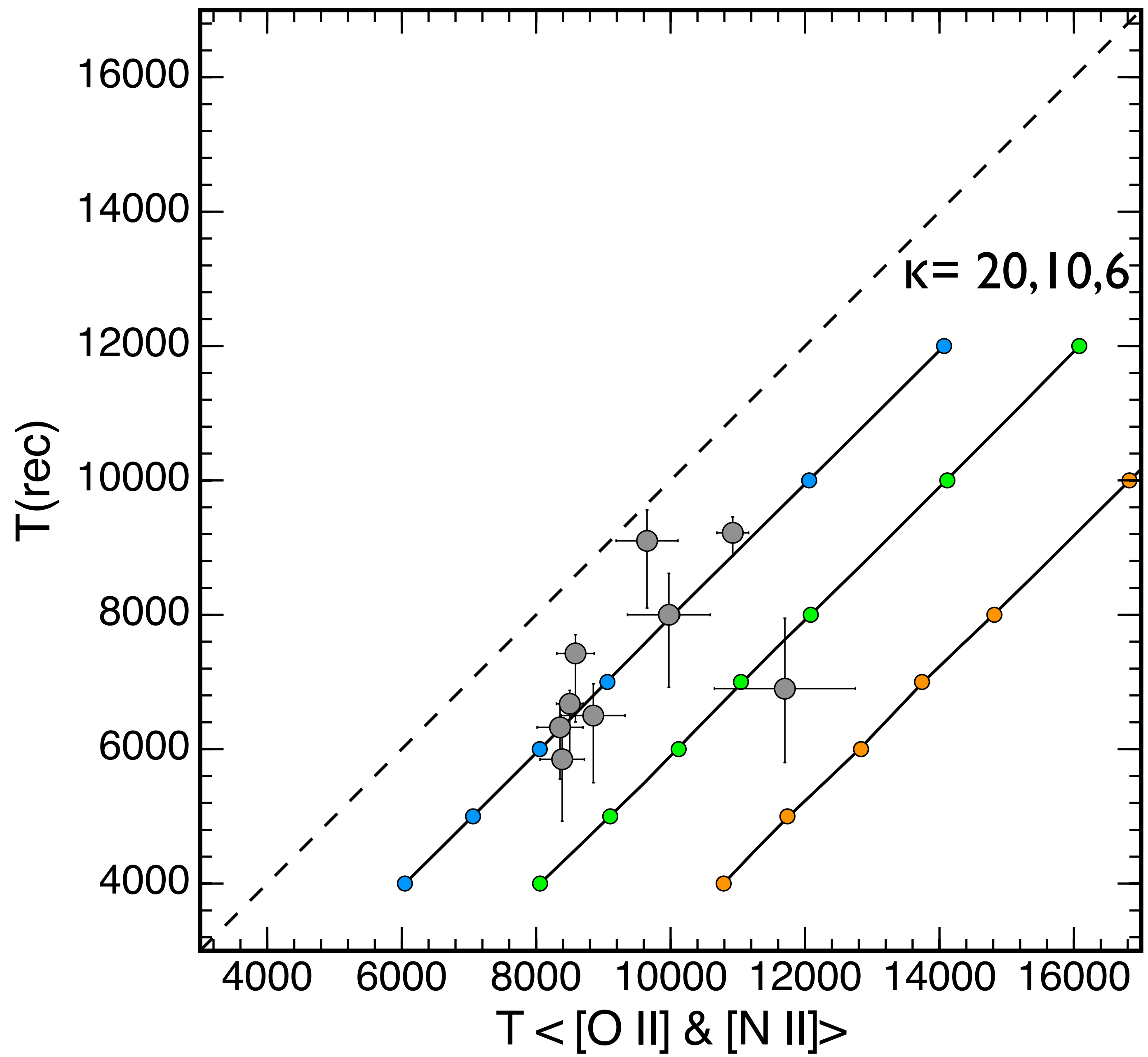
Resolving electron temperature discrepancies

- If you have a non-equilibrium energy distribution with more "hot" electrons than a standard MB distribution, you will get increased excitation into the upper $^1S_0$ [OIII] energy level (while not changing the $^1D_2$ excitation much)
- The "temperature" is calculated from the flux ratios of the λ4363 to (λ4959+λ5007) lines
- So the "temperature" will be overestimated if there are more "hot" electrons that expected.

Resolving electron temperature discrepancies



ORL vs. CEL


κ= 20,10,6
T(rec)
T < [O II] & [N II]>
16000
14000
12000
10000
8000
6000
4000
4000
6000
8000
10000
12000
14000
16000

So a kappa distribution provides an automatic and natural explanation of the Optical Recombination Line problem!

Only two parameters required, kappa and the internal energy temperature, T_U

Thank you