Gravitational-wave progenitors

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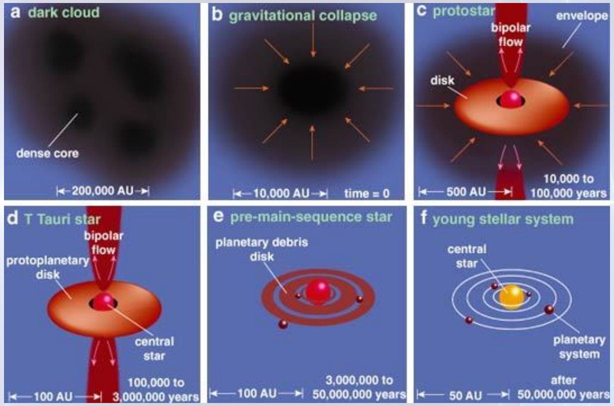
Lecture #5

NCU, Summer Semester 2022

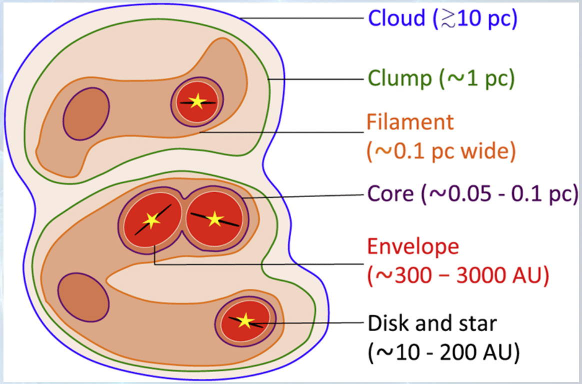
Previously on GW-progenitors…

Star-formation (of massive stars)

- under active research
- low-mass stars:

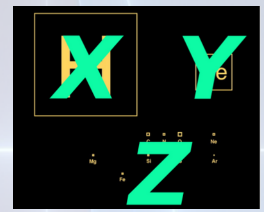


- massive stars?
  - strong radiation may blow away the material
  - hierarchical star formation?



Onset of stellar evolution: ZAMS

- Zero-Age Main Sequence
  - (core) composition: same as the molecular cloud

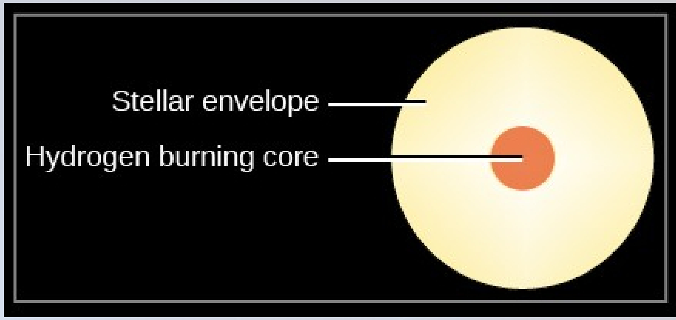


$Z_{\odot} \sim 0.014$ (<2%)
$Z_{LMC} \sim 0.004$
$Z_{SMC} \sim 0.002$
$Z_{GCs} \sim <0.005$
$Z_{PopIII} = 0$

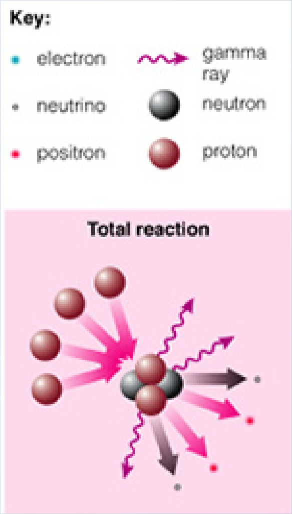
- hydrogen burning starts (in the core)
- hydrostatic & thermodynamic equilibrium
  - no bipolar outflows etc.
  - stellar structure equations hold*

*"pre-MS": last phases of star-formation modelled using the structure equations

Longest phase of stellar evolution: MS



- Main Sequence
  - ***core***-hydrogen-burning phase
- lasts for ~90% of the lifetime (longest of them all)
- core temperatures: ~40M K
- in massive stars: CNO cycle
  - low-mass stars like the Sun: pp-chain
- $4\ ^{1}H \rightarrow\ ^{4}He + \gamma$
- end of MS: Terminal-Age Main Sequence (TAMS)

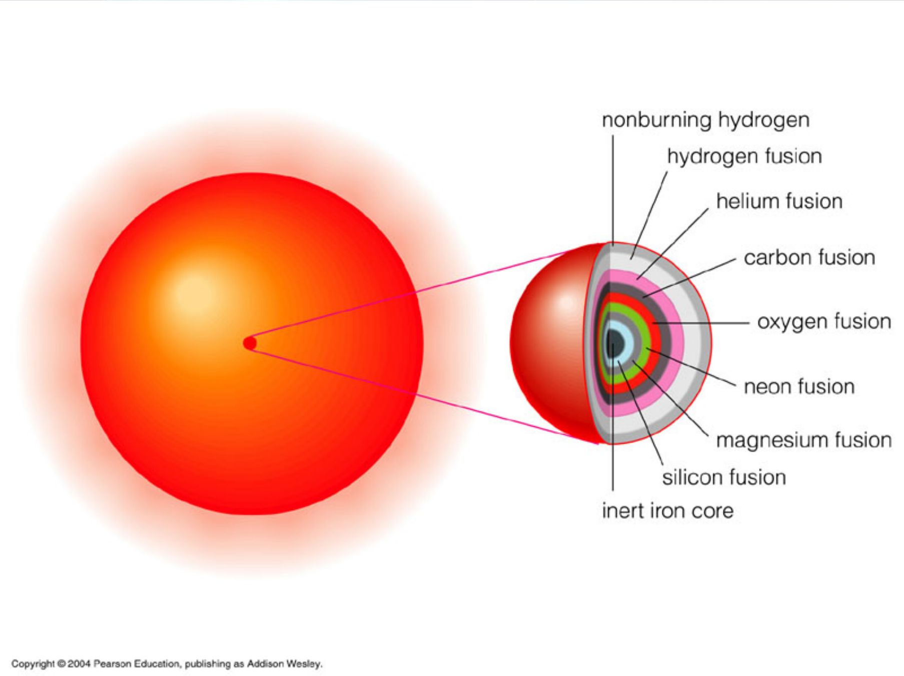


Post-MS

- Includes:
  - core-He-burning (& shell-H-burning)
  - core-C-burning (& shell-He & shell-H-burning)
  - core-O-burning (& shell-C, shell-He, shell-H…
  - core-Ne-burning (& shell…
  - core-Si-burning (& shell...

Temp.

- onion-structure of massive stars



Note: the onion layers become more and more complex nearing the end of the lifetime

• In

Temp.

Table 4.1 Major nuclear-burning processes

Nuclear fuel	*Process*	$T_{\text{threshold}}$ $(10^6\ K)$	*Products*	*Energy per nucleon (MeV)*
H	$p-p$	~4	He	6.55 (low-mass stars)
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C + C	600	O, Ne, Na, Mg	0.54
O	O + O	1000	Mg, S, P, Si	~0.3
Si	Nuc. eq.	3000	Co, Fe, Ni	<0.18

core O burning (& shell C, shell He, shell H...

Stellar Fusion Requirements

Fusion	Fusion By-product	Minimum Core Temperature	Minimum Core Density	Minimum Stellar Mass*
Hydrogen	He	13 million K	100 gm/cc	0.08 solar masses
Helium	C, O	100 million K	100,000 gm/cc	0.5 solar masses
Carbon	O, Ne, Mg, Na	500 million K	200,000 gm/cc	4 solar masses
Neon	O, Mg	1.2 billion K	4 million gm/cc	about 8 solar masses
Oxygen	Mg, Si, S, P	1.5 billion K	10 million gm/cc	about 8 solar masses
Silicon	Si, S, Ar, Ca, Ti, Cr, Fe, Ni	around 3 billion K	30 million gm/cc	about 8 solar masses

• on

Note: th
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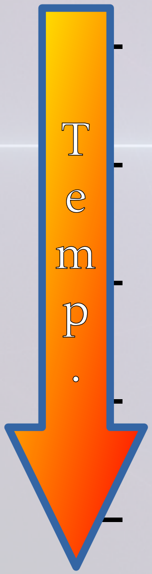
esium fusion
n

• In



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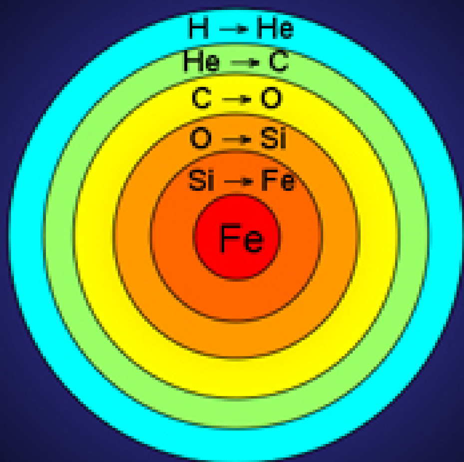
H				
H				
C				
O				
S				

core ... H...

For a 25 solar mass star:



Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

• on

Note: th
more
nearing

Fusion				...imum Stellar ...ss*
Hydrogen				... solar masses
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gen
usion
n fusion
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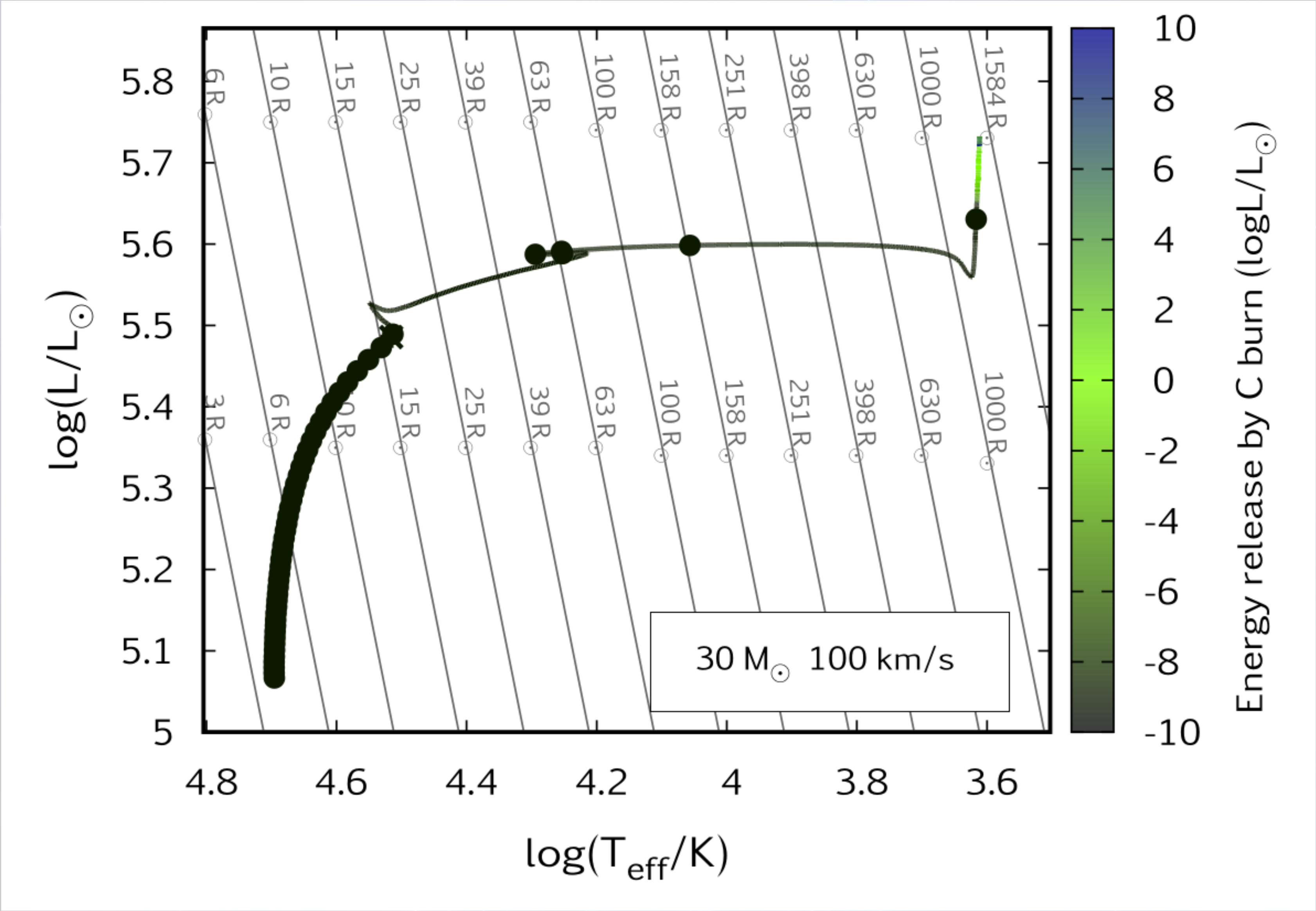
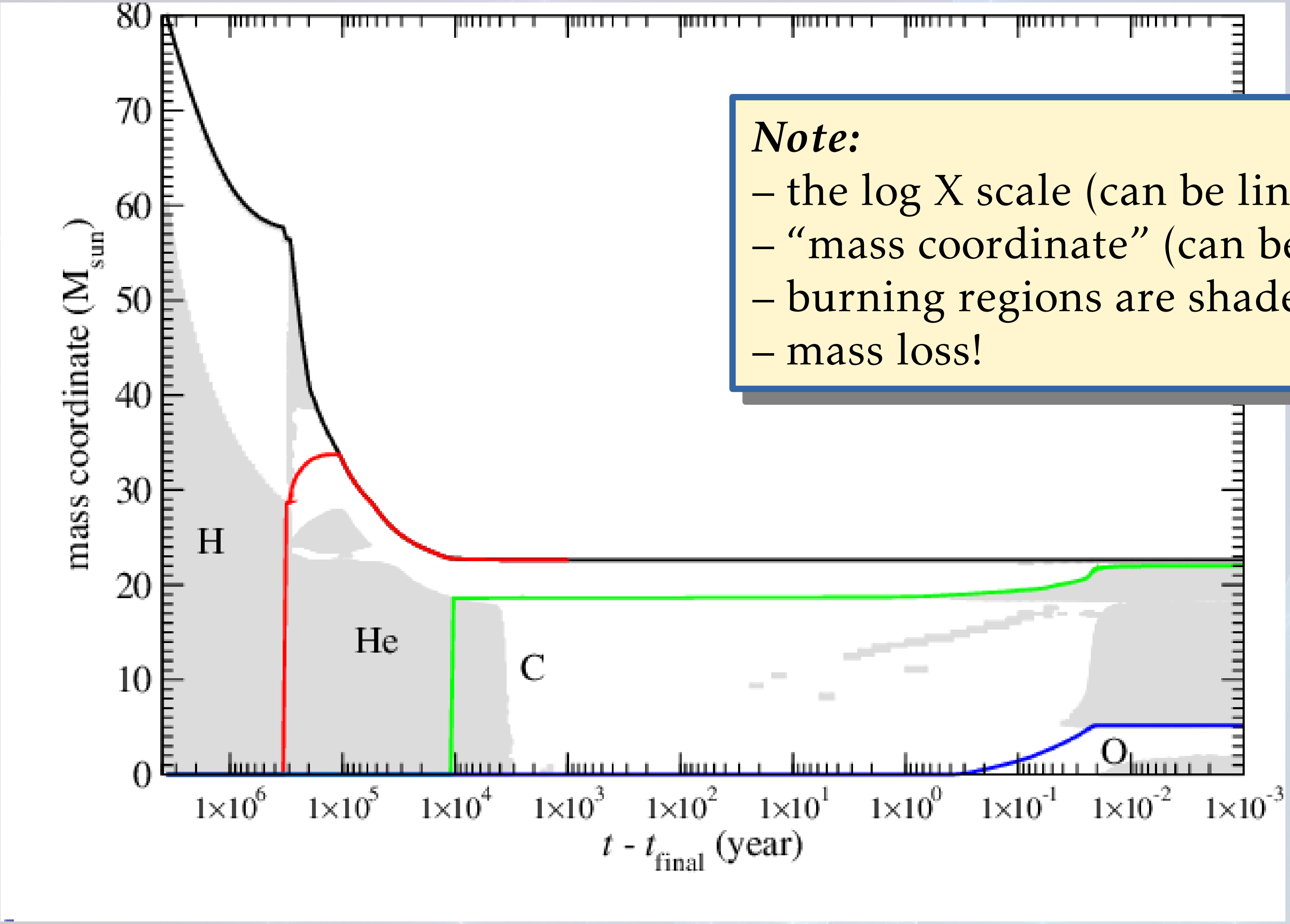
on fusion
esium fusion
n

How much do we see from this in the HRD?

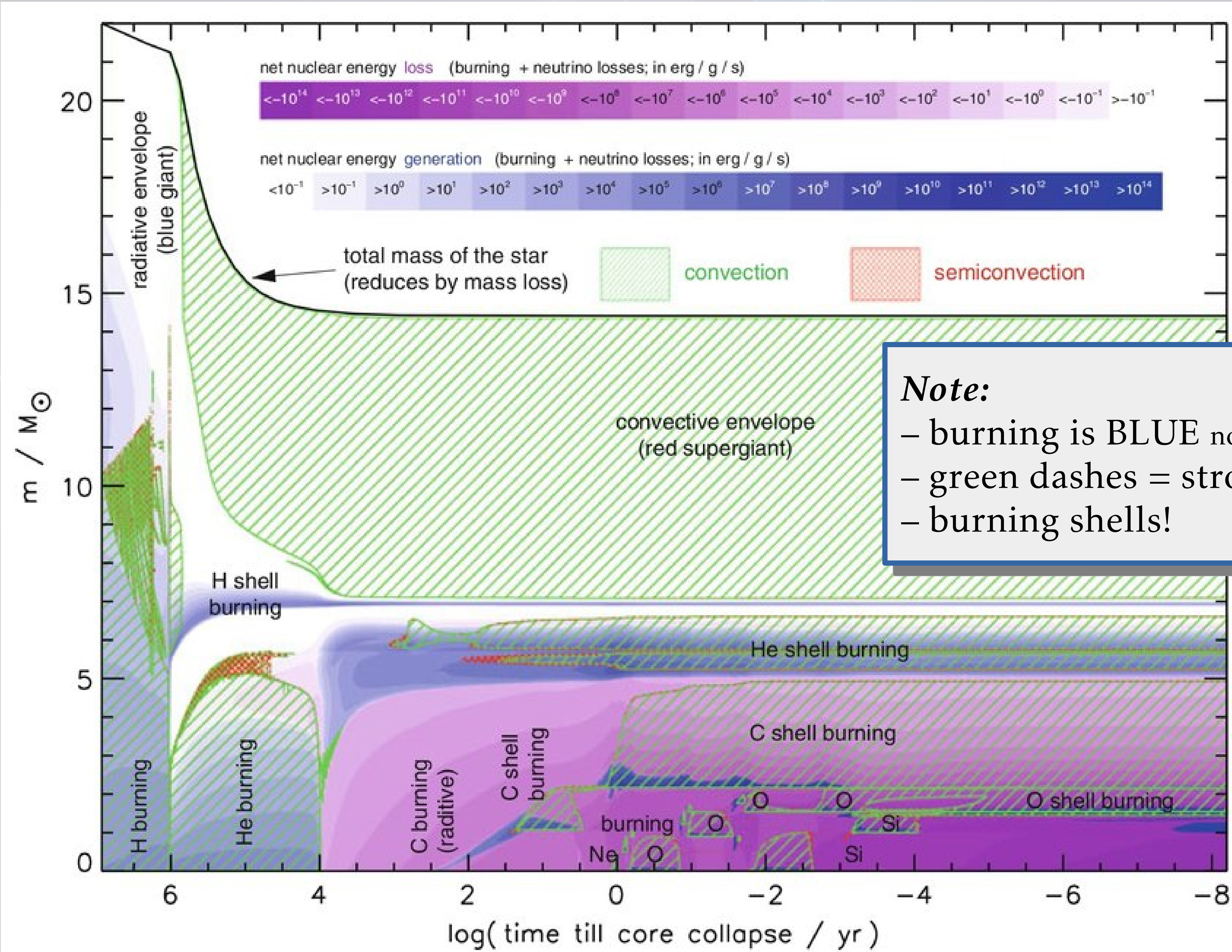


Kippenhahn diagram



Note:
- the log X scale (can be linear too)
- "mass coordinate" (can be radius too)
- burning regions are shaded
- mass loss!

Credit: Leung, Nomoto & Blinnikov (2019)

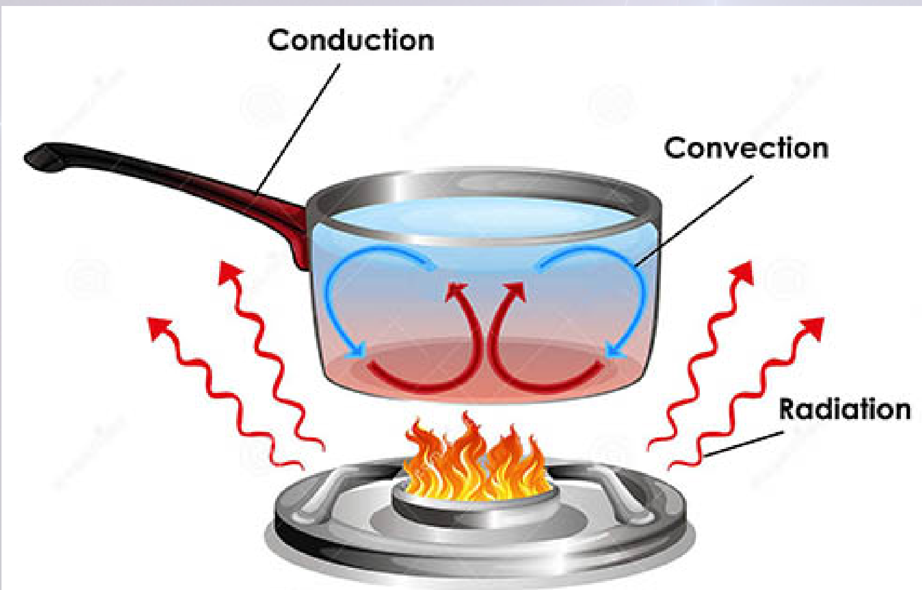


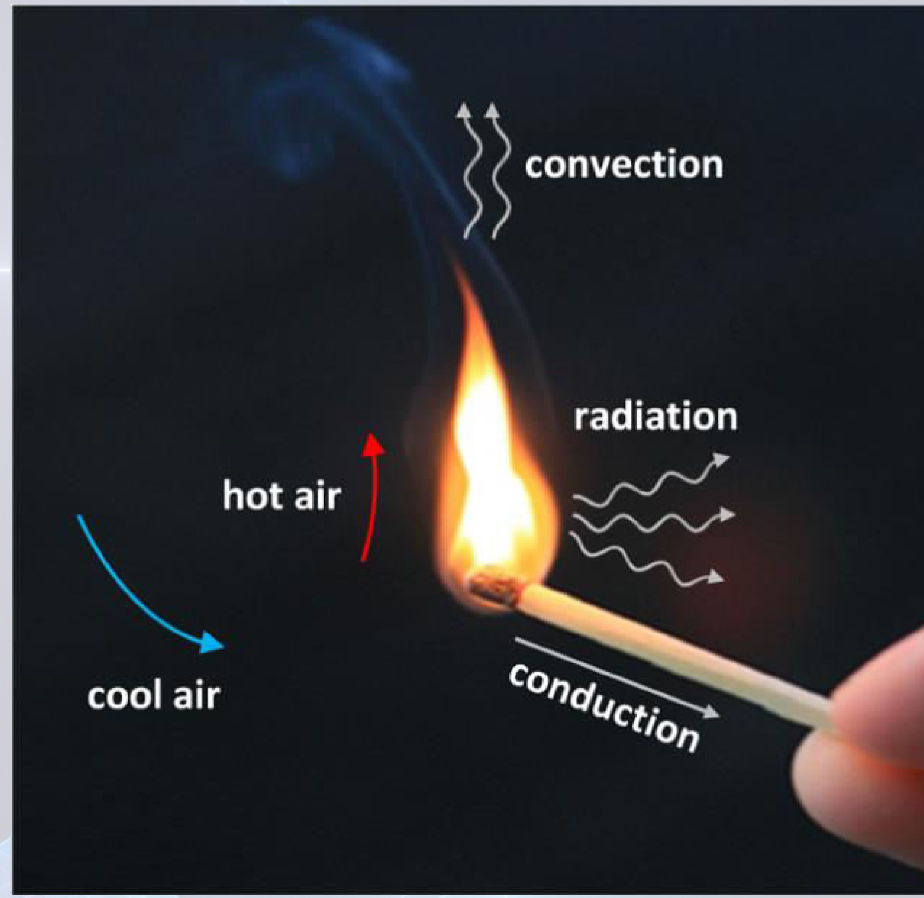
Note:
- burning is BLUE not green/purple
- green dashes = strong mixing
- burning shells!

Credit: Braithwaite & Spruit (2015)

Some words about convection

and about ***heat transfer*** in general





– convection arises wherever heat needs to be transported extra efficiently
e.g. burning core of massive stars, envelope of (super)giants and low-mass stars…
– leads to strong mixing (cf. boiling soup)

Some ection

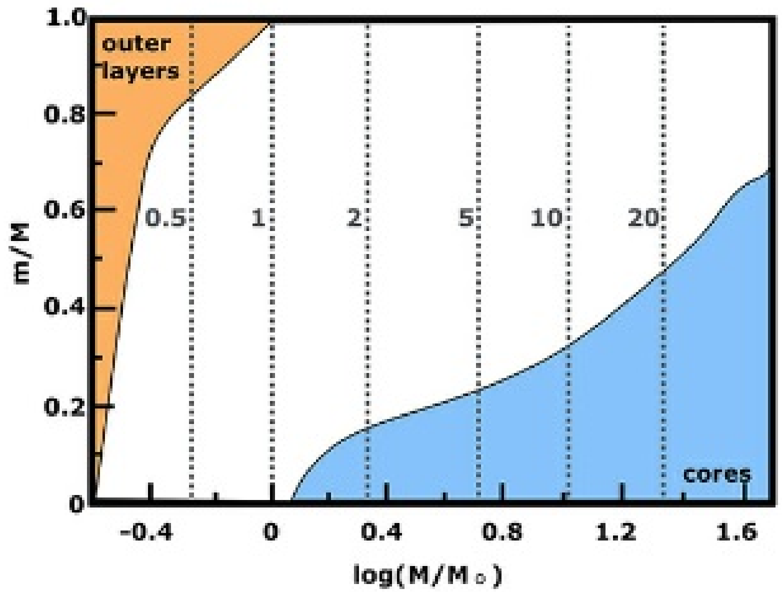


Figure 7.6. Occurrence of convection in stars at the beginning of the core H-fusion phase (ZAMS). The mass of convective envelopes (orange) and convective cores (blue) is expressed as a fraction of the stellar mass, from *m/M* = 0 in the core to *m/M* = 1 at the surface. The vertical lines indicate the stel-

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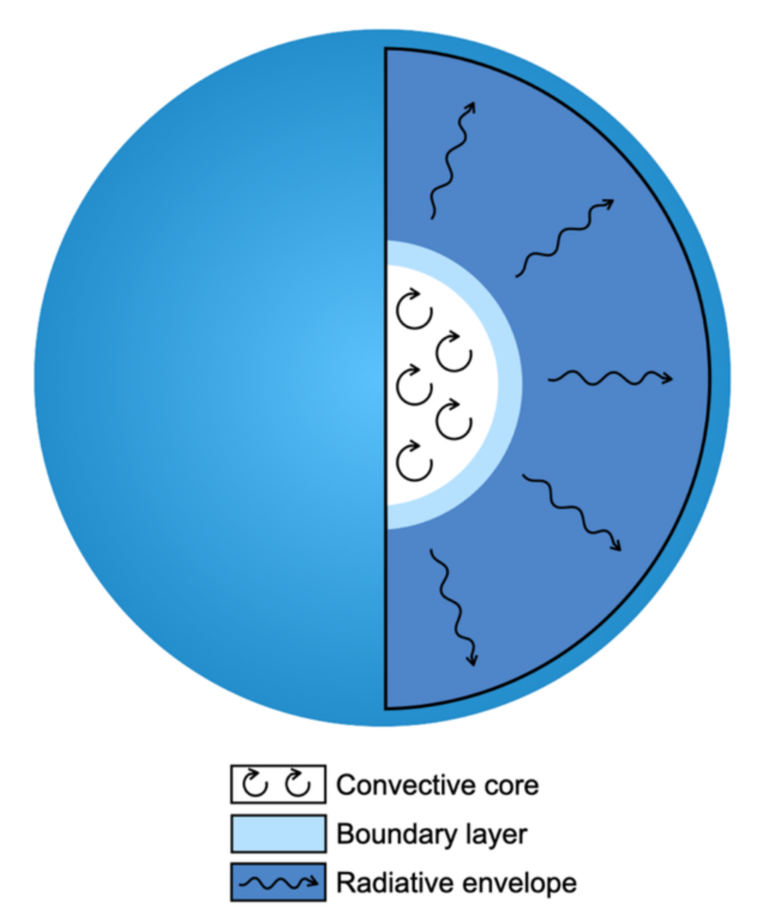
e.g. burning core of massive stars, envelope of (super)giants and low-mass stars…
– leads to strong mixing (cf. boiling soup)

Some more words on ***internal mixing***

hardcore stuff

- convection is just one type of mixing
- other types:
  - convective overshooting
  - rotational mixing
  - sheer mixing
  - "semi-convection"
  - thermohaline mixing
  - …

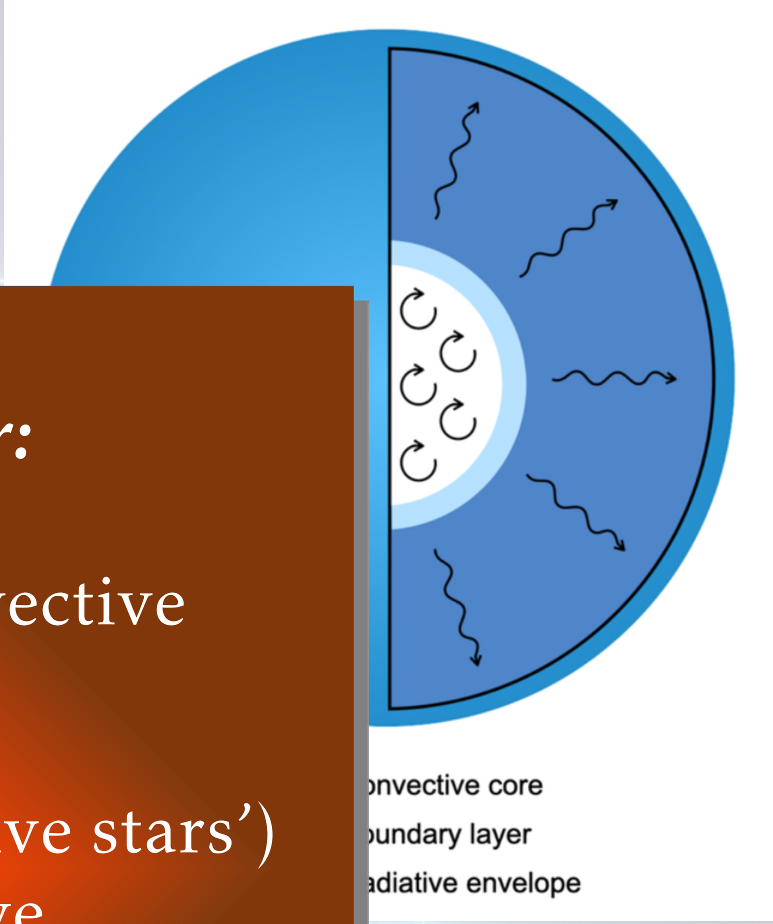


Credit: May G. Pedersen (KITP)

hardcore stuff

Some more words on ***internal mixing***

- convection is just one type of mixing



. Pedersen (KITP)

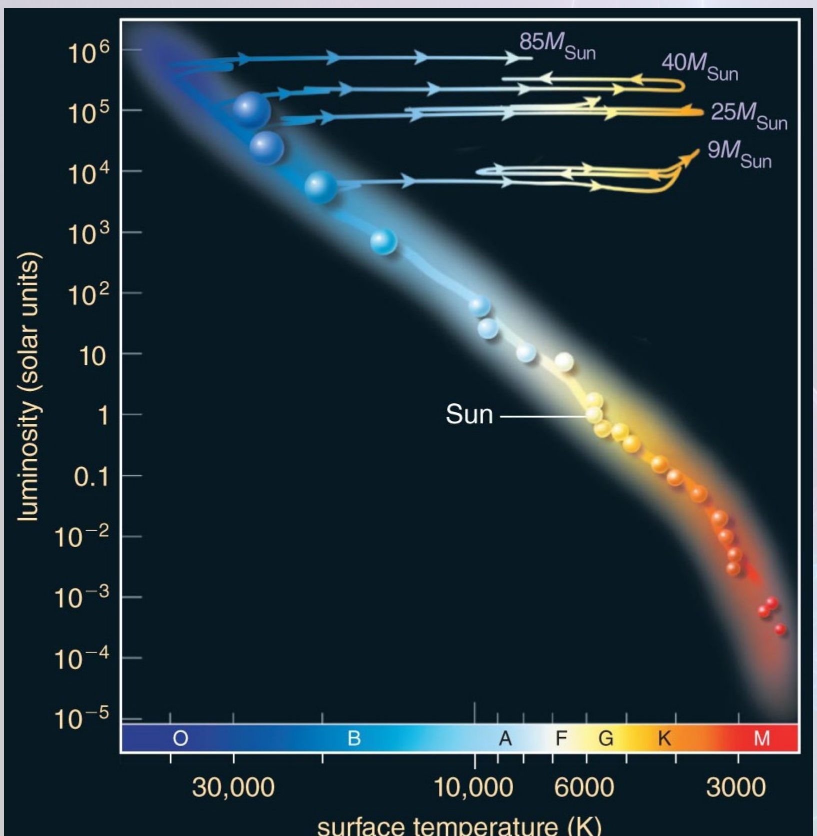
Make sure to remember:

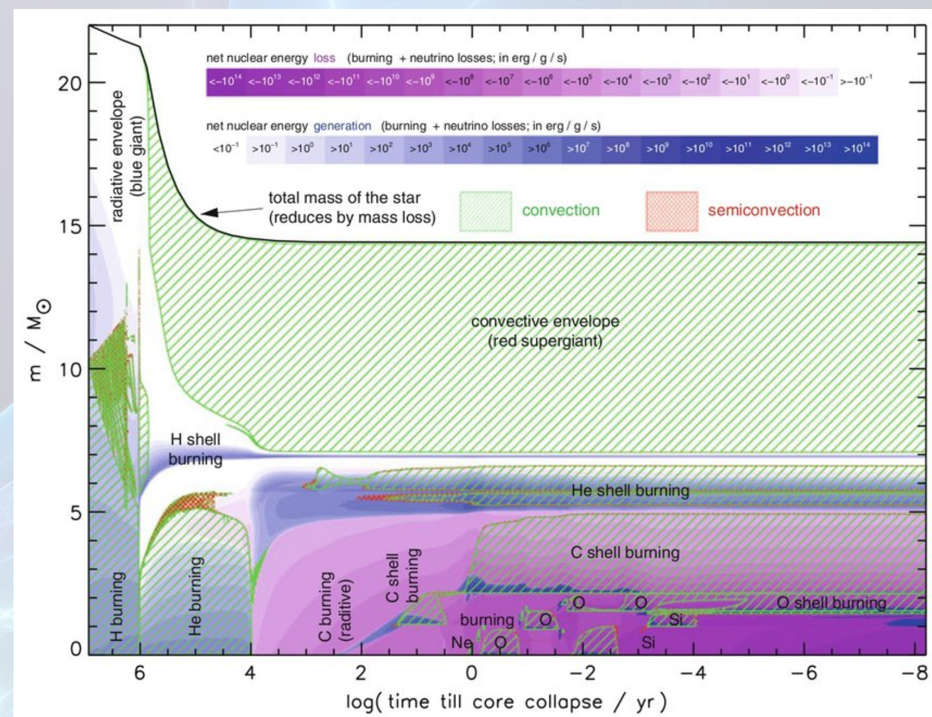
– massive stars's cores are convective
(the Sun's core is radiative!)

– supergiants' (aka post-MS massive stars') envelope is ***also*** convective
(will be important later, in binary interactions)

HRD vs. Kippenhahn

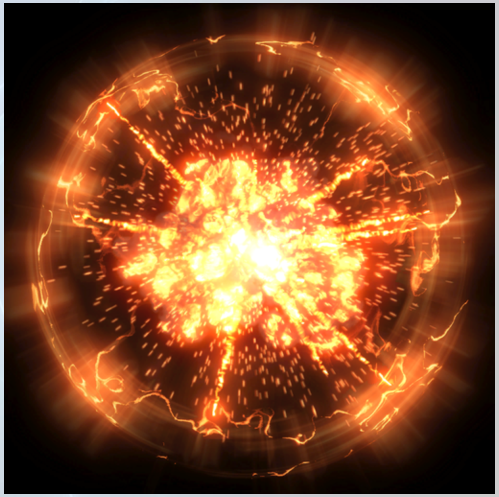
- surface T, L
  - helps observational comparison
- interior structure
  - e.g. pre-supernova structure, mixing…





Today…

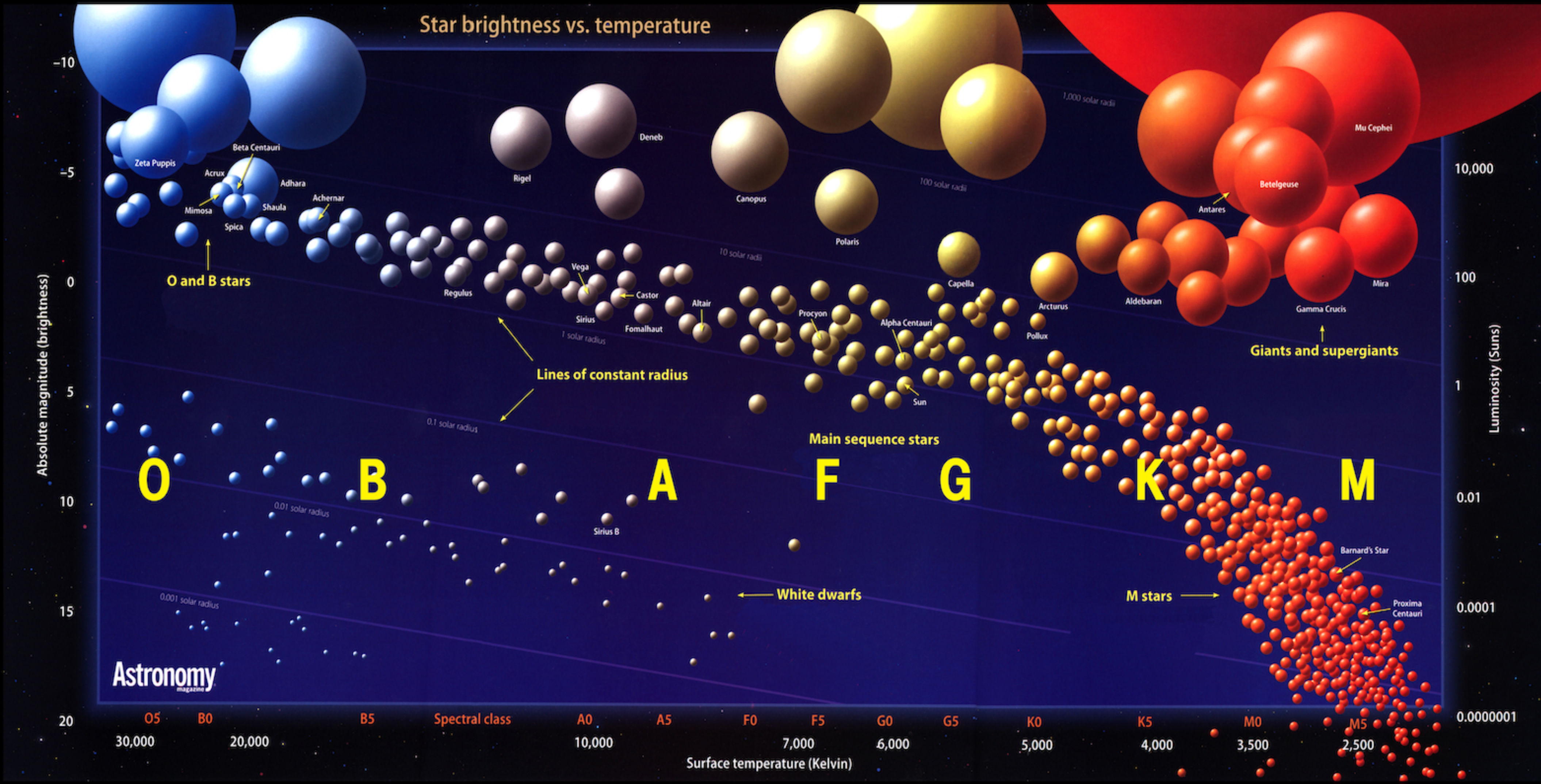
EXPLOSIONS!!

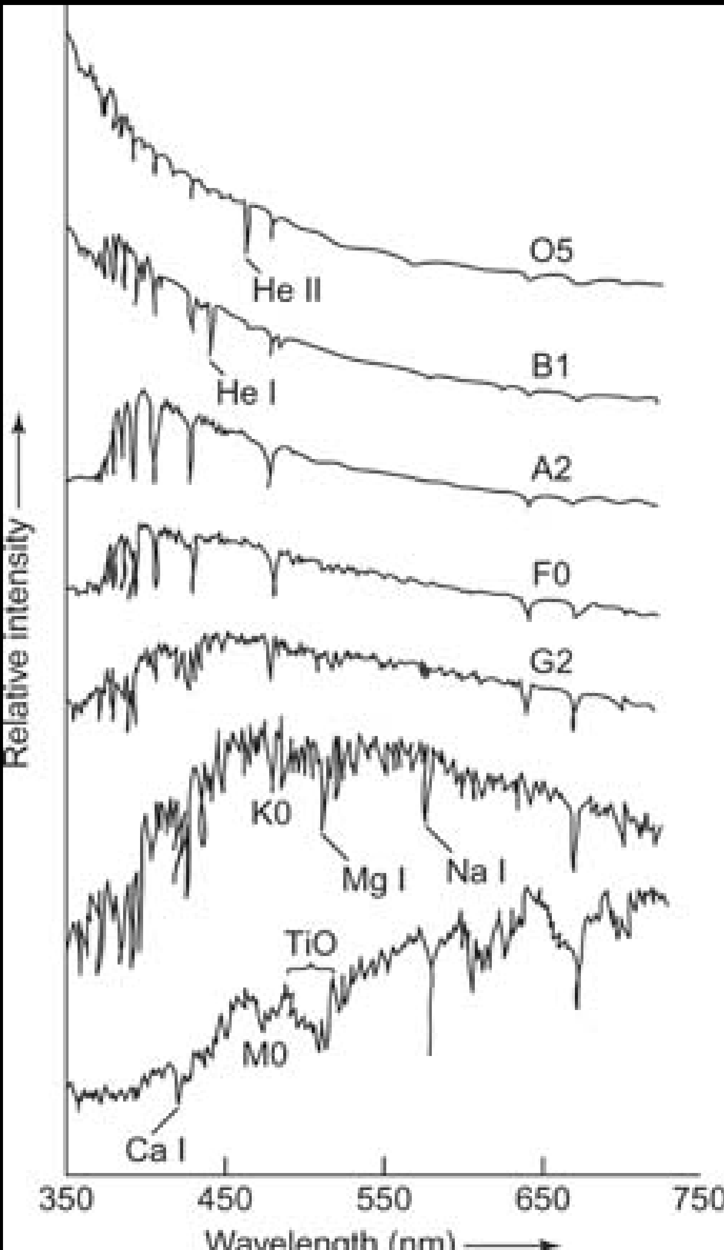


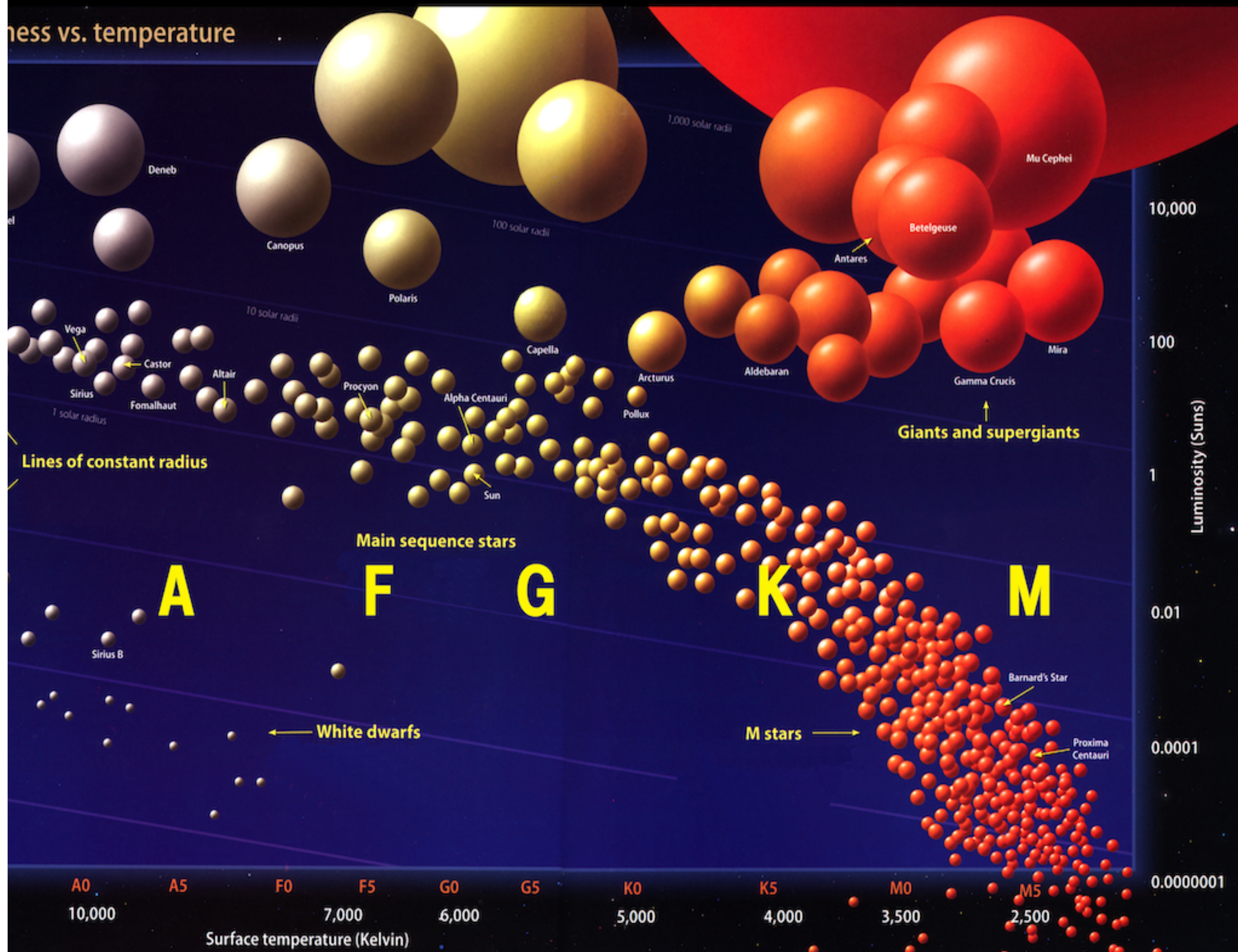
But before…

Stellar classification
and the Black Body approximation

Some history… :)


Star brightness vs. temperature
Absolute magnitude (brightness)
–10
–5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
Rigel
Deneb
Canopus
Polaris
Capella
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
Arcturus
Pollux
Aldebaran
Antares
Betelgeuse
Mu Cephei
Mira
Gamma Crucis
Barnard's Star
Proxima Centauri
Sirius B
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
0.001 solar radius
O and B stars
Lines of constant radius
Giants and supergiants
Main sequence stars
White dwarfs
M stars
O
B
A
F
G
K
M
O5
B0
B5
Spectral class
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
30,000
20,000
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)
Astronomy magazine


O5
He II
B1
He I
A2
F0
G2
K0
Mg I
Na I
TiO
M0
Ca I
Relative intensity
350
450
550
650
750
Wavelength (nm)


ness vs. temperature
Deneb
Canopus
Polaris
Mu Cephei
Betelgeuse
Antares
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
Capella
Arcturus
Pollux
Aldebaran
Mira
Gamma Crucis
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Sirius
Fomalhaut
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A
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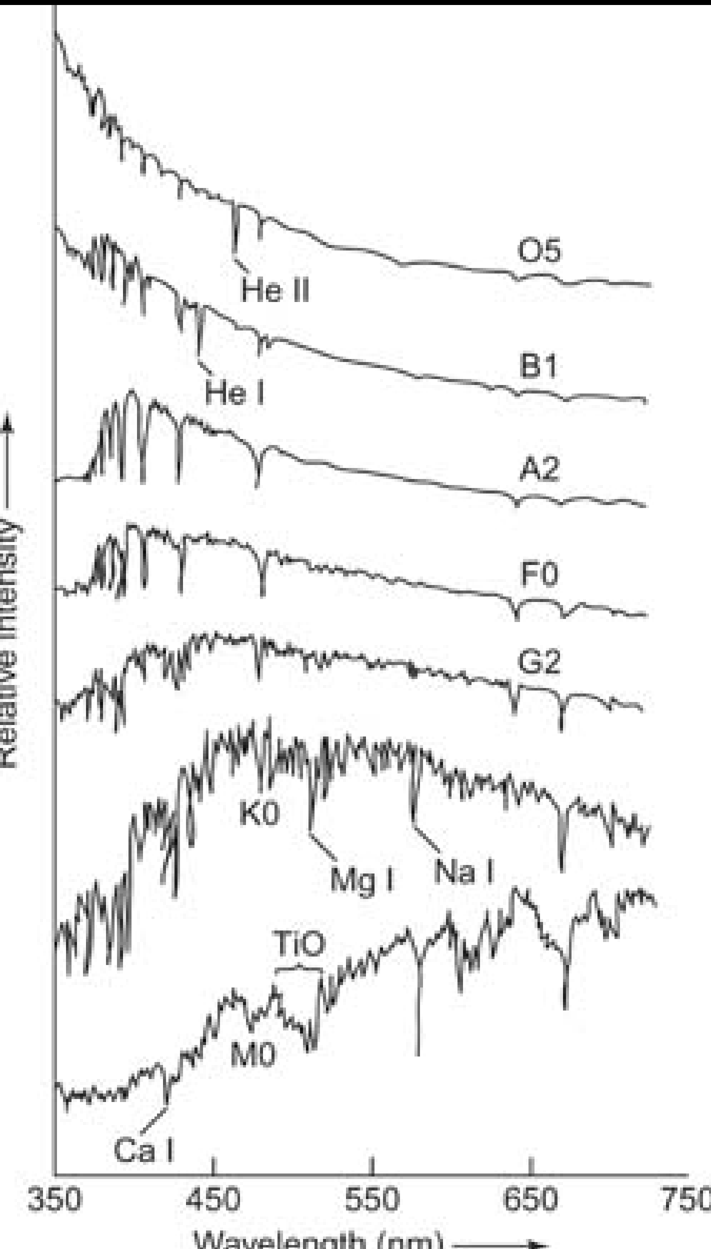
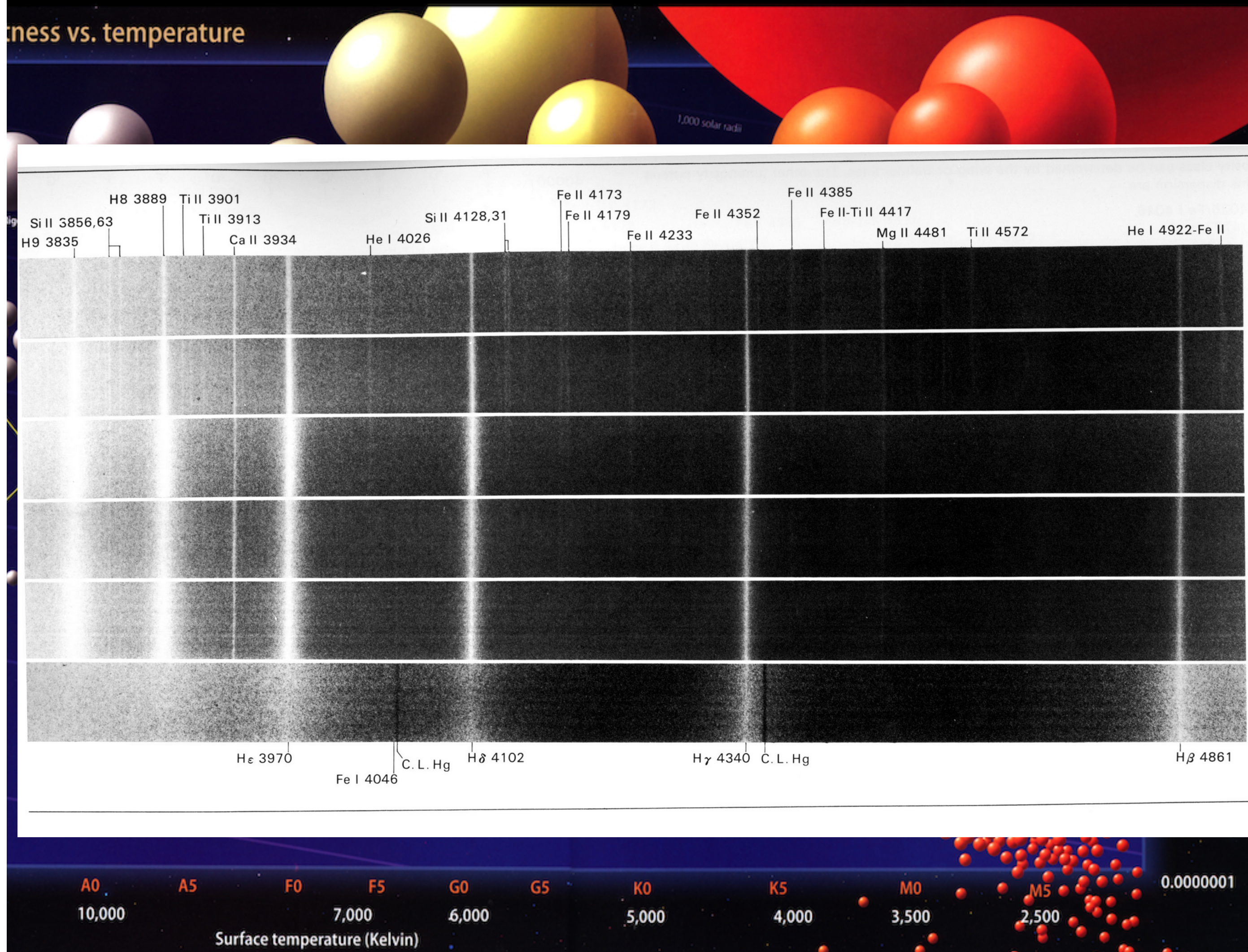
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)
10,000
100
1
0.01
0.0001
0.0000001
Luminosity (Suns)


O5
He II
B1
He I
A2
F0
G2
K0
Mg I
Na I
TiO
M0
Ca I
350
450
550
650
750
Wavelength (nm)


ness vs. temperature
1,000 solar radii
Si II 3856,63
H9 3835
H8 3889
Ti II 3901
Ti II 3913
Ca II 3934
He I 4026
Si II 4128,31
Fe II 4173
Fe II 4179
Fe II 4233
Fe II 4352
Fe II 4385
Fe II-Ti II 4417
Mg II 4481
Ti II 4572
He I 4922-Fe II
Hε 3970
Fe I 4046
C. L. Hg
Hδ 4102
Hγ 4340
C. L. Hg
Hβ 4861
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
10,000
7,000
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5,000
4,000
3,500
2,500
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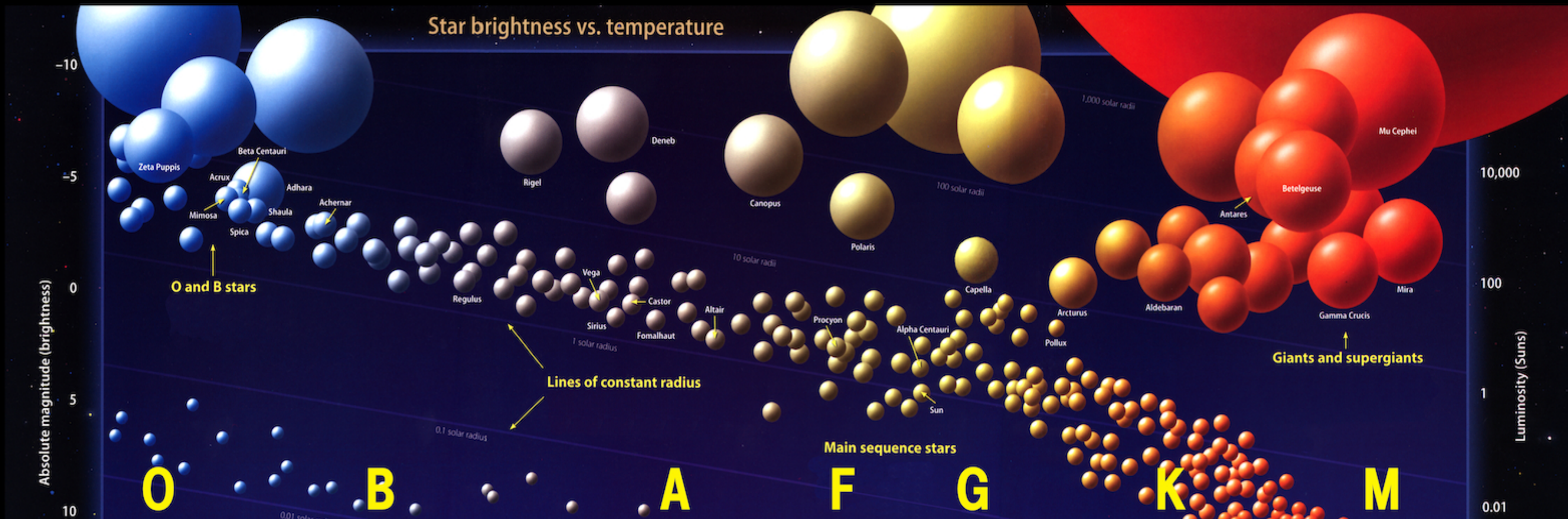
Surface temperature (Kelvin)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1,000 solar radii
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10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
O
B
A
F
G
K
M


Make sure to read more!

Suggested article:
"Women Astronomers
at Harvard at the Turn of the Century"

https://www.carleton.edu/goodsell/research/student-research/women/harvard/

...also: come to Torun Observatory ;) :D

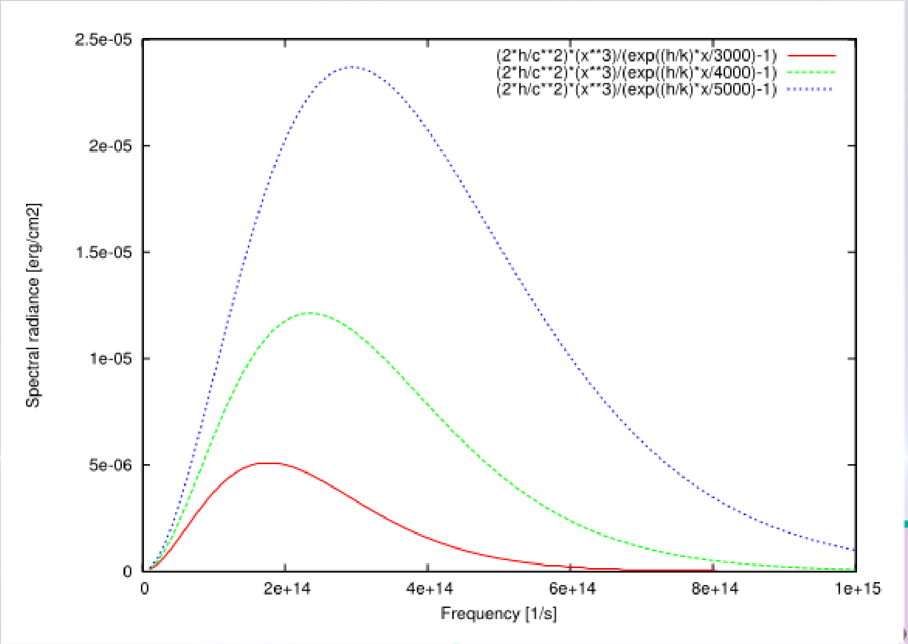
Planck law

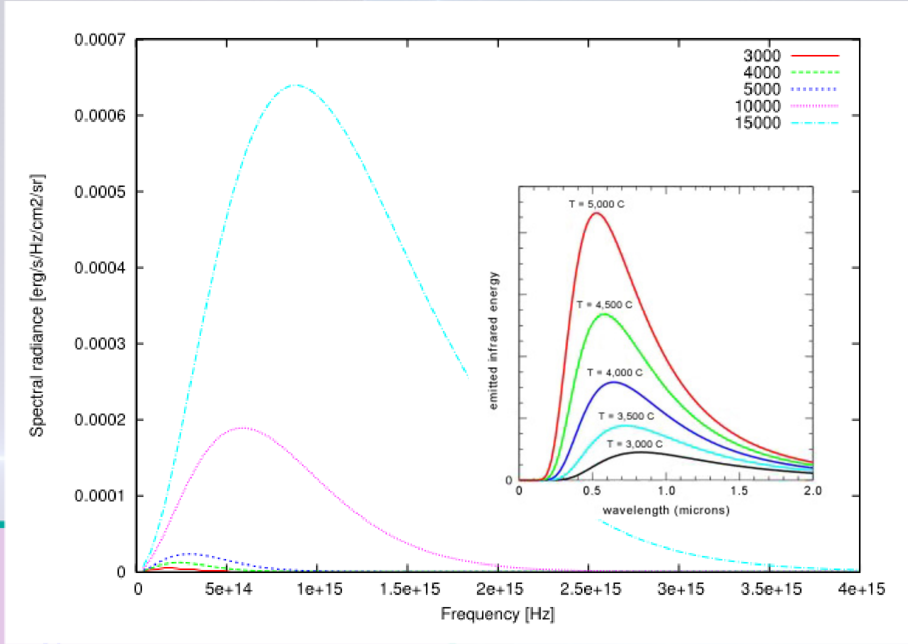
$$B(\nu, T_{eff}) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T_{eff}}} - 1} \qquad (3)$$

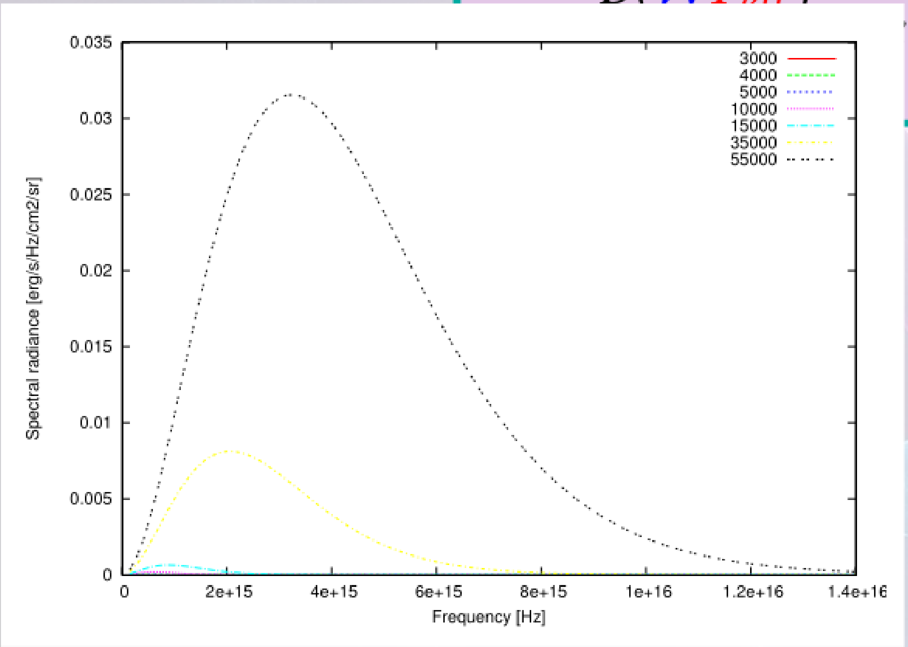
here: as a function of frequency
(works with wavelength as well)

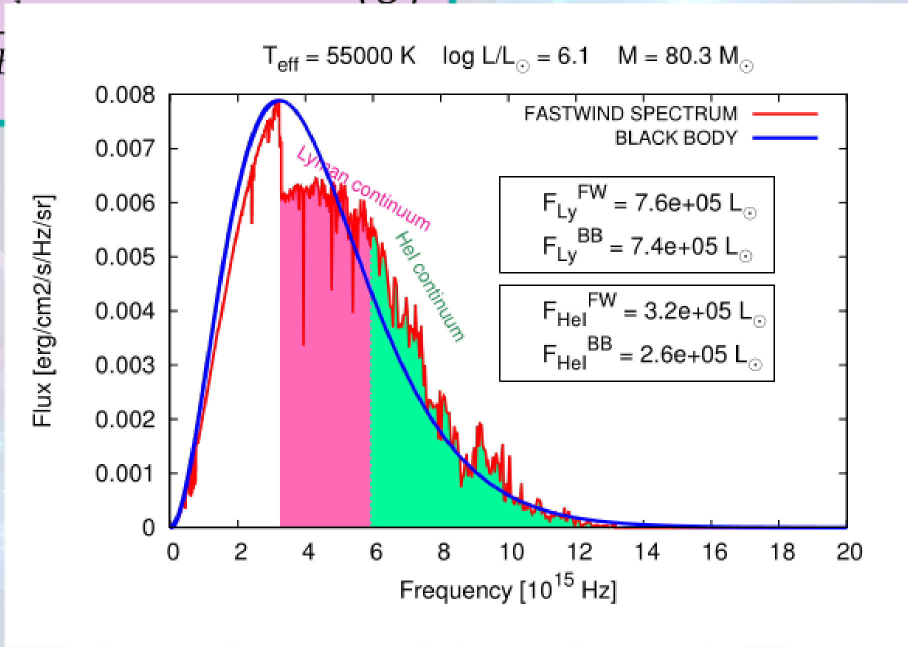
Note: there is a T value in it!

Radiation field of stars with different T_{eff}



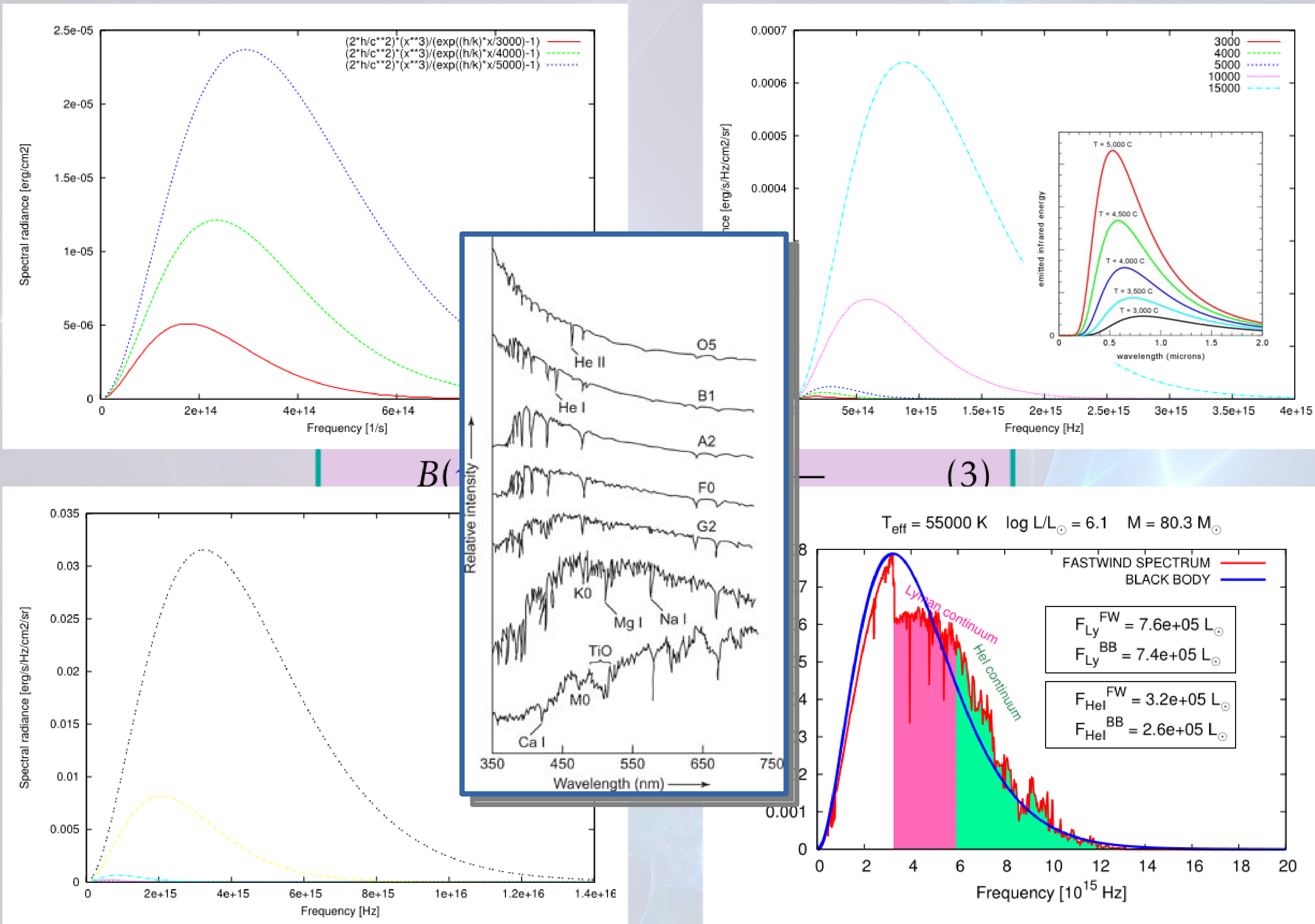






(3)

Radiation field of stars with different T_{eff}

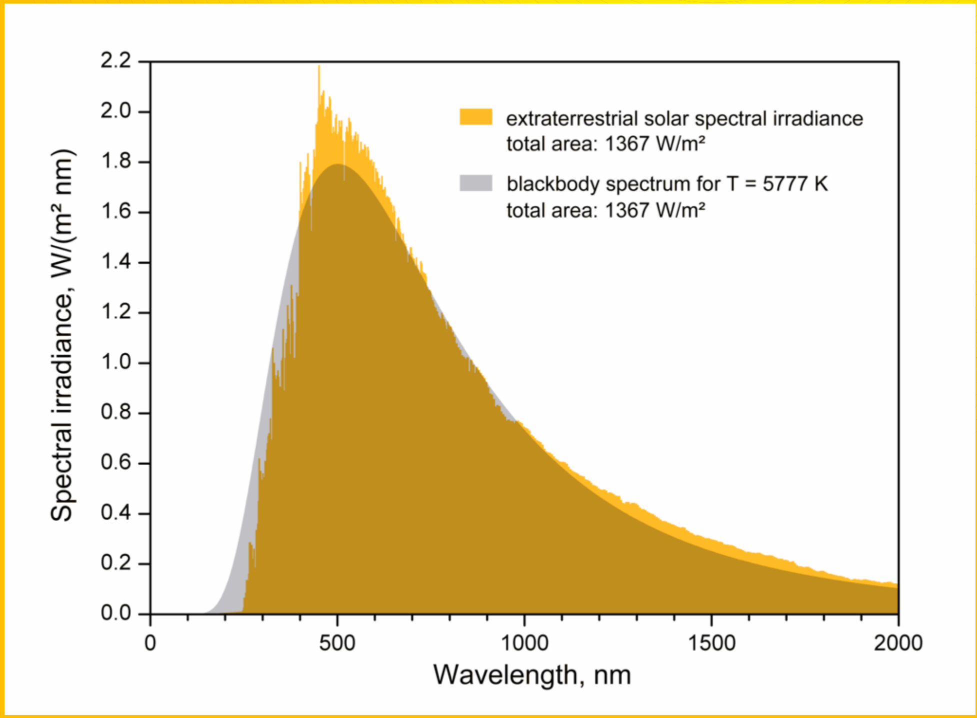


Moral of the story:

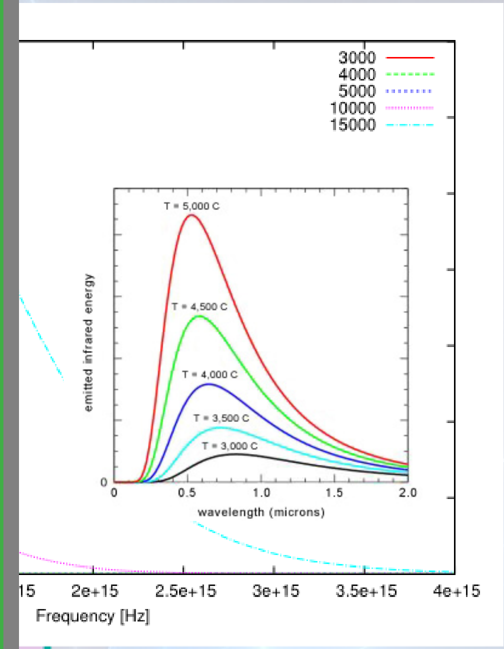
Stars are perfect Black Bodies.

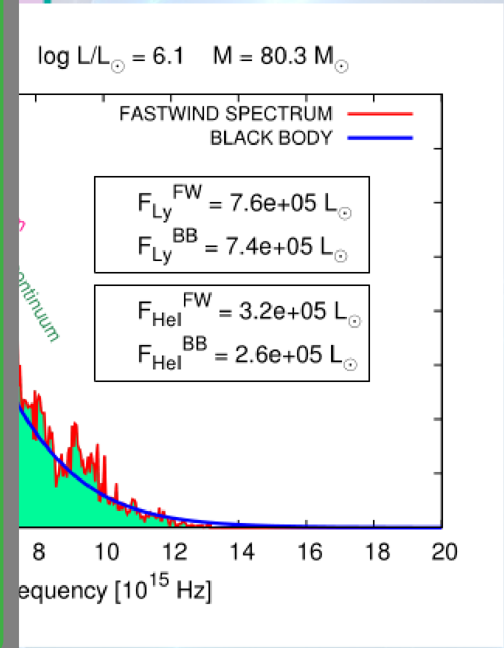
(Most of the time, more or less; but basically they are.)

Their T_{eff} in the HRD is the T_{eff} from the Planck law.



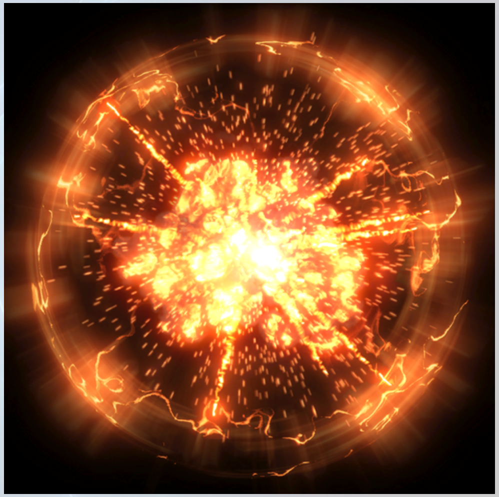
T_{eff}





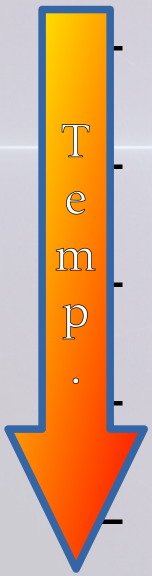
And now…

EXPLOSIONS!!

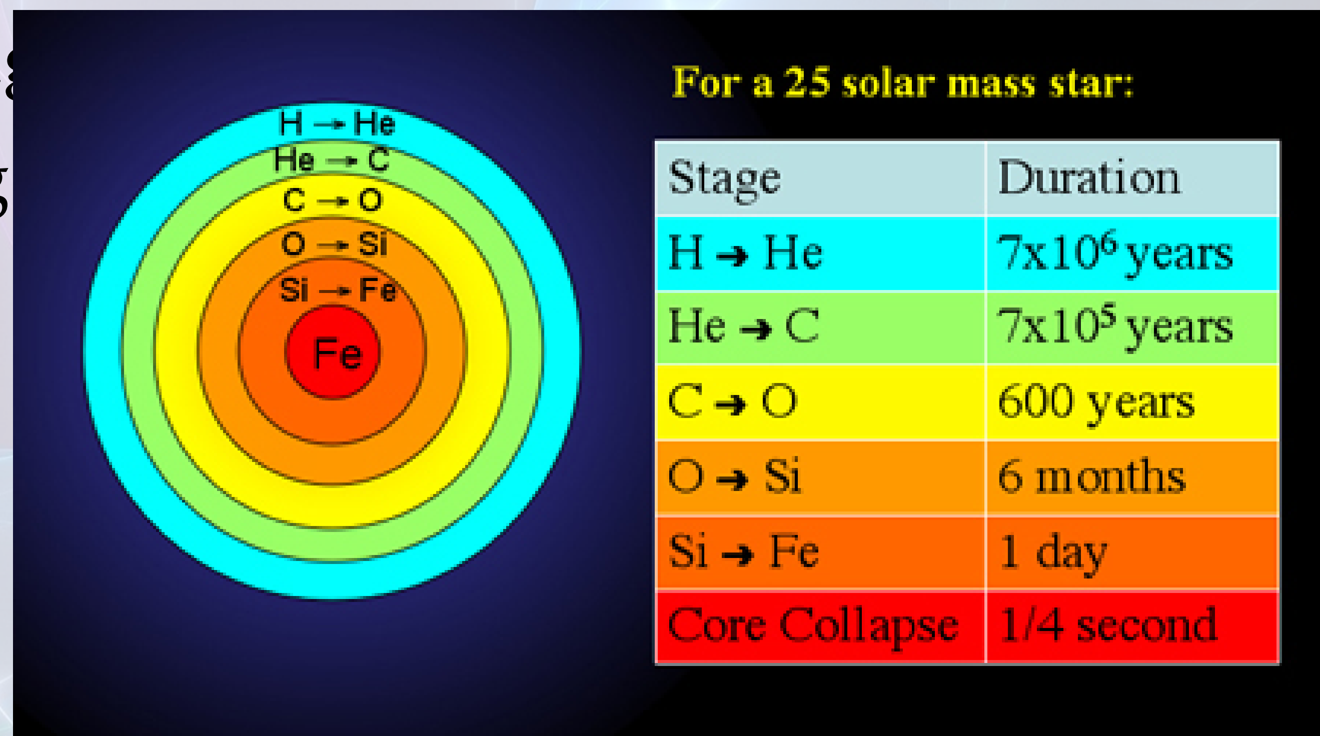


Pre-supernova structure – iron core

- Includes:



  - core-He-burning (& shell-H-burning)
  - core-C-burning (& shell-He & shell-H-burning)
  - core-O-burning (& shell-C, shell-He, shell-H…
  - core-Ne-burnin
  - core-Si-burning
- onion-structure



Stage	Duration
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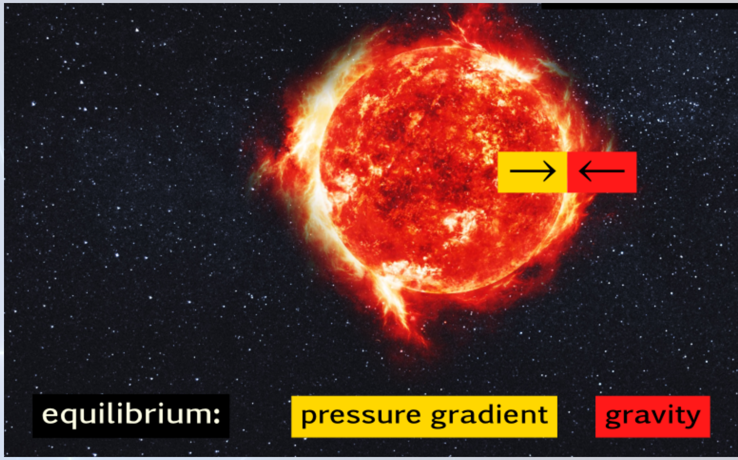
Core Collapse	1/4 second

Core collapse

- Gravity takes over
  - end of the long-term equilibrium
  - fall-in: on the free-fall timescale



Core collapse

- Gravity takes over
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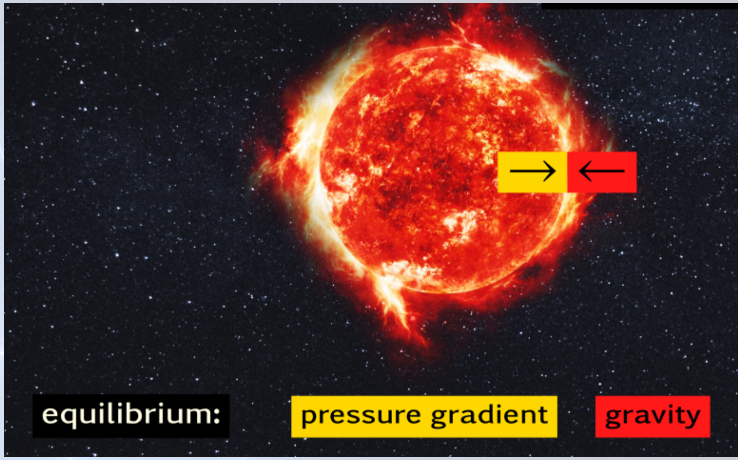
  - fall-in: on the free-fall timescale
- …is there something to stop it?
  - Well… it depends.



Core collapse

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- …is there something to stop it?
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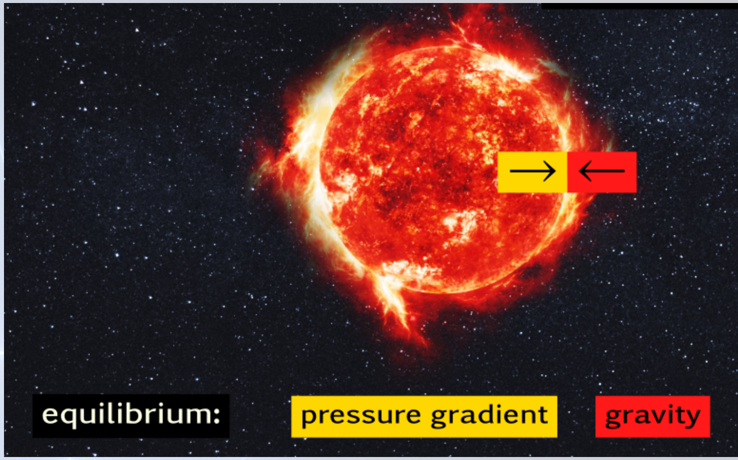
  - Most of the time (“classical” case): a neutron star forms in the center (“proto-neutron-star”)



Core collapse

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  - Well… it depends.
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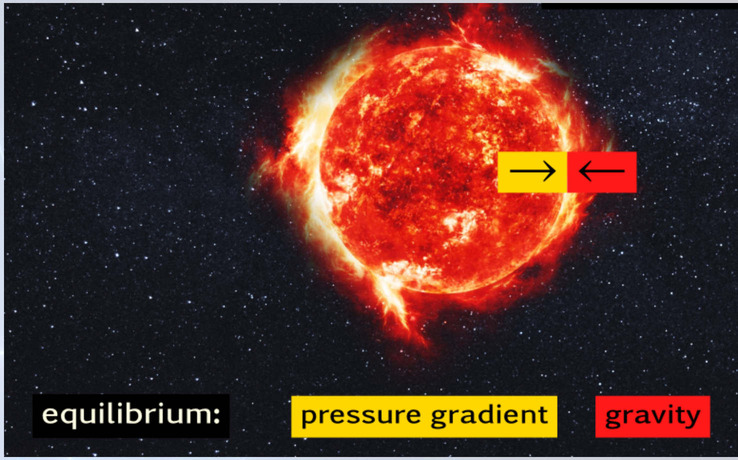
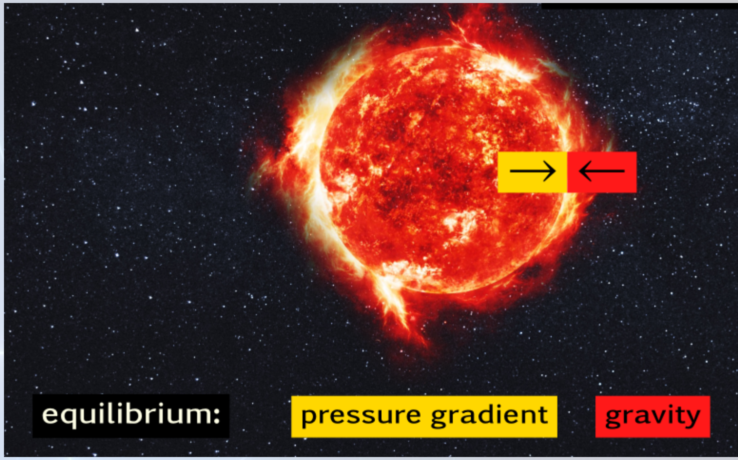
    - a neutron star is: one giant nucleus. dense. stable.



Core collapse



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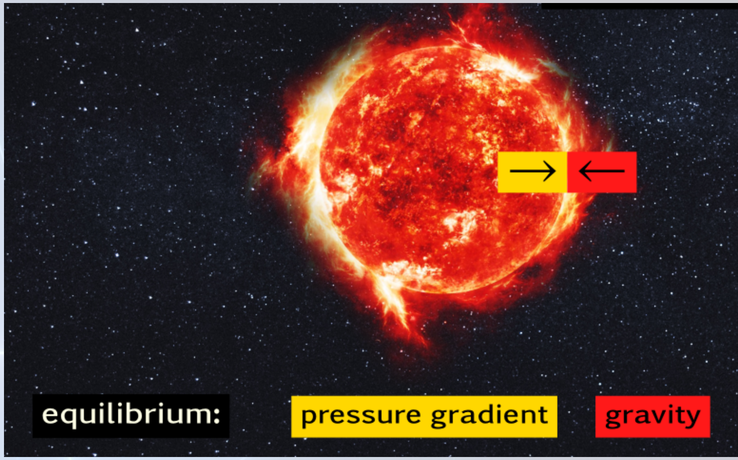

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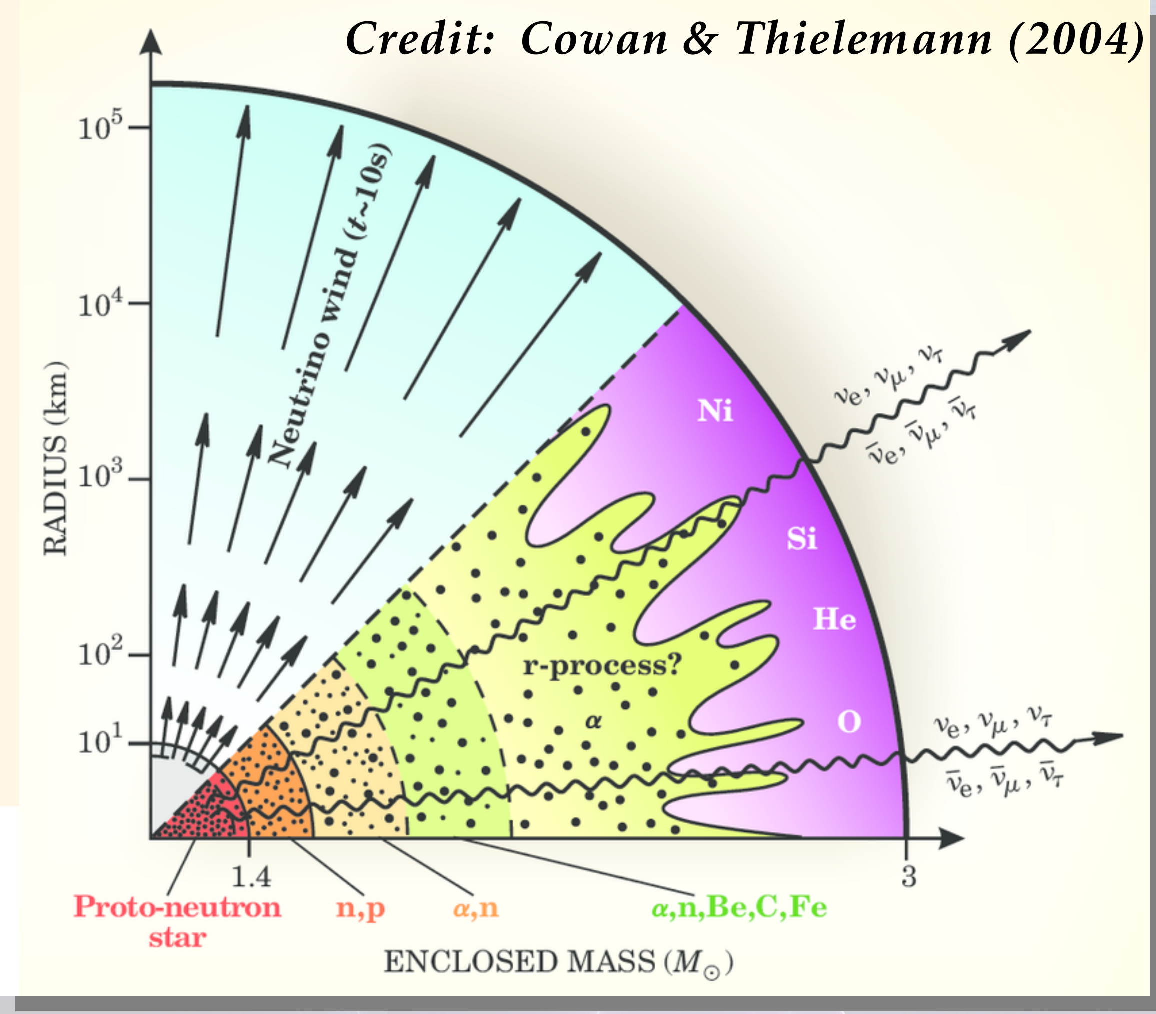

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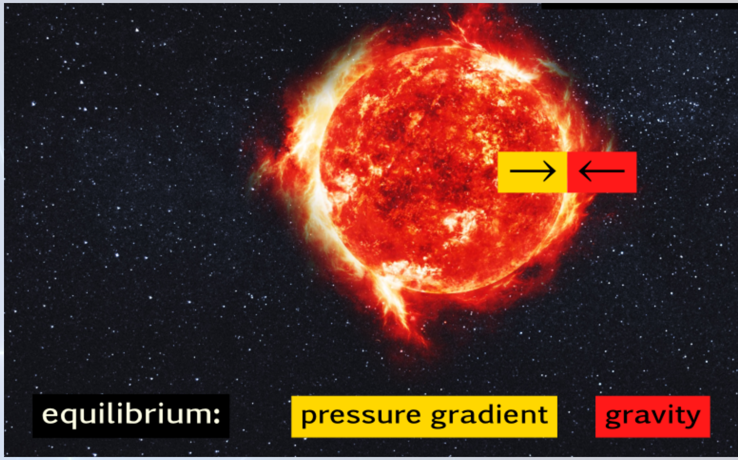

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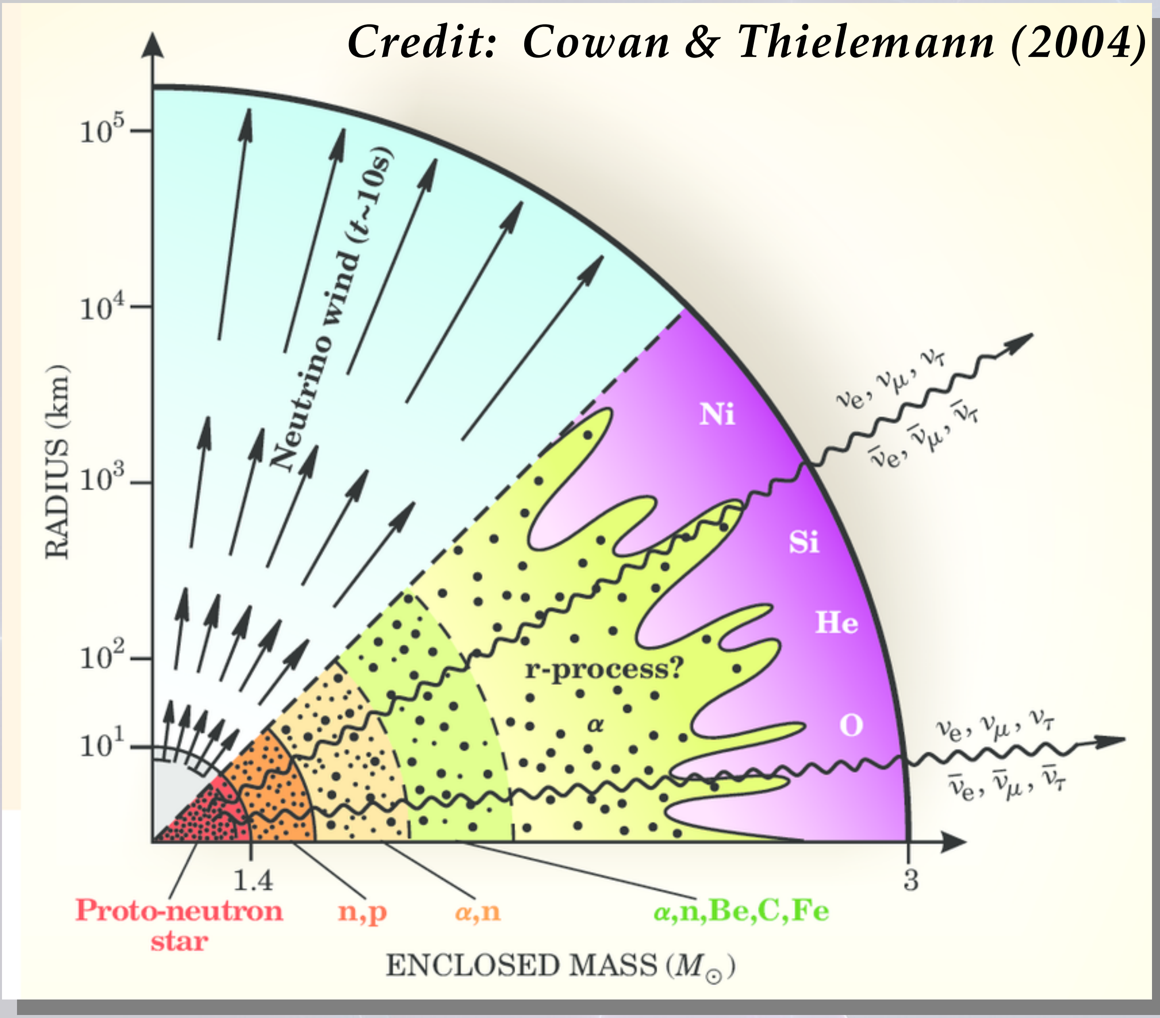
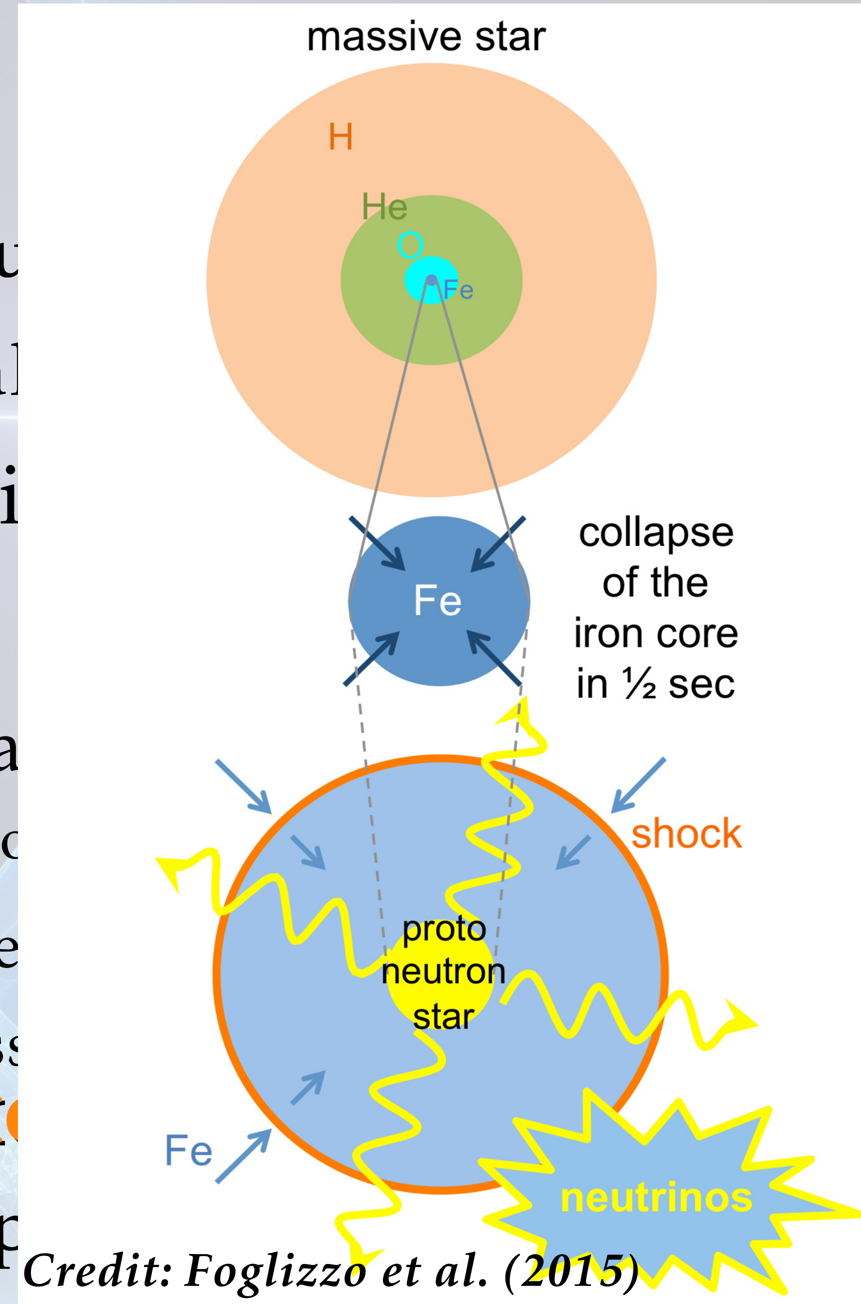


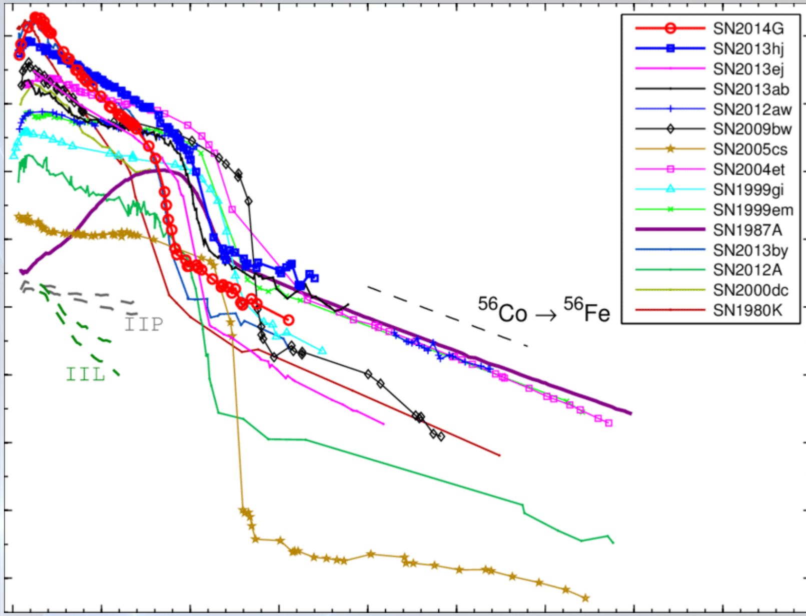
Credit: Cowan & Thielemann (2004)



Credit: Foglizzo et al. (2015)

Results of a CCSN

- supernova lightcurve
  - photons: emitted in the shock
  - observed at many wavelenths $=$ ***spectrum***
  - decay phase: ^{56}Co → ^{56}Fe
- explosive nuclear burning: r-process (**r**apid)
  - lots of free neutrons: rapid neutron-capture
  - elements heavier than iron
- remnant: NS… or BH



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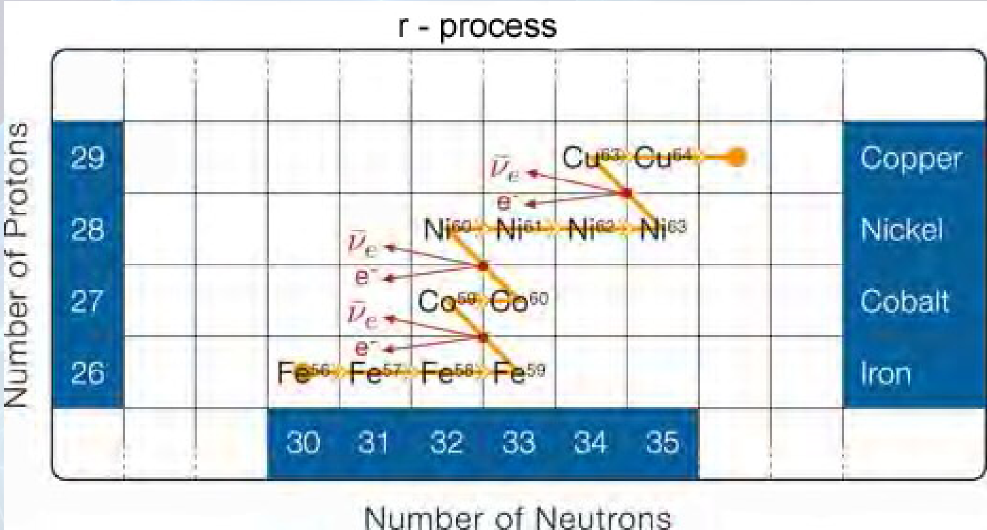
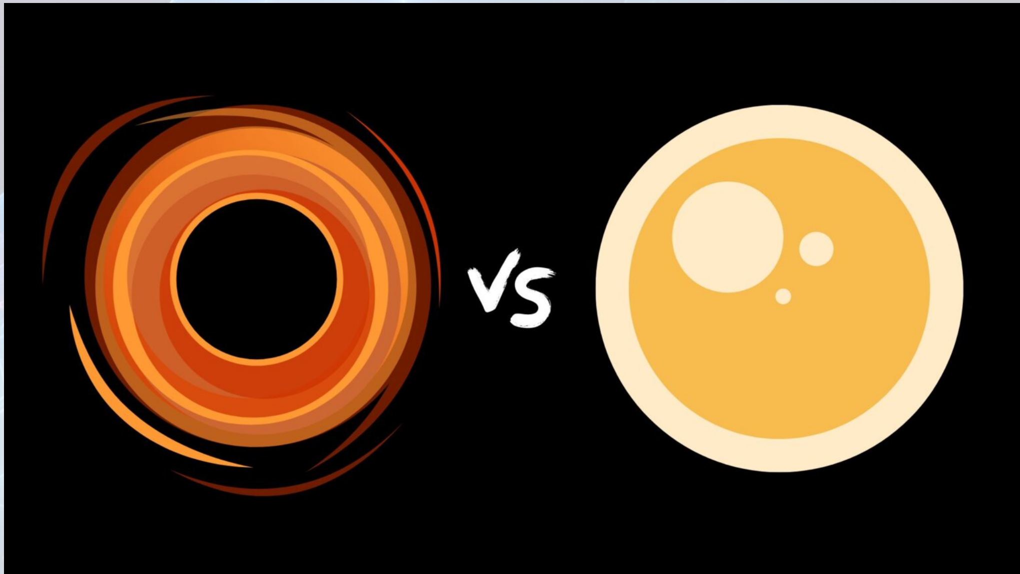


Fate of the proto-NS

- depends on the mass of the object
  - $M_{ini} < \sim 20\ M_{\odot}$: NS
  - $> \sim 20\ M_{\odot}$: BH
  - but… explosion physics is complicated (as is stellar evolution…)



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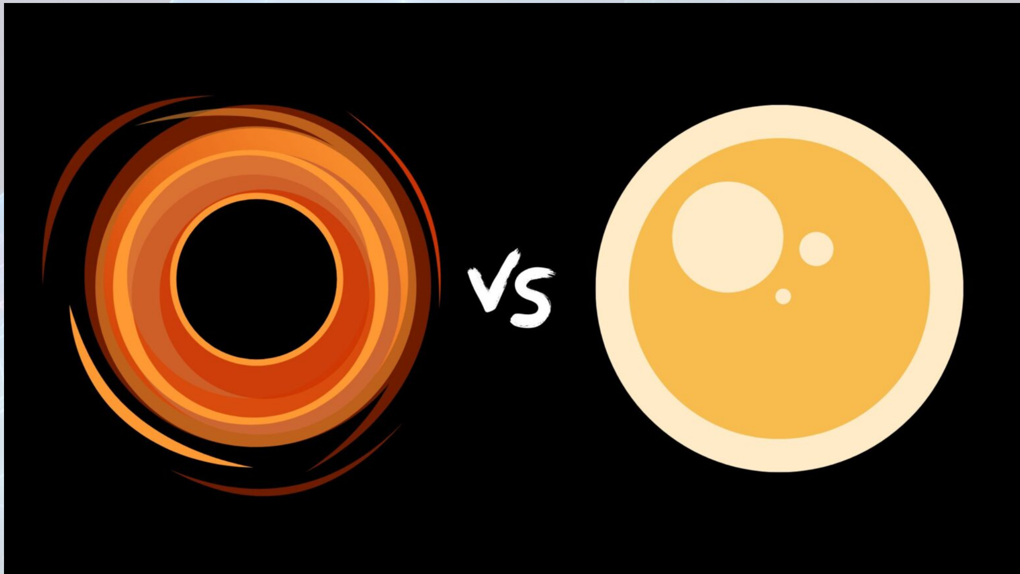

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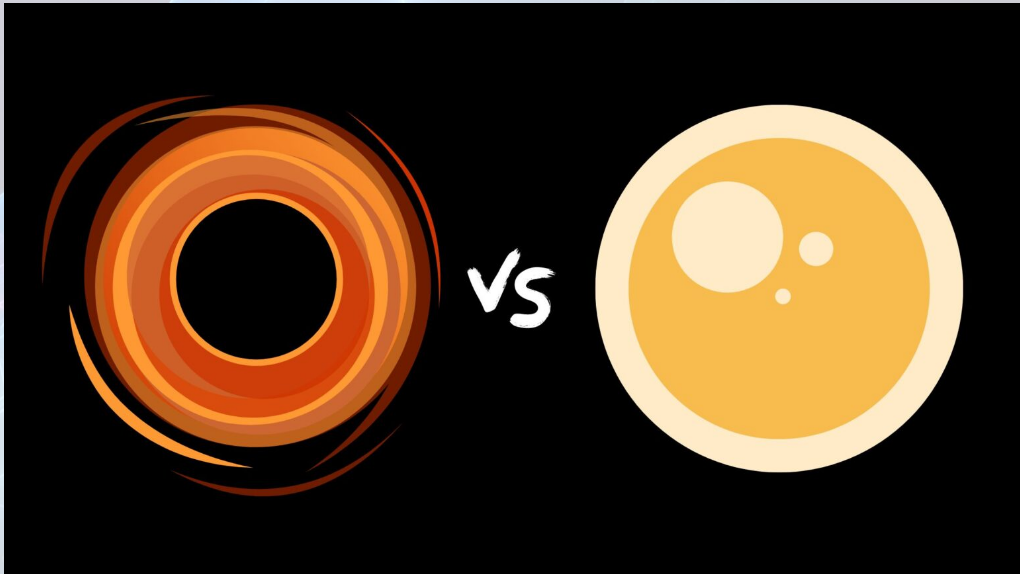

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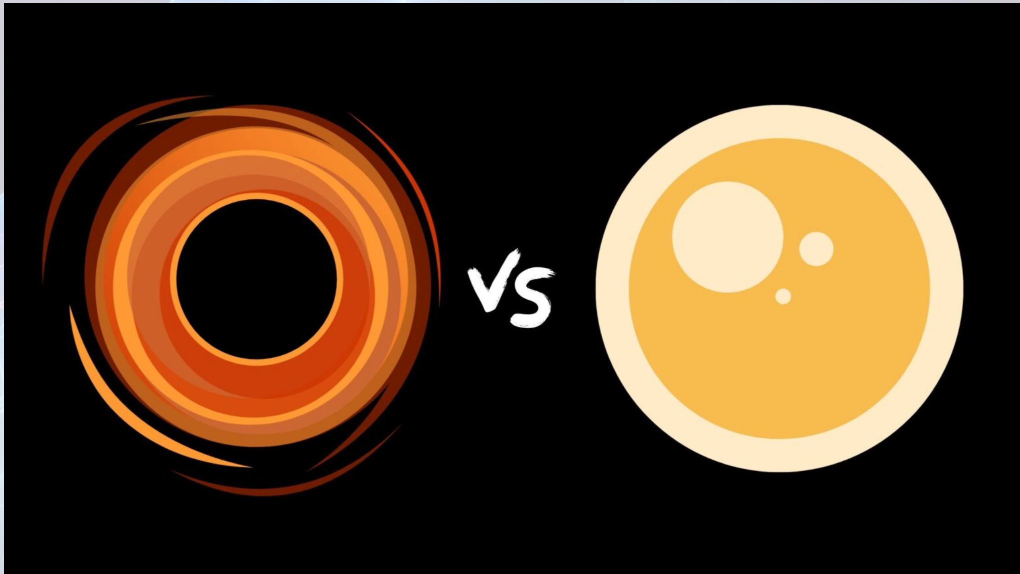

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***Not* the Chandrasekhar limit!** ~1.4 $M_\odot$
(= limit between NSs and white dwarfs)

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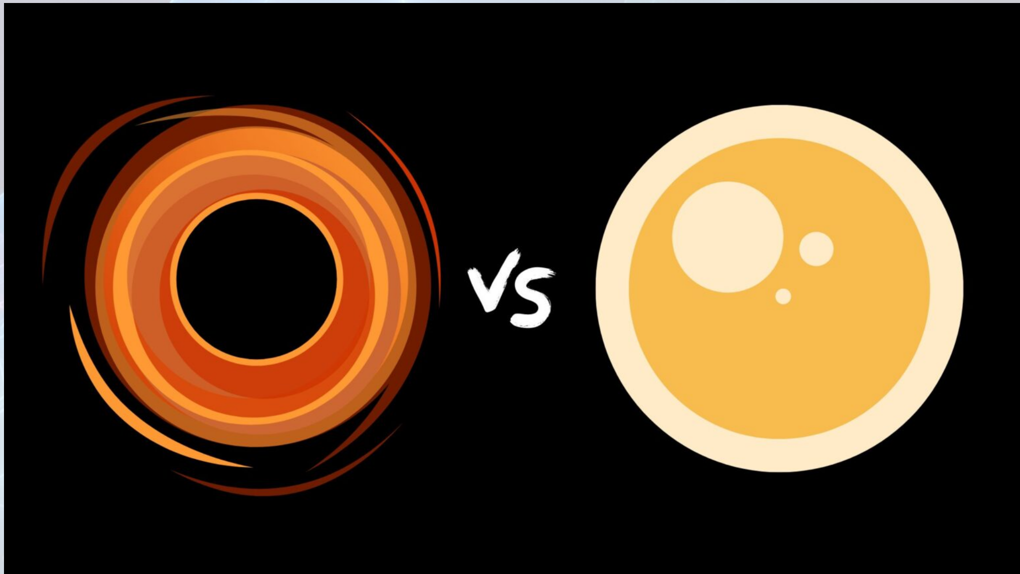

So far: core-collapse SNe

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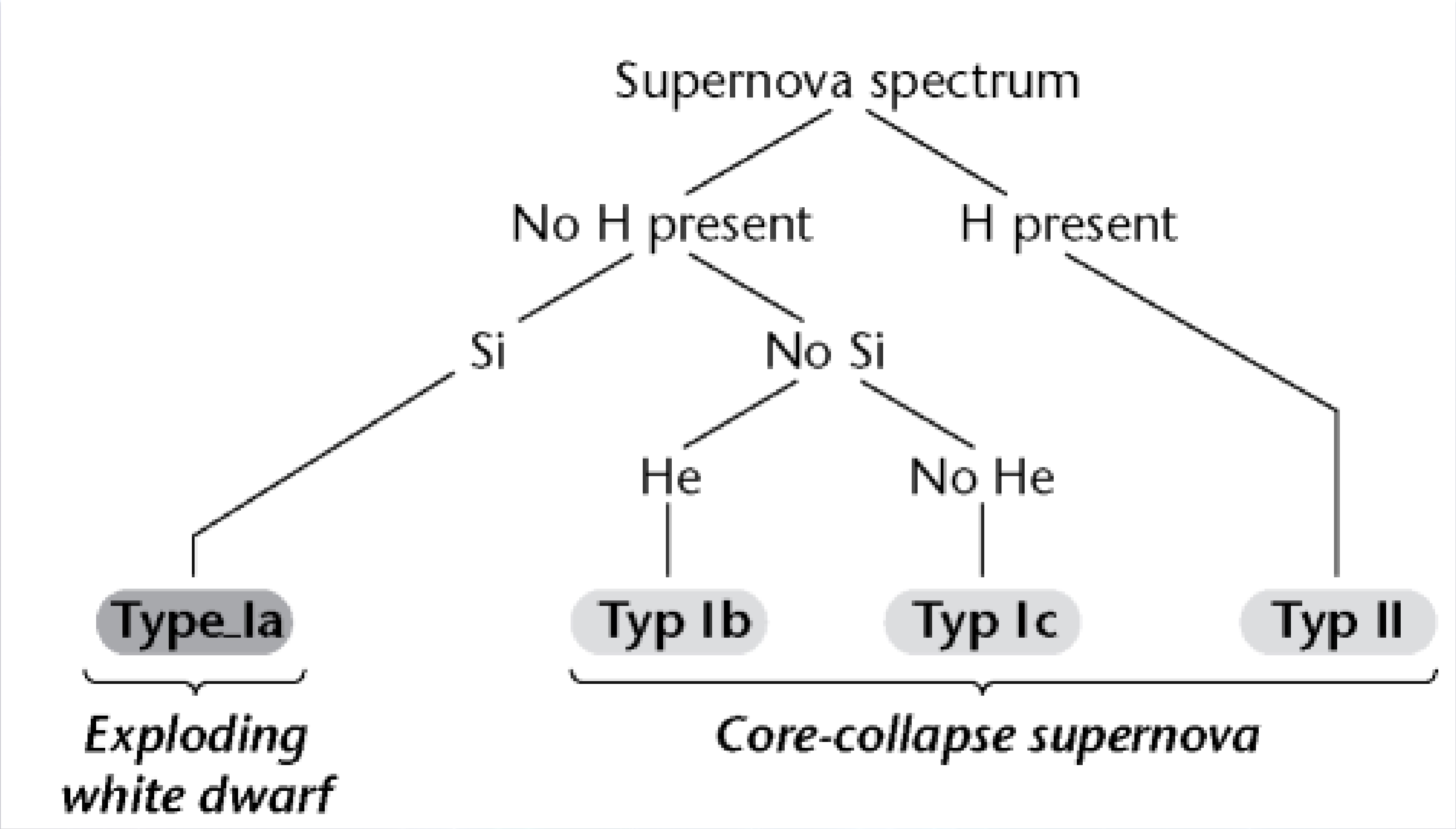

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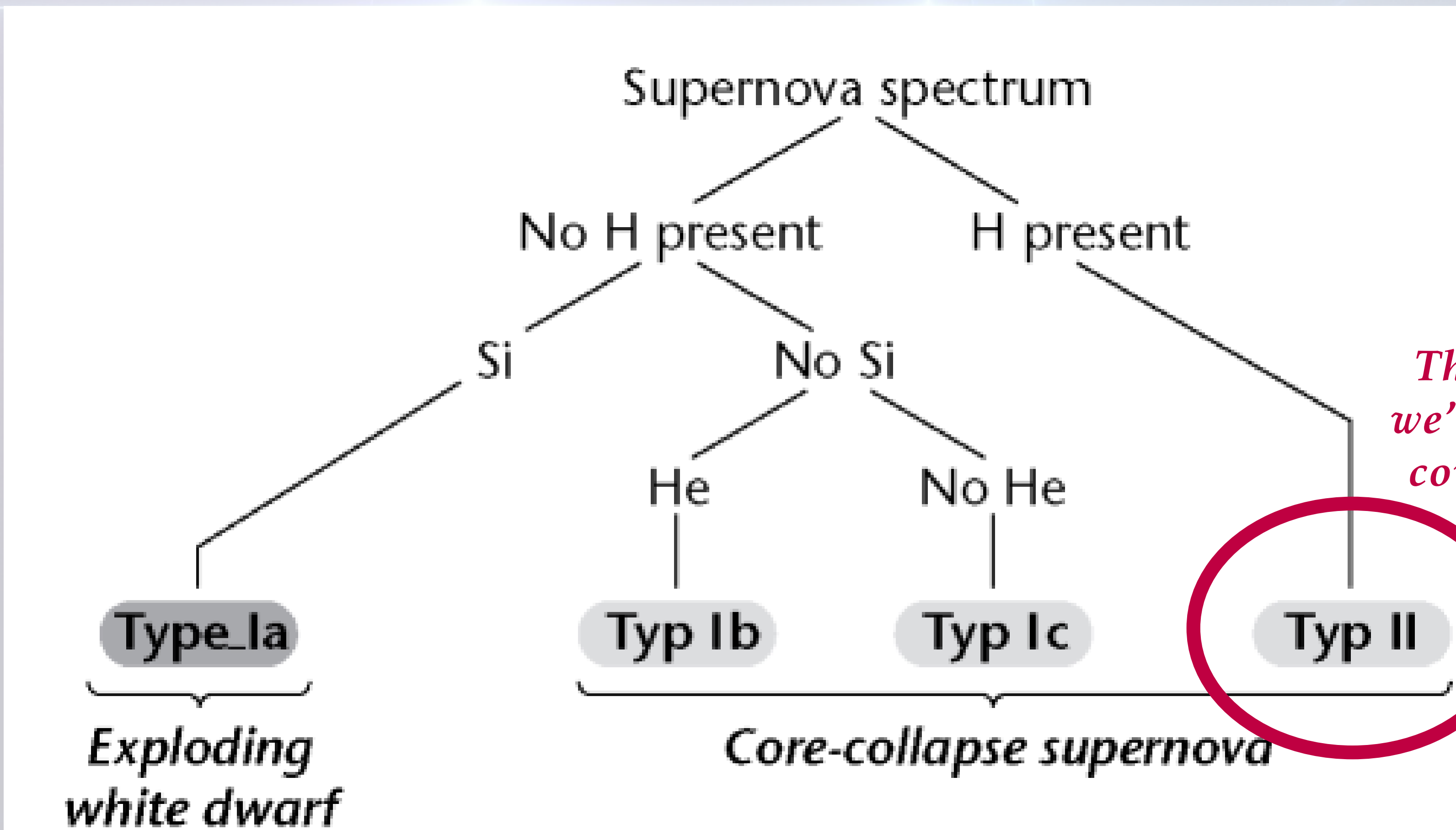
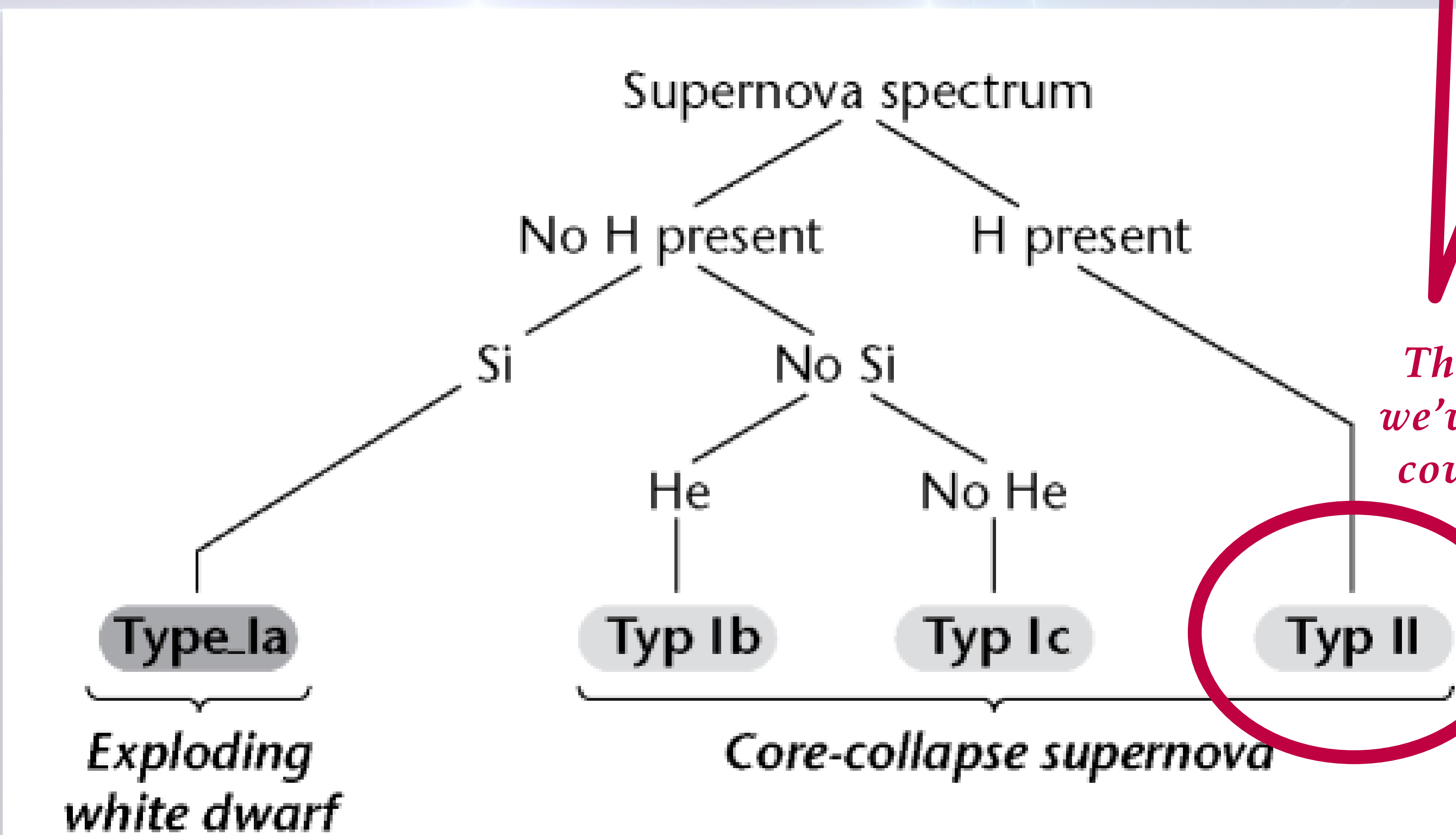


That's what we've actually covered here

So far: core-collapse SNe

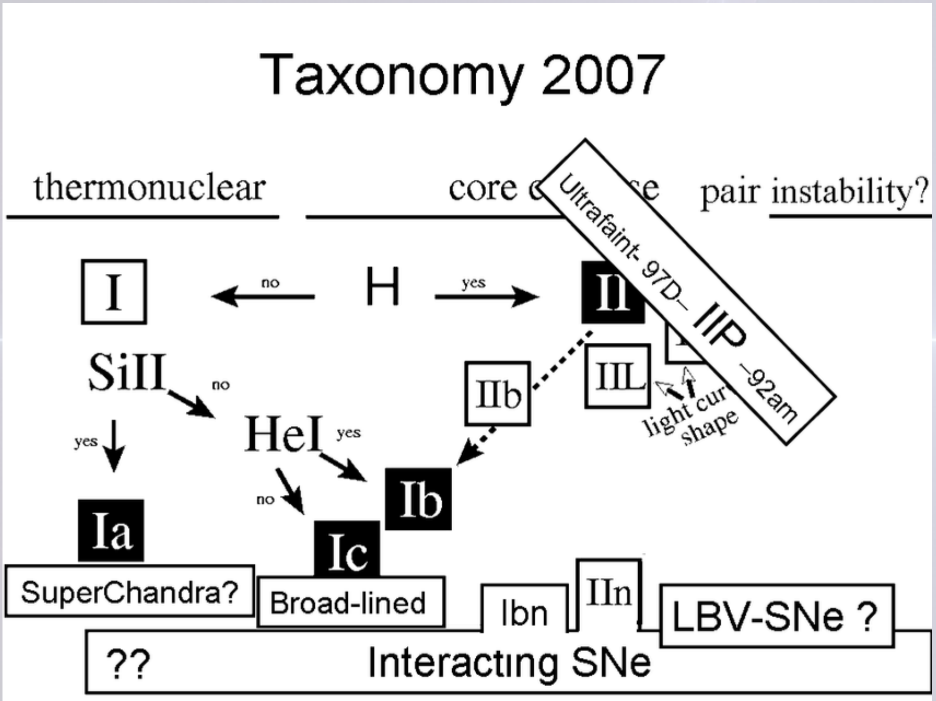
- There are so many other types…
- Classified by observers (simple picture):

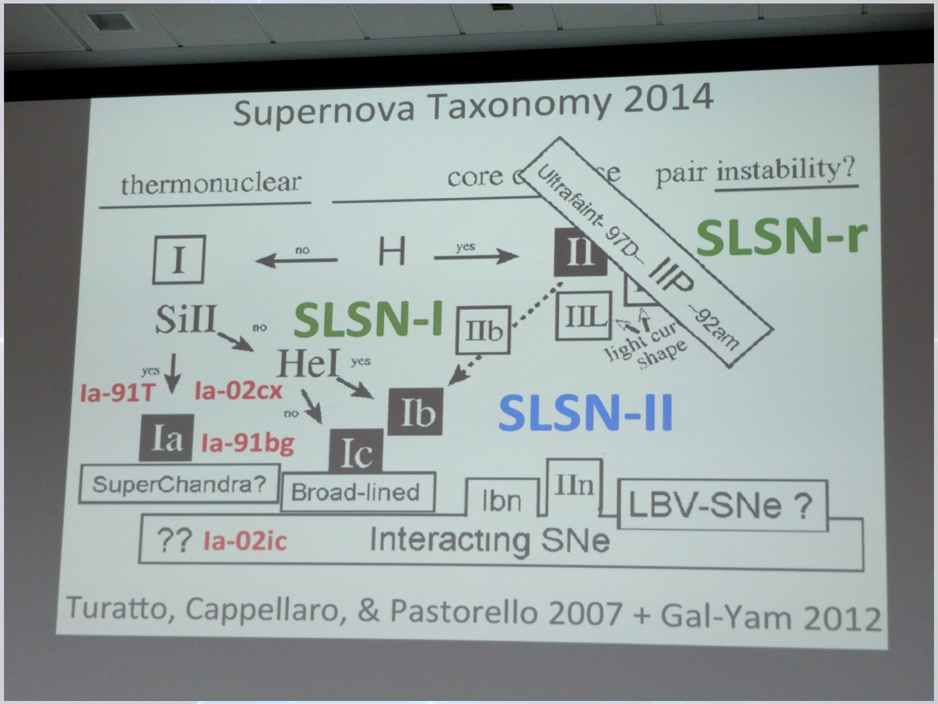
Progenitor:
a massive star with
a H-rich envelope

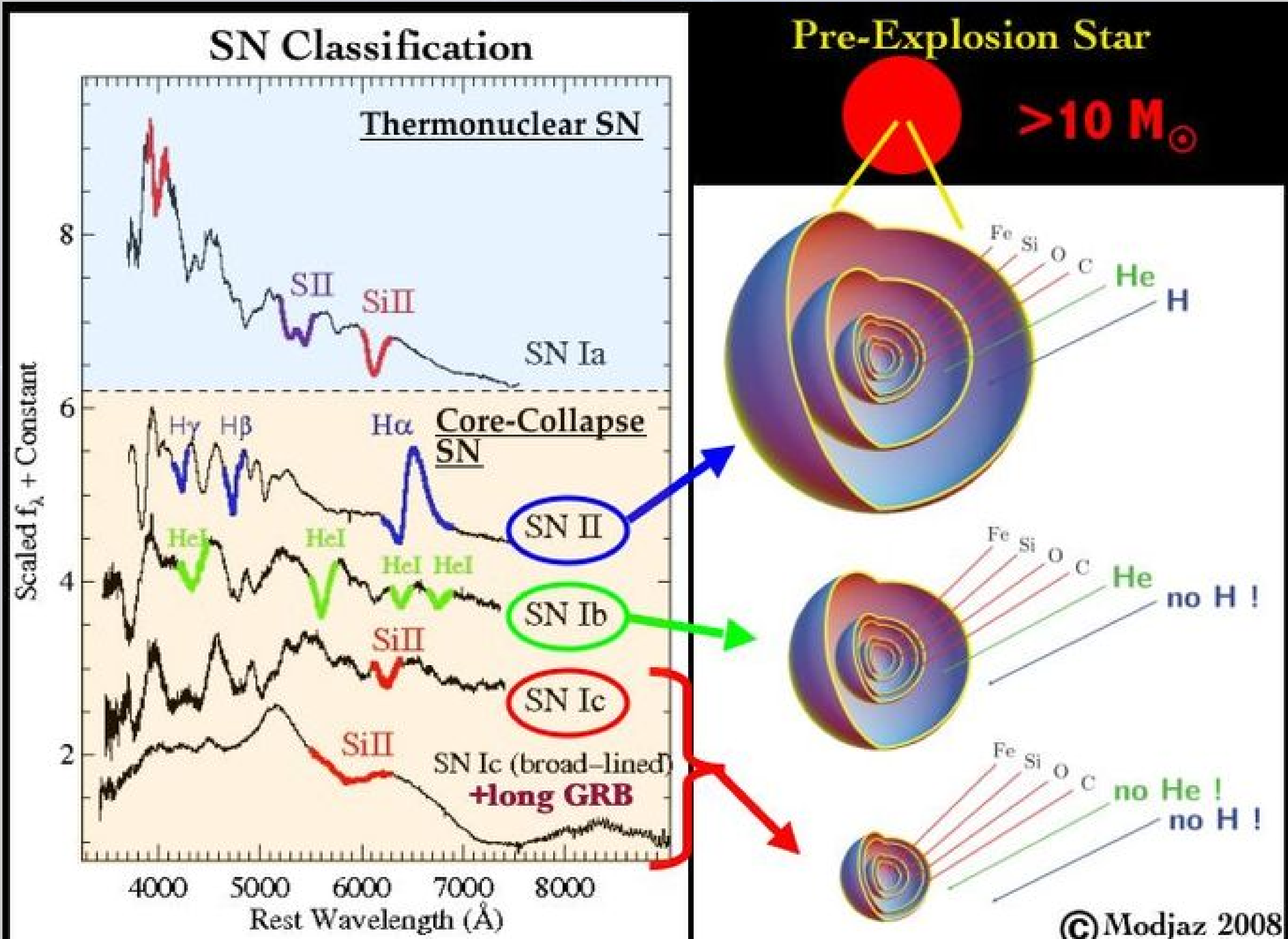


That's what we've actually covered here

Full supernova taxonomy *as of 2022?*







SN Classification
Thermonuclear SN
SII
SiII
SN Ia
Core-Collapse SN
Hγ
Hβ
Hα
SN II
HeI
HeI
HeI
HeI
SN Ib
SiII
SN Ic
SiII
SN Ic (broad-lined)
+long GRB
Scaled f_λ + Constant
2
4
6
8
4000
5000
6000
7000
8000
Rest Wavelength (Å)
Pre-Explosion Star
>10 $M_\odot$
Fe
Si
O
C
He
H
Fe
Si
O
C
He
no H !
Fe
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O
C
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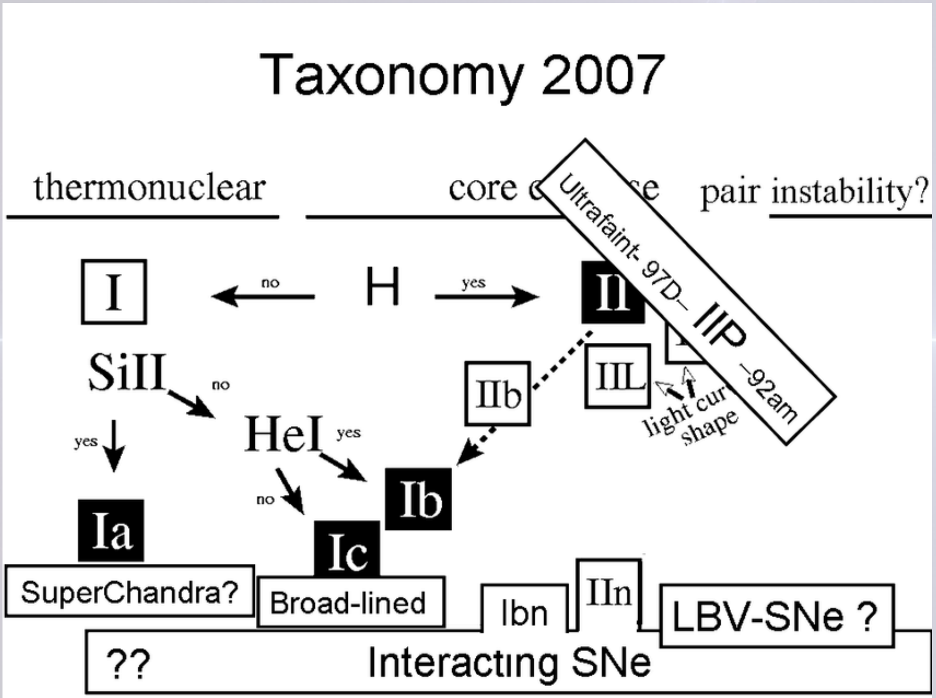

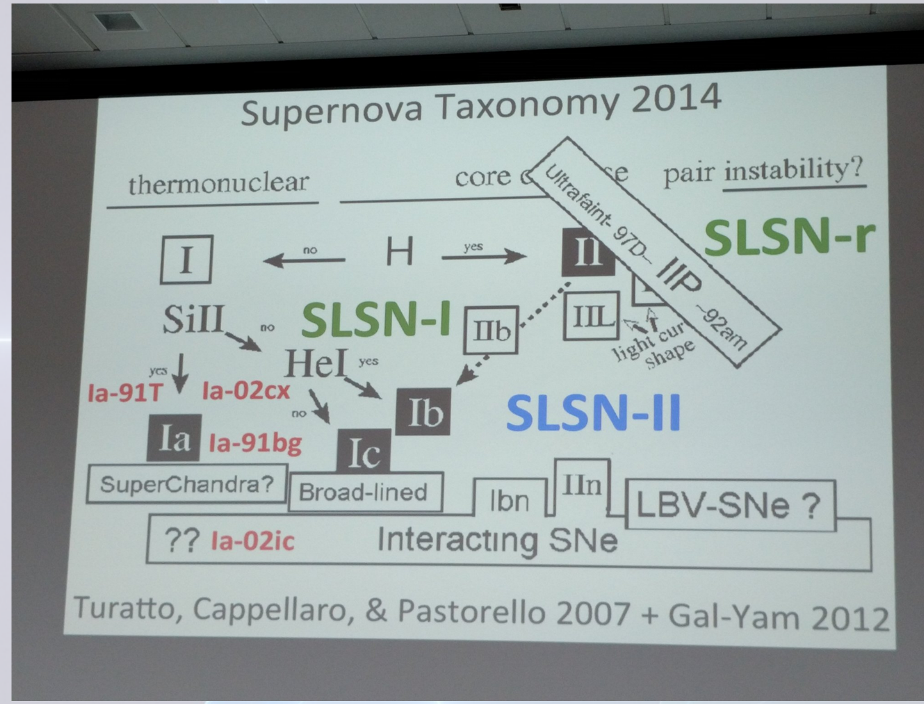

Need to consider additionally (at the very least):

– rotation (leading to e.g. Gamma-ray bursts or Superluminous SNe)
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– binarity (leading to, basically, anything we want but also to GWs)

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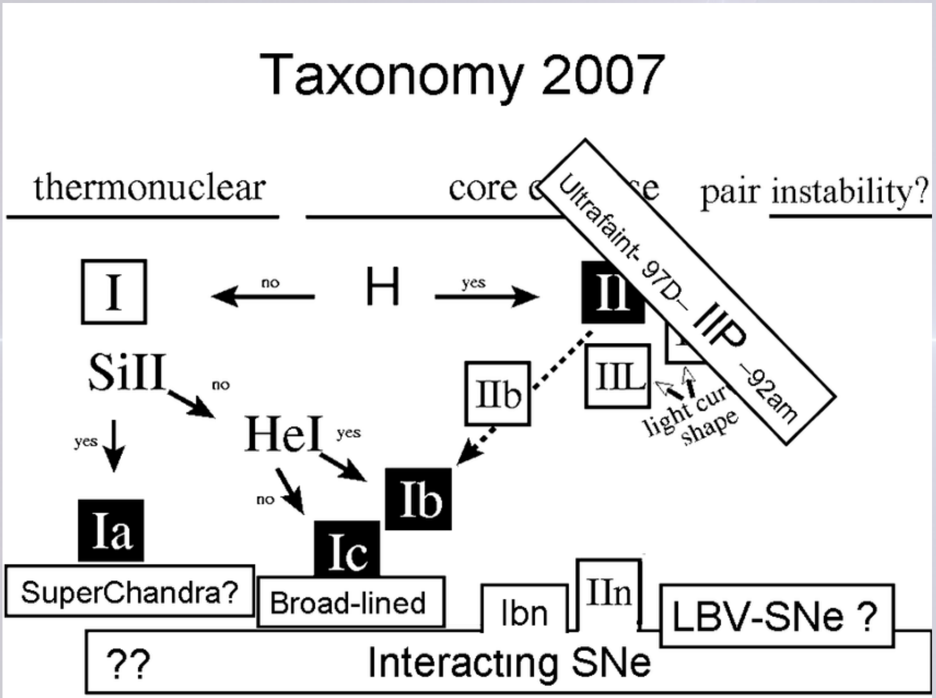

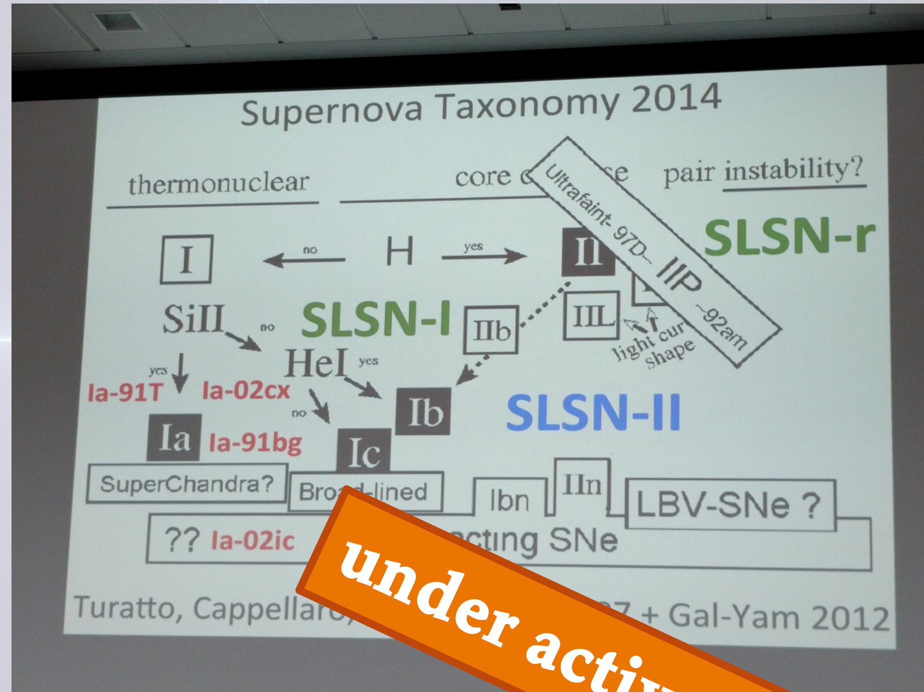

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