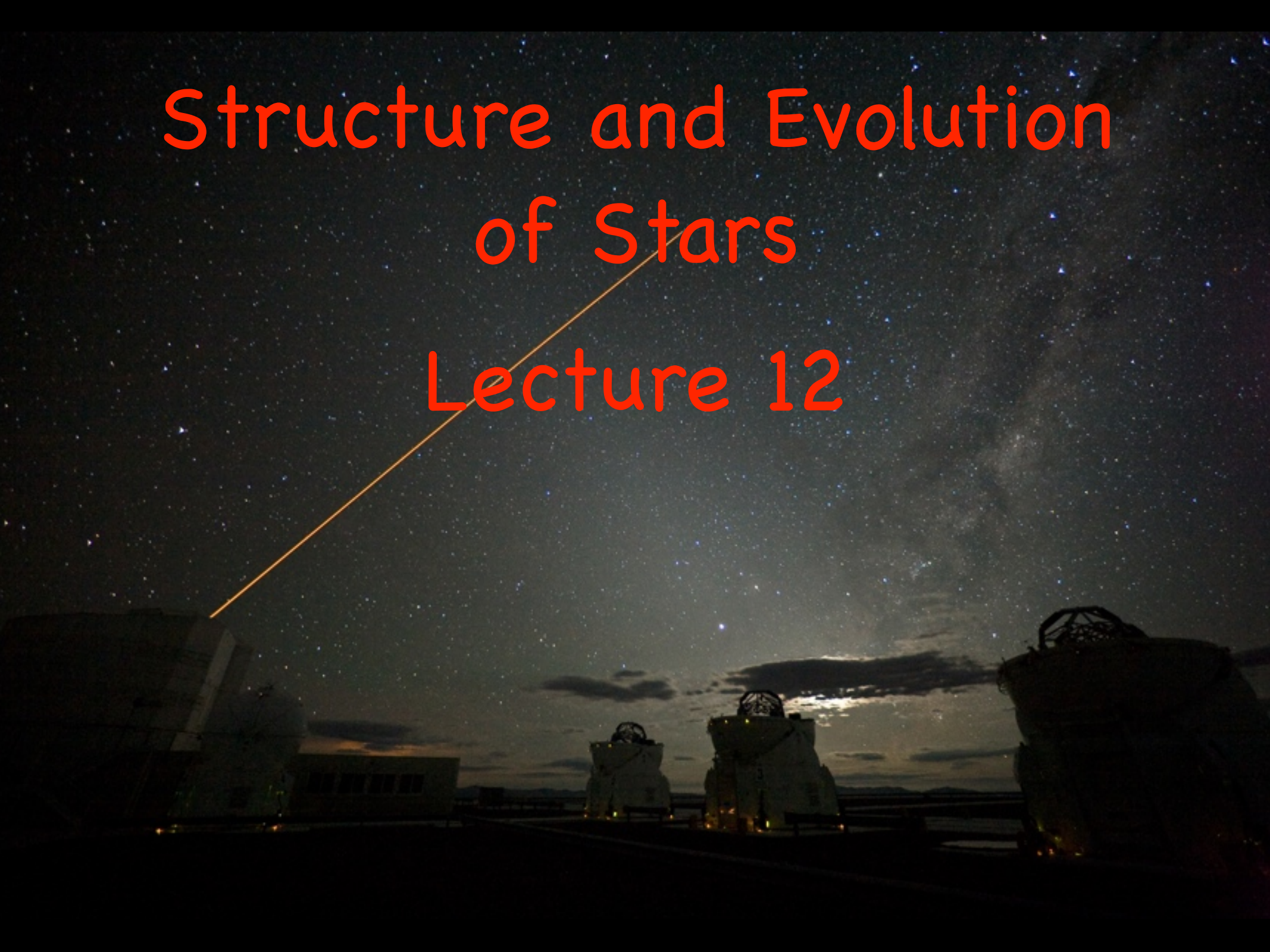
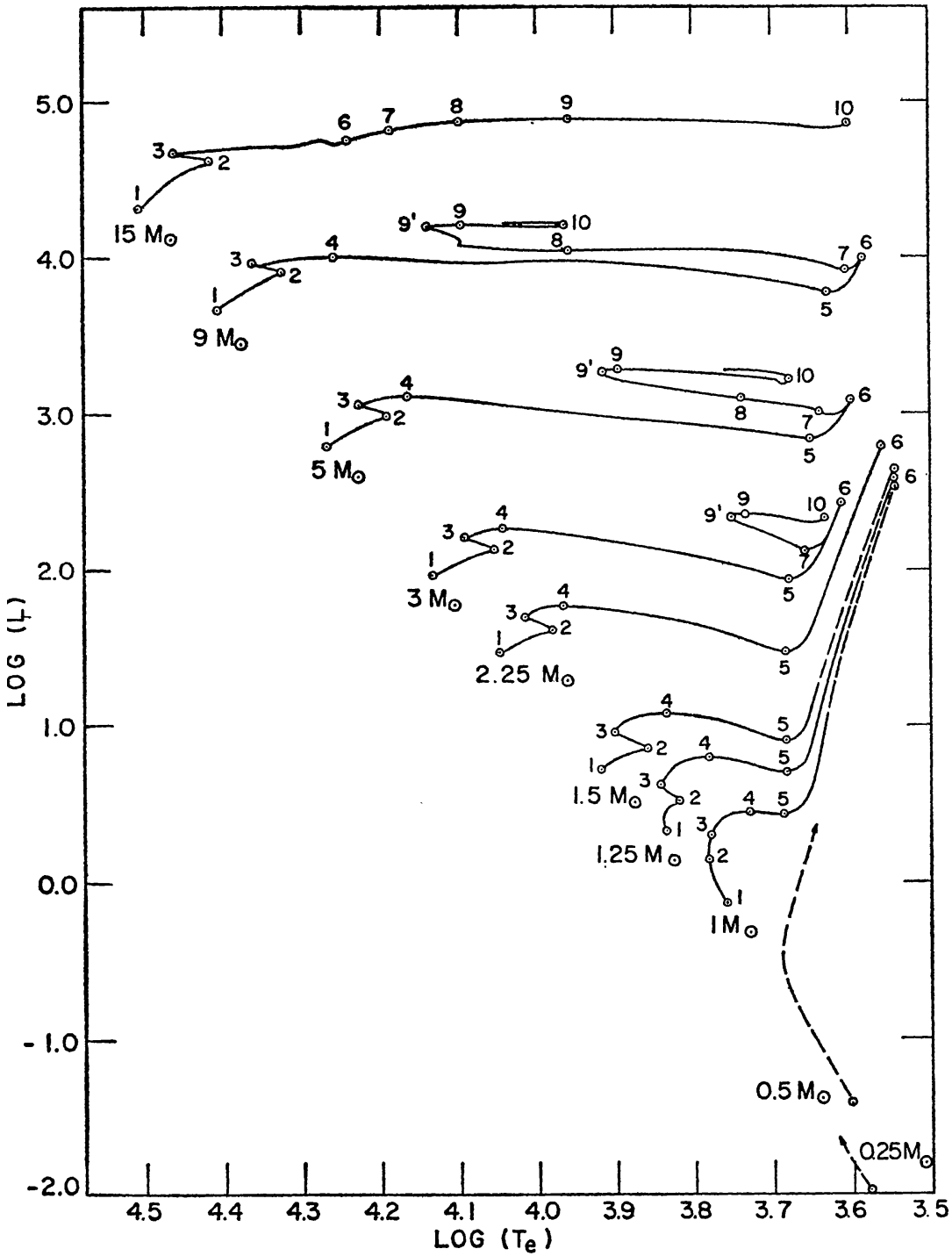
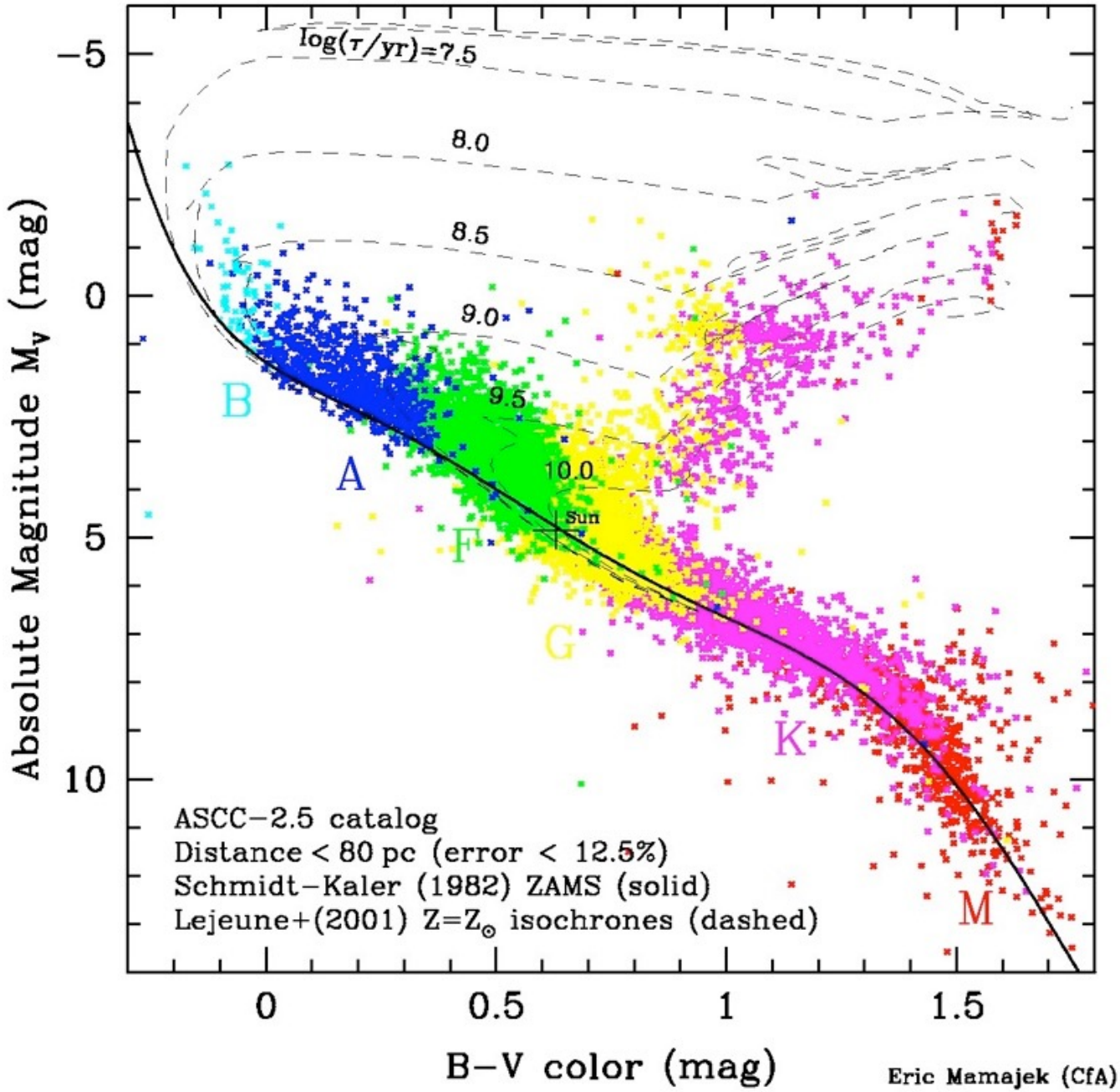
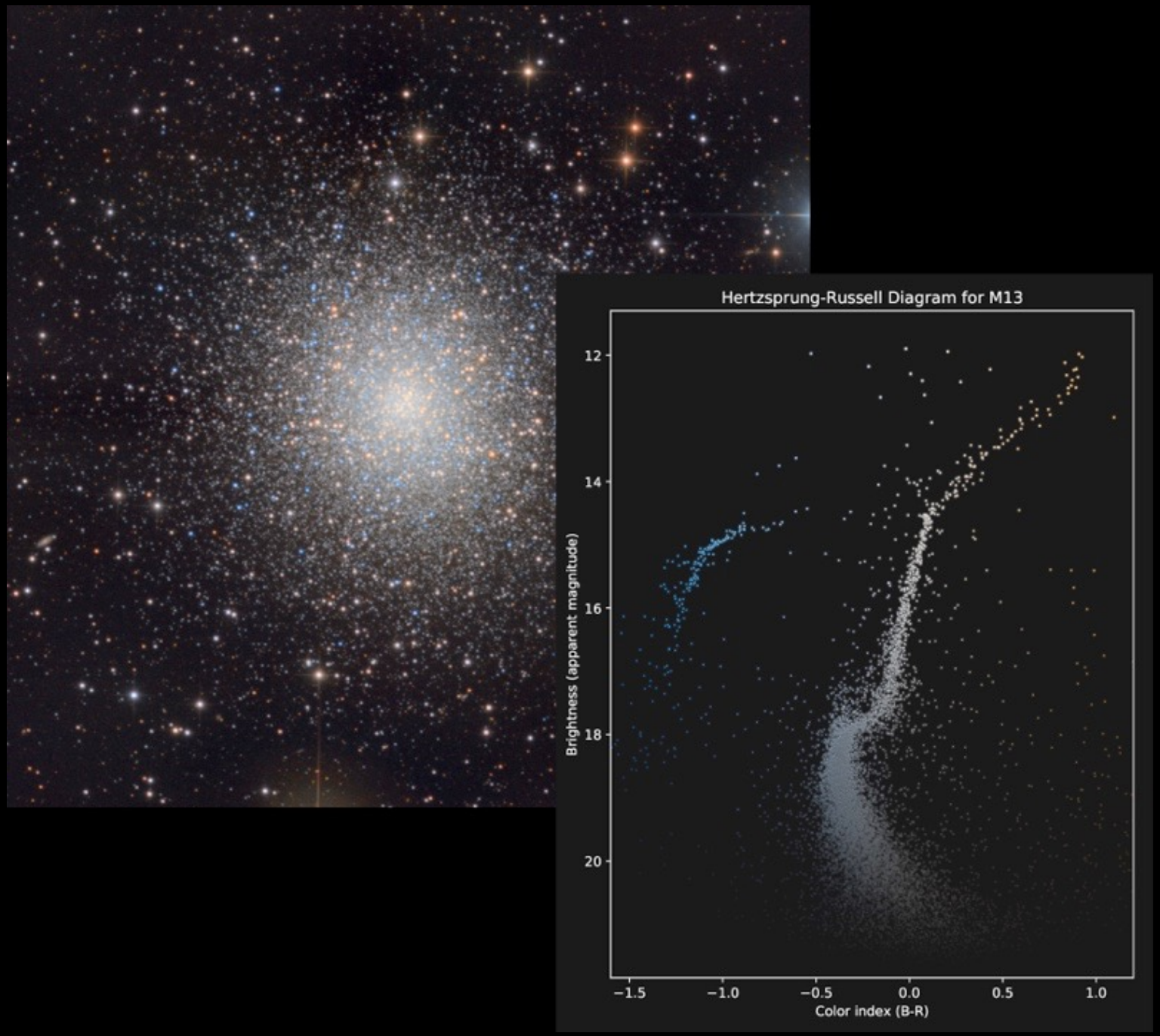
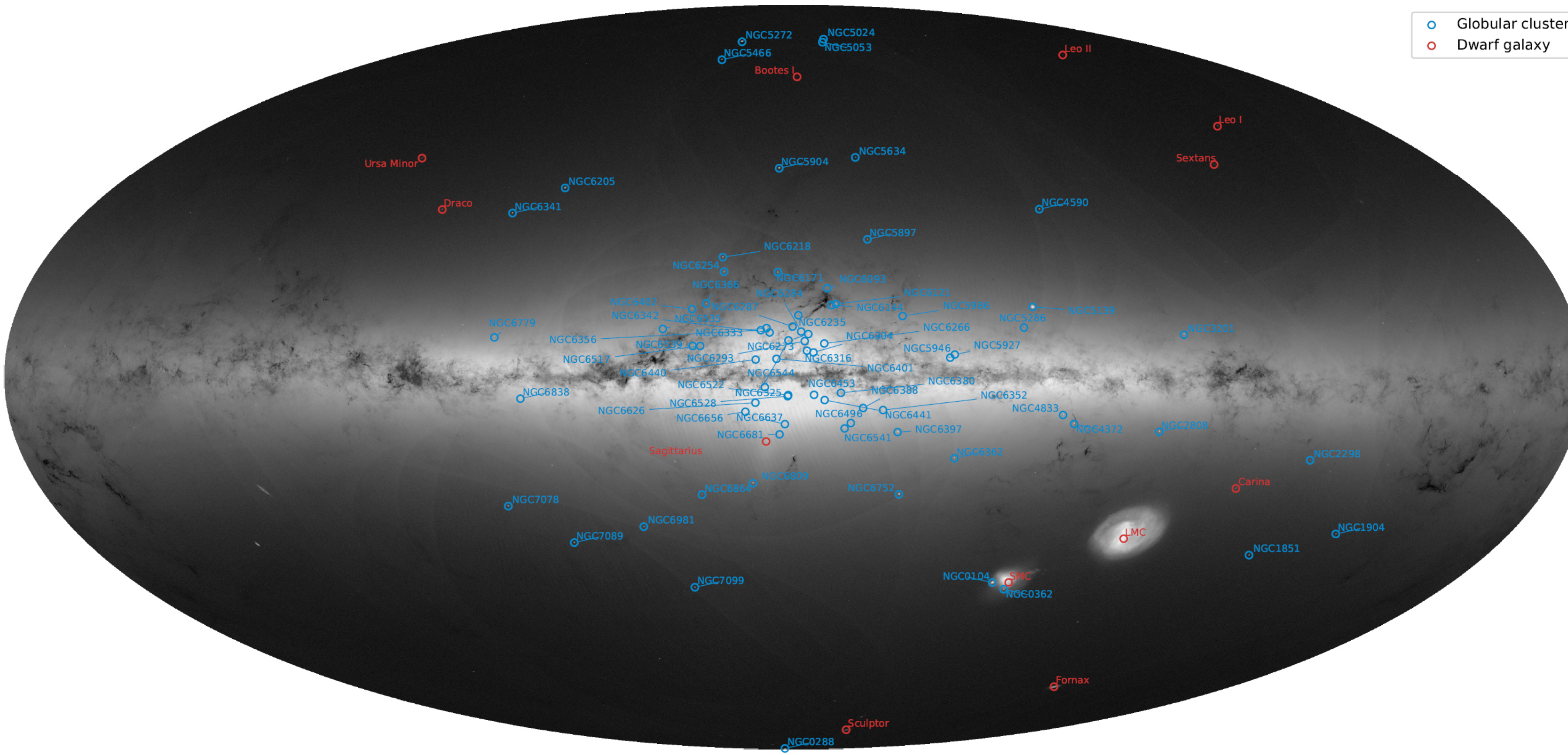

Structure and Evolution
of Stars
Lecture 12


LOG (L)
LOG (Te)
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
-2.0
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
15 M⊙
9 M⊙
5 M⊙
3 M⊙
2.25 M⊙
1.5 M⊙
1.25 M⊙
1 M⊙
0.5 M⊙
0.25M⊙

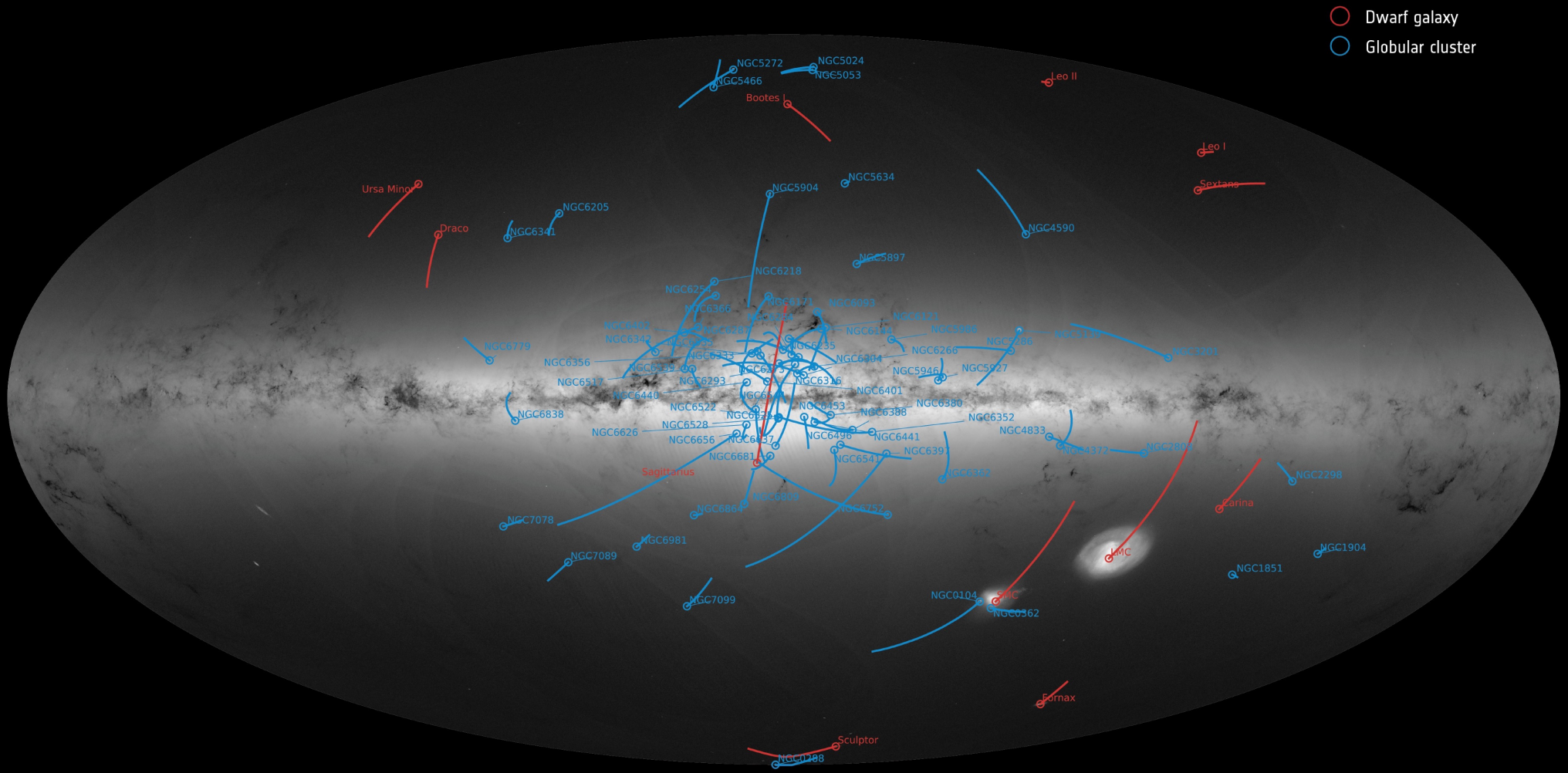
Iben 1967


log(τ/yr)=7.5
8.0
8.5
9.0
9.5
10.0
Sun
B
A
F
G
K
M
ASCC−2.5 catalog
Distance < 80 pc (error < 12.5%)
Schmidt−Kaler (1982) ZAMS (solid)
Lejeune+(2001) Z=Z⊙ isochrones (dashed)
Absolute Magnitude M_V (mag)
B−V color (mag)
−5
0
5
10
0
0.5
1
1.5
Eric Mamajek (CfA)


Hertzsprung-Russell Diagram for M13
Brightness (apparent magnitude)
12
14
16
18
20
−1.5
−1.0
−0.5
0.0
0.5
1.0
Color index (B-R)

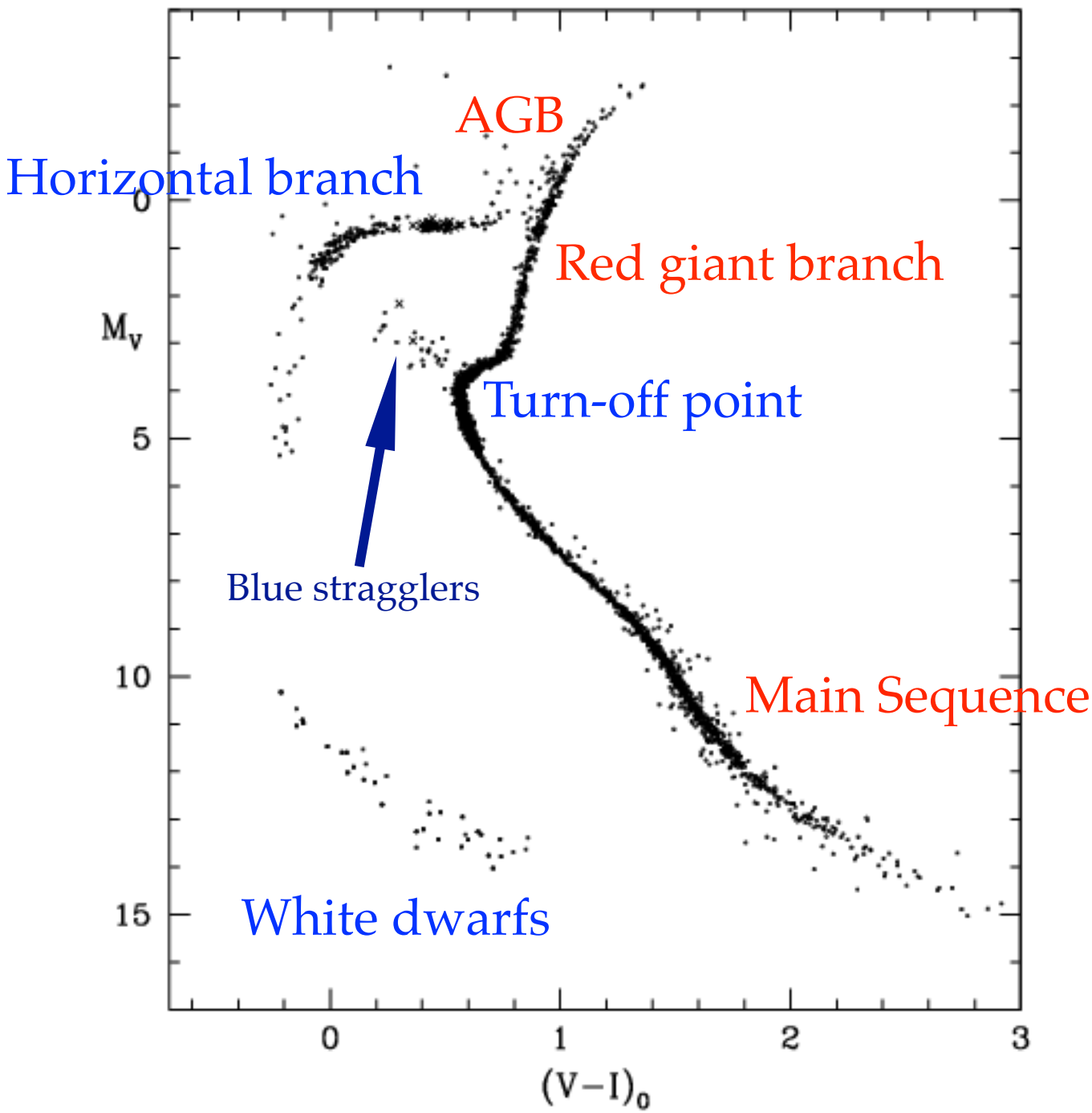

Globular cluster
Dwarf galaxy
NGC5272
NGC5024
NGC5053
NGC5466
Bootes I
Leo II
Leo I
Sextans
Ursa Minor
Draco
NGC5904
NGC5634
NGC6205
NGC6341
NGC4590
NGC5897
NGC6218
NGC6254
NGC6366
NGC6171
NGC6093
NGC6779
NGC6342
NGC6356
NGC6333
NGC6235
NGC6266
NGC6304
NGC5946
NGC5927
NGC5286
NGC3201
NGC6517
NGC6293
NGC6273
NGC6316
NGC6401
NGC6440
NGC6544
NGC6522
NGC6380
NGC6388
NGC6352
NGC6838
NGC6528
NGC6626
NGC6656
NGC6637
NGC6441
NGC6496
NGC4833
NGC4372
NGC2808
NGC6397
NGC6541
NGC6681
Sagittarius
NGC6362
NGC2298
NGC6809
NGC6864
NGC6752
Carina
NGC7078
NGC6981
NGC7089
LMC
NGC1904
NGC1851
NGC0104
SMC
NGC0362
NGC7099
Fornax
Sculptor
NGC0288

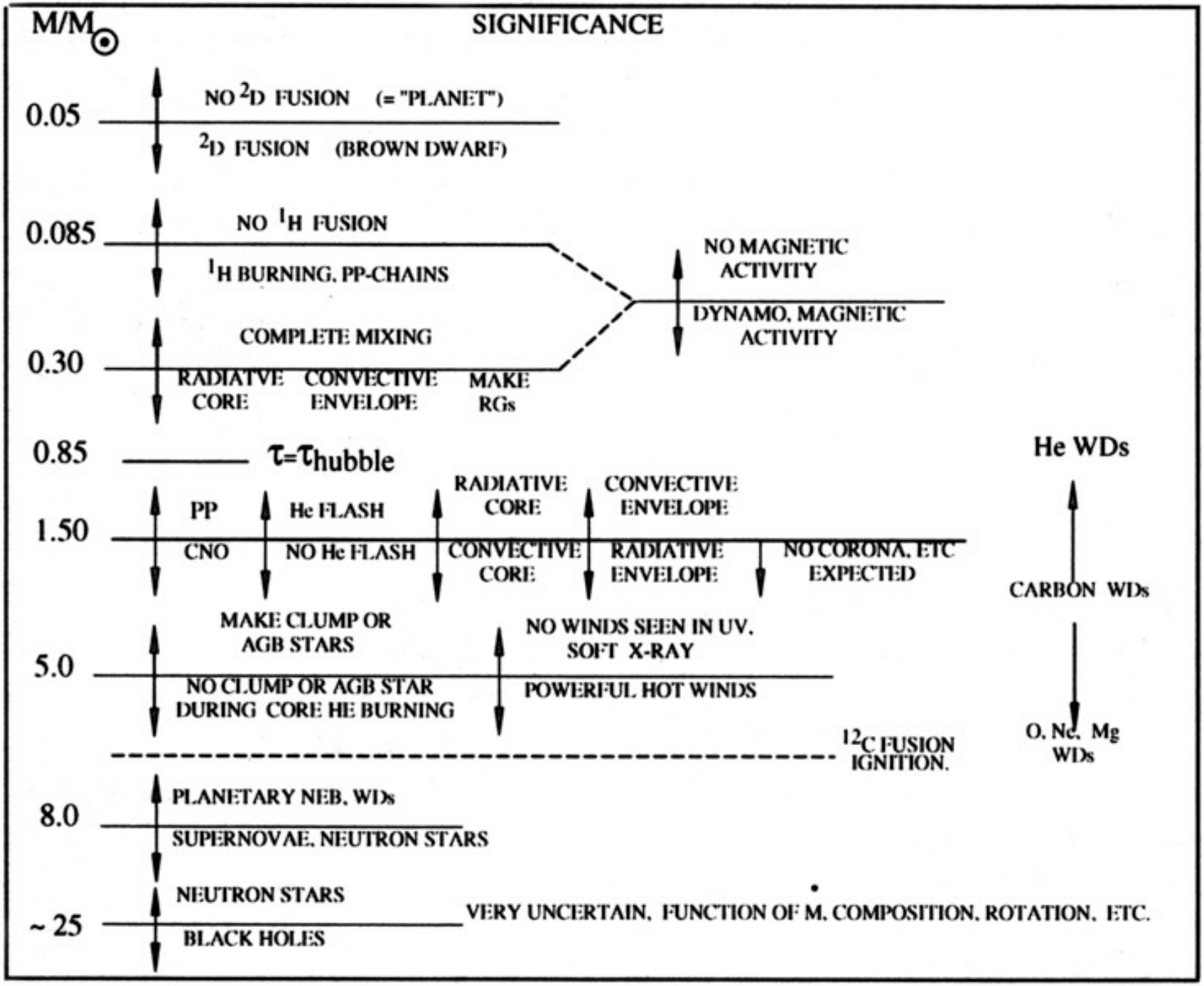
→ GAIA'S GLOBULAR CLUSTERS AND DWARF GALAXIES

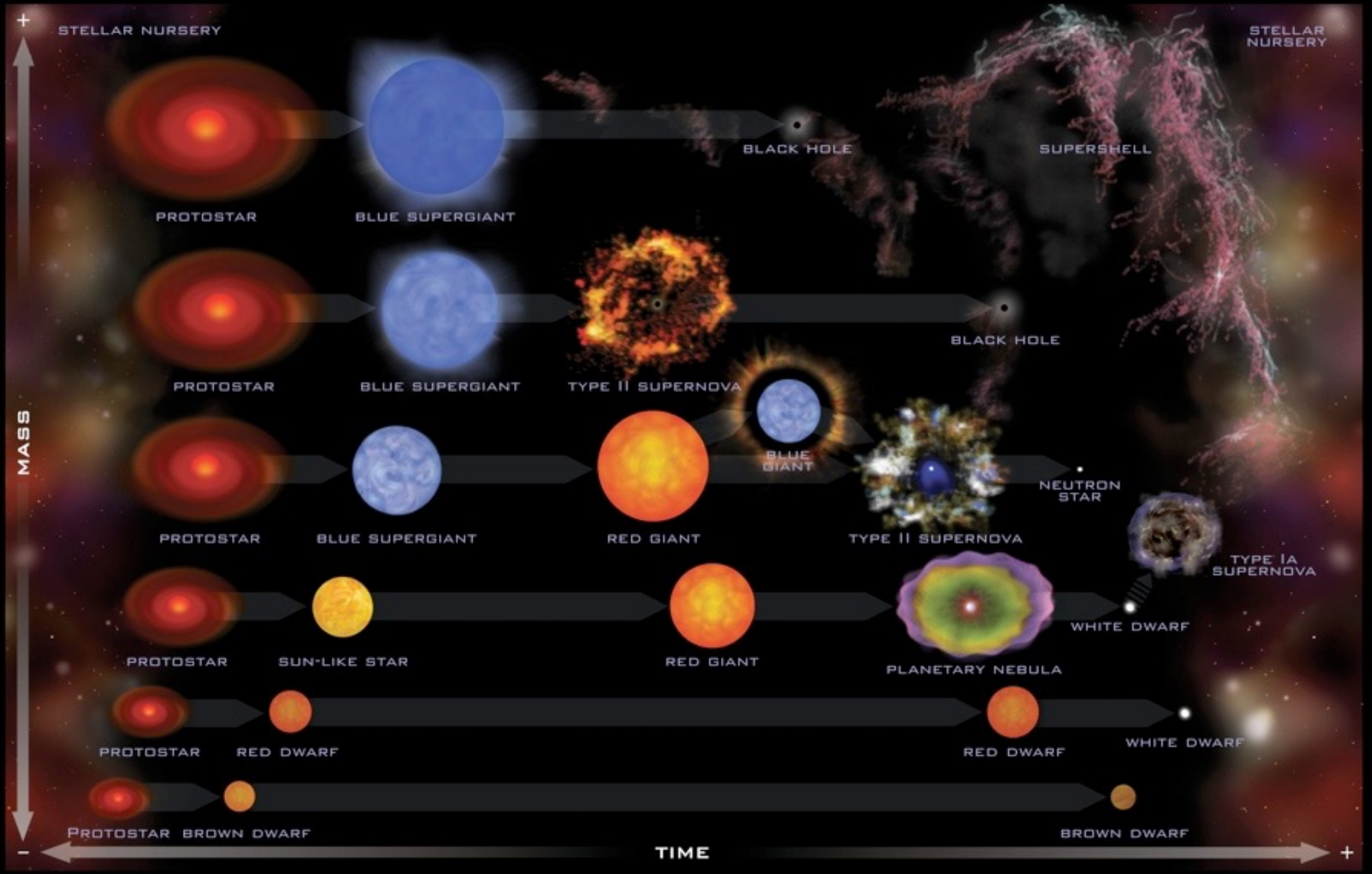


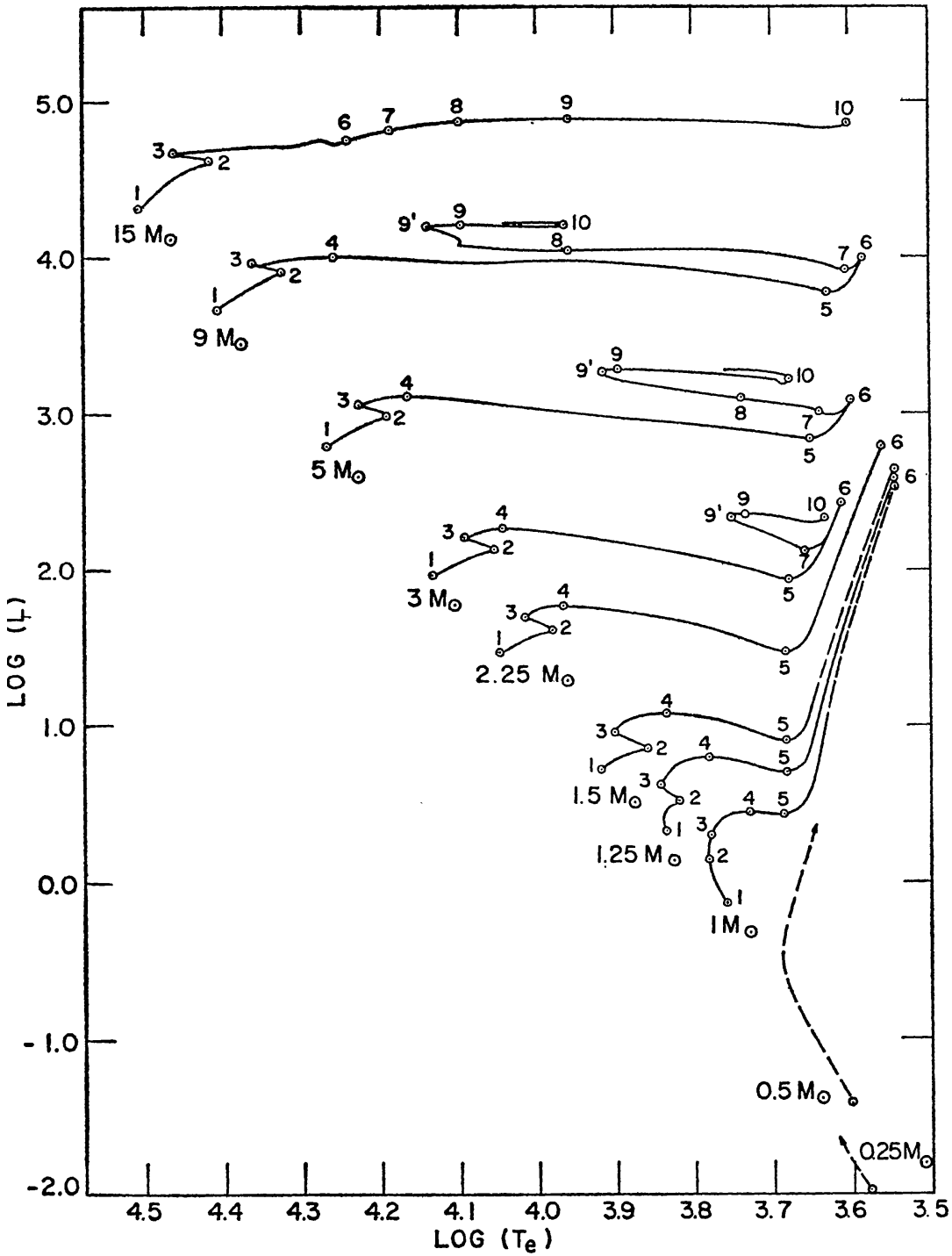
Credit: ESA/Gaia/DPAC

HR diagram of a typical globular cluster



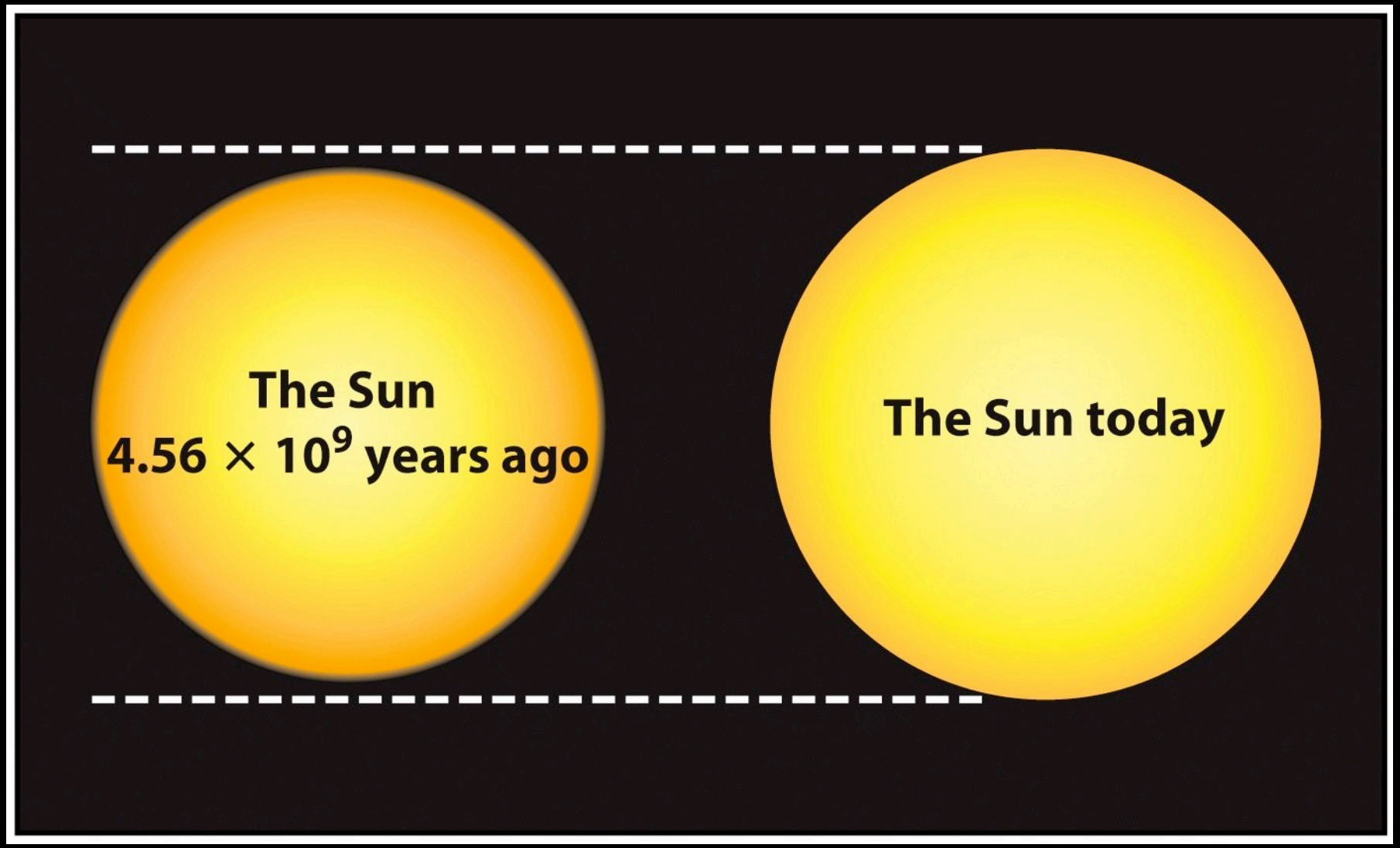

M/M⊙
SIGNIFICANCE
0.05
NO 2D FUSION (= "PLANET")
2D FUSION (BROWN DWARF)
0.085
NO 1H FUSION
1H BURNING, PP-CHAINS
0.30
COMPLETE MIXING
RADIATVE CORE
CONVECTIVE ENVELOPE
MAKE RGs
NO MAGNETIC ACTIVITY
DYNAMO, MAGNETIC ACTIVITY
0.85
τ=τhubble
He WDs
1.50
PP
CNO
He FLASH
NO He FLASH
RADIATIVE CORE
CONVECTIVE CORE
CONVECTIVE ENVELOPE
RADIATIVE ENVELOPE
NO CORONA, ETC EXPECTED
CARBON WDs
5.0
MAKE CLUMP OR AGB STARS
NO CLUMP OR AGB STAR DURING CORE HE BURNING
NO WINDS SEEN IN UV, SOFT X-RAY
POWERFUL HOT WINDS
12C FUSION IGNITION.
O, Ne, Mg WDs
8.0
PLANETARY NEB, WDs
SUPERNOVAE, NEUTRON STARS
~ 25
NEUTRON STARS
BLACK HOLES
VERY UNCERTAIN, FUNCTION OF M, COMPOSITION, ROTATION, ETC.


+
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
MASS
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
NEUTRON STAR
TYPE II SUPERNOVA
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
WHITE DWARF
PLANETARY NEBULA
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
–
TIME
+

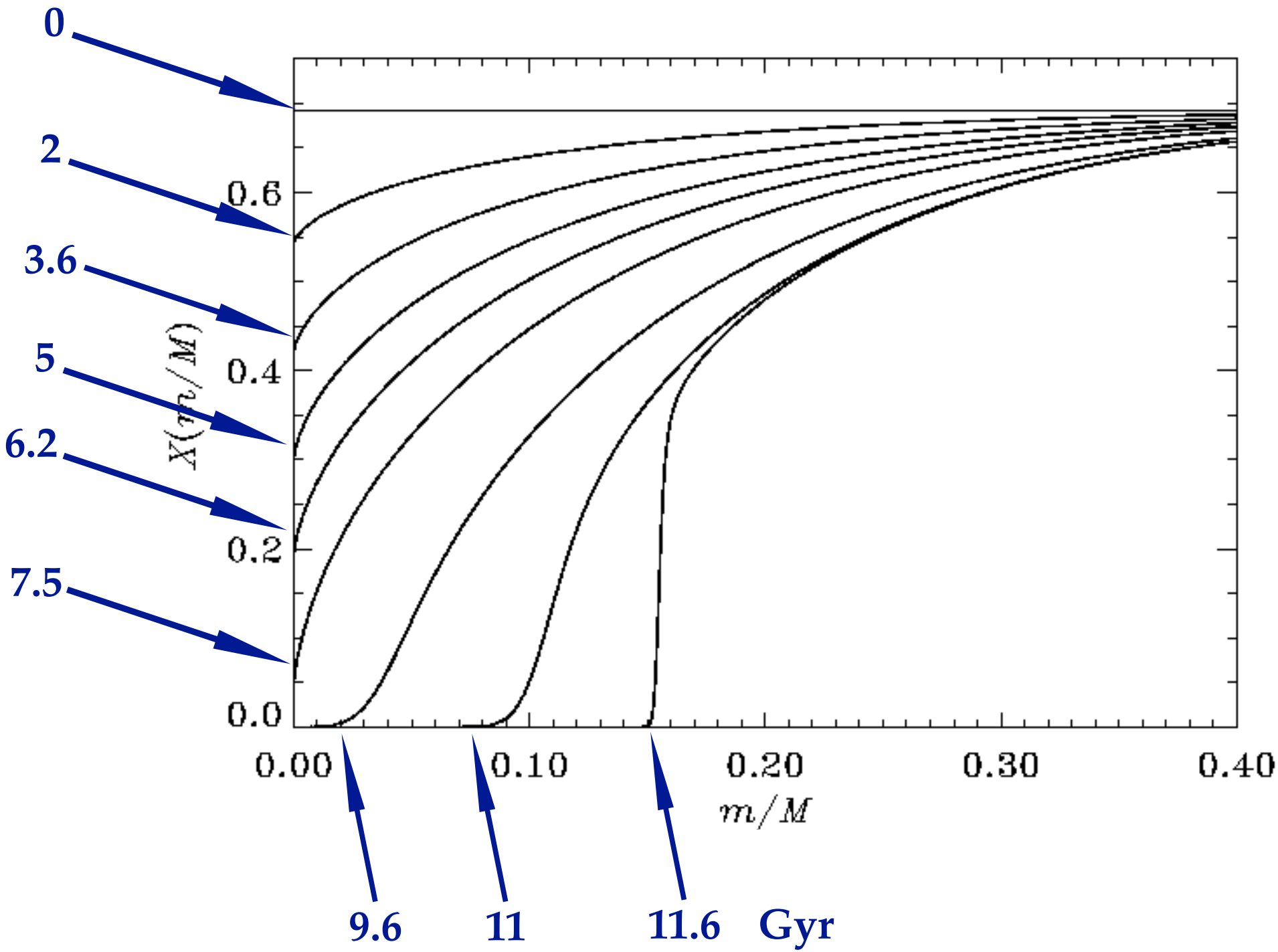

LOG (L)
LOG (Te)
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
-2.0
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
15 M⊙
9 M⊙
5 M⊙
3 M⊙
2.25 M⊙
1.5 M⊙
1.25 M⊙
1 M⊙
0.5 M⊙
0.25M⊙

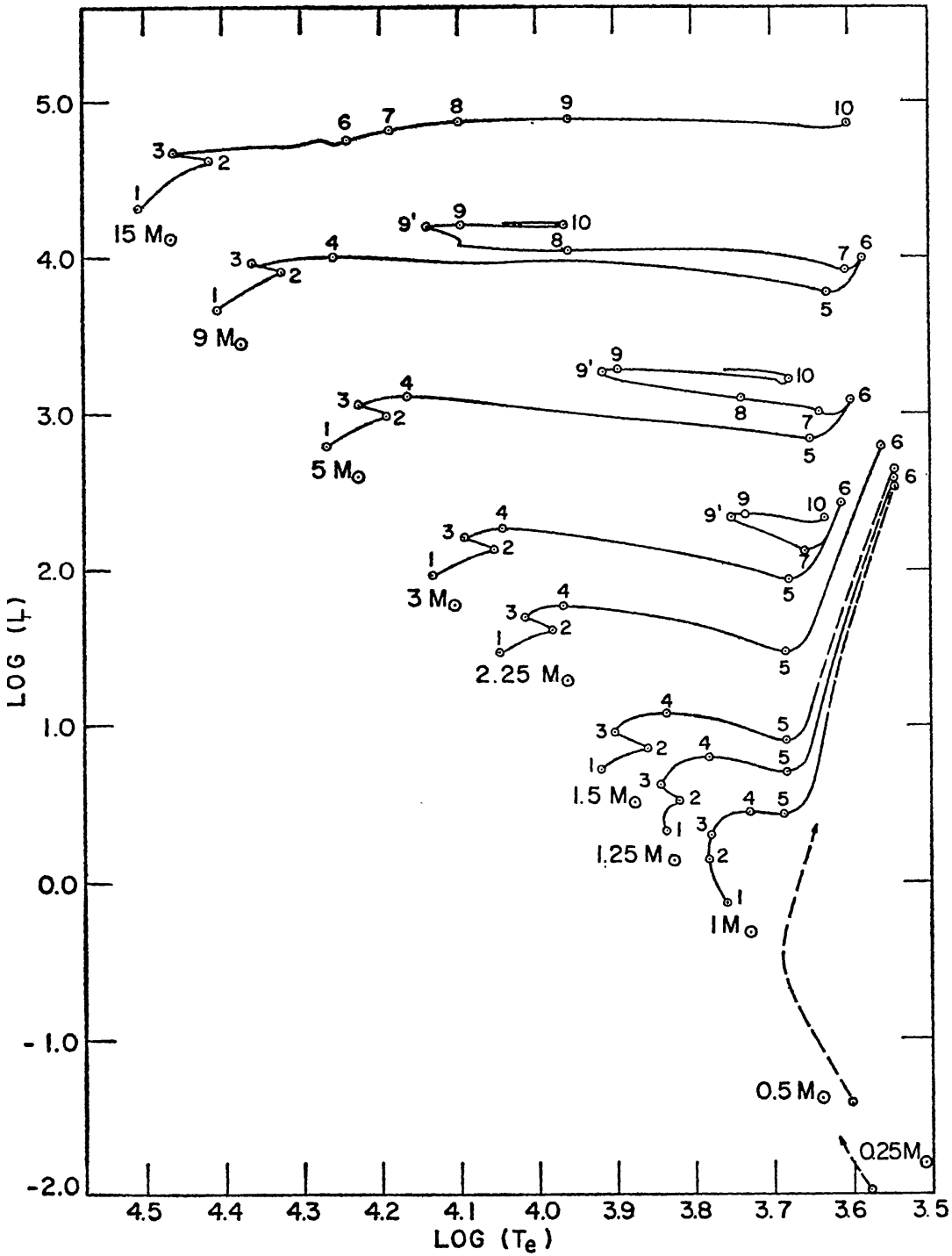
Iben 1967

Gradual change in size of Sun

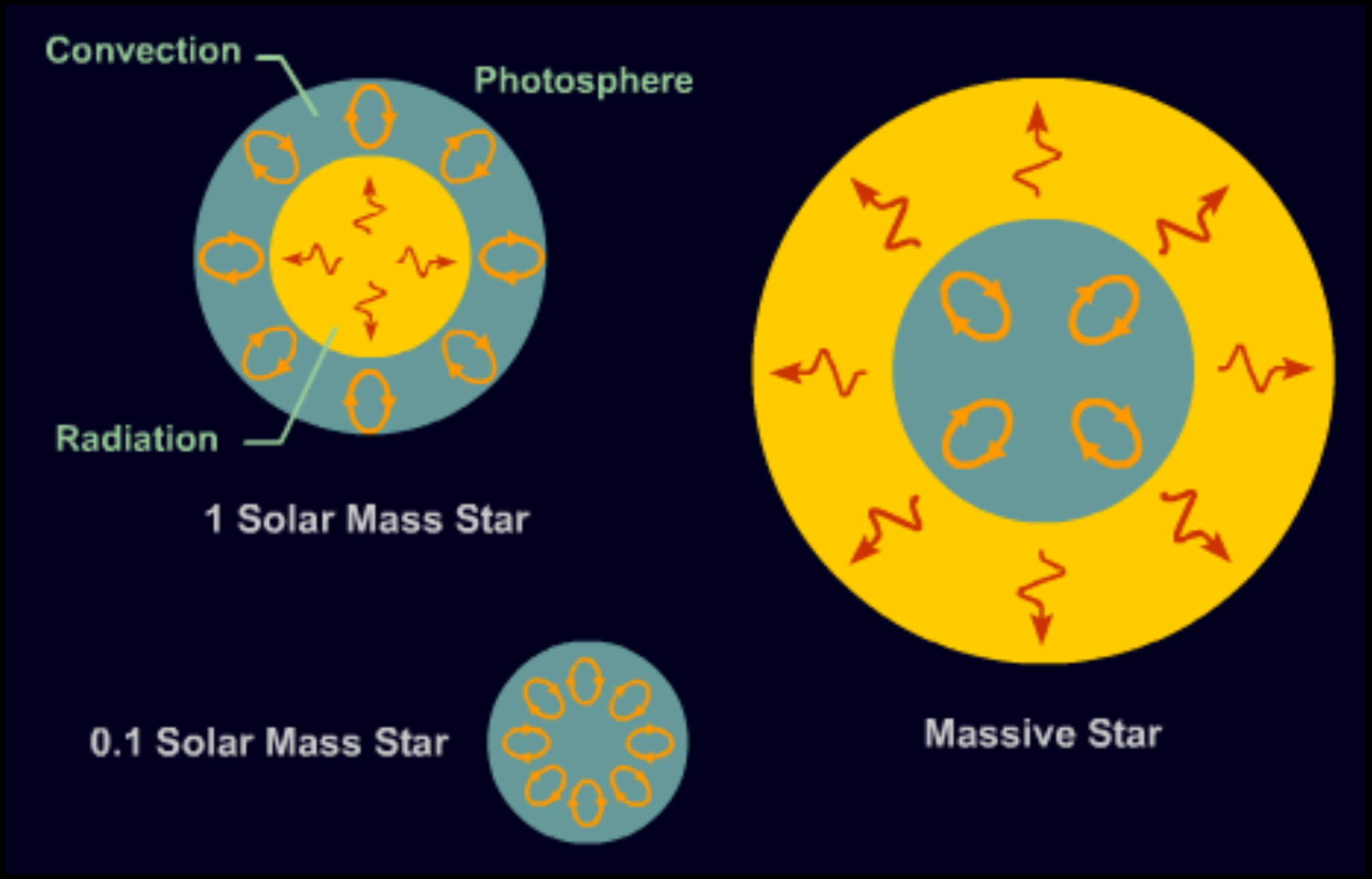


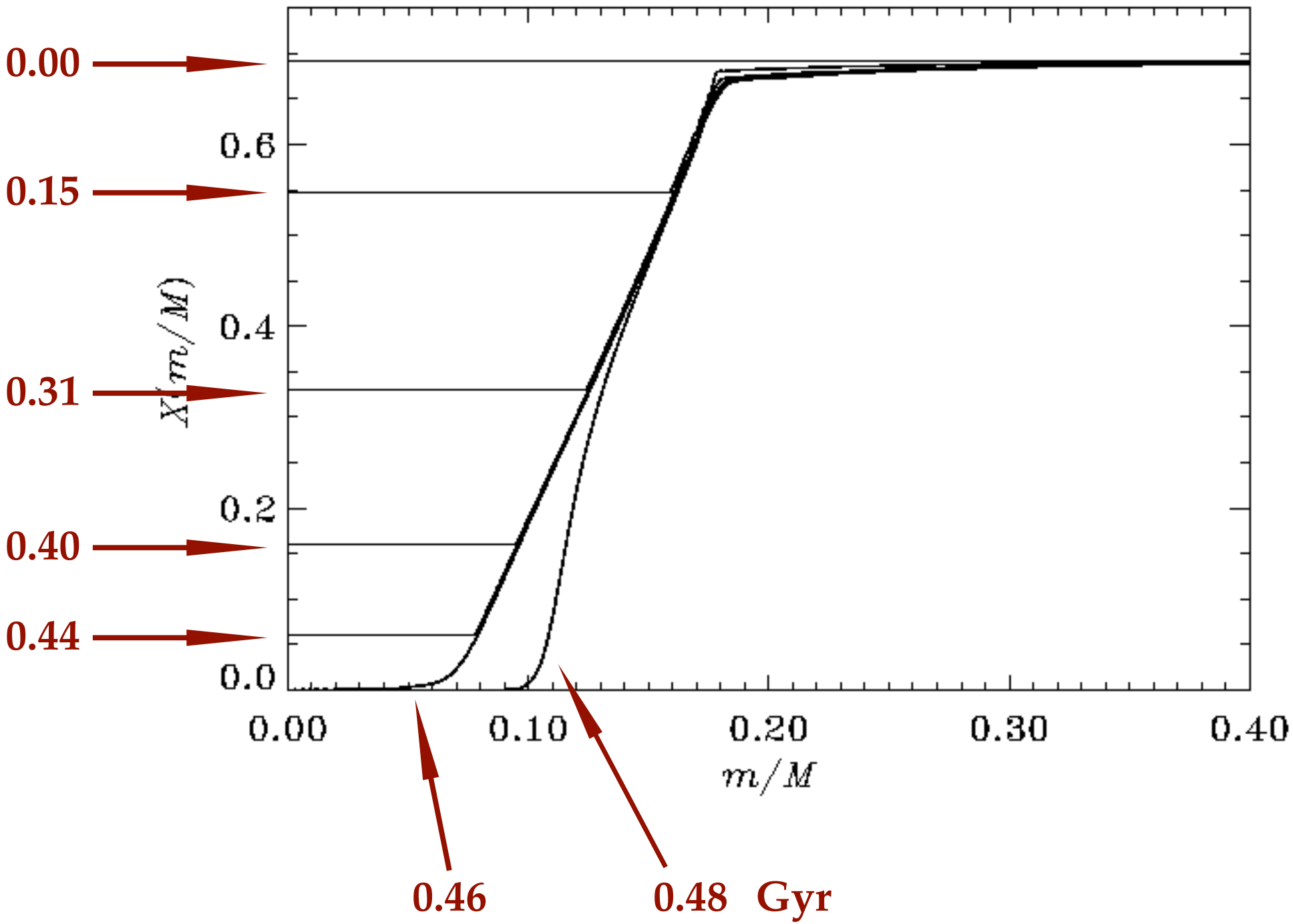
Now 40% brighter, 6% larger, 5% hotter

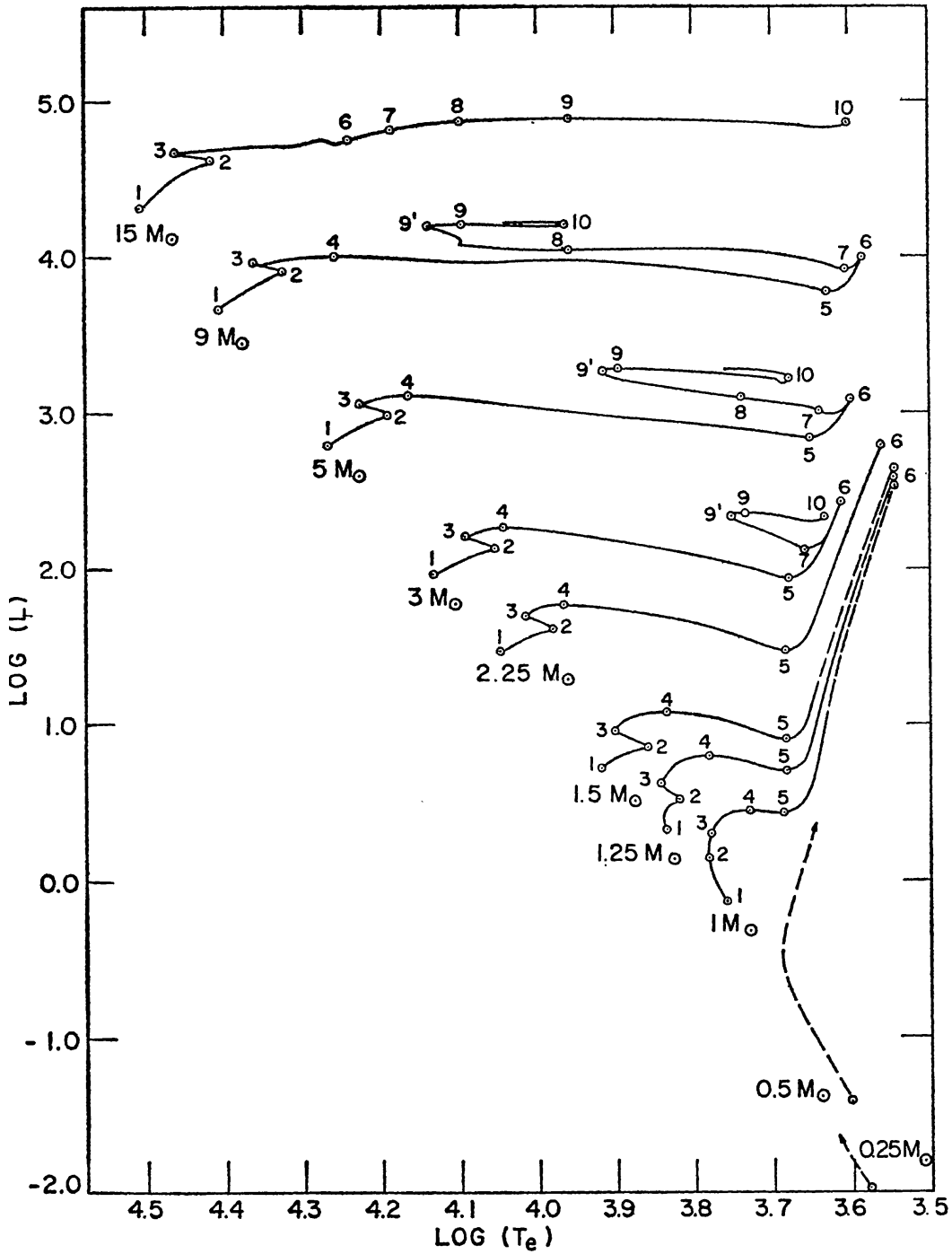

0
2
3.6
5
6.2
7.5
0.0
0.2
0.4
0.6
$X(m/M)$
0.00
0.10
0.20
0.30
0.40
m/M
9.6
11
11.6
Gyr


LOG (L)
LOG (Te)
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
-2.0
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
15 M⊙
9 M⊙
5 M⊙
3 M⊙
2.25 M⊙
1.5 M⊙
1.25 M⊙
1 M⊙
0.5 M⊙
0.25M⊙

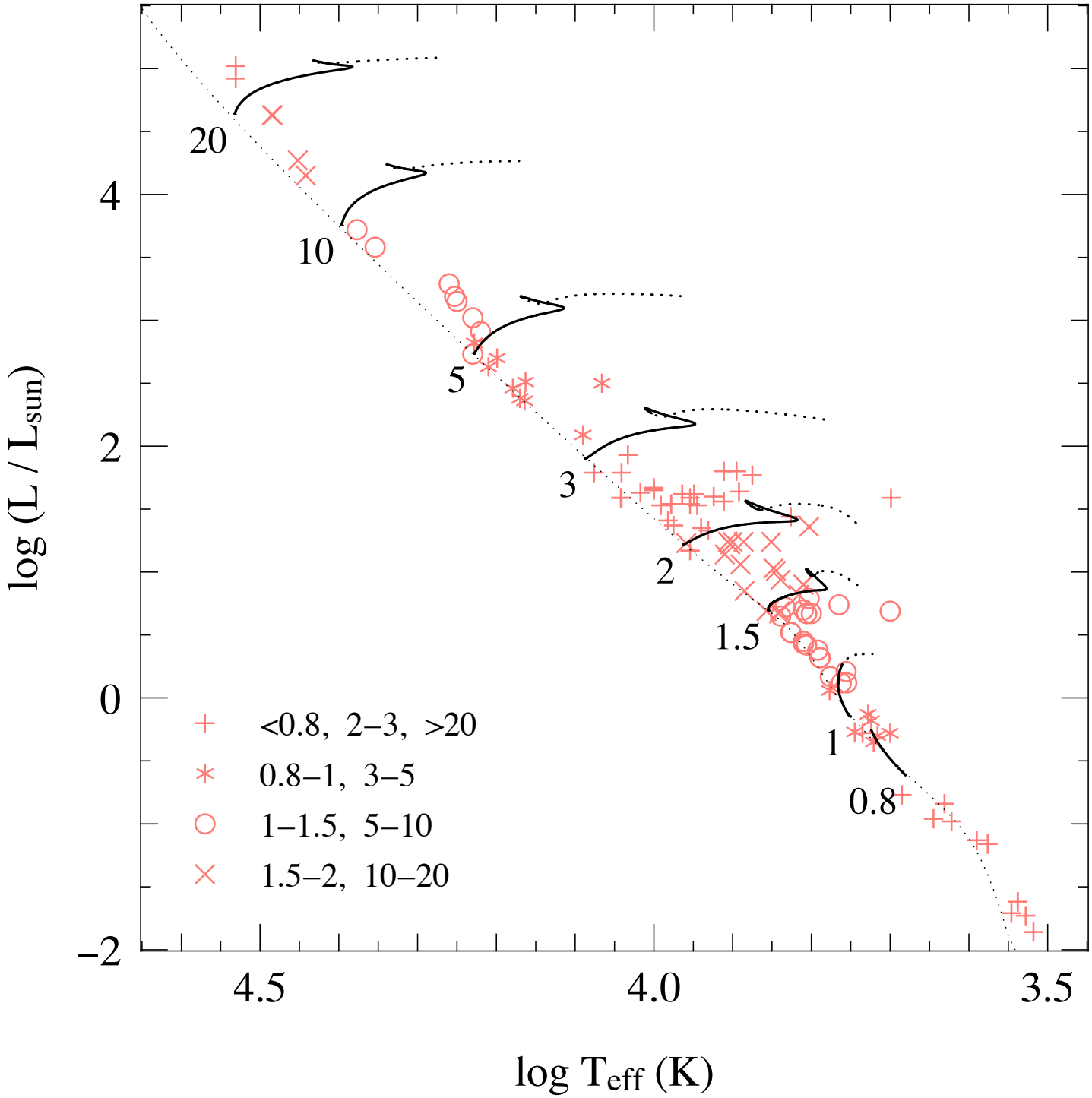
Iben 1967

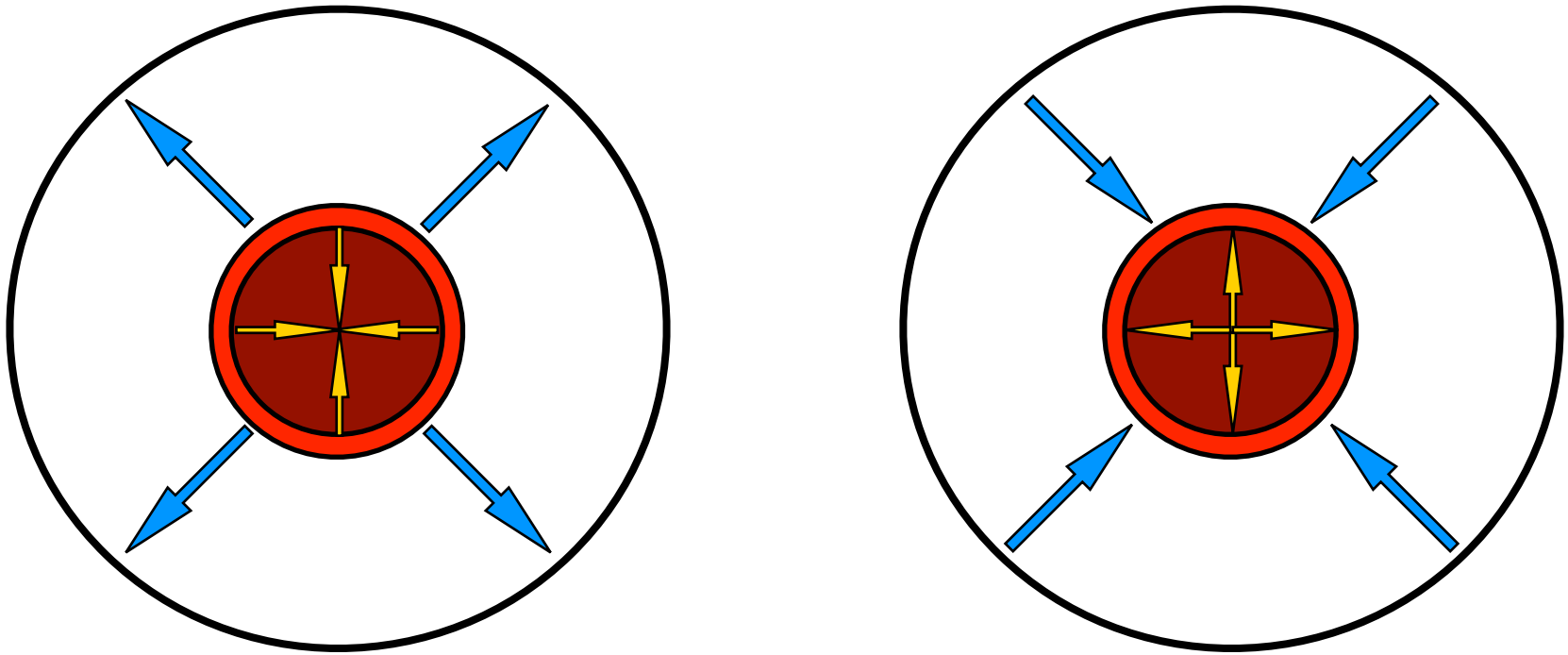

Convection
Photosphere
Radiation
1 Solar Mass Star
0.1 Solar Mass Star
Massive Star


0.00
0.15
0.31
0.40
0.44
0.6
0.4
0.2
0.0
$X(m/M)$
0.00
0.10
0.20
0.30
0.40
m/M
0.46
0.48 Gyr

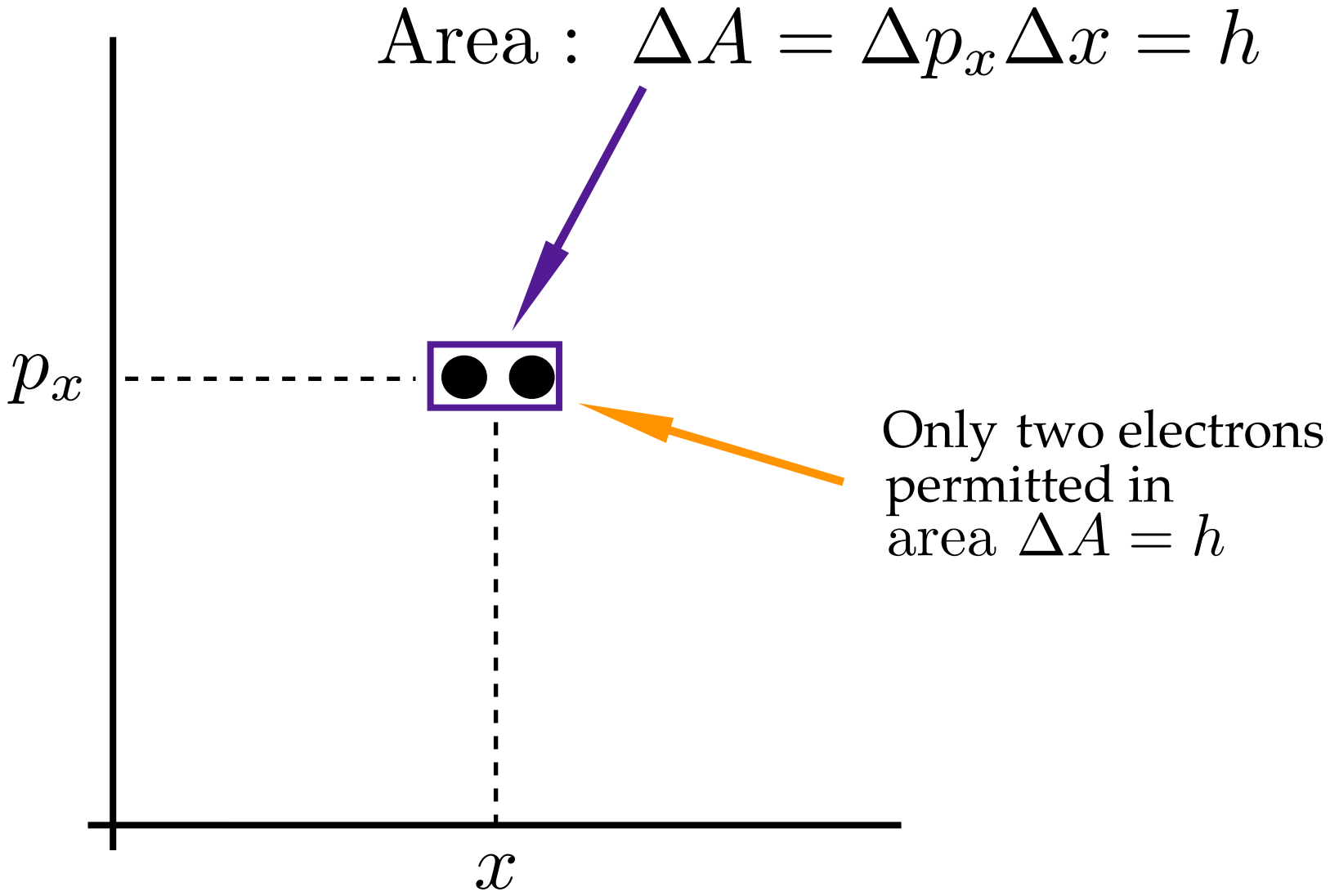

LOG (L)
LOG (T_e)
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
-2.0
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
15 $M_\odot$
9 $M_\odot$
5 $M_\odot$
3 $M_\odot$
2.25 $M_\odot$
1.5 $M_\odot$
1.25 $M_\odot$
1 $M_\odot$
0.5 $M_\odot$
0.25$M_\odot$

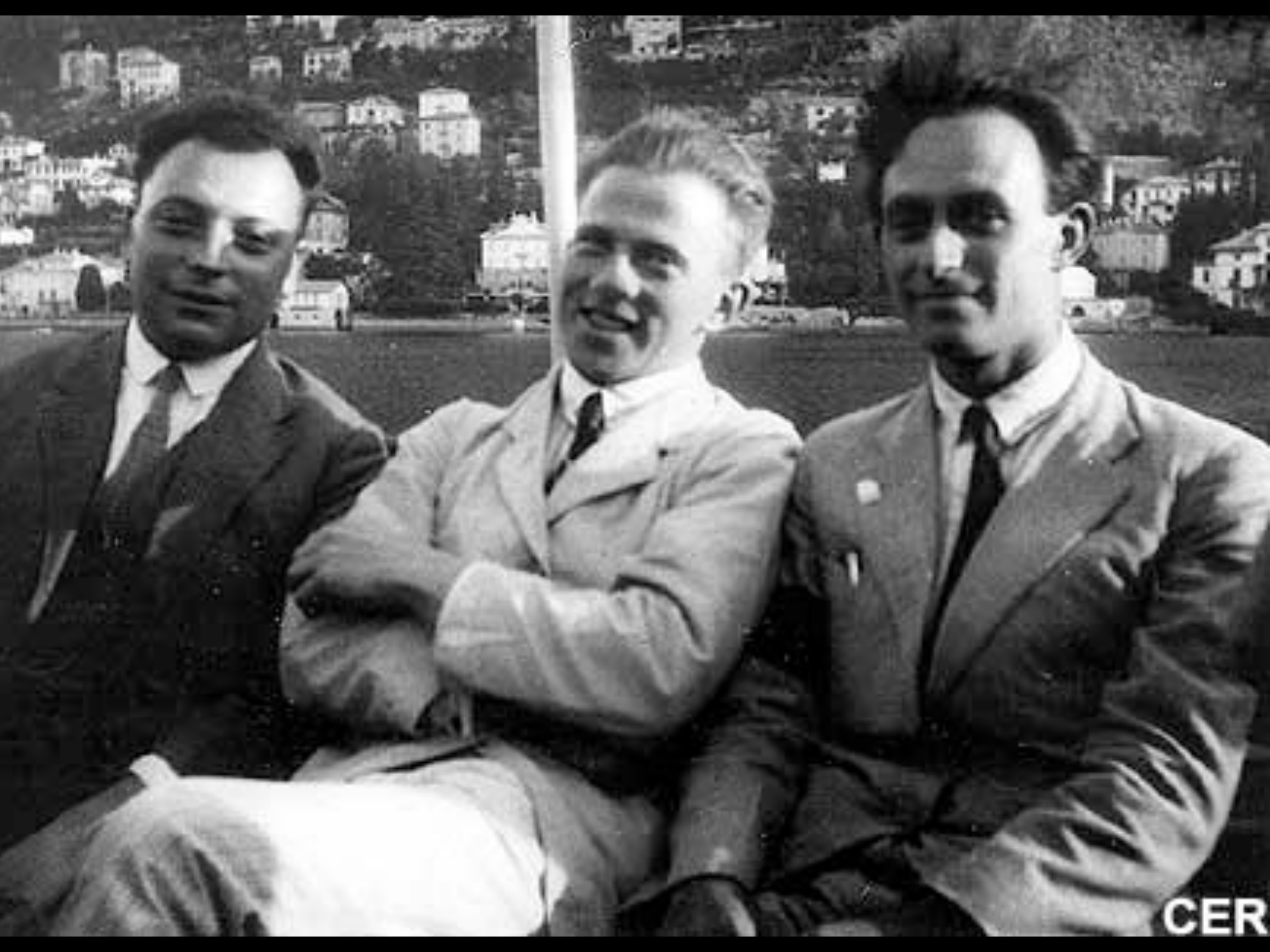
Iben 1967

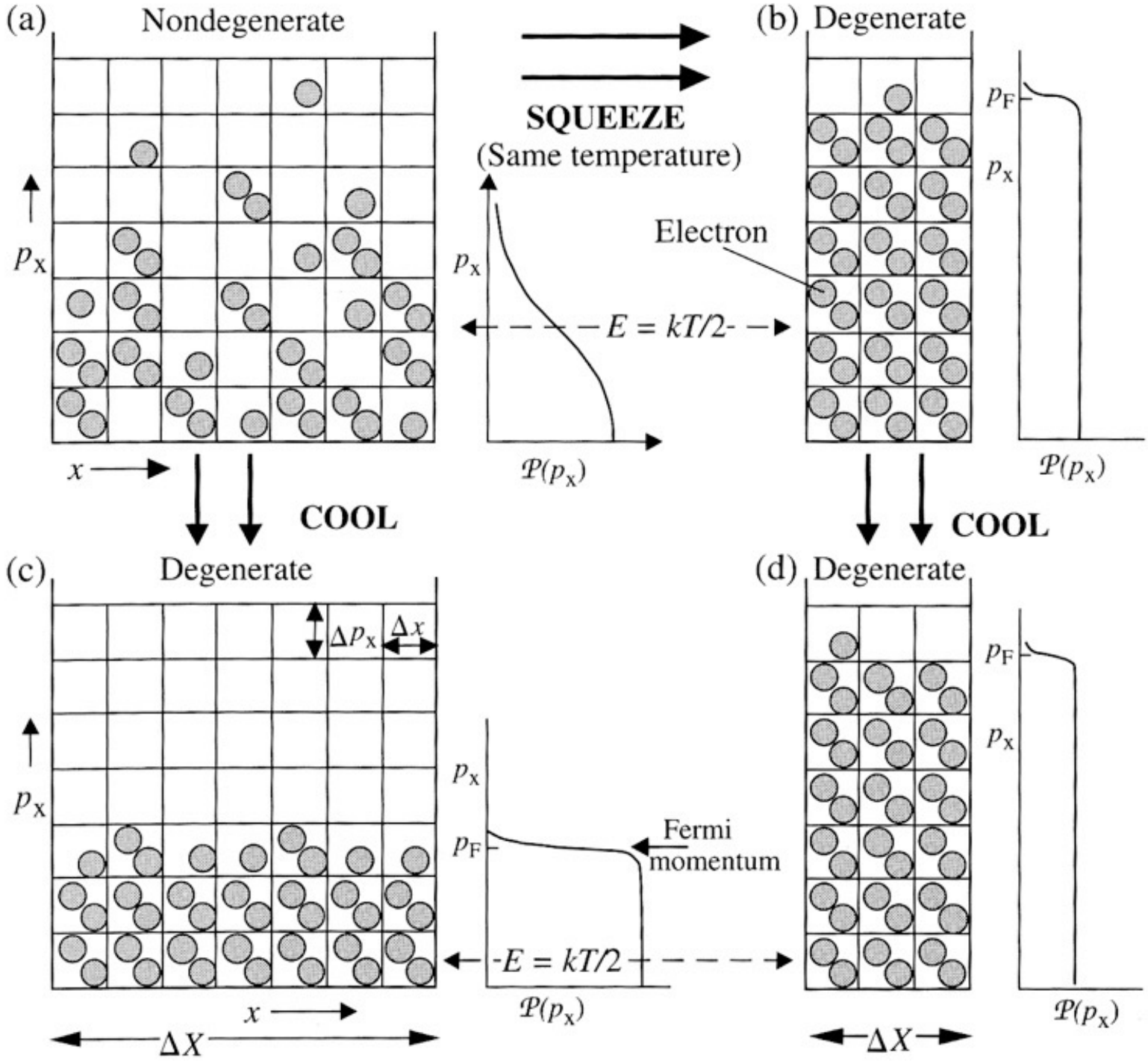

20
10
5
3
2
1.5
1
0.8
<0.8, 2–3, >20
0.8–1, 3–5
1–1.5, 5–10
1.5–2, 10–20
log (L / L$_{sun}$)
log T$_{eff}$ (K)
4
2
0
−2
4.5
4.0
3.5

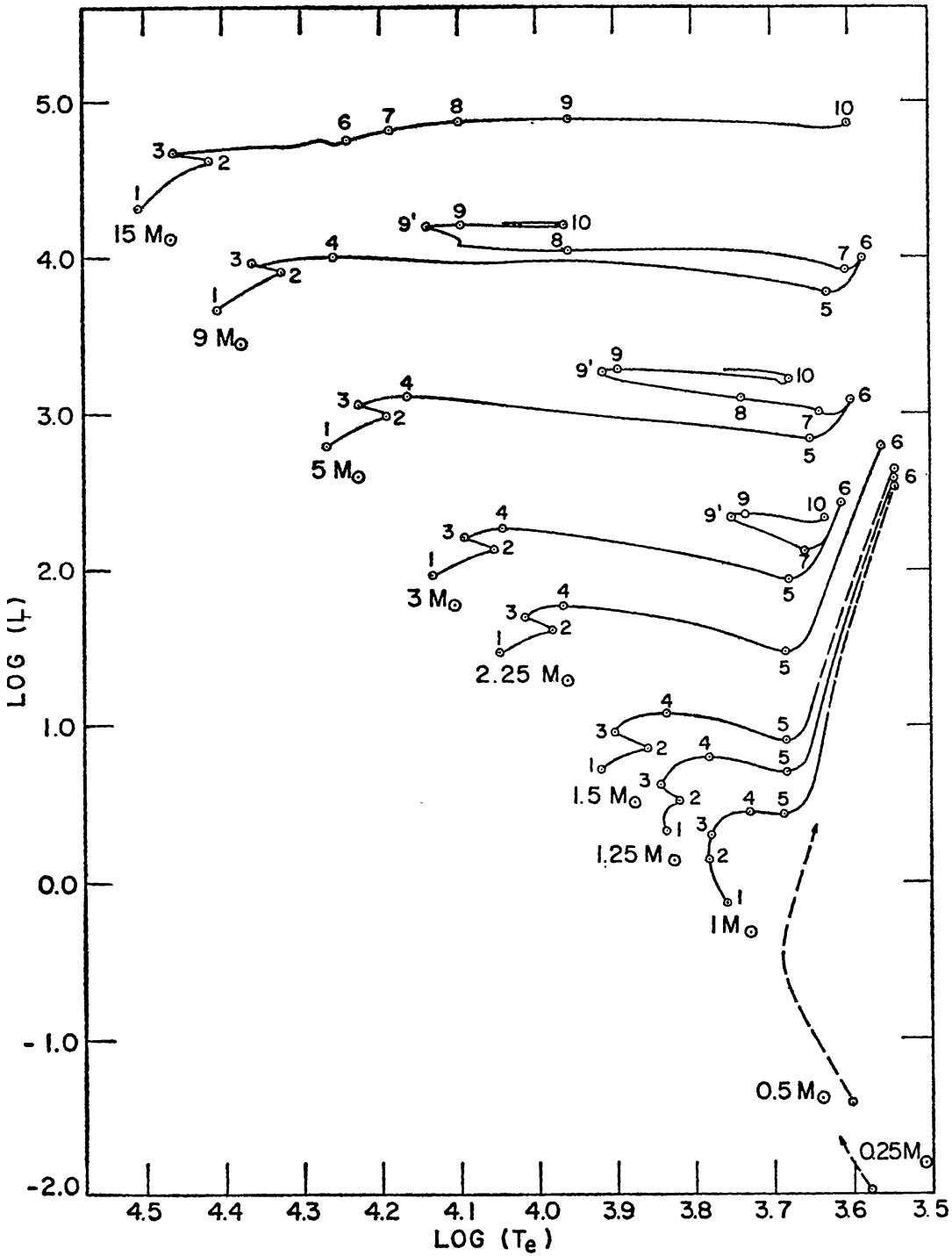


The Mirror Principle of Shell-Burning Stars

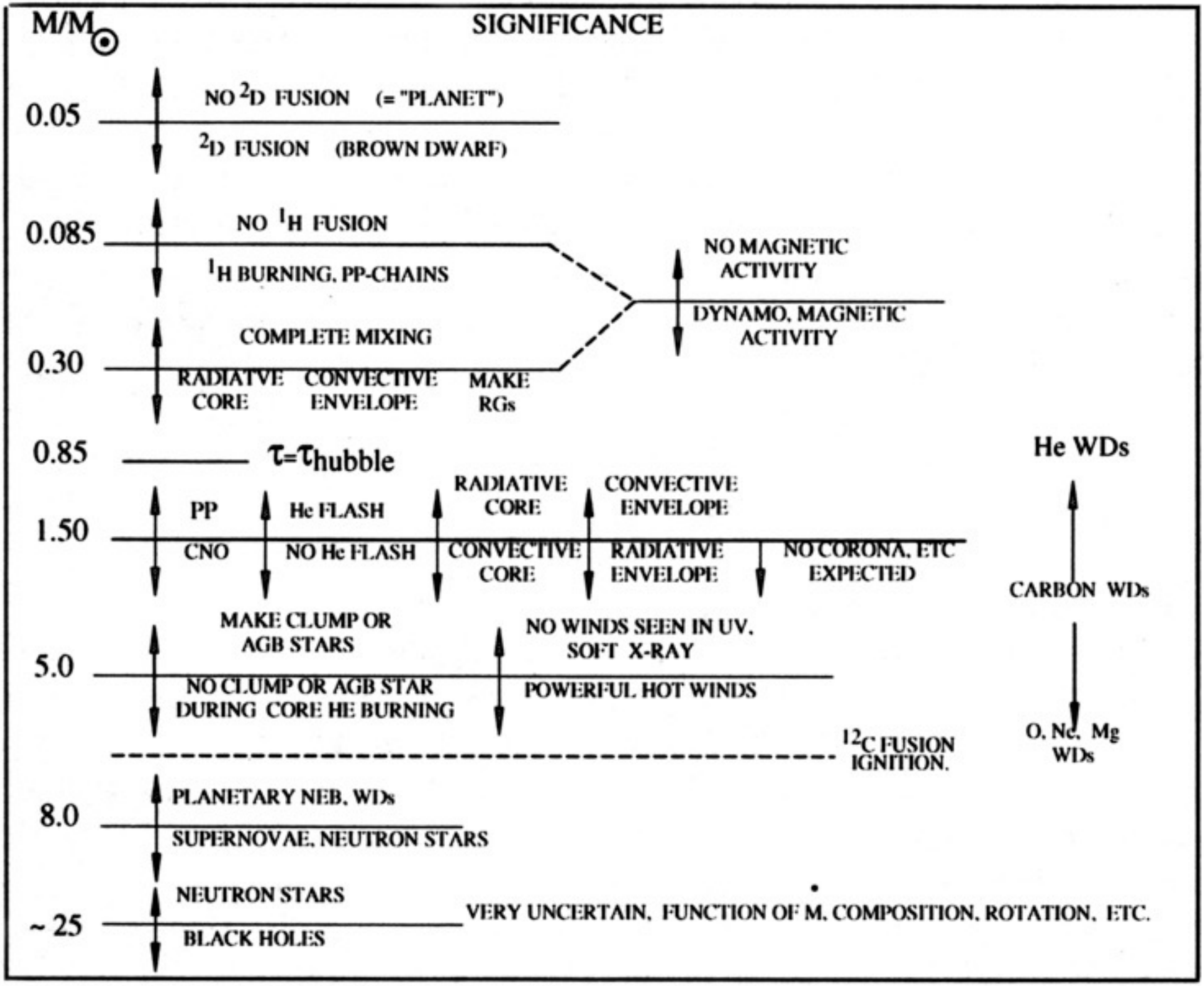

Area : $\Delta A = \Delta p_x \Delta x = h$
p_x
x
Only two electrons
permitted in
area $\Delta A = h$

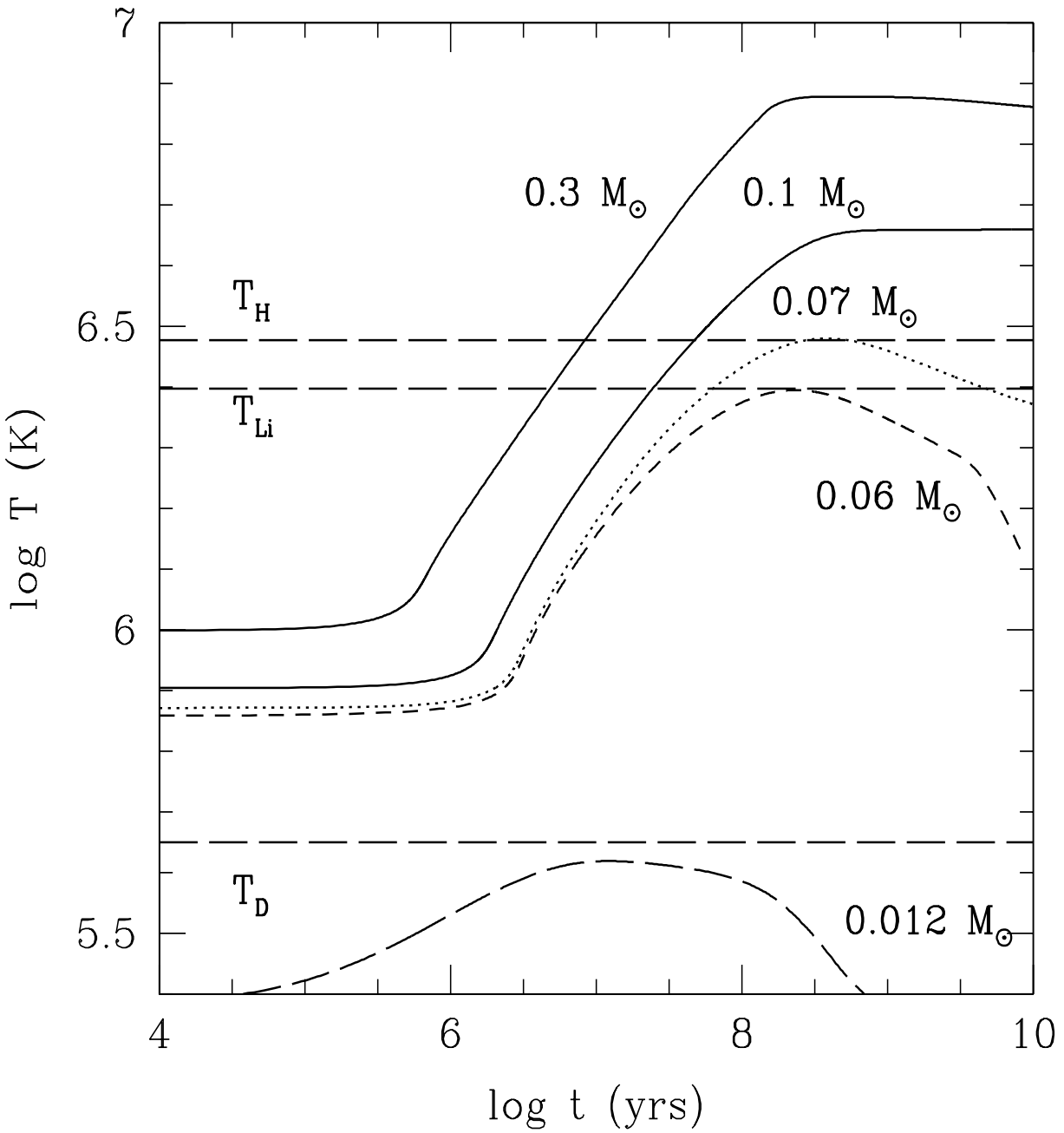

CER


(a) Nondegenerate
(b) Degenerate
SQUEEZE
(Same temperature)
Electron
p_x
x
$E = kT/2$
$\mathcal{P}(p_x)$
p_F
COOL
COOL
(c) Degenerate
(d) Degenerate
Δp_x
Δx
Fermi momentum
$-E = kT/2$
ΔX


LOG (L)
LOG (Te)
5.0
4.0
3.0
2.0
1.0
0.0
- 1.0
-2.0
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
15 M⊙
9 M⊙
5 M⊙
3 M⊙
2.25 M⊙
1.5 M⊙
1.25 M⊙
1 M⊙
0.5 M⊙
0.25M⊙

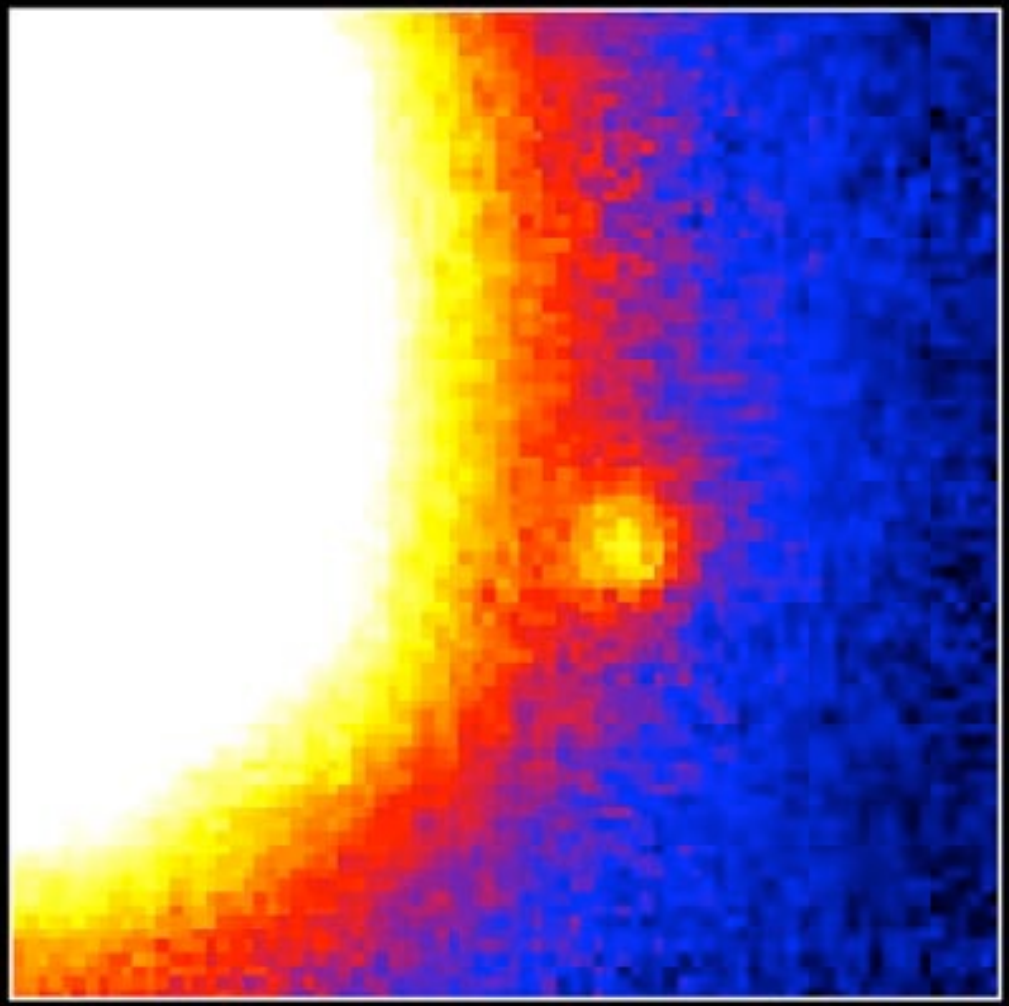
Iben 1967


M/M⊙
SIGNIFICANCE
0.05
NO 2D FUSION (= "PLANET")
2D FUSION (BROWN DWARF)
0.085
NO 1H FUSION
1H BURNING, PP-CHAINS
0.30
COMPLETE MIXING
RADIATVE CORE
CONVECTIVE ENVELOPE
MAKE RGs
NO MAGNETIC ACTIVITY
DYNAMO, MAGNETIC ACTIVITY
0.85
τ=τhubble
He WDs
1.50
PP
CNO
He FLASH
NO He FLASH
RADIATIVE CORE
CONVECTIVE CORE
CONVECTIVE ENVELOPE
RADIATIVE ENVELOPE
NO CORONA, ETC EXPECTED
CARBON WDs
5.0
MAKE CLUMP OR AGB STARS
NO CLUMP OR AGB STAR DURING CORE HE BURNING
NO WINDS SEEN IN UV, SOFT X-RAY
POWERFUL HOT WINDS
12C FUSION IGNITION.
O, Ne, Mg WDs
8.0
PLANETARY NEB, WDs
SUPERNOVAE, NEUTRON STARS
~ 25
NEUTRON STARS
BLACK HOLES
VERY UNCERTAIN, FUNCTION OF M, COMPOSITION, ROTATION, ETC.

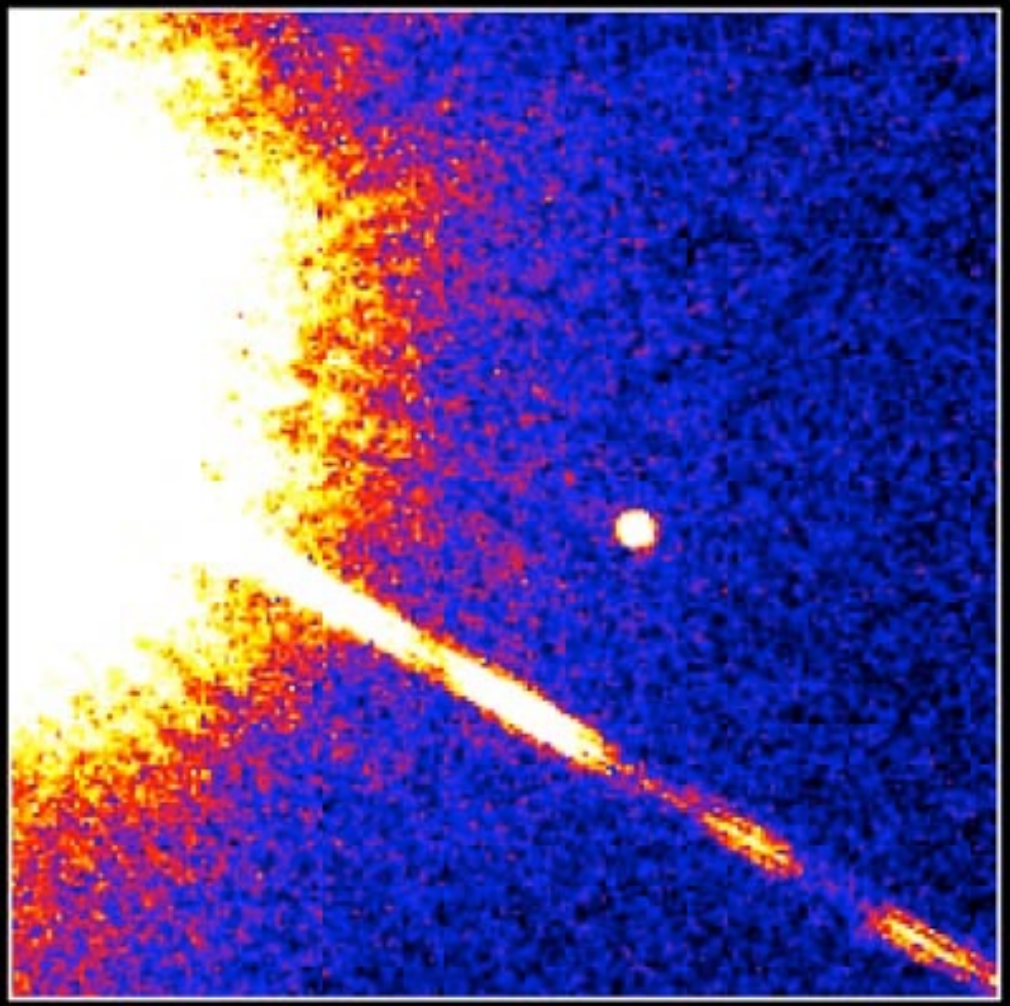


Chabrier & Baraffe 2000

Brown Dwarf Gliese 229B

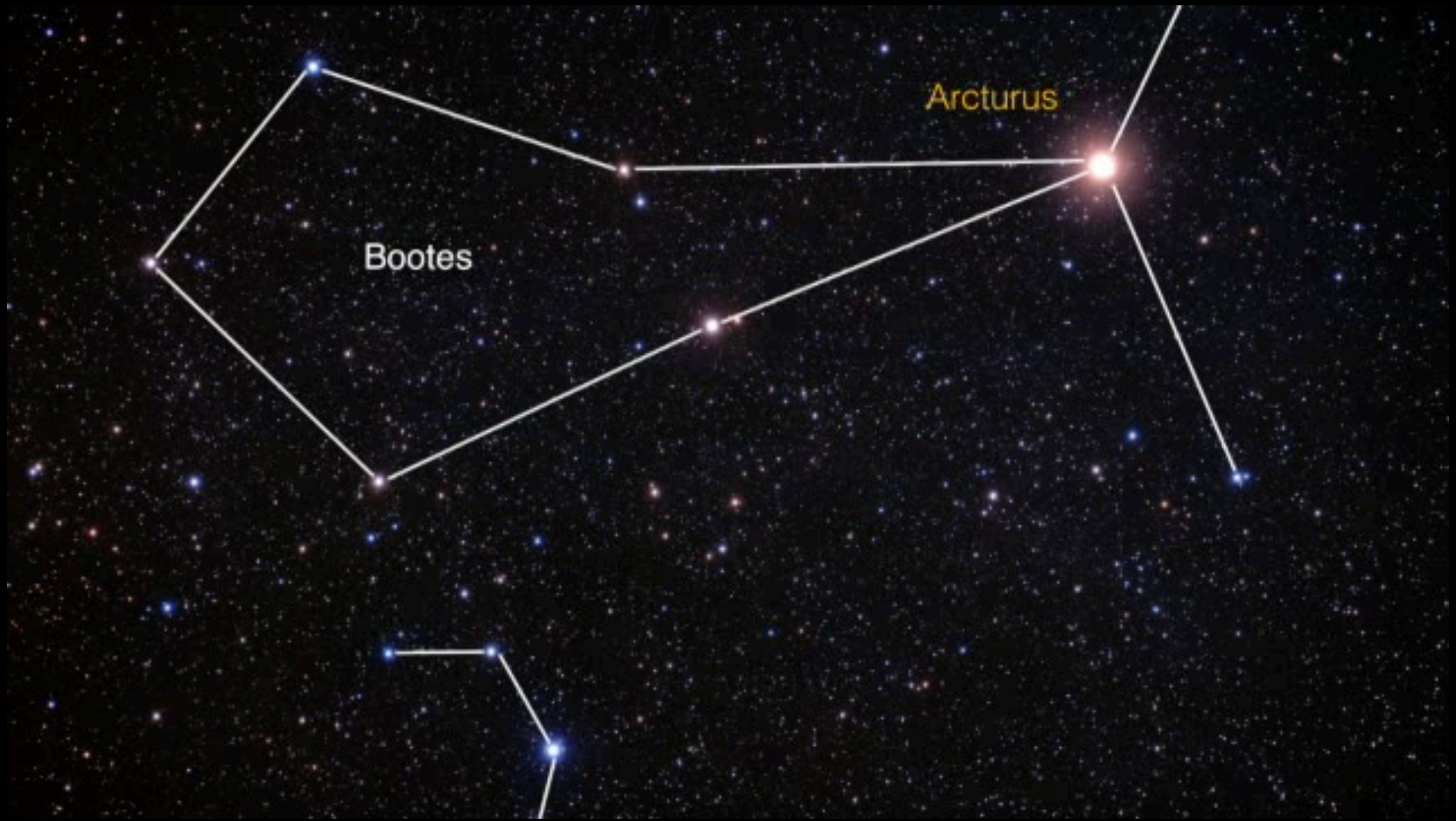


Palomar Observatory
Discovery Image
October 27, 1994



Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

PRC95-48 • ST ScI OPO • November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA


Arcturus
Bootes