Living with a Red Dwarf

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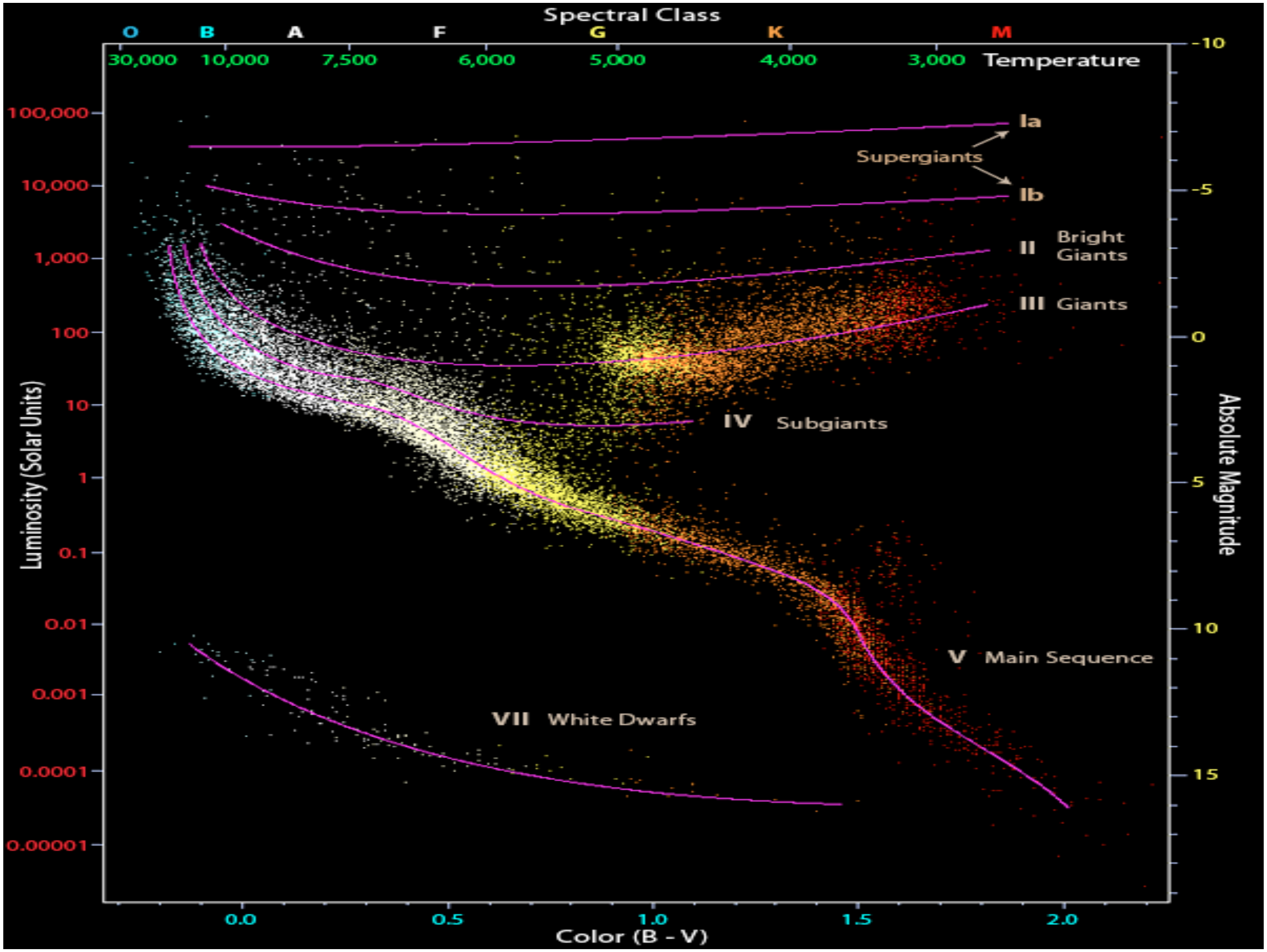
The H-R diagram



What makes a star shine?

- Fusion of light elements into heavy elements
- Hydrogen is by far the most abundant fuel in the Universe
- Main sequence stars burn H into He
- 90% of stars are main sequence stars
- Stars do not evolve *along* the Main Sequence.
  they enter the Main Sequence when they start fusing H,
  and leave it when H fuel is exhausted

The mass-luminosity relation

Luminosity: The power output of a star

For stars burning H to He,

$$\mathcal{L} \sim \begin{cases} M^4 & \text{if } M > .4 M_\odot \\ M^{2.3} & \text{if } M < .4 M_\odot \end{cases}$$

$\rightarrow$ *Low-mass stars are dimmer*

Relation between color, luminosity and mass

- For any radiating body, dominant wavelength is inversely proportional to temperature
- Cooler = more red. Hotter = more blue
- Relevant temperature for star is ”surface” (photosphere) temperature, where light escapes from

Relation between color, luminosity and mass

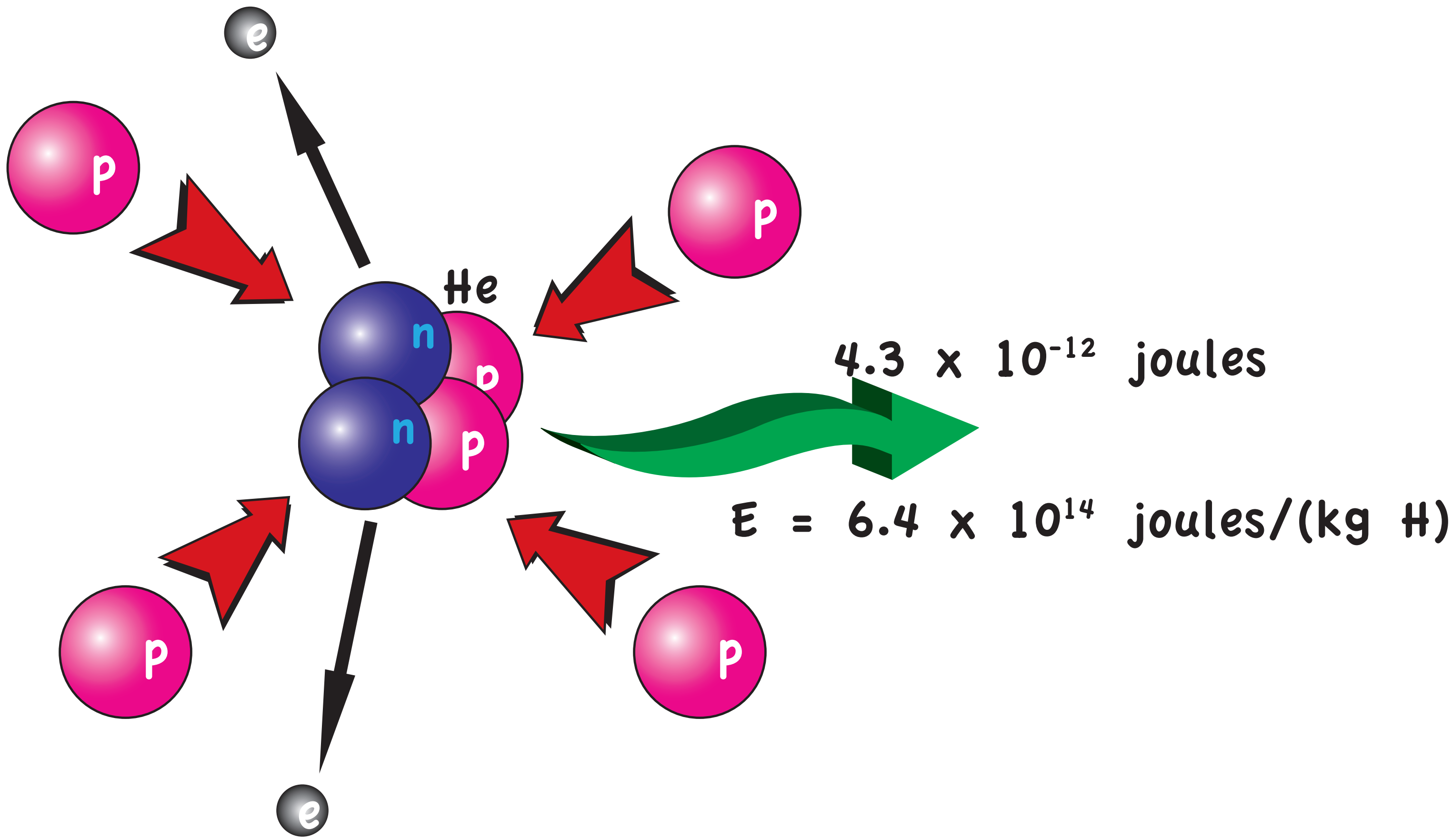
$\mathcal{L} = 4\pi r^2 \sigma T^4$, so $T^4 \sim \mathcal{L}/r(M)^2$

$r(M) \sim M^\alpha$, (e.g. $\alpha = \frac{1}{3}$ if mean density were constant). Then:

$$T \sim \begin{cases} M^{1-\frac{1}{2}\alpha} & \text{if } M > .4 M_\odot \\ M^{.575-\frac{1}{2}\alpha} & \text{if } M < .4 M_\odot \end{cases}$$

$\rightarrow$ *Low-mass stars smaller, cooler and redder*

How long does a main sequence star shine?

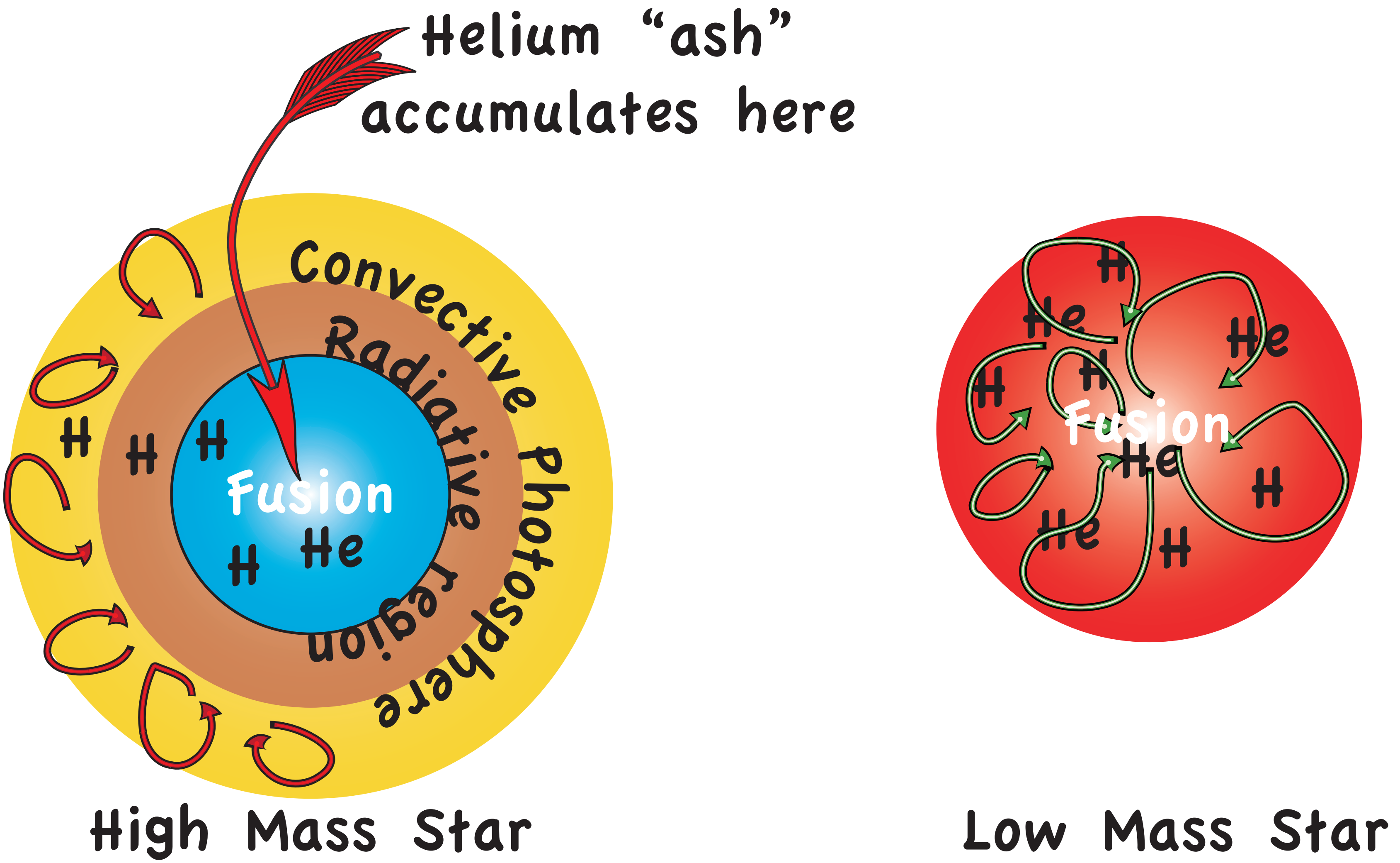


Total conversion lifetime $t_\infty = M \cdot E/\mathcal{L}$

100 billion years for Sun,

– vs 10 billion years actual main sequence lifetime for a Sunlike star

To burn H, you have to mix it into the core



From mass-luminosity relation, total conversion lifetime is:

$$t_\infty = \frac{E \cdot M}{\mathcal{L}} = \begin{cases} t_{\infty,\odot}(\frac{M}{M_\odot})^{-3} & \text{if } M > .4M_\odot \\ 4.7t_{\infty,\odot}(\frac{M}{M_\odot})^{-1.3} & \text{if } M < .4M_\odot \end{cases}$$

e.g. 2.2 *trillion* years for $M = .3M_\odot$ (like GJ581)

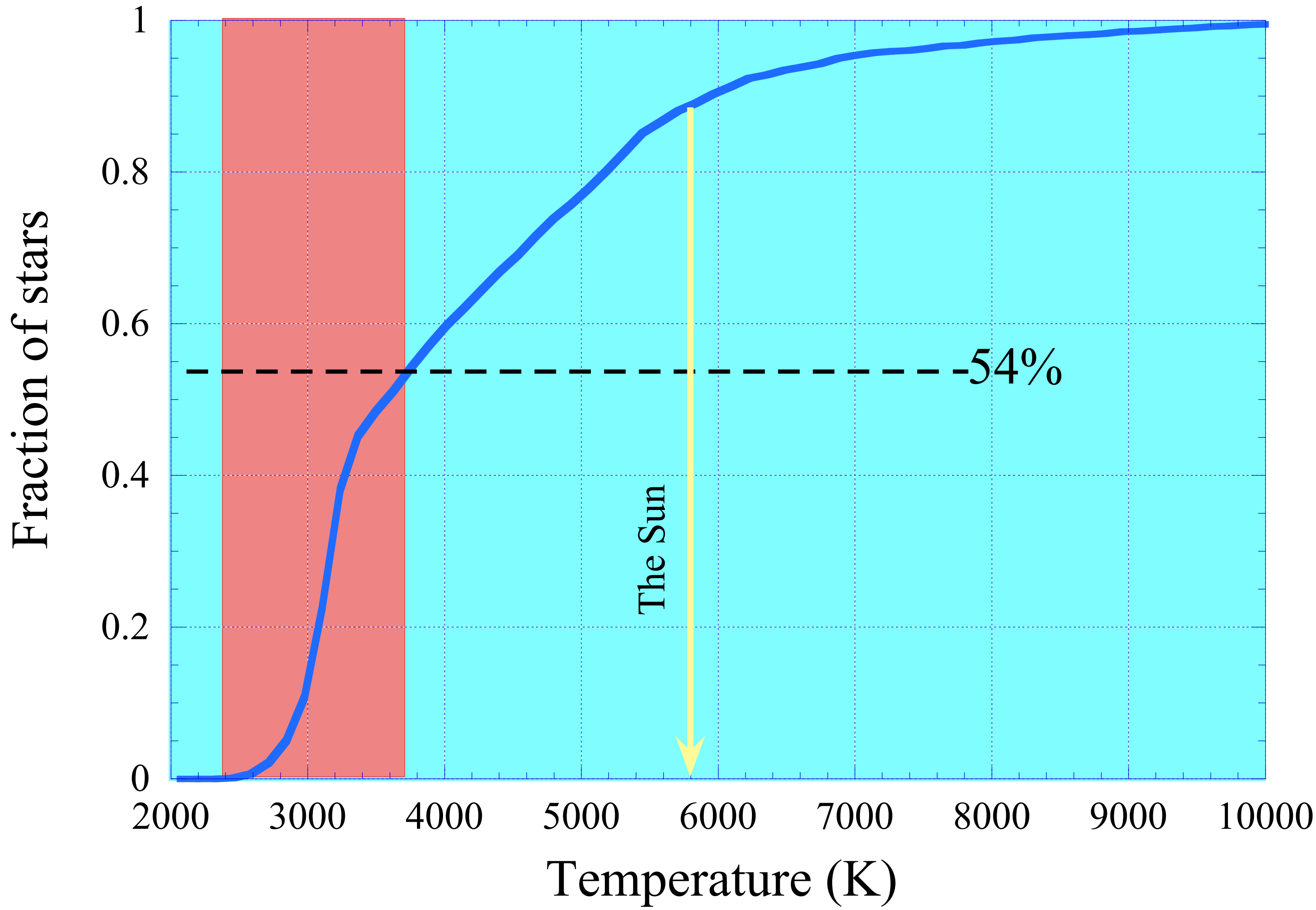
M stars are extremely long-lived, evolve slowly

M stars in the Universe

Commonly estimated that 70% of stars
(76% of main-sequence stars) are M-dwarfs

But our ability to do a complete census of dim stars is limited, even in our own galaxy.

M stars in our neighborhood

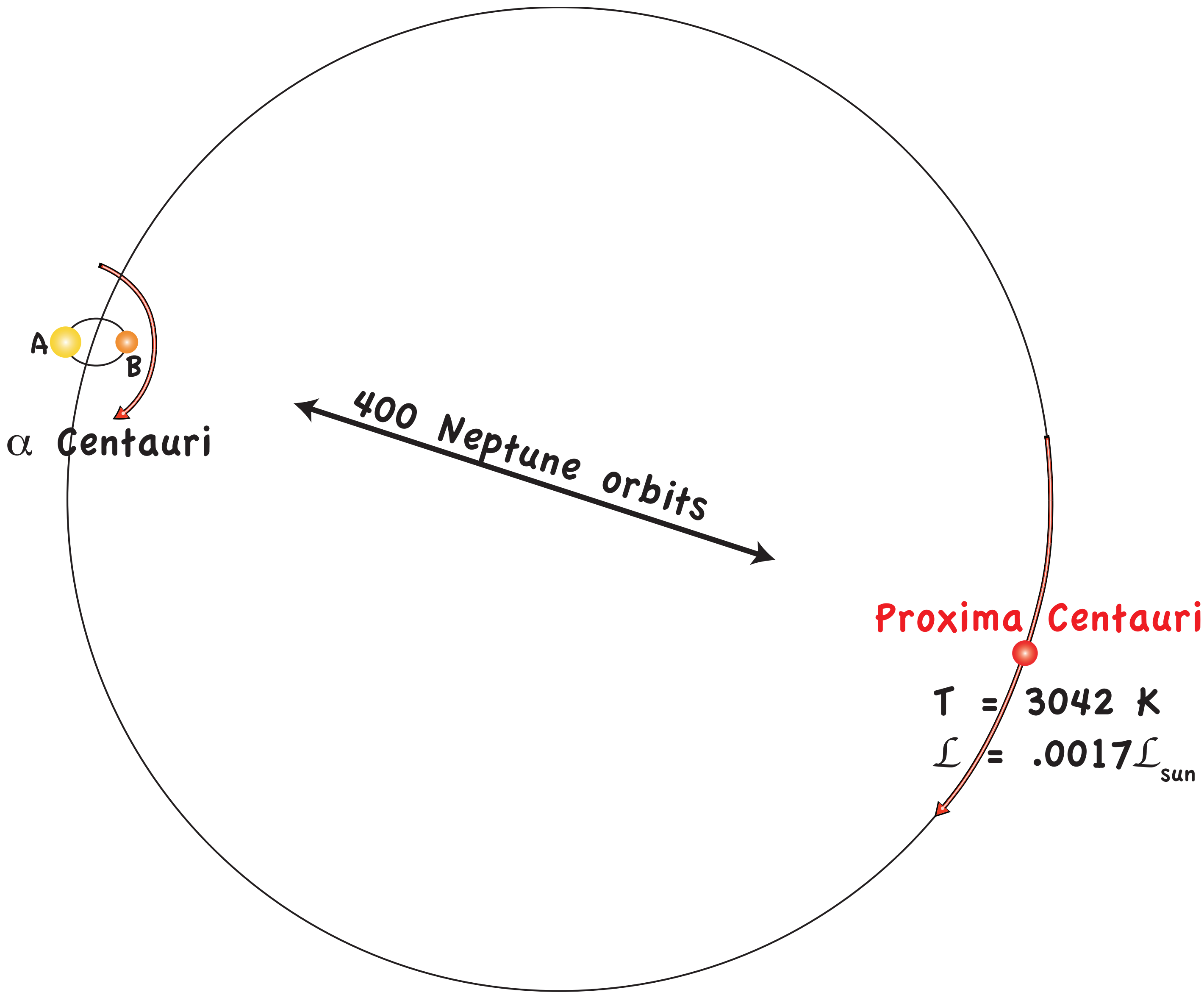


Gliese catalog of the $\sim 3,803$ stars within 25 parsecs (82 light years)

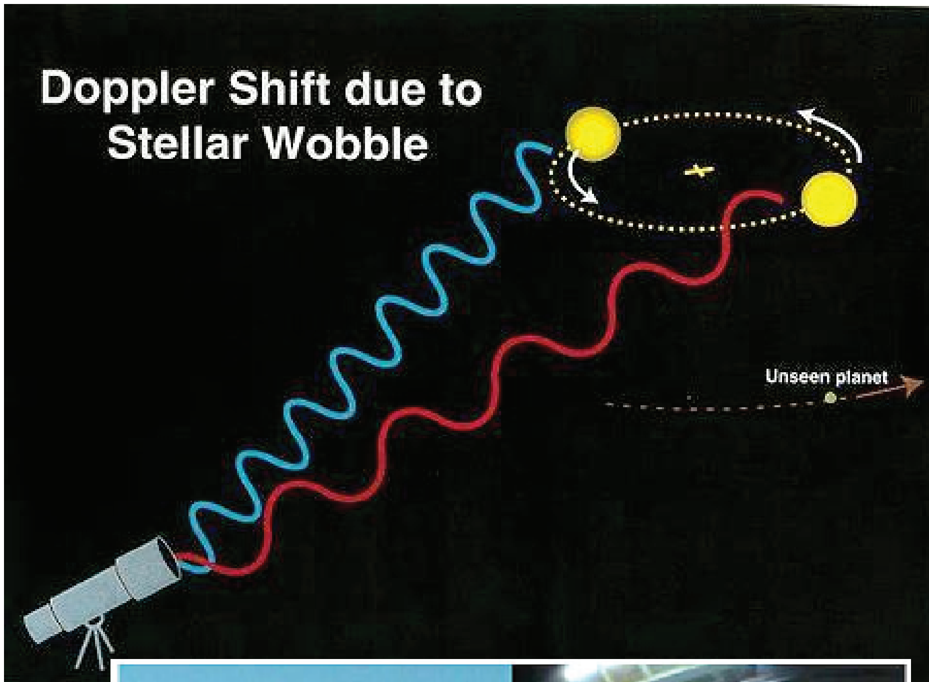
46 of the 71 stars in the 50 nearest systems are M stars

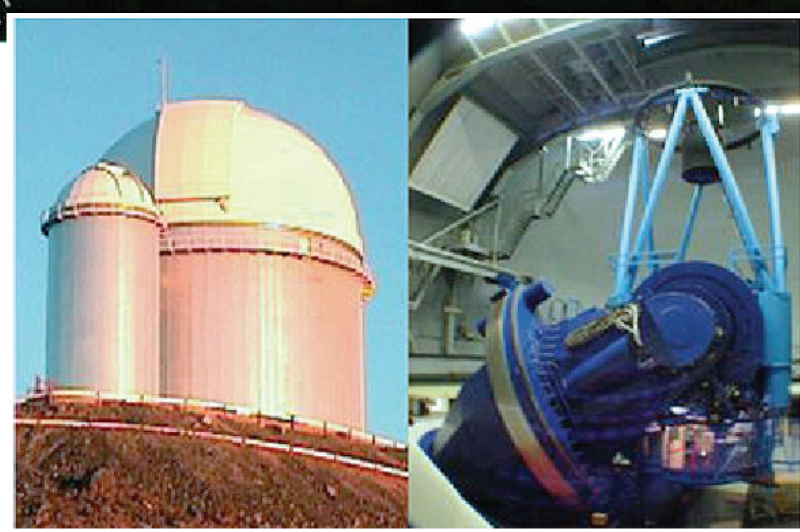
	Star system	Distance in light-years	Stellar type (s)
1	Alpha Centauri	4.24-4.37	M, G, K
2	Barnard's Star	5.96	M
3	Wolf 359	7.78	M
4	Lalande 21185	8.29	M
5	Sirius	8.58	A, D
6	Luyten 726-8	8.73	M, M
7	Ross 154	9.68	M
8	Ross 248	10.32	M
9	Epsilon Eridani	10.52	K
10	Lacaille 9352	10.74	M
11	Ross 128	10.92	M
12	EZ Aquarii	11.27	M, M, M
13	Procyon	11.40	F, D
14	61 Cygni	11.40	K, K
15	Struve 2398	11.53	M, M
16	Groombridge 34	11.62	M, M
17	Epsilon Indi	11.82	K, T, T
18	DX Cancri	11.83	M
19	Tau Ceti	11.89	G
20	GJ 1061	11.99	M
21	YZ Ceti	12.13	M
22	Luyten's Star	12.37	M
23	Teegarden's Star	12.51	M
24	SCR 1845-6357	12.57	M, T
25	Kapteyn's Star	12.78	M
26	Lacaille 8760	12.87	M
27	Kruger 60	13.15	M, M
28	DEN 1048-3956	13.17	M
29	UGPS 0722-05	13.26	T
30	Ross 614	13.35	M, M
31	WISE 1541-2250	13.70	Y
32	WISE 0350-5658	13.70	Y
33	Wolf 1061	13.82	M
34	Van Maanen's Star	14.07	D
35	Gliese 1	14.23	M
36	Wolf 424	14.31	M, M
37	TZ Arietis	14.51	M
38	Gliese 687	14.80	M
39	LHS 292	14.80	M
40	Gliese 674	14.81	M
41	GJ 1245	14.81	M, M, M
42	Gliese 440	15.06	D
43	GJ 1002	15.31	M
44	Gliese 876	15.34	M
45	LHS 288	15.61	M
46	WISE 1405+5534	15.76	Y
47	Gliese 412	15.83	M, M
48	Groombridge 1618	15.85	K
49	AD Leonis	15.94	M
50	DENIS J081730.0-615520	16.07	T

Our closest neighbor is an M-star



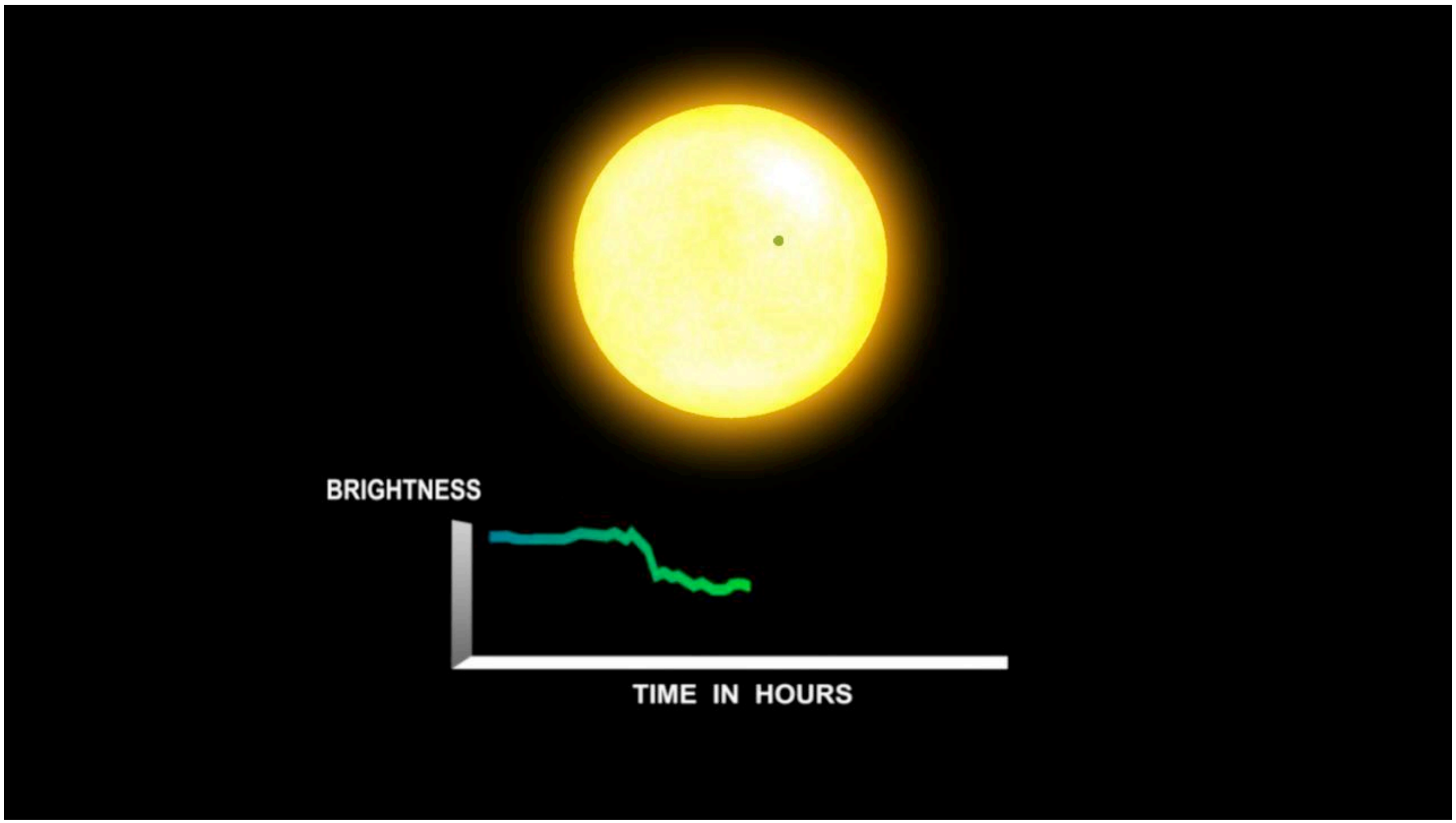
Radial velocity surveys



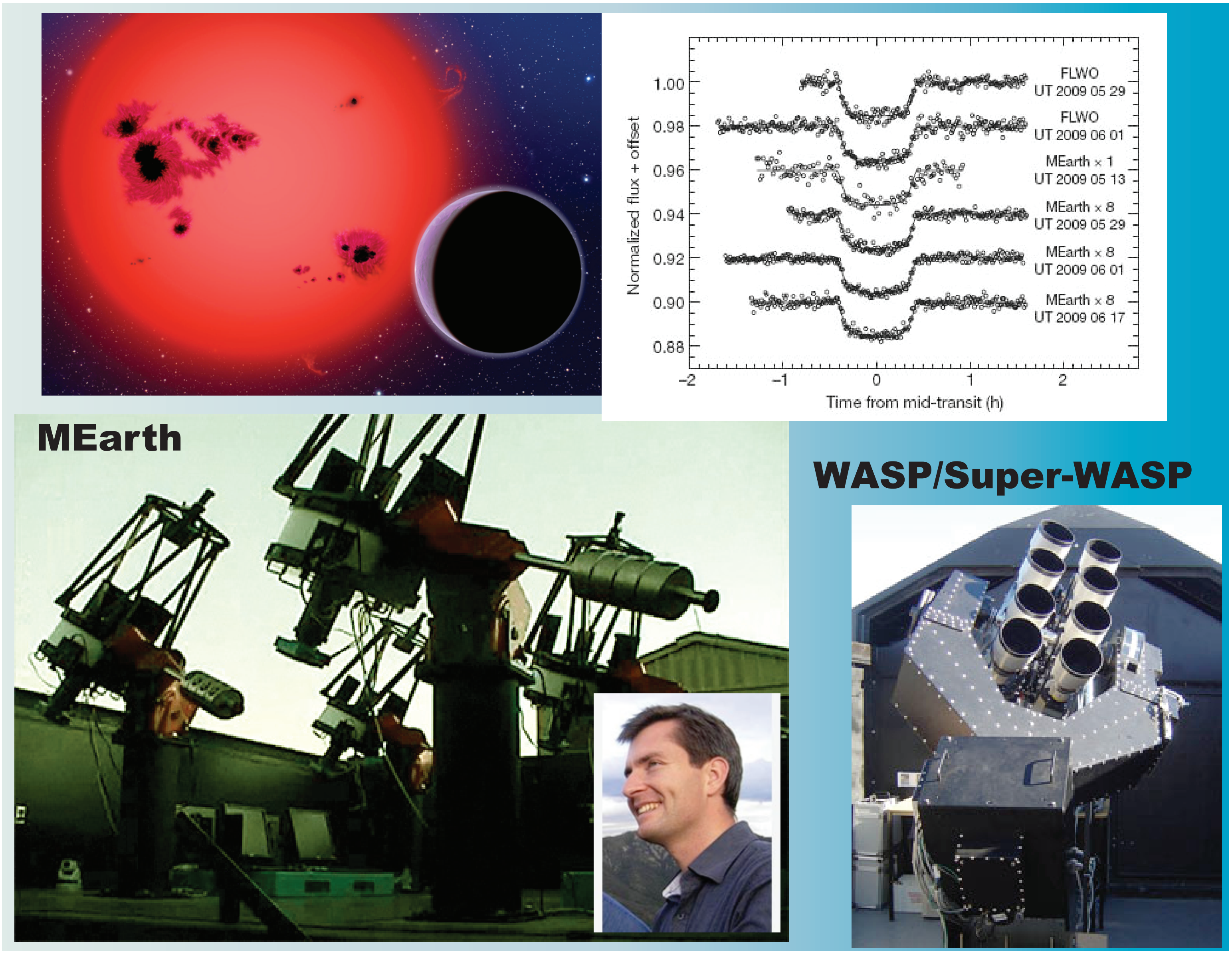


e.g. HARPS (Chile)

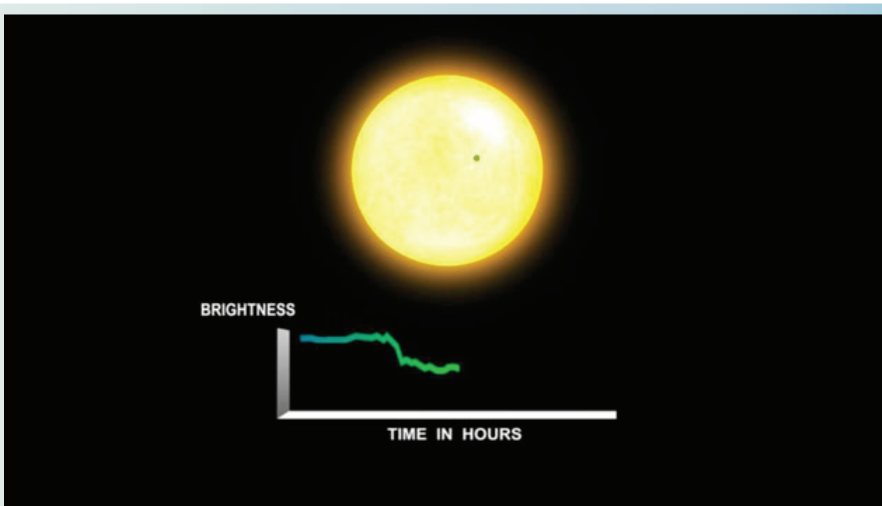
Transit method

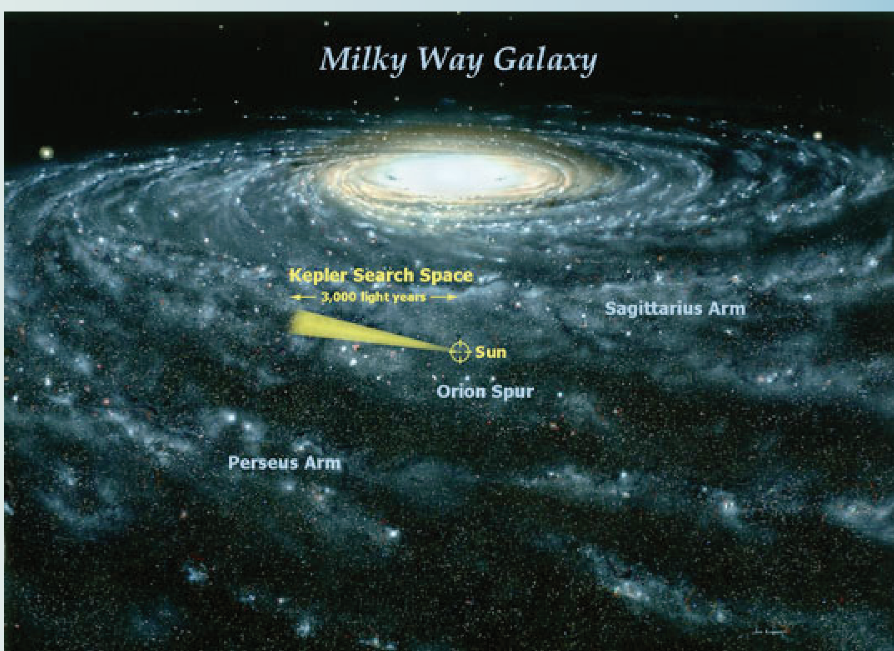


Ground based transit surveys

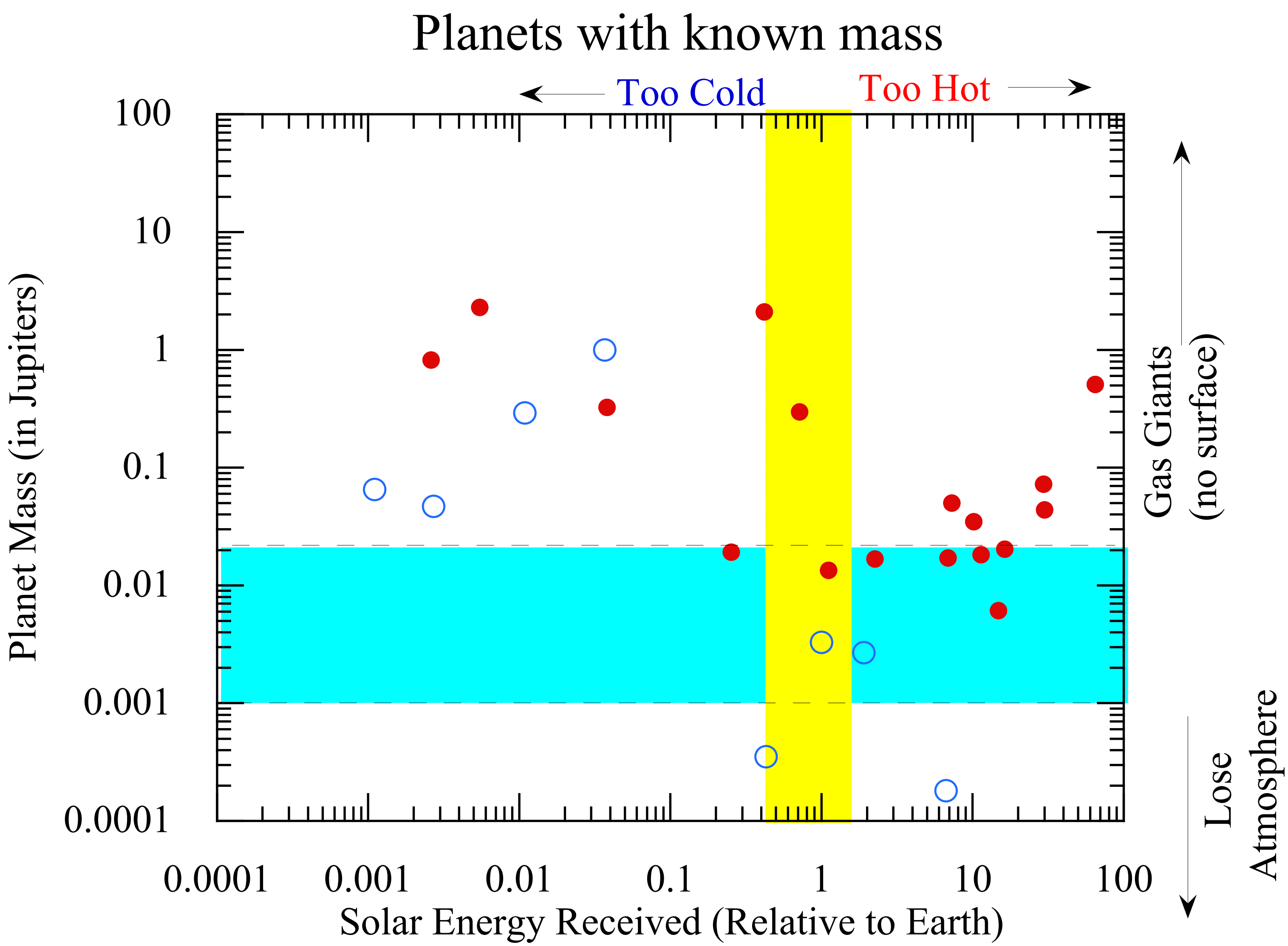


Kepler: Space-based transit survey

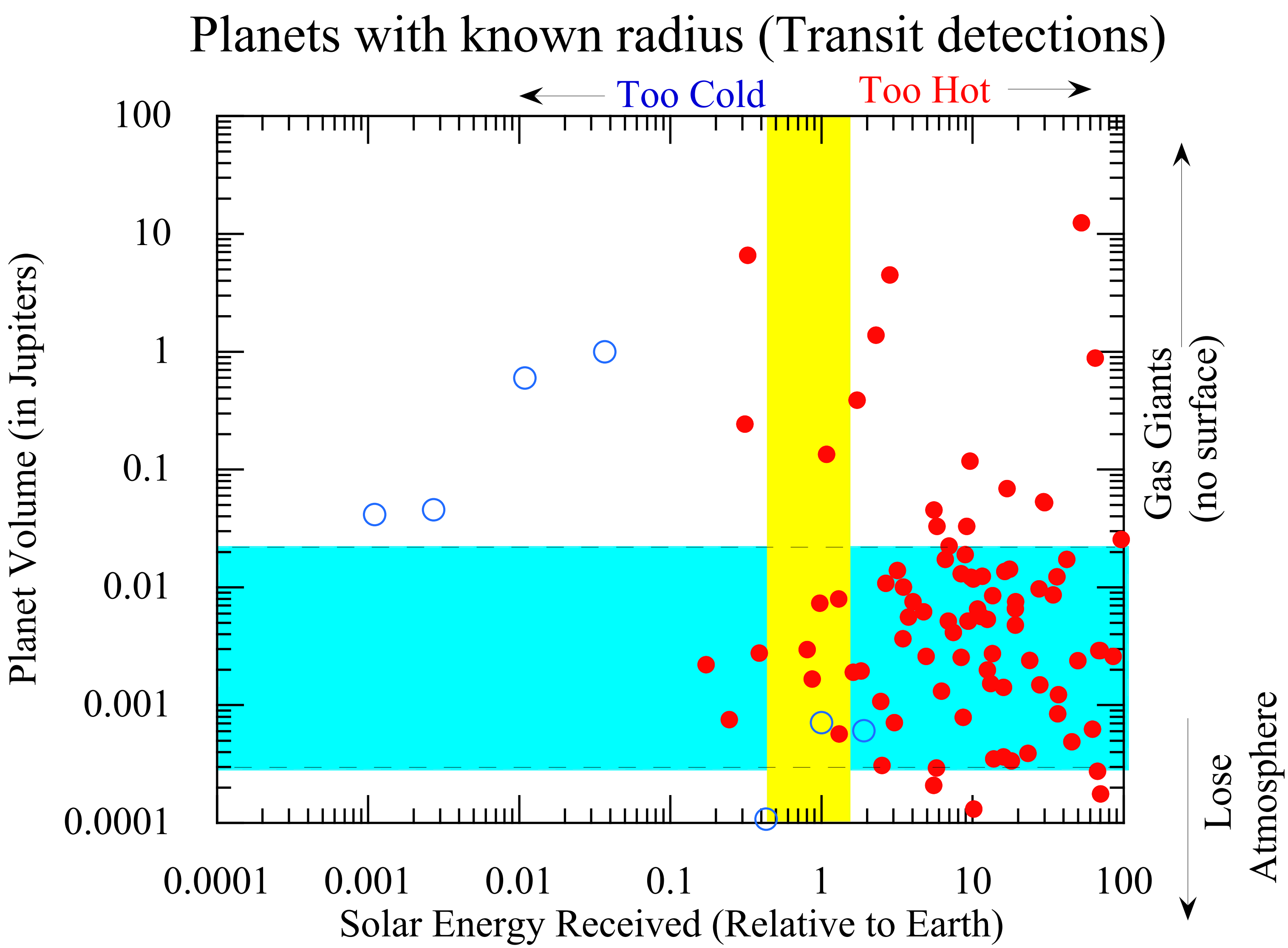




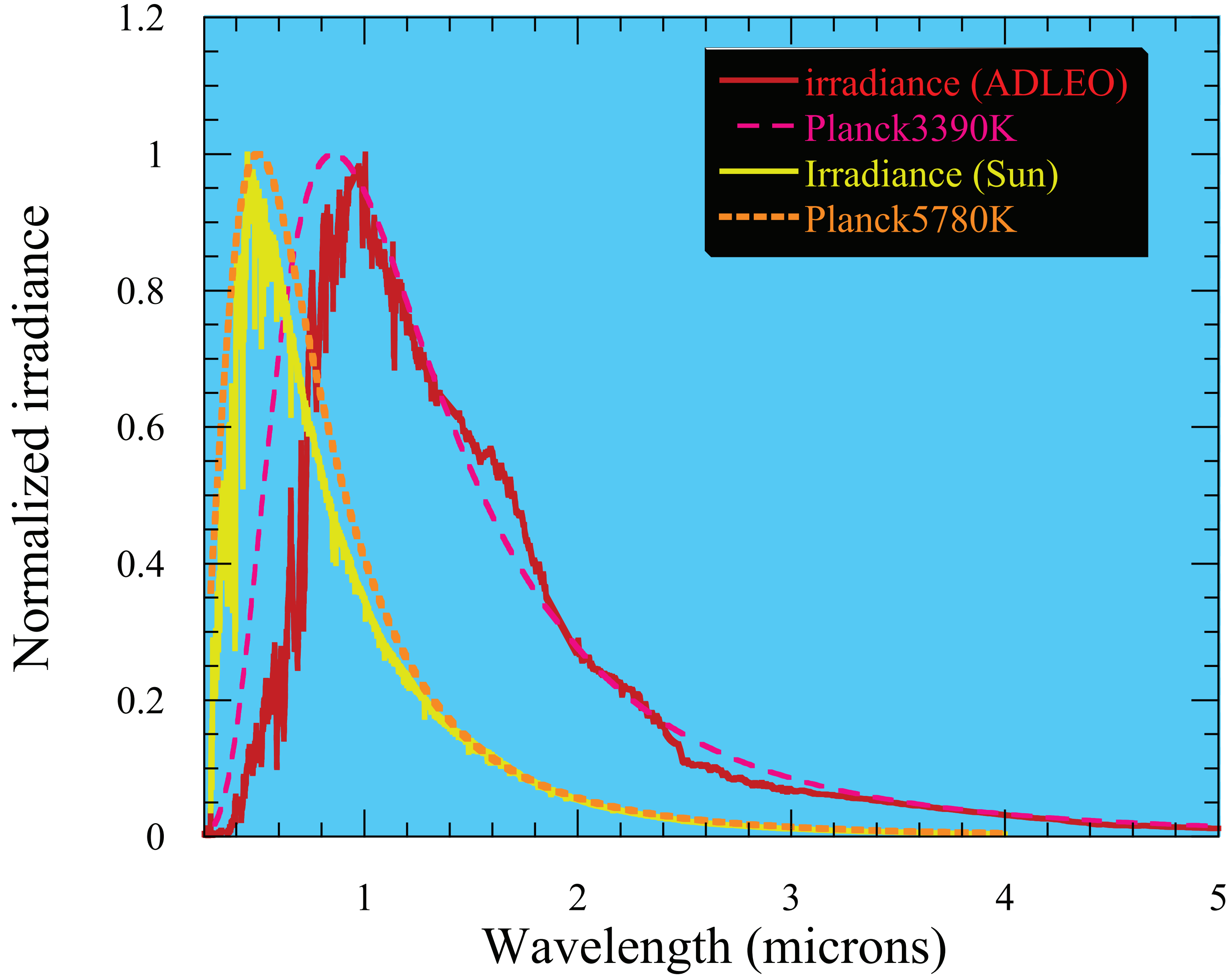
Do planets form around M-stars?



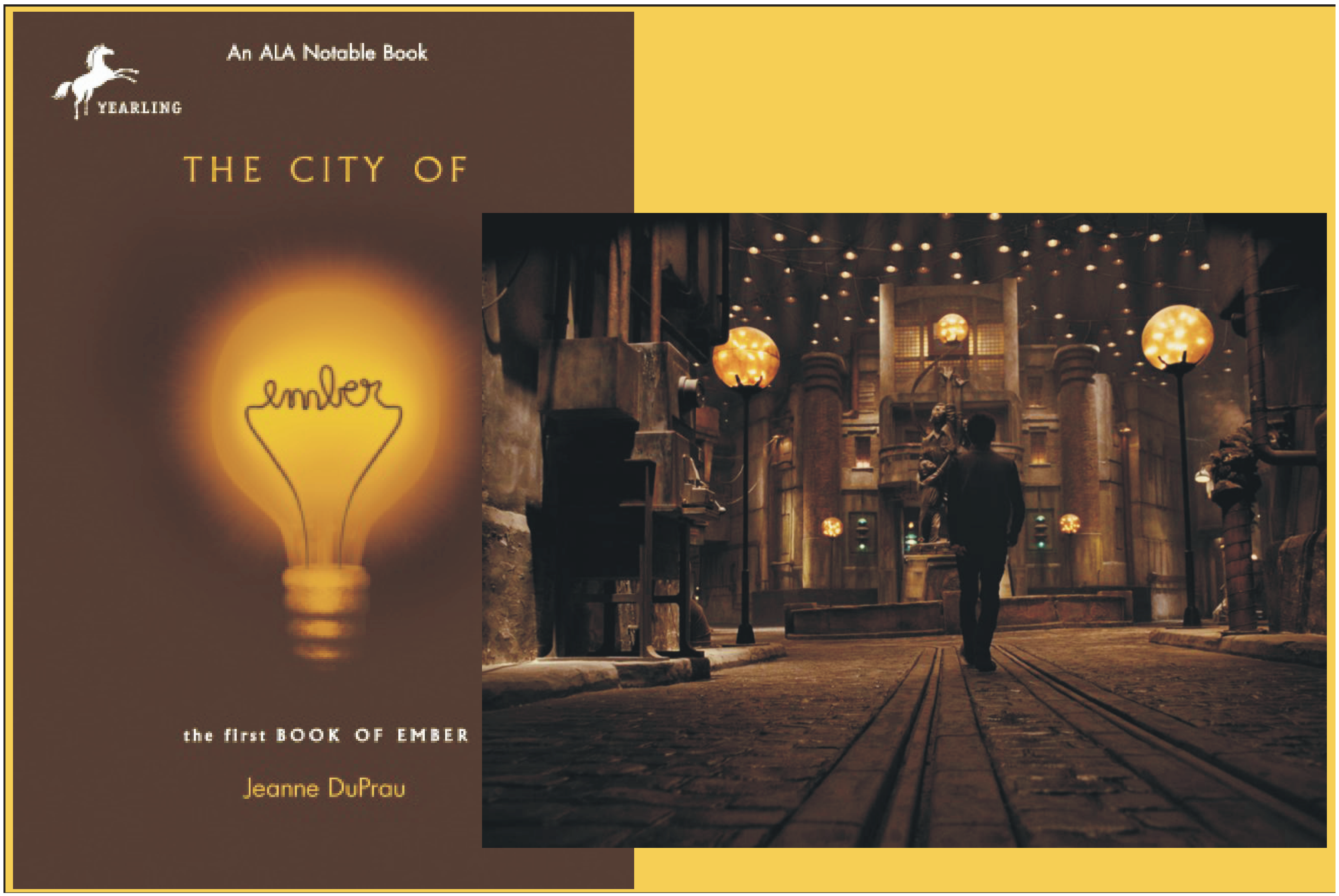
Do planets form around M-stars?



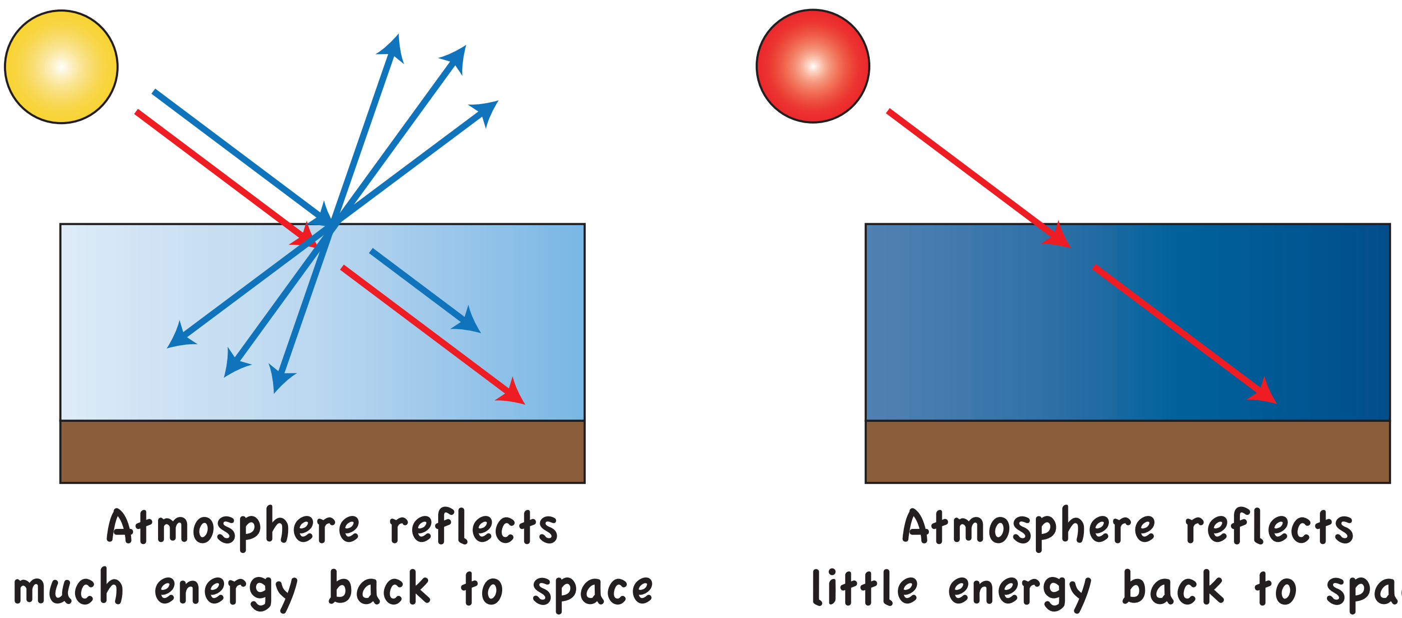
Red dwarfs are redder than the Sun...



... but not so red as the name implies

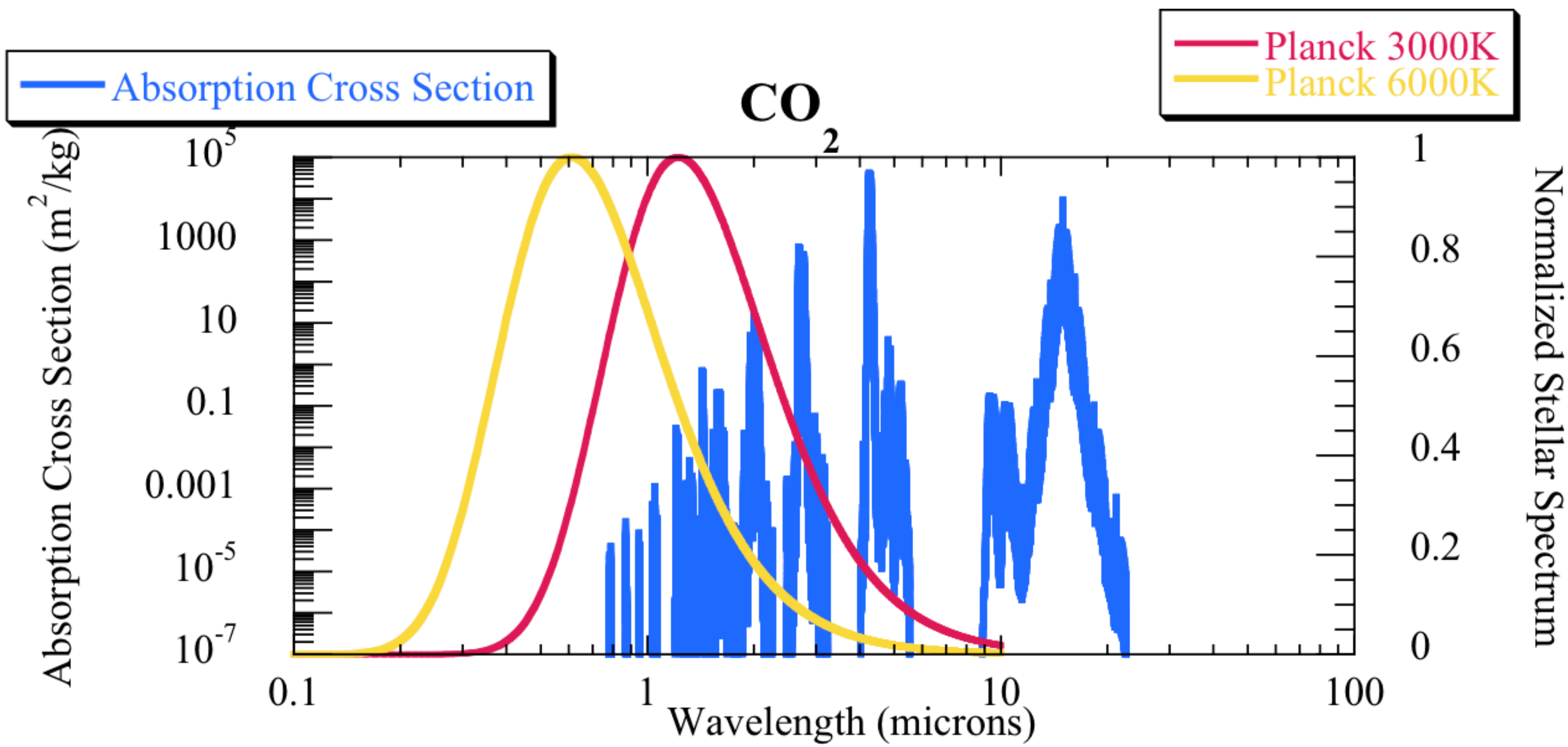


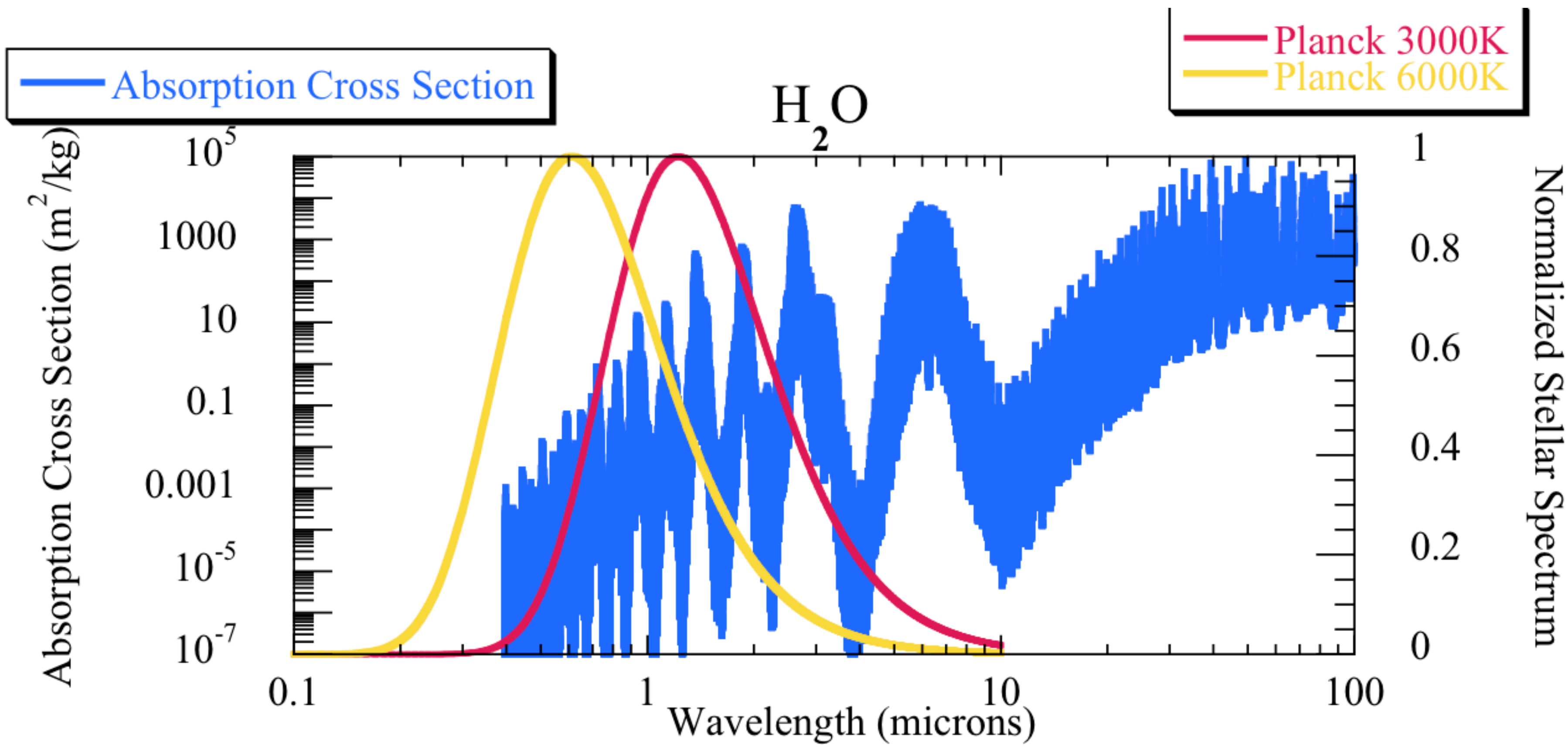
Consequences: Not as much blue to make the sky blue



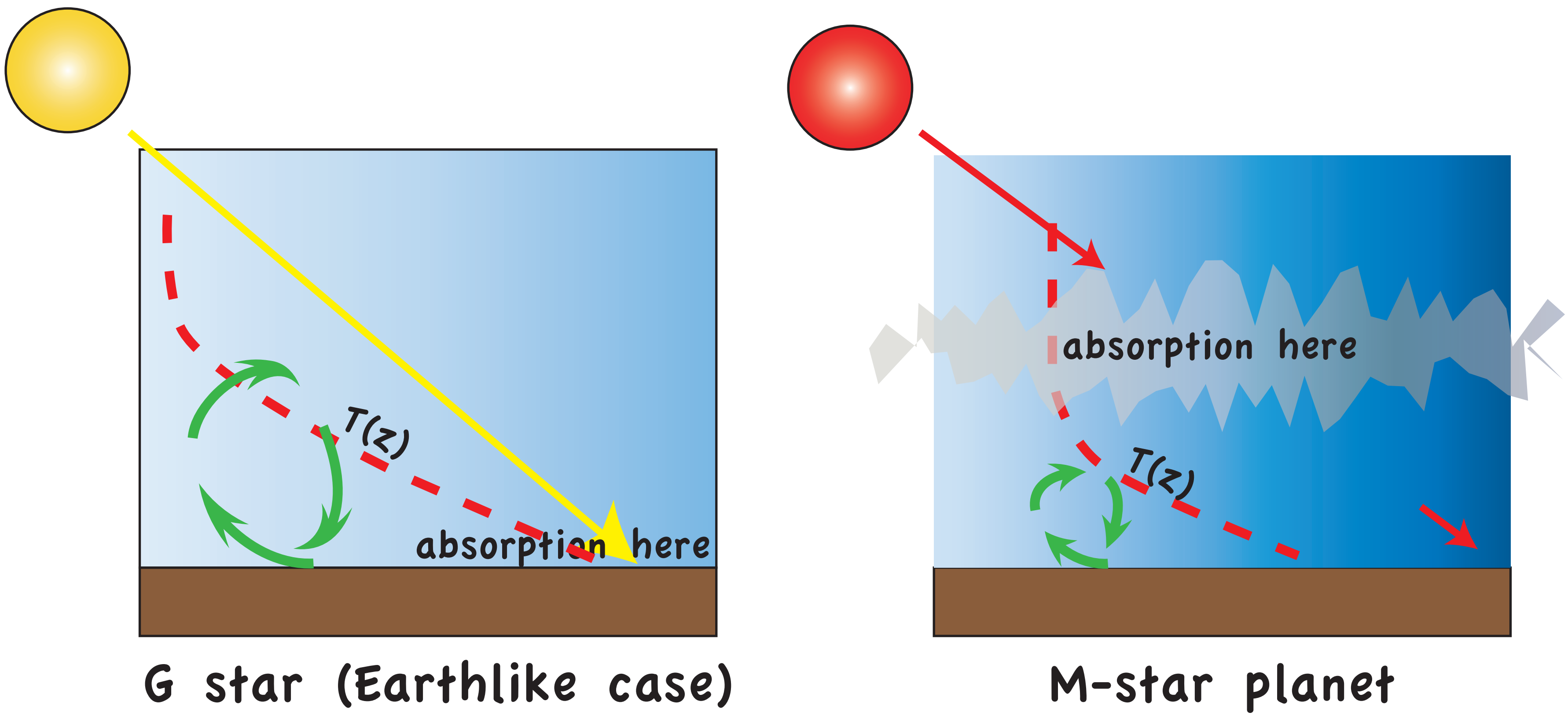
All other things being equal, M-dwarf planets absorb more of the incident stellar radiation

But more of the stellar radiation is deposited high in the atmosphere, less at the ground and in deep atmosphere

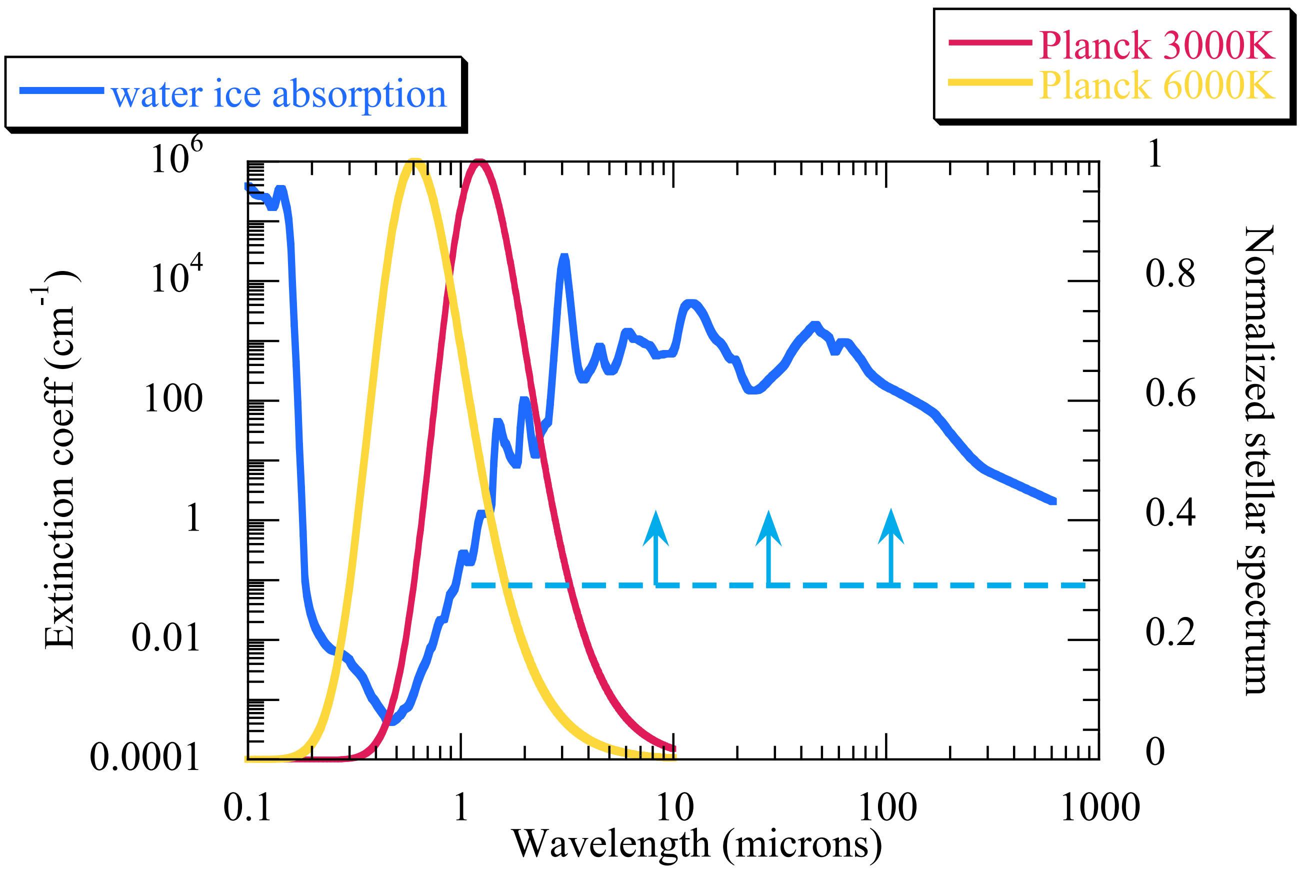


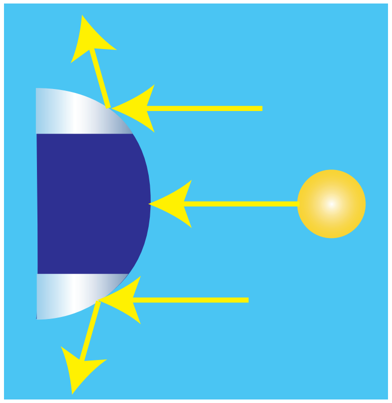

Absorption Cross Section
Planck 3000K
Planck 6000K
H2O
Absorption Cross Section (m2/kg)
10^5
1000
10
0.1
0.001
10^-5
10^-7
1
0.8
0.6
0.4
0.2
0
Normalized Stellar Spectrum
0.1
1
10
100
Wavelength (microns)

Implies weaker convection, shallower troposphere

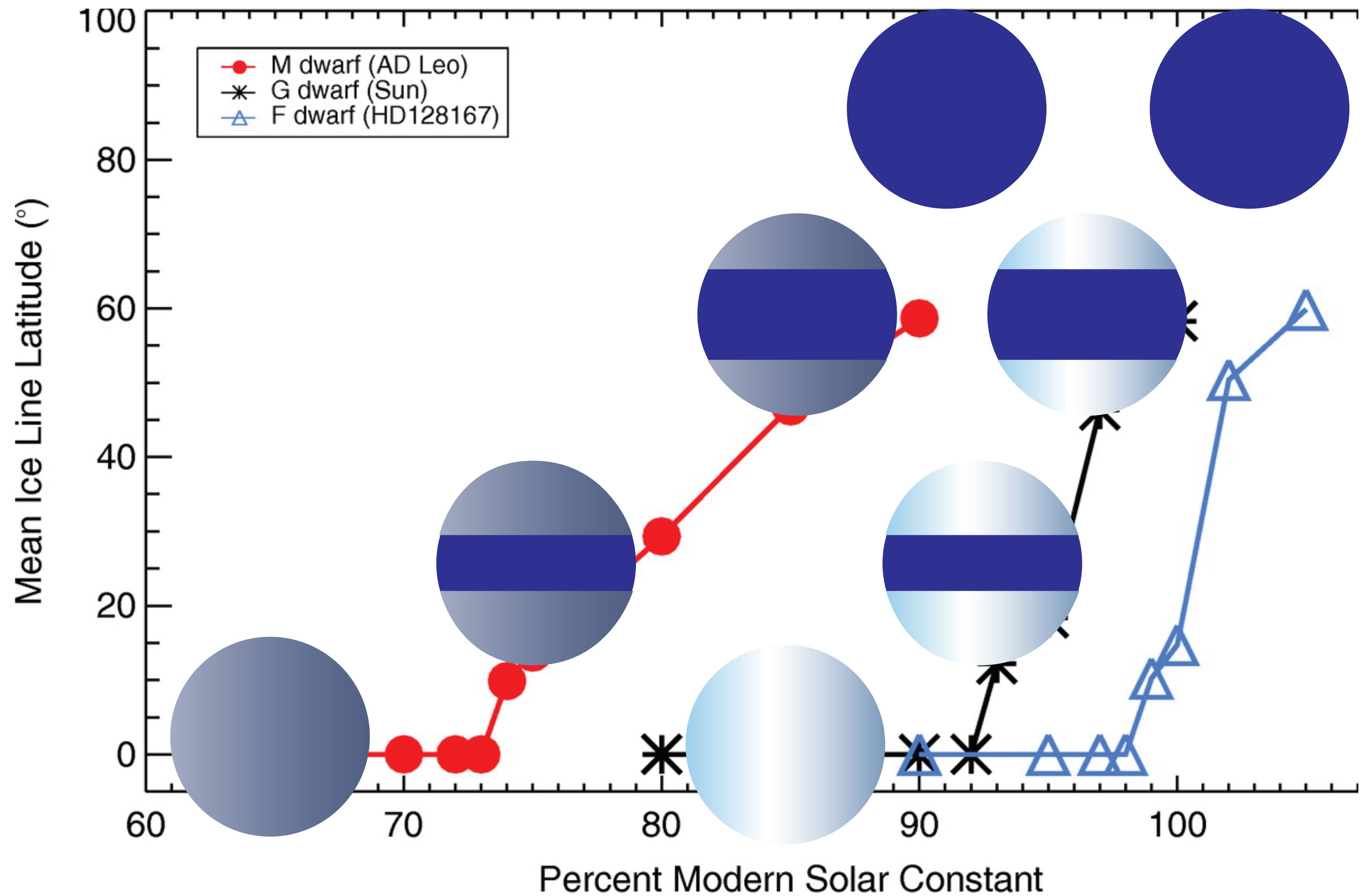


Consequences:Ice and snow are not as ”white” as on Earth





Reduced reflectivity contrast between ice/snow and ocean makes it harder for a planet to freeze over and turn into a Snowball



Shields, et al *Astrobiology* 2013, computed with 300ppm CO_2

But this doesn’t affect the outer edge of the habitable zone, because the dense atmospheres needed to make a planet habitable there make the planetary reflectivity nearly independent of the surface characteristics.

For dim stars, habitable zone planets are in close orbits

$$\boxed{L_\circledast = \frac{\mathcal{L}}{R^2}}$$ ($\mathcal{L}$ in units of Solar luminosity, R = orbital dist. in a.u.)

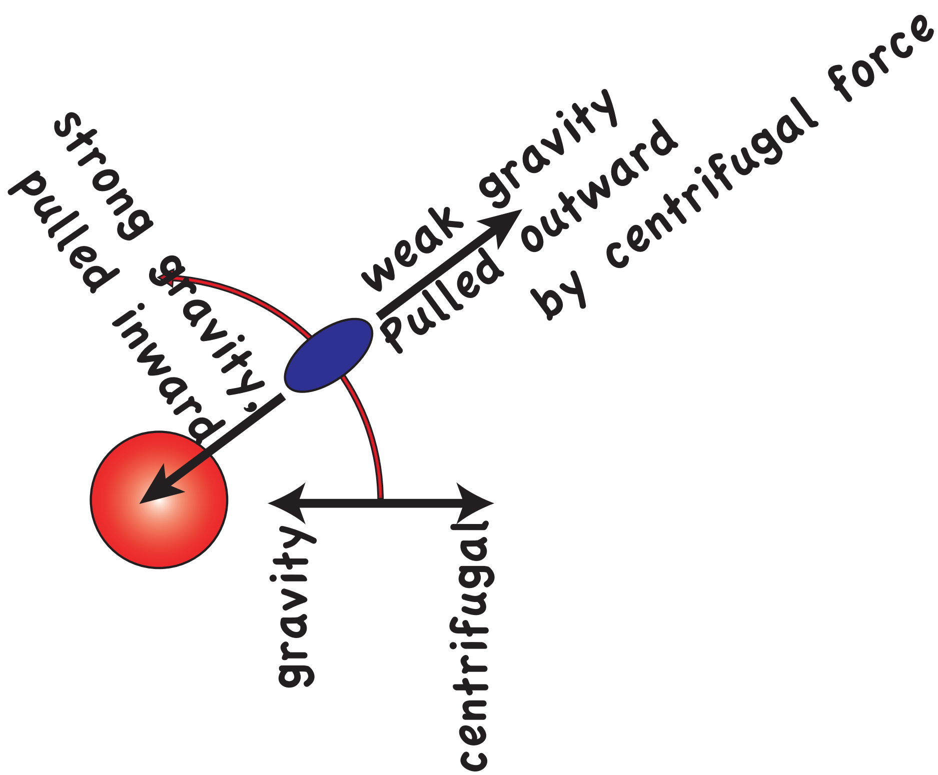
$$L_\circledast = 1 \to \boxed{R = \mathcal{L}^{\frac{1}{2}} = .44M^{1.15}}$$ (M measured in Solar masses)

Orbital period (Earth years): $\boxed{P = R^{1.5}/M^{.5} = .39M^{1.22}}$

e.g for Gliese 581:

$M = .3 \to R = .11$ a.u. $P = .09$ years = 33 Earth days

Strong tidal stresses slow the planets rotation

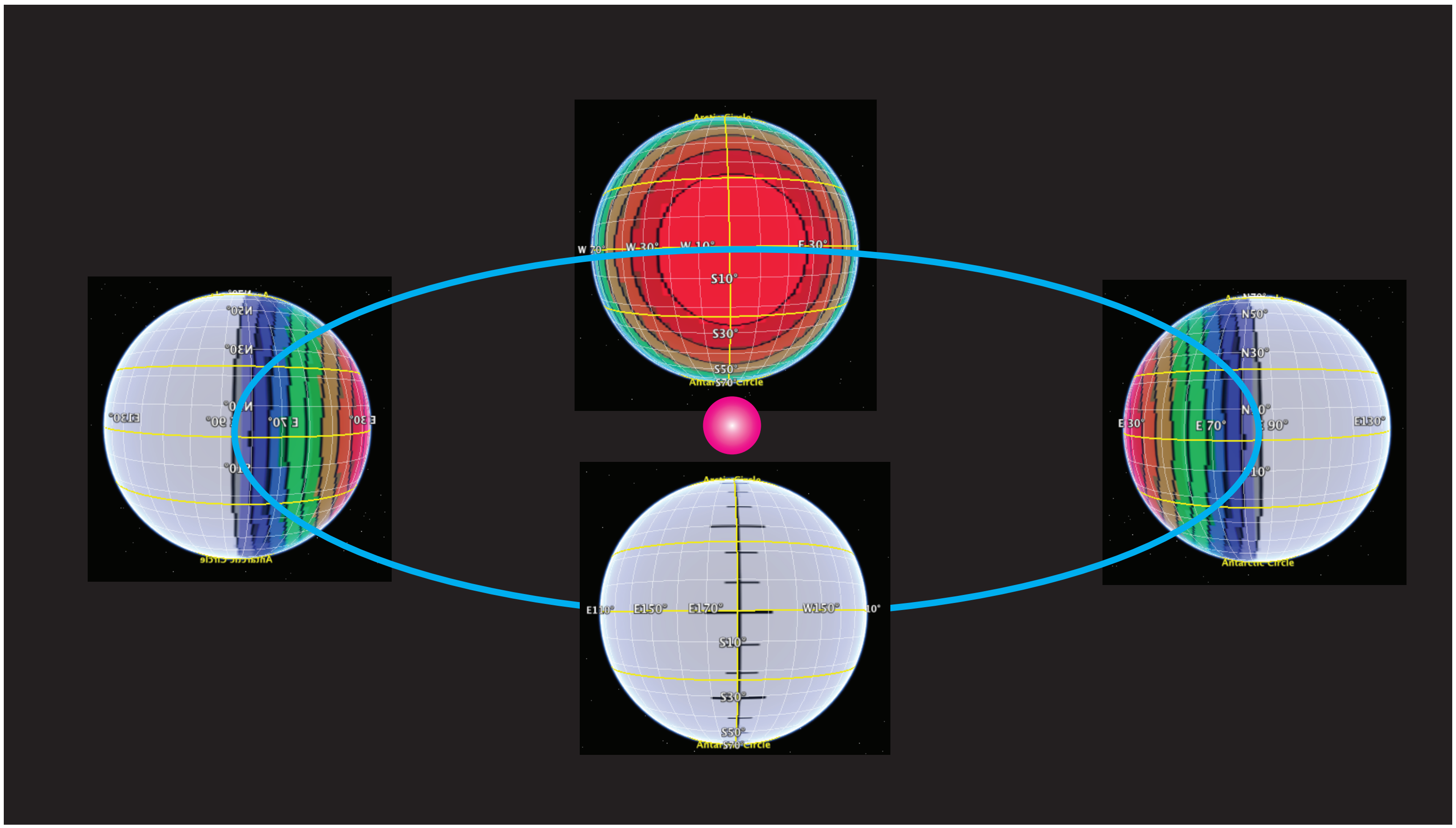


Stress: $\boxed{M/r^3 = 11.7M^{-2.45}}$

(e.g. 1 for Earth, 17.25 for Mercury, 223 for the HZ of GJ581)

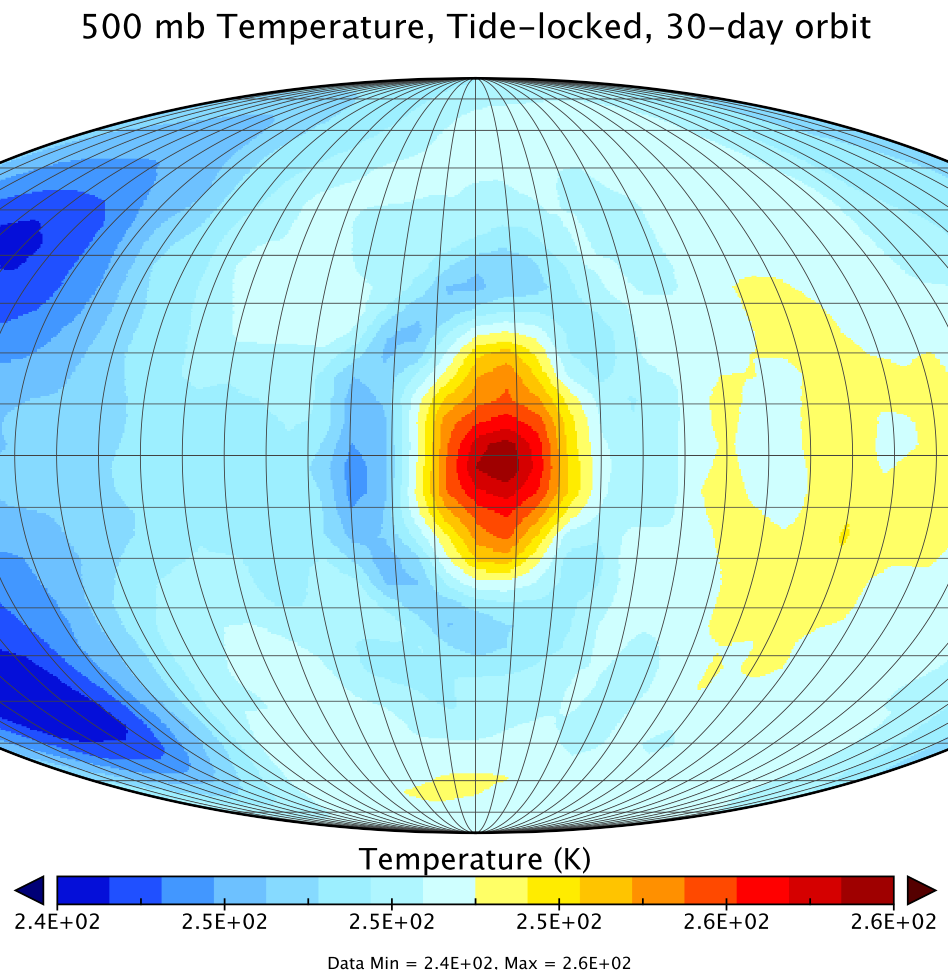
For circular orbit, end-state is tide-locked

Tide-locked planets in circular orbits have permanent dayside and nightside



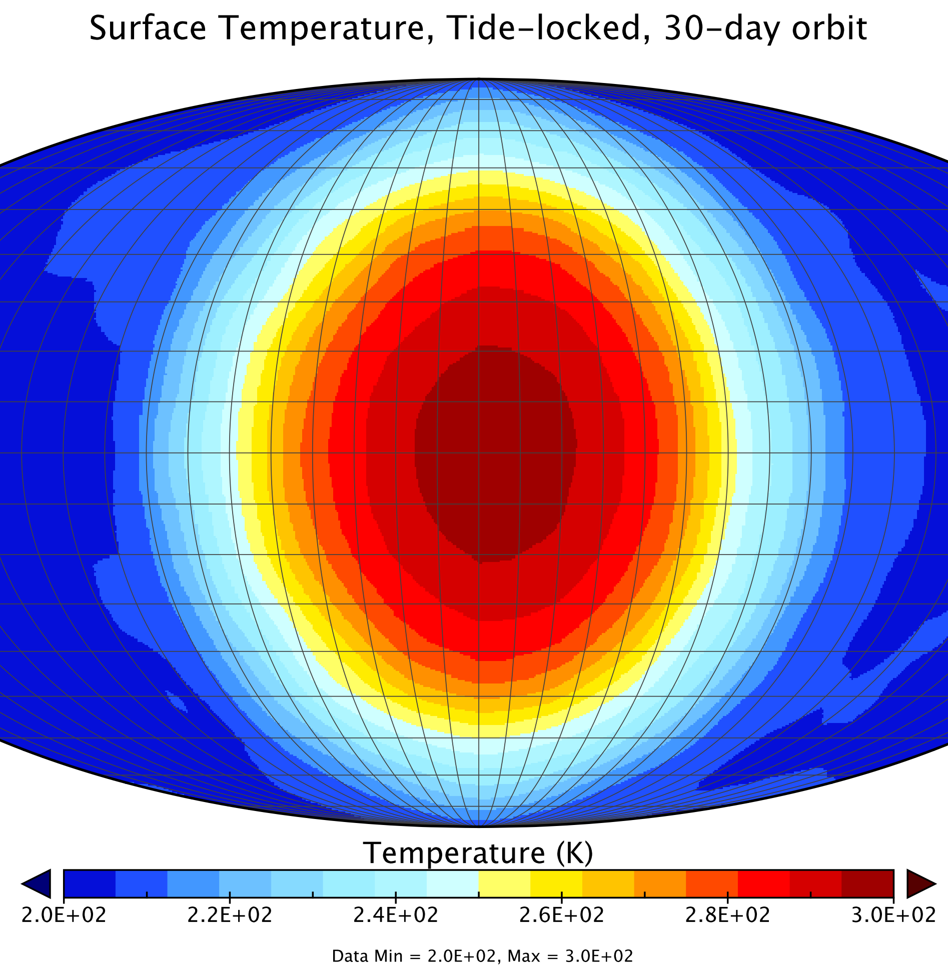
Substellar point (local noon, where star is directly overhead)
is geographically fixed

Slow rotation → weak Coriolis force → weak temperature gradients in the atmosphere

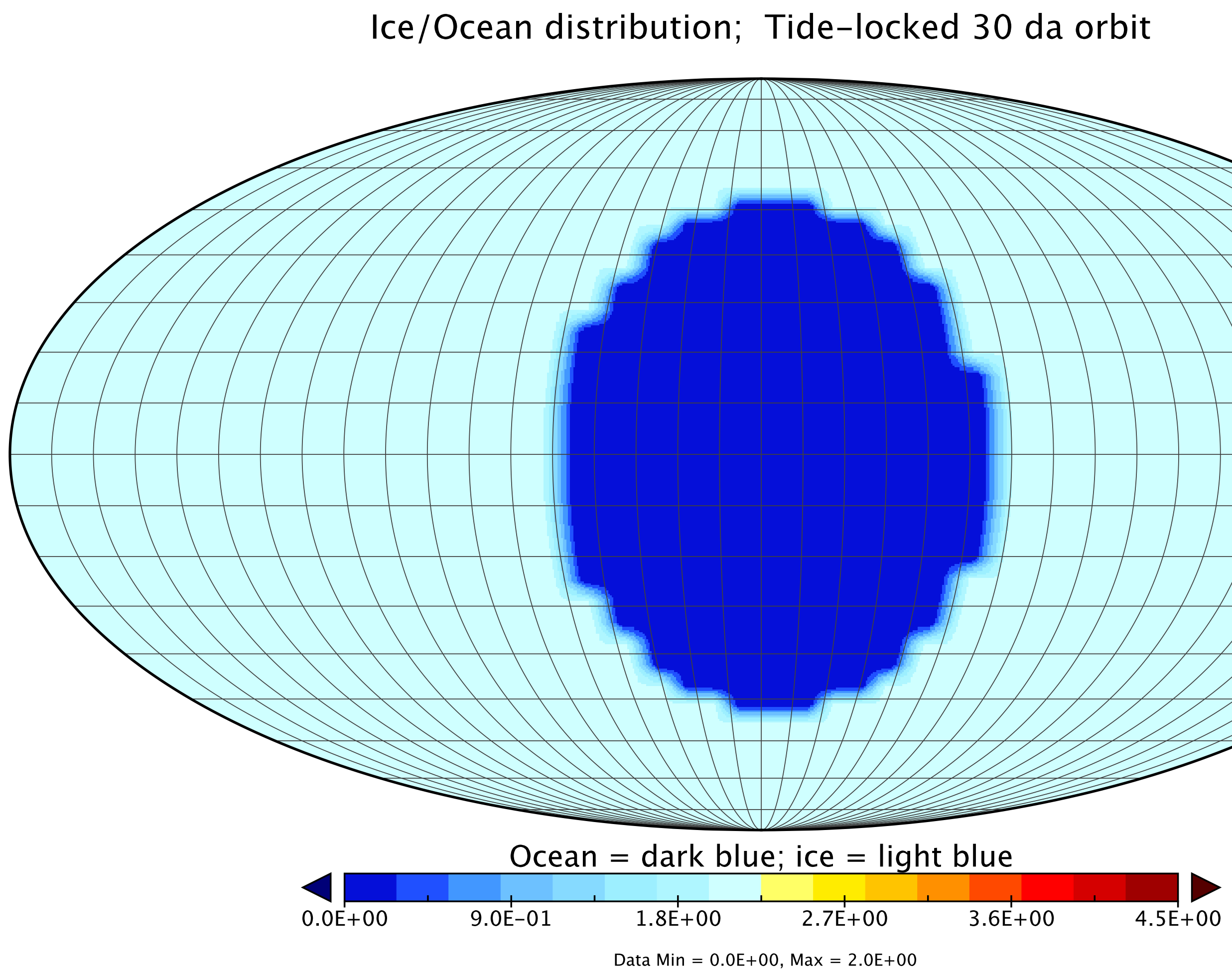


i.e. atmosphere doesn’t condense out onto the nightside

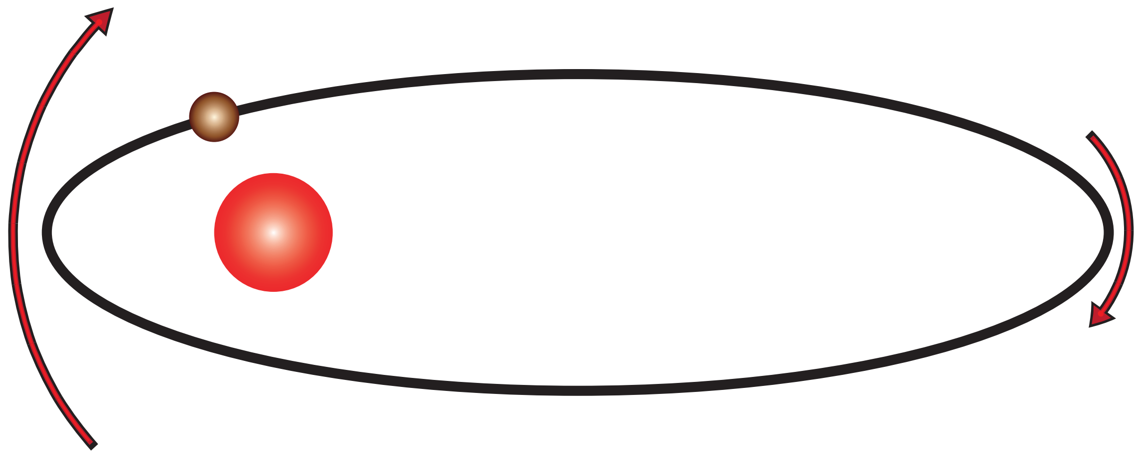
But there can be strong temperature gradients near the surface,



... and even ice formation if the planet has an ocean

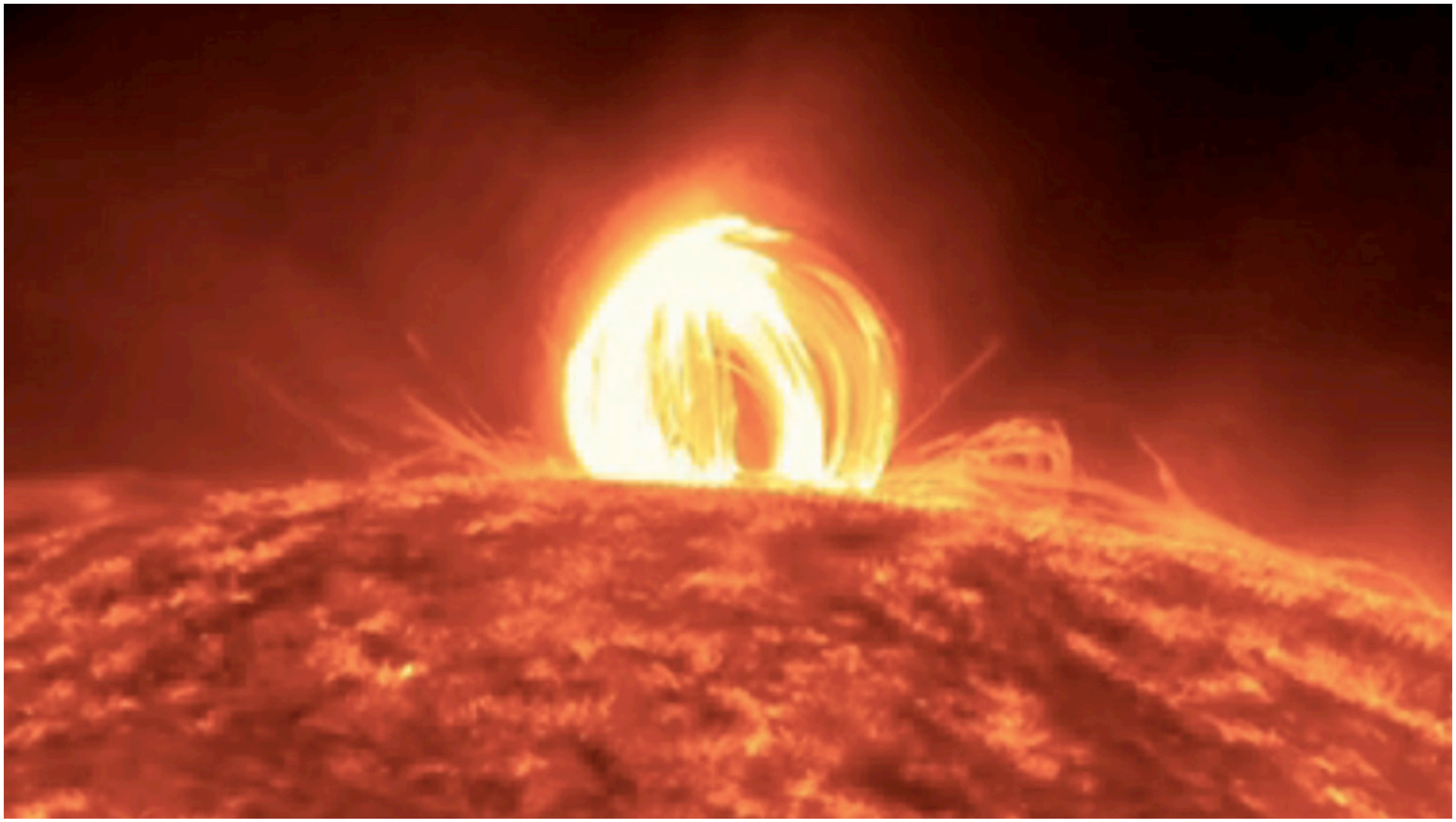


But if the orbit is elliptical ...



- Variation in orbital angular speed with distance from star means that exact tide-locked states are no longer possible.
- Quasi-synchronous states, where substellar point rocks back and forth a bit
- Low-order spin-orbit resonances.
(e.g. 3 days per two years, as for Mercury

So, neighborhood of M-dwarfs is great real estate, but there's a catch ...



M-star rotation and deep convection make strong magnetic fields, promote flaring, activity

→ Strong extreme ultraviolet and X-ray emission (relative to luminosity)

Ultraviolet (UV) is important because ...

- Very shortwave ultraviolet (EUV) and X-rays are absorbed high up in the atmosphere, and heat it to the point where the atmosphere can escape to space.
- i.e. it's the rocket fuel that brings molecules up to escape velocity and can launch atmosphere out of the gravity well.
- Shorter wave ultraviolet drives photochemistry, and can break up heavy molecules into lighter components that escape more easily.
- Low mass stars can take a half billion years to enter the main sequence, and UV/X-ray luminosity is further elevated throughout this time.
- But as M stars age on the main sequence, they can quiet down
  If planets can regenerate an atmosphere later, habitability could be recovered. (but no easy way to regenerate a nitrogen atmosphere).
- *More on all this in Lecture 2*

Summary

- There are likely to be many planets in the habitable zone of M stars
- With an atmosphere, they would have unusual seasonal/diurnal cycles, shallower tropospheres with weak convection.
- Weak horizontal temperature gradients aloft, monsoonal circulations with most of rainfall and warm waters under the substellar point
- ... but none of this is a threat to habitability
- The main question is whether any of these planets formed with, and retained volatiles (atmosphere, ocean).
- But we know *some* are all atmosphere!
  (cf. GJ1214b, more in Lecture 3)
- Essential next step is a catalog of which M star planets
  have retained an atmosphere