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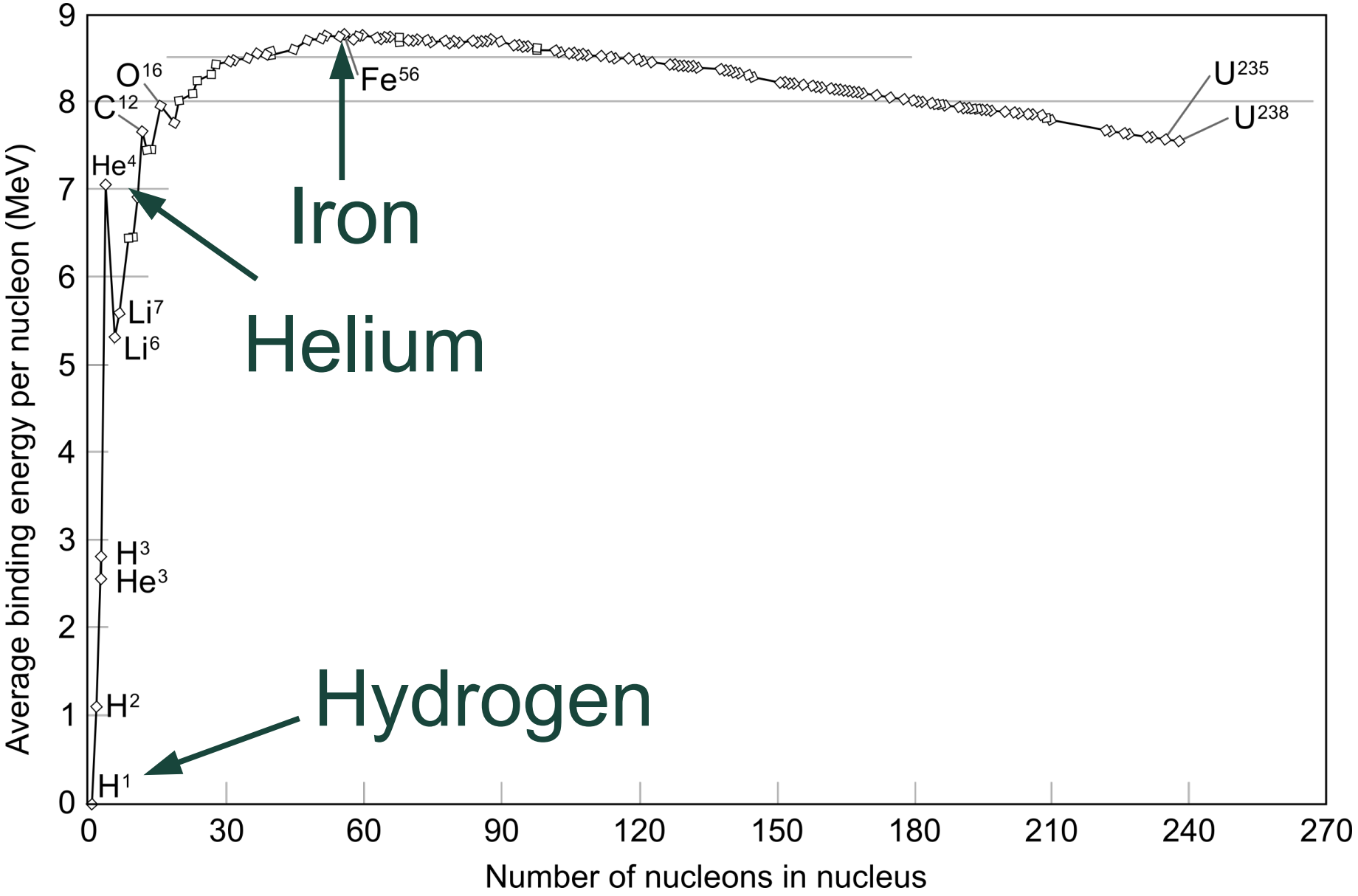
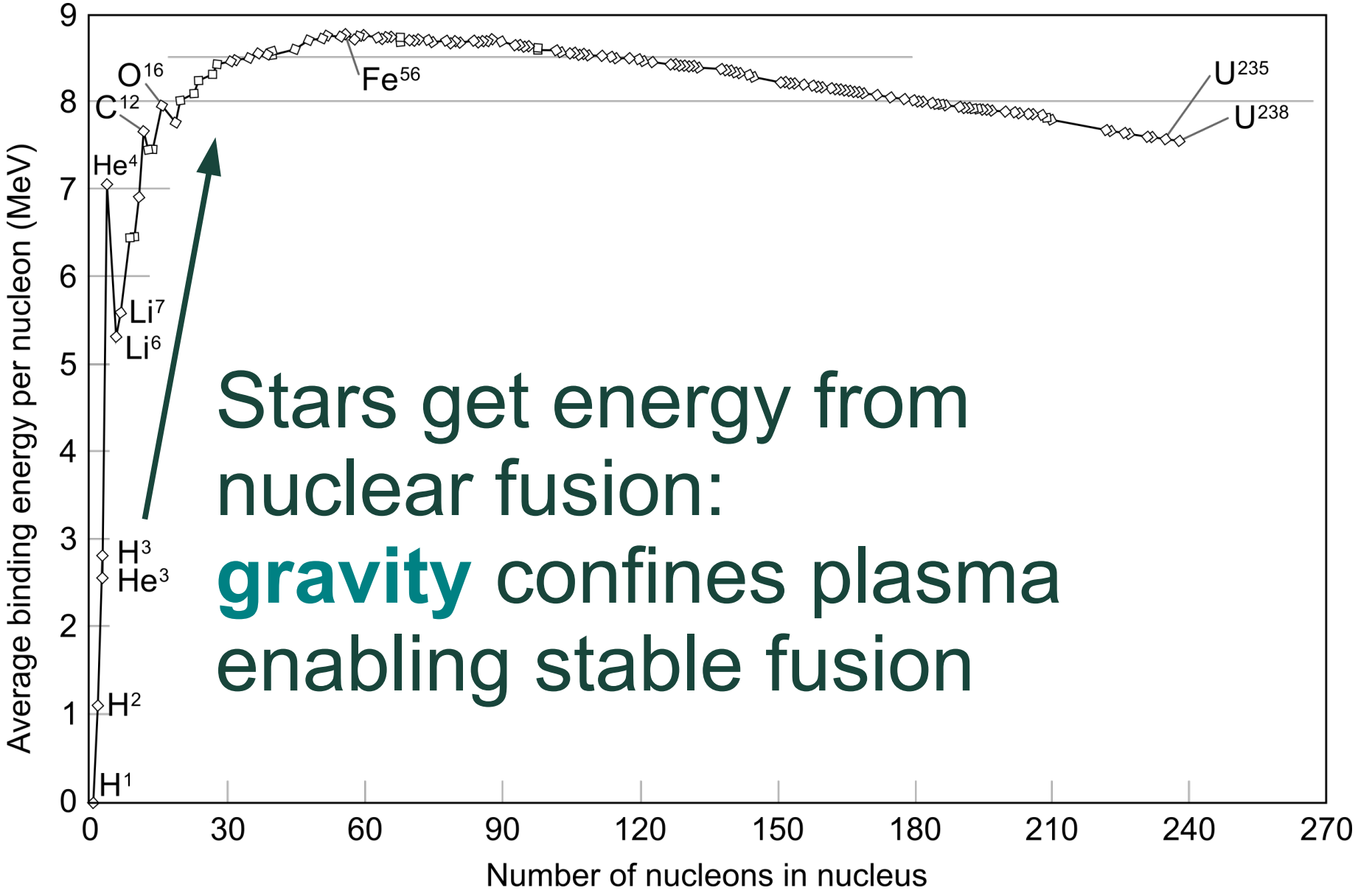
How do stars form?

Nuclear vs. EM forces



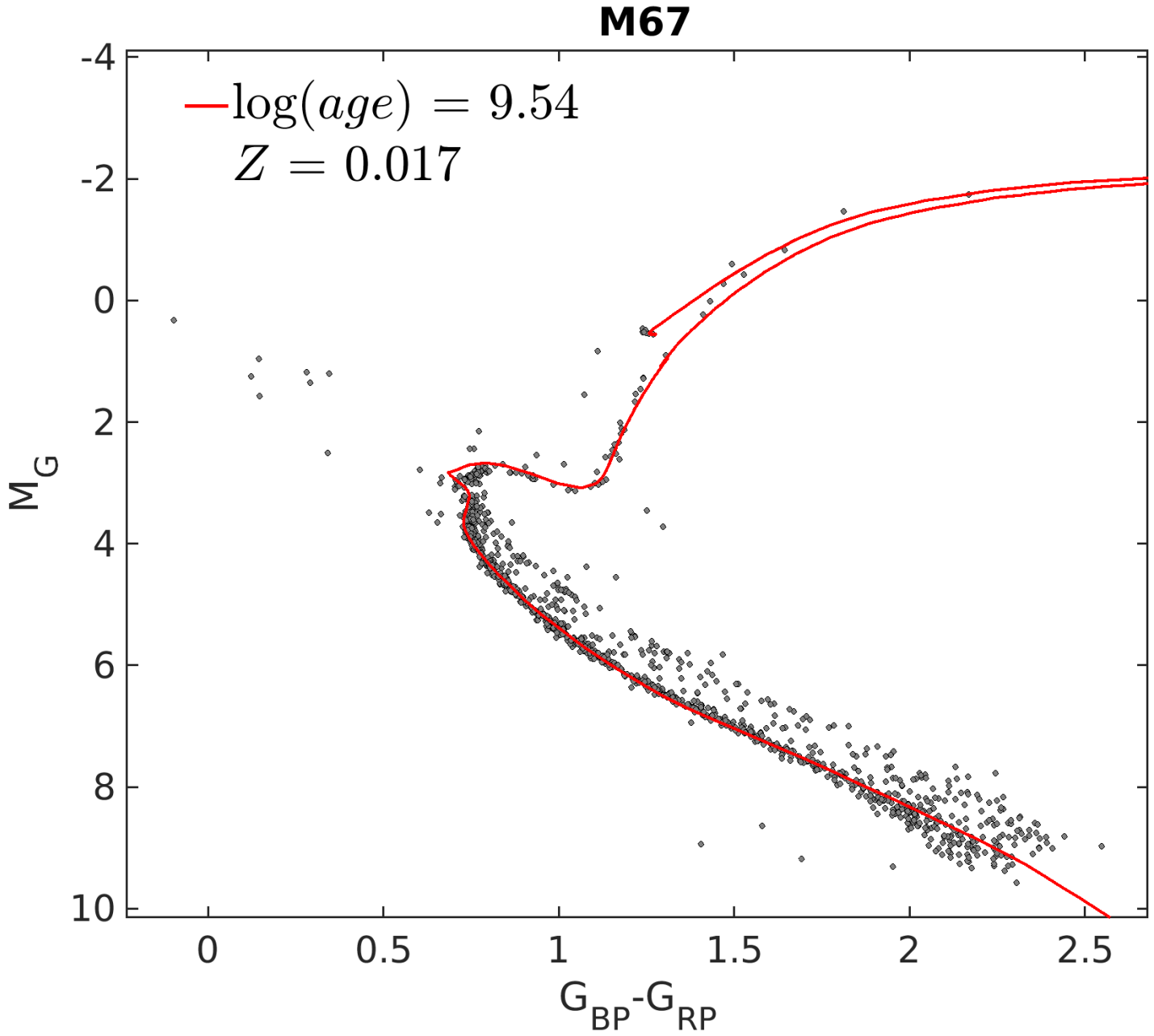
Stars have limited fuel supply



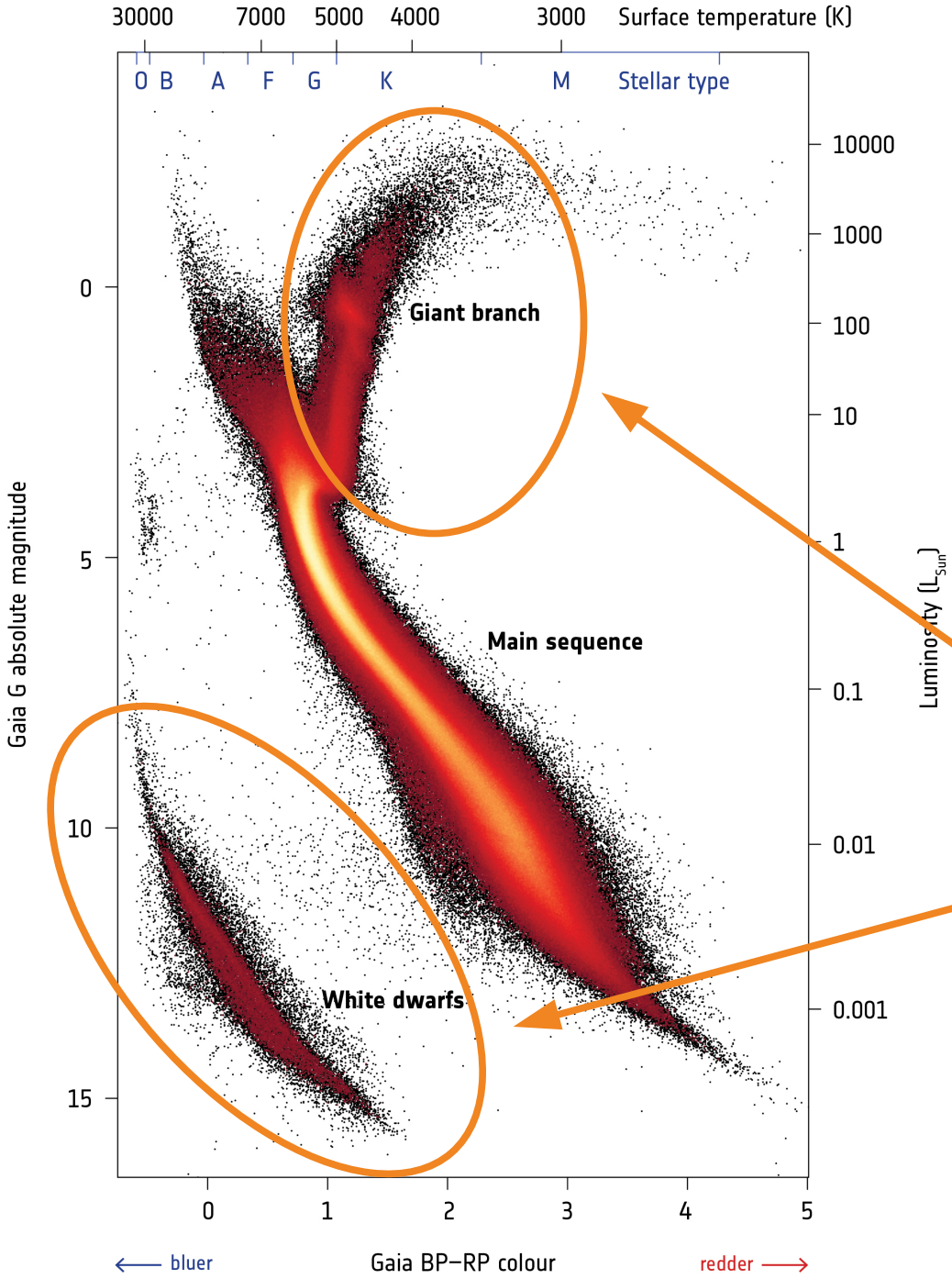
A star cluster has **same-age stars**

M67 image by N. Carboni & G. Parker

Isochrones: HR positions of **same-age stars**

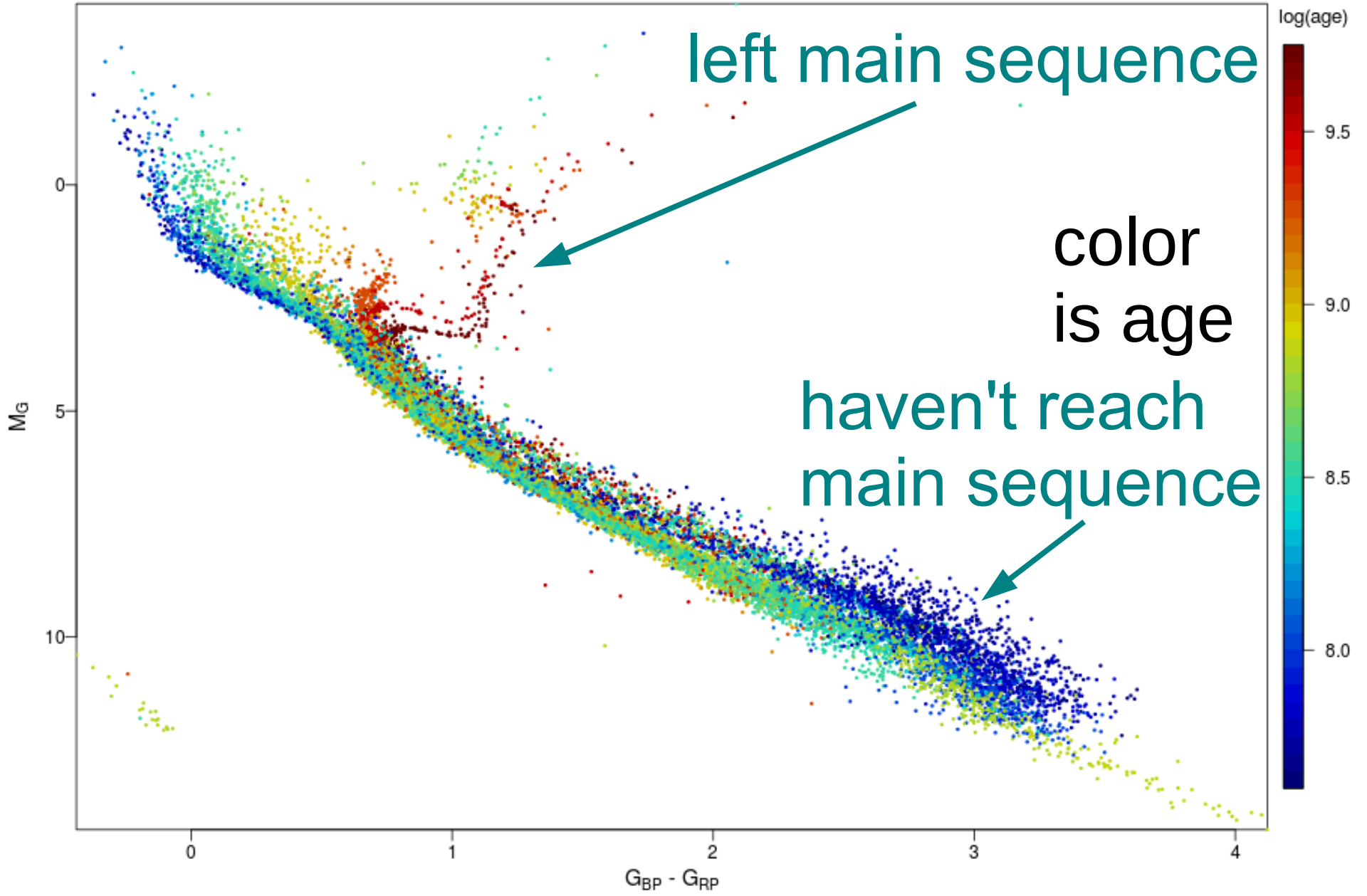


Gaia field stars HR diagram

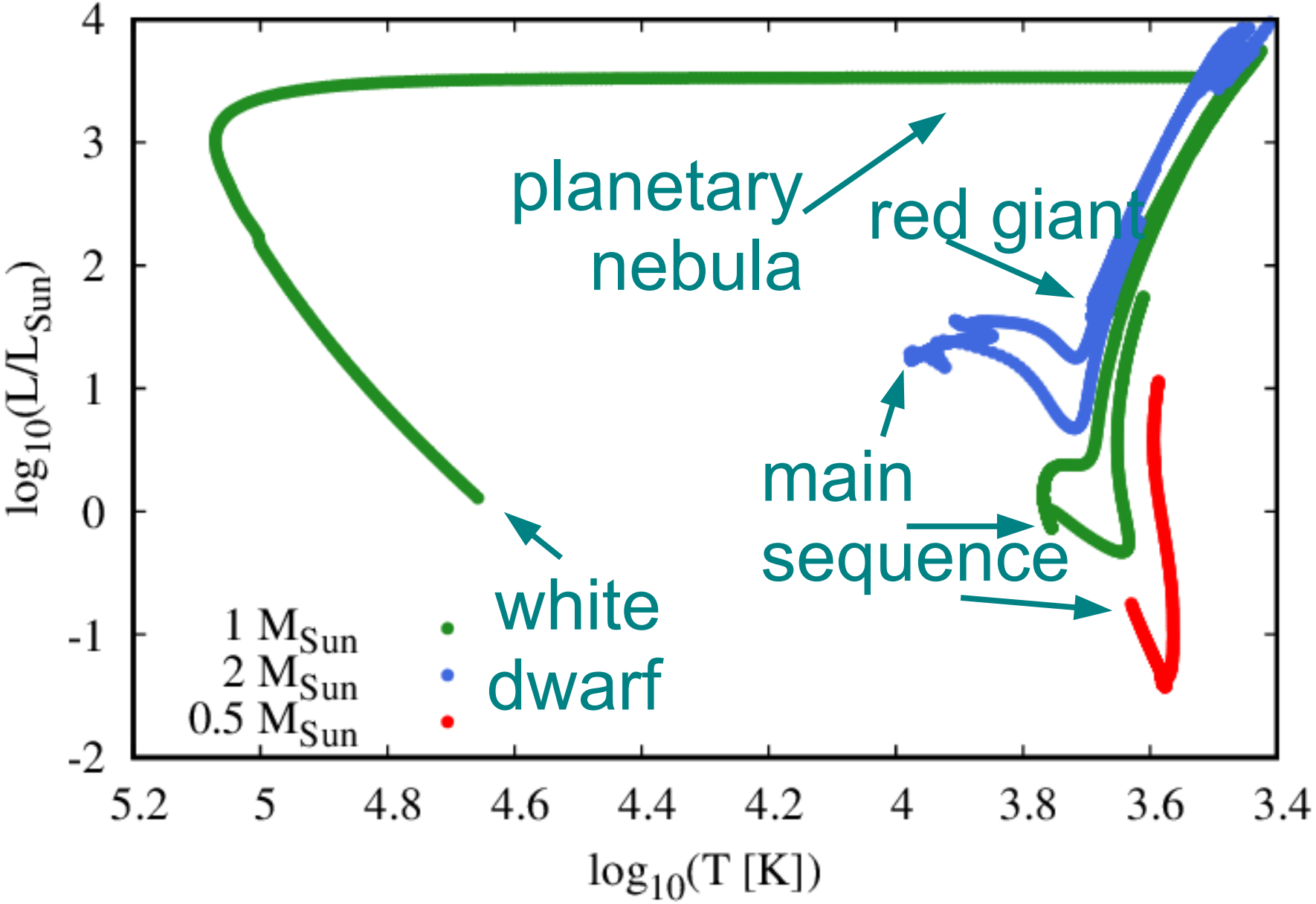


Stars that are out of Hydrogen fuel in their cores

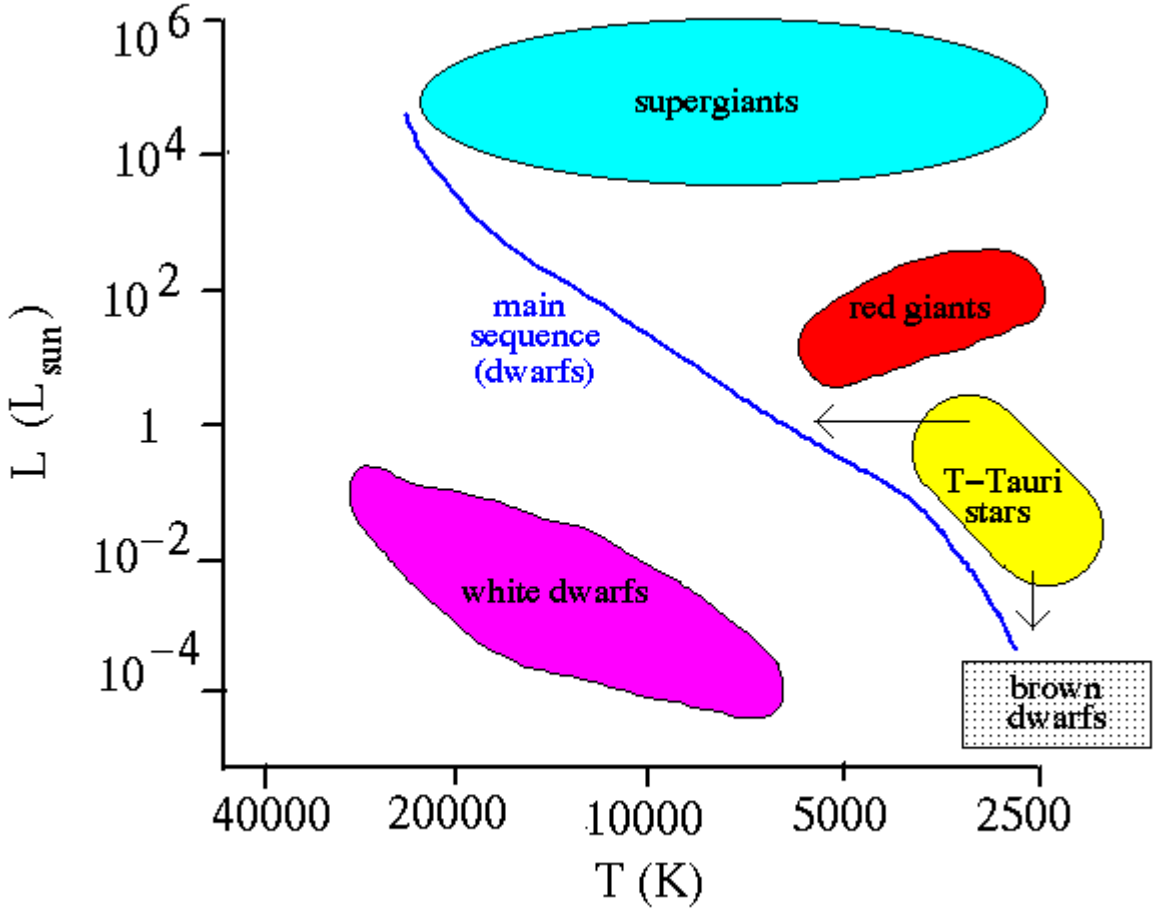
Gaia HR: open clusters

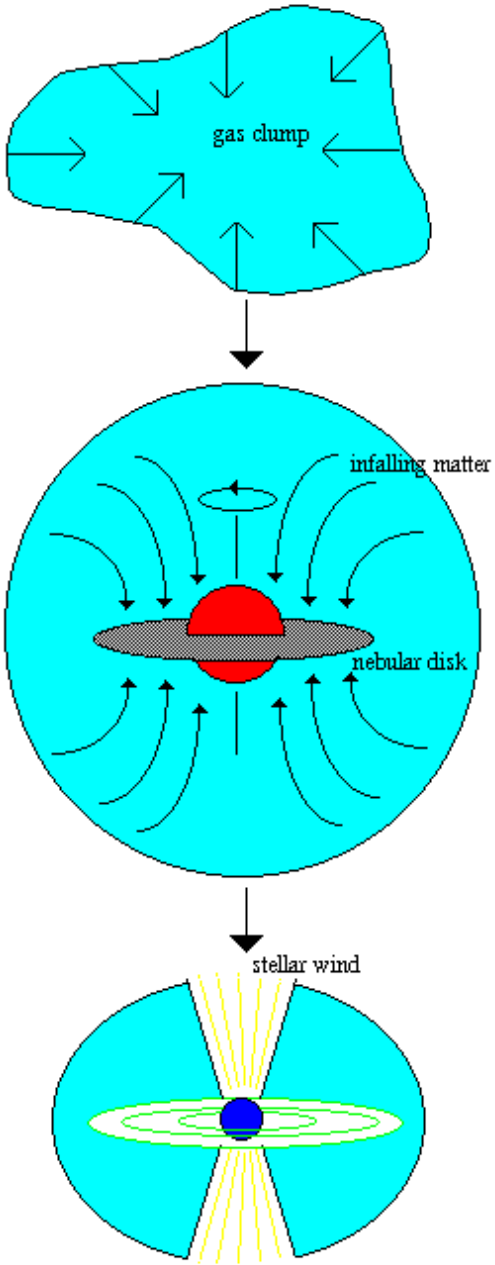


HR tracks


4
3
2
1
0
-1
-2
5.2
5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
log10(L/LSun)
log10(T [K])
planetary nebula
red giant
main sequence
white dwarf
1 MSun
2 MSun
0.5 MSun

T Tauri stars





Interstellar space is not exactly empty

- Atoms/ions/molecules
- Dust grains
- Electromagnetic radiation
- Cosmic rays: ions with non-thermal (high) energies
- Magnetic fields

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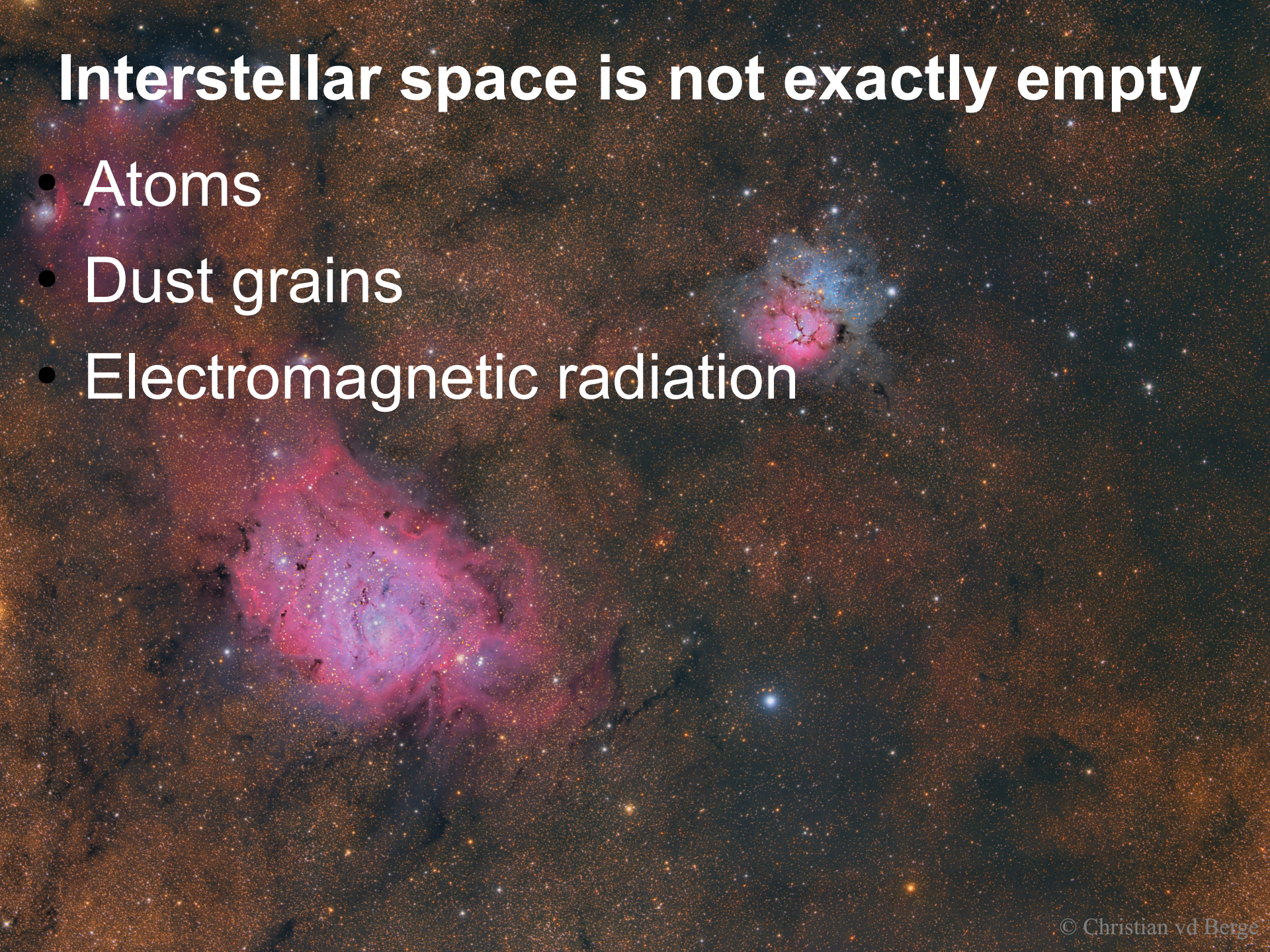

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Interstellar gas

- Balance between pressure and gravity
- Heated by stars (radiation & winds)
- Cooled by thermal radiation (line and free-free emission)
- Adiabatic expansion/contraction
- Heat transport by turbulence

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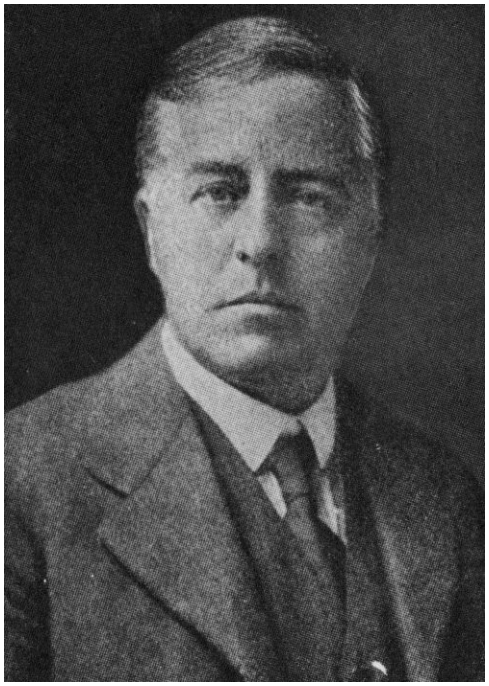
Gravitational (Jeans') instability

- **Gravity** pulls matter in
- **Pressure** pushes it back
- When pressure wins -> **oscillations** (sound waves)
- When gravity wins -> **collapse**



Sir James H. Jeans
(1877-1946)

Equilibrium if $$\frac{dp}{dr} = -\frac{G\rho(r)M_{enc}(r)}{r^2}$$

Two ways of thinking about Jeans' instability

1) To compress a gas cloud we need to **apply work**, but **gravitational energy** gets released...

2) If the gas cloud is compressed, it will take **sound_speed times cloud_size** to restore the balance. This time should be smaller than the **free-fall time**.

Jeans' mass

$$M_J \propto T^{3/2} n^{-1/2}$$

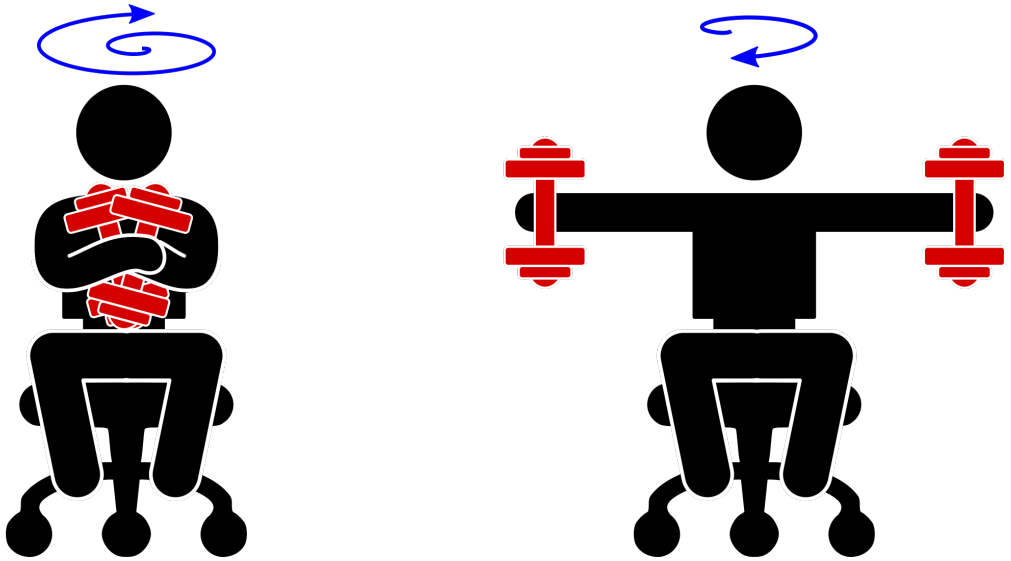
The gas cloud is unstable if it is either very massive at a given temperature (think **galaxy formation**) or very cool at a given mass (**star formation**)

Stars form in giant molecular (cold) clouds

Angular momentum conservation

$$L = I\omega$$

$L = I \cdot \omega$ $L = I \cdot \omega$

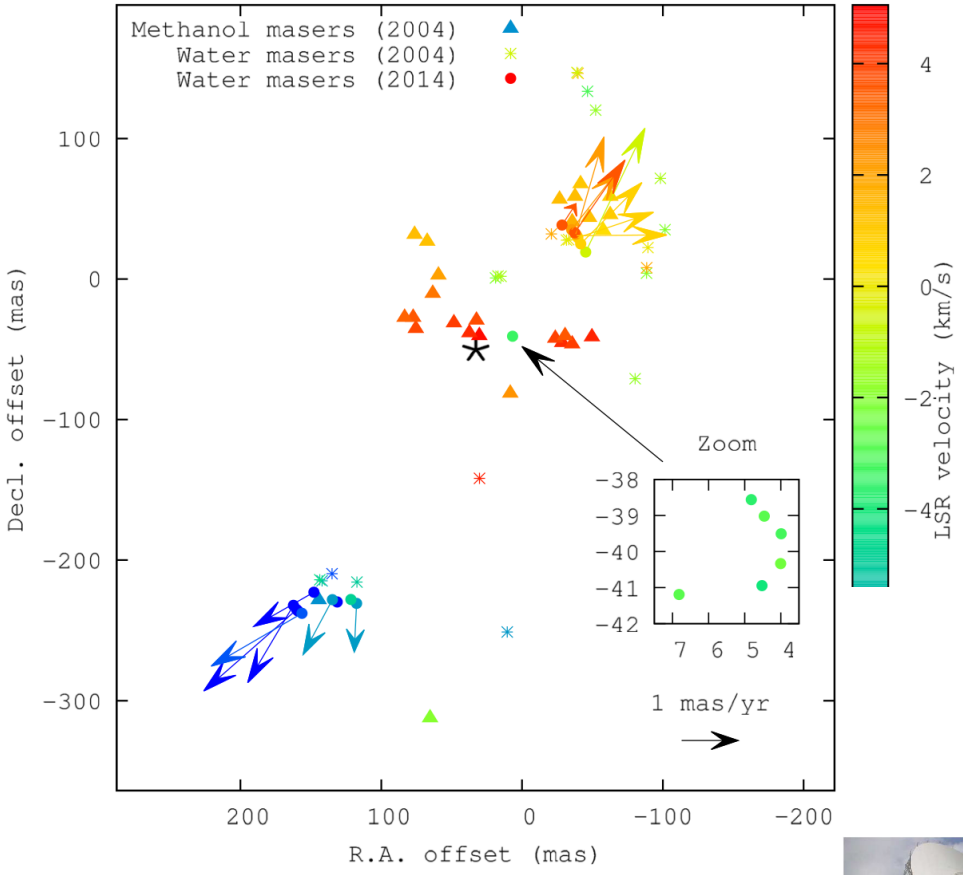


See the video

External forces may aid star formation

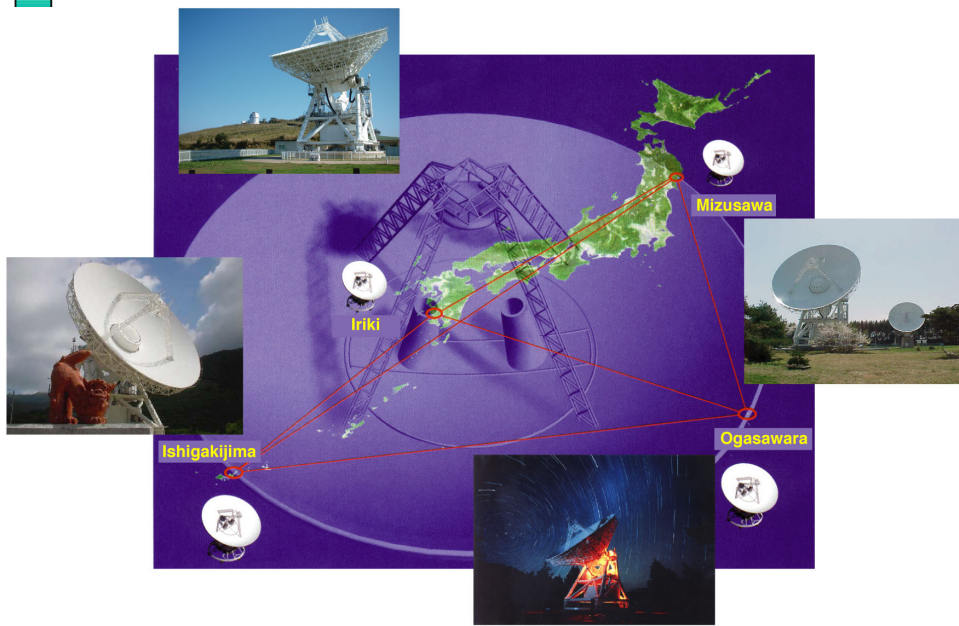
Herbig-Haro objects

Cosmic masers



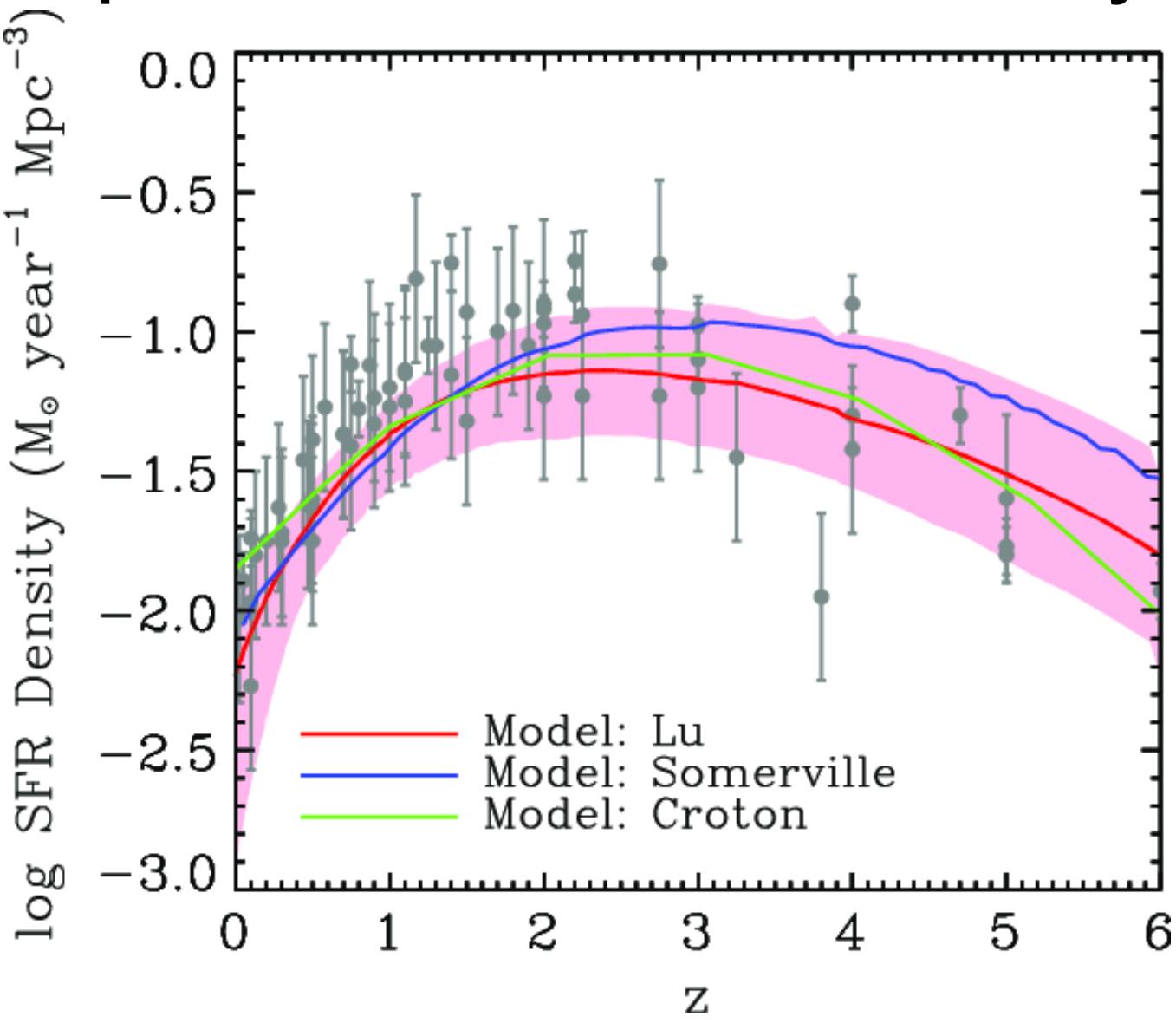
plot from
Hunter et al. arXiv:1806.06981

VERA radio interferometry array in Japan is dedicated to cosmic maser studies



Cosmic noon

peak of star formation rate ~10 Gyr ago (z~2)



plot from
Lu et al. 2014, ApJ, 795, 123

Summary

- **Stars** we see today **have different ages**
- Stars form in dense **molecular clouds**
- **Star formation continues** today, but at lower rate than in early universe
- **Conservation of angular momentum** makes stars spin and creates disks around young stars that may form planets