Through the Fully Convective Boundary: An Overview of Low-mass Stars and Brown Dwarfs

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KITP

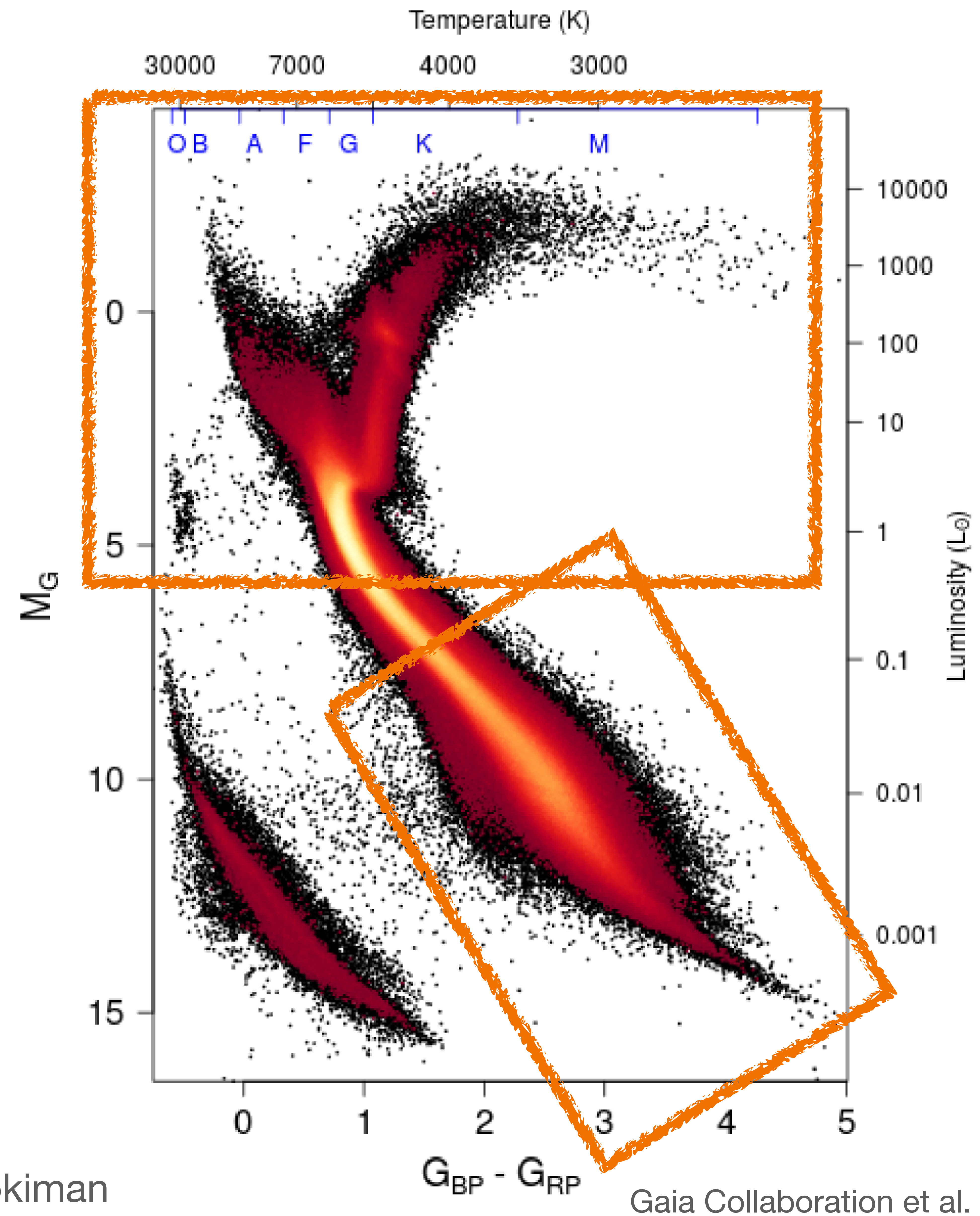
Probes of Transport in Stars
December 9th 2021

Overview of the overview

- Low-mass stars (M dwarfs)
  - Fully convective boundary
  - Empirical evidence of the fully convective boundary
  - Magnetic activity and rotation period evolution

- Brown dwarfs
  - Definition
  - Evolution
  - Clouds
  - Formation

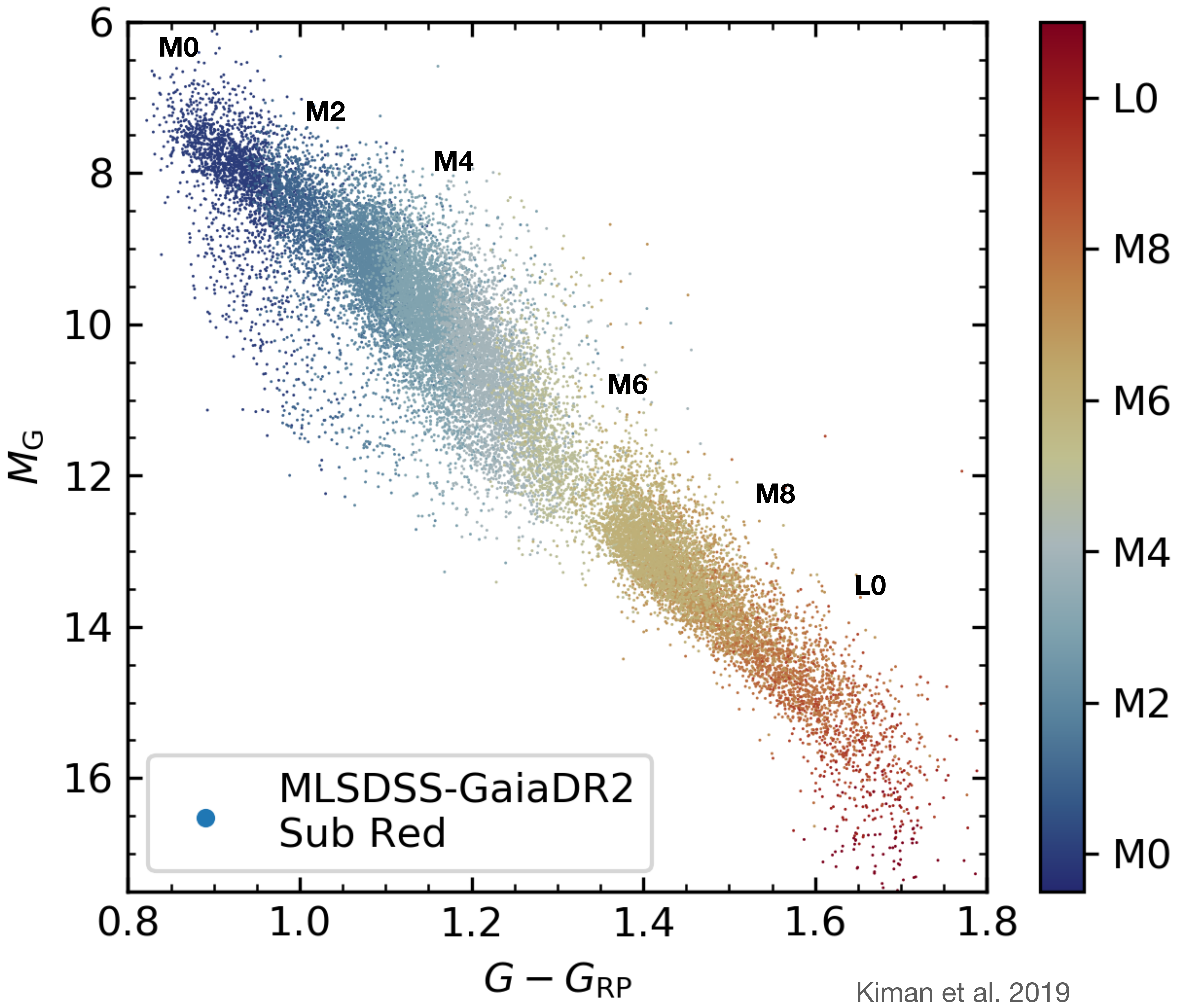
The end of the main sequence



Gaia Collaboration et al. 2018

- Mass ($M_\odot$) < 0.6
- Teff < 3800 K
- Radius ($R_\odot$) < 0.6

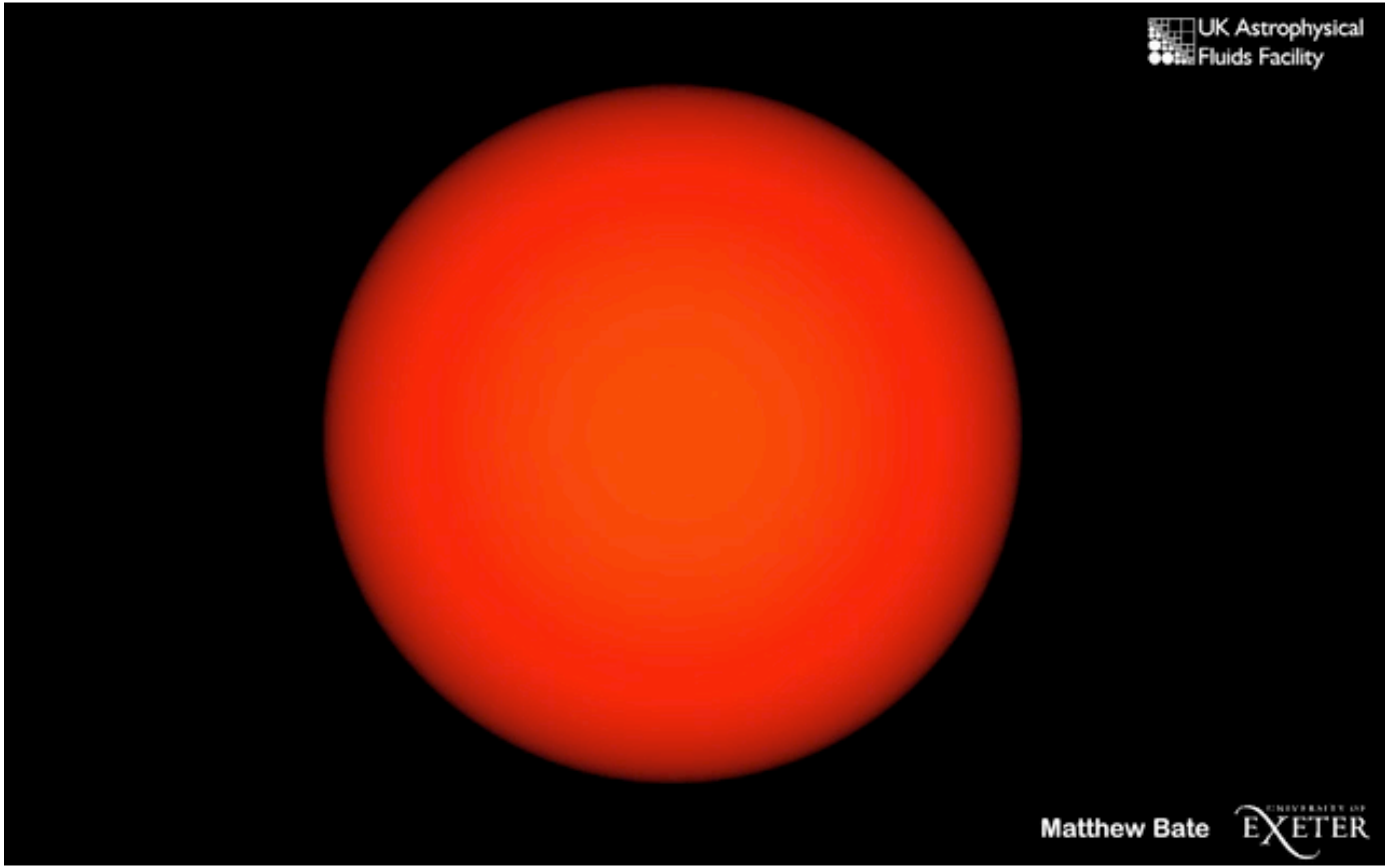
Low-mass stars or M dwarfs are the coolest stars



Kiman et al. 2019

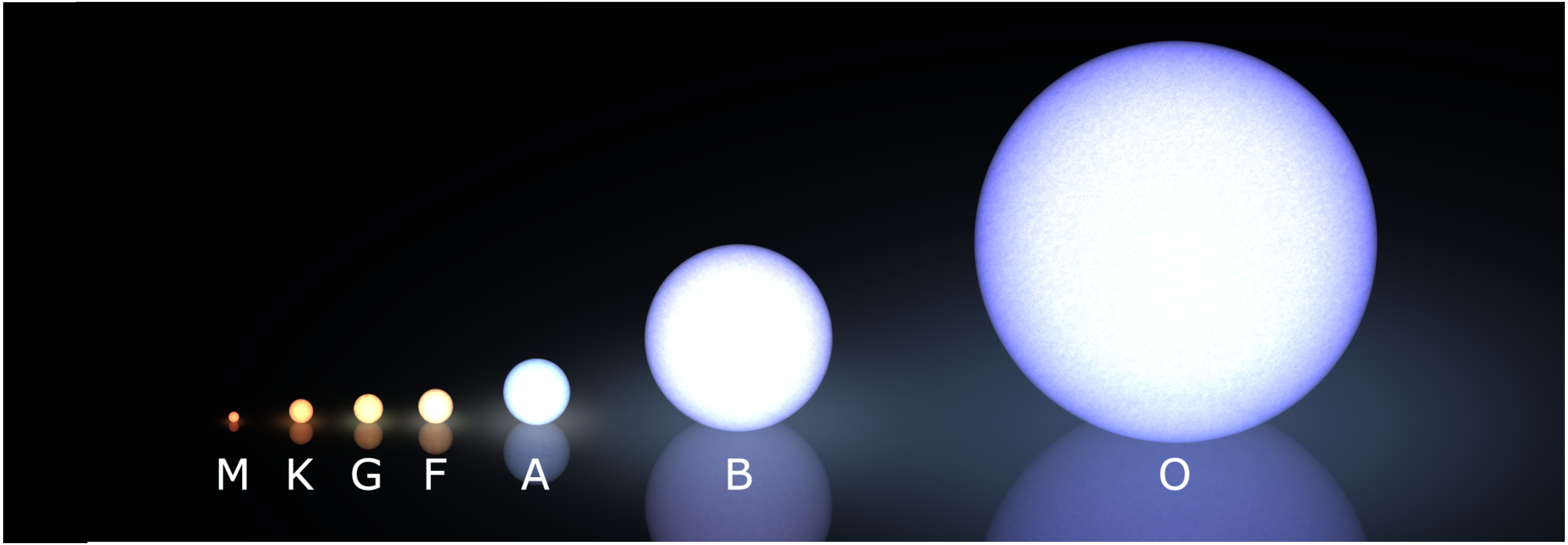
- 0.08 < Mass ($M_{\odot}$) < 0.6
- 2200 K < Teff < 3800 K
- 0.1 < Radius ($R_{\odot}$) < 0.6
- They are the most common star in the Galaxy, so they can help to understand its composition and evolution
- Major targets in the search for “Earth-like” exoplanets
- Every M dwarf that has ever lived is still there.

A Star is Born



- 50 $M_\odot$ molecular cloud
- Gravity starts pulling the gas together to form a dense "core".
- The formation of stars and brown dwarfs begins in this dense core
- As the stars and brown dwarfs interact with each other, many are ejected from the cloud.

According to the mass of the molecular cloud, different stars are formed



Credit: sun.org

M dwarfs can be used to study the fully convective boundary

SpT comparison	G,K Solar-type stars	M0-M3	> M3

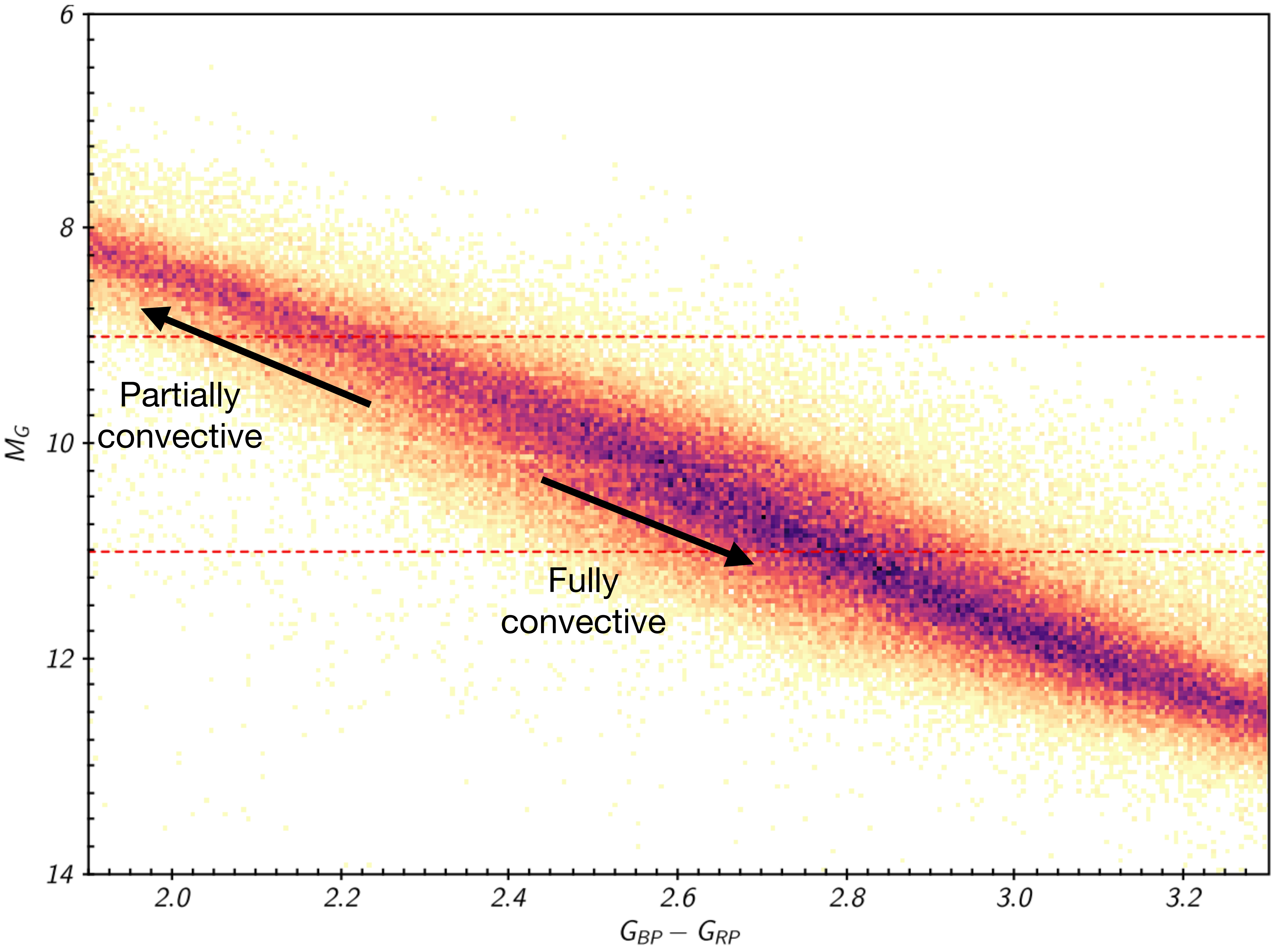
Partially convective

Partially convective

Fully convective

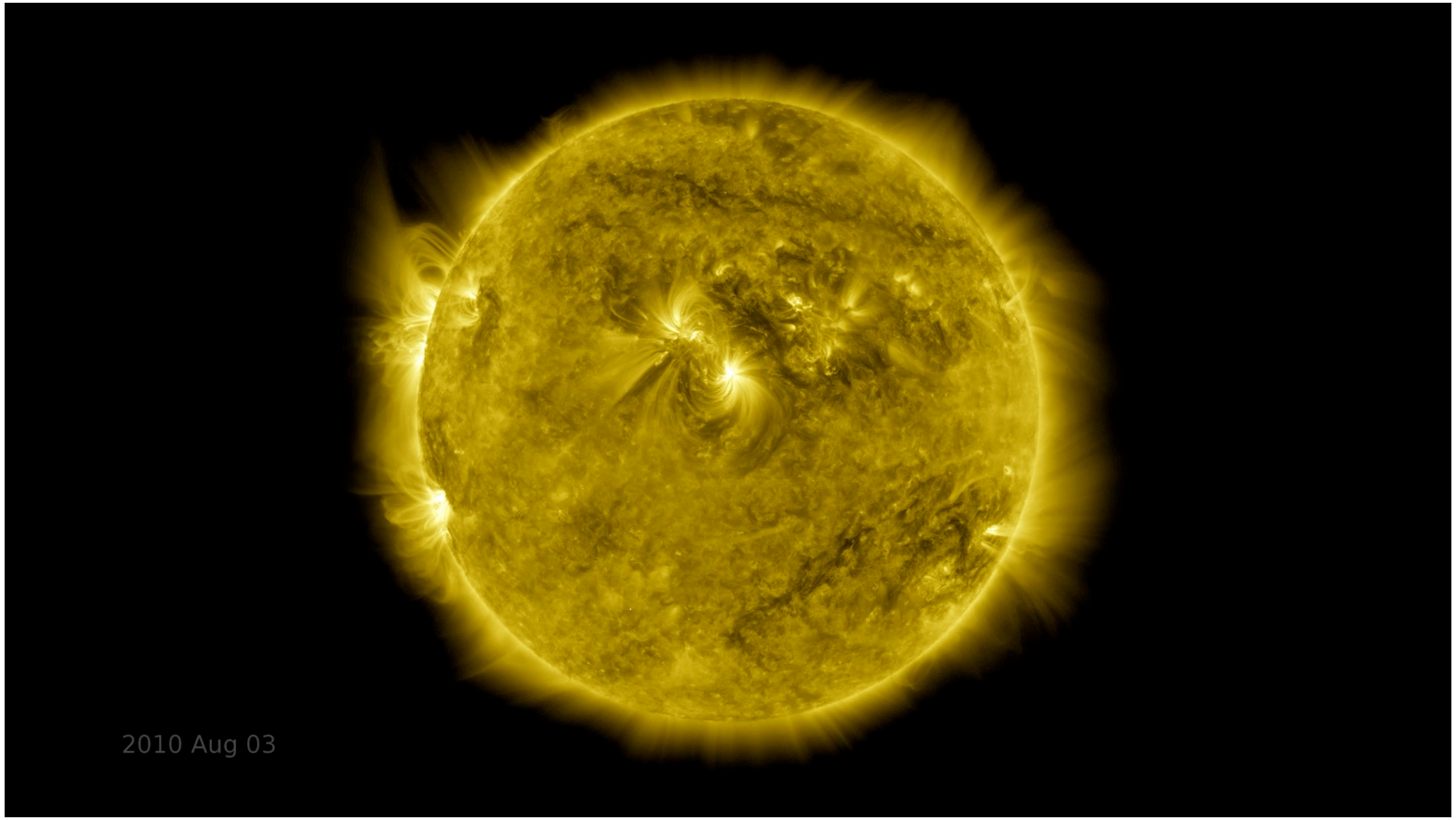
Credit: sun.org

Fully convective boundary in the data



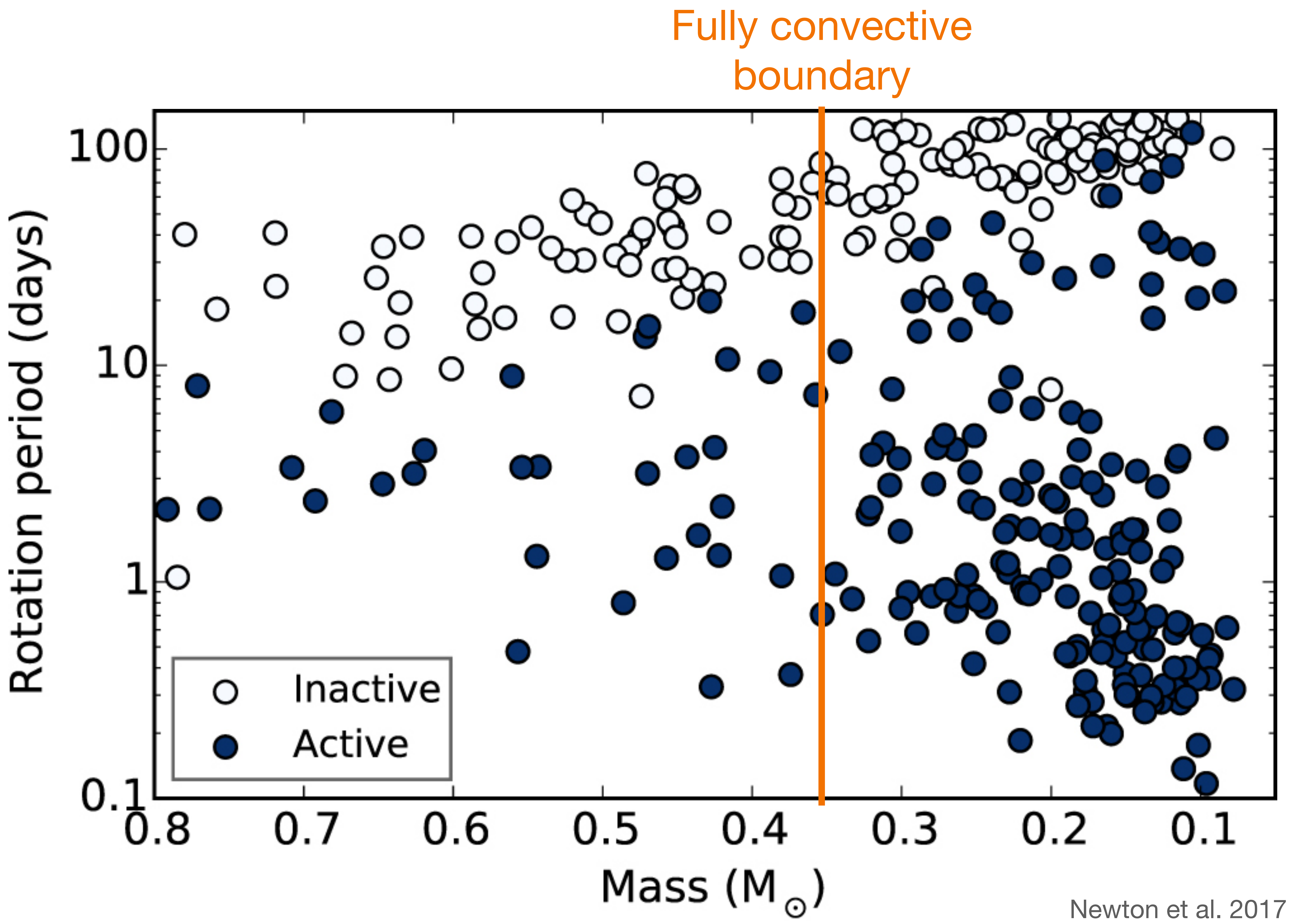
Jao et al. 2018
Predicted by van Saders & Pinsonneault 2012

Magnetic activity and rotation period should be affected by the transition into fully convective



Credits: NASA's Goddard Space Flight Center/SDO

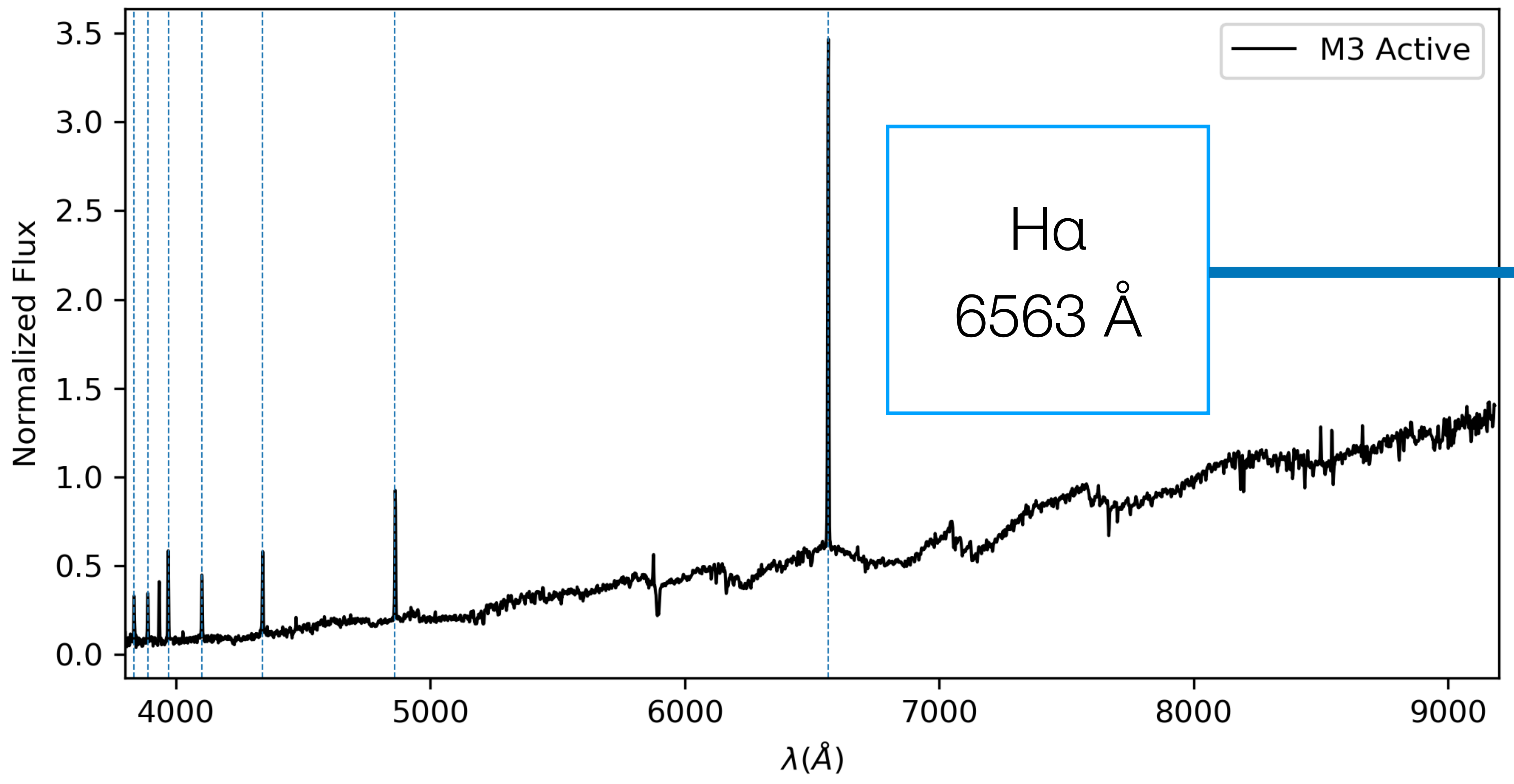
Increase in fast rotators as convective envelop gets thicker

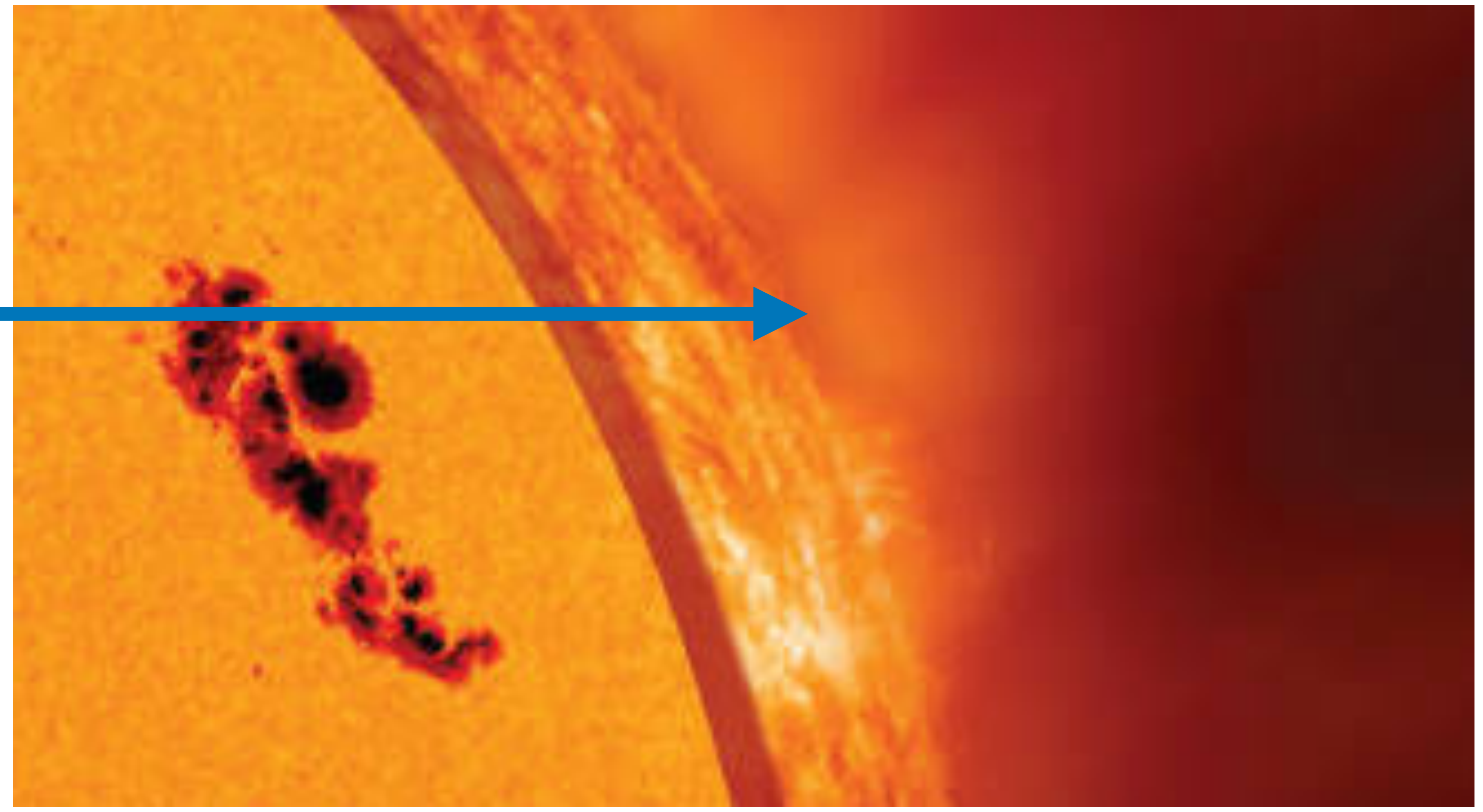


Newton et al. 2017

Are the slow rotators older than fast rotators or are these two different populations?

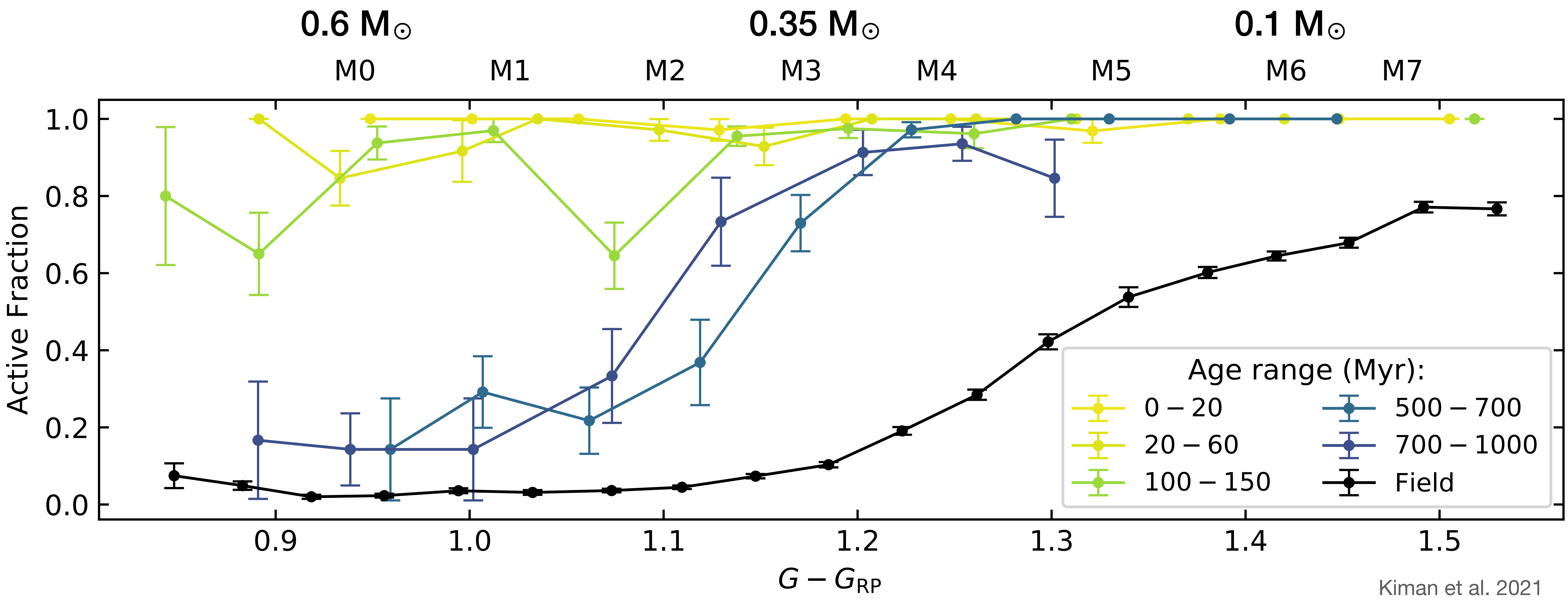
Hα emission line as magnetic activity indicator





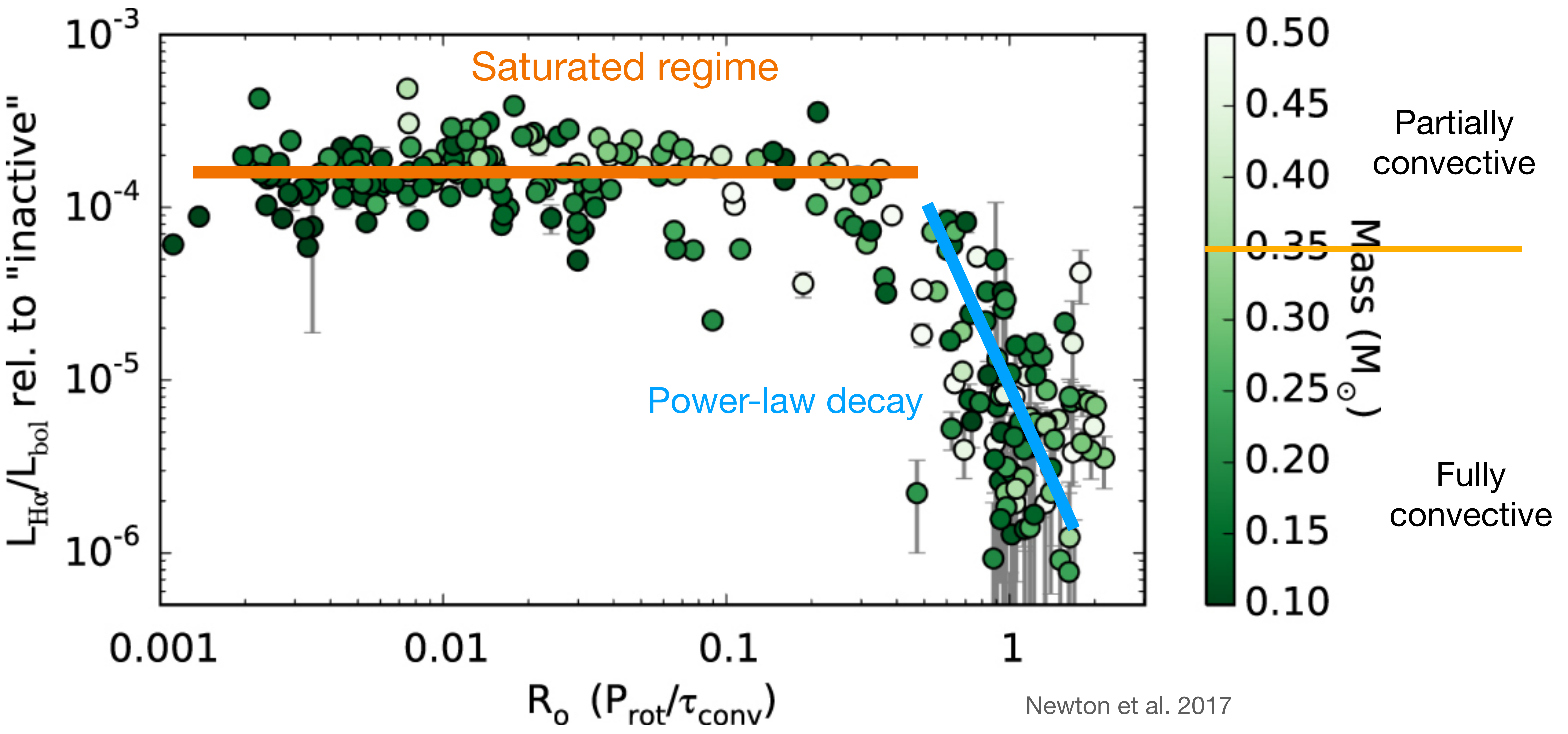
Credit: NASA/Jenny Mottar

Magnetic activity across the fully convective boundary



Fully convective stars are also active and seem to stay active longer.

Rotation-activity relation holds across the fully convective boundary



Newton et al. 2017

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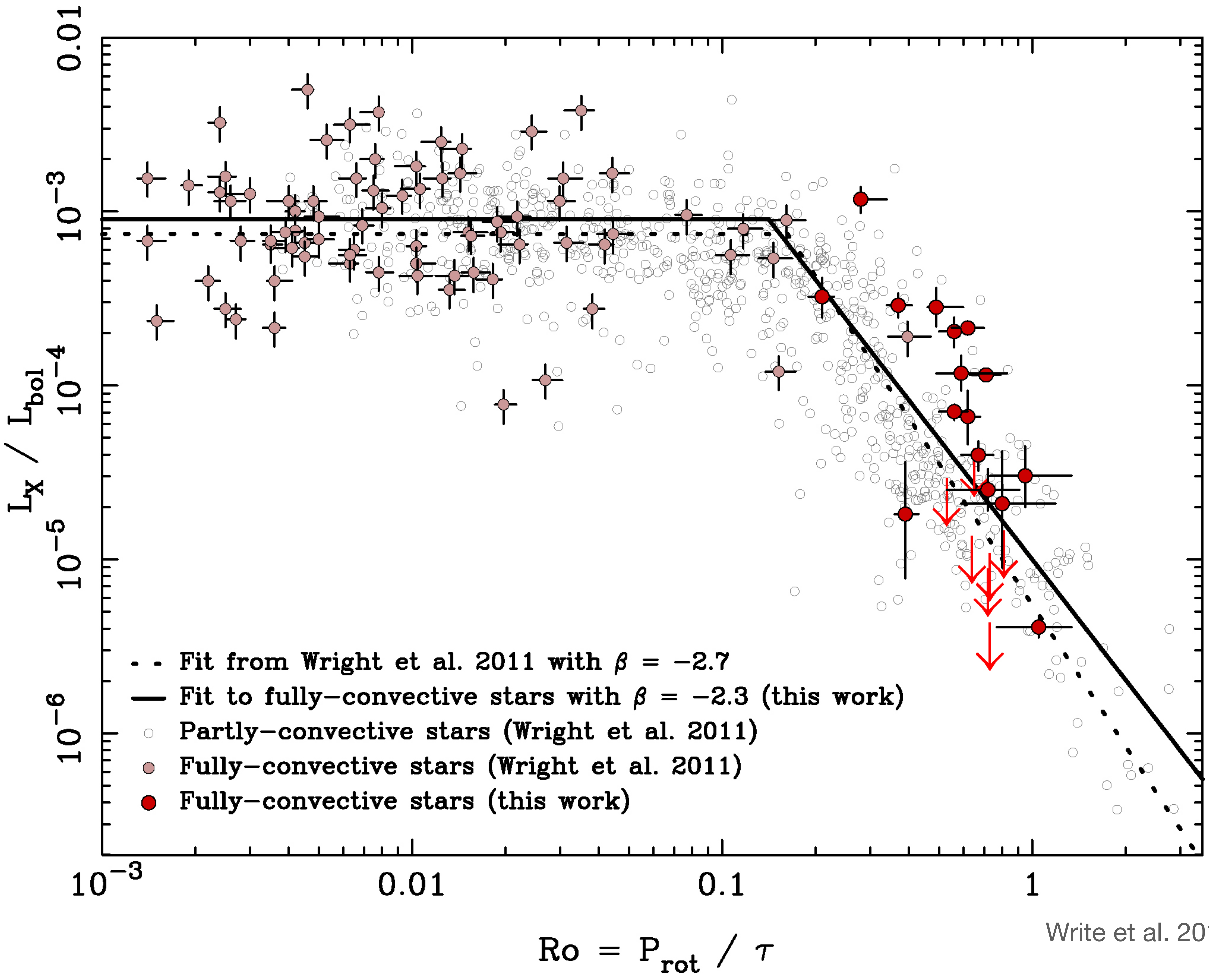
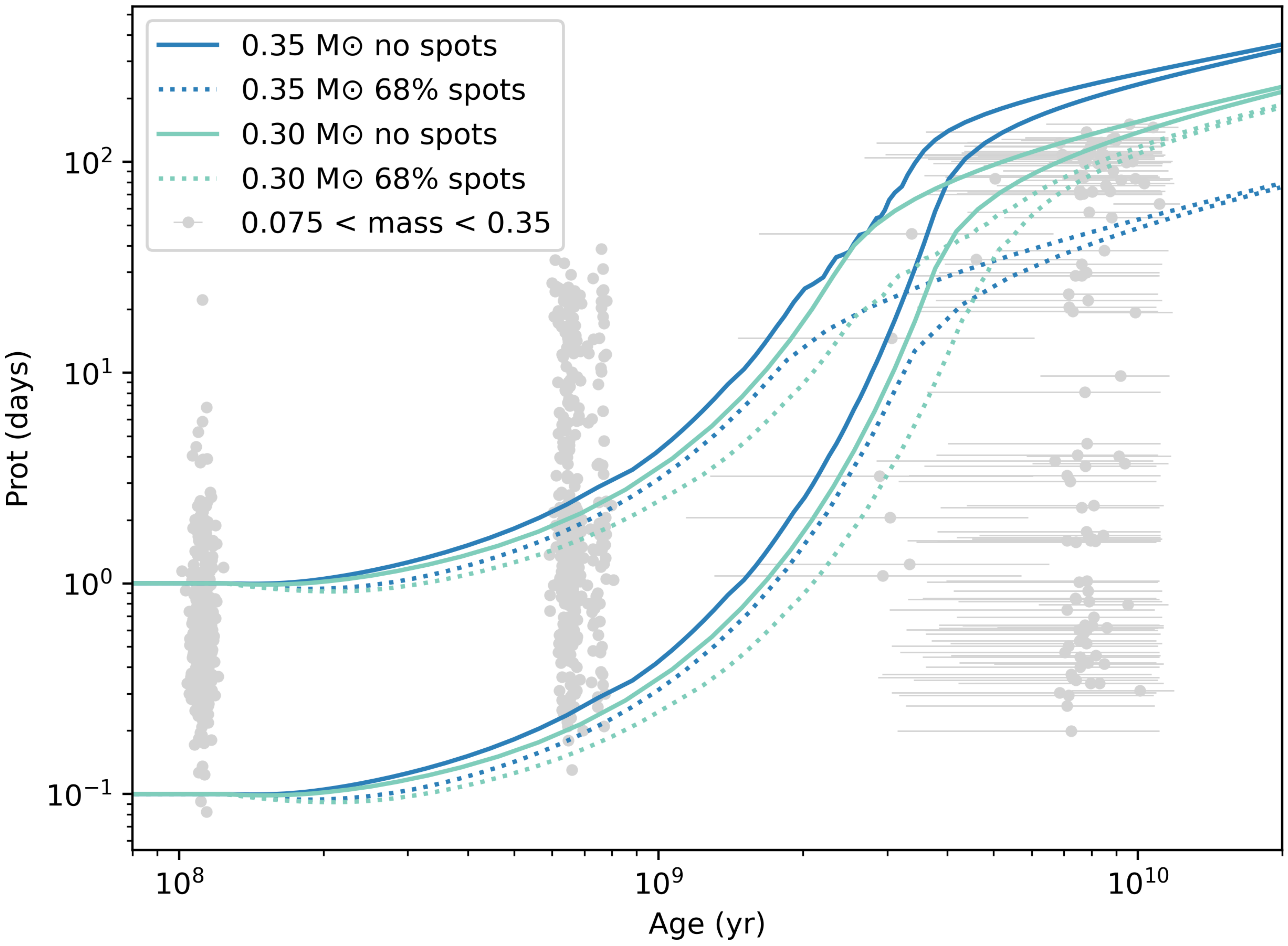
Rotation-activity relation holds across the fully convective boundary



Write et al. 2018

Work in progress: rotation period as a function of age



Kiman et al. in prep

Some open questions

- How is the magnetic field of fully convective stars generated?
- Why are there fast rotators and slow rotators in a field population of fully convective stars?
- Why are magnetic activity indicators saturated for small Rossby number?

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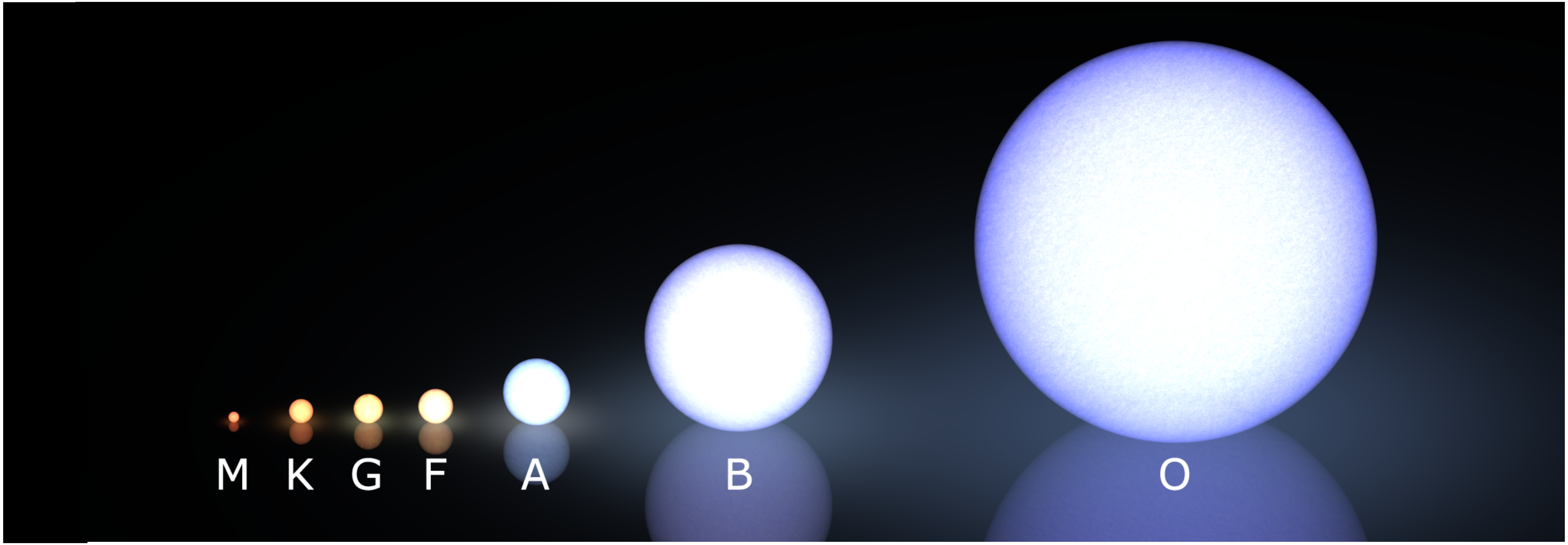
Daniella Bardalez Gagliuffi
Emily Rice
Jackie Faherty
Austin Rothermich
Johanna Vos (she/her)
Kelle Cruz (she/they)
Mark Popinchalk (He/Him)
Eileen Gonzales
Rocio Kiman
Lisseth Gonzales
Emily Calamari
Afra Ashraf
Jose Adorno
Elena Mitra
janani

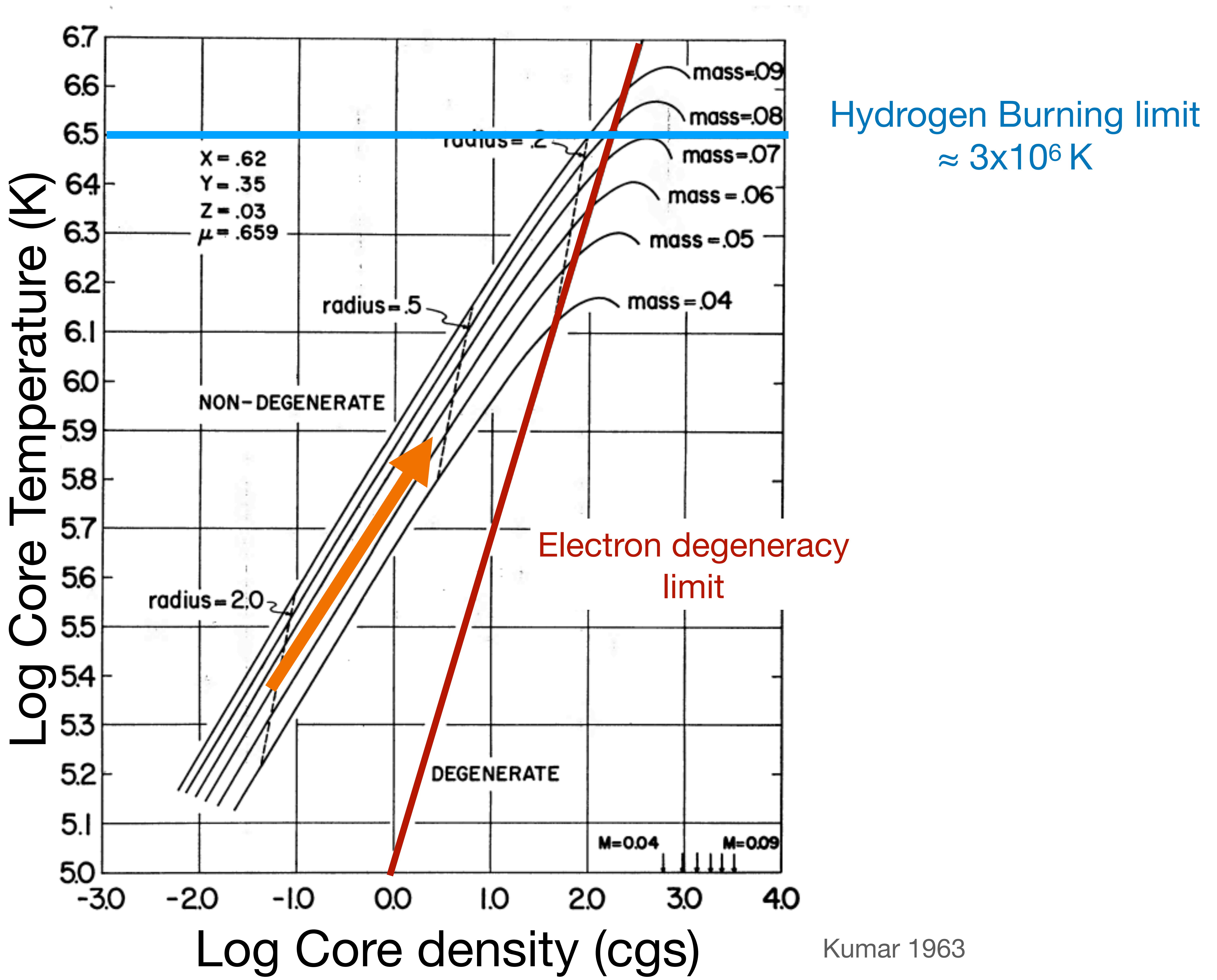
BDNYC

Is there a limit of mass where the object can’t fuse H?



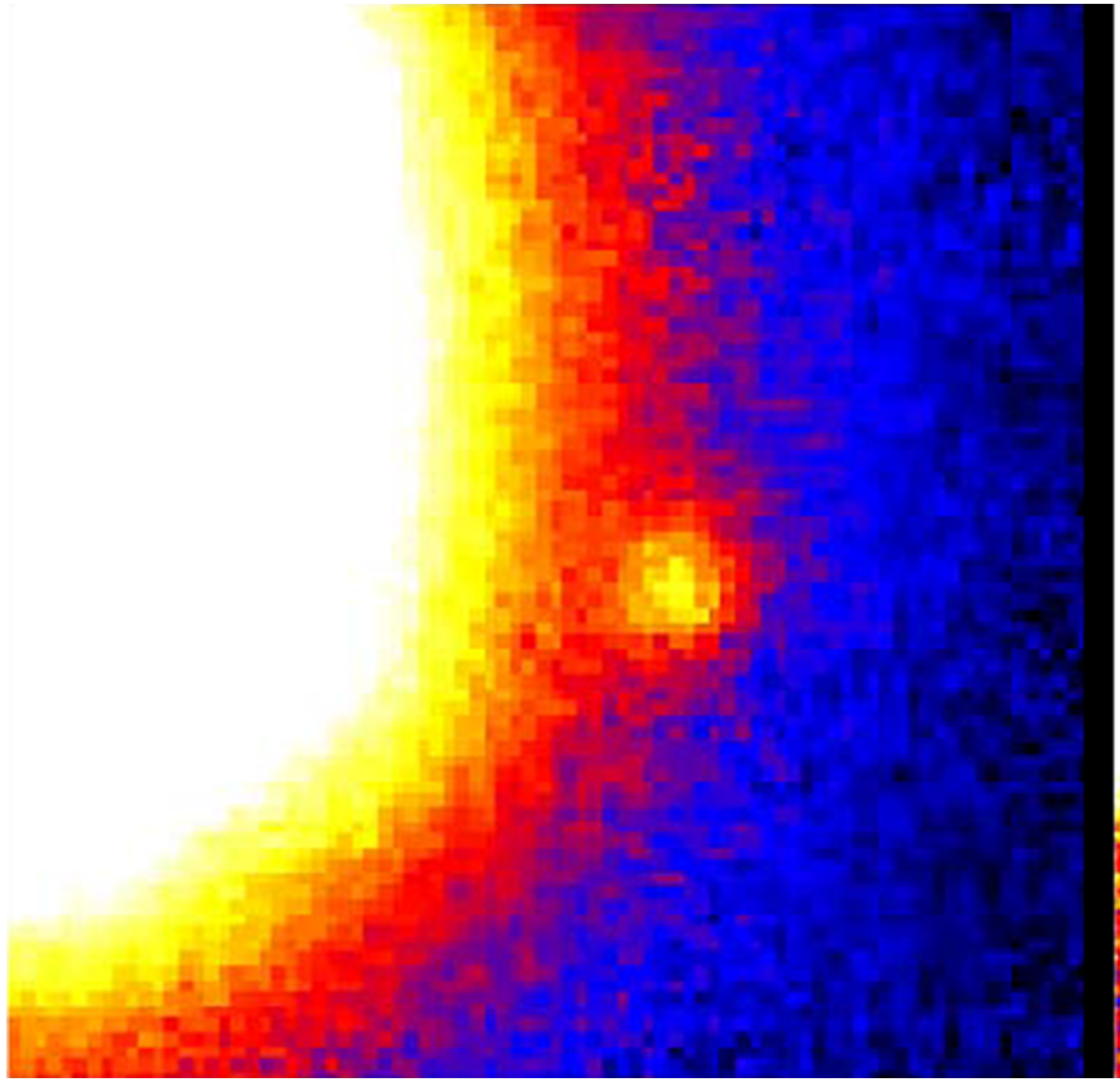
Credit: sun.org

Brown Dwarfs were predicted in 1963



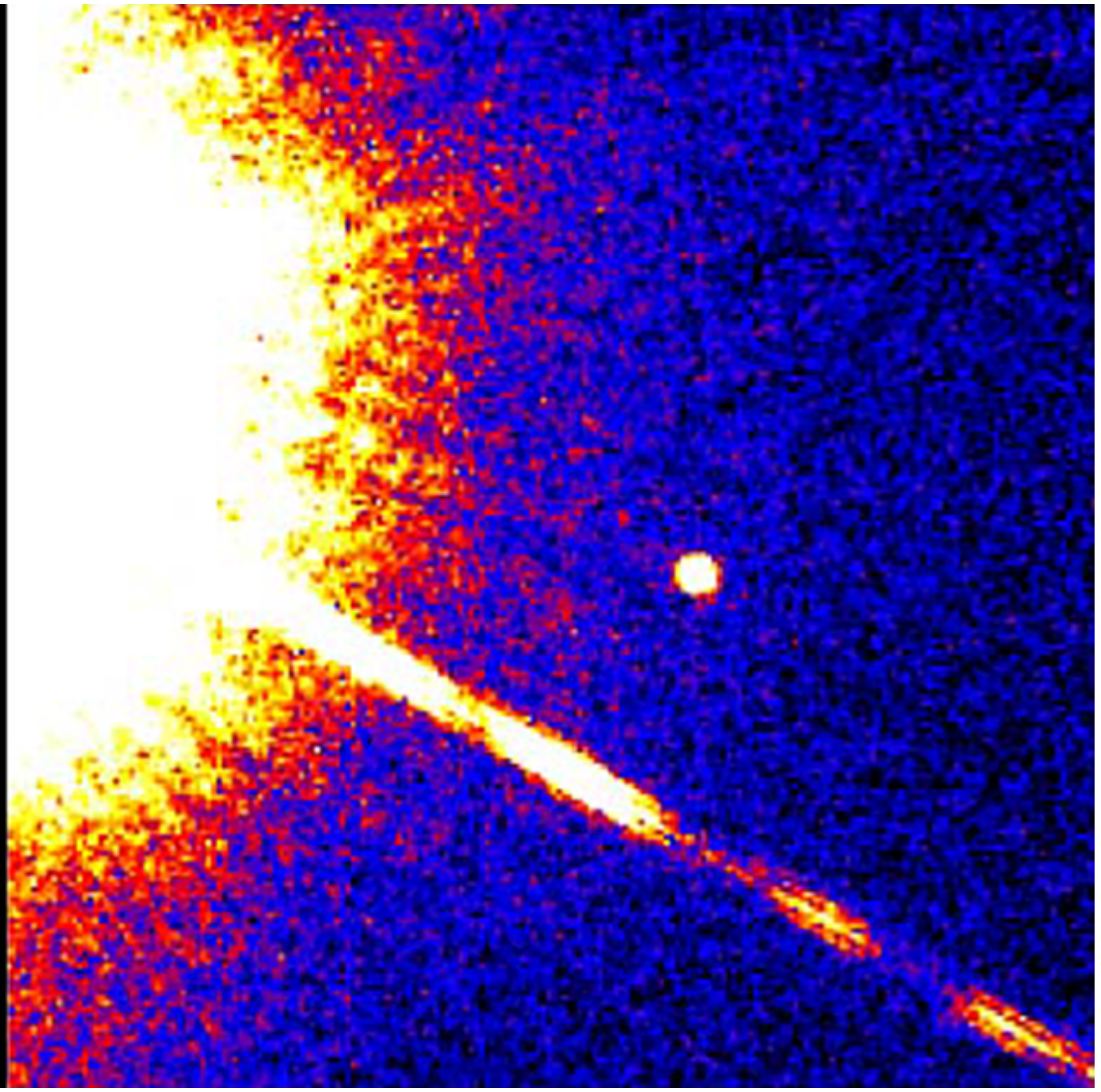
Kumar 1963

First Brown Dwarf found in 1995: GL 229B



Credit: T. Nakajima (Caltech), S. Durrance (JHU)

Palomar Telescope (1994)



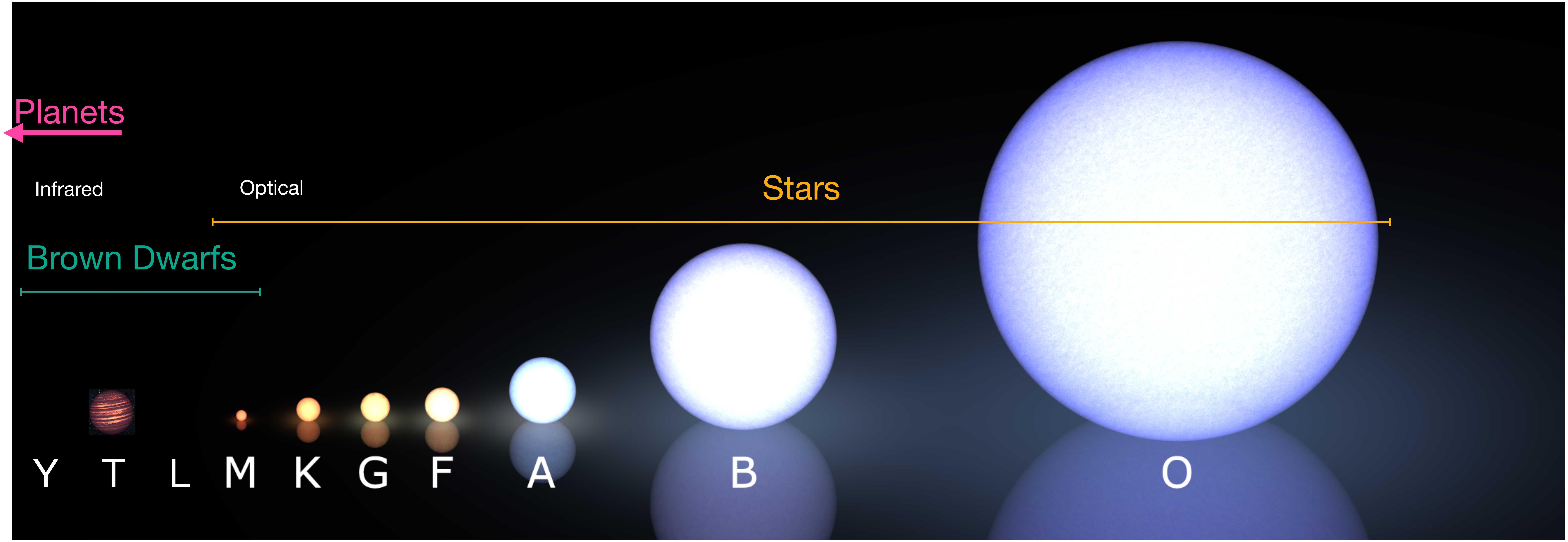
Credit: S. Kulkarni (Caltech), D.Golimowski (JHU) and NASA

Hubble Space Telescope's Wide Field Planetary Camera-2 (1995)

- Companion to an M1 dwarf
- 1000 K
- Spectral type T7

Golimowski et al. 1998
Nakajima et al. 1995; Oppenheimer at al. 1995

Low-Mass Stars and Brown Dwarfs



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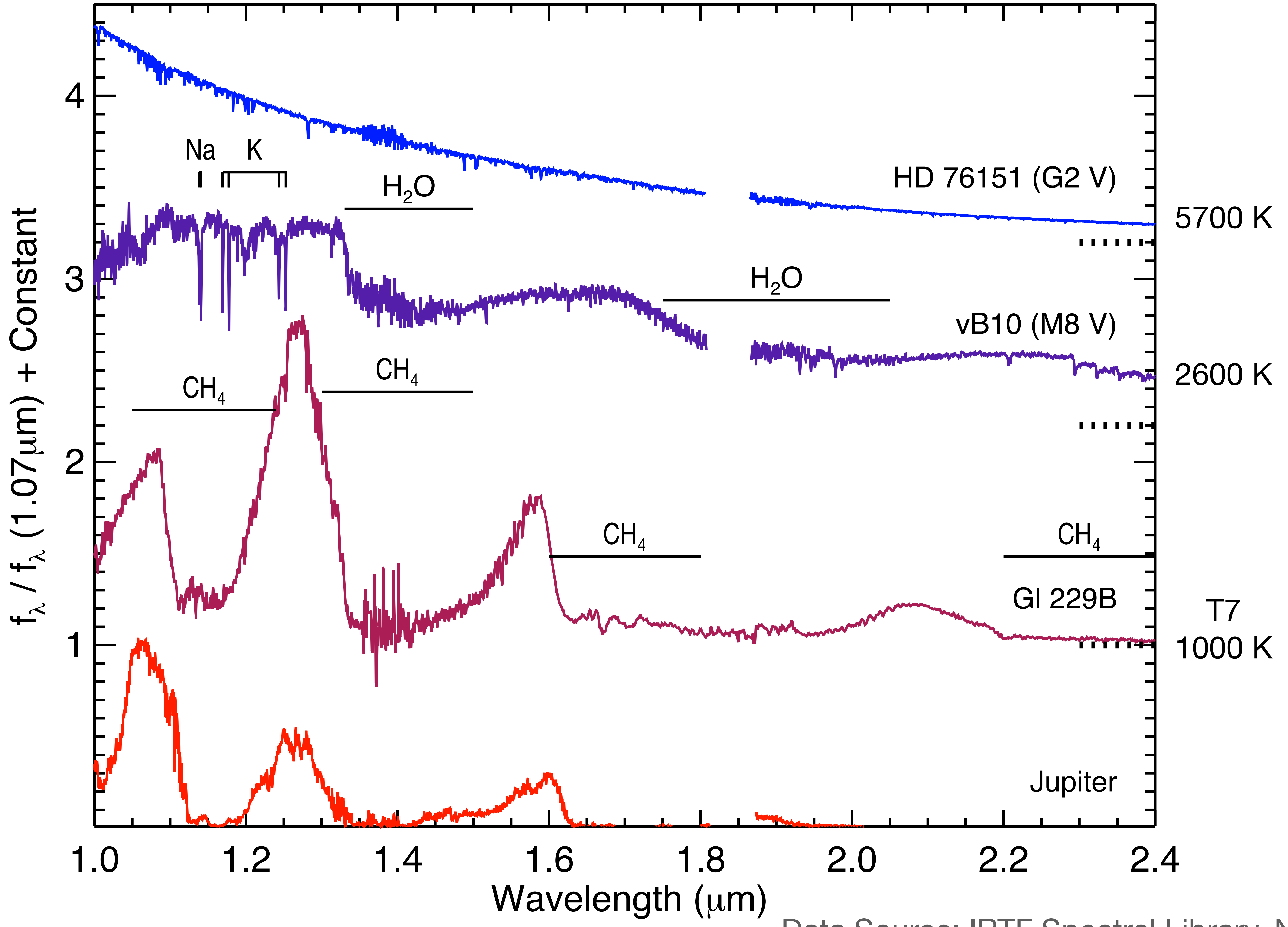
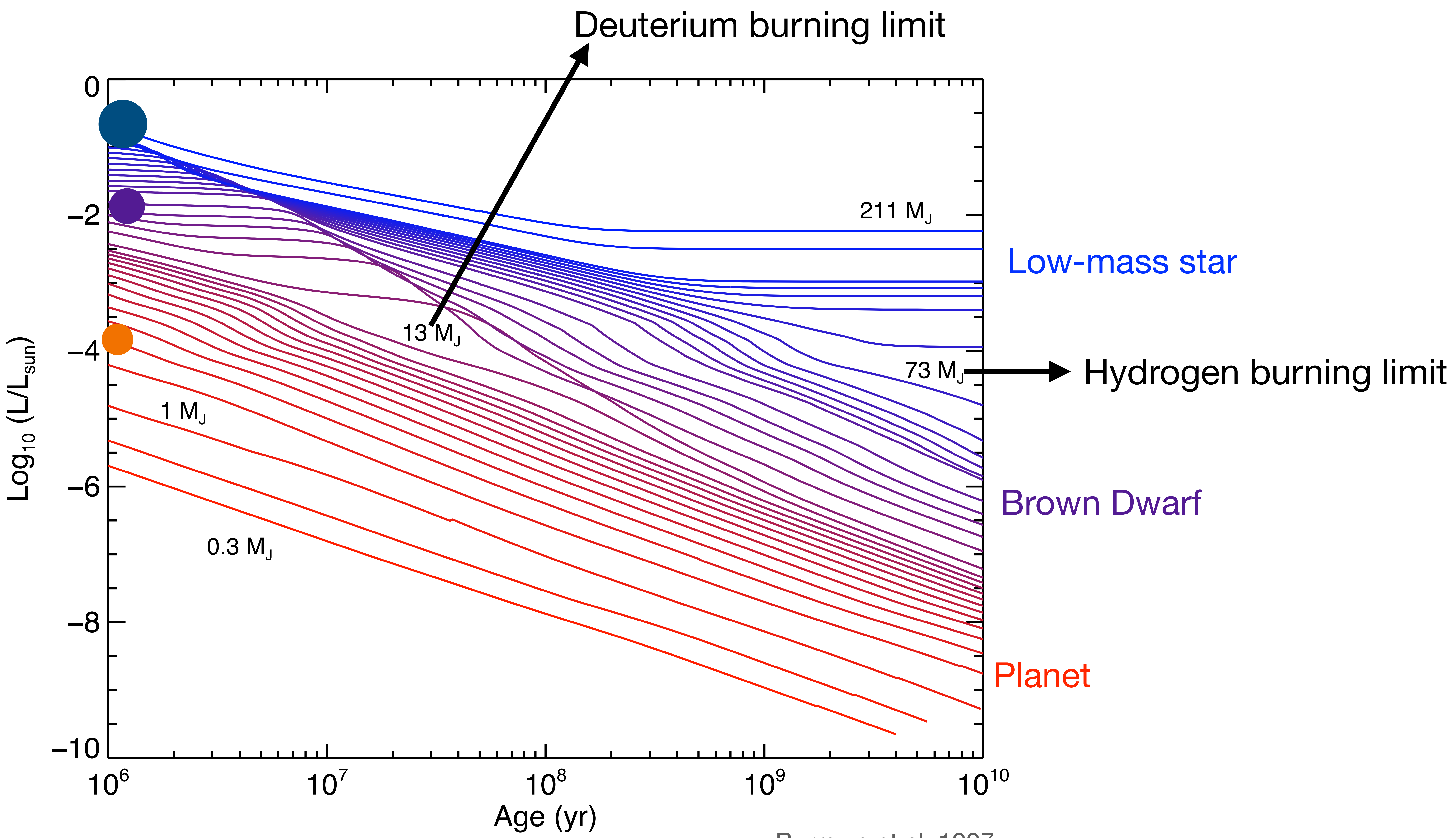
How can I distinguish a Brown Dwarf



Data Source: IRTF Spectral Library, NIRSPEC BDSS
Credit: Michael C. Cushing, Ph.D.

Mass-age-luminosity Brown Dwarf degeneracy

What defines a Brown Dwarf is its evolution: they cool and dim with time.



Burrows et al. 1997
Credit: Michael C. Cushing, Ph.D.

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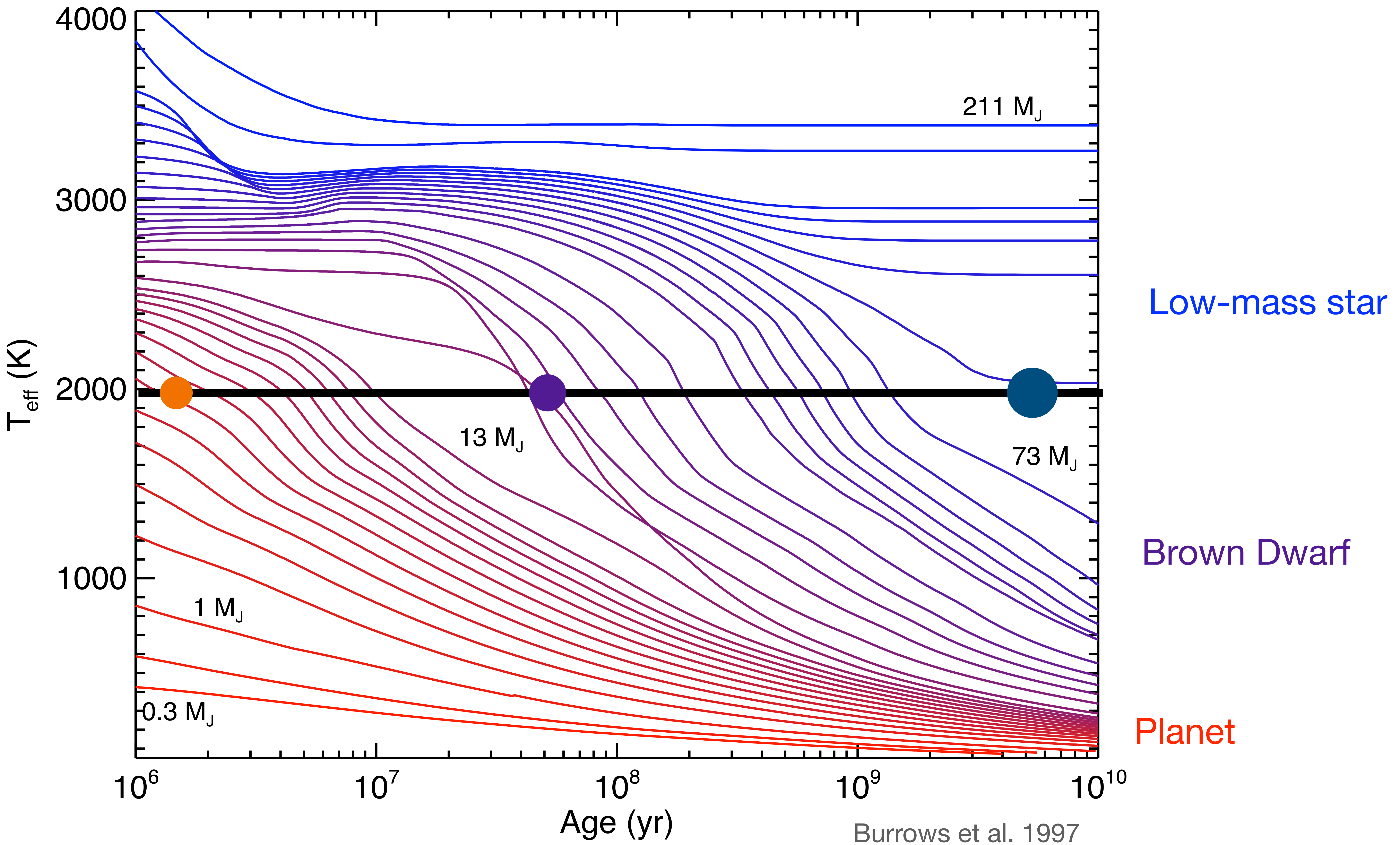
Temperature evolution of Brown Dwarfs



Burrows et al. 1997
Credit: Michael C. Cushing, Ph.D.

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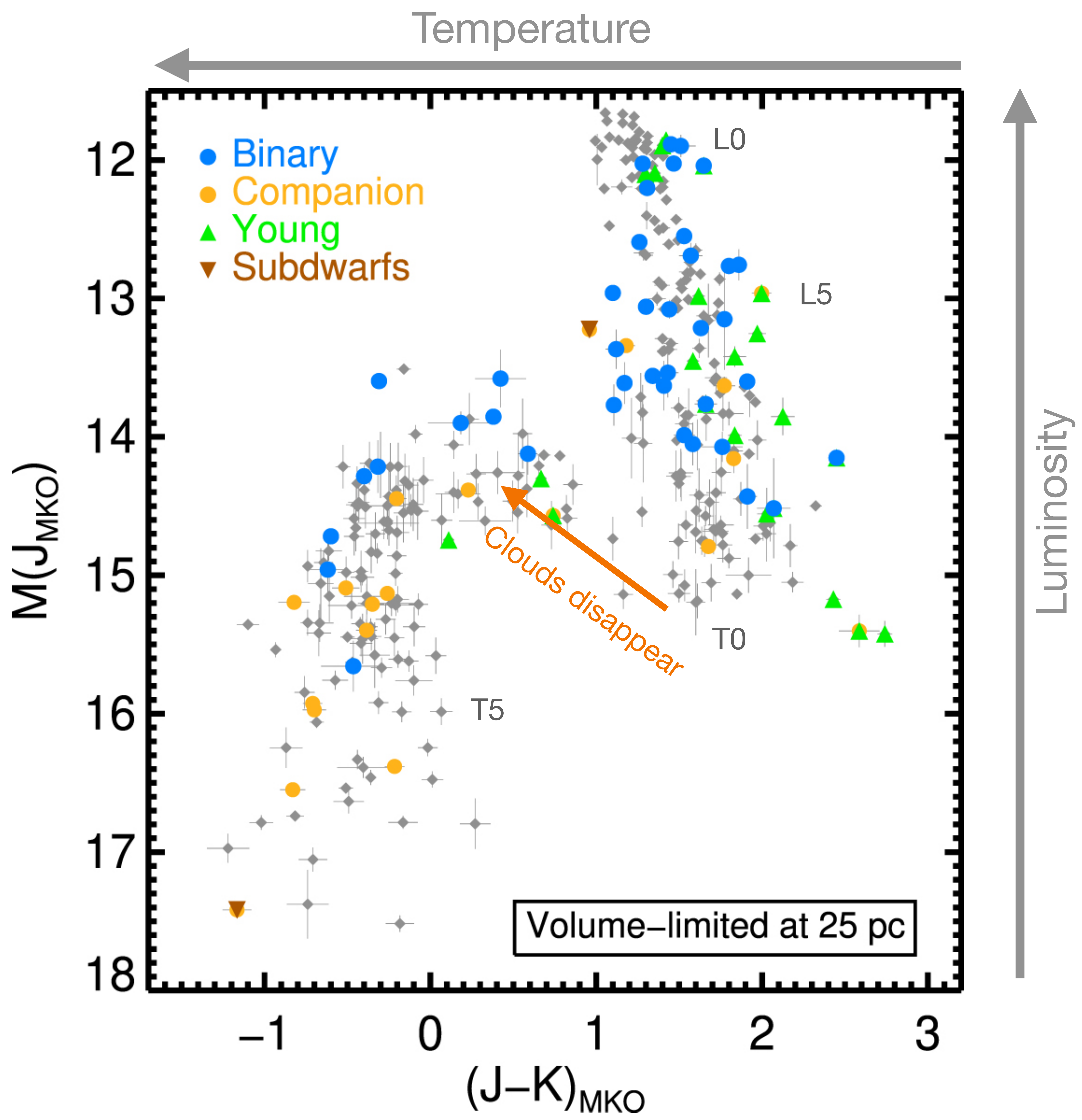
Properties of Brown Dwarfs

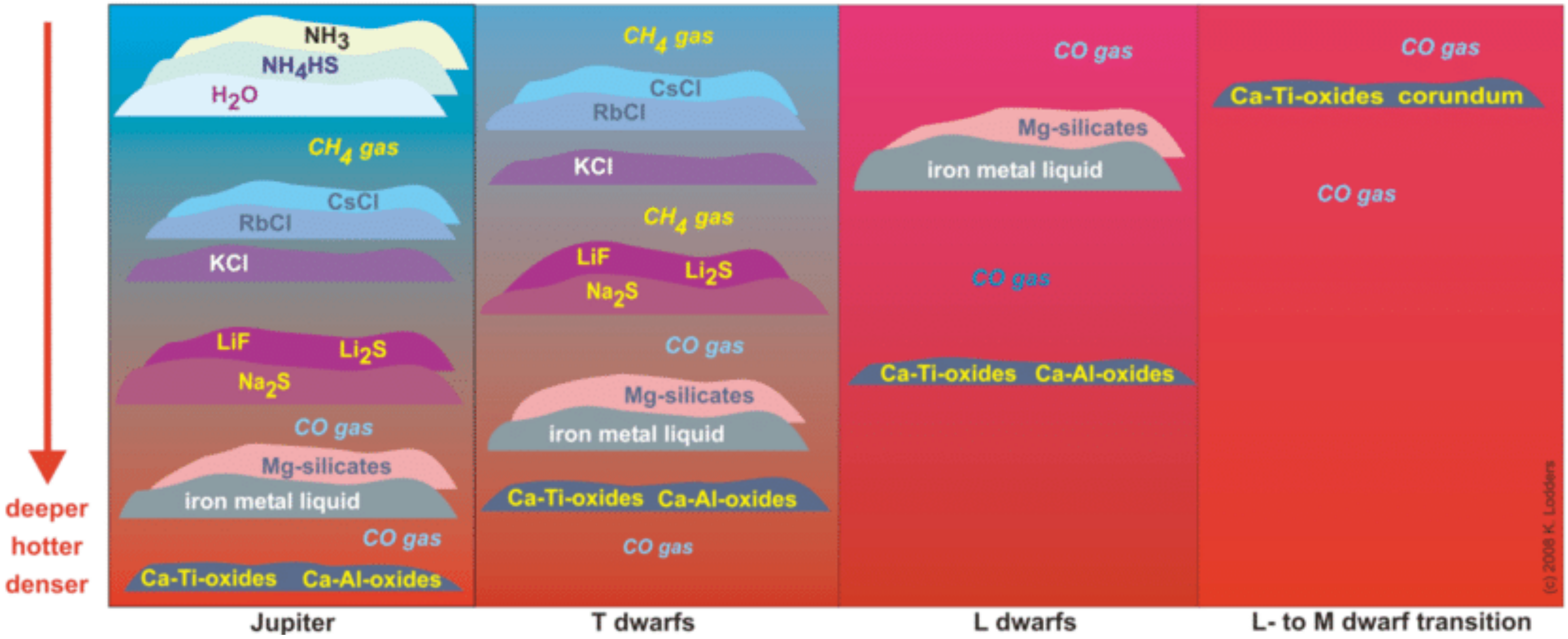


- $0.01 < \text{Mass}\ (M_\odot) < 0.08$ // $11 < \text{Mass}\ (M_J) < 83$
- $250\ K < T_{eff} < 2700\ K$
- $0.8 < \text{Radius}\ (R_\odot) < 1.2$ // $0.08 < \text{Radius}\ (R_J) < 0.1$

480 K is oven temperature

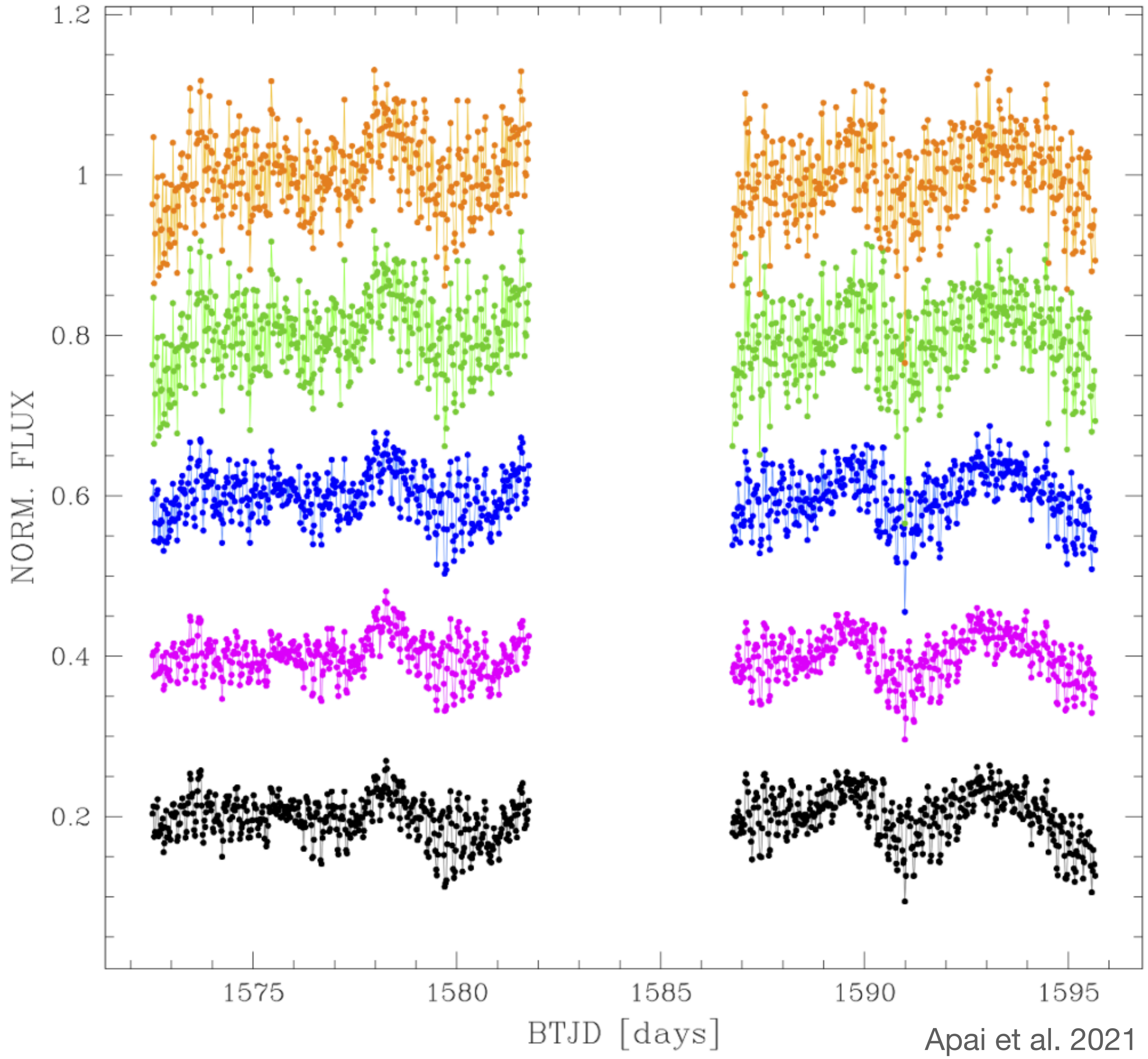
Best et al. 2020

What are clouds in Brown Dwarfs made of?

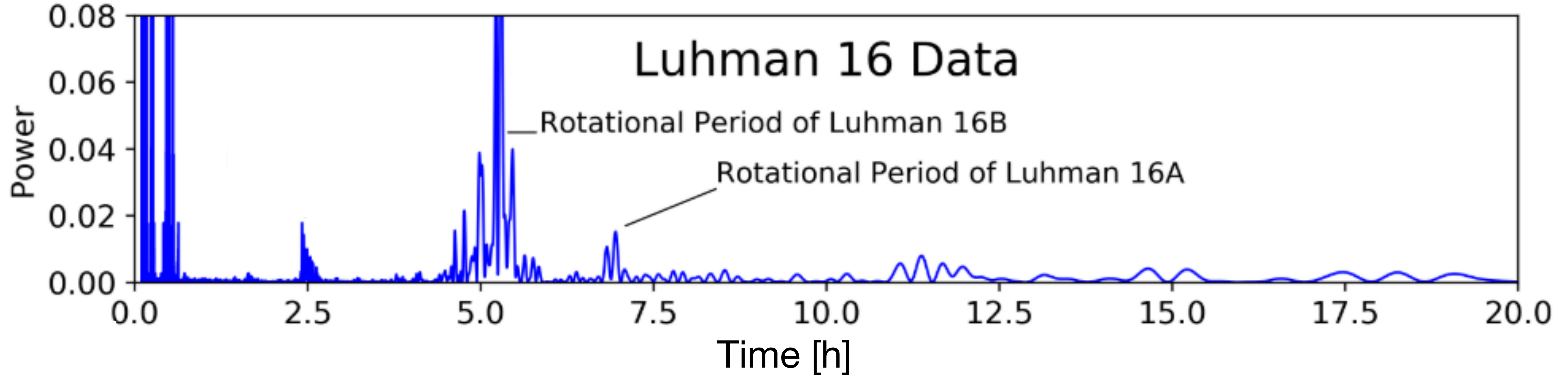


Lodders & Fegley 2006

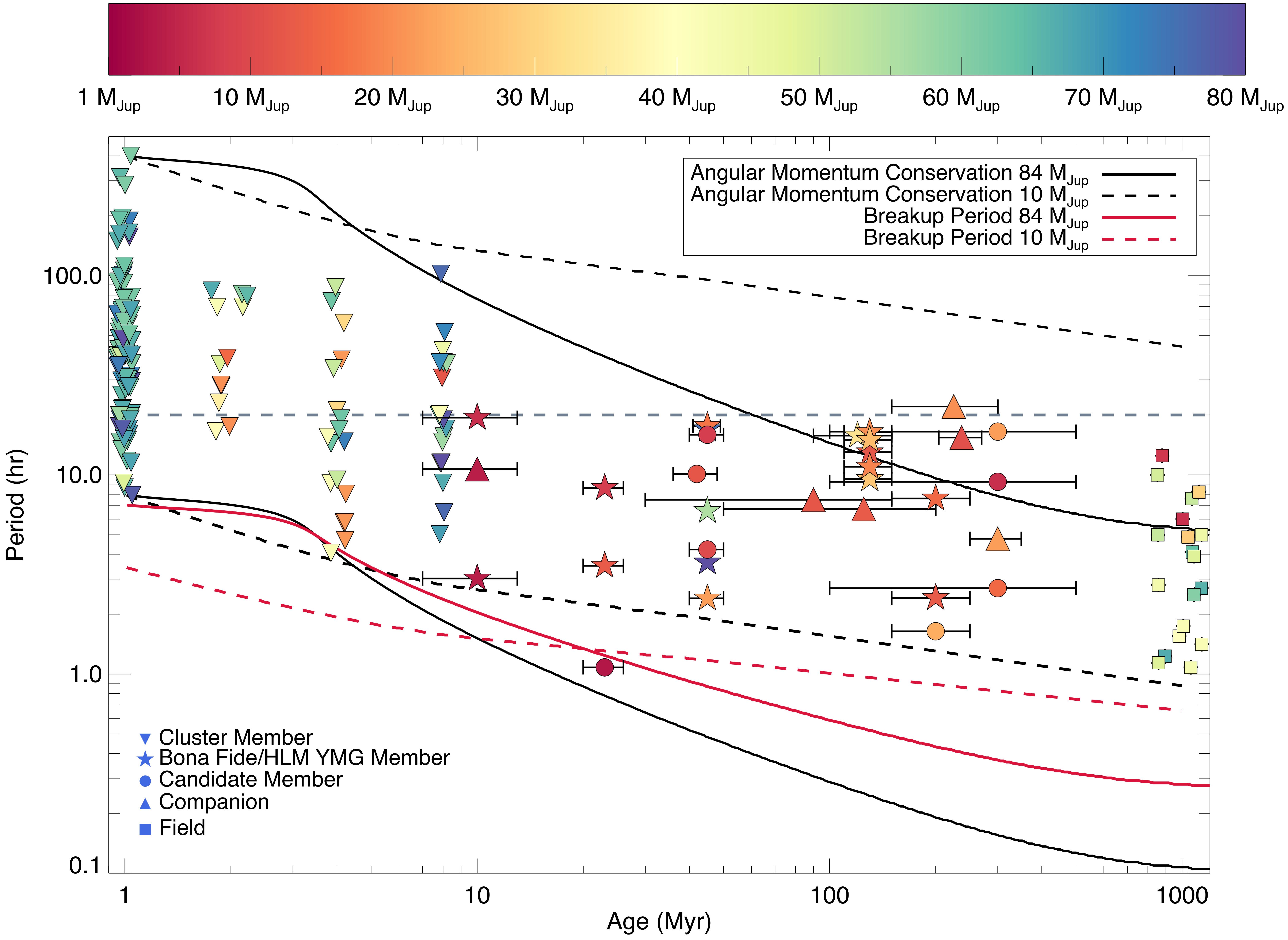
Variability on Brown Dwarfs is caused by clouds



Apai et al. 2021



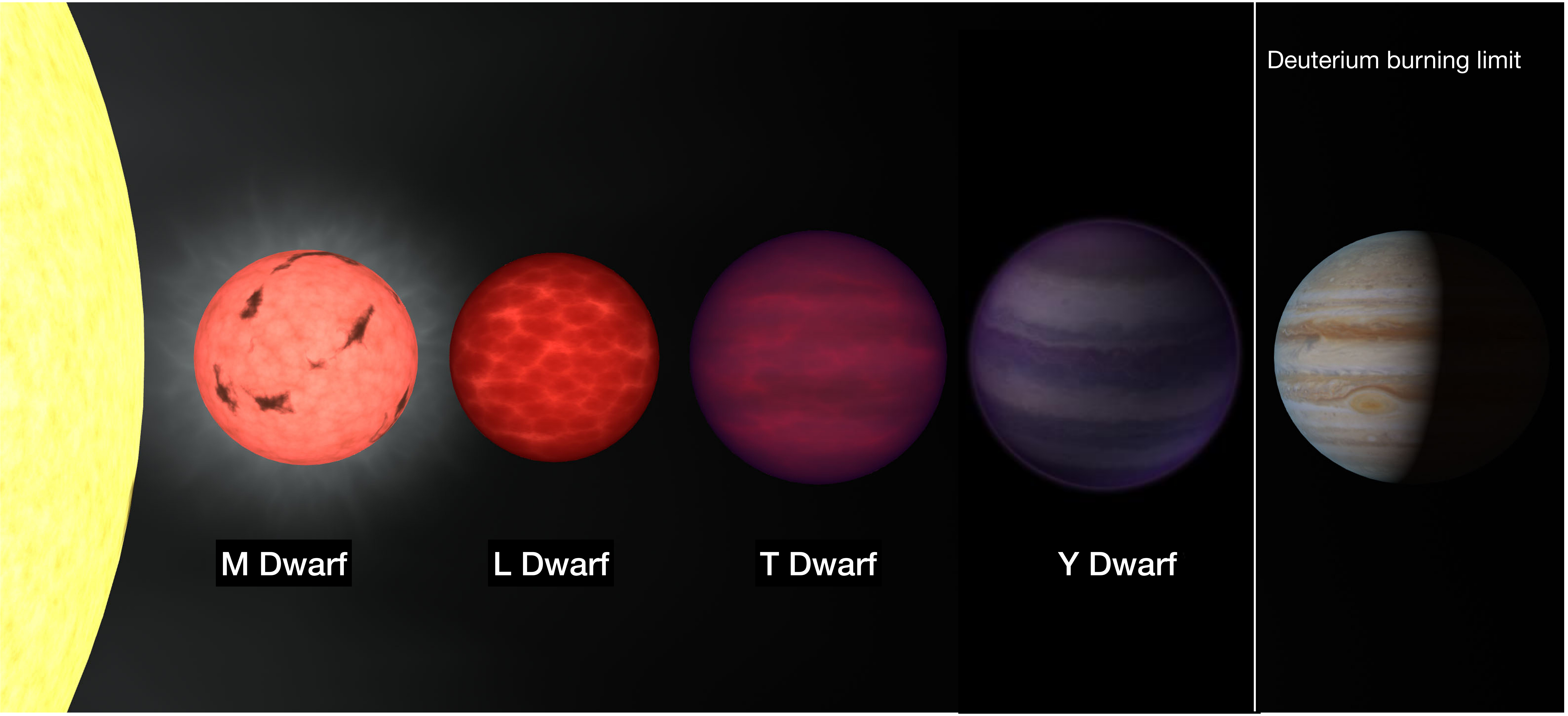
Rotation Period evolution of Brown Dwarfs



Vos et al. 2021 accepted

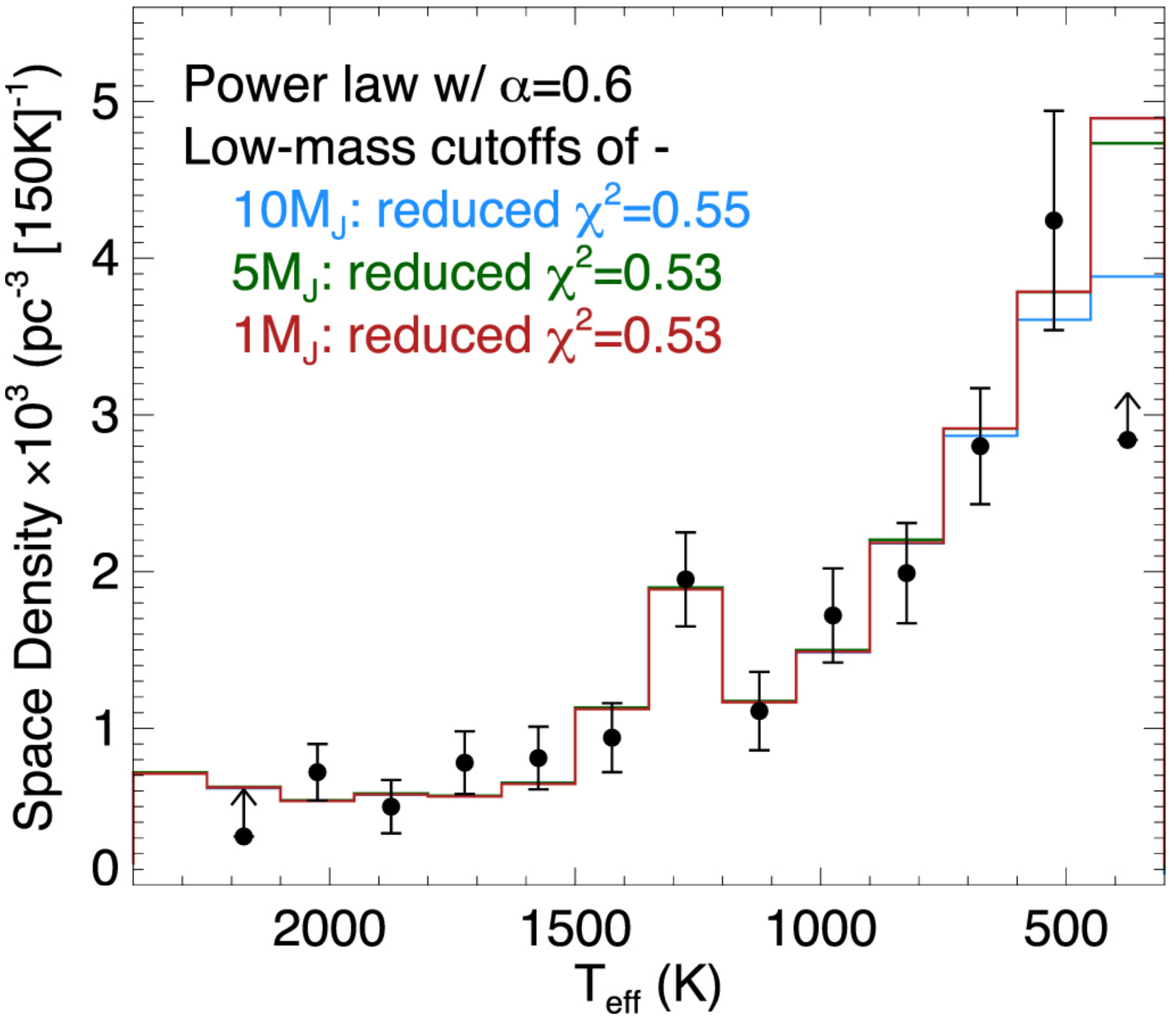
Historically Deuterium burning limit divided Brown Dwarfs and Planets

13 M_J (0.01 $M_\odot$)



(Not to scale) Credit: CalTech, JPL, NASA

Mass function of Brown Dwarfs can inform us about formation



Kirkpatrick et al. 2021

Possible formation mechanisms

- Gravoturbulent/Turbulent fragmentation
- Ejection
- Photoevaporation
- Disk fragmentation

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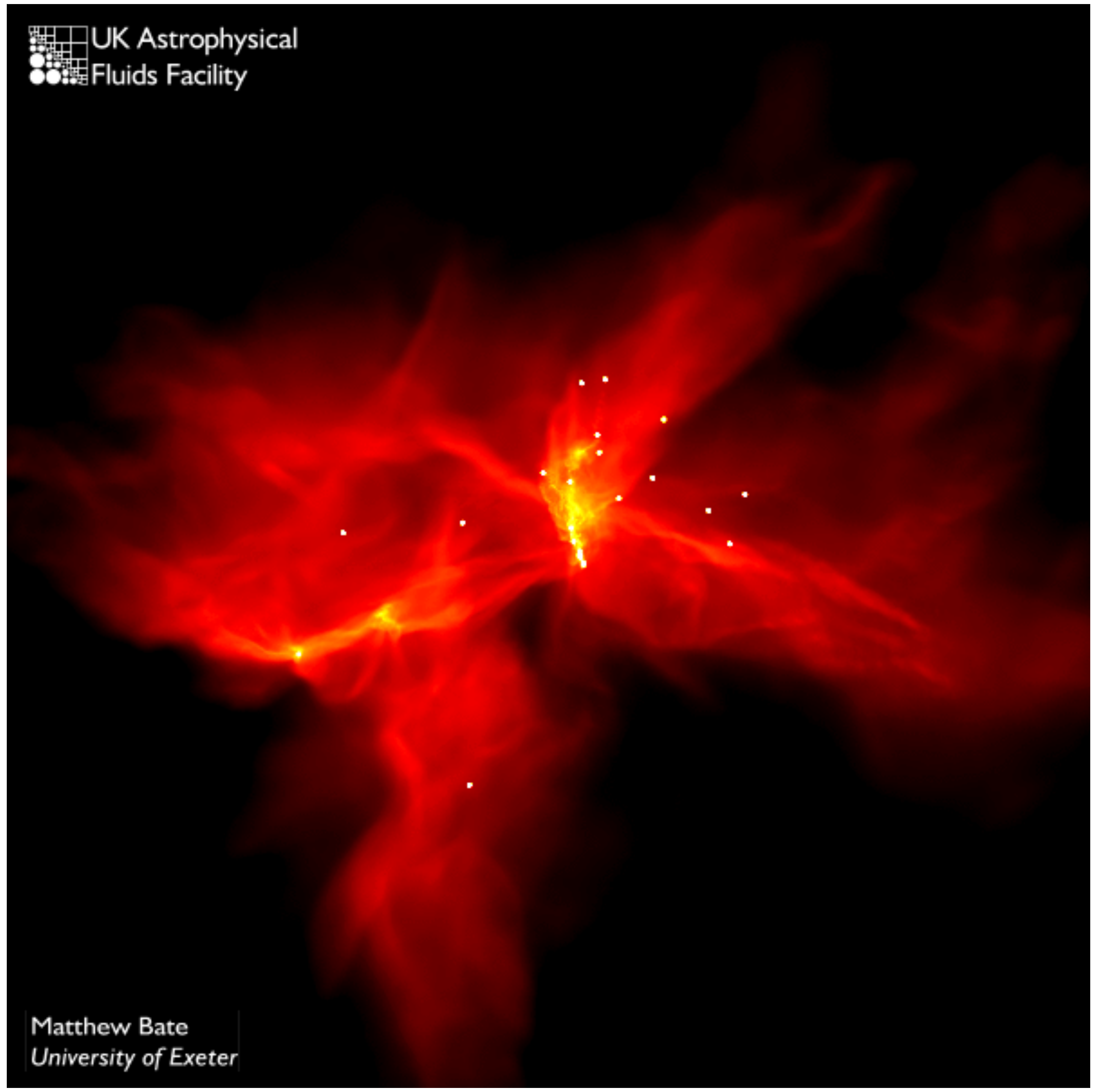

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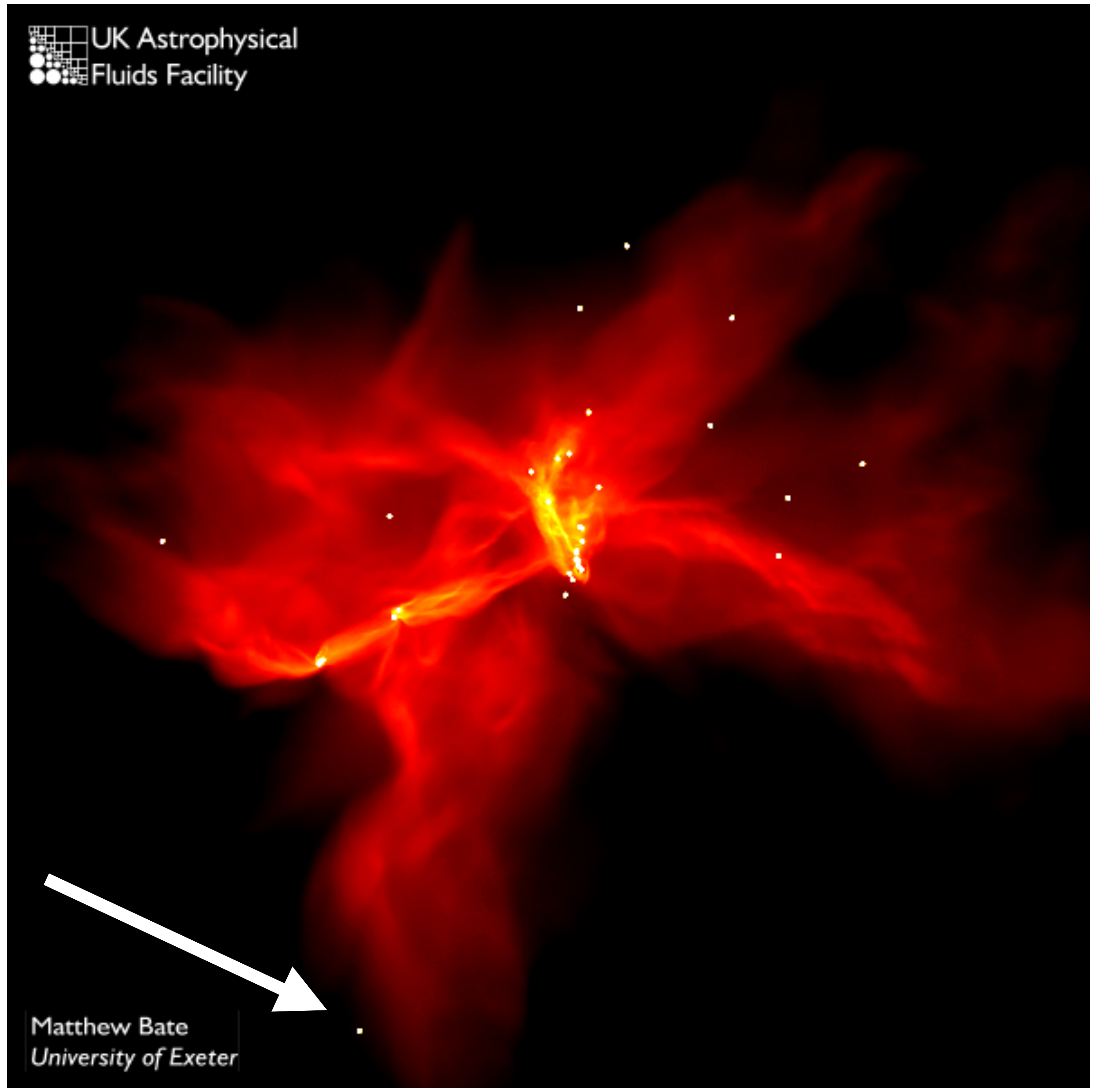
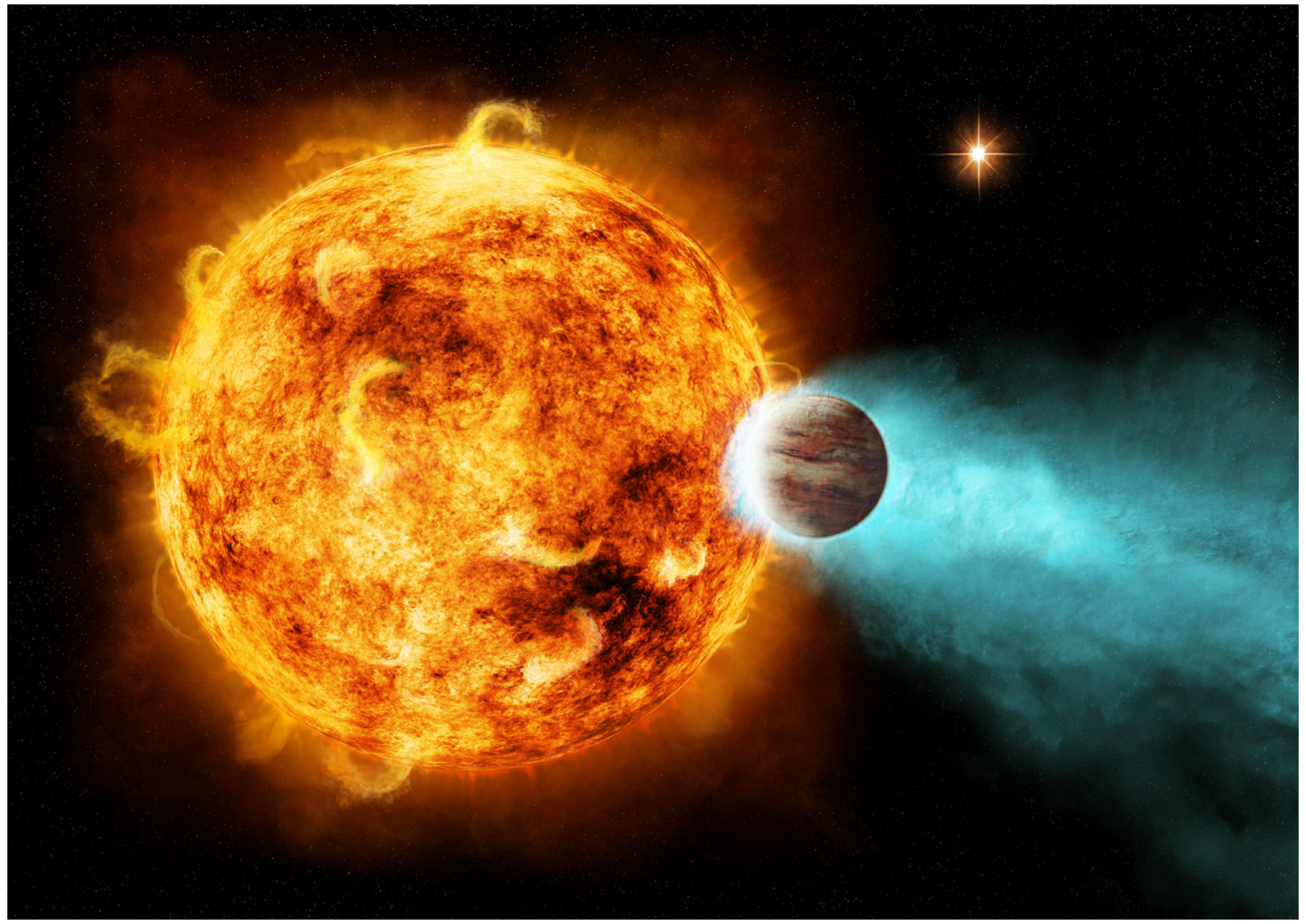


Possible formation mechanisms

- Gravoturbulent/Turbulent fragmentation
- Ejection
- **Photoevaporation**
- Disk fragmentation



NASA/Ames/JPL-Caltech

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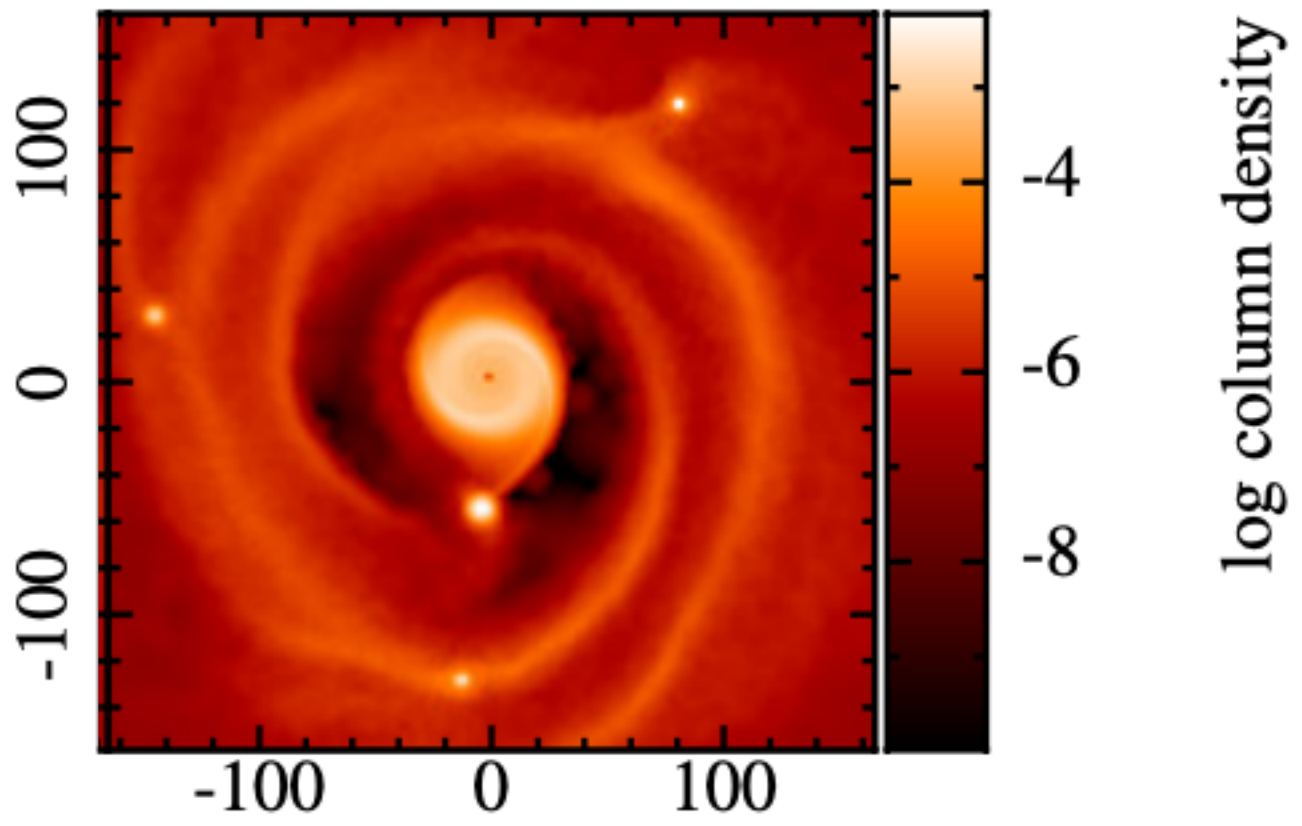

Cadman et al. 2020

Some open questions

- How do Brown Dwarfs form?
- What is the smallest mass of the mass function and the implication on numbers of Brown Dwarfs?
- What is the composition and short/long term evolution of Brown Dwarf atmospheres?

Summary

Some Low-mass stars open questions:

- How is the magnetic field of fully convective stars generated?
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Some Brown Dwarfs open questions:

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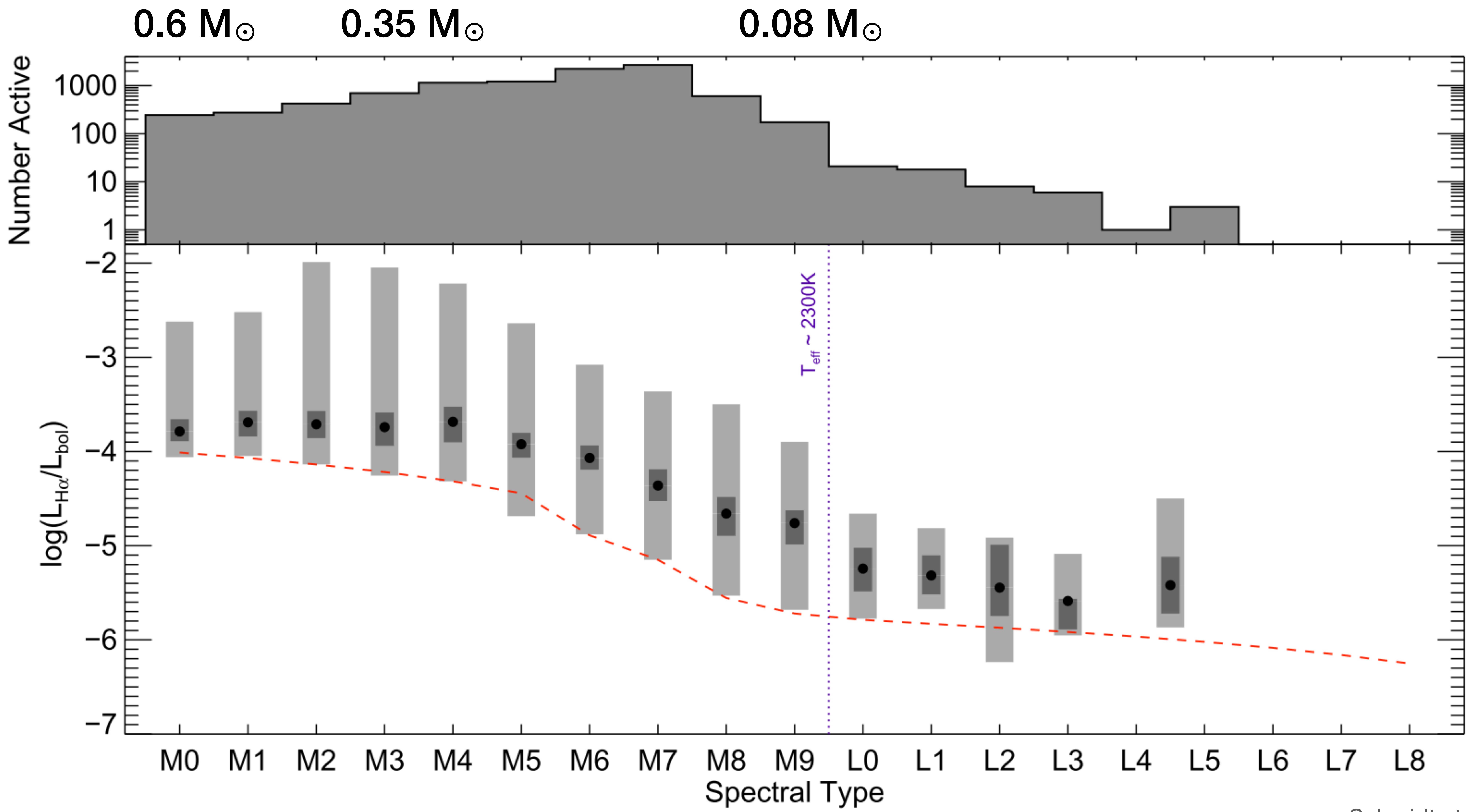
Magnetic activity is generated by rotation even in fully convective stars



Schmidt et al. 2015

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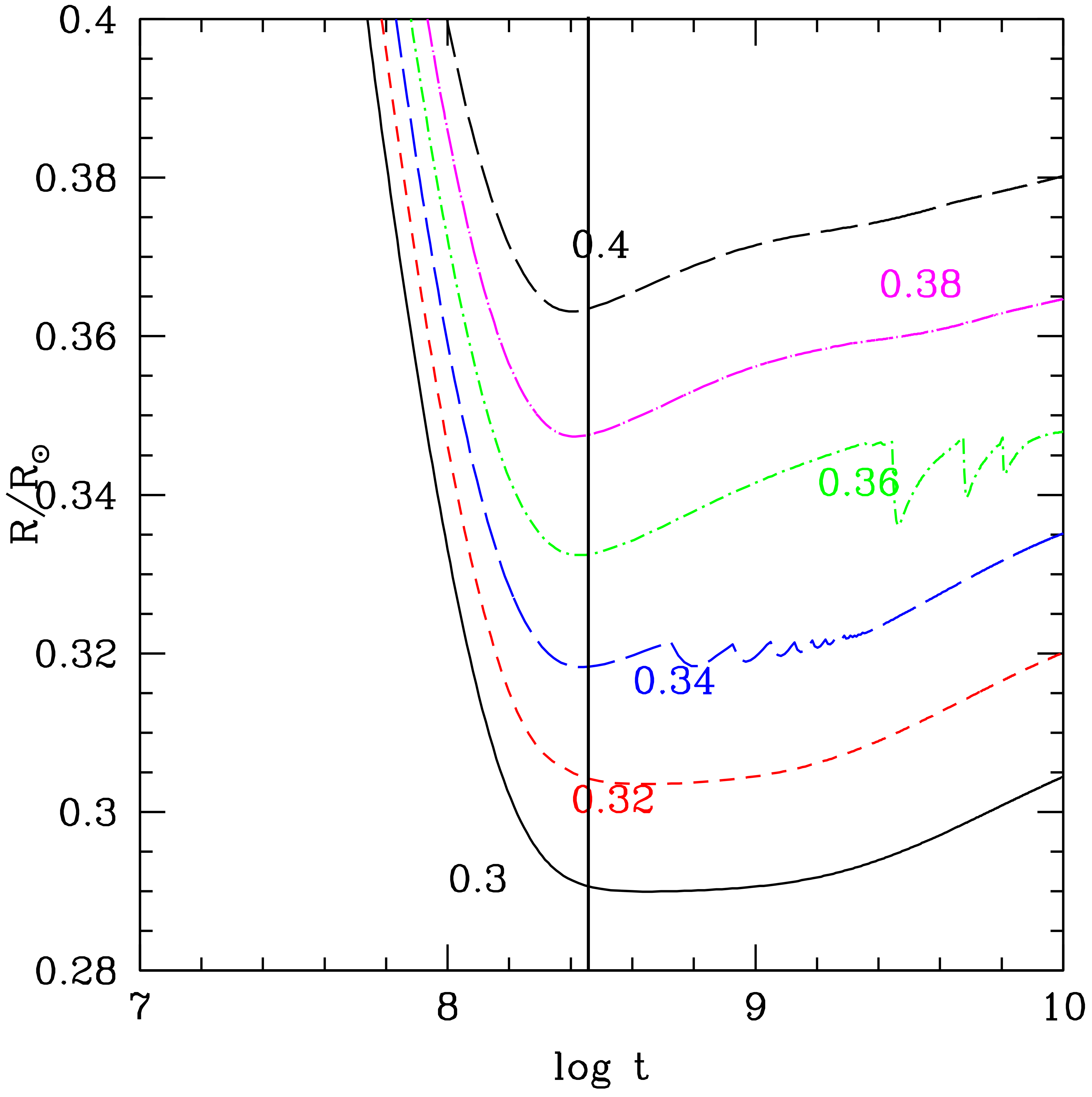
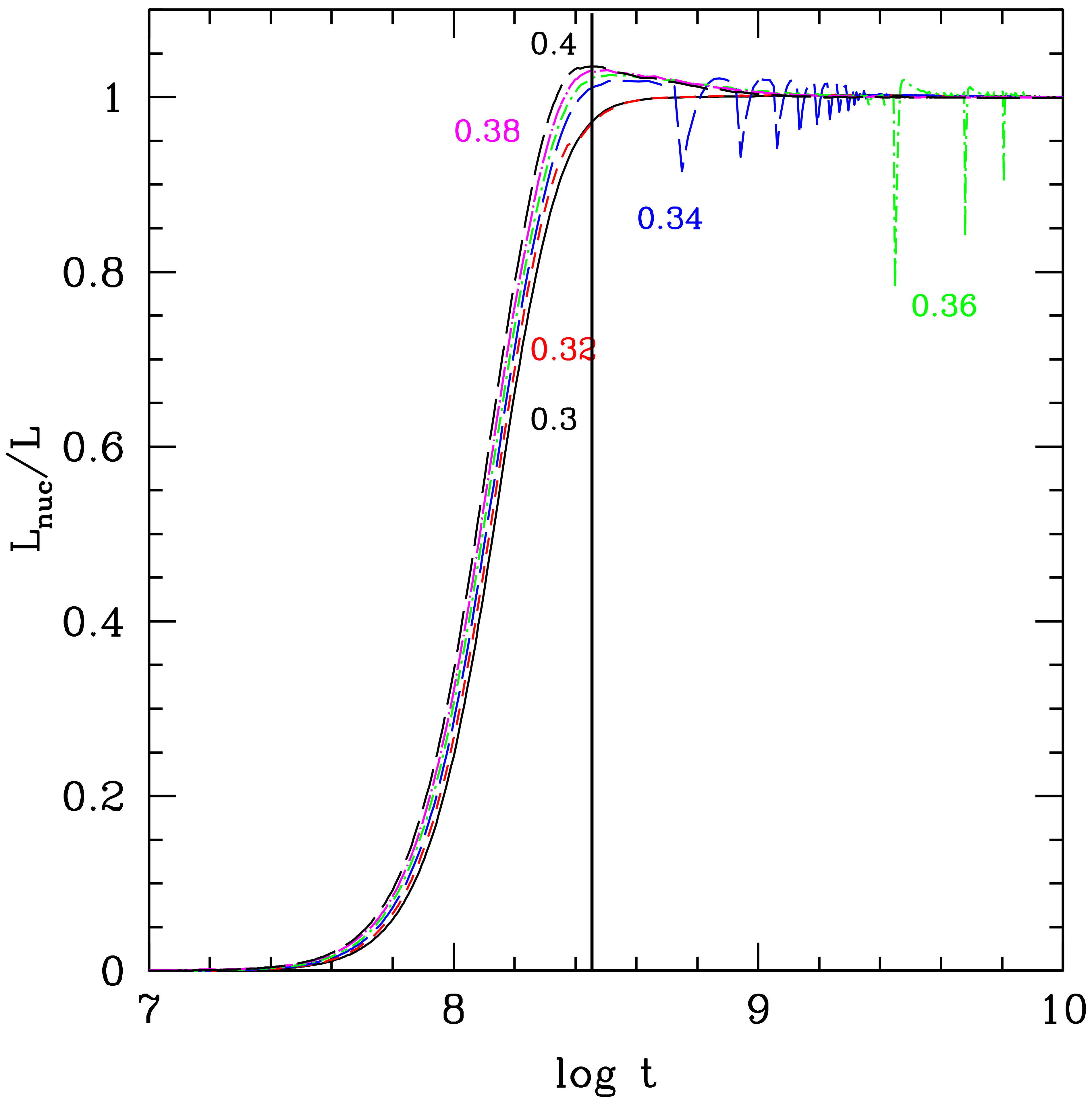
Fully convective boundary in the theory

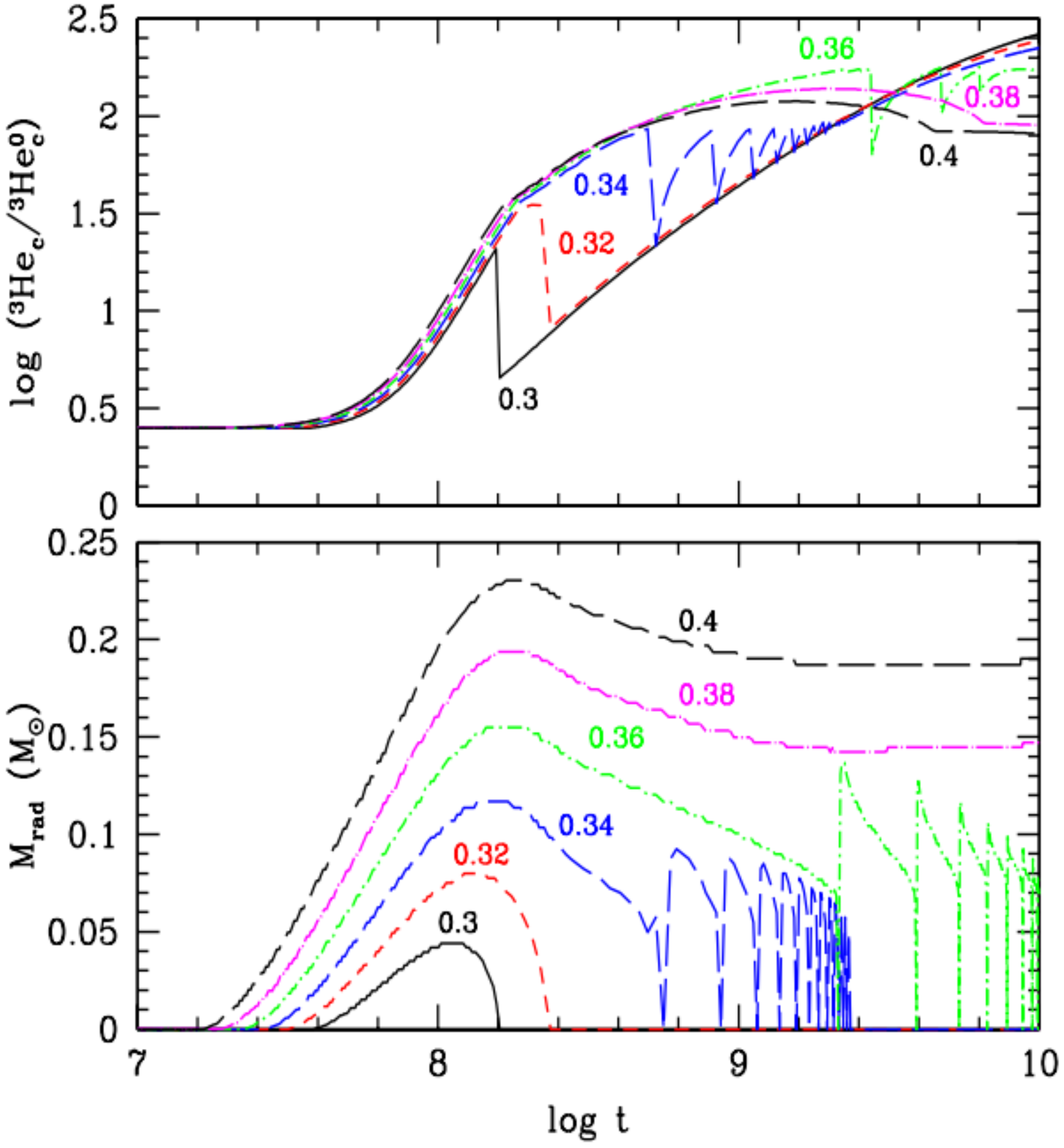




Baraffe et al. 2018

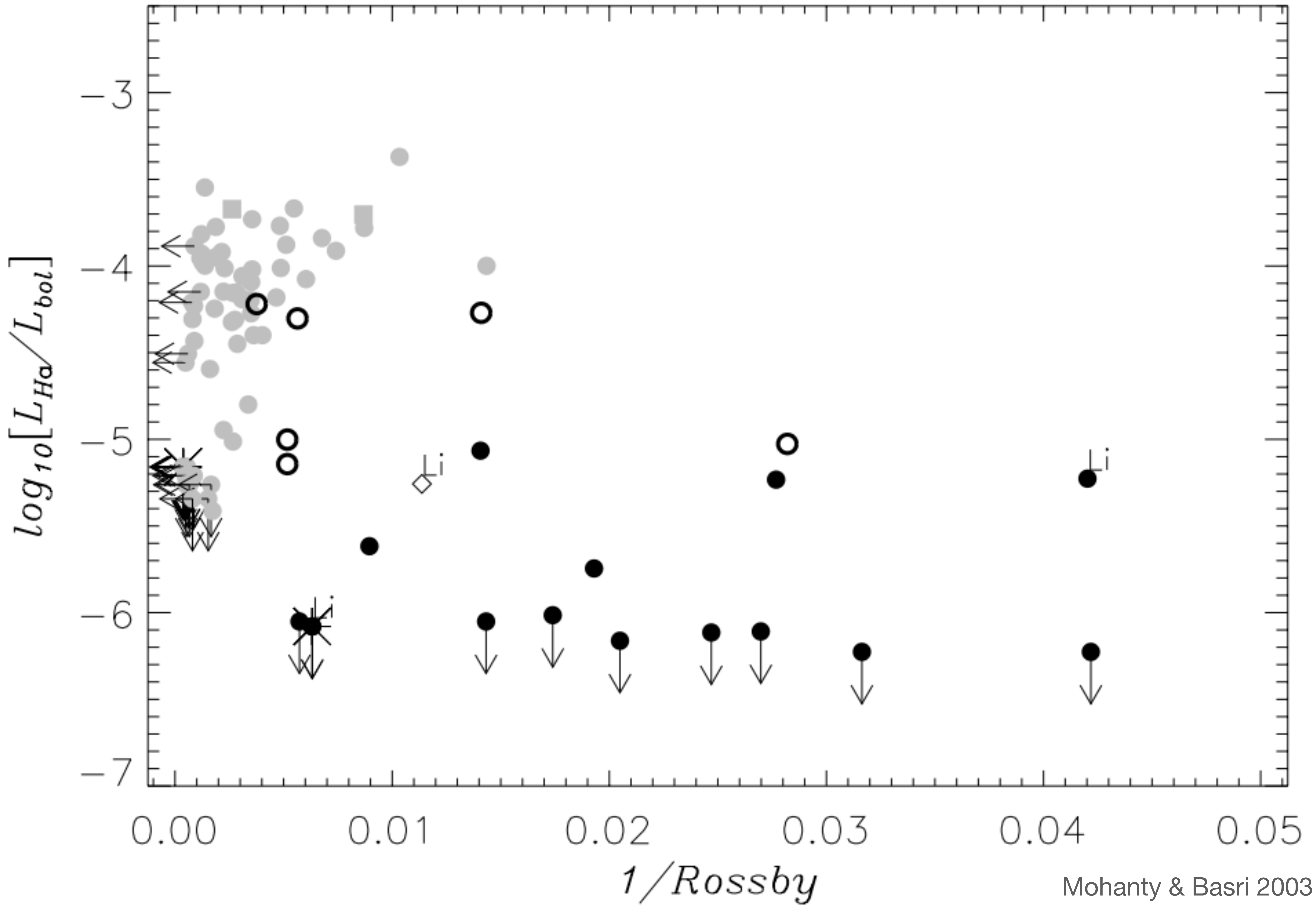
First found by van Saders & Pinsonneault 2012

Fully convective boundary in the theory



Baraffe et al. 2018

The relation between magnetic activity and rotation brakes for ultra-cool dwarfs



Mohanty & Basri 2003

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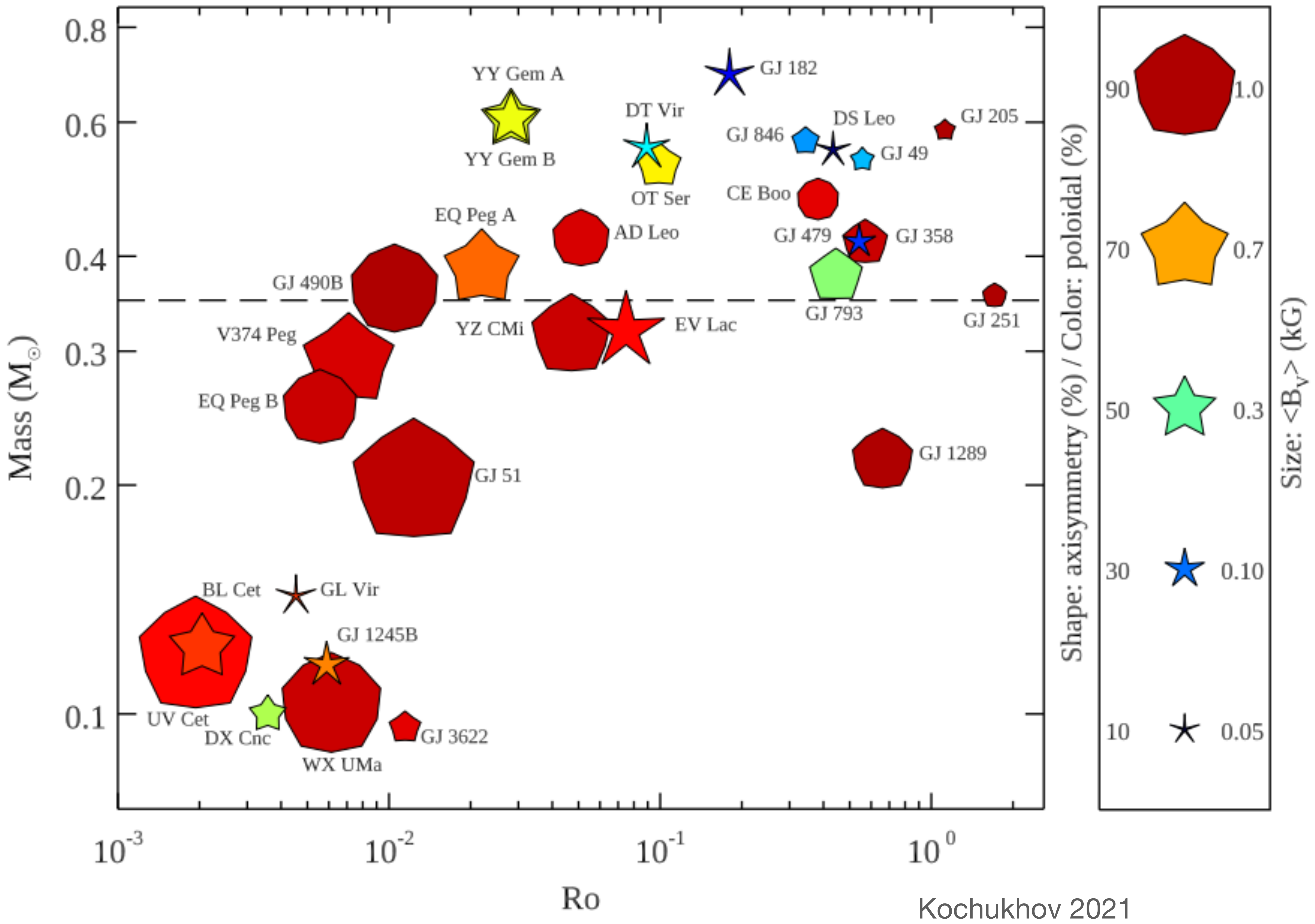
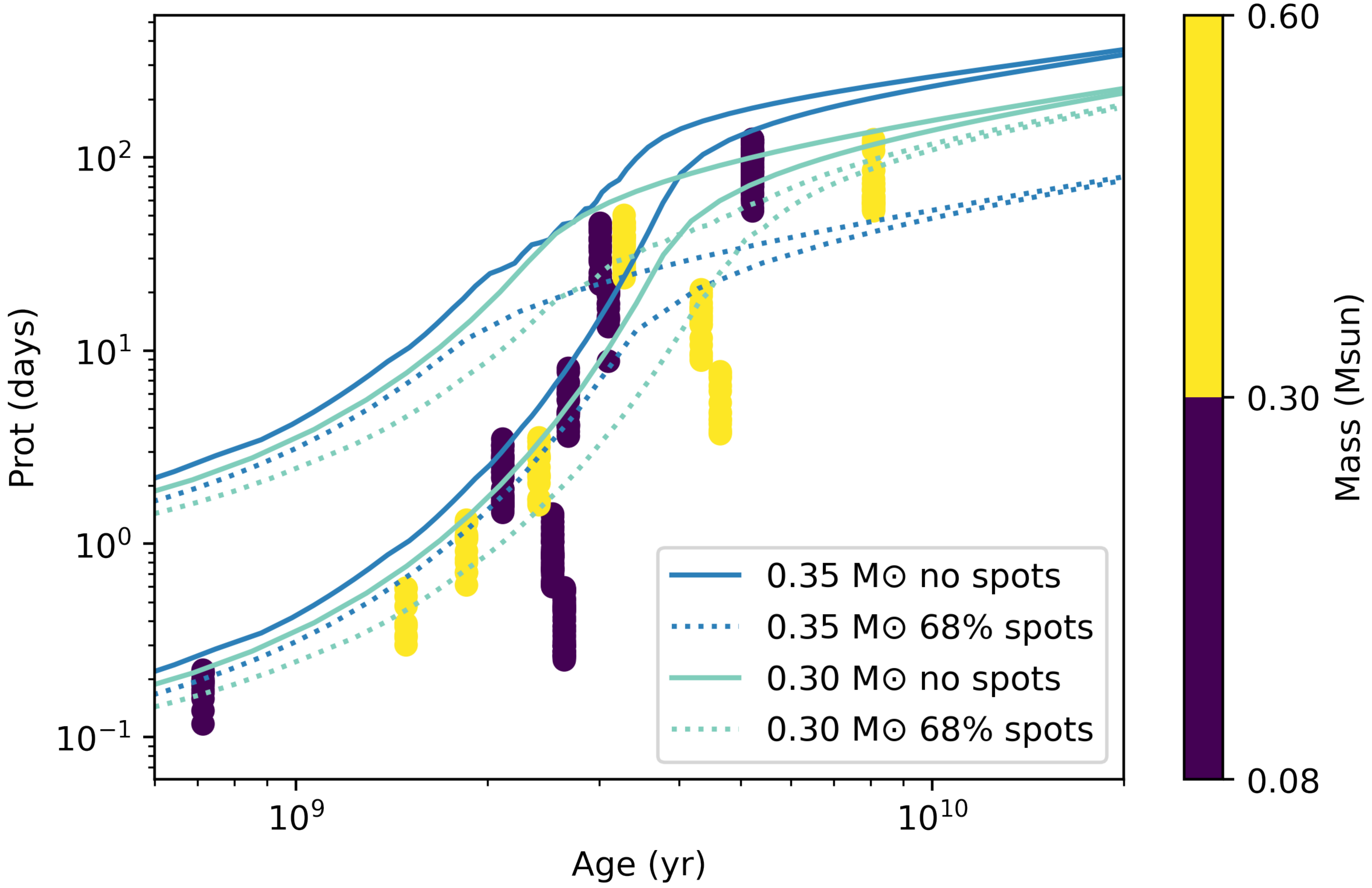
Magnetic field measurements of M dwarfs



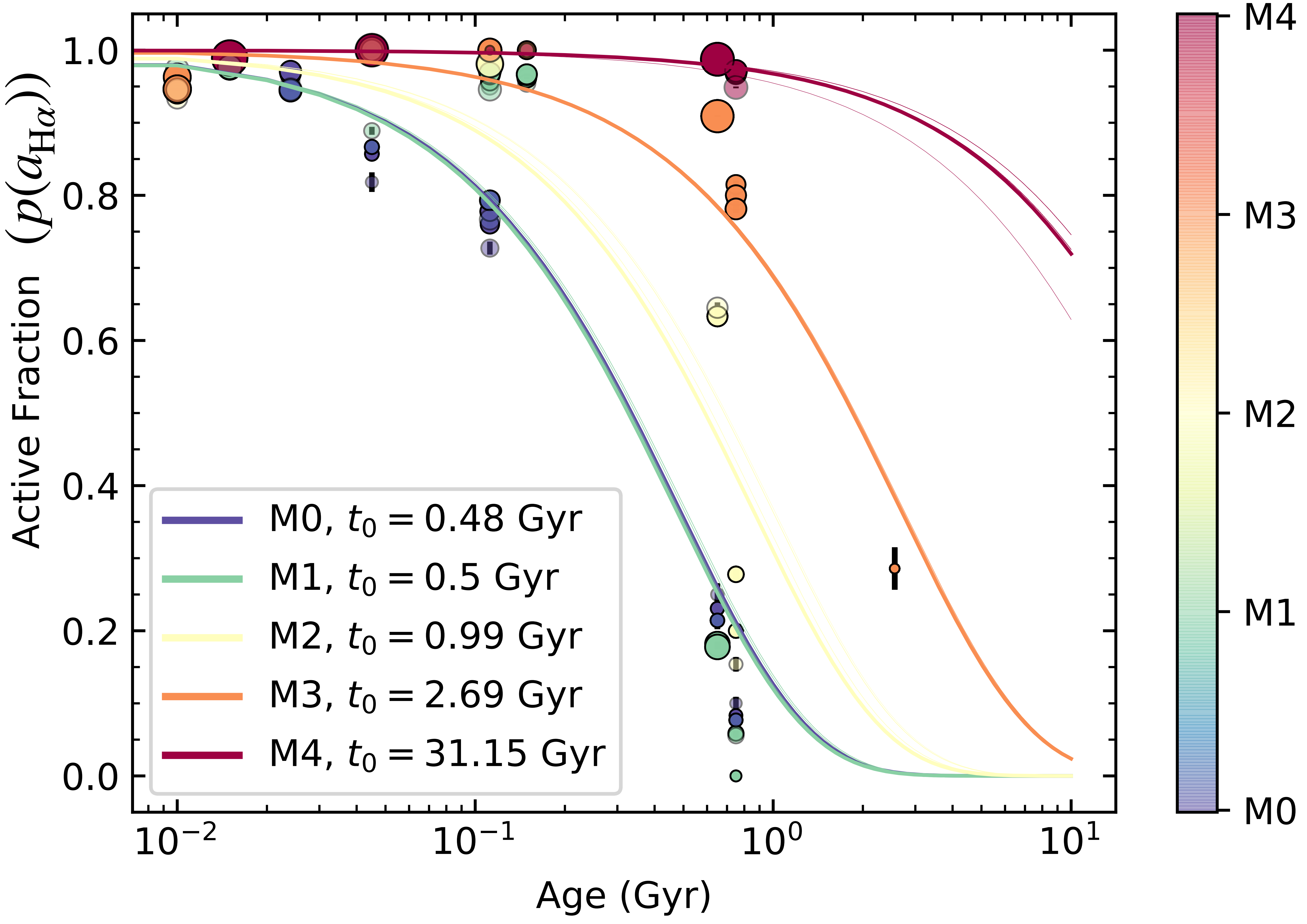
Kochukhov 2021

Work in progress: rotation period as a function of age



Kiman et al. in prep

The active fraction changes with time for M dwarfs

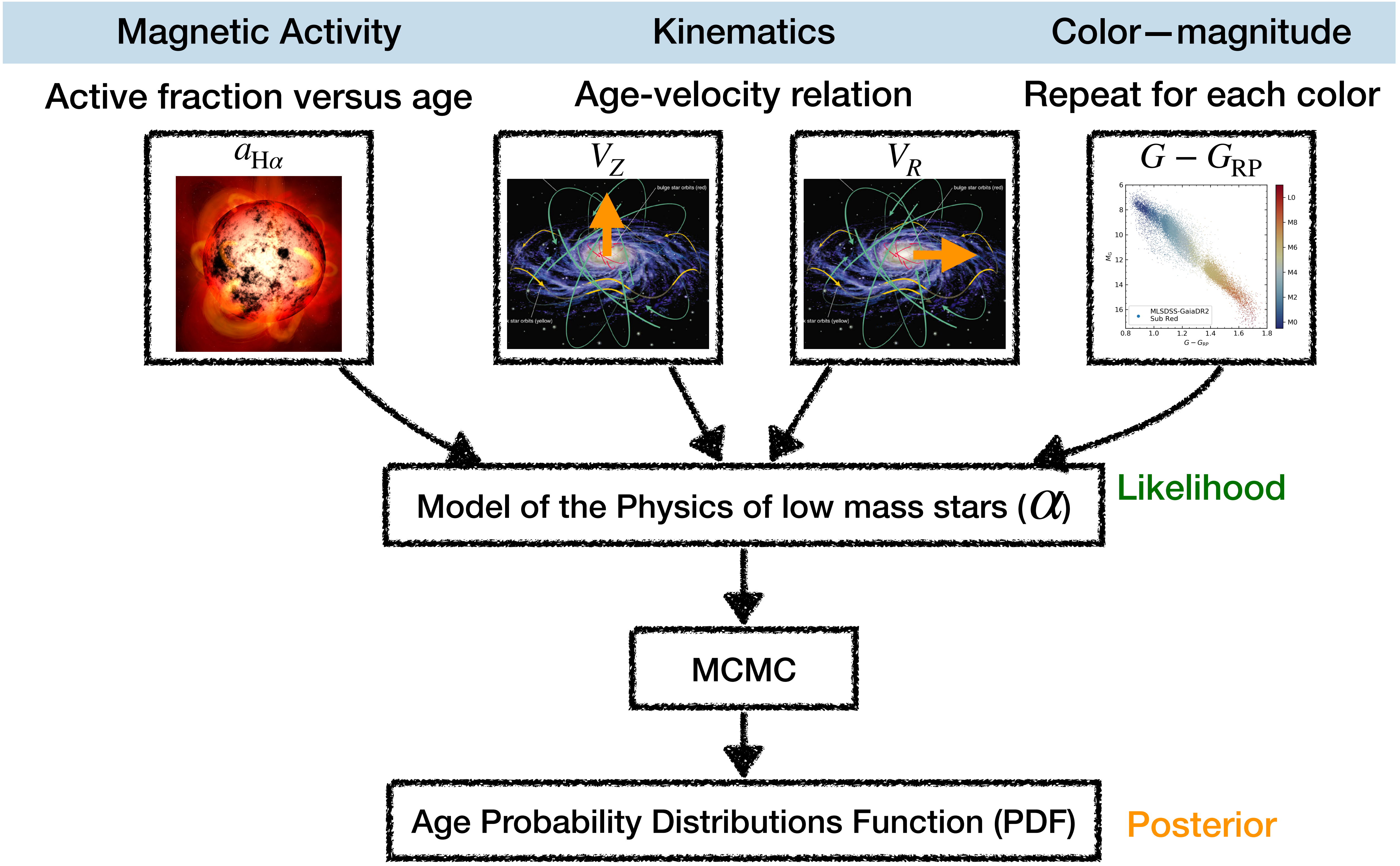


Kiman et al. in prep

$$a_{\mathrm{H}\alpha} = \begin{cases} 1 & \text{active} \\ 0 & \text{inactive} \end{cases}$$

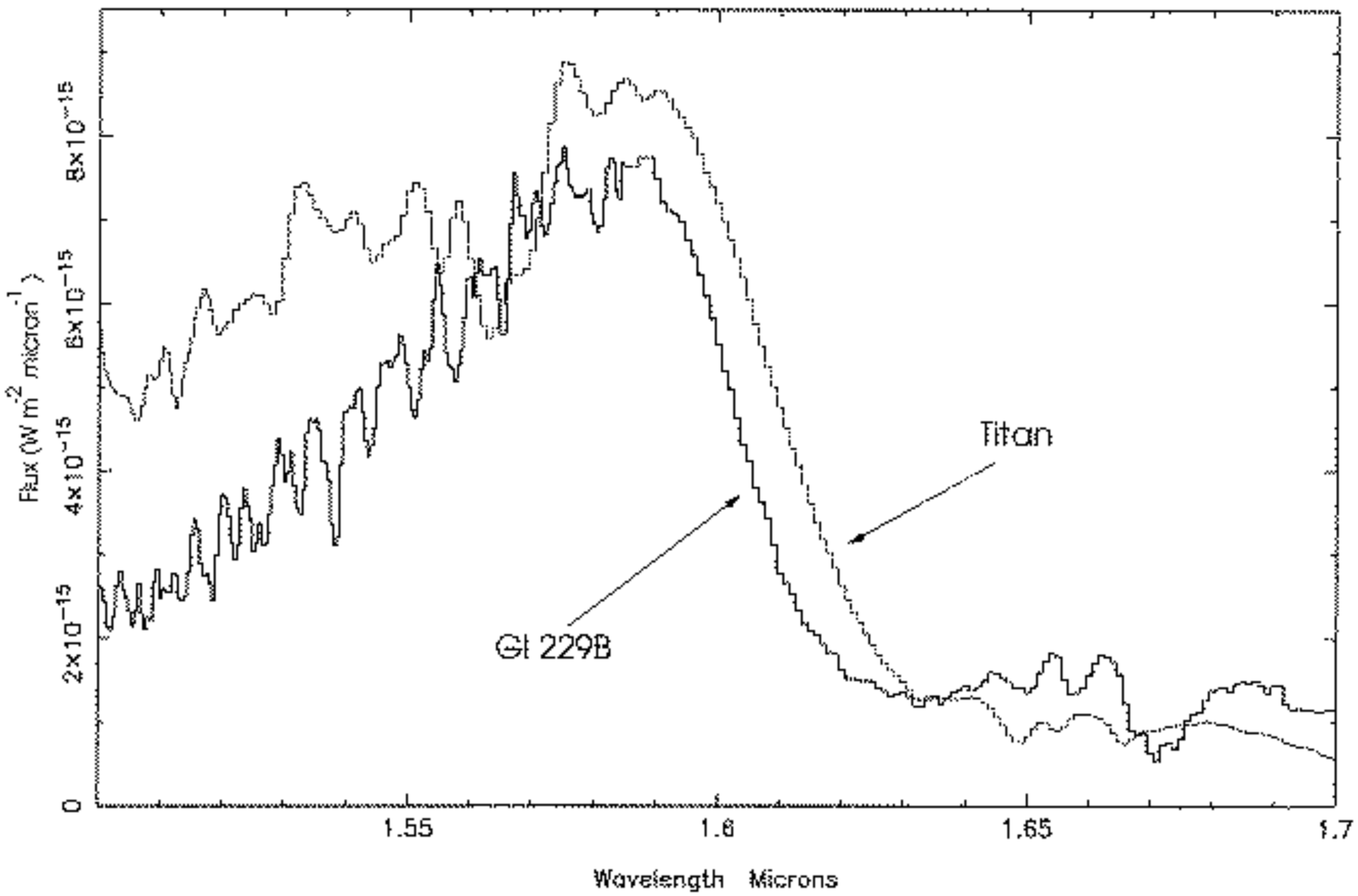
$$p(a_{\mathrm{H}\alpha}) = e^{-\frac{t}{t_0}}$$

`mdwarfdate`: Bayesian method to estimate M dwarf ages



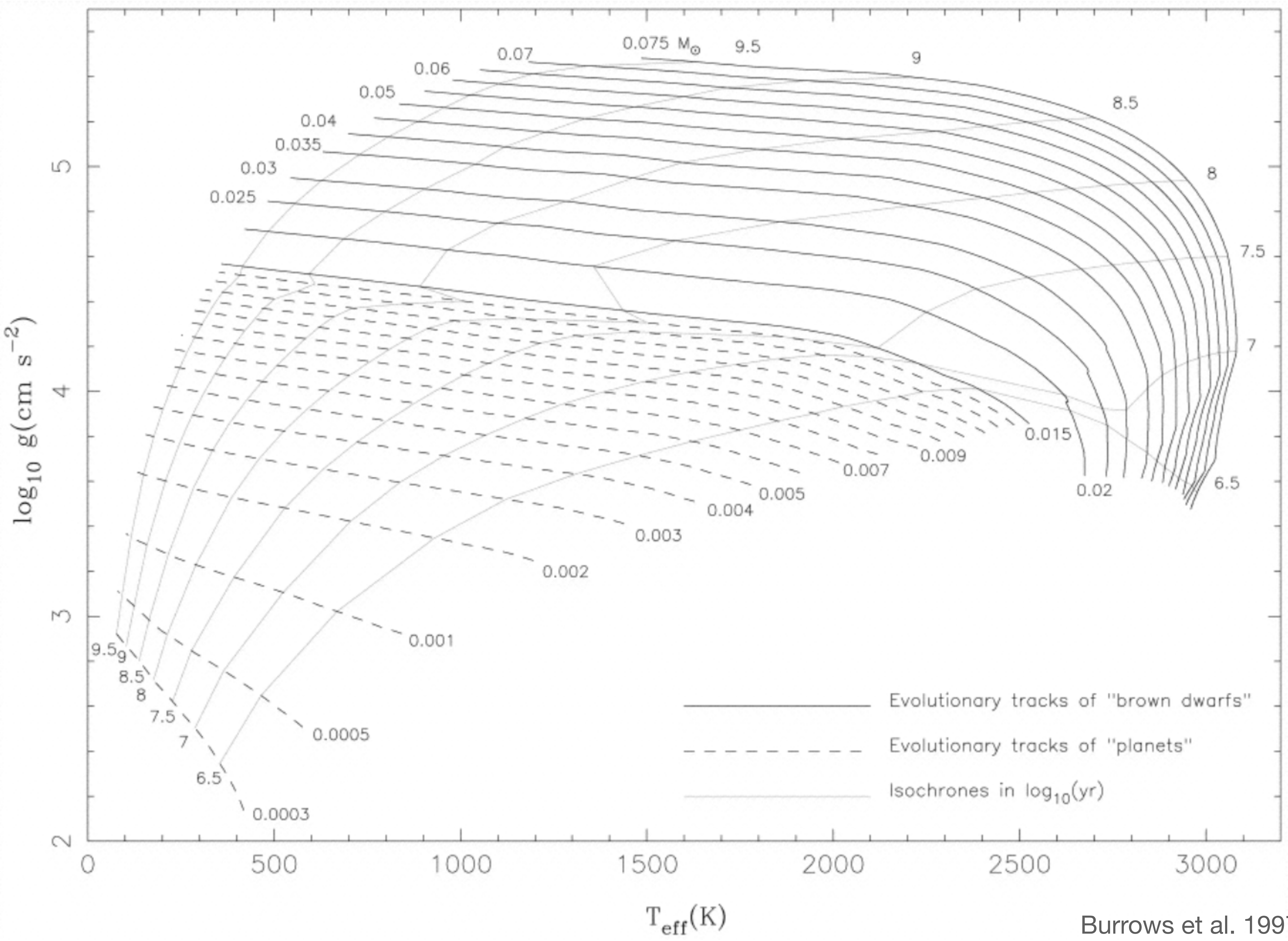
How can I distinguish a Brown Dwarf

We know is not a star because of the presence of Metane. Then the object has to be cool to keep it.



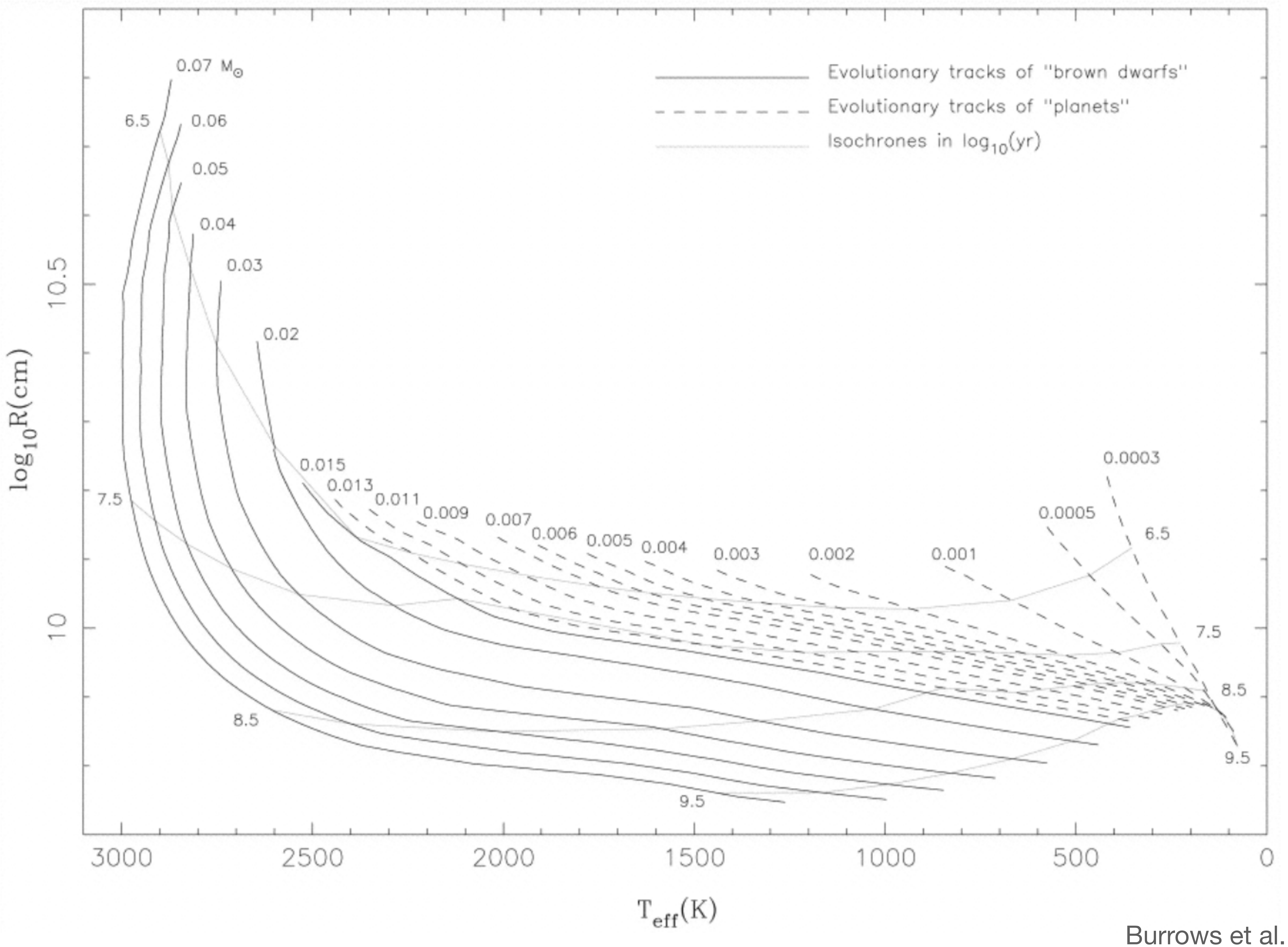
Geballe et al. 1996

Surface gravity evolution of Brown Dwarfs



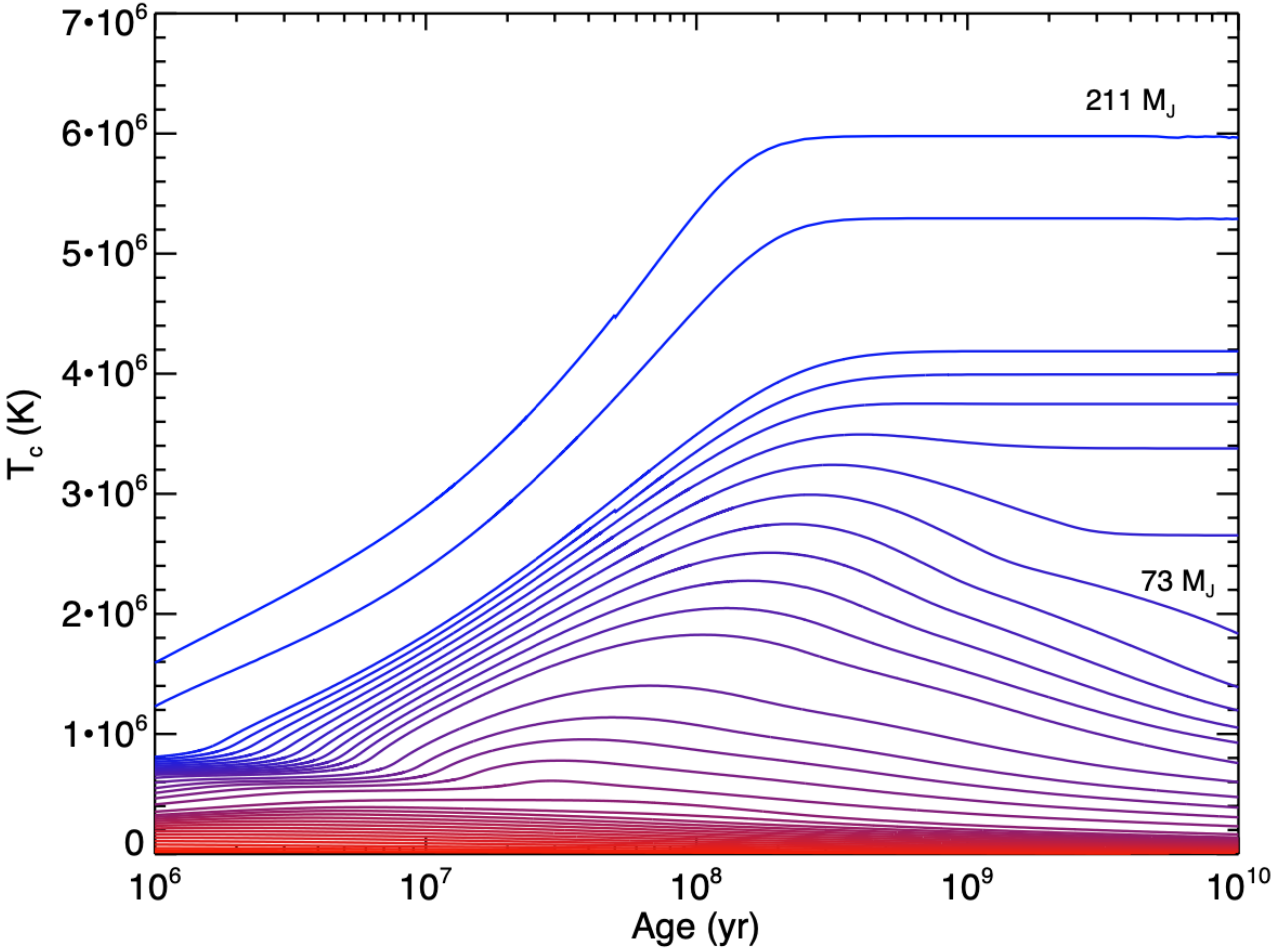
Burrows et al. 1997b

Radius evolution of Brown Dwarfs



Burrows et al. 1997b

Central temperature evolution of Brown Dwarfs



Burrows et al. 1997b