THE FIRST STARS

Joseph Silk
2nd Gresham Lecture
Nov 4 2015

The Orion Nebula

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • WFI

NASA / JPL-Caltech / T. Megeath (University of Toledo) & M. Robberto (STScI)

ssc2006-21a

Radio (0.4 GHz)

Atomic Hydrogen

Radio (2.7 GHz)

Molecular Hydrogen

Infrared

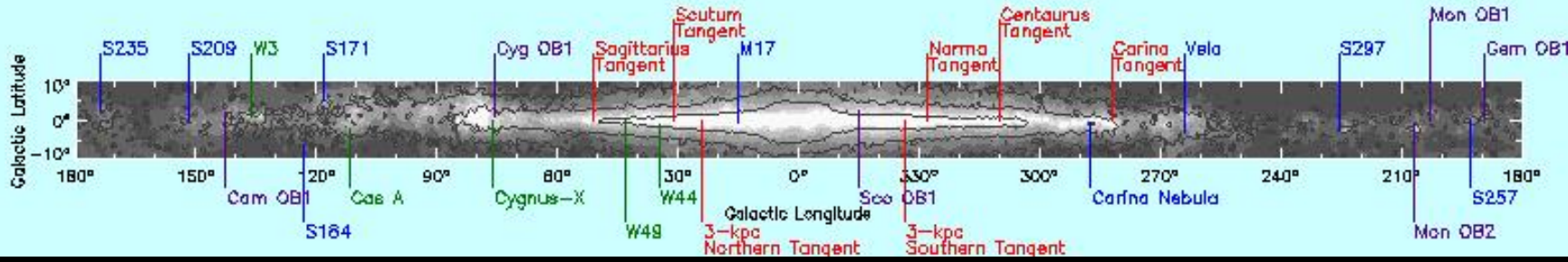
Mid Infrared

Near Infrared

Optical

X-Ray

Gamma Ray



Finder

STARS

- What is a star
- We are formed from the ashes of the stars
- How are stars made?
- How were the first stars made?

THE HOLY GRAIL OF STAR FORMATION

- Can we predict the masses of stars? ■ No
- Can we account for the efficiency of star formation? ■ No
- Can we account for the rate of star formation? ■ No

What's missing?

A robust theory of star formation

We can still understand the key concepts

Isaac Newton 1643-1727

if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space.And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

if the sun at rest were an opaque body like the planets or the planets lucid bodies like the sun, how he alone should be changed into a shining body whilst all they continue opaque, or all they be changed into opaque ones whilst he remains unchanged, I do not think explicable by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent.

Isaac Newton, letter to Richard Bentley, December 10, 1692

James Jeans (1877-1946)

James Jeans:

"We have found that as Newton first conjectured….

All celestial bodies originate by a process of fragmentation of nebulae out of chaos, of stars out of nebulae, of planets out of stars and satellites out of planets."

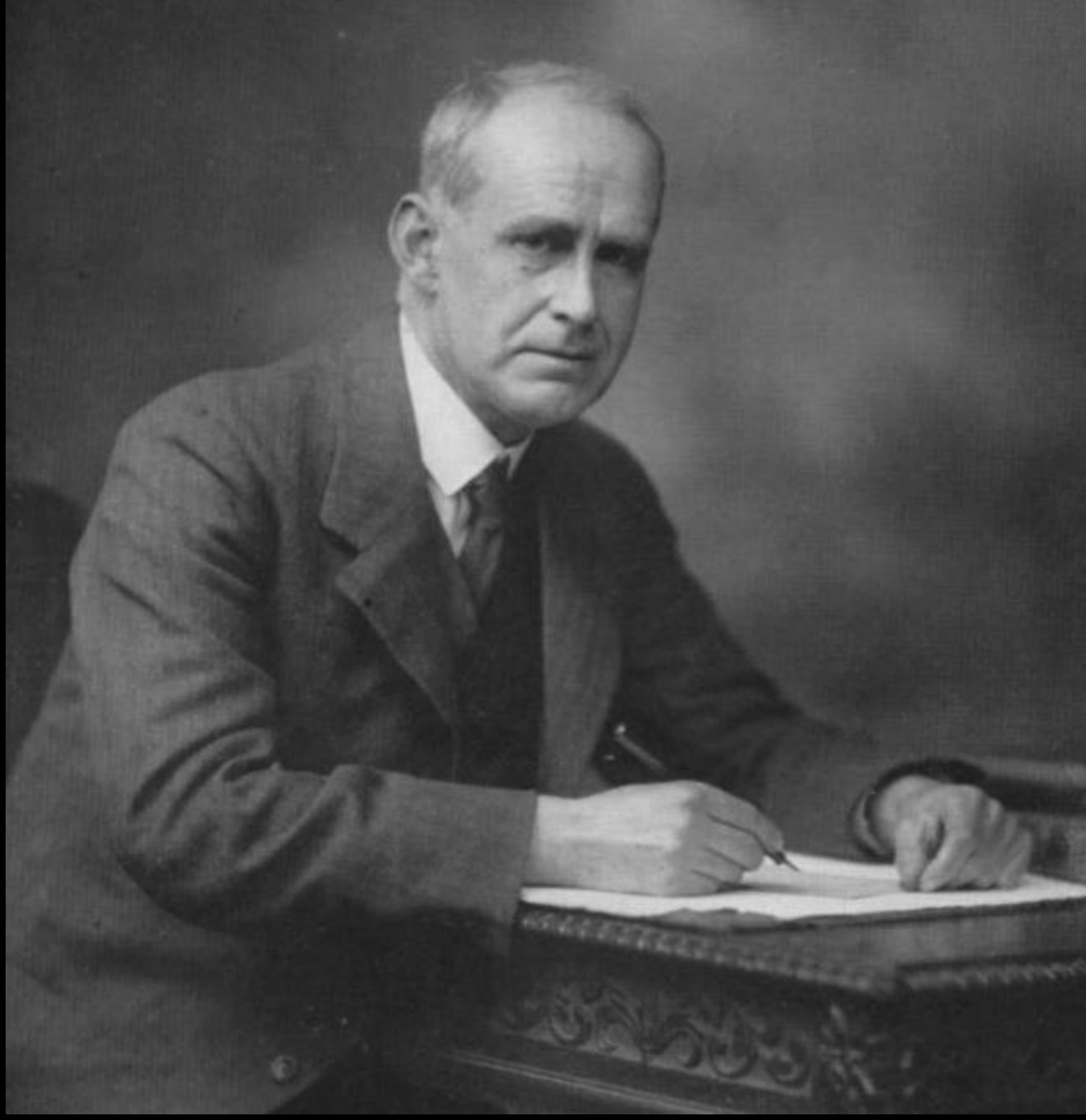
“From the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician.’’

Criterion for gravitational stability found by Jeans (1902):

pressure opposes collapse:

sound waves must cross region to communicate pressure changes before collapse

Arthur Eddington (1882-1946)



Eddington believed that the number of protons in the universe could be derived exactly:

15,747,724,136,275,002,577,605,653,961,181,555,468,044,717,914,527,116,709,366,231,425,076,185,631,031,296

or

136×2^{256}

1931

Arthur Eddington: imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion, "What 'happens' is the stars."

"We can imagine a physicist on a cloud-bound planet who has never heard tell of the stars calculating the ratio of radiation pressure to gas pressure for a series of globes of gas of various sizes, starting, say, with a globe of mass 10 gm., then 100 gm., 1000 gm., and so on, so that his *n*th globe contains 10^n gm. . . . Regarded as a tussle between matter and aether (gas pressure and radiation pressure) the contest is overwhelmingly one-sided except between Nos. 33-35, where we may expect something interesting to happen.

What 'happens' is the stars.

We draw aside the veil of cloud beneath which our physicist has been working and let him look up at the sky. There he will find a thousand million globes of gas nearly all of mass between his 33rd and 35th globes – that is to say, between $\frac{1}{2}$ and 50 times the sun's mass."

Sir Arthur S. Eddington: The Internal Constitution of the Stars, 1926

What determines the mass of a star?

A struggle between gravity versus (electromagnetic) pressure

It all reduces to one number:
a dimensionless constant that controls the masses of stars $\alpha_g \equiv G m_p^2 e^{-2} \approx 3.10^{-37}$

Its so small because gravity is really weak…while charge neutrality mostly cancels out since electrons are – charged and protons are + charged but it adds up over many atoms, about 10^{57} in the sun

There are 3 important stellar masses

mass of the most massive star….the Eddington mass about 100 M_{sun}

mass of the smallest star that burns hydrogen…0.08 M_{sun}

maximum mass of a white dwarf star…the Chandrasekhar mass 1.7 M_{sun}

G is Newton's constant, m_p is the mass of a proton, m_e is the mass of an electron

The lifetime of a star depends mostly on its mass (and composition)

Thermonuclear fuel supply is proportional to hydrogen mass M

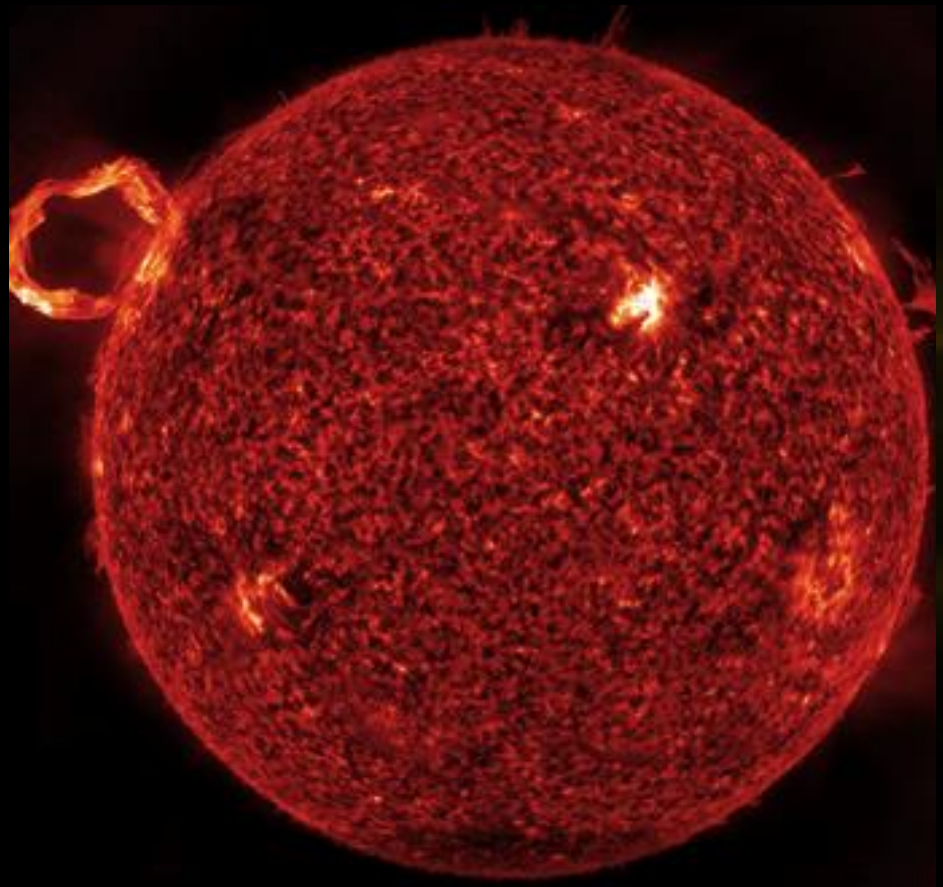
Luminosity is proportional to mass cubed M^3

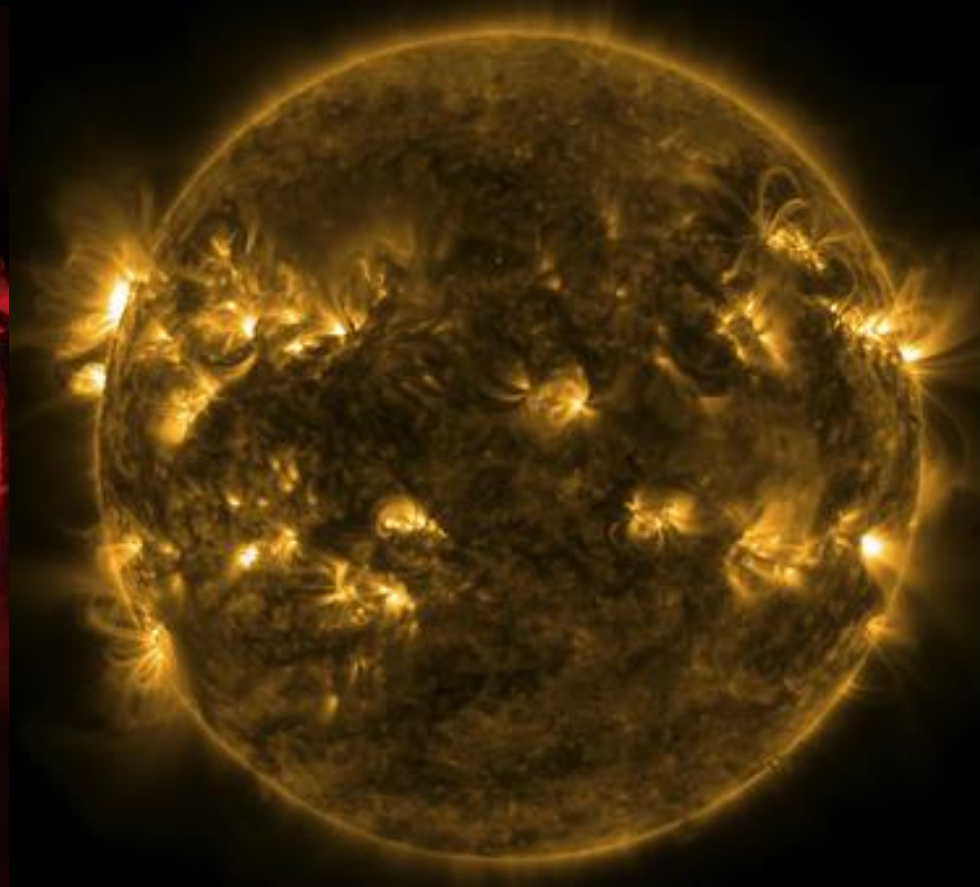
So lifetime of a star is proportional to M/M^3 or M^{-2}

The sun will live for ten billion years…..
but a $100M_{sun}$ star only lives a million years!

10^6 years is a mere instant in the lifetime of the Milky Way, so we should see many dying stars!

The sun



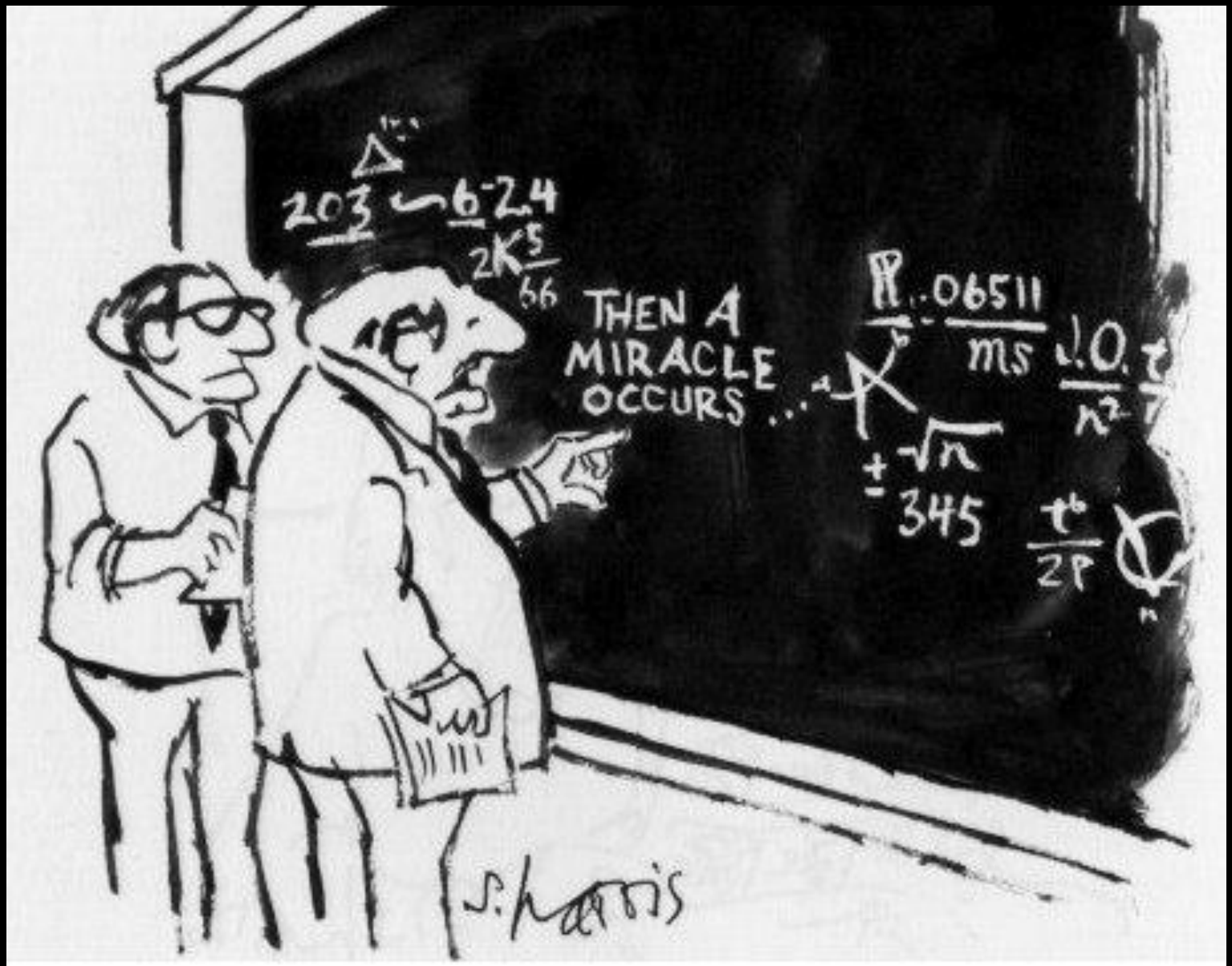


The Sun seen from space

xray

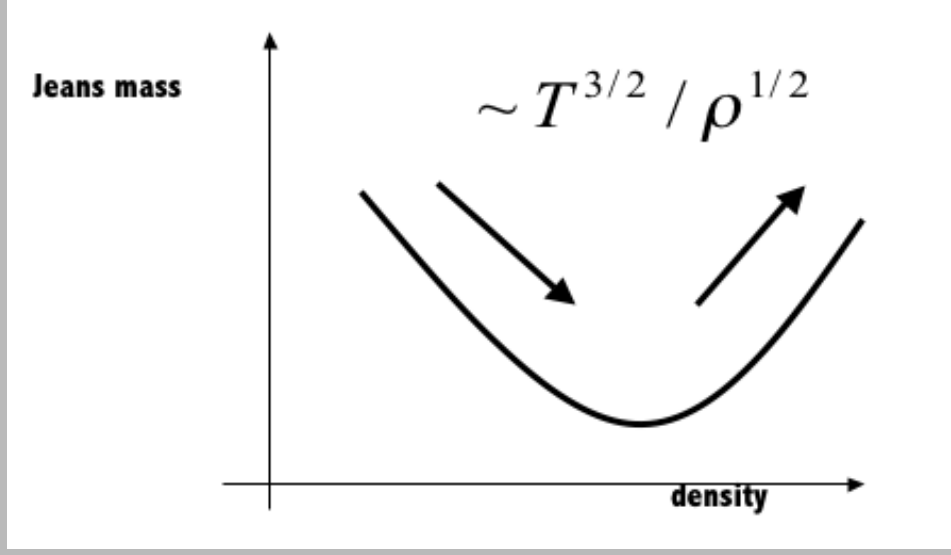
The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.

Georges Lemaitre 1931



"I think you should be more explicit here in step two."

Fragmentation into stars



- Fundamental theory applied to a diffuse interstellar cloud that is collapsing under self-gravity
- Minimum **fragmentation** mass

$$\gg a_g^{-3/2} a m_p \gg 0.01 M_{sun}$$

This is a robust but wrong result!

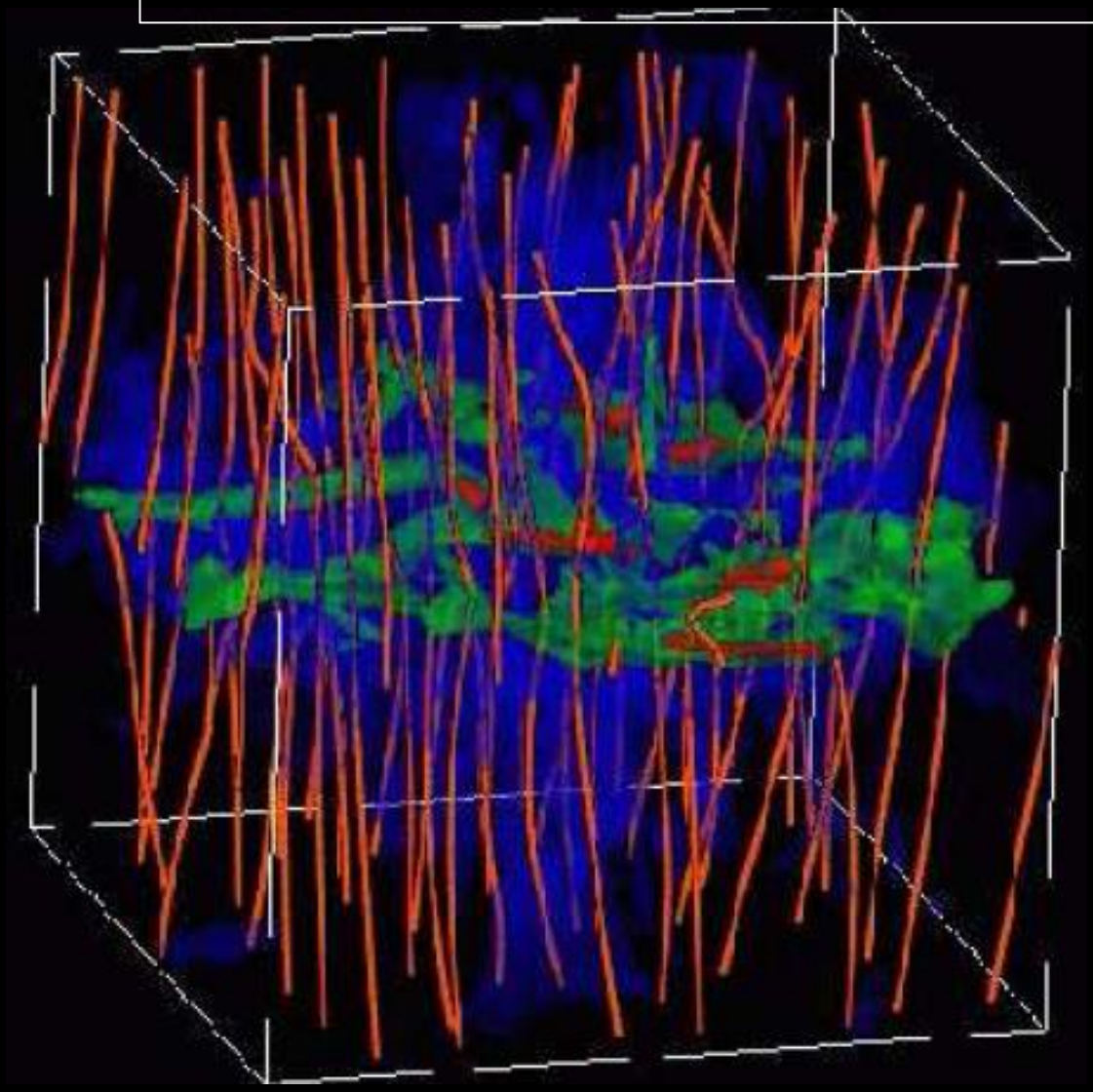
- Resolution: ***fragmentation*** + continuing ***accretion*** of cold gas, halted by ***feedback*** that taps stellar energy via magnetic turbulence

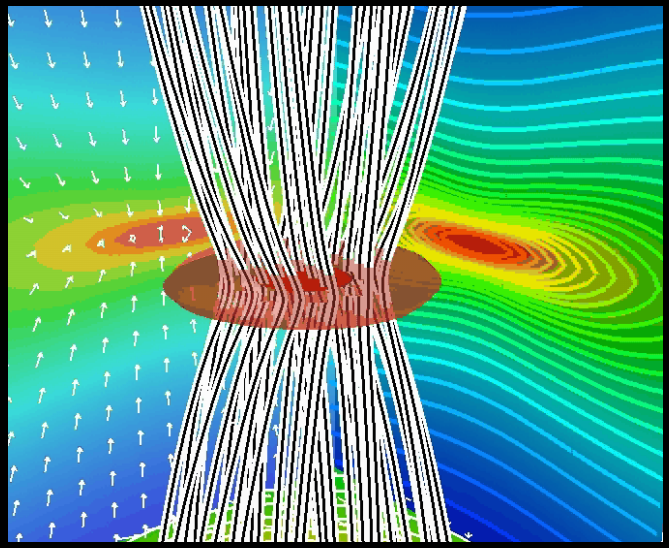
- accretion rate=(sound speed)^3/G and lack of metals means warmer clouds

Þ first stars were massive!

α is the fine-structure constant =1/137 m_p is the mass of a proton $a_g \circ G m_p^2 e^{-2} \gg 3.10^{-37}$

Magnetic fields are everywhere in the universe.
They control the rate at which stars form today





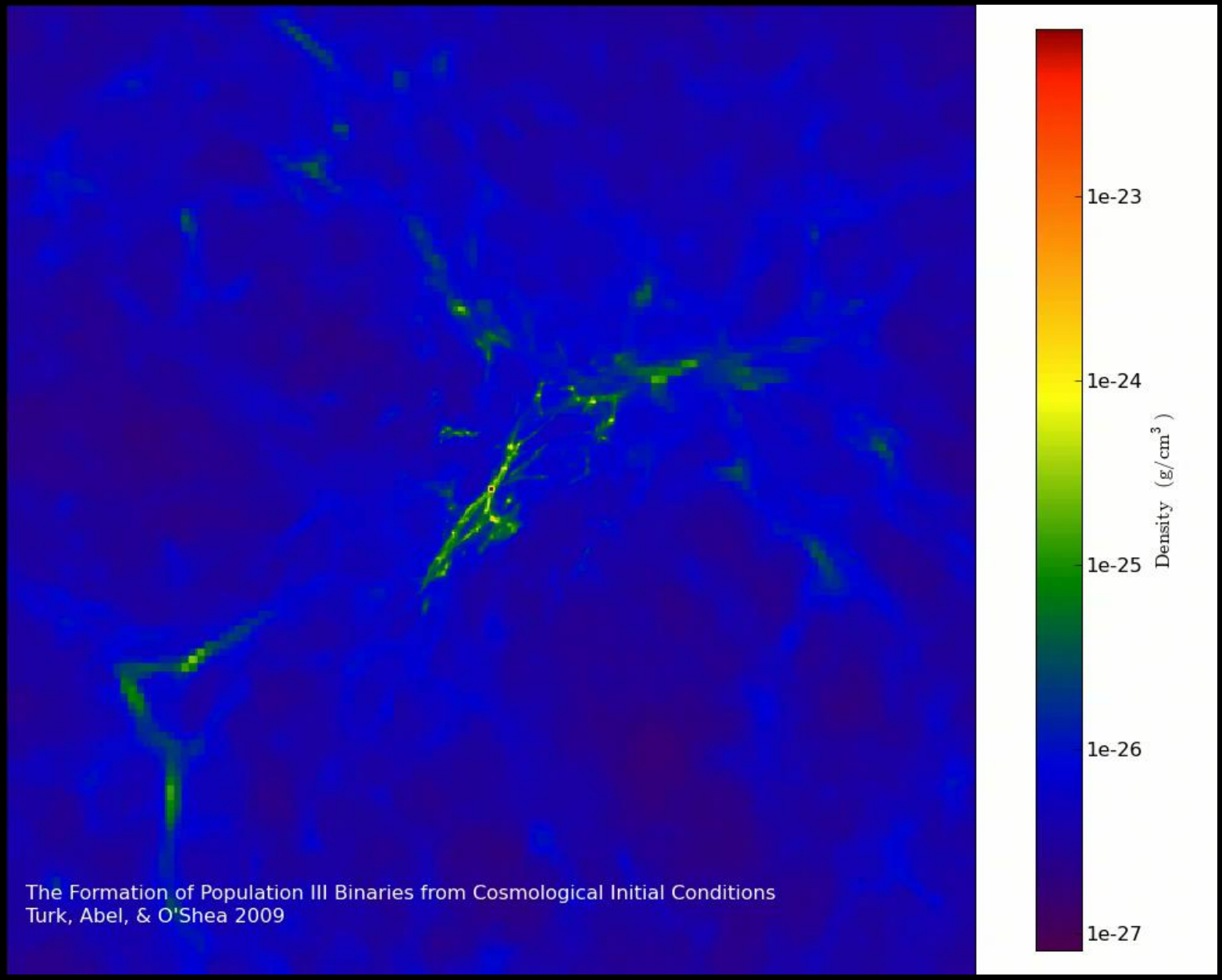
Li & Nakamura 2008

Dust is everywhere in the universe

Numerical simulation of first star formation

- Just gas cooling by hydrogen molecules
- No dust

The first stars: fragmentation

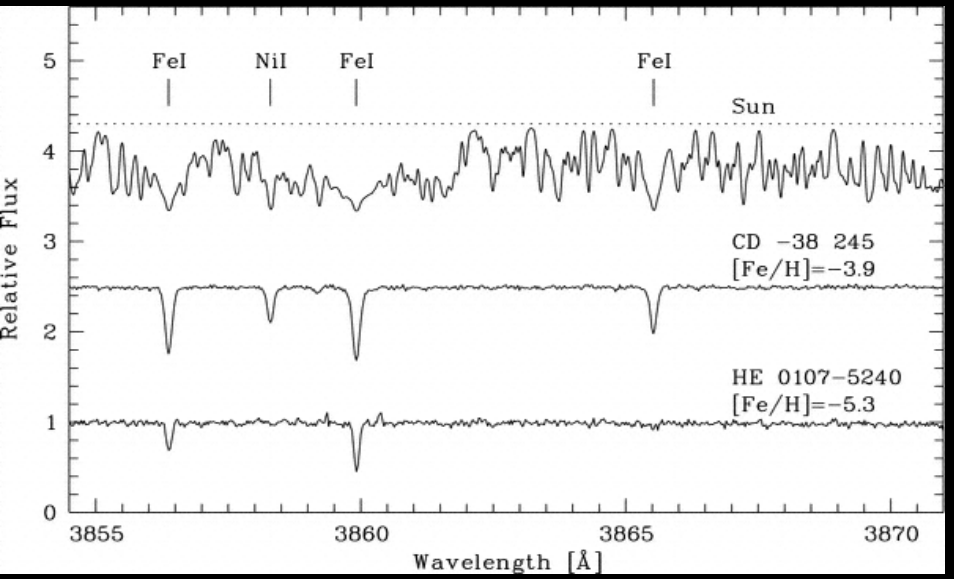


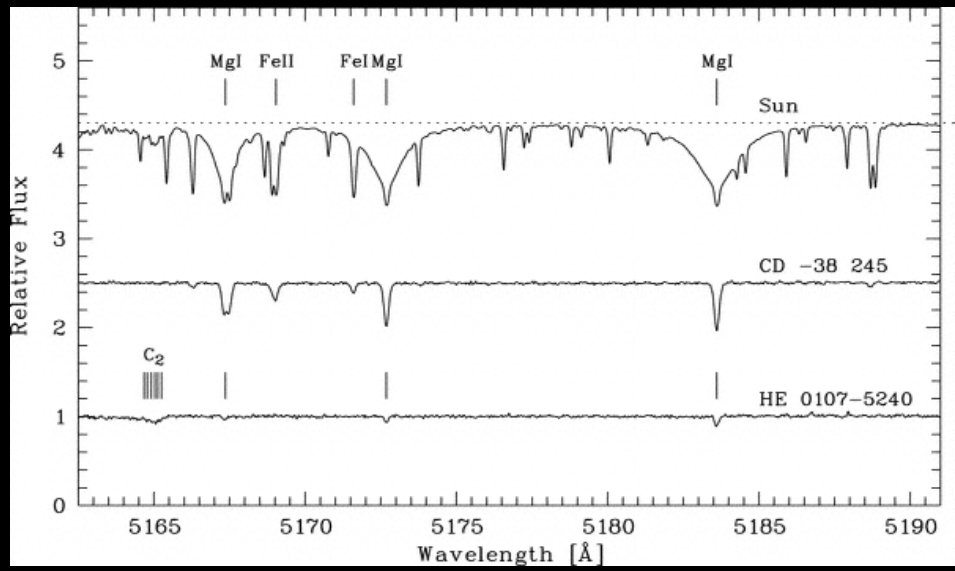
How to find traces of the first stars

- First stars were massive and short-lived
- But their enriched debris polluted interstellar clouds
- The next generation of stars included many less massive survivors

The first stars are very metal poor

The third most iron-poor star in the Galaxy

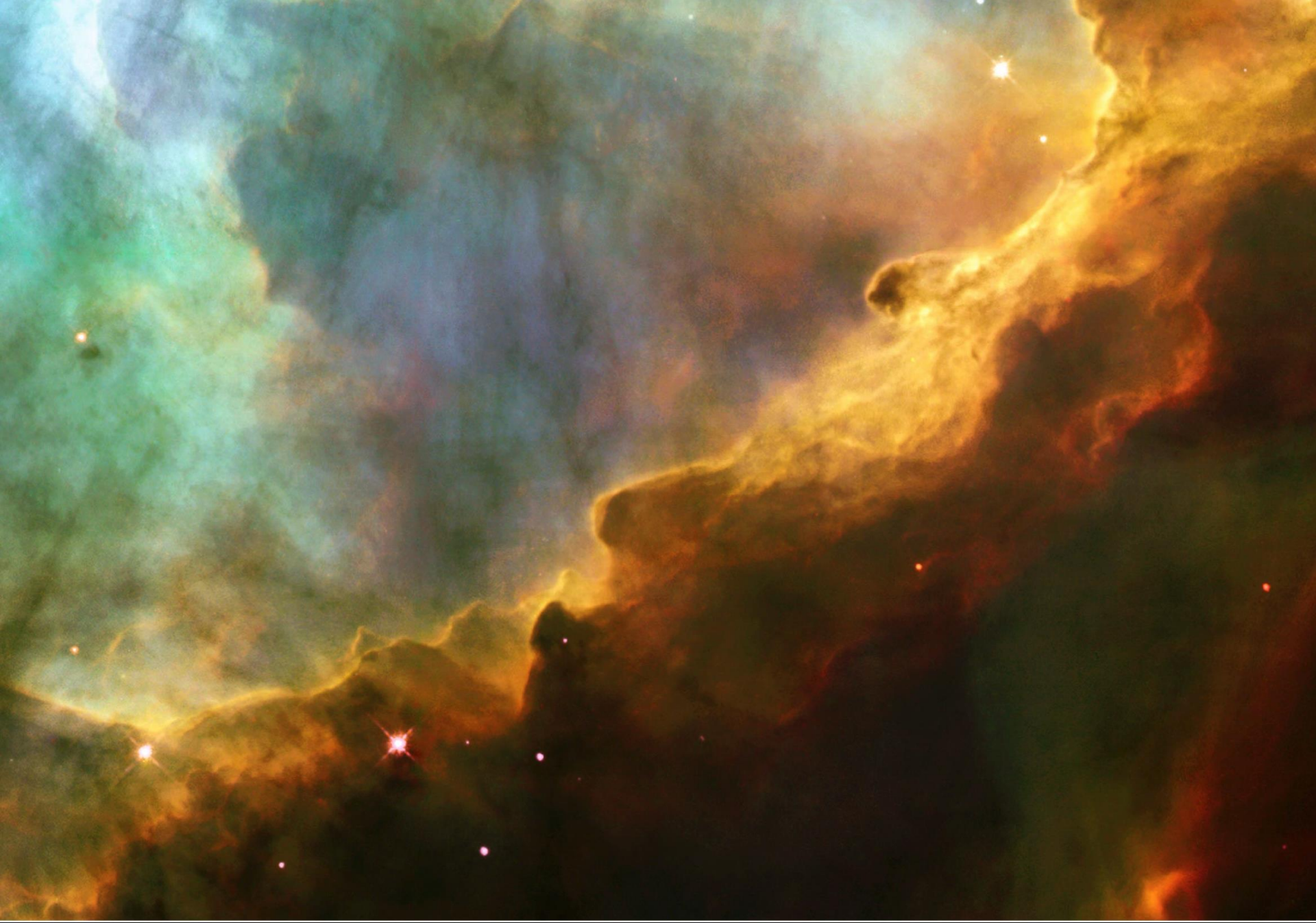




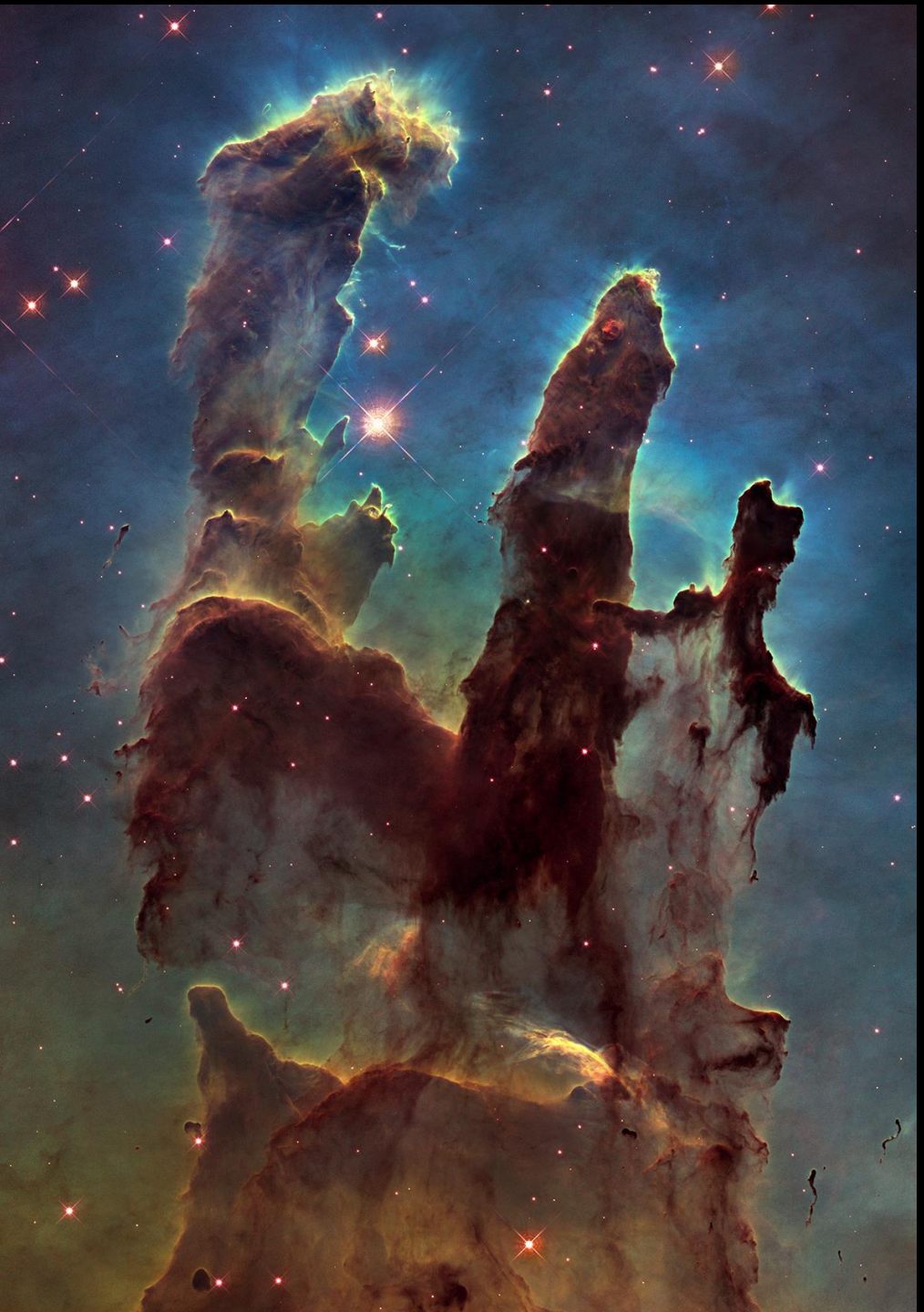
a fossil from the first star population

Christlieb et al. (2004)

STELLAR WOMB



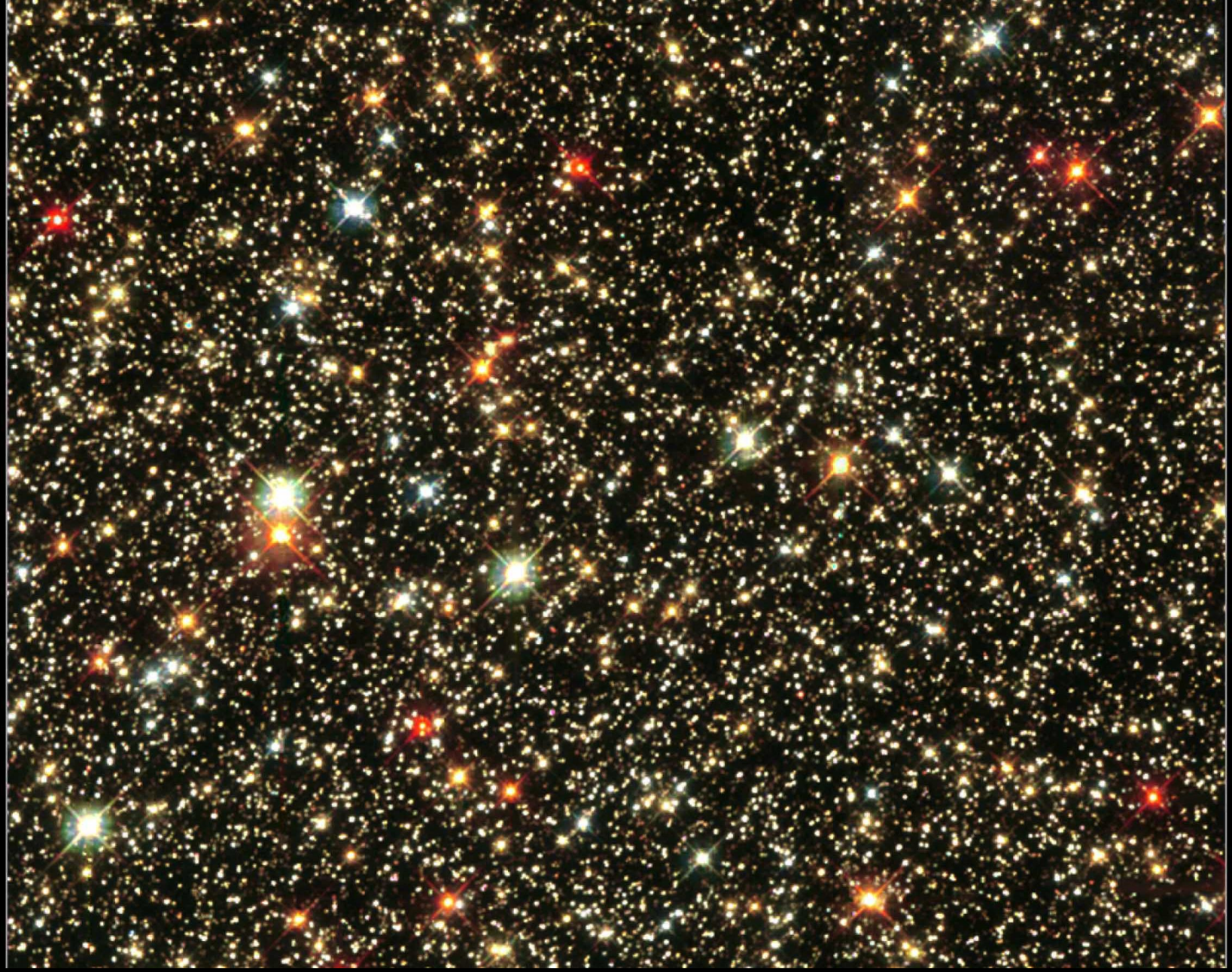
STELLAR BIRTH



STELLAR YOUTH

30 Doradus in the Large Magellanic Cloud

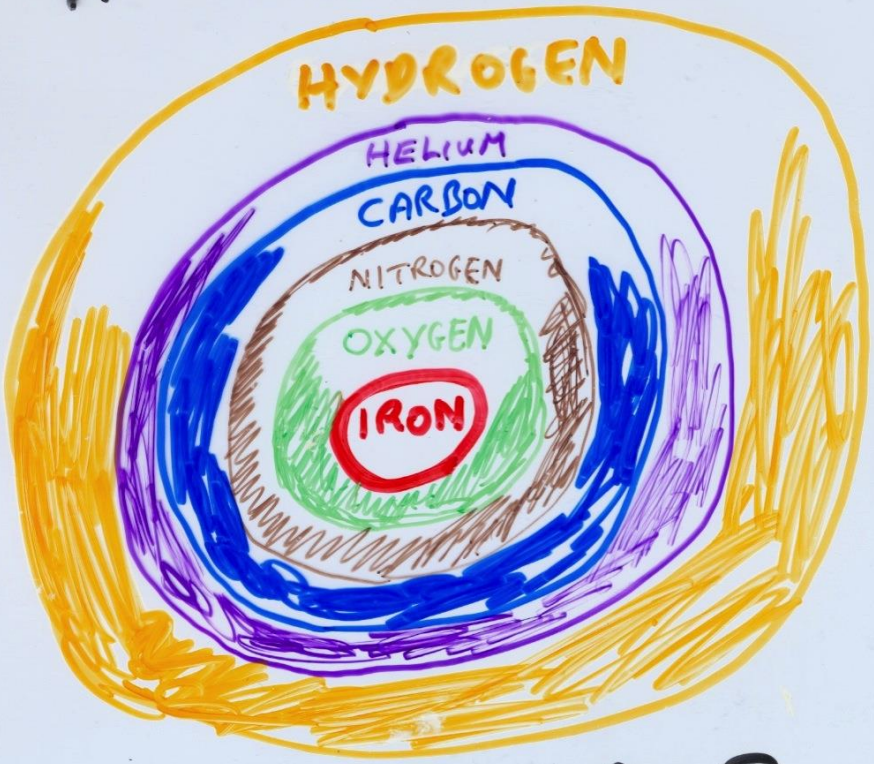
STELLAR MATURITY




Many stars are not alone

STELLAR DEATH

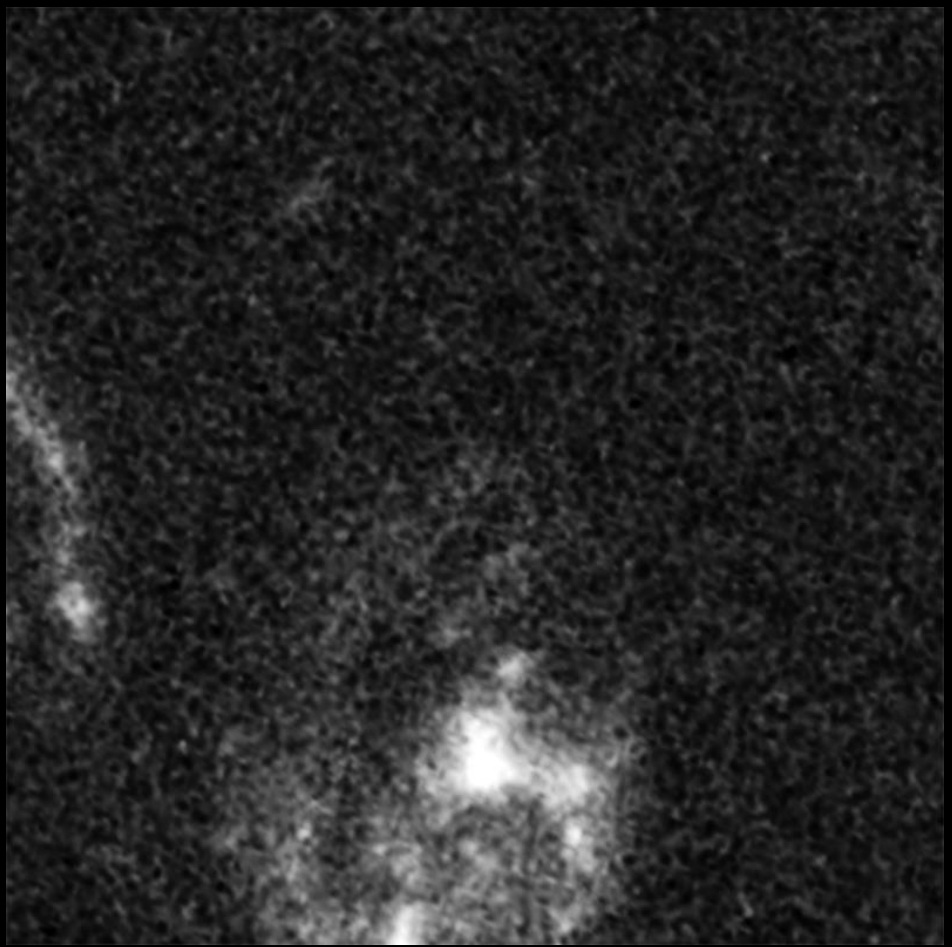
A MASSIVE STAR EVOLVES



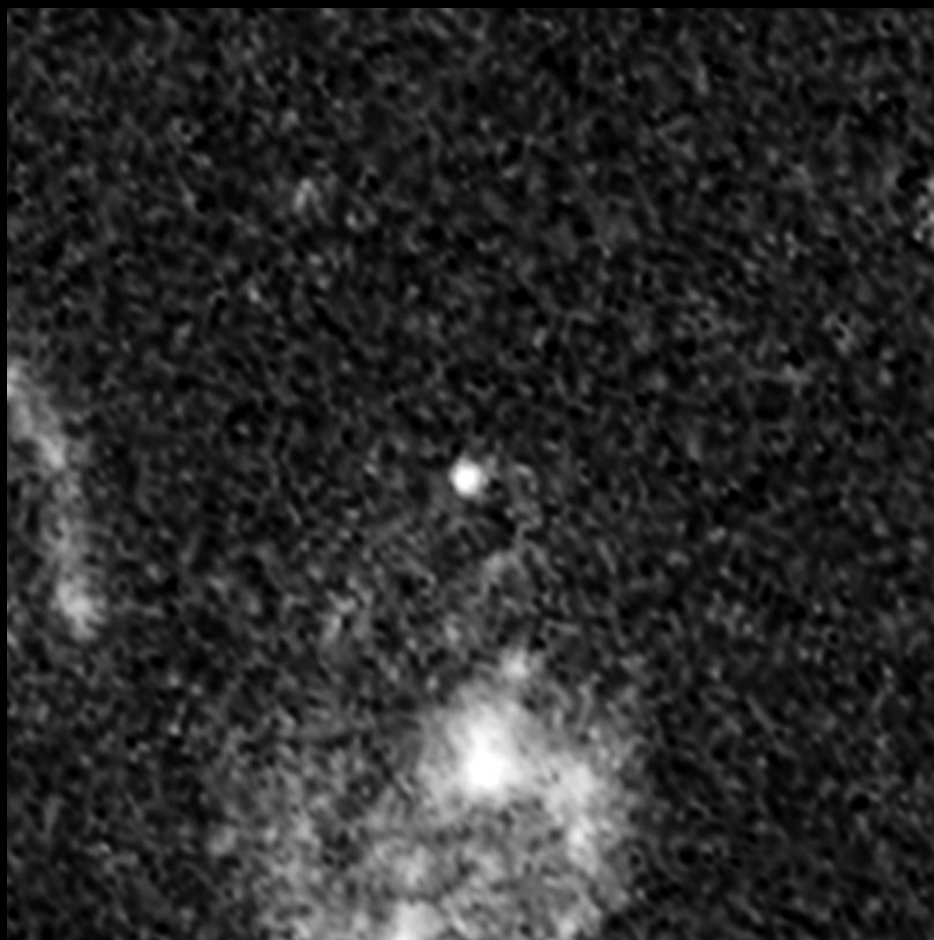
AND EXPLODES

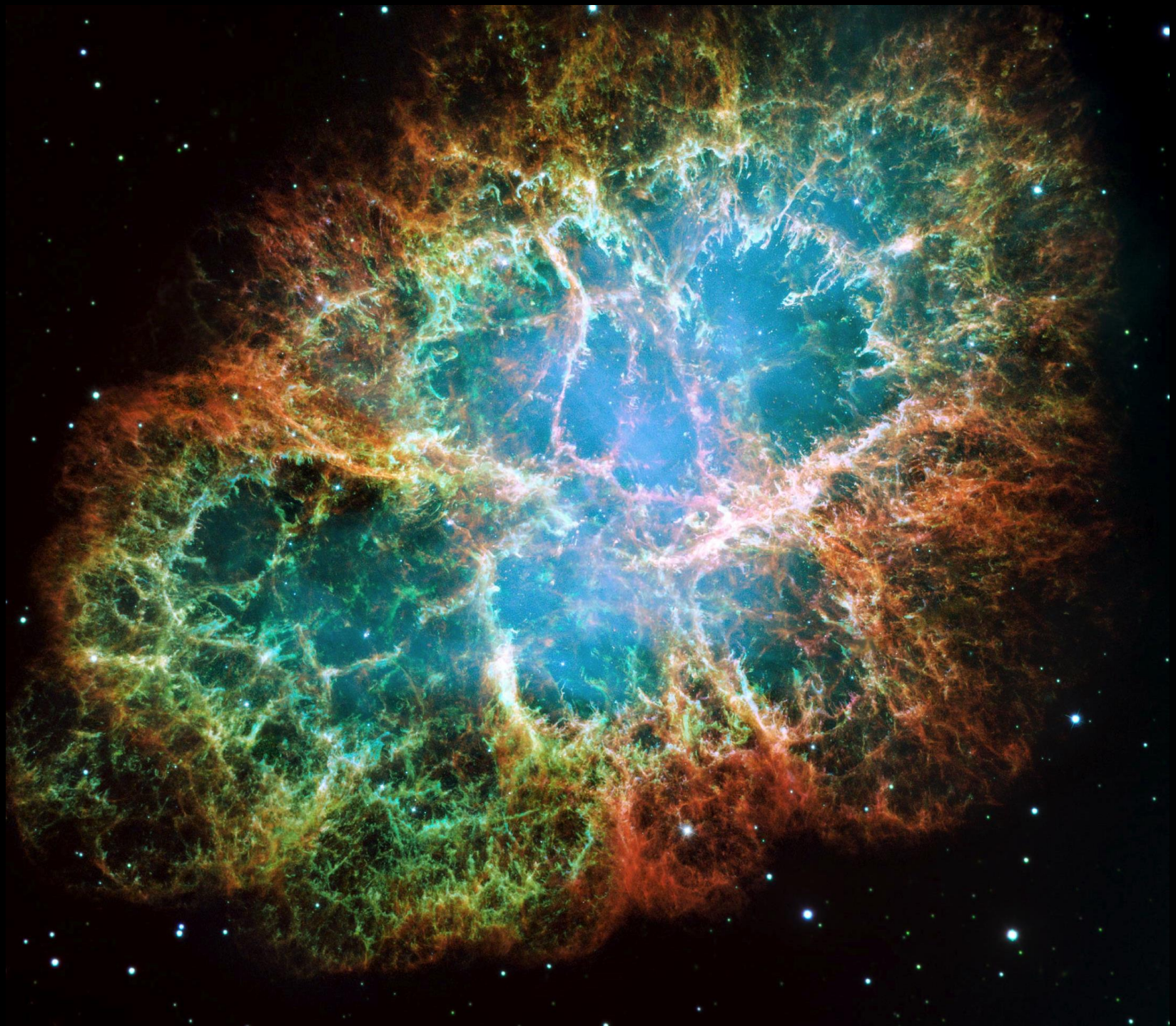
FROM ITS ASHES OUR SOLAR SYSTEM FORMED

Before



After

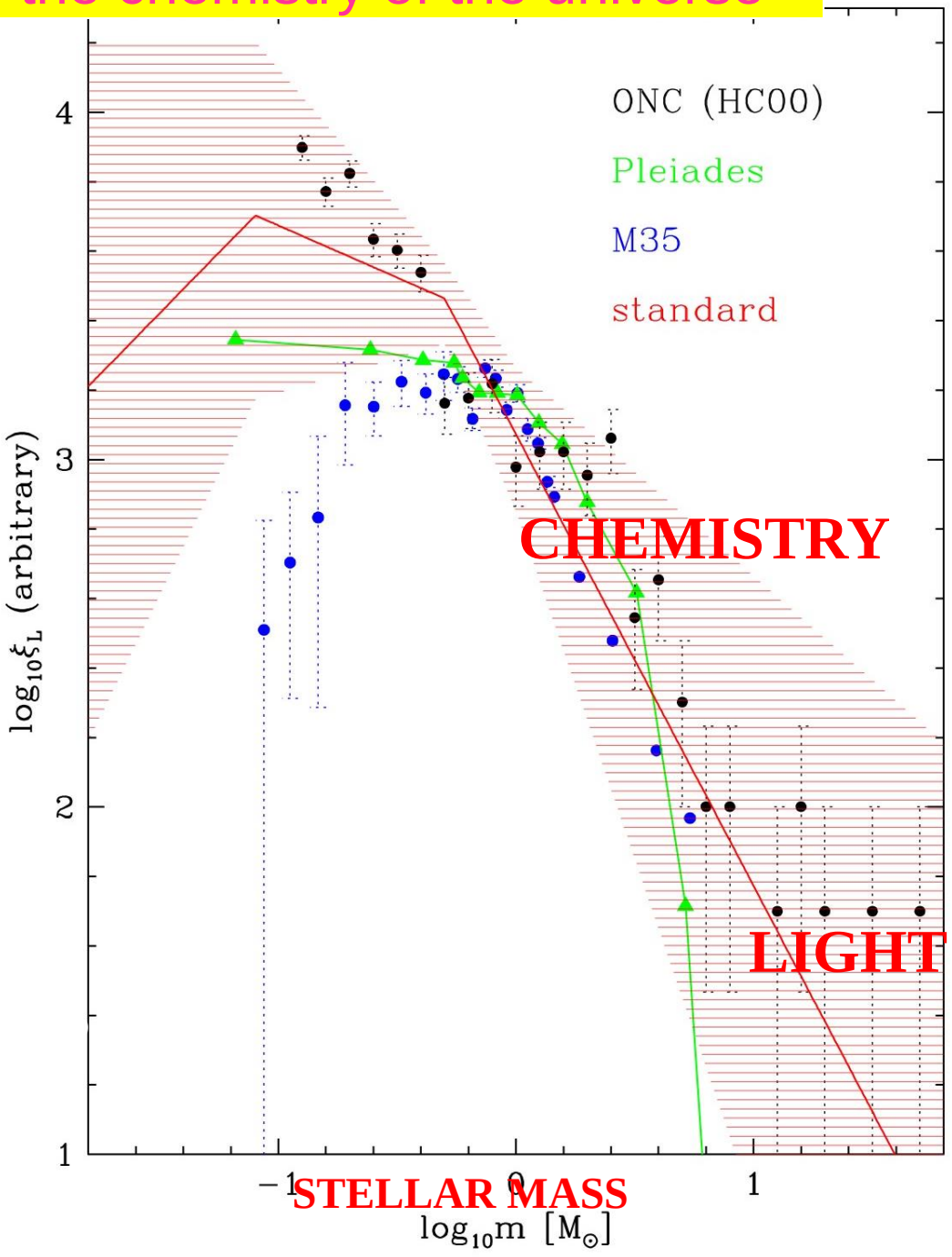




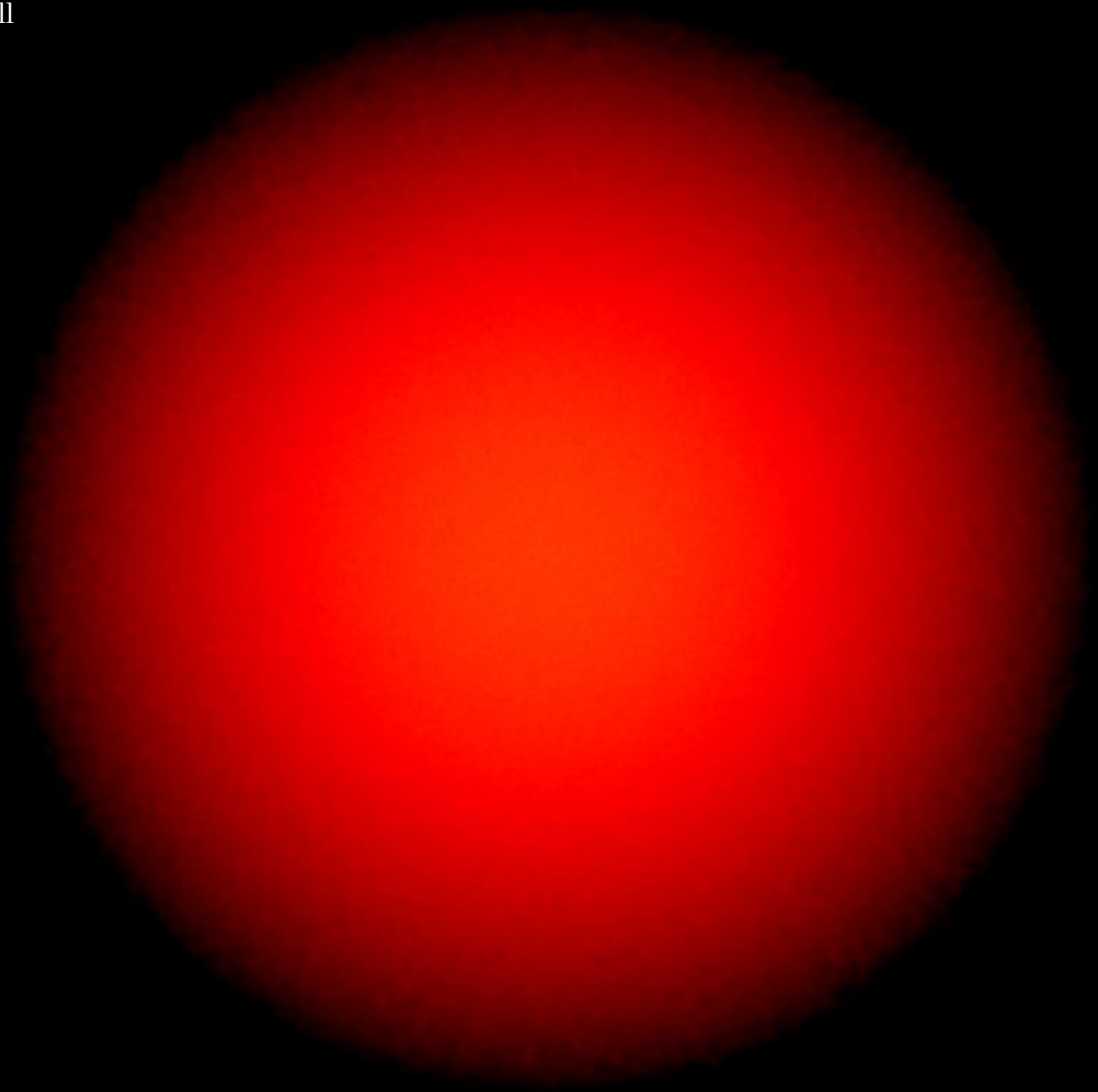
supernova remnant

Star deaths create the chemistry of the universe

Mass distrbution
of newly born stars



I. Bonnell



Have we directly detected POPULATION III?

POP I is the MW disk: young stars

POP II is the MW halo: old stars

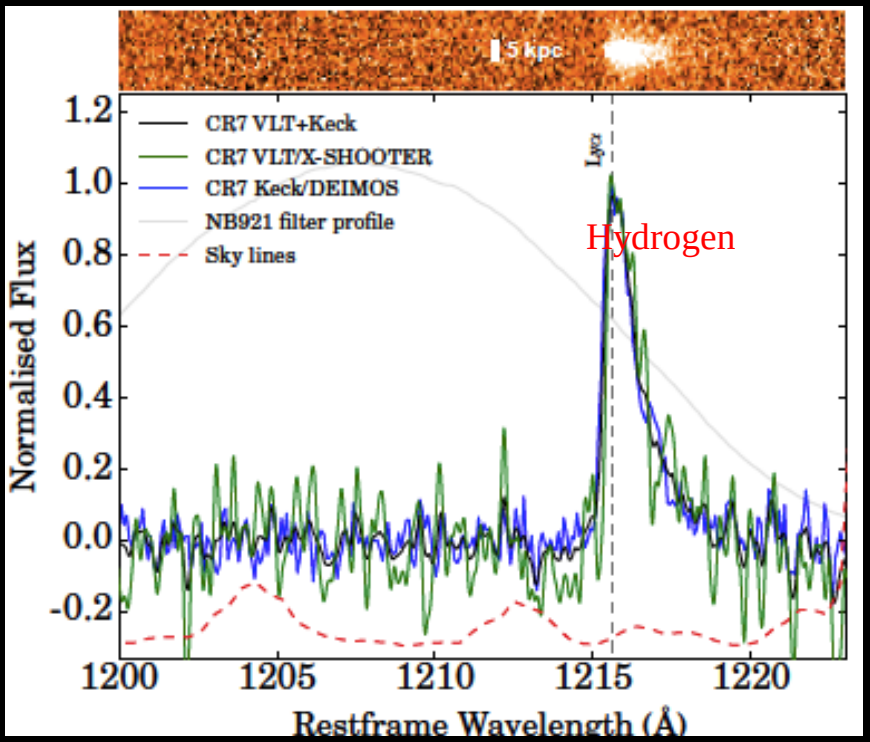
POP III is the hypothetical population of the first stars

Milky Way look-alikes

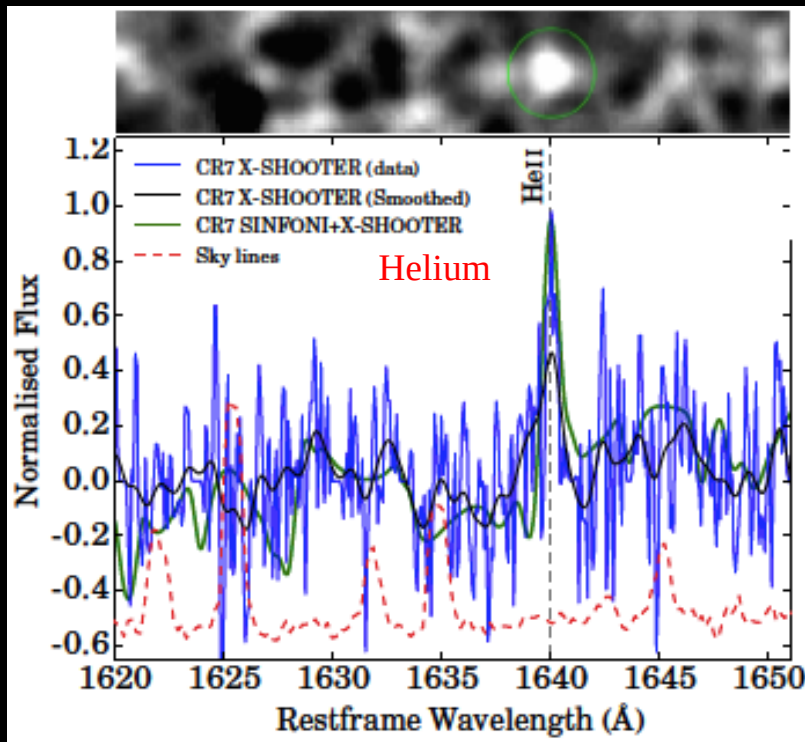
Have we detected the real POPULATION III?

- POP I is the MW disk
- POPII is the MW halo
- POPIII is the population of the first stars
- The only example so far is at redshift 6.6: CR7

strong in hydrogen and helium emission, no metals



Sobral 2015



The first stars

- They are massive & long gone but their polluted environment survives
- Interstellar clouds contaminated by metals form long-lived low mass stars
- We recognise these as being the lowest metallicity stars in our galaxy
- Their abundance patterns trace the masses of the first stars: they are fossils
- We may be already seeing them far far away