Radial Velocity Method

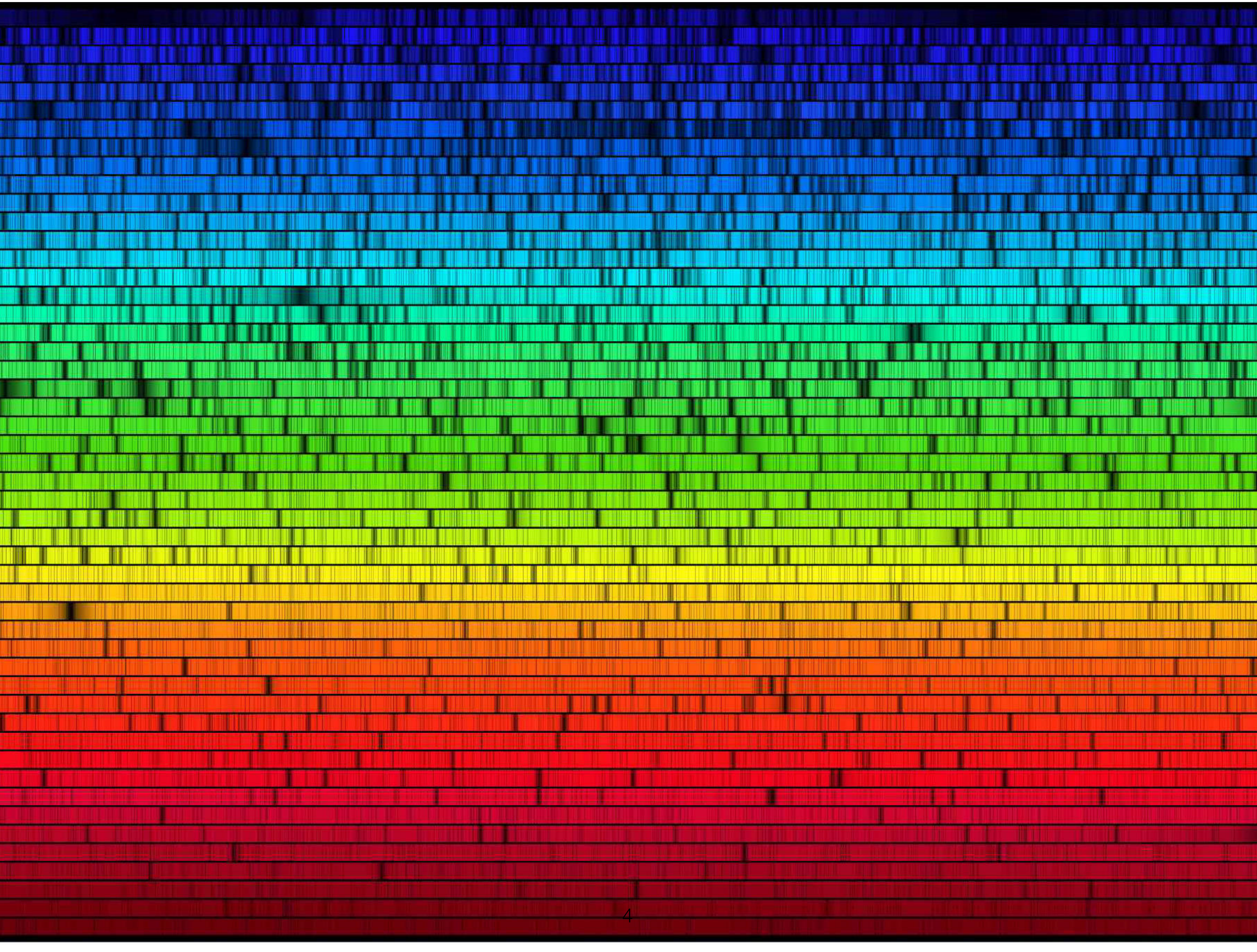
How to find planets around other stars
(and win the Nobel Prize)

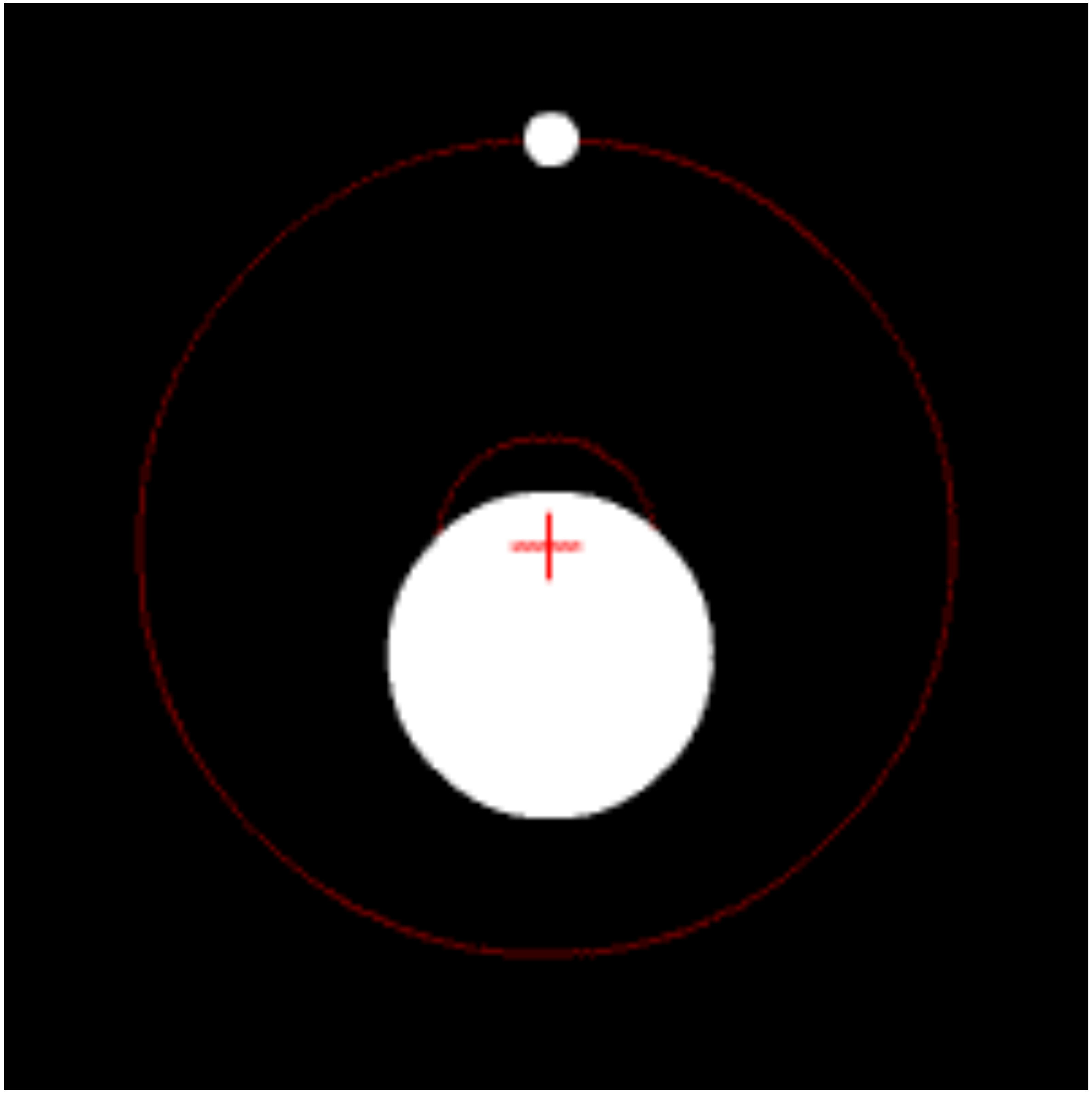
Planets around pulsars

- A pulsar is a neutron star, spinning rapidly, with a beam of radio emission that flashes at us once per revolution. Very stable period (1.4 solar masses in a 10 km sphere, spinning tens to hundreds of rotations / second).
- Wolszczan & Frail announced 2 planet-mass objects around PSR 1257+12 in 1992. One more discovered since.
- Recoil velocity of the pulsar can be derived from timing the arrival of the pulses.
- Horrible place to live (recent supernova, lots of radiation, …)

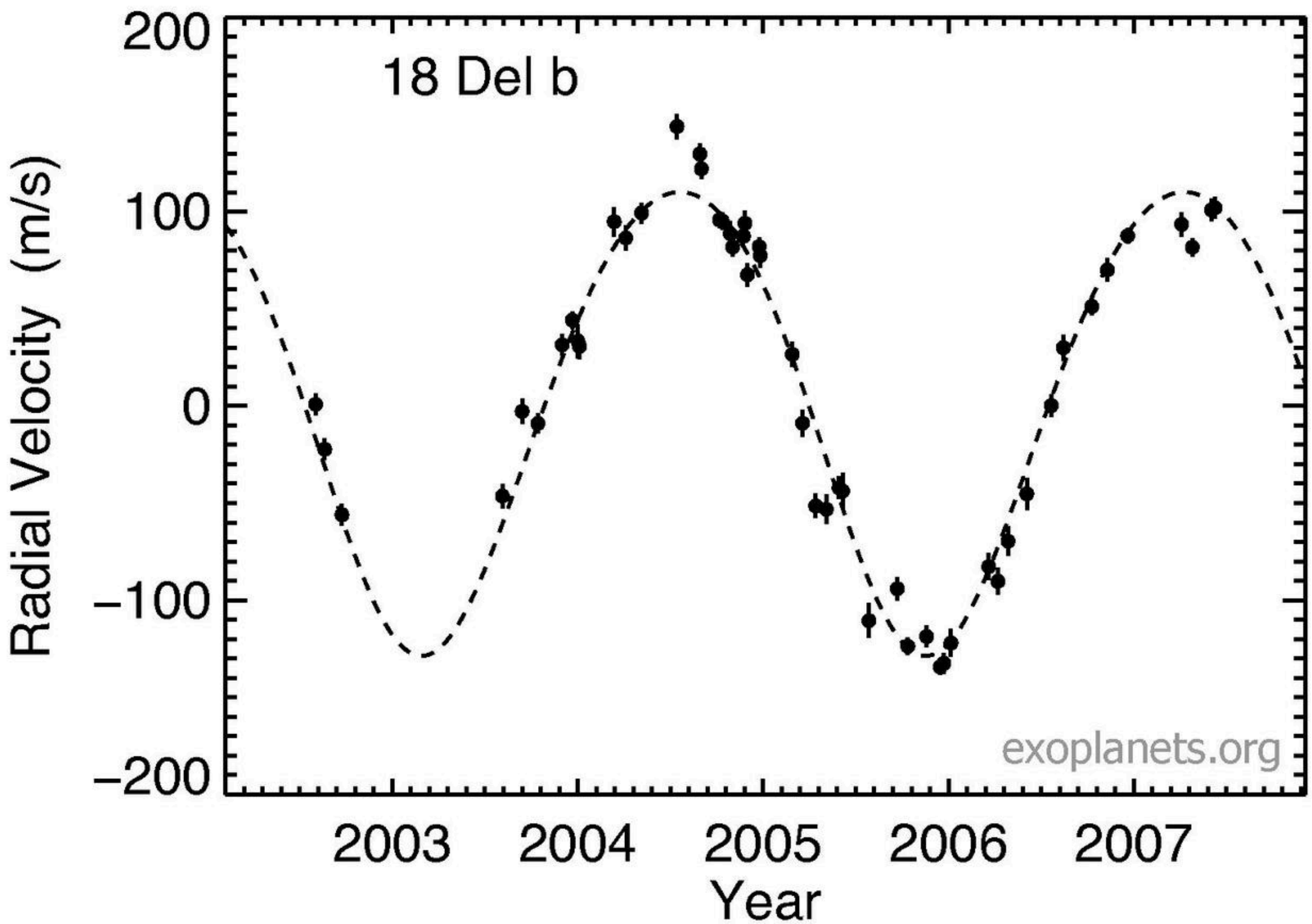
What about ordinary stars?

- Take a spectrum covering the visible wavelength range, into the near infrared (400-1000 nanometers) at high resolution, as often as possible.
- Carefully remove areas due to earth atmosphere absorption
- Compare the spectra to get the Döppler shift as a function of time. If there's a planet there'll be a wave in that signal (star moving toward and away from us, in recoil from the planet's motion).
- The signal is small; related to the mass ratio of planet to star, and the radius of the orbit. Jupiter moves the sun at up to 13 m/sec; the earth at 9 cm/sec
- HARPS spectrograph (on La Silla, Chile) can detect down to 1-3 m/sec or so.





Planet in orbit around a star, showing motion of both objects.



Radial velocity for planet 18 Delphini b
Note vertical scale ~ 100 m/sec
Period of orbit is about 2.5 years.

- Measure K, the amplitude of the wave in the velocity, and the orbital period P_{orb}. Get mass of star M_s as accurately as possible from other means (spectral analysis, comparison to wide binary stars).

- The mass function $f = P_{orb}\, K^3 / (2\pi G) = M_p^3 \sin^3 i / M_s^2$

- Here i is the (unknown) inclination of the orbit to the line of sight. So you basically get $M_p \sin i$

- The sine of the inclination angle is between zero (pole-on) and one (edge-on), so this gives you a “Minimum Mass” for the planet.

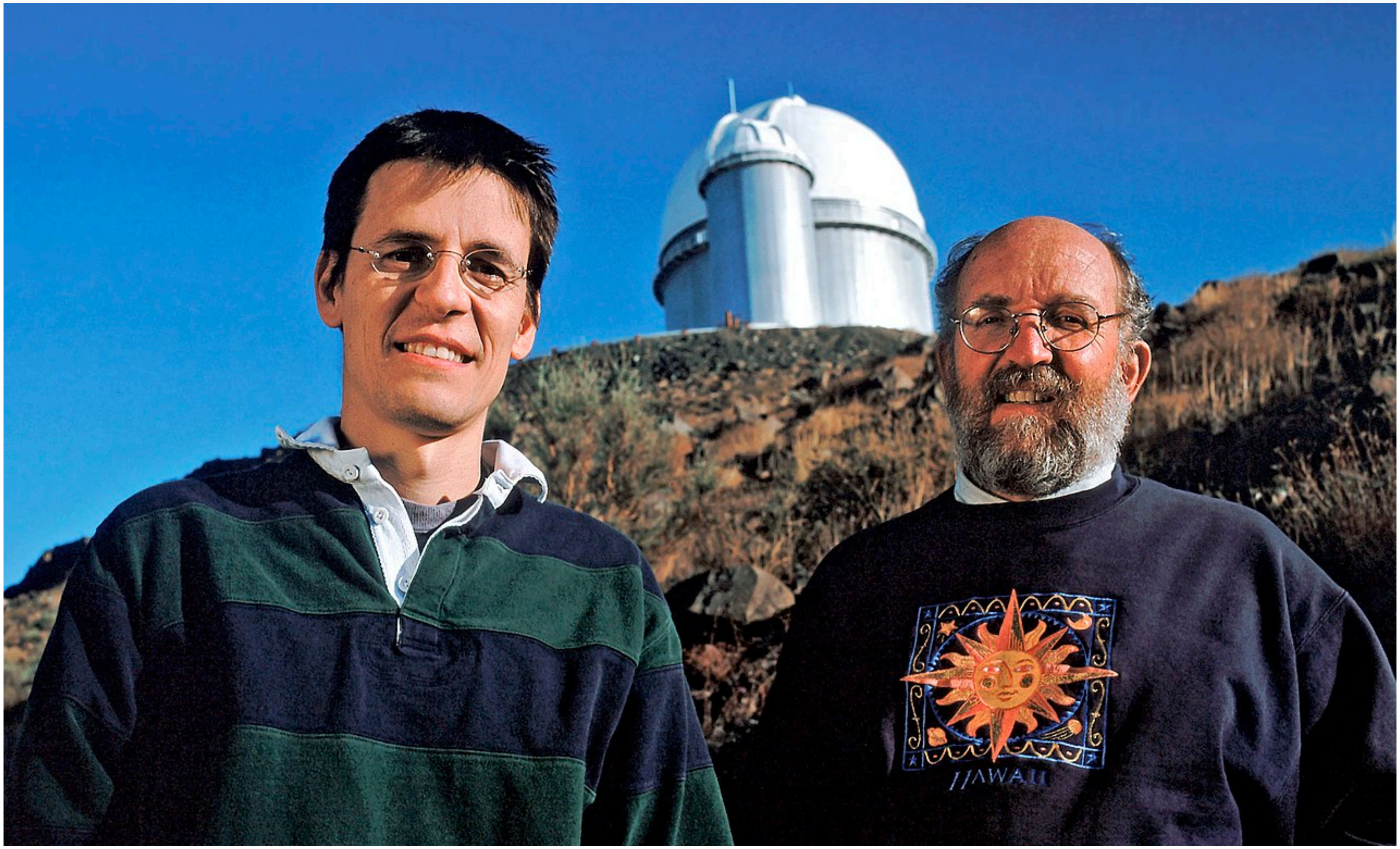
First planet around another sun-like star

- In 1995, Michel Mayor and Didier Queloz (U. Geneva) published results for the planet 51 Pegasi b.

- 51 Pegasi is 50.5 light years from us, in the constellation Pegasus. Its mass is 1.11 solar masses, radius 1.23 times our sun, luminosity 1.36 times our sun.

- 51 Peg b has a mass of 0.46 Jupiter masses, and an orbital period of 4.23 days. Semi-major axis is 0.0527 AU or 7.88 million km. This is extremely close to the star.

- Mean temp on the day side is 1284 K.



Queloz and Mayor, on La Silla, 2012.

They shared half the Nobel Prize in physics for 2019.

- The discovery of 51 Peg b was quite a surprise, since nothing comparable exists in our solar system.

- Theory said giant planets should form more or less where Jupiter and Saturn are in our solar system, beyond the “snow line” where water ice is a good solid rock, and where there’s lots of material in a pre-solar disk because there’s more real estate out there.

- Some simulations show giant planets migrating during the formation process; perhaps “Hot Jupiters” migrate in to really tight orbits (and some of them are lost into the star). Others might be ejected from the system entirely, to wander the void alone.

- As of Feb 16, 2020, there are 880 confirmed exoplanets discovered by the radial velocity method. 648 systems, 156 with multiple planets.

- Close-in planets (with tight, short-period orbits) are easier to find, as are massive planets.

- Masses range from .01 to 89 Jupiter masses. 0.01 $M_{jup} = 3.7\ M_{earth}$.

- This method can detect planets at a variety of orbital inclination angles.

- The physical size of the planet is not available from this method.

- Note current instruments cannot detect earth-size planets around sun-like stars.

- But we can detect earth-size planets, in the “habitable zone,” around lower mass stars.

- The Habitable Zone is where, given a suitable atmosphere, temperatures would allow liquid water on the surface of a planet. The distances from the star depend on how bright the star is.

- Proxima Centauri is a faint red star, 4.14 light years away, M=0.12 M_{sun}, surface temp 3050 K. It orbits the Alpha Cen system (which is itself binary)

- Prox Cen b is a planet of 95% earth mass, in an 11-day orbit at 0.048 AU from the star. T = 216 K (-57 C). Cold, but maybe not too cold.

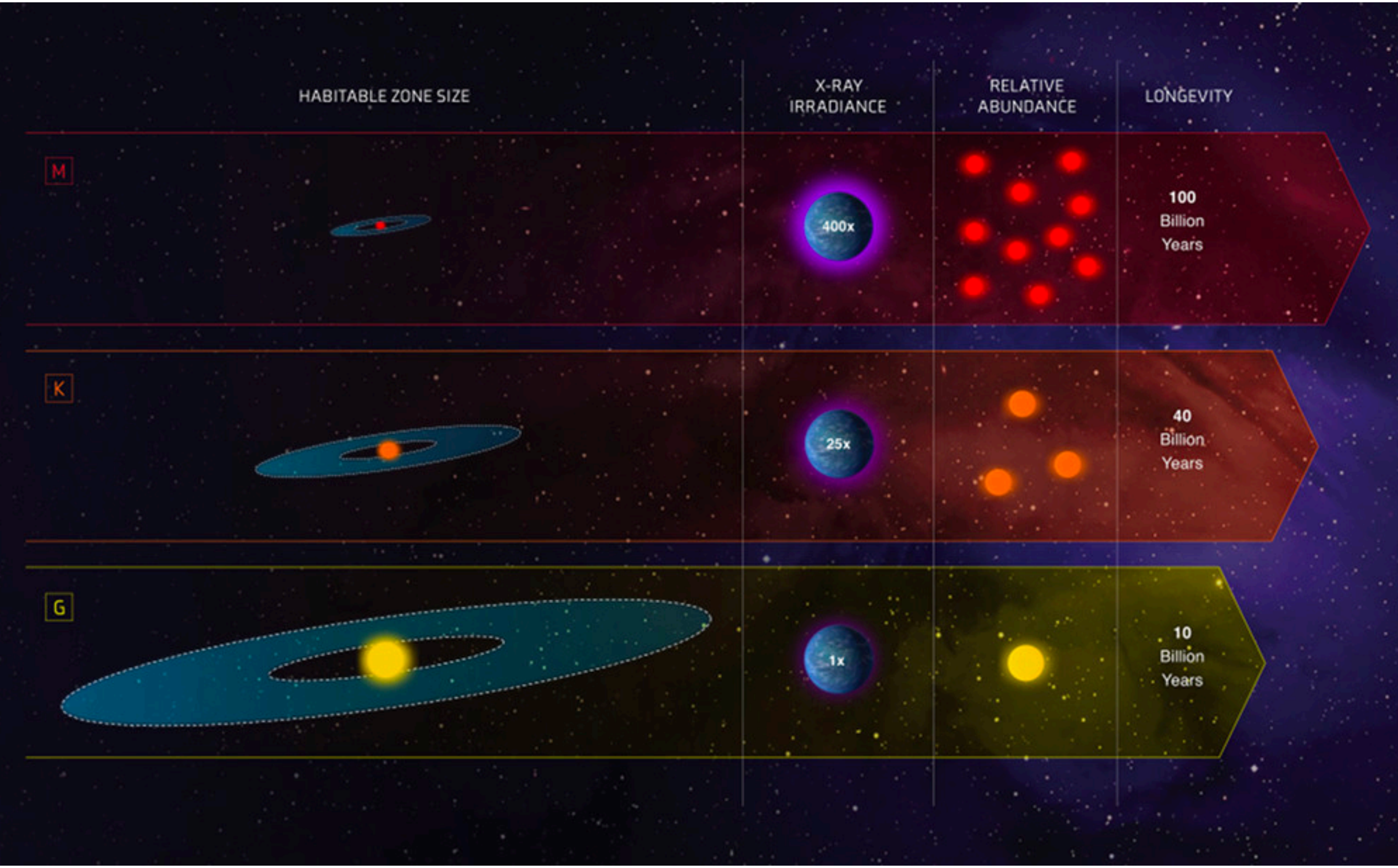
- So that’s kind of exciting: the very nearest star has an earth-mass planet that could possibly have liquid water on the surface!

- Or, you know, maybe not…

- Lower mass stars tend to be more active, with more flares, sunspots, x-ray emission, etc, that could drive off an atmosphere (unless protected by a planetary magnetic field).

- Also close-in planets like this will tend to be tide-locked, so one side always faces the star.

- Most of the moons in our solar system are tide-locked with their planets, so the same side always faces their planet.
- Tidal distortion dissipates energy as the moon rotates until finally it settles into a prolate shape (like a football) with the long axis pointing at the planet.
- In some cases, the planet also makes it to this state (Pluto and Charon are there; the Earth's rotation is slowing down but has a long way to go.)
- A planet close to its star, if it's tide-locked and has an atmosphere, would have really alien weather, possibly with strong winds. Heat on the day side makes air rise, to be replaced with cooler air coming from the night side.


HABITABLE ZONE SIZE
X-RAY IRRADIANCE
RELATIVE ABUNDANCE
LONGEVITY
M
400x
100 Billion Years
K
25x
40 Billion Years
G
1x
10 Billion Years

Host stars and nomenclature

- Stars come in a variety of masses. They need more than about 8% of the sun’s mass to burn hydrogen to helium in their cores. Some known stars are 60 to perhaps 100 times the mass of the sun.

- Lower mass stars are much more common than heavy ones. The sun is more massive than about 75% of stars.

- The sun is a “G” type star; cooler/lighter classes are K (orange) and M (red). Lifetimes vary as the cube of the mass, with light stars lasting longer. Lower mass stars tend to be more active (flares, x-ray emission, etc.)

- Half the star systems in the sky have more than one star in them (binary systems or triples, …)

- In binary star systems, the most massive object is called A, second one B, etc. For example, Alpha Centauri is a triple system. Alpha Cen A is a sun-like G star (1.1 M_{sun}); Alpha Cen B is a cooler K-type orange star (0.9 M_{sun}) in an 80 year orbit, 17.5 AU away.

- Alpha Cen C is Proxima Cen, and we've talked about that already… 0.12 M_{sun}, orbiting A&B in a half-million year orbit.

- Planets are named with small letters after the name of the star. So Proxima Cen b could also be called Alpha Cen Cb (first known planet around the 3rd stellar member of the Alpha Cen system).

- Conclusions:

- There are weird planets out there, like hot Jupiters, tide-locked planets, etc.

- Planets are pretty common.

- The method is biased in favor of close-in and/or large planets.

- Background signals include motion of gas in the stellar atmosphere.

- This method only gives $M \sin i$, with the inclination unknown.