Gravitational-wave progenitors

Dorottya Szécsi

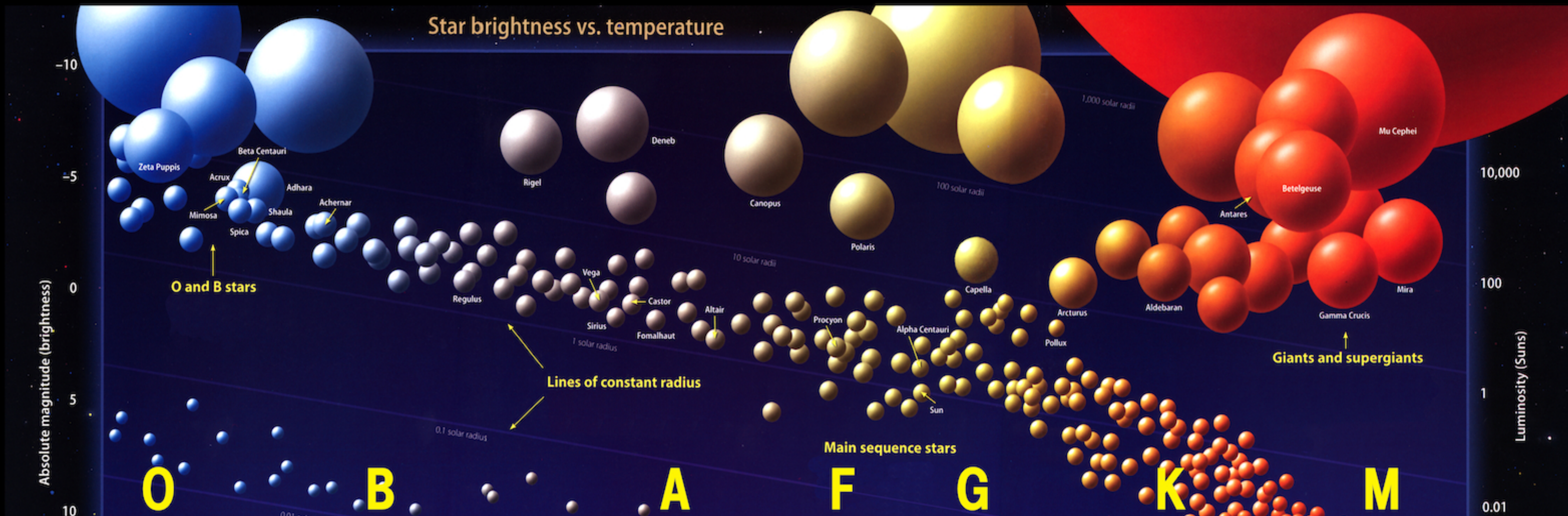
dorottya.szecsi@gmail.com

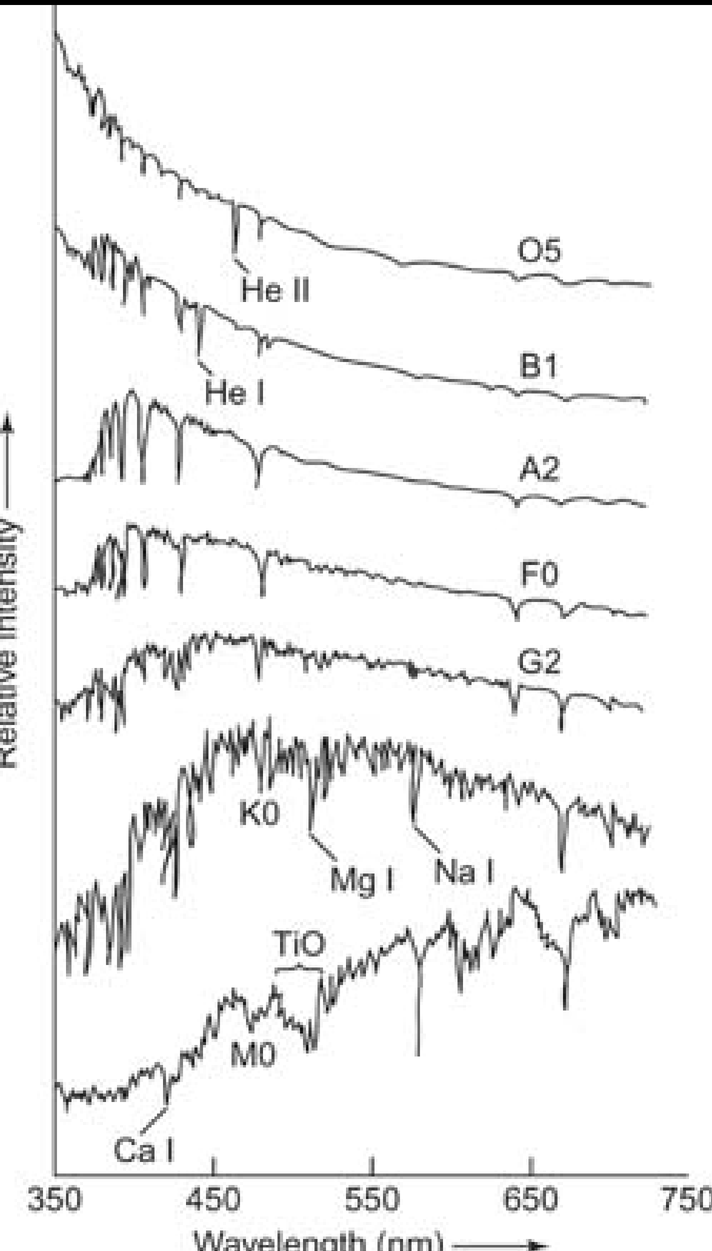
Lecture #6

NCU, Summer Semester 2022

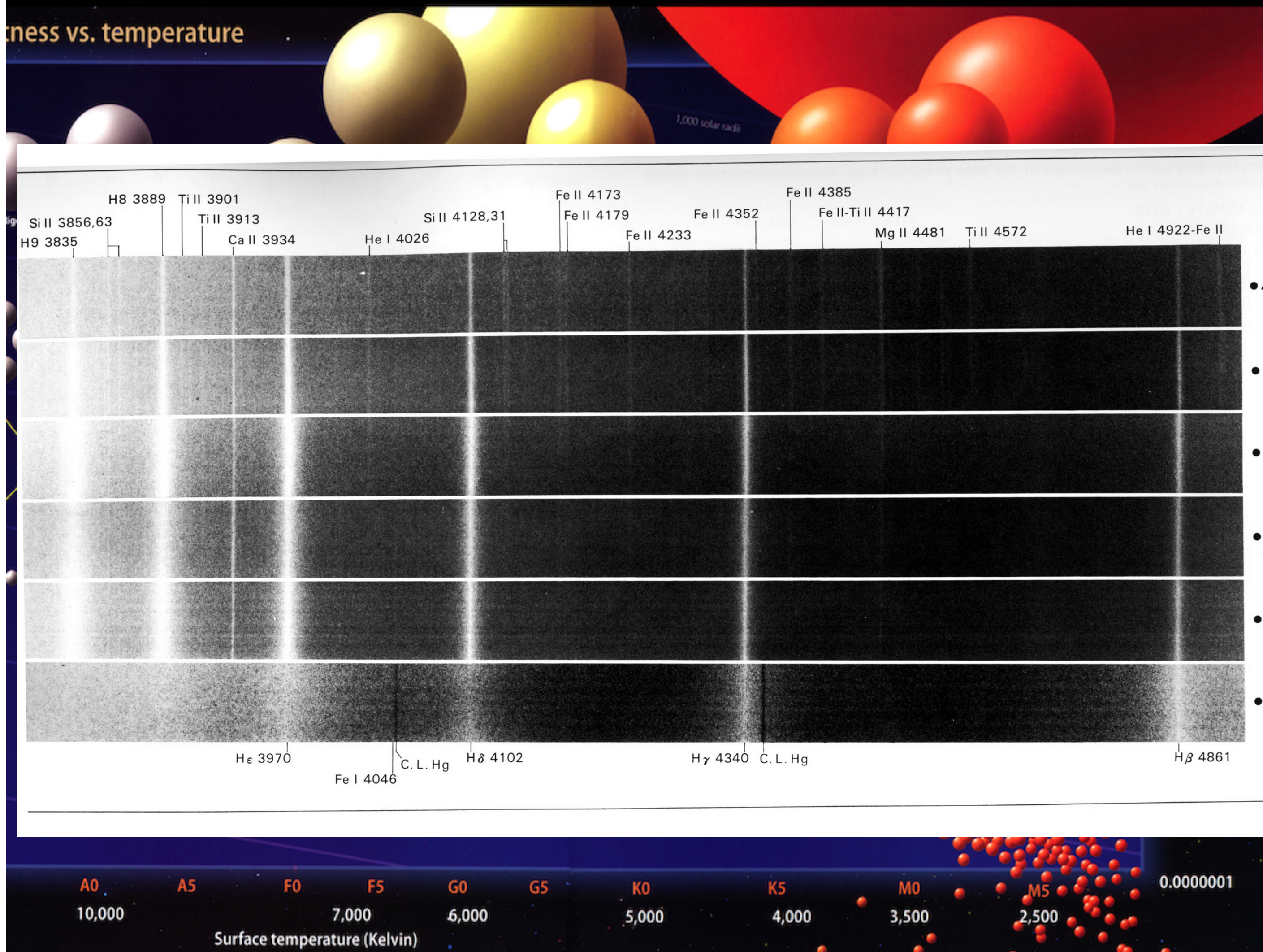
wallpapersget.com

Previously on GW-progenitors…

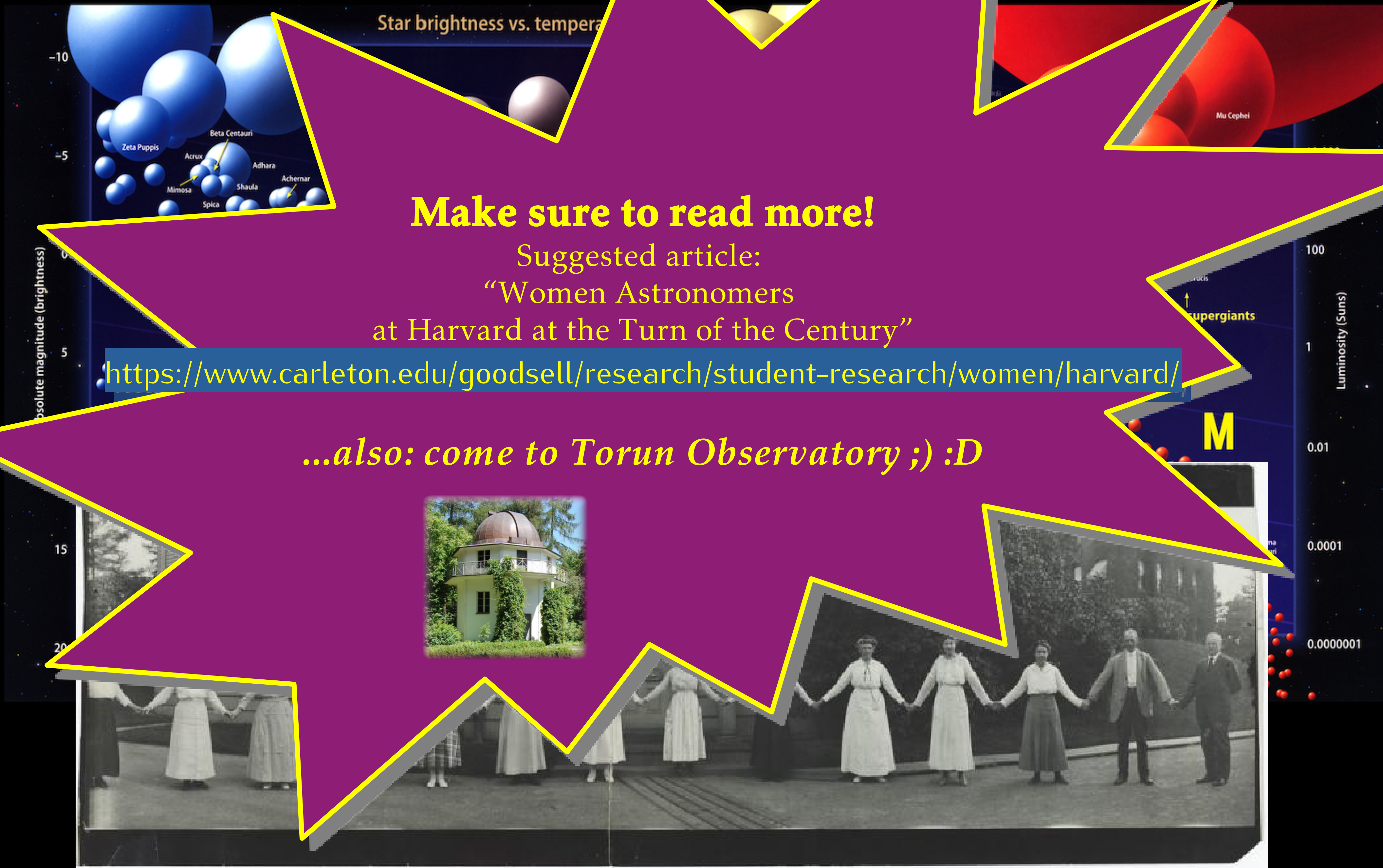

Star brightness vs. temperature
Absolute magnitude (brightness)
-10
-5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
O and B stars
Rigel
Deneb
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Canopus
Polaris
Capella
Procyon
Alpha Centauri
Sun
Arcturus
Pollux
Aldebaran
Antares
Betelgeuse
Mu Cephei
Mira
Gamma Crucis
Giants and supergiants
Lines of constant radius
Main sequence stars
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
O
B
A
F
G
K
M

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
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
6,000
5,000
4,000
3,500
2,500
0.0000001
Surface temperature (Kelvin)



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

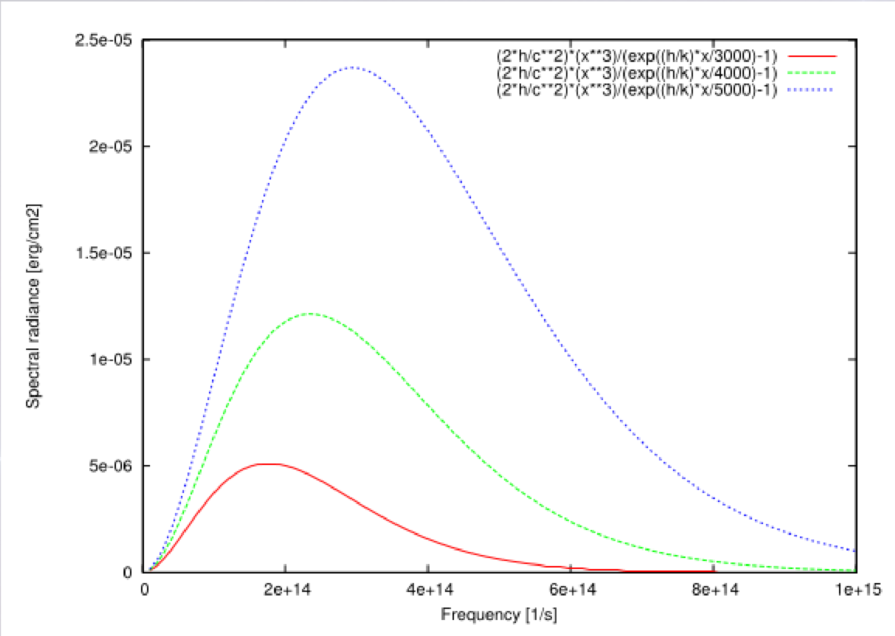
Planck law

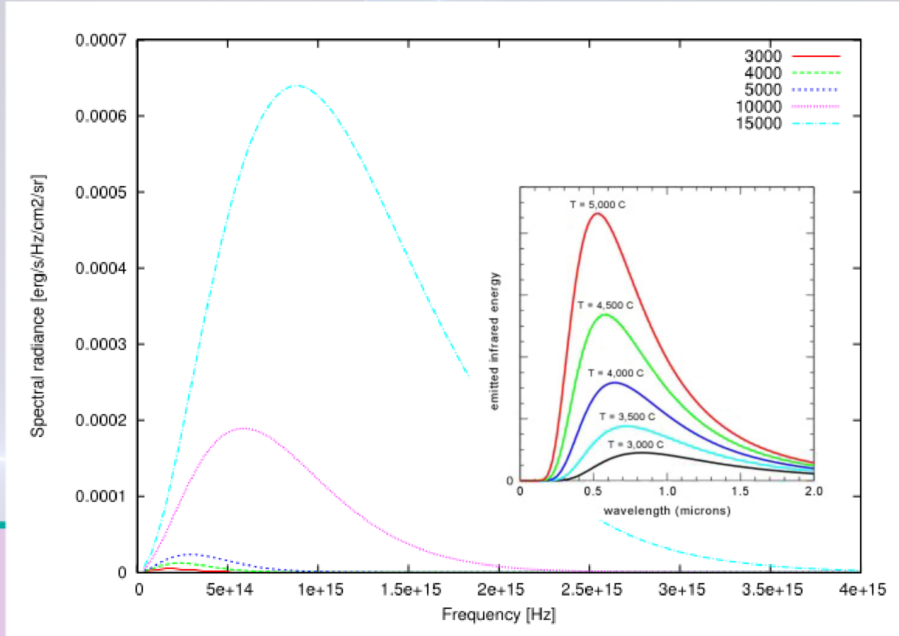
$$B(\nu, T_{eff}) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T_{eff}}} - 1} \qquad (3)$$

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

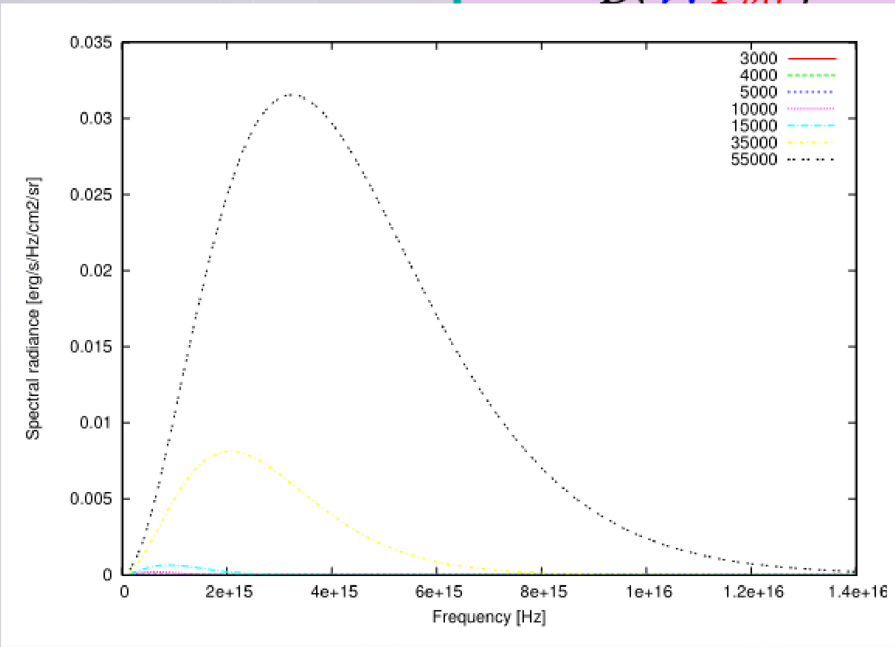
Note: there is a T value in it!

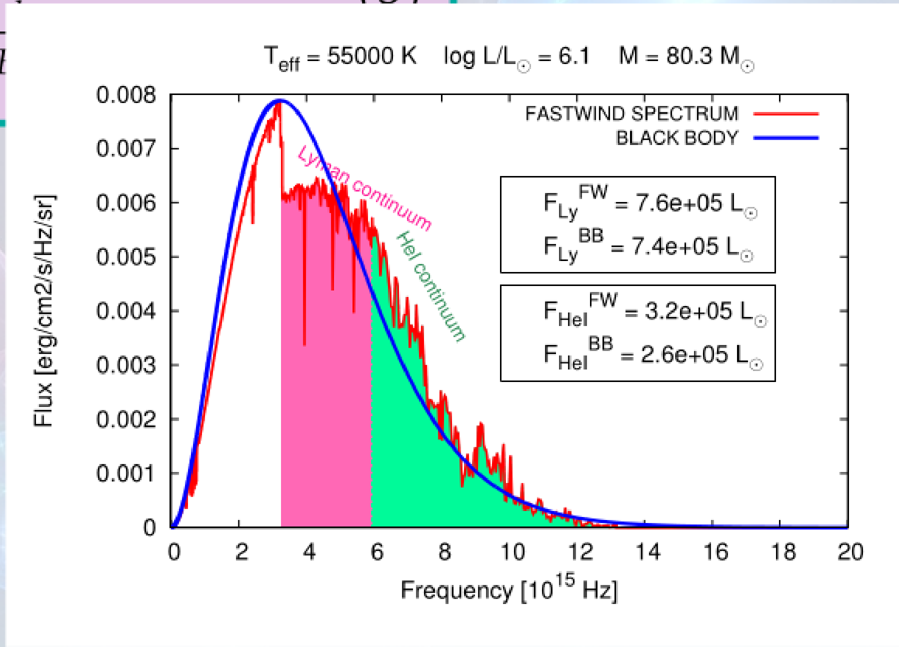
Radiation field of stars with different T_{eff}





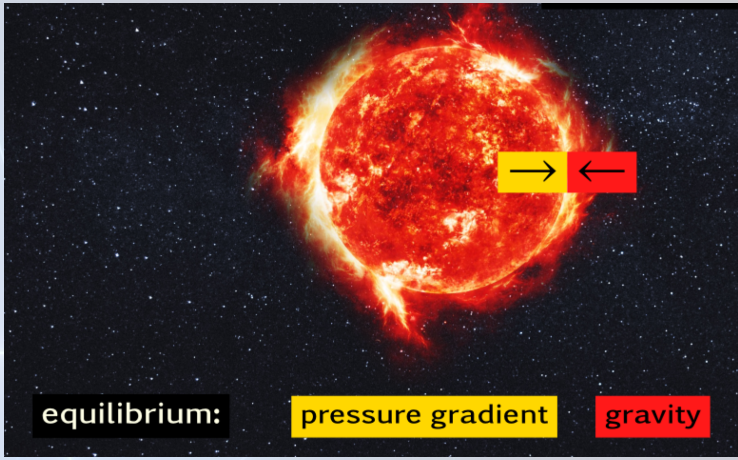
$B(\nu, T_{eff}) = \frac{2h}{\;\;2}$ … (3)





Core collapse

- Gravity takes over
  - end of the long-term equilibrium
  - fall-in: on the free-fall timescale
- …is there something to stop it?
  - Well… it depends.
  - Most of the time ("classical" case): a neutron star forms in the center ("proto-neutron-star")
    - a neutron star is: one giant nucleus. dense. stable.
    - bounce-back, shock waves, emission of neutrinos and light = **SUPERNOVA EXPLOSION**



apse

u

al

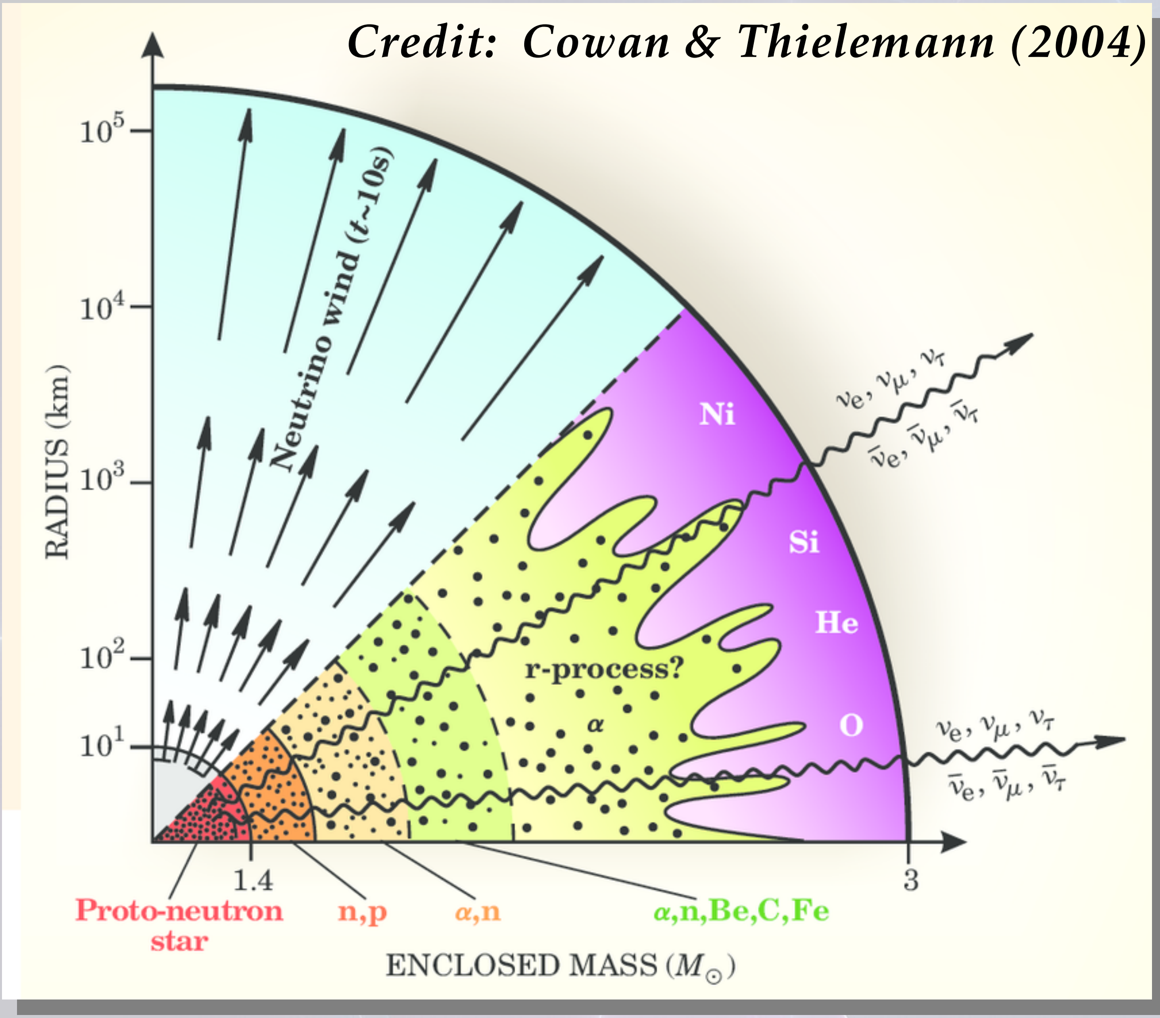
i

a

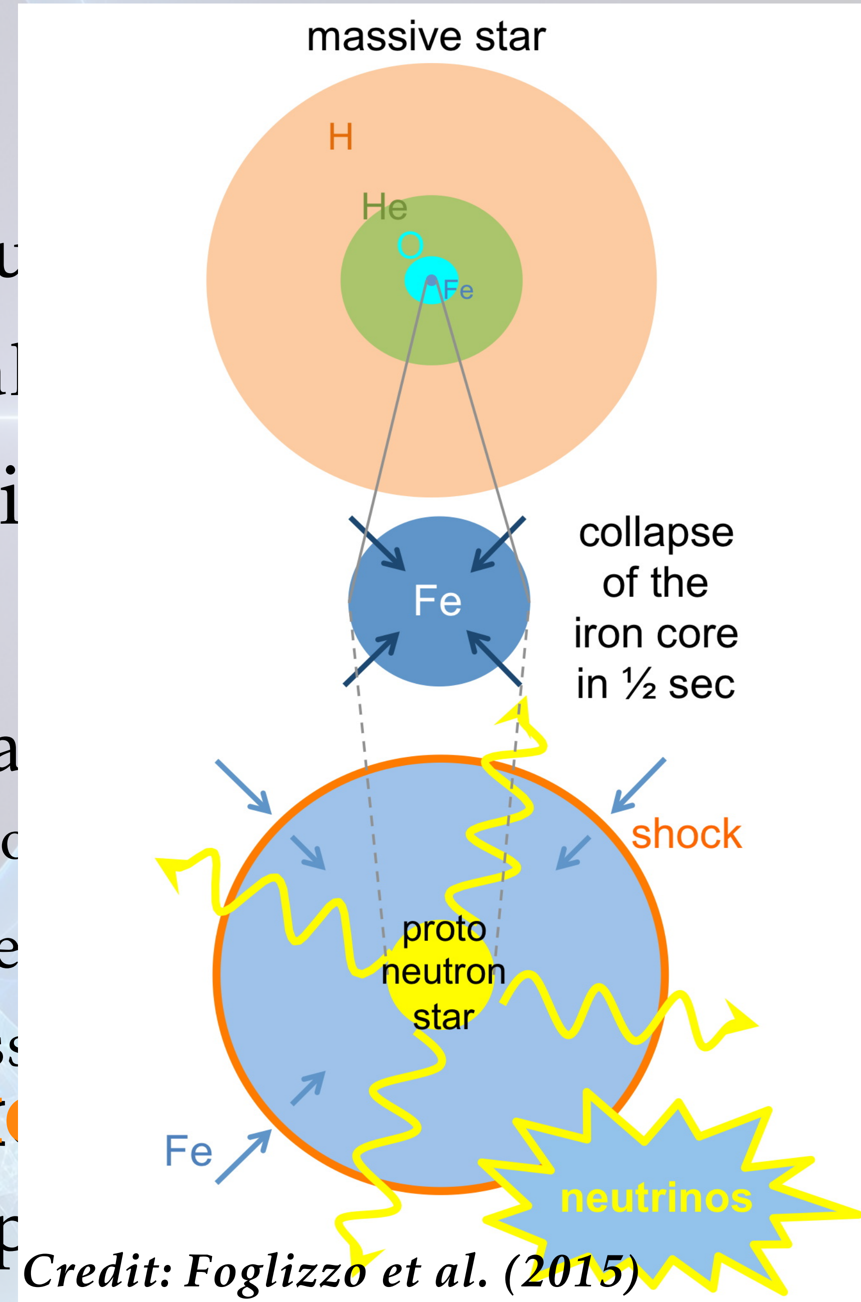
forms in the center ("proto-neutro

- a neutron star is: one giant nucle
- bounce-back, shock waves, emis light = **SUPERNOVA EXPLOSI**

– technically: a core-collapse sup



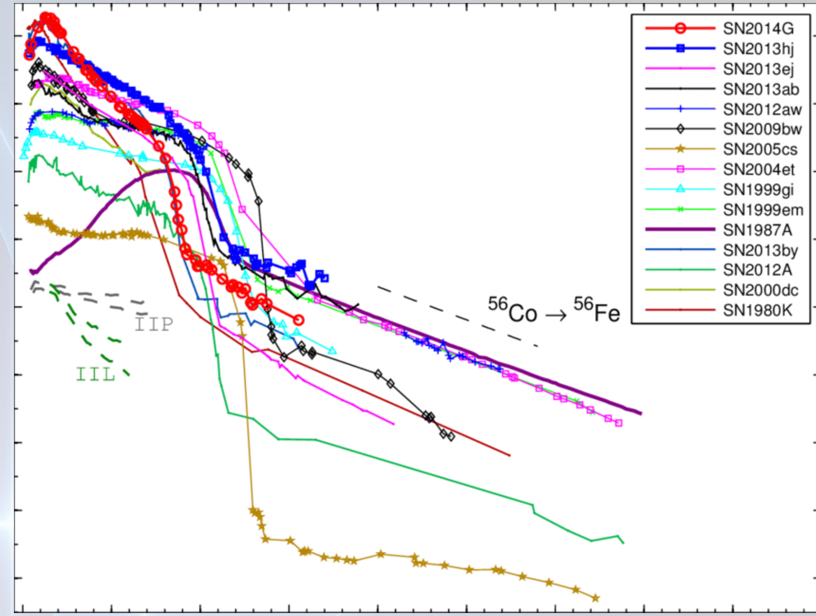
Credit: Cowan & Thielemann (2004)



Credit: Foglizzo et al. (2015)

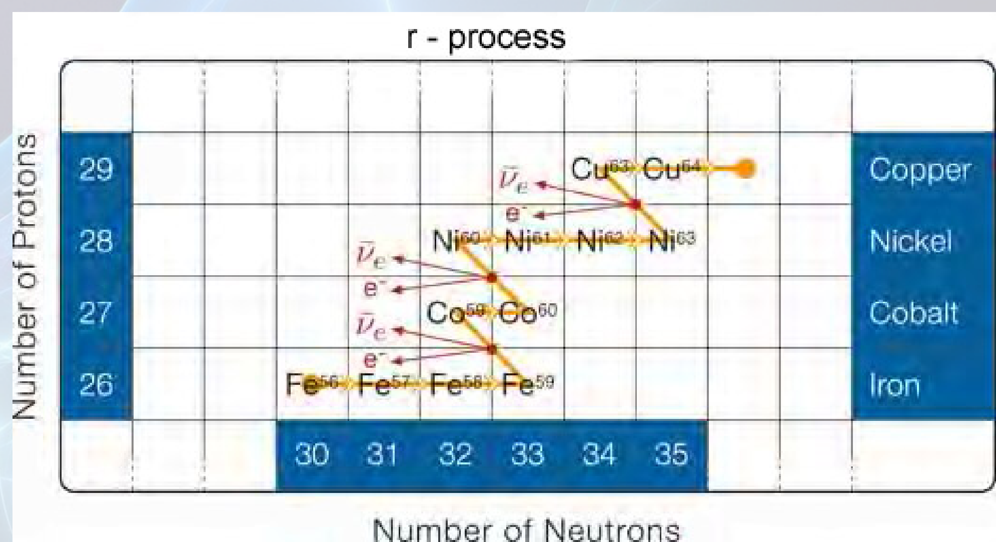
Results of a CCSN

- supernova lightcurve
  - photons: emitted in the shock
  - observed at many wavelenths = ***spectrum***
  - decay phase: ^{56}Co → ^{56}Fe



credit: Bose, Kumar et al. (2015)

- explosive nuclear burning: r-process (**r**apid)
  - lots of free neutrons: rapid neutron-capture
  - elements heavier than iron
- remnant: NS… or BH



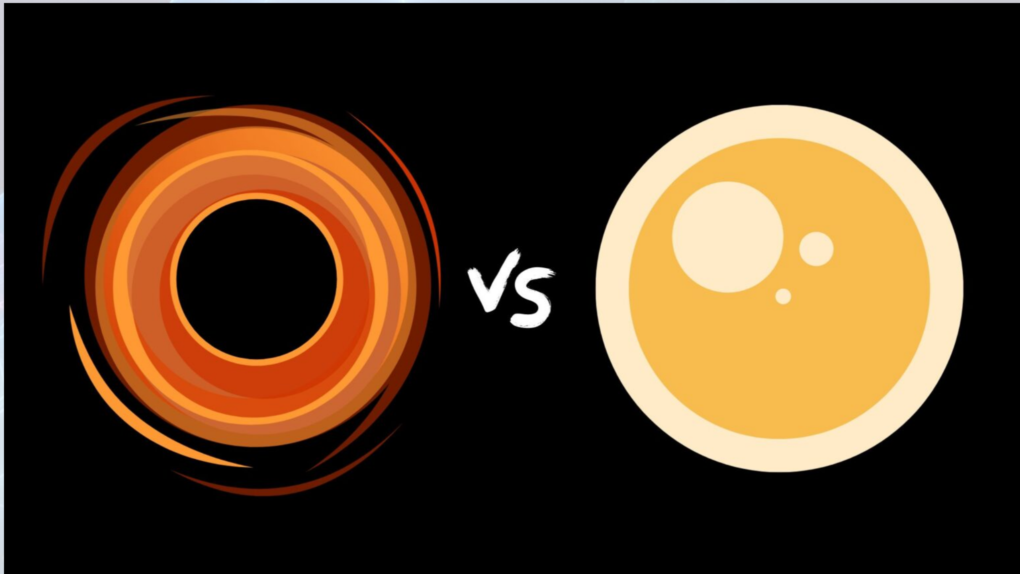
Fate of the proto-NS

- 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…)

under active research

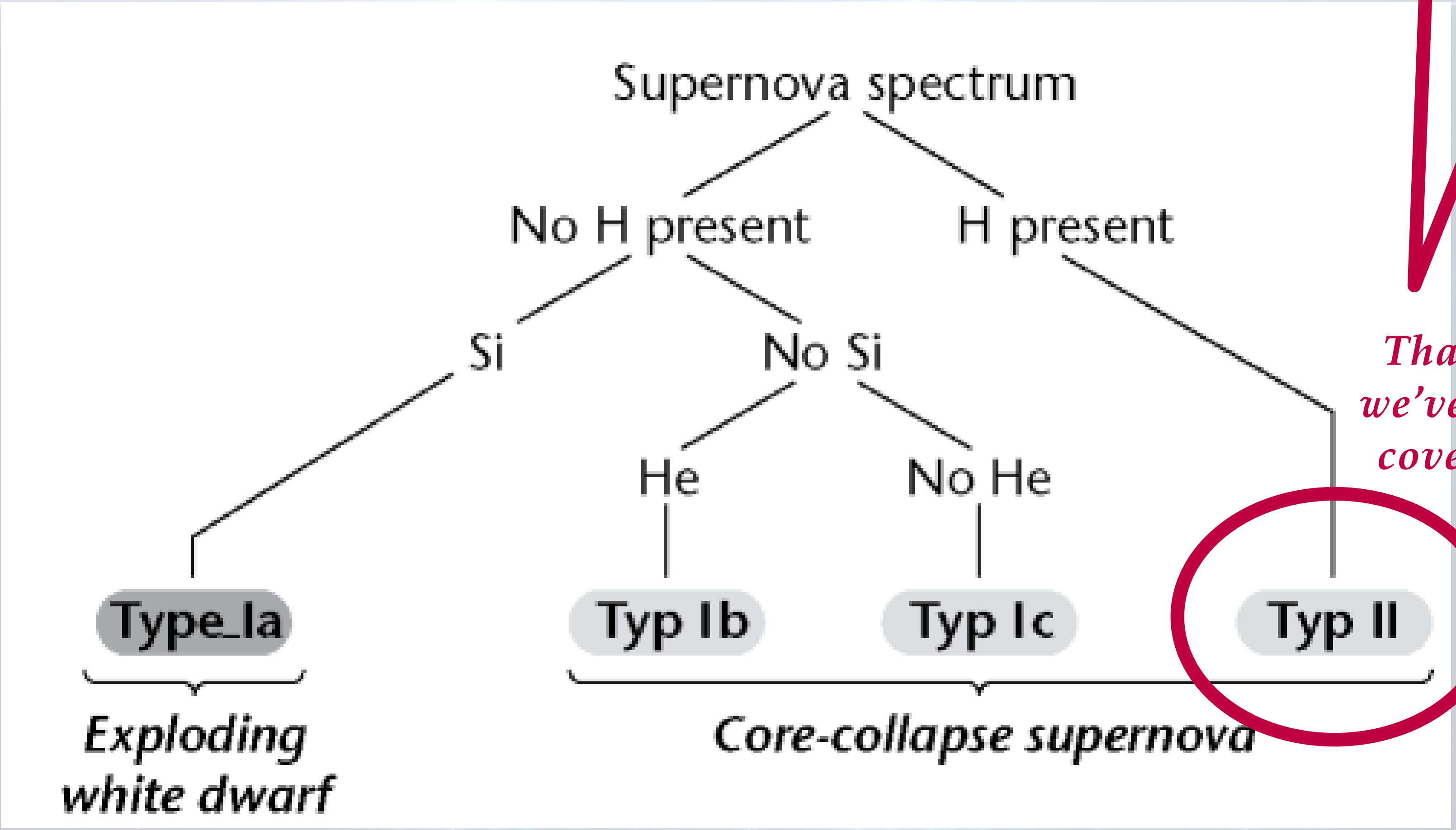
Not ***the Chandrasekhar limit!*** *~1.4 $M_\odot$*
(= limit between NSs and white dwarfs)

- Tolman–Oppenheimer–Volkoff limit: **2.16 $M_\odot$**
  - maximum observed mass of a neutron star is 2.14 $M_\odot$ for PSR J0740+6620 discovered in 2019



So far: core-collapse SNe

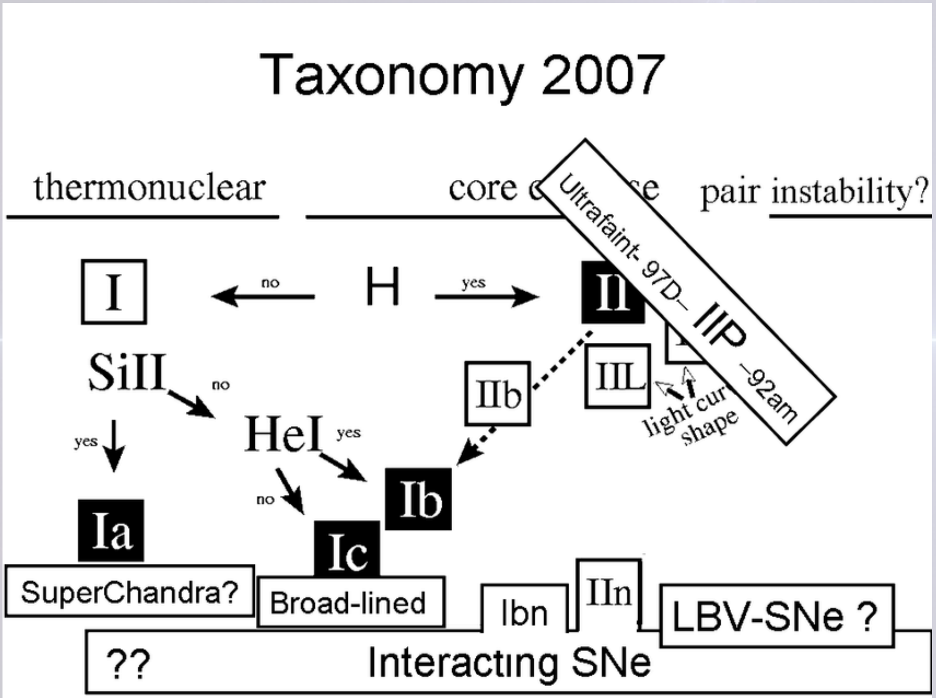
- There are so many other types…
- Classified by observers (simple picture):

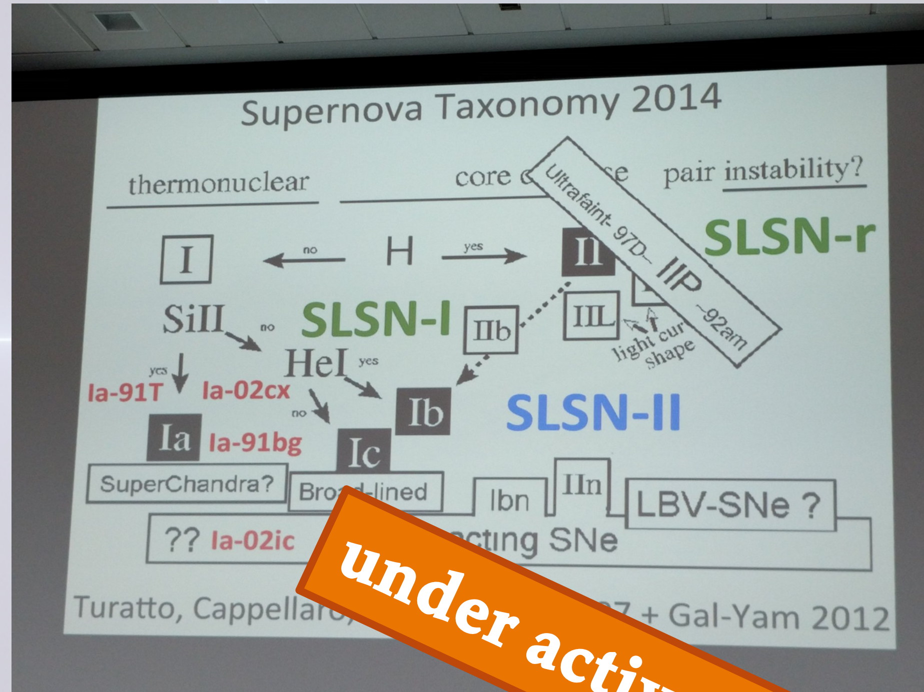


Progenitor:
a massive star with
a H-rich envelope

That's what we've actually covered here

Full supernova taxonomy *as of 2022?*





under active research

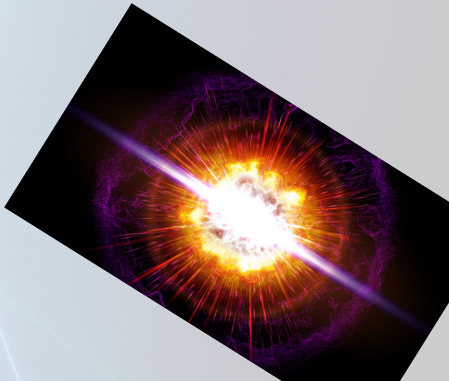
Need to consider additionally (at the very least):

– rotation (leading to e.g. Gamma-ray bursts or Superluminous SNe)
– pair-creation mechanism (leading to Pair Instability Supernovae, PISNe)
– binarity (leading to, basically, anything we want :P but also to GWs ;))

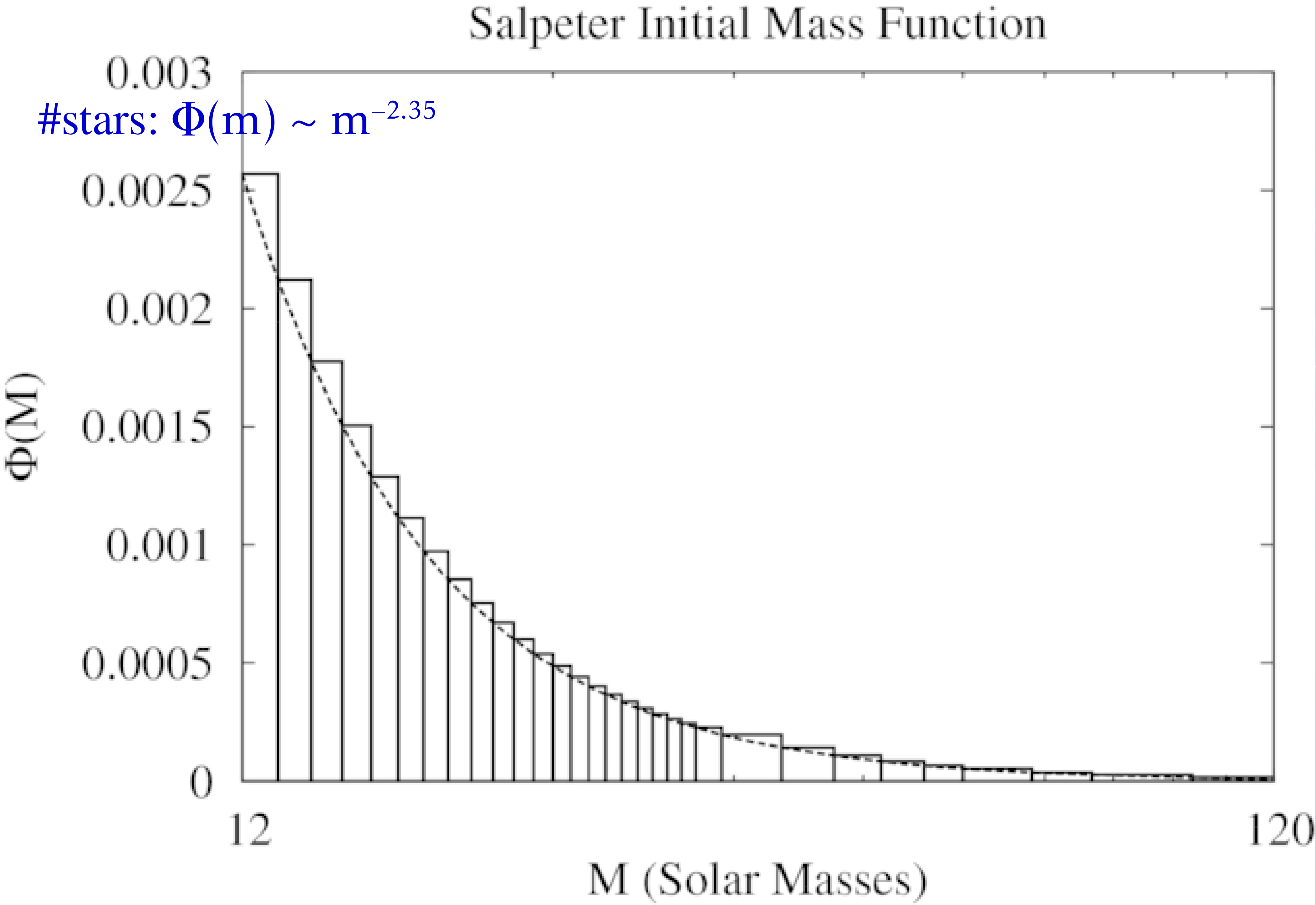
Today…

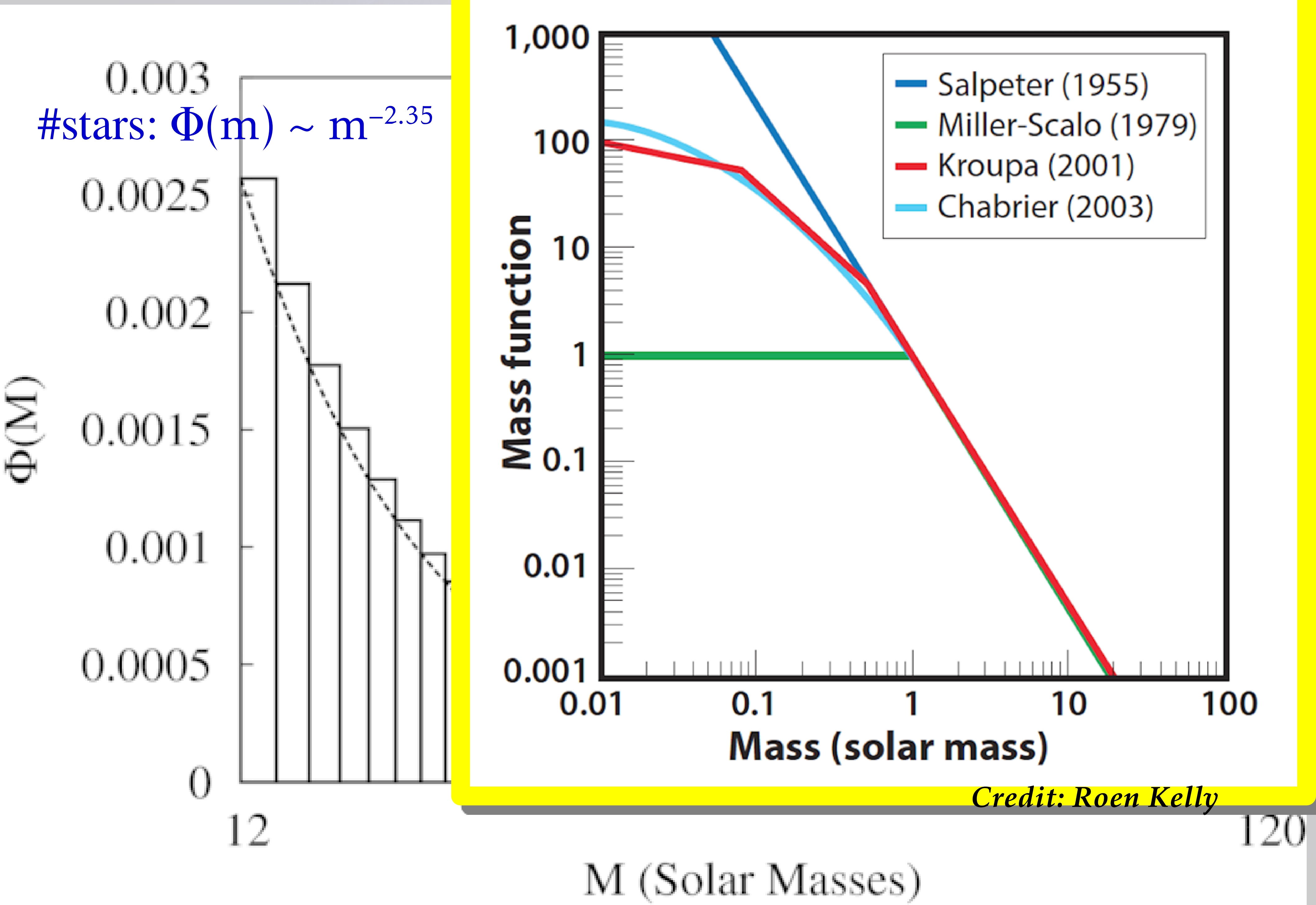
CORPSES.

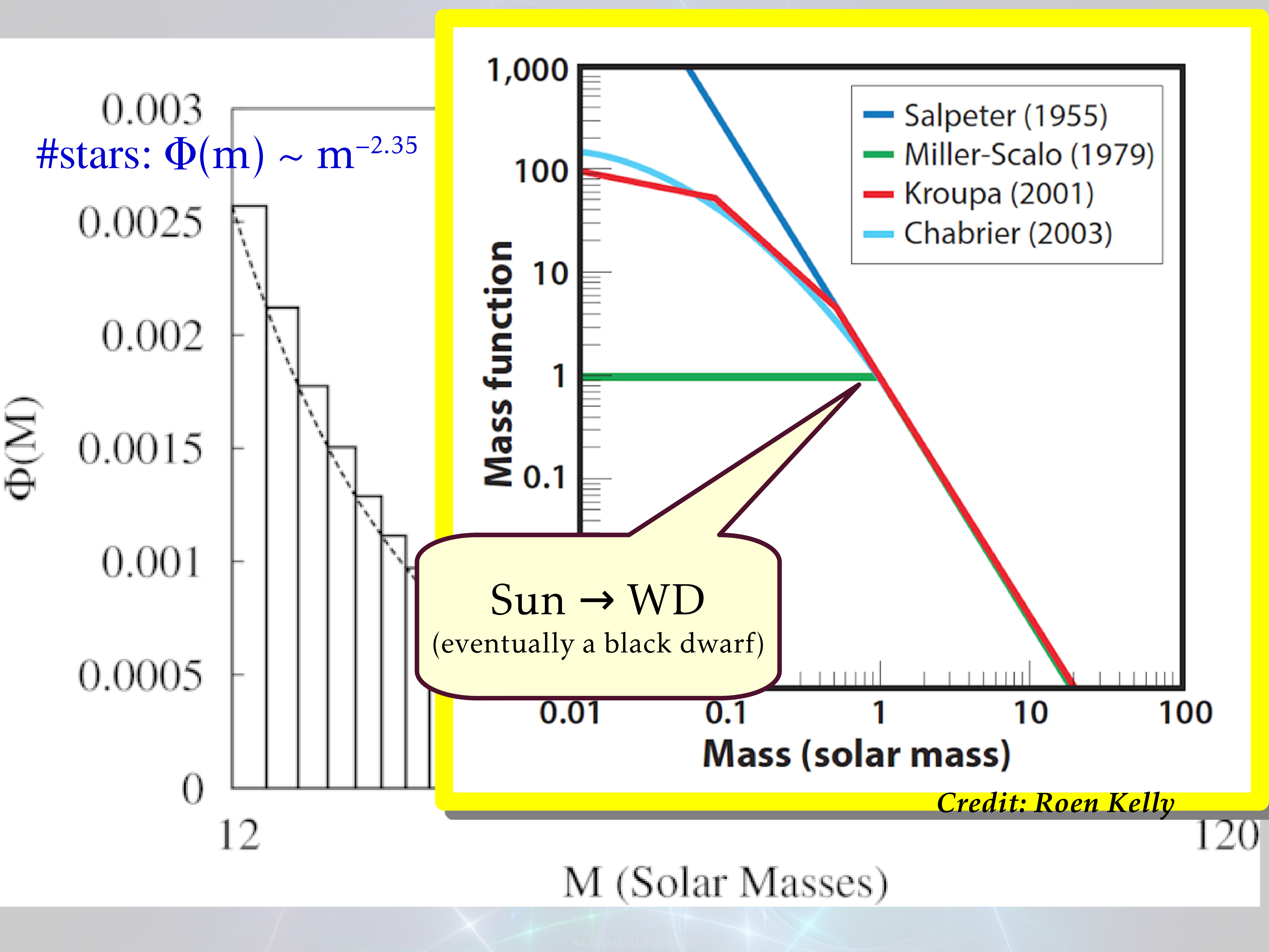
And also: some more explosions ;)



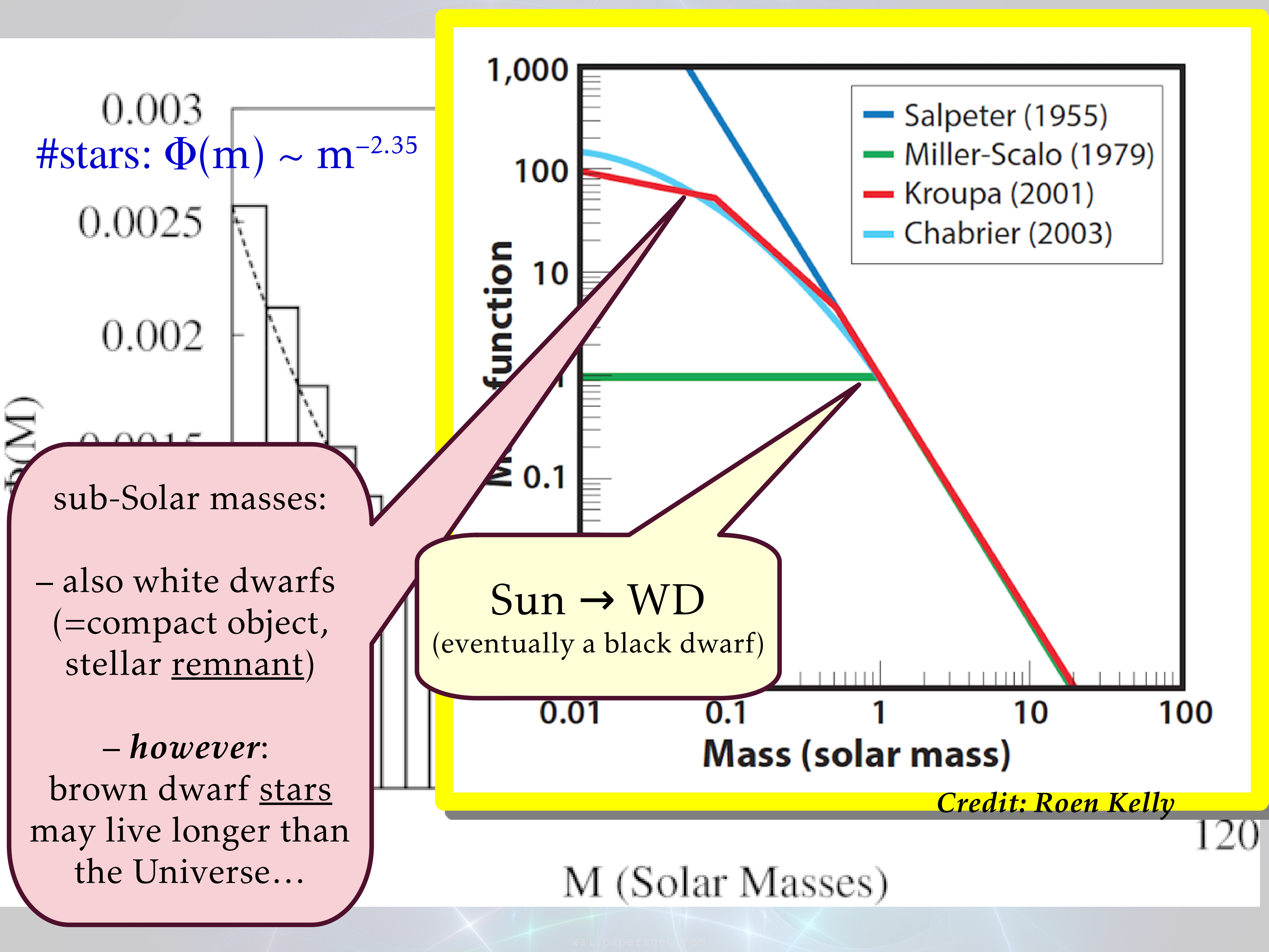
#stars: $\Phi(m) \sim m^{-2.35}$

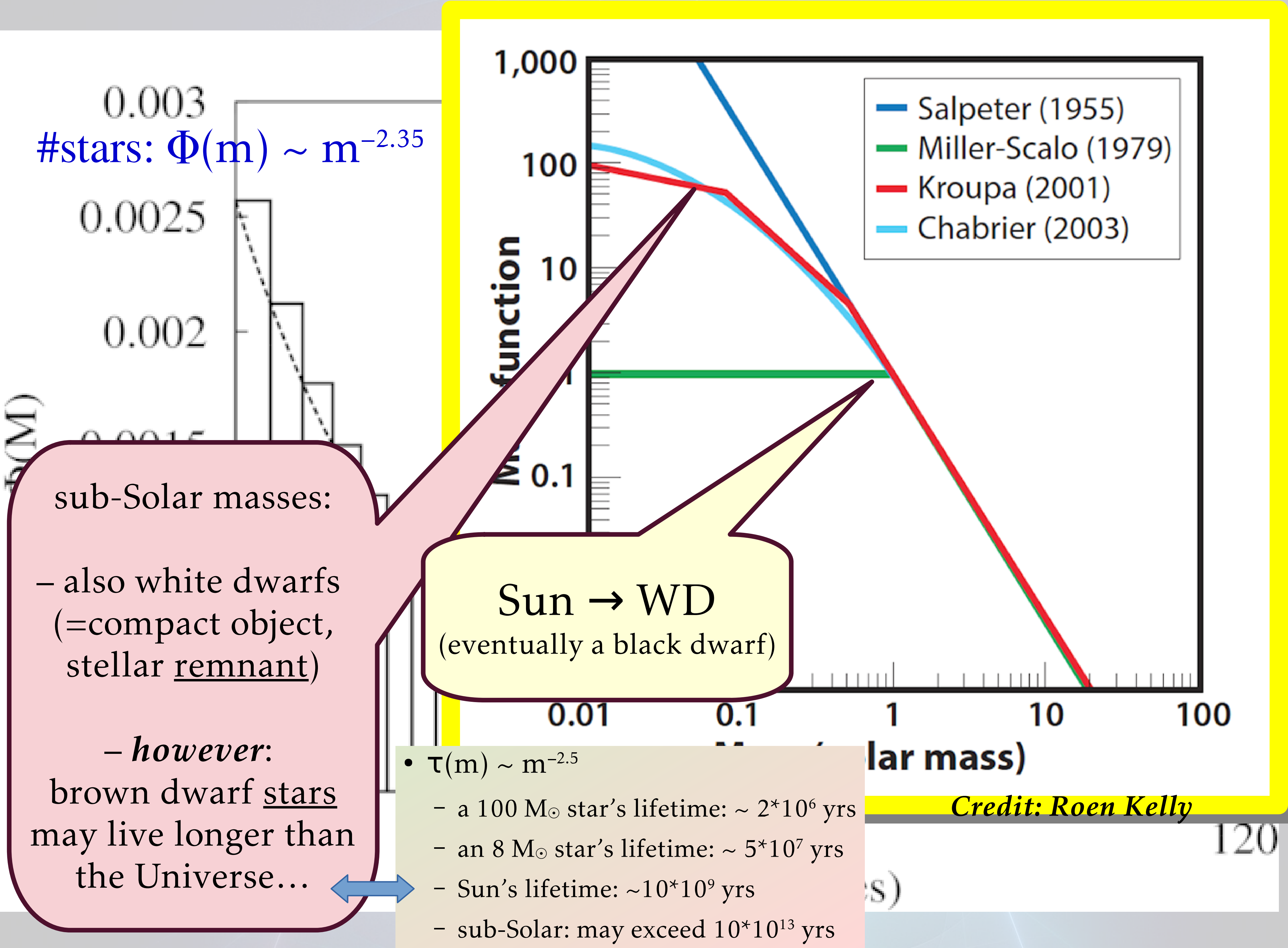



#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Φ(M)
12
120
M (Solar Masses)
1,000
100
10
1
0.1
0.01
0.001
Mass function
0.01
0.1
1
10
100
Mass (solar mass)
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
Credit: Roen Kelly



#stars: $\Phi(m) \sim m^{-2.35}$
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Φ(M)
12
120
M (Solar Masses)
1,000
100
10
1
0.1
Mass function
0.01
0.1
1
10
100
Mass (solar mass)
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
Sun → WD
(eventually a black dwarf)
Credit: Roen Kelly


#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
120
M (Solar Masses)
1,000
100
10
0.1
0.01
0.1
1
10
100
Mass (solar mass)
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
Credit: Roen Kelly
sub-Solar masses:
– also white dwarfs (=compact object, stellar remnant)
– however: brown dwarf stars may live longer than the Universe…
Sun → WD
(eventually a black dwarf)


#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
1,000
100
10
0.1
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
0.01
0.1
1
10
100
sub-Solar masses:
– also white dwarfs (=compact object, stellar remnant)
– however: brown dwarf stars may live longer than the Universe…
Sun → WD
(eventually a black dwarf)
• τ(m) ~ m^−2.5
– a 100 M⊙ star's lifetime: ~ 2*10^6 yrs
– an 8 M⊙ star's lifetime: ~ 5*10^7 yrs
– Sun's lifetime: ~10*10^9 yrs
– sub-Solar: may exceed 10*10^13 yrs
Credit: Roen Kelly
120

What are compact objects?

stellar 'corpses'

= remnants

- three main types:
  - white dwarf
  - neutron star
  - black hole

(white dwarf, neutron star:) **degenerate stars**

other (speculative) degenerate stars:
– quark star
– preon star
– boson star
– … (see e.g. Wikipedia)

What are compact objects?

stellar 'corpses'
= remnants

- three main types:
  - white dwarf
  - neutron star
  - black hole

  (white dwarf and neutron star: **degenerate stars**)

other (speculative) degenerate stars:
– quark star
– preon star
– boson star
– … (see e.g. Wikipedia)

- WDs: electron degeneracy
  - nuclei (He/O/C/Ne/Mg) are ***not*** in degenerate state
- NSs: neutron degeneracy too

What are compact objects?

stellar 'corpses' **= remnants**

- three main types:
  - white dwarf
  - neutron star
  - black hole

(white dwarf and neutron star: **degenerate stars**)

other (speculative) degenerate stars:
– quark star
– preon star
– boson star
– … (see e.g. Wikipedia)

- WDs: electron degeneracy
  - nuclei (He/O/C/Ne/Mg) are ***not*** in degenerate state

composition depends on mass (i.e. stellar evolution of the low-mass star in question)

- NSs: neutron degeneracy too

wallpaperagent.com

What are compact objects?

stellar 'corpses' **= remnants**

- three main types:
  - white dwarf
  - neutron star
  - black hole

(white dwarf and neutron star: **degenerate stars**)

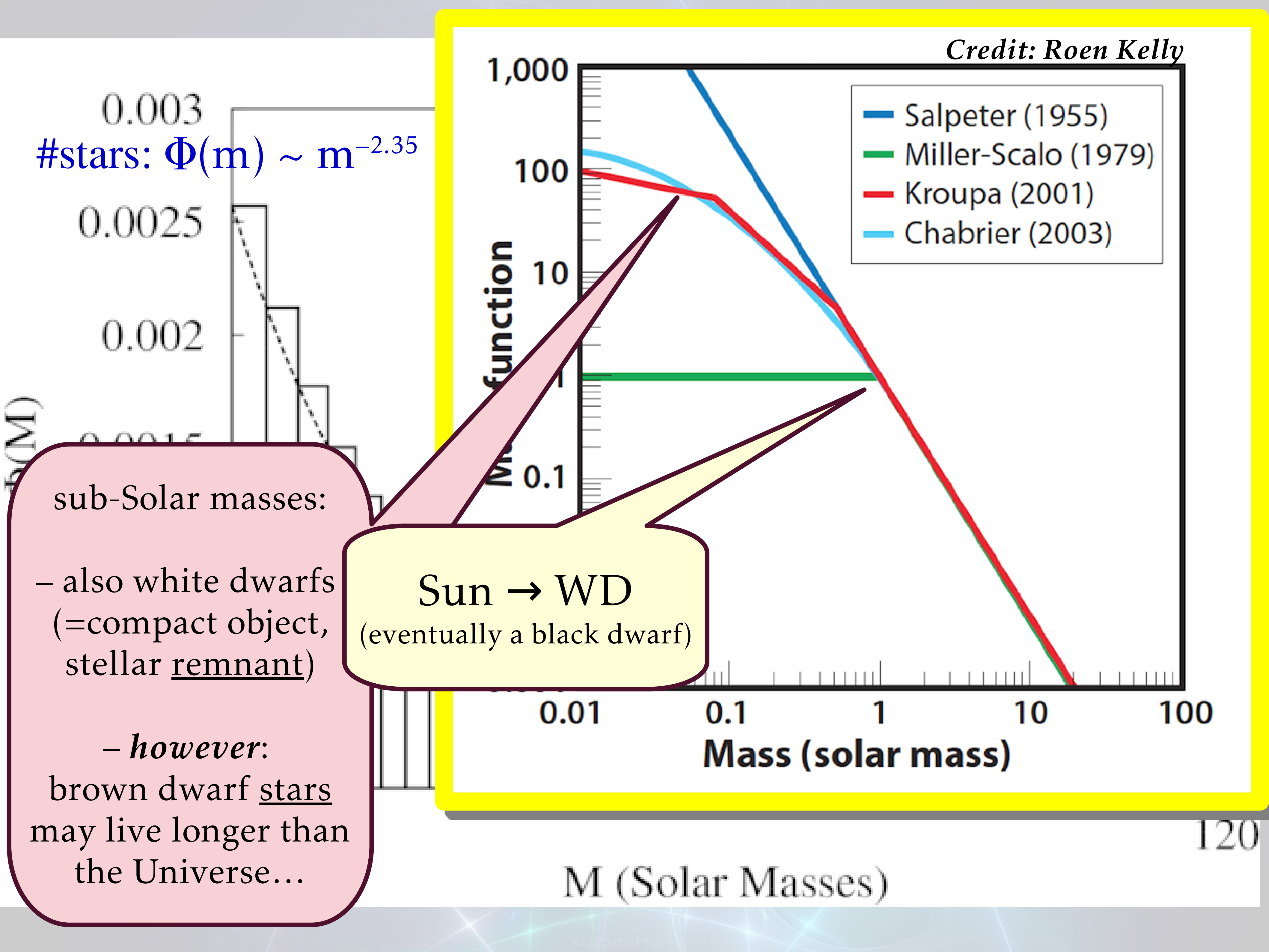
other (speculative) degenerate stars:
– quark star
– preon star
– boson star
– … (see e.g. Wikipedia)

- WDs: electron degeneracy
  - nuclei (He/O/C/Ne/Mg) are ***not*** in degenerate state

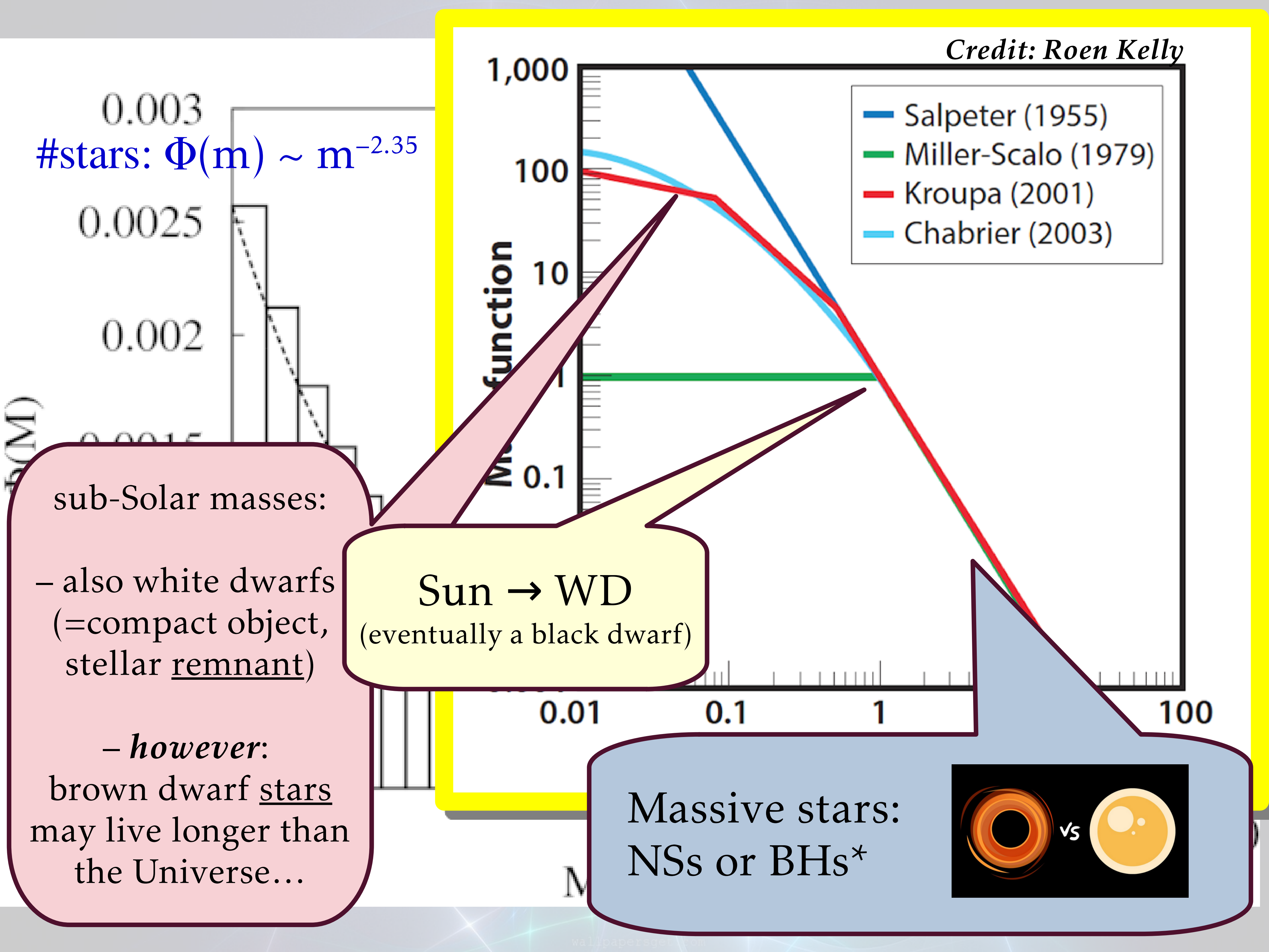
composition depends on mass (i.e. stellar evolution of the low-mass star in question)

- NSs: neutron degeneracy too

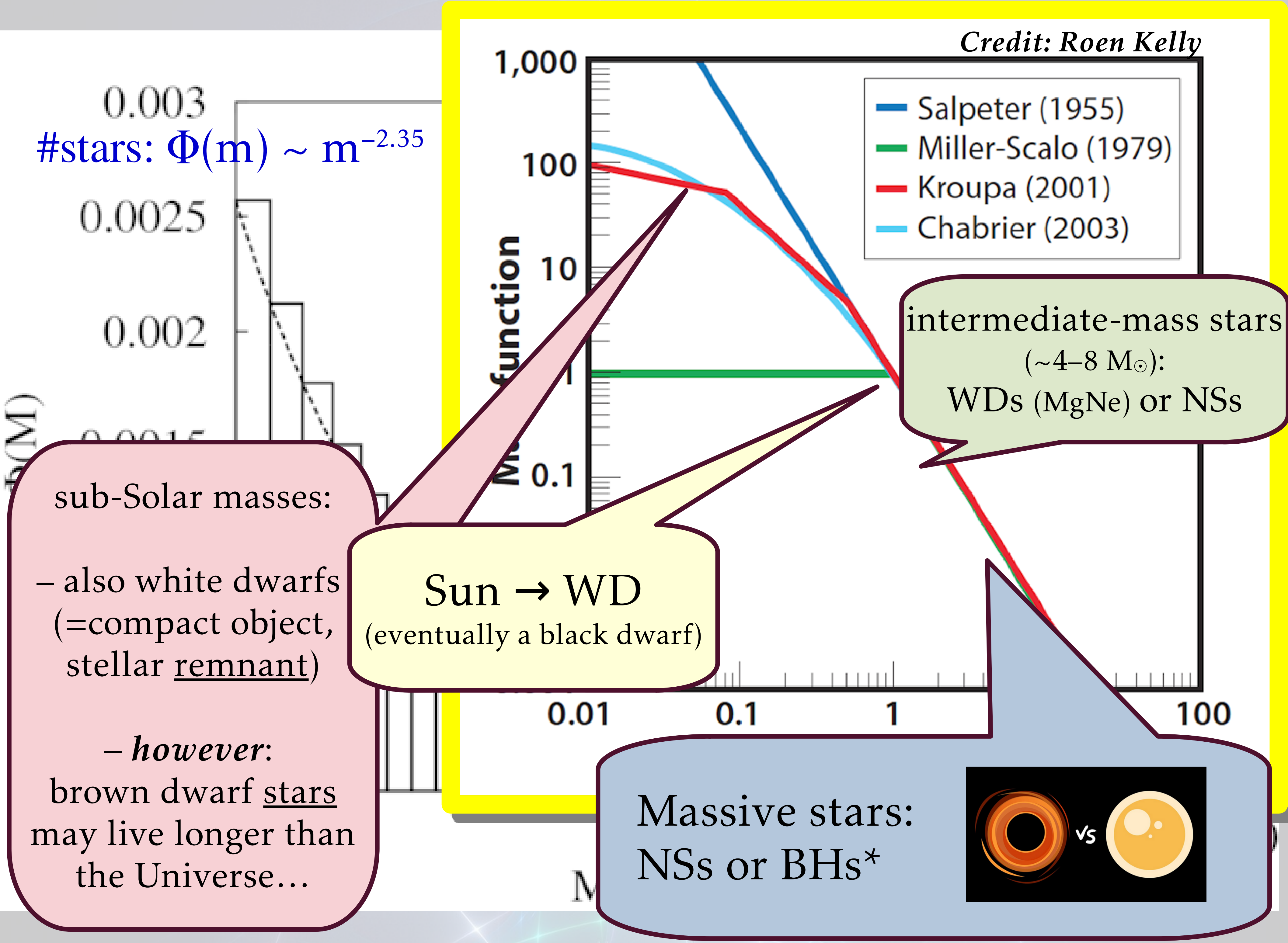
degeneracy pressure → **stability** against (self-)gravity



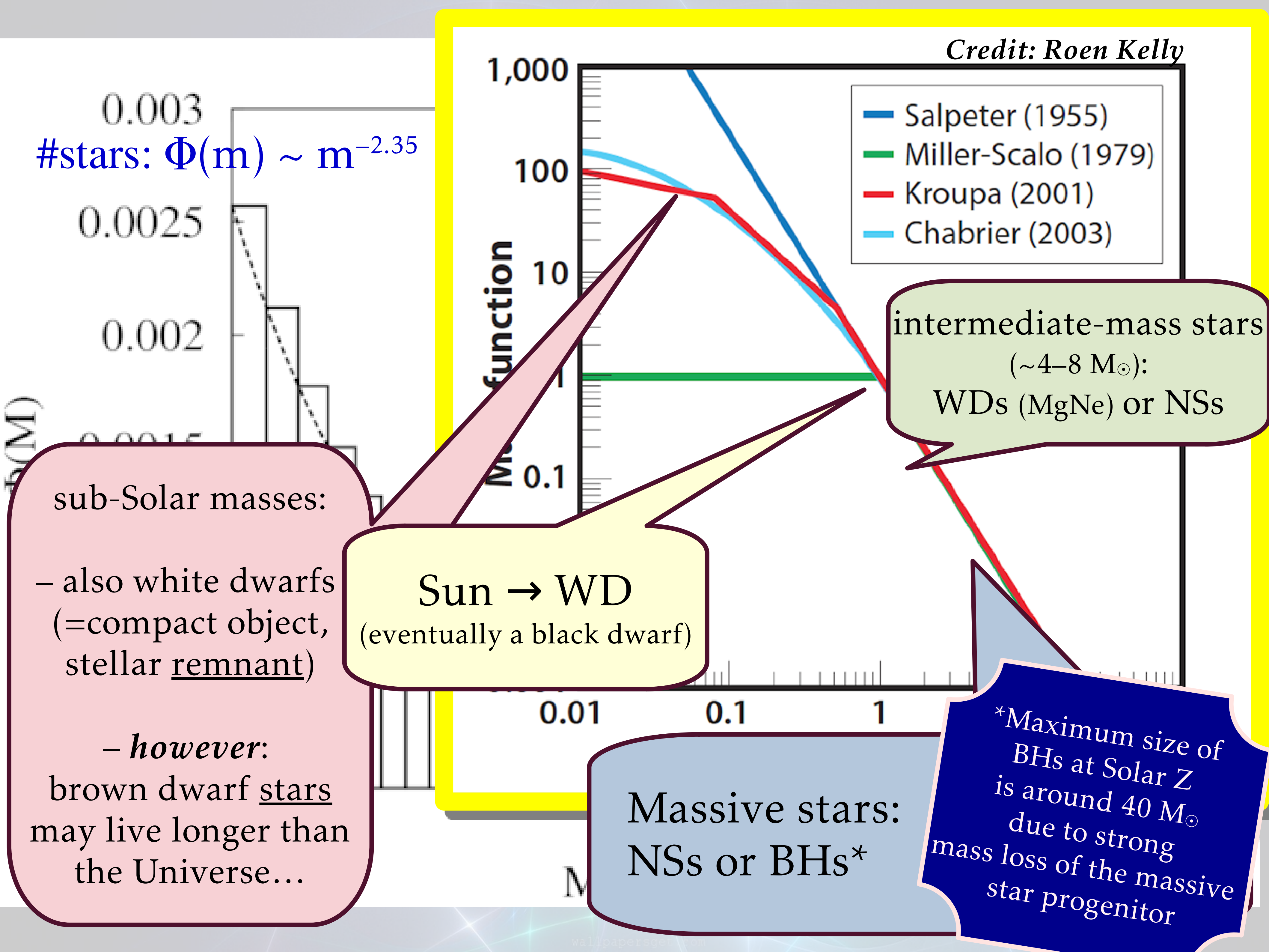
#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
Credit: Roen Kelly
1,000
100
10
0.1
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
0.01
0.1
1
10
100
Mass (solar mass)
sub-Solar masses:
– also white dwarfs (=compact object, stellar remnant)
– however: brown dwarf stars may live longer than the Universe…
Sun → WD
(eventually a black dwarf)
120
M (Solar Masses)



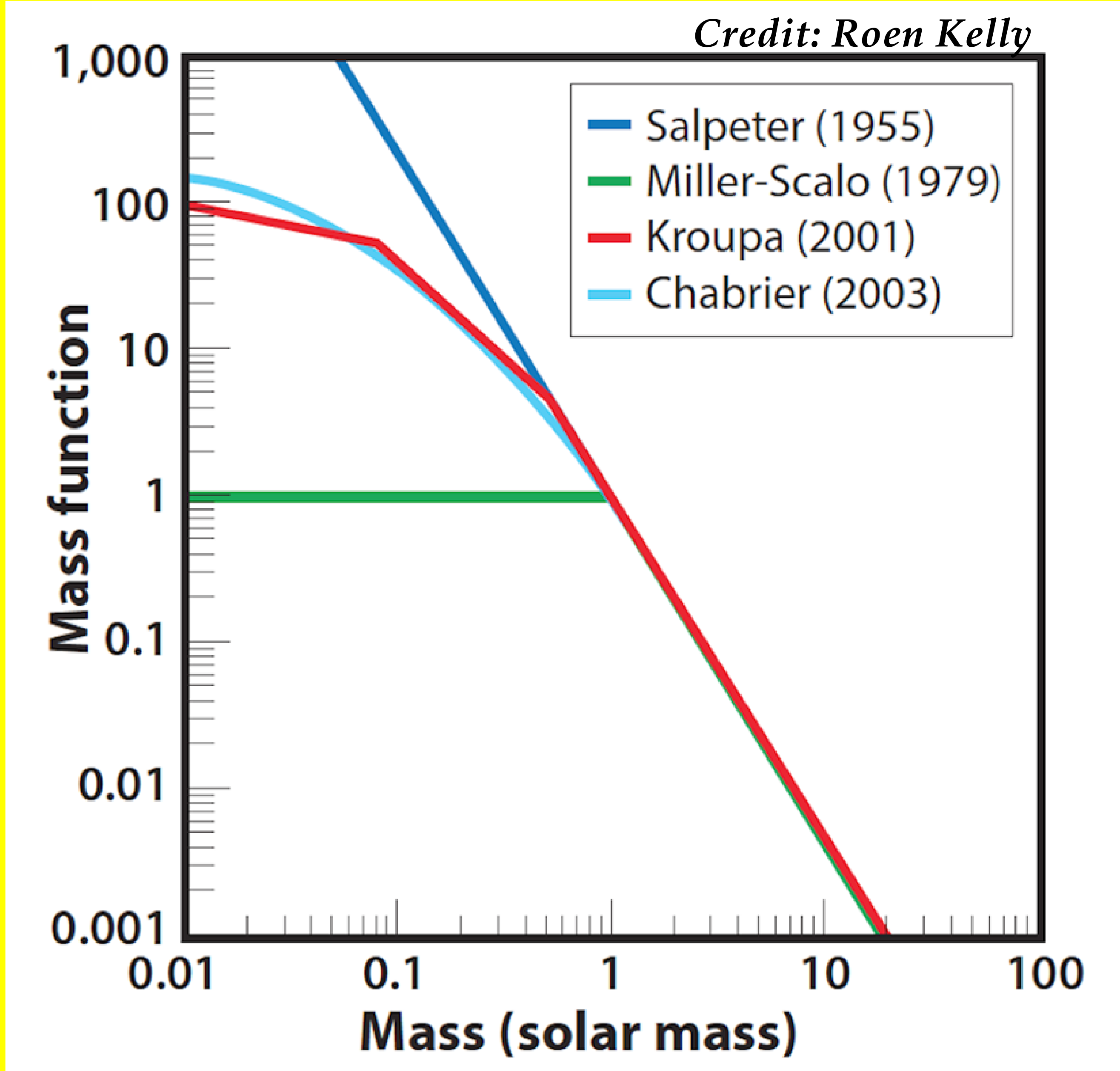
#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
Credit: Roen Kelly
1,000
100
10
0.1
0.01
0.1
1
100
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
sub-Solar masses:
– also white dwarfs (=compact object, stellar remnant)
– however: brown dwarf stars may live longer than the Universe…
Sun → WD
(eventually a black dwarf)
Massive stars: NSs or BHs*
vs



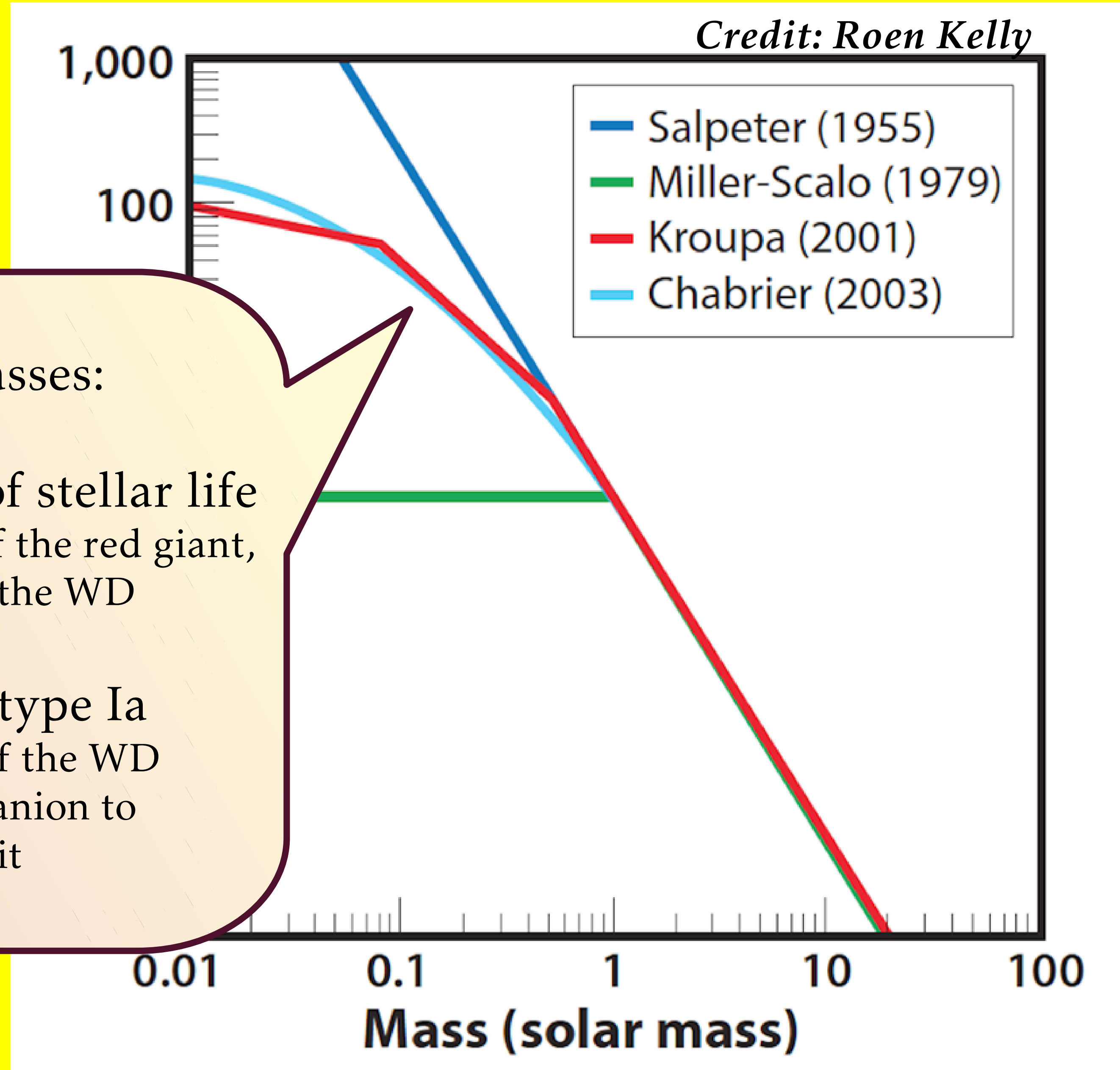
Credit: Roen Kelly
0.003
#stars: Φ(m) ~ m^−2.35
0.0025
0.002
1,000
100
10
0.1
function
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
intermediate-mass stars
(~4–8 M☉):
WDs (MgNe) or NSs
sub-Solar masses:
– also white dwarfs
(=compact object,
stellar remnant)
– however:
brown dwarf stars
may live longer than
the Universe…
Sun → WD
(eventually a black dwarf)
0.01
0.1
1
100
Massive stars:
NSs or BHs*
vs


Credit: Roen Kelly
#stars: Φ(m) ~ m^−2.35
0.003
0.0025
0.002
1,000
100
10
0.1
0.01
0.1
1
Salpeter (1955)
Miller-Scalo (1979)
Kroupa (2001)
Chabrier (2003)
intermediate-mass stars
(~4–8 M⊙):
WDs (MgNe) or NSs
sub-Solar masses:
– also white dwarfs
(=compact object,
stellar remnant)
– however:
brown dwarf stars
may live longer than
the Universe…
Sun → WD
(eventually a black dwarf)
Massive stars:
NSs or BHs*
*Maximum size of
BHs at Solar Z
is around 40 M⊙
due to strong
mass loss of the massive
star progenitor

Explosion types?



Explosion types?



Sun & sub-Solar masses:

– no explosion at the end of stellar life
i.e. ejection of the outer layers of the red giant, planetary nebula around the WD

– ***LATER:*** supernova type Ia
thermonuclear explosion of the WD
IF there is a binary companion to transfer mass onto it

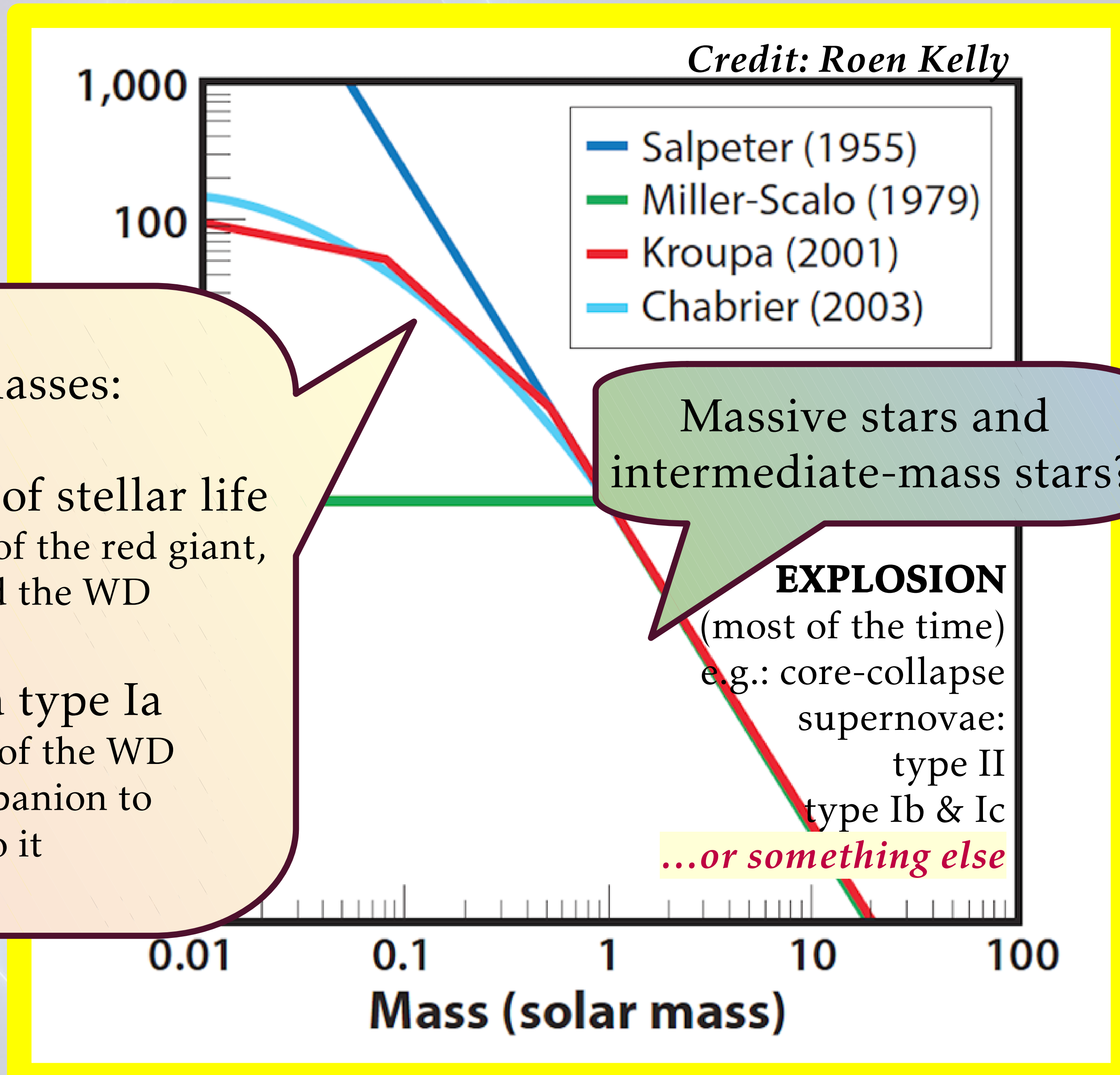
Side-note: type Ia Sne are standard candles in cosmology

Explosion types?

Sun & sub-Solar masses:

– no explosion at the end of stellar life
i.e. ejection of the outer layers of the red giant, planetary nebula around the WD

– ***LATER:*** supernova type Ia
thermonuclear explosion of the WD
IF there is a binary companion to transfer mass onto it

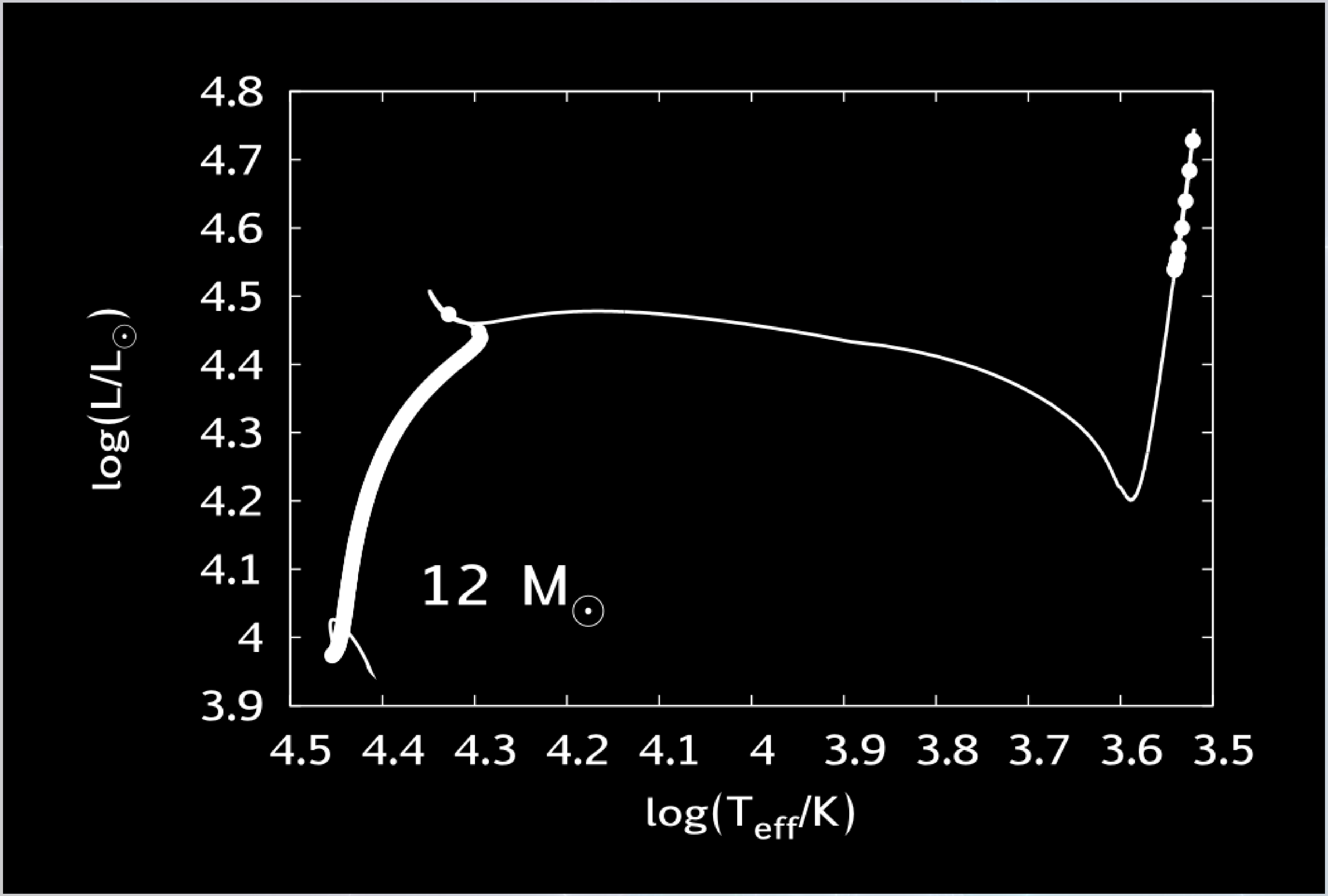


Massive stars and intermediate-mass stars?

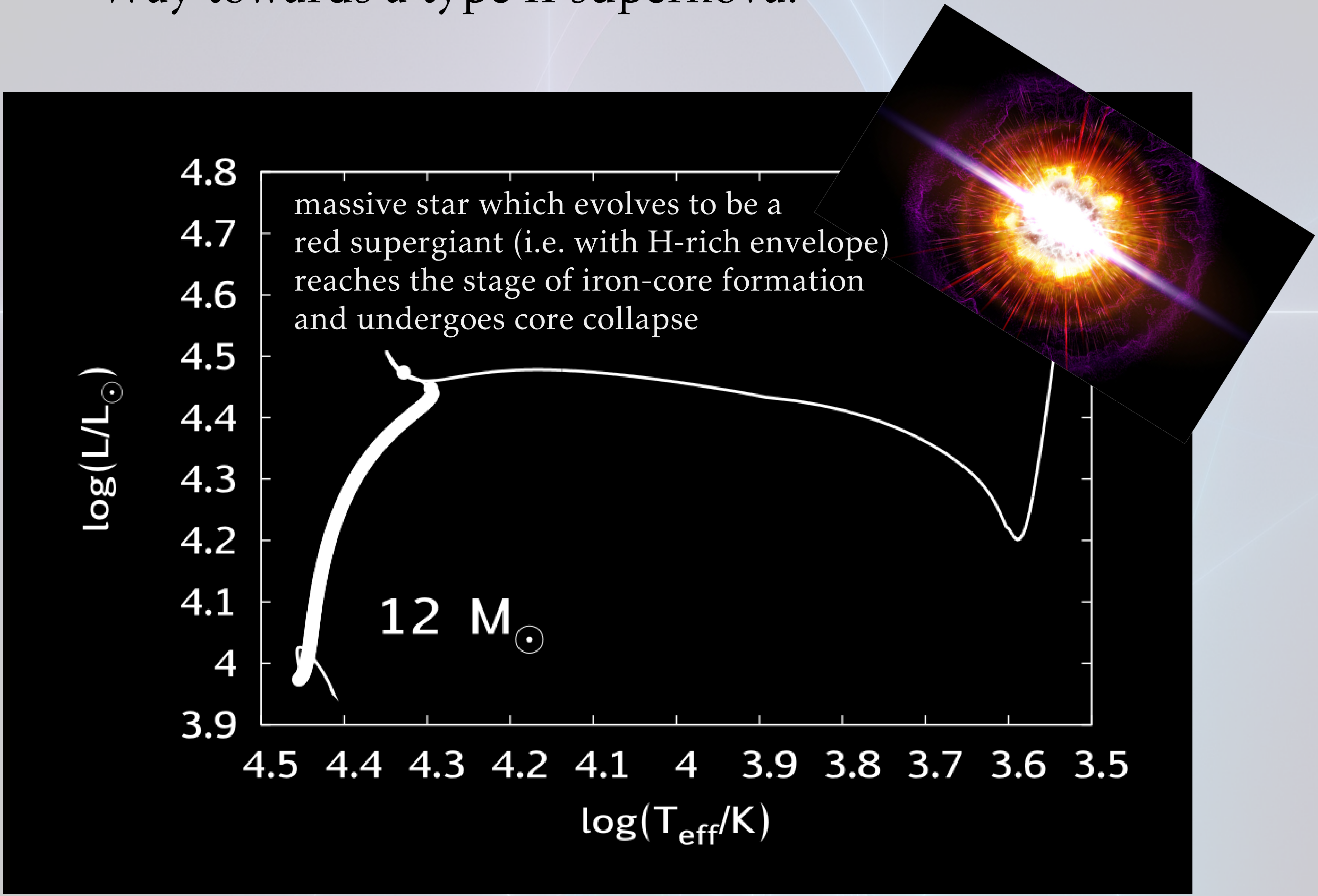
EXPLOSION
(most of the time)
e.g.: core-collapse supernovae:
type II
type Ib & Ic
...or something else

Side-note: type Ia Sne are standard candles in cosmology

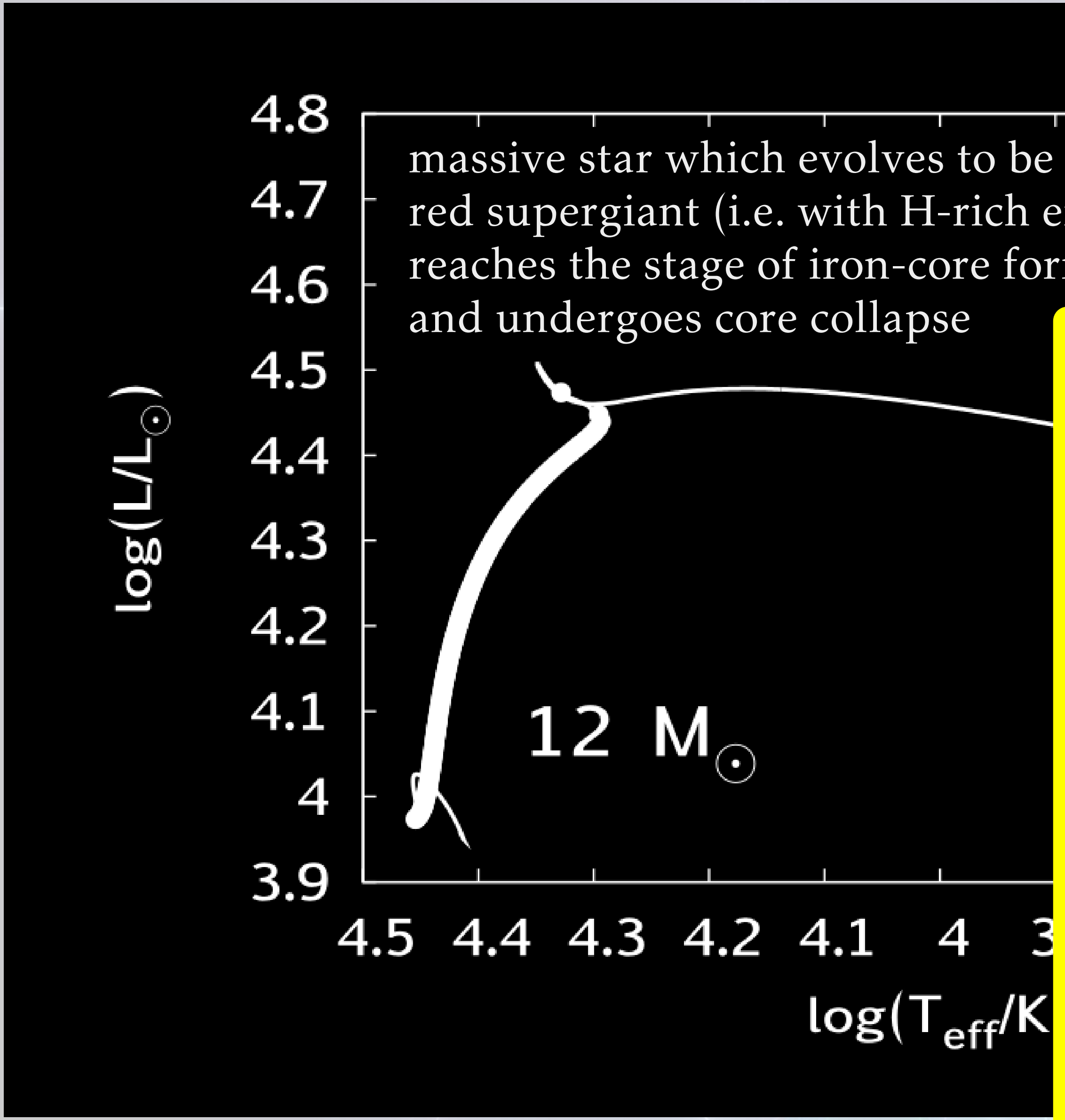
Way towards a type II supernova:

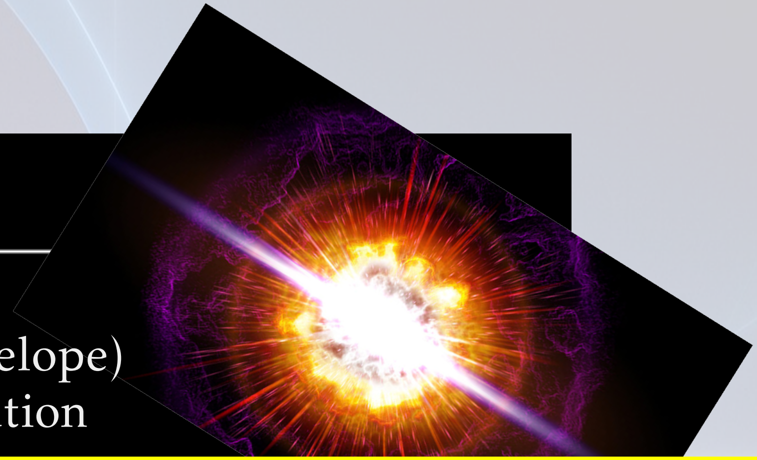


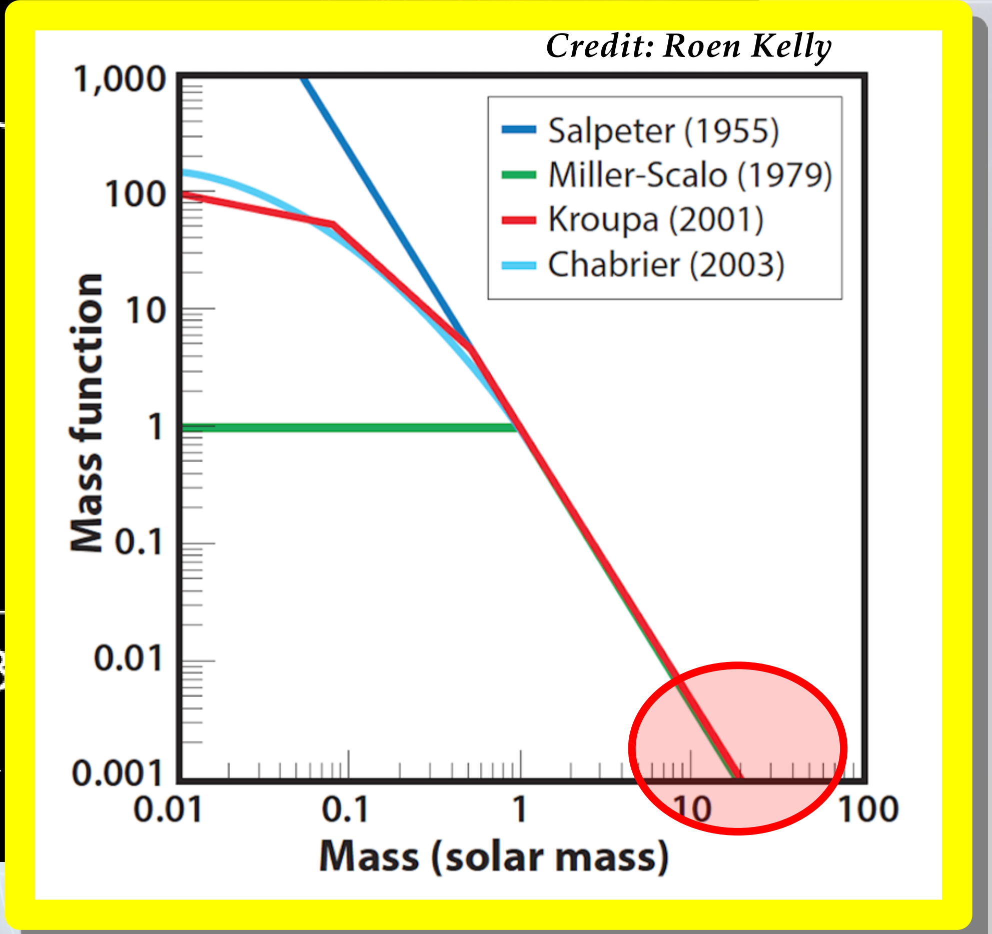
Way towards a type II supernova:



Way towards a type II supernova:

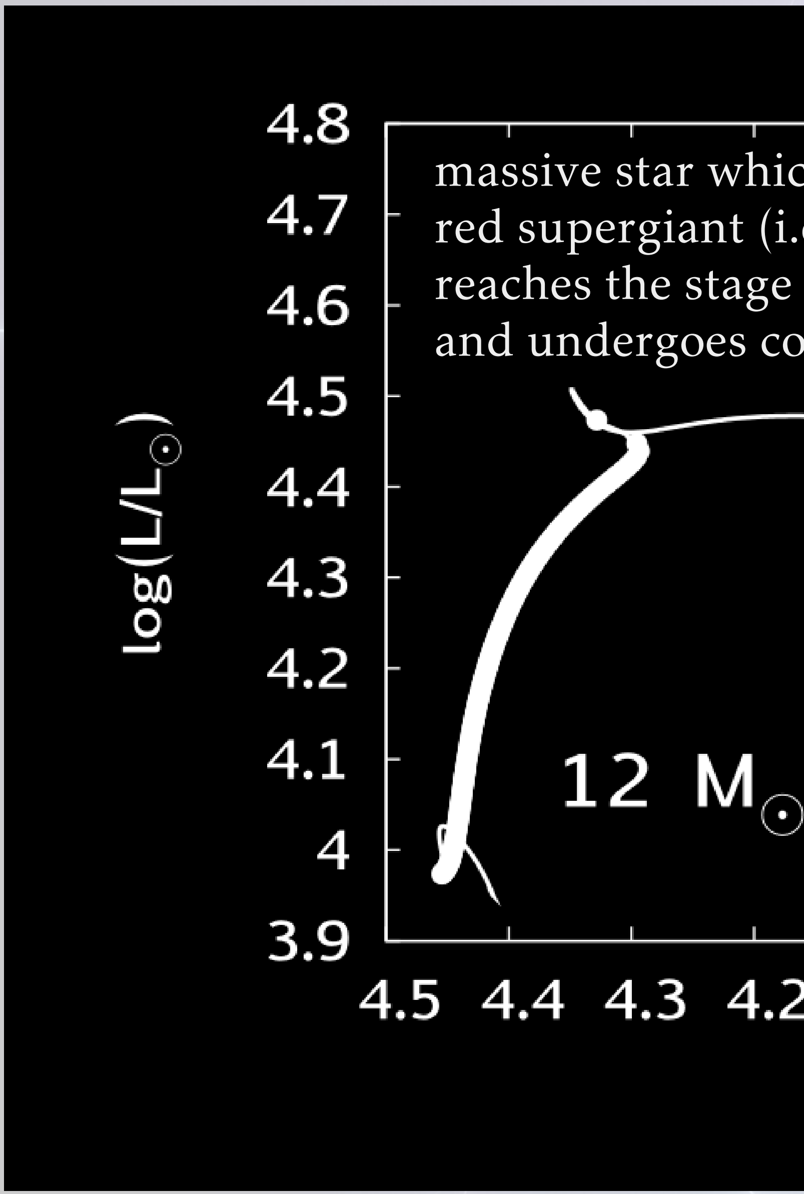


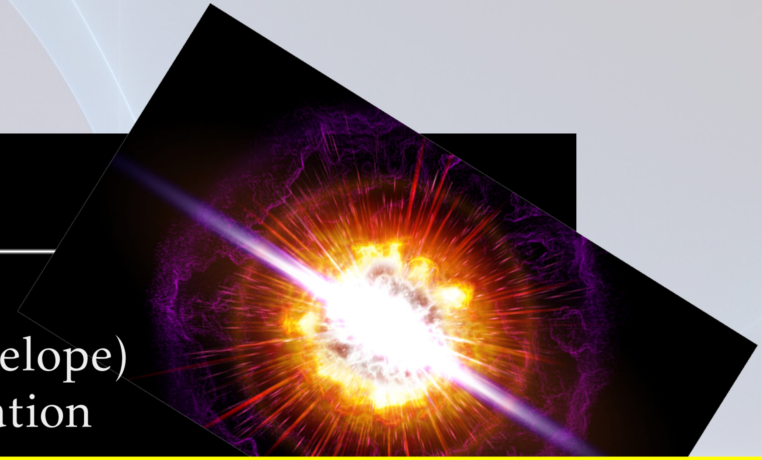




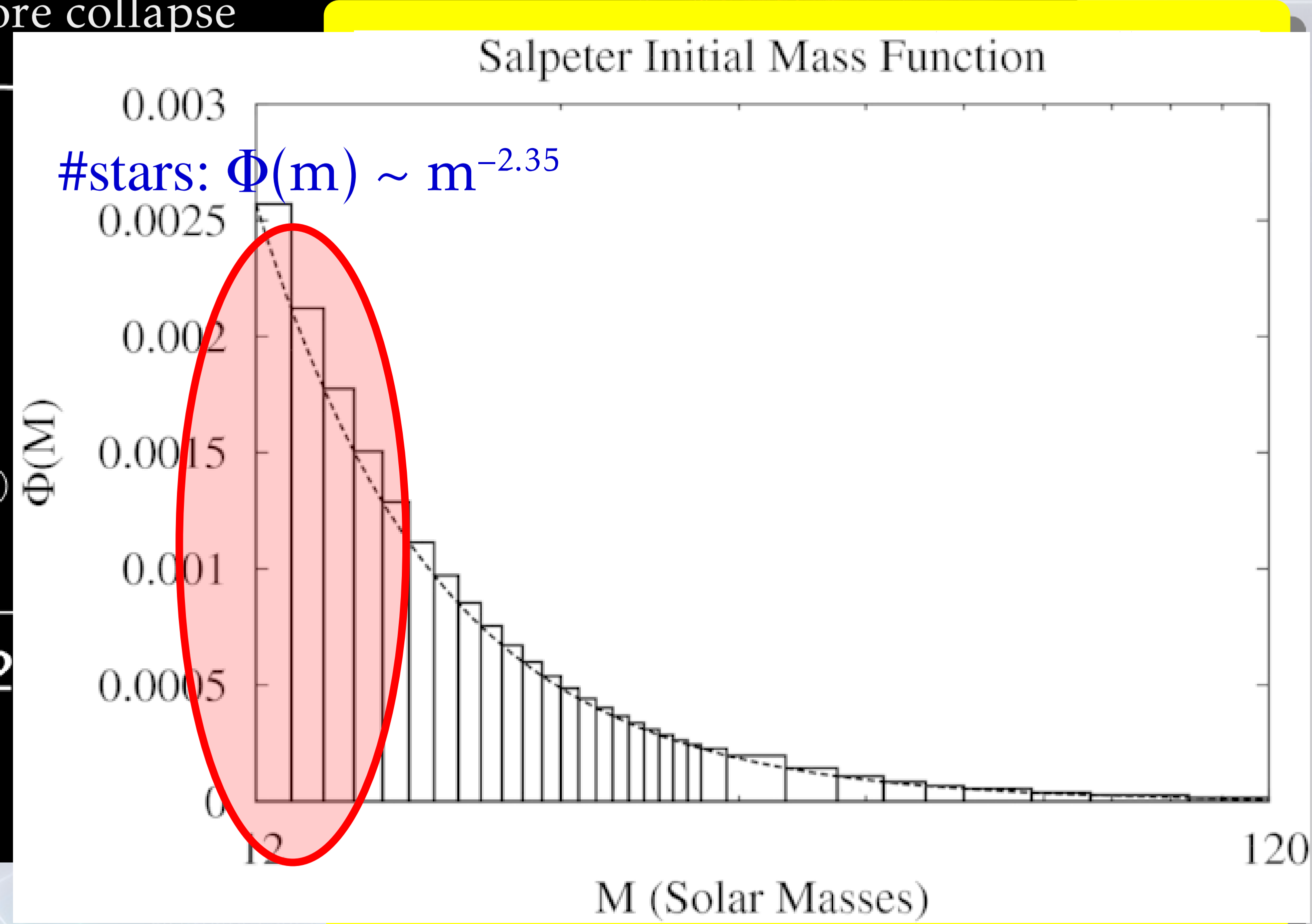
Way towards a type II supernova:

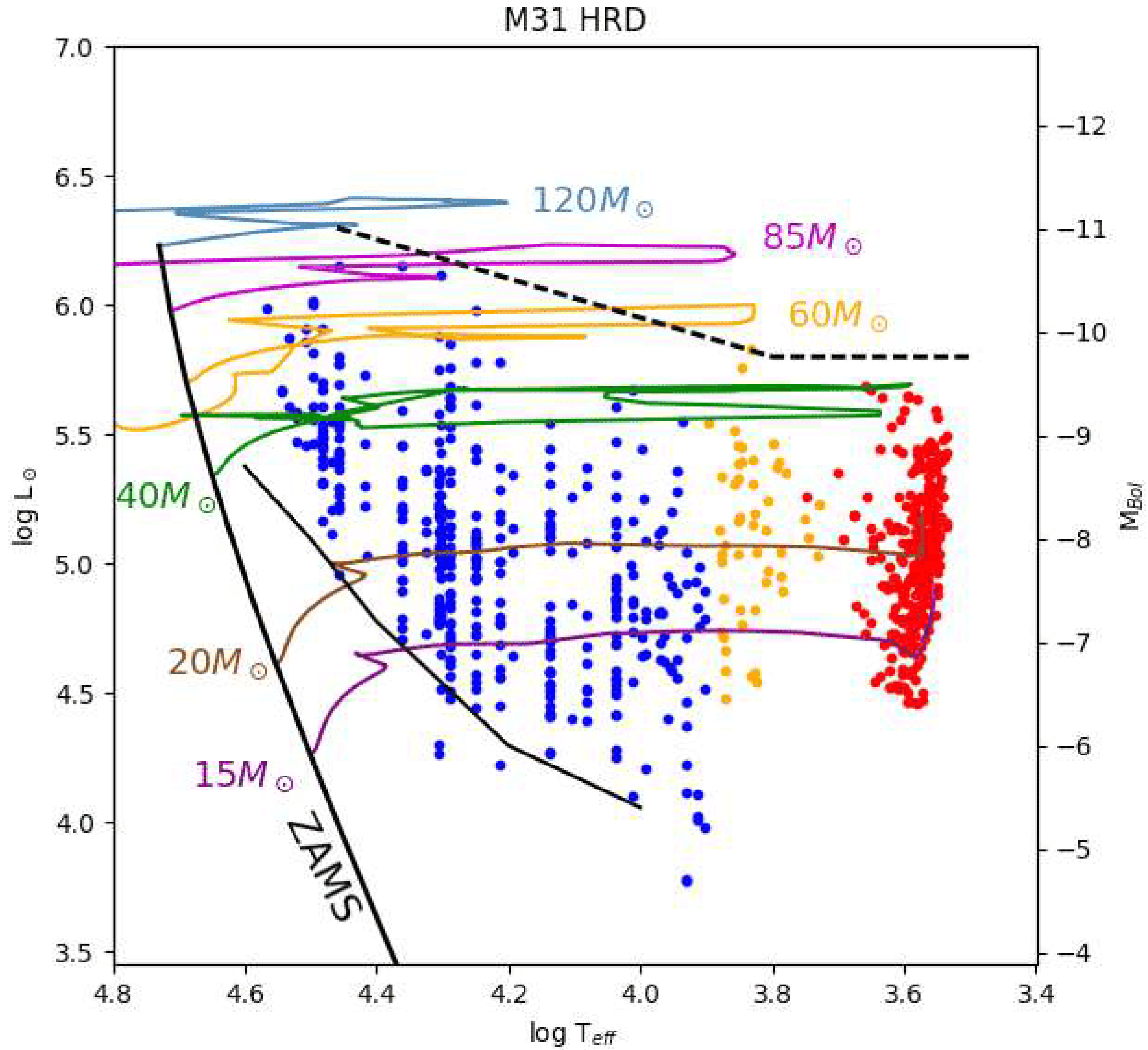
massive star which evolves to be a red supergiant (i.e. with H-rich envelope) reaches the stage of iron-core formation and undergoes core collapse





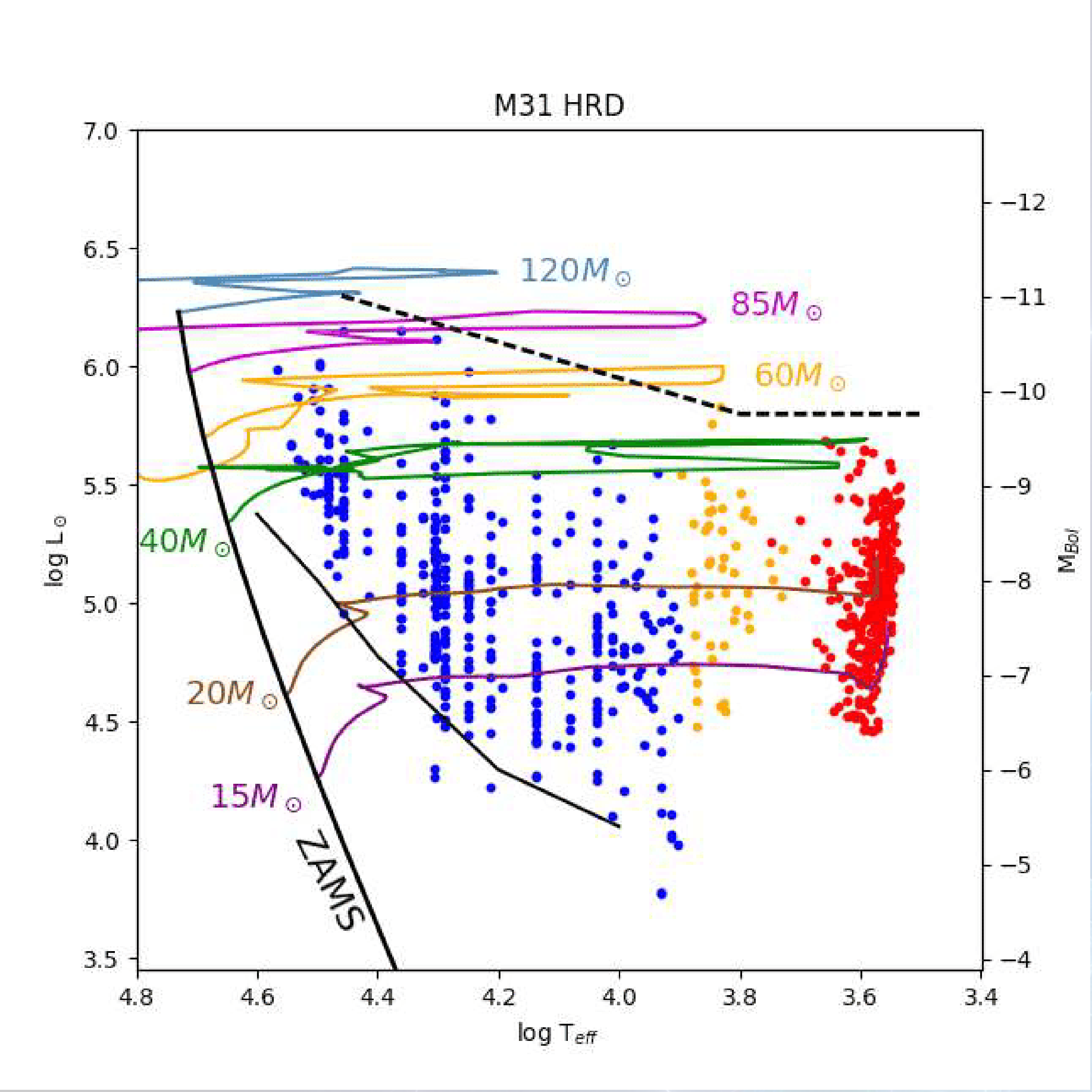
#stars: $\Phi(m) \sim m^{-2.35}$





red-supergiant progenitor
→ **type II**

Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

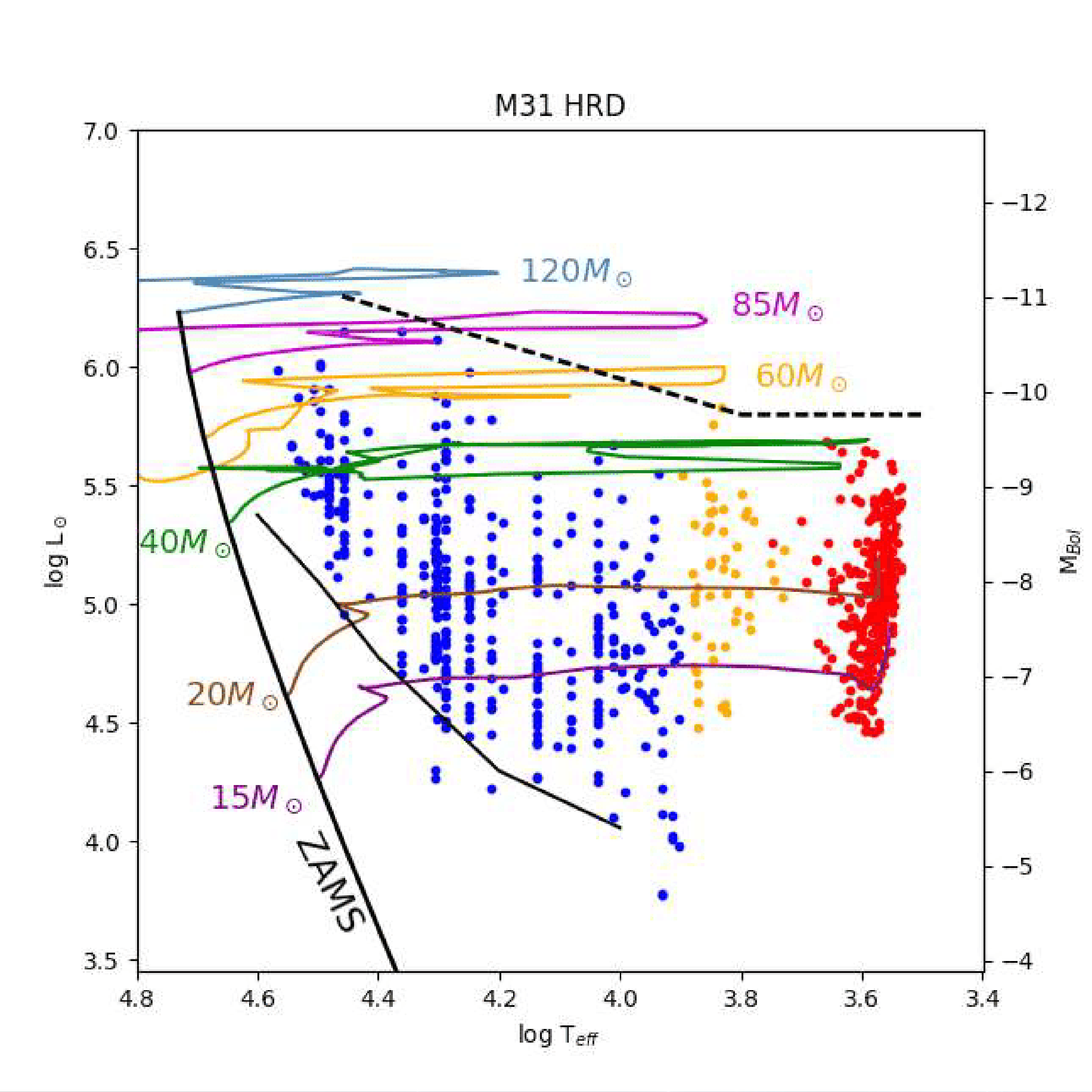


‘stripped’ progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

red-supergiant progenitor
→ **type II**

Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

*stripping = loss of H-rich top layers
In the context of ***single*** stars:
'stripping' is due to losing
mass in the strong wind
In the context of ***binary*** stars:
mass transfer



'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ type Ib or Ic

red-supergiant progenitor
→ type II

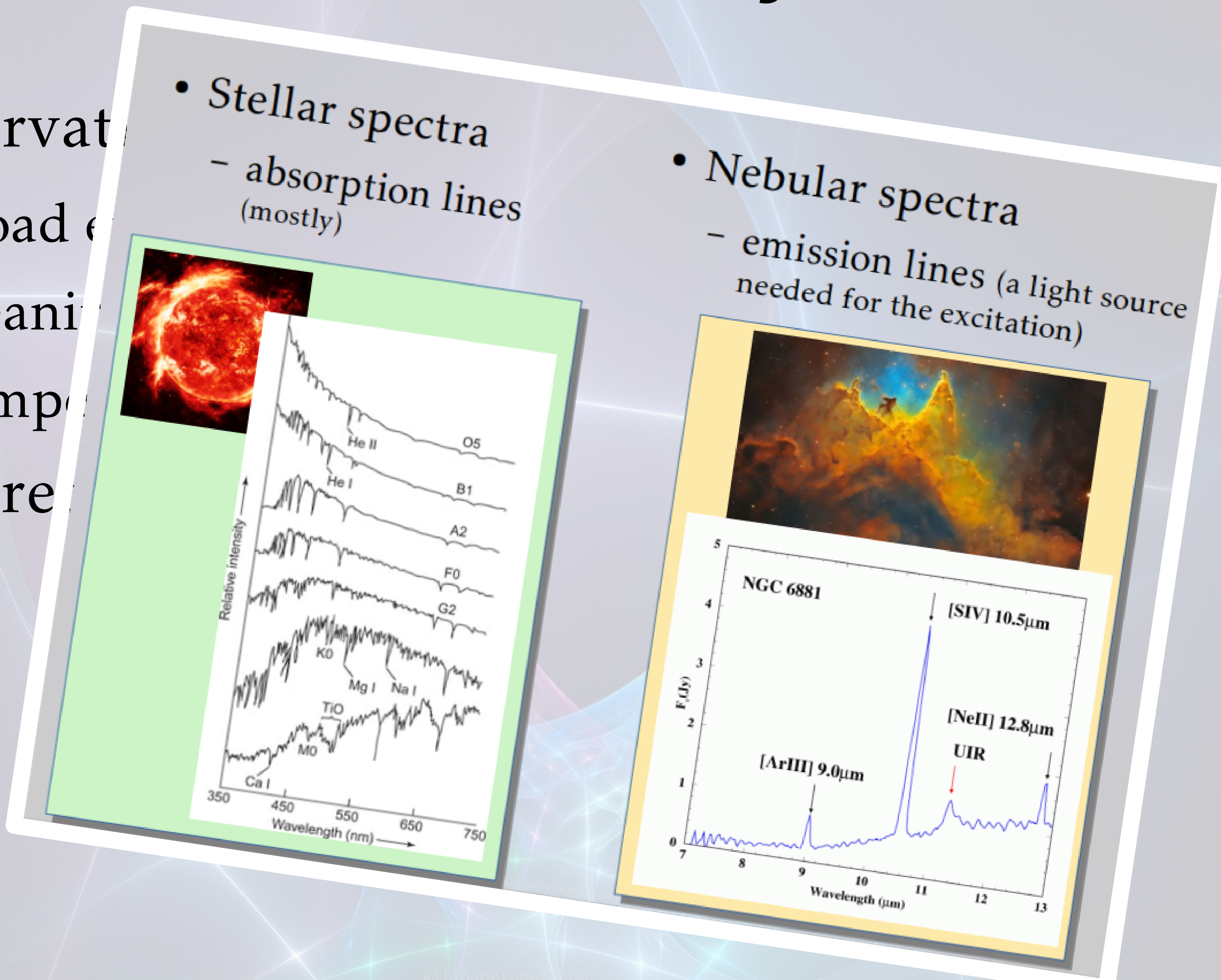
Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

Side-notes on Wolf-Rayet stars

- Observationally:
  - broad emission lines in the spectrum
  - meaning there is a nebula around the star
  - composition: (usually) H-free
- Theoretically:

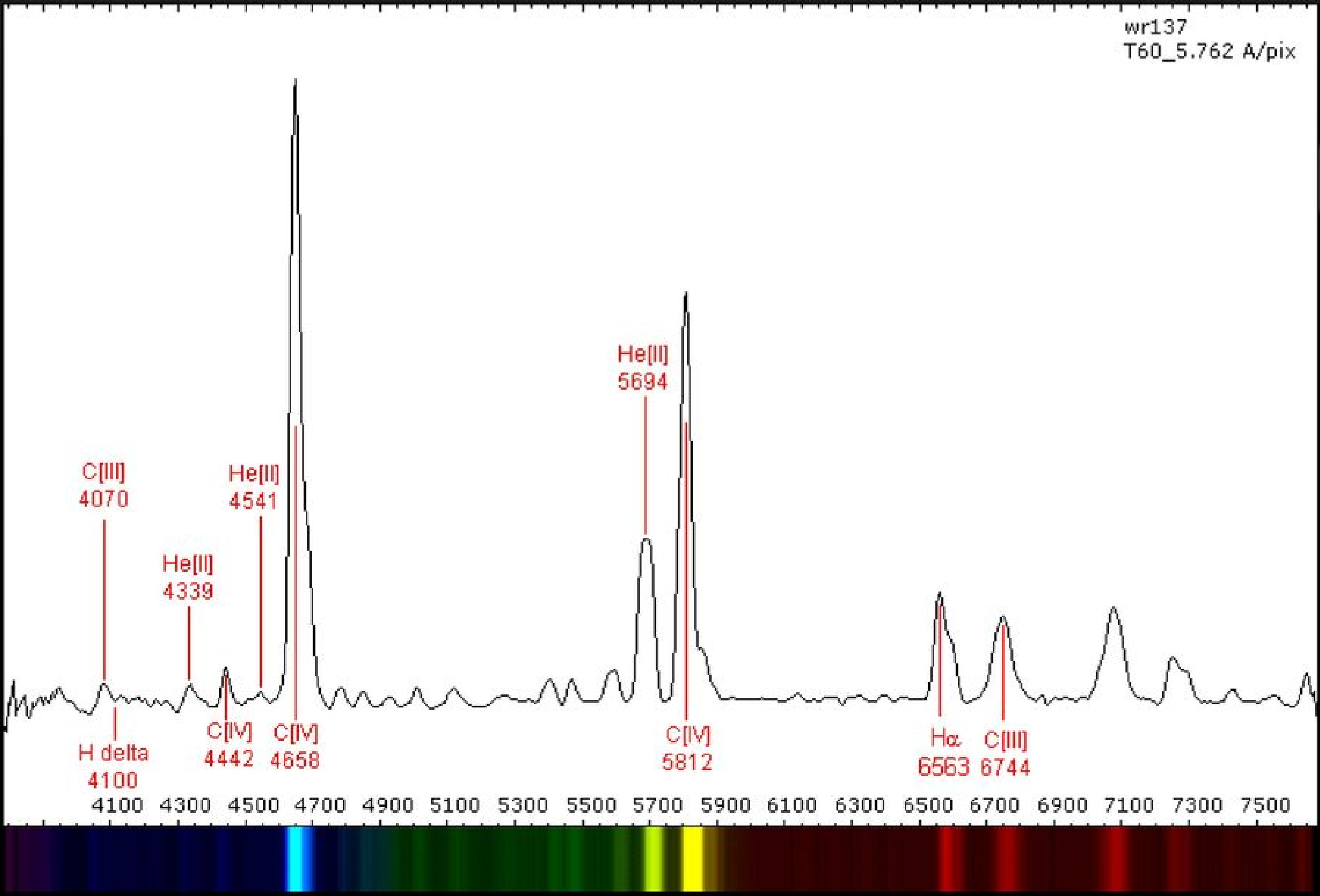
Side-notes on Wolf-Rayet stars

- Observat
  - broad e
  - meani
  - comp
- Theore



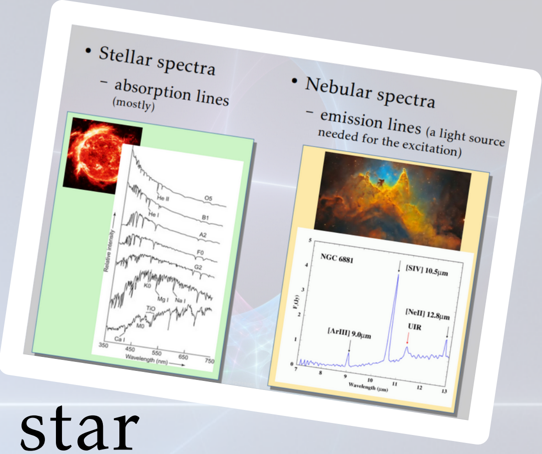
FIRST OBSERVATION

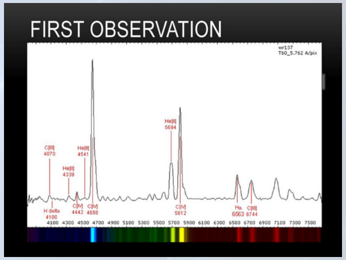
1867: Wolf & Rayet



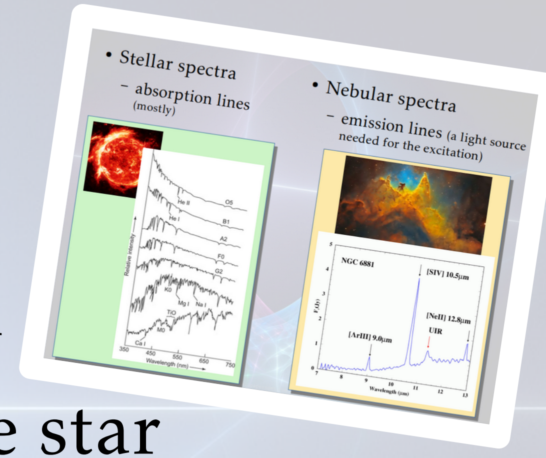
Side-notes on Wolf-Rayet stars

- Observationally:
  - broad emission lines in the spectrum
  - meaning there is a nebula around the star
  - composition: (usually) H-free
- Theoretically:

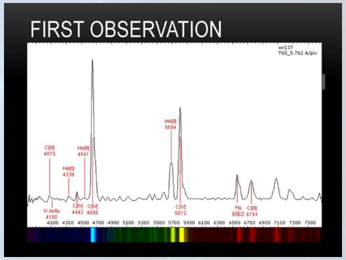




Side-notes on Wolf-Rayet stars



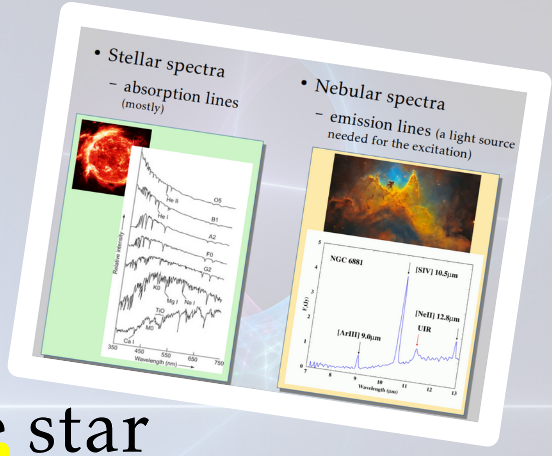
- Observationally:
  - broad emission lines in the spectrum
  - meaning there is a nebula around the star
  - composition: (usually) H-free

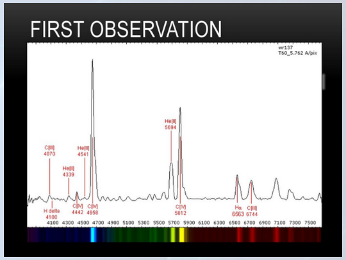


- Theoretically:
  - a H-free star with a nebula around it can be produced by:
    - strong wind (single & binary stars) when the mass is very high (> 40 $M_\odot$, but highly Z-dependent!)
    - binary interaction (needs a close-enough companion & a so-called non-conservative mass transfer, etc.)

Side-notes on Wolf-Rayet stars

- Observationally:
  - broad emission lines in the spectrum
  - meaning th... ...he star
  - composit...

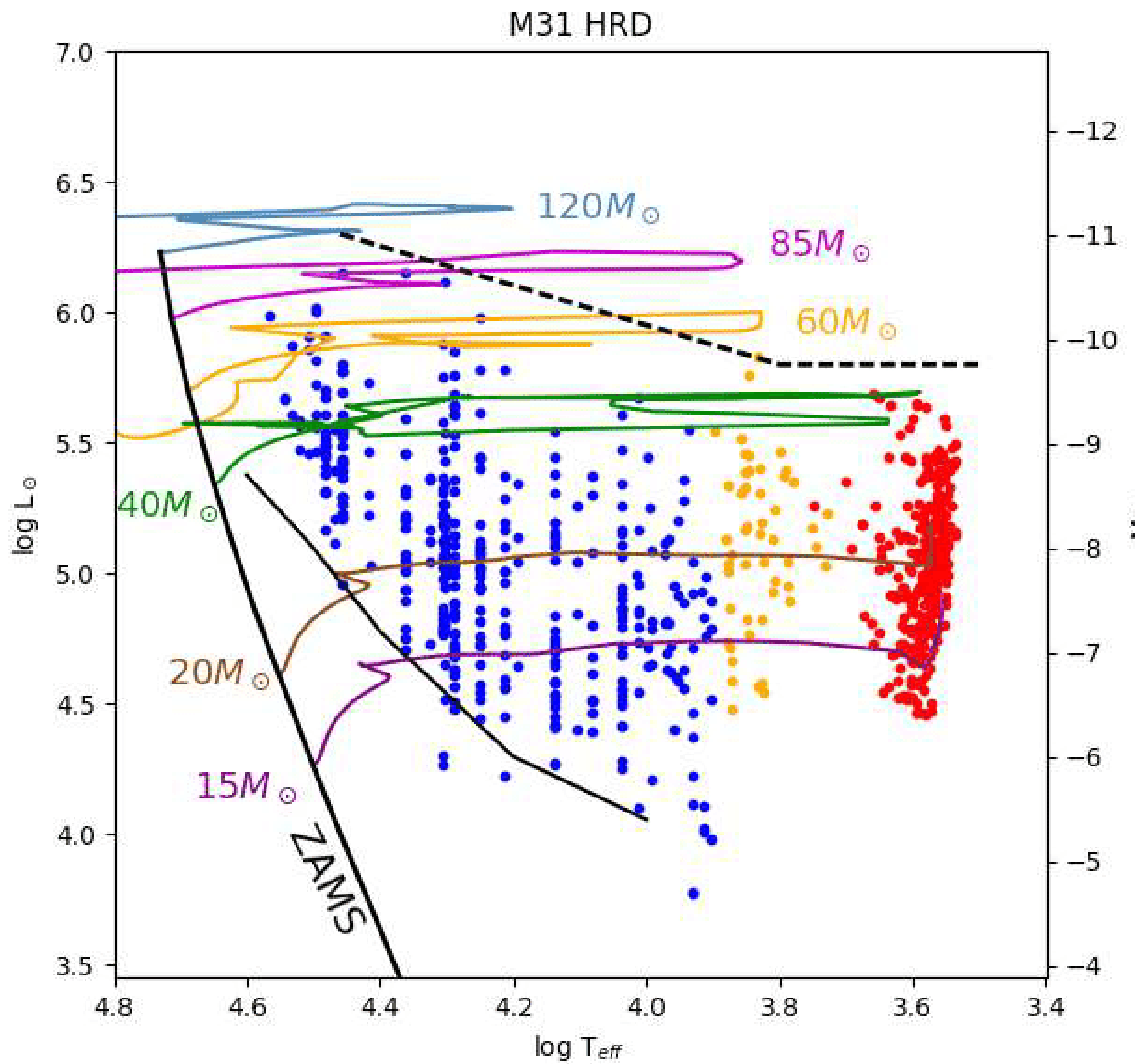




- Theoretica...
  - a H-free s... ...can be produced by:
    - strong wind (single & binary stars) when the mass is very high (> 40 $M_\odot$, but highly Z-dependent!)
    - binary interaction (needs a close-enough companion & a so-called non-conservative mass transfer, etc.)

Interesting to consider:
in theory, a star could be H-free without a nebula, right?

would that still be a WR star?



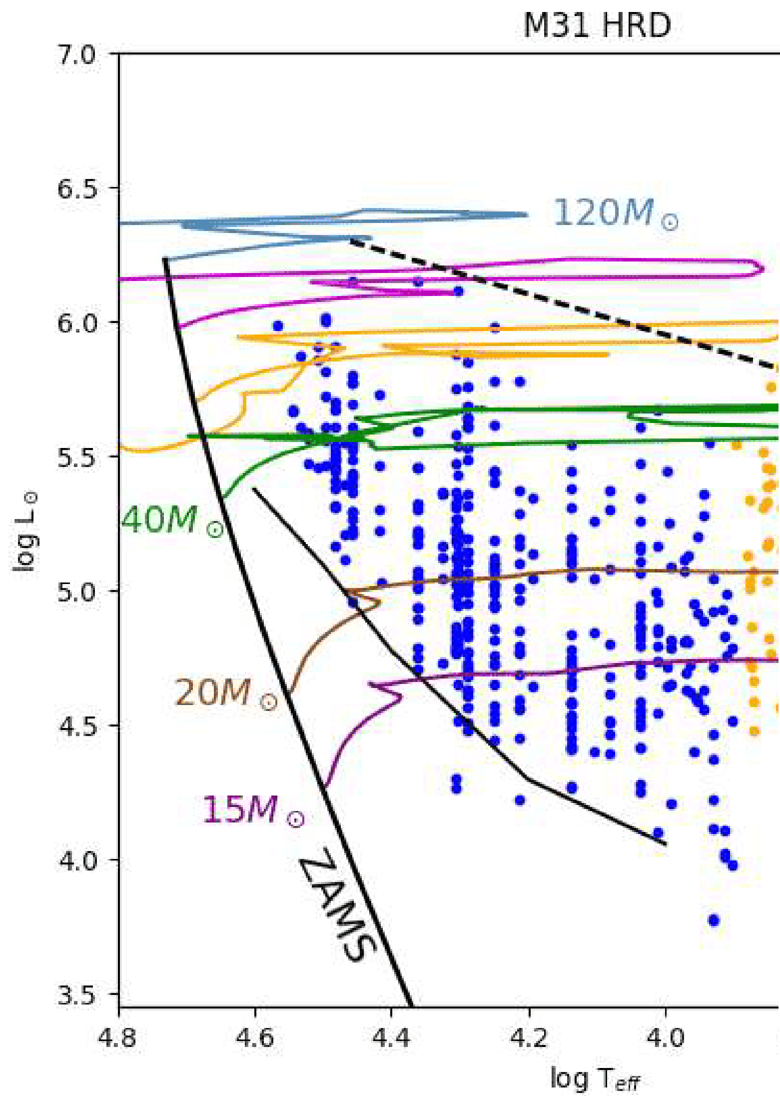
*stripping = loss of H-rich top layers
In the context of ***single*** stars:
'stripping' is due to losing
mass in the strong wind
In the context of ***binary*** stars:
mass transfer

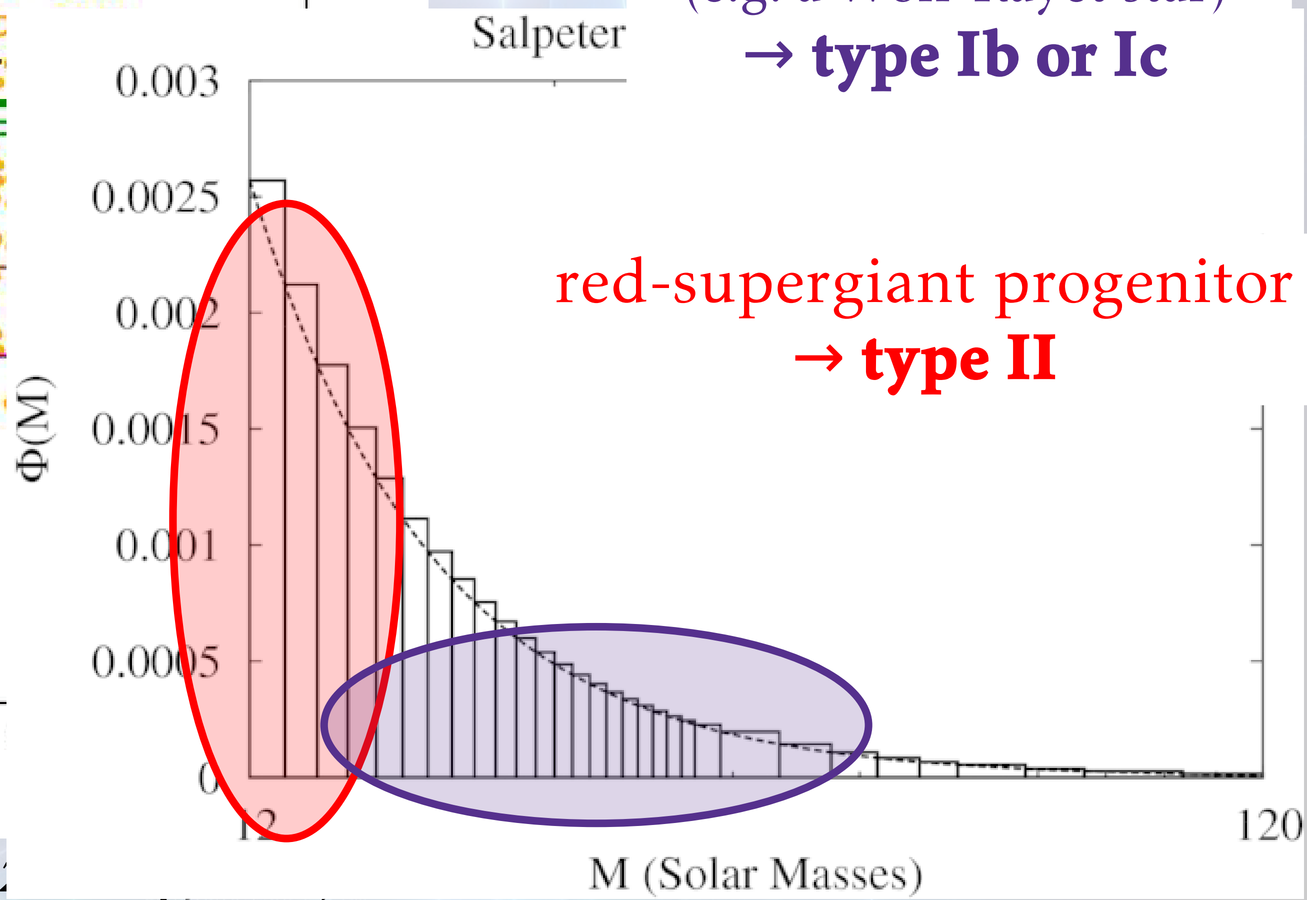
'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

red-supergiant progenitor
→ **type II**

Credit: Roberta Humphreys & al. (2017, ApJ. 844.)

*stripping = loss of H-rich top layers
In the context of ***single*** stars:
'stripping' is due to losing
mass in the strong wind
In the context of ***binary*** stars:
mass transfer





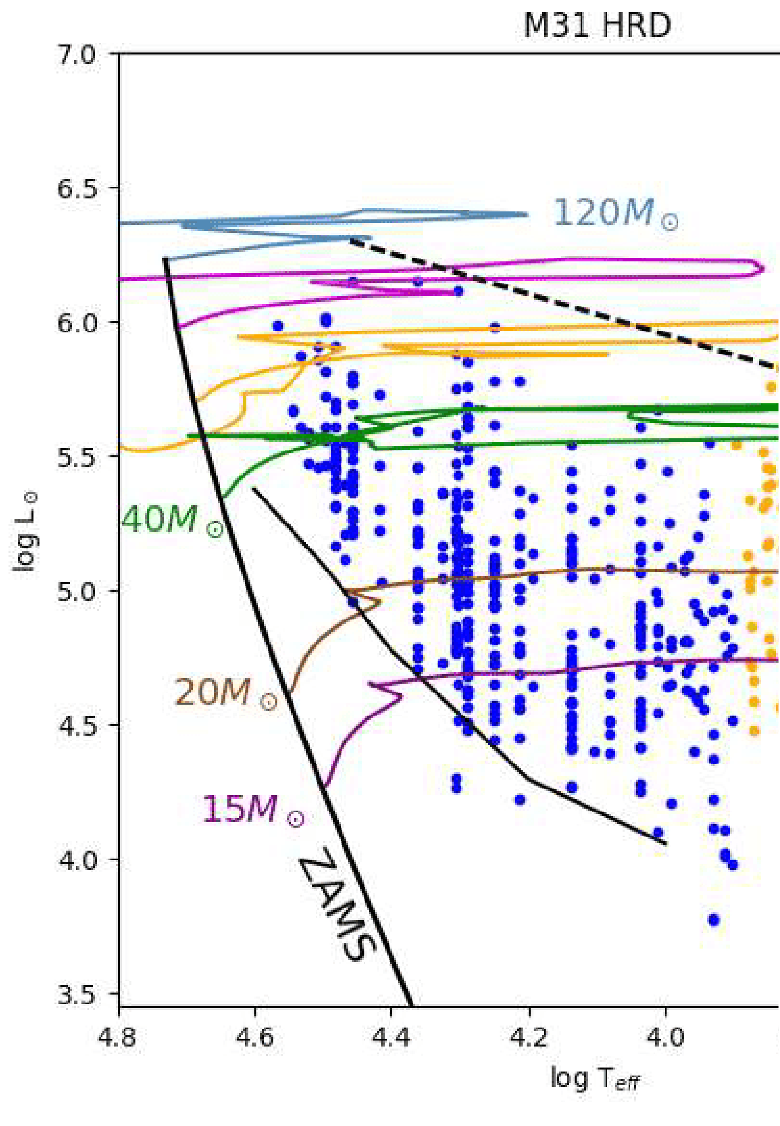
'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

red-supergiant progenitor
→ **type II**

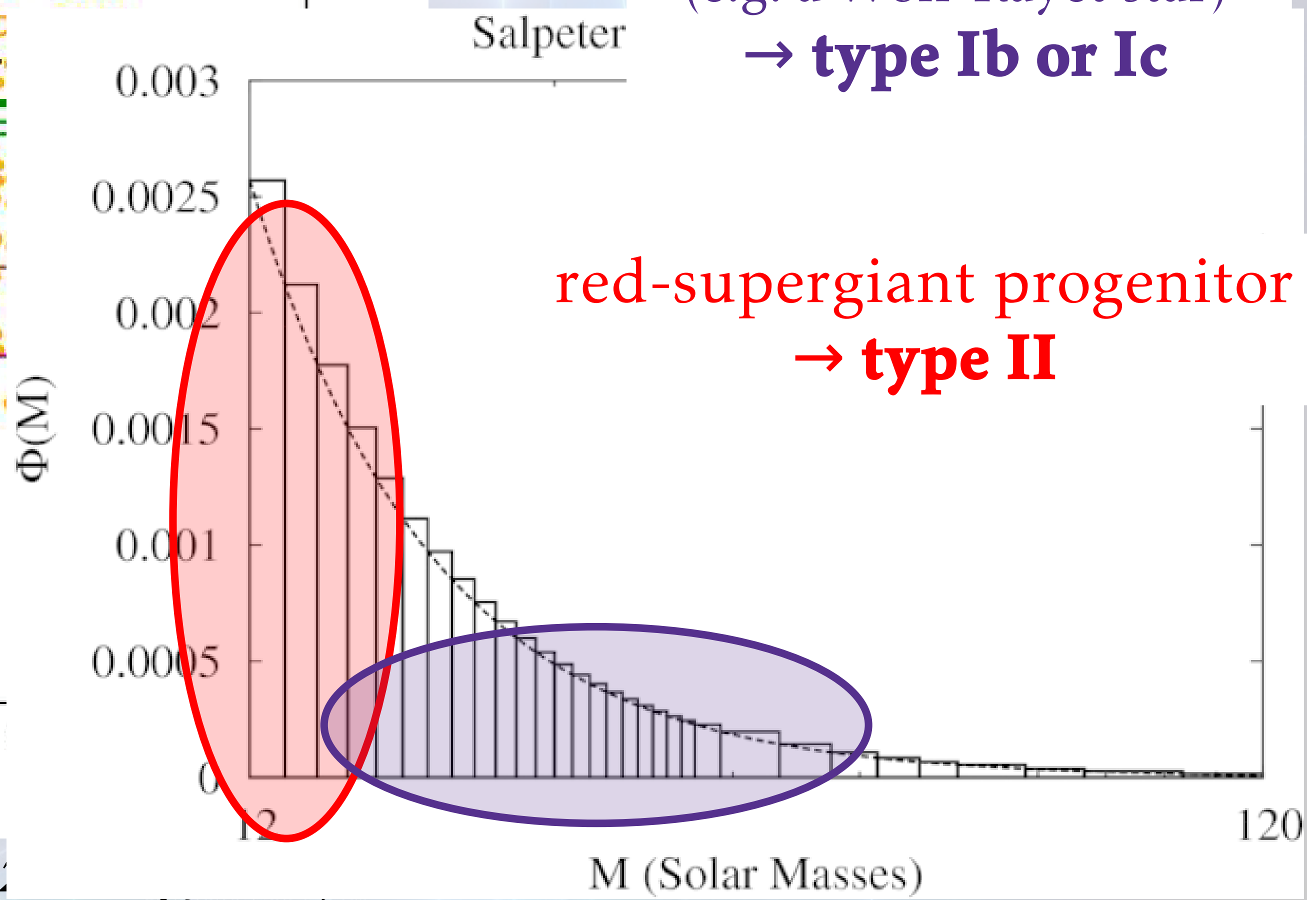
Credit: Roberta Humphreys & al. (

This is only true: single stars
at solar metallicity
no (or slow) rotation

*stripping = loss of H-rich top layers
In the context of ***single*** stars:
'stripping' is due to losing
mass in the strong wind
In the context of ***binary*** stars:
mass transfer



'stripped' progenitor*
(e.g. a Wolf-Rayet star)
→ **type Ib or Ic**

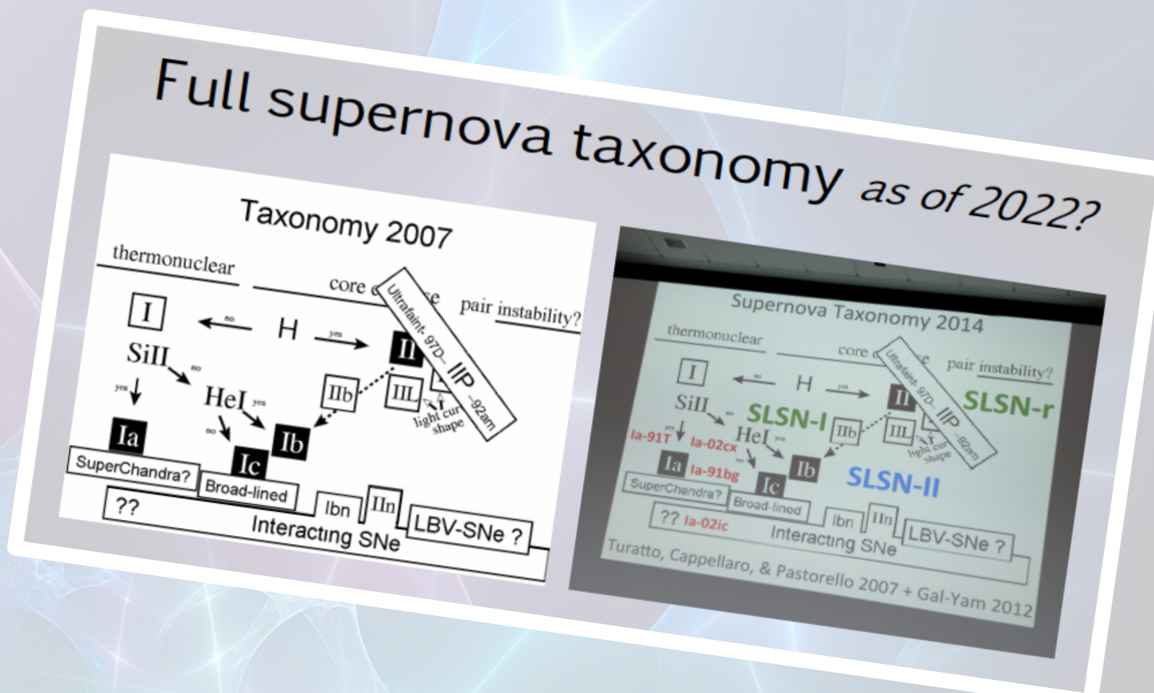


red-supergiant progenitor
→ **type II**

Credit: Roberta Humphreys & al. (

What happens at

→ sub-Solar metallicities?
→ fast-rotating stars?
→ stars in a binary system?



Sub-Solar metallicities

(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

Sub-Solar metallicities

(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Sub-Solar metallicities

(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one

Sub-Solar metallicities

(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one
  - higher chance to form a BH after the collapse

metallicities

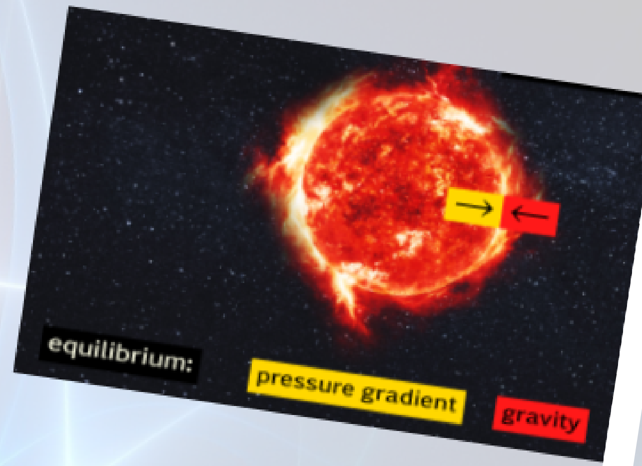
nd no binary companion)

• N

Cons

Core collapse

- Gravity takes over
  - end of the long-term equilibrium
  - fall-in: on the free-fall timescale
- …is there something to stop it?
  - Well… it depends.
  - Most of the time ("classical" case): a neutron star forms in the center ("proto-neutron-star")
    - a neutron star is: one giant nucleus. dense. stable.
    - bounce-back, shock waves, emission of neutrinos and light = **SUPERNOVA EXPLOSION**



Sub-Solar metallicities

(and still no rotation and no binary companion)

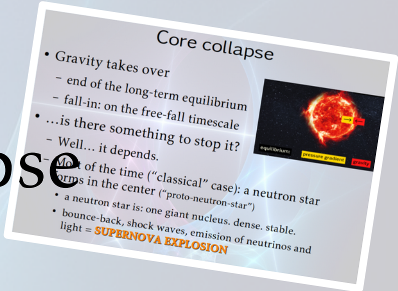
- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one
  - higher chance to form a BH after the collapse



Sub-Solar metallicities

(and still no rotation and no binary companion)

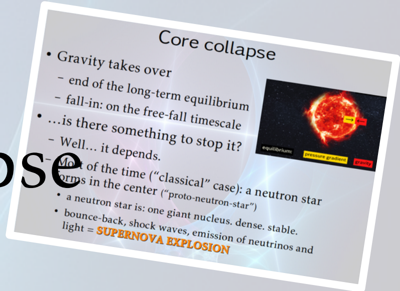
- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one
  - higher chance to form a BH after the collapse
  - key question: is there something to **STOP** the collapse?



Sub-Solar metallicities

(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

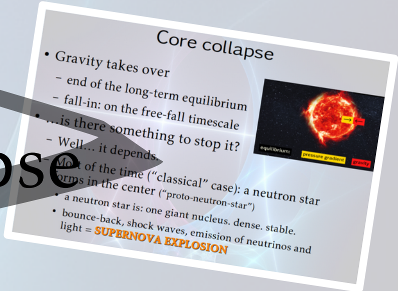
  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one
  - higher chance to form a BH after the collapse
  - key question: is there something to **STOP** the collapse?
  - if yes: CCSN

    type II, Ib/c



Sub-Solar metallicities

(and still no rotation and no binary companion)

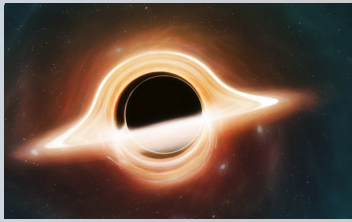
- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:

- if an iron core is able to form, then it will be a **more massive** one
  - higher chance to form a BH after the collapse
  - key question: is there something to **STOP** the collapse?
  - if yes: CCSN (type II, Ib/c) — if no: direct fall-in into a BH (no explosion)



Sub-Solar metallicities

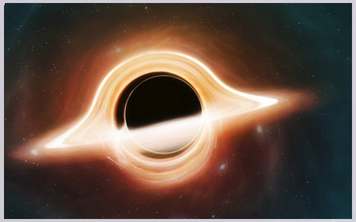
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:



Consequence #2:

Sub-Solar metallicities

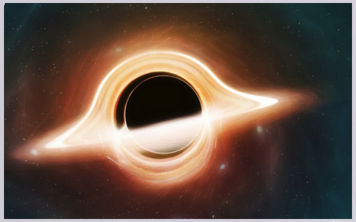
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

  → stars live their lives with more mass retained

  → also ***end*** their lives with more mass retained

Consequence #1:



Consequence #2:

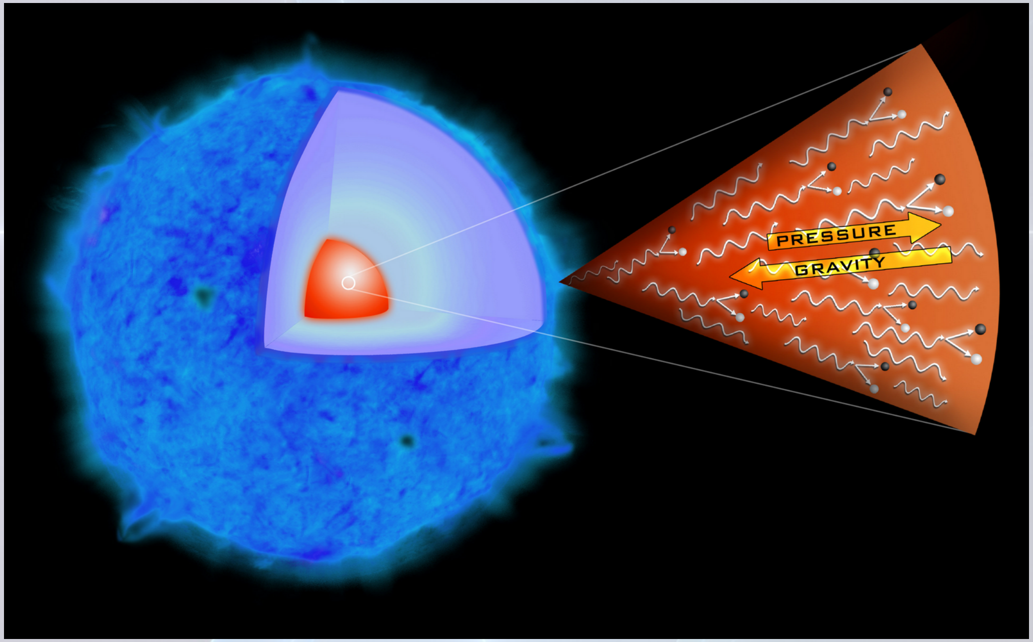
sometimes even the iron-core won't be able to form

Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow$ e- & e+



Collapse

Explosive O-burning → supernova

No remnant!

Why?

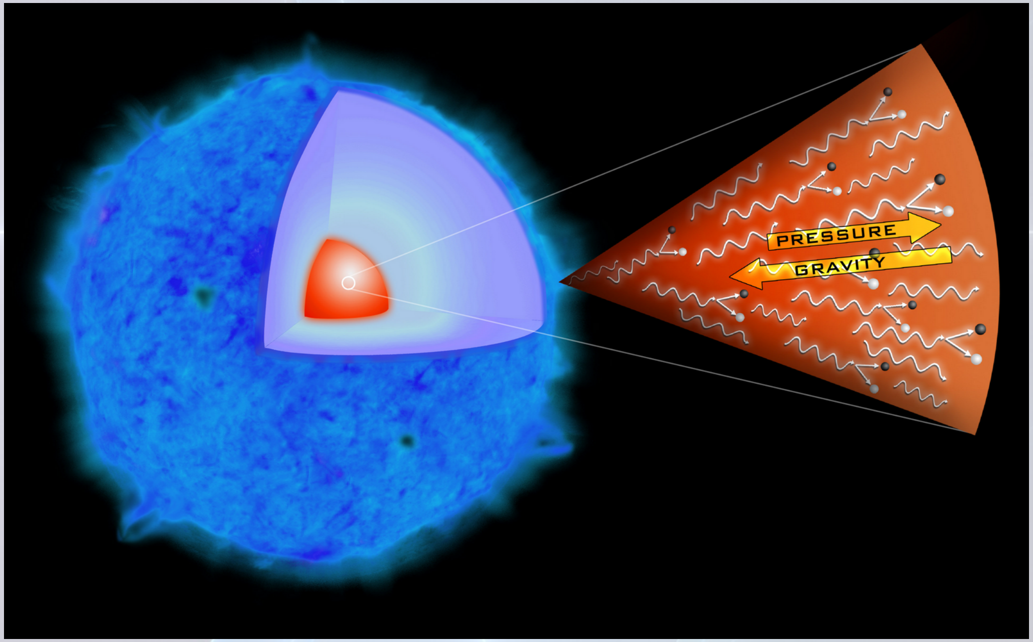
Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow e^- \, \& \, e^+$

can happen already in stars with $\gtrapprox 60\ M_\odot$

Collapse



Explosive O-burning $\rightarrow$ supernova

No remnant!

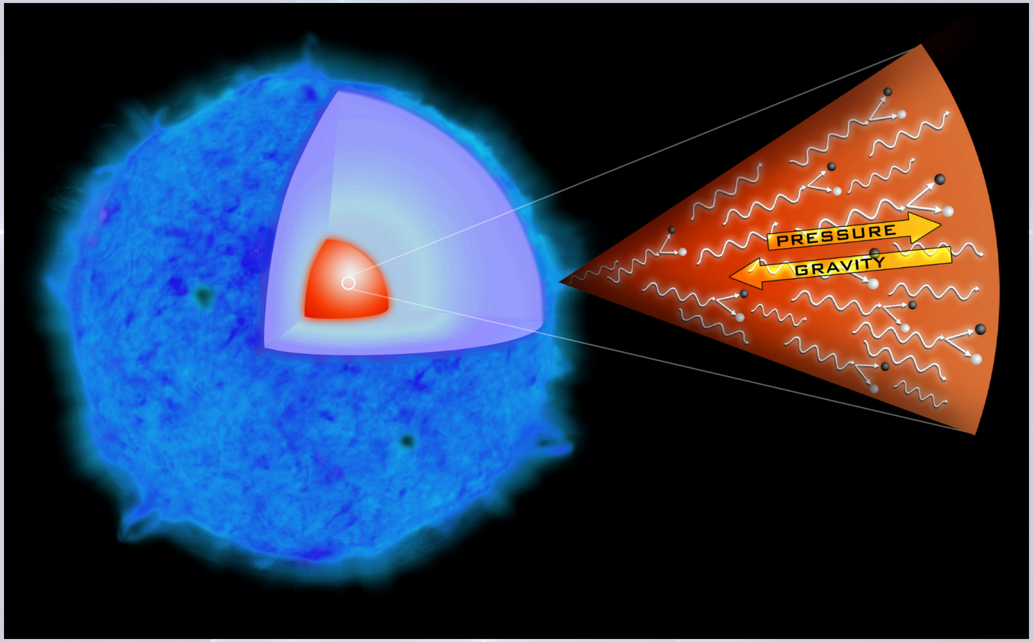
Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow e^- \,\&\, e^+$

can happen already in stars with $\gtrsim 60\ M_\odot$



Collapse

key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

No remnant!

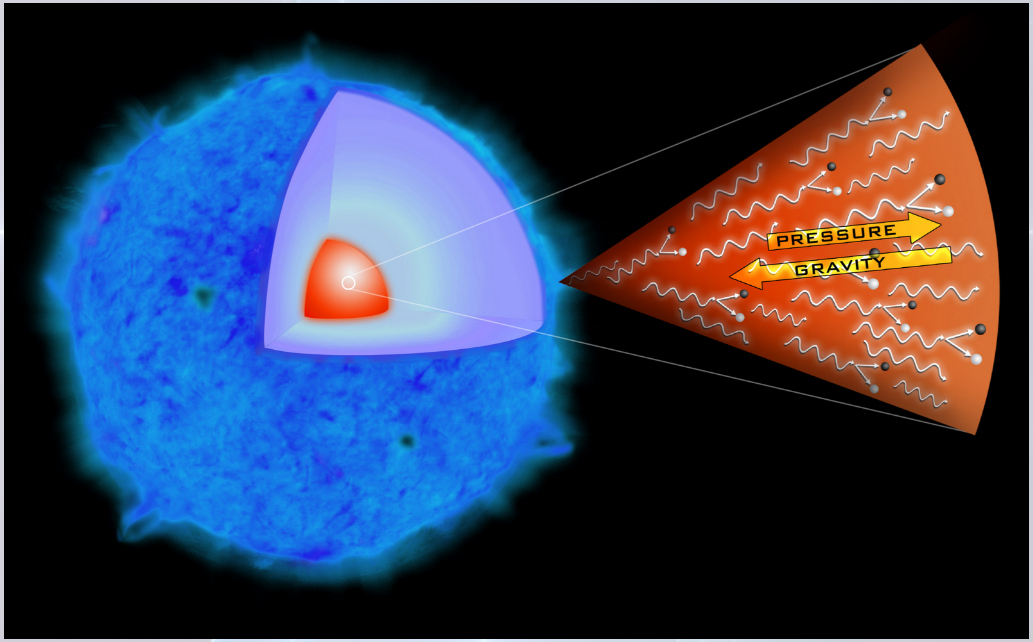
Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow e^- \,\&\, e^+$

can happen already in stars with $\gtrapprox 60\ M_\odot$



Collapse

key question, as always:
is there something to stop it?
…if not:

Explosive O-burning → supernova

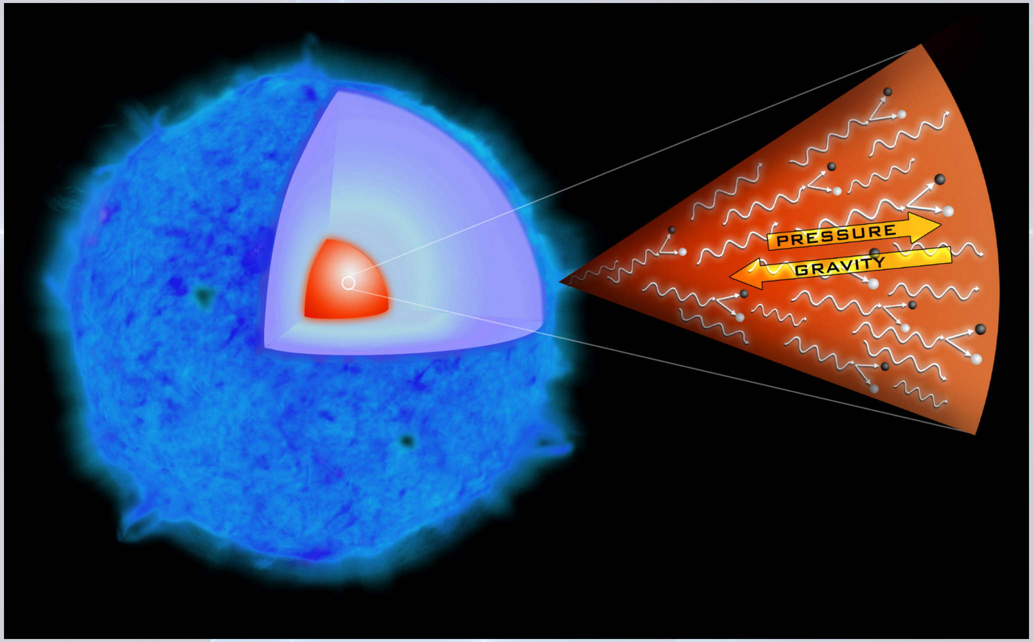
happens with stars ~140-260 $M_\odot$

No remnant!

Why?

Pair Instability

happens in ***quite*** massive stellar cores



Photon pressure drops due to $\gamma\gamma \rightarrow e^- \ \& \ e^+$

can happen already in stars with $\gtrapprox 60\ M_\odot$

Collapse

key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 $M_\odot$

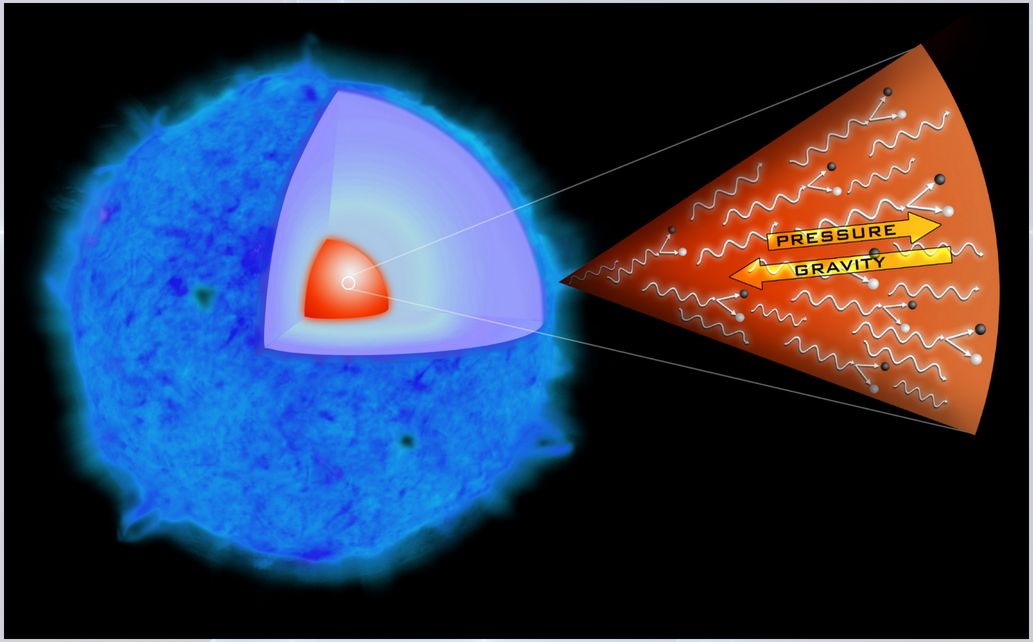
pair-instability supernova (PISN)

No remnant!

Why?

Pair Instability

happens in ***quite*** massive stellar cores



Photon pressure drops due to γγ → e- & e+

can happen already in stars with ≧ 60 M⊙

Collapse

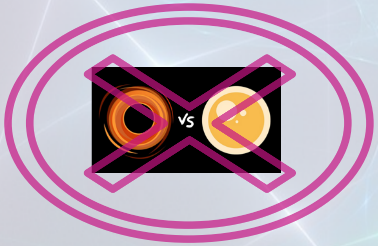
key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 M⊙

pair-instability supernova (PISN)

No remnant!



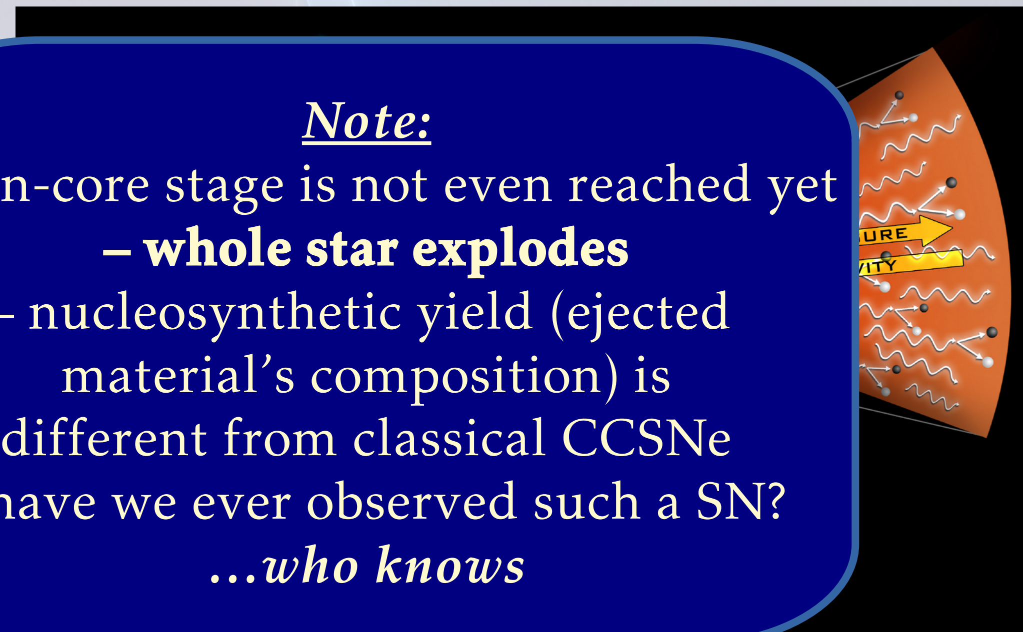
Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow e^- \,\&\, e^+$

can happen already in stars with ≳ 60 M☉



Note:
– iron-core stage is not even reached yet
– whole star explodes
– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe
– have we ever observed such a SN?
…who knows

Collapse

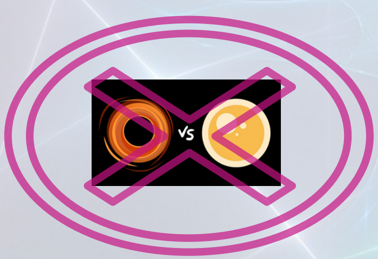
key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 M☉

pair-instability supernova (PISN)

No remnant!



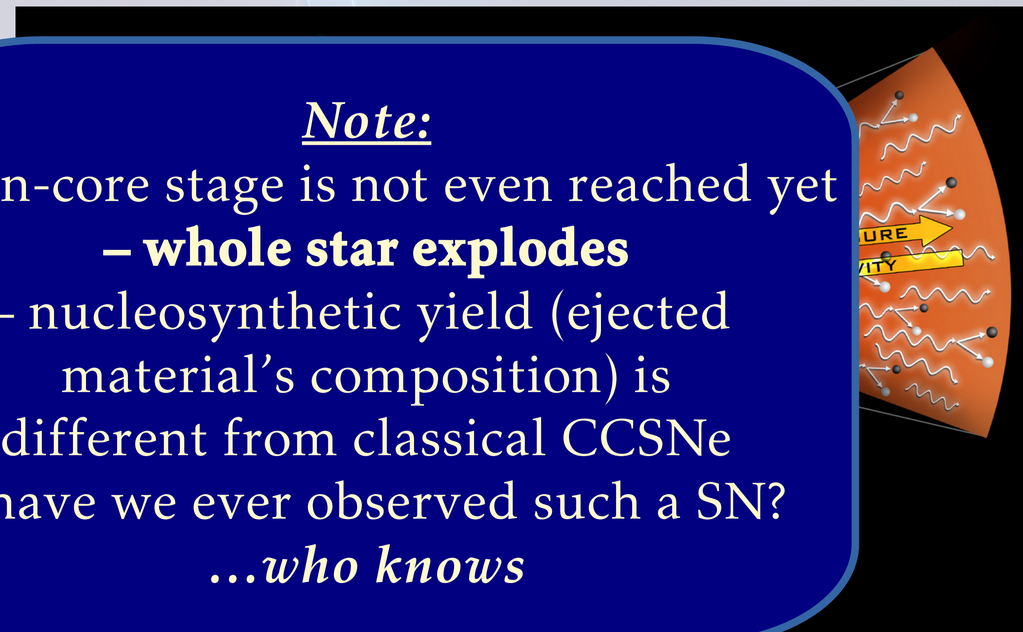
Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to
γγ → e- & e+

can happen already in stars with ≳ 60 $M_\odot$



Note:
– iron-core stage is not even reached yet
– whole star explodes
– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe
– have we ever observed such a SN?
…who knows

Collapse

key question, as always:
is there something to stop it?
…if not:

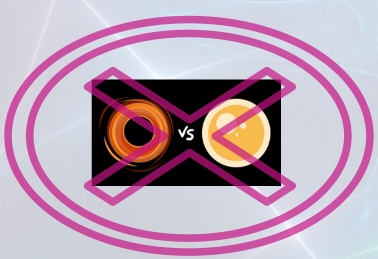
Explosive O-burning
→ supernova

happens with stars ~140-260 $M_\odot$

pair-instability supernova (PISN)

stars between 60–140 $M_\odot$:
collapse is stopped by the star re-gaining its hyrostatic stability

No remnant!



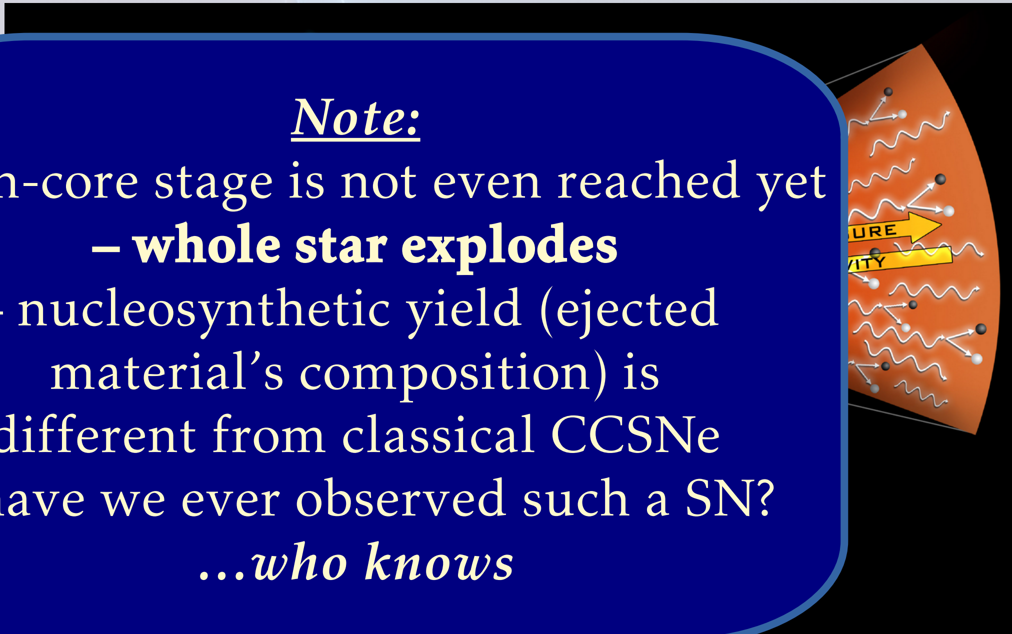
Why?

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to $\gamma\gamma \rightarrow e^- \& e^+$

can happen already in stars with ≳ 60 M☉



Note:

– iron-core stage is not even reached yet

– whole star explodes

– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe

– have we ever observed such a SN?

…who knows

Collapse

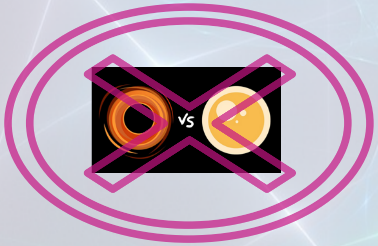
key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 M☉

pair-instability supernova (PISN)

No remnant!



stars between 60–140 M☉:
collapse is stopped by the star re-gaining its hyrostatic stability

might* lead to a 'pulsational pair-instability supernova' (pPISN)

because layers lost in the pulsations ***might*** collide and emit light

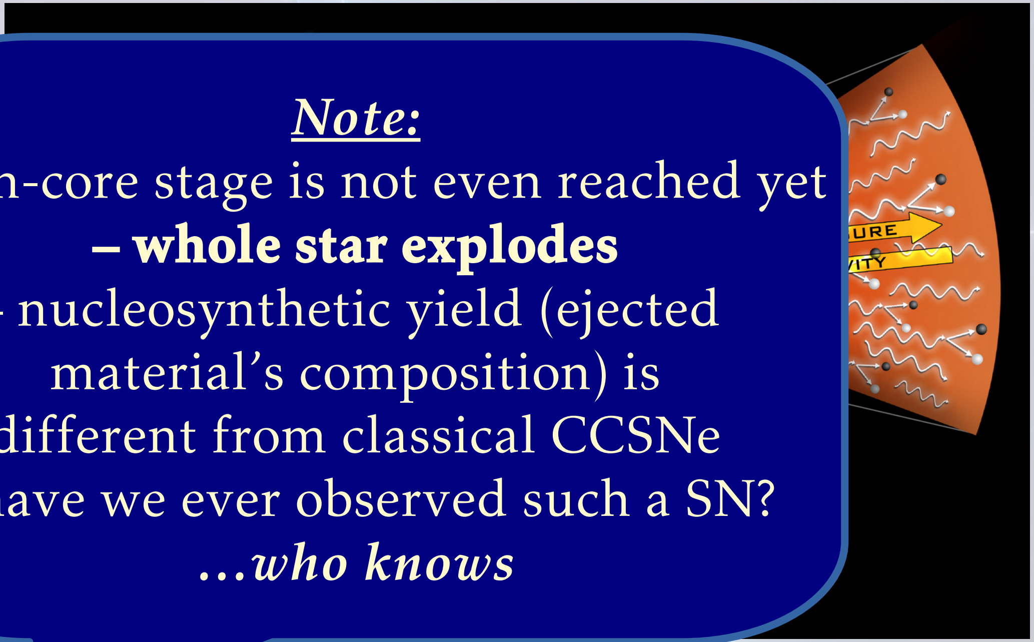
above 260 $M_\odot$:
again direct collapse into BH
(gravity wins)

Pair Instability

happens in ***quite*** massive stellar cores

Photon pressure drops due to
$\gamma\gamma \rightarrow$ e- & e+

can happen already in stars with $\gtrapprox$ 60 $M_\odot$



Note:

– iron-core stage is not even reached yet

– whole star explodes

– nucleosynthetic yield (ejected material's composition) is different from classical CCSNe

– have we ever observed such a SN?

…who knows

Collapse

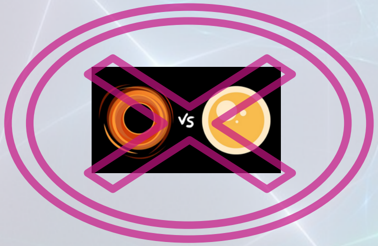
key question, as always:
is there something to stop it?
…if not:

Explosive O-burning
→ supernova

happens with stars ~140-260 $M_\odot$

pair-instability supernova (PISN)

No remnant!



stars between 60–140 $M_\odot$:
collapse is stopped by the star re-gaining its hyrostatic stability

might* lead to a
'pulsational pair-instability supernova' (pPISN)

because layers lost in the pulsations
might collide and emit light

Sub-Solar metallicities

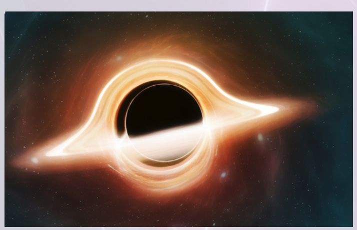
(and still no rotation and no binary companion)

- Main effect: mass loss becomes WEAKER

→ stars live their lives with more mass retained

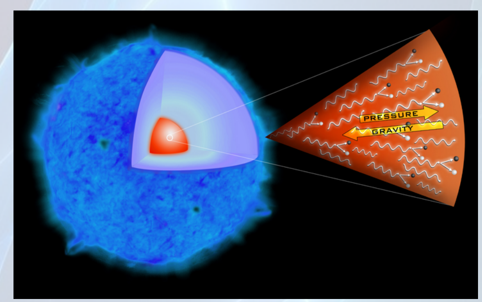
→ also ***end*** their lives with more mass retained

Consequence #1:



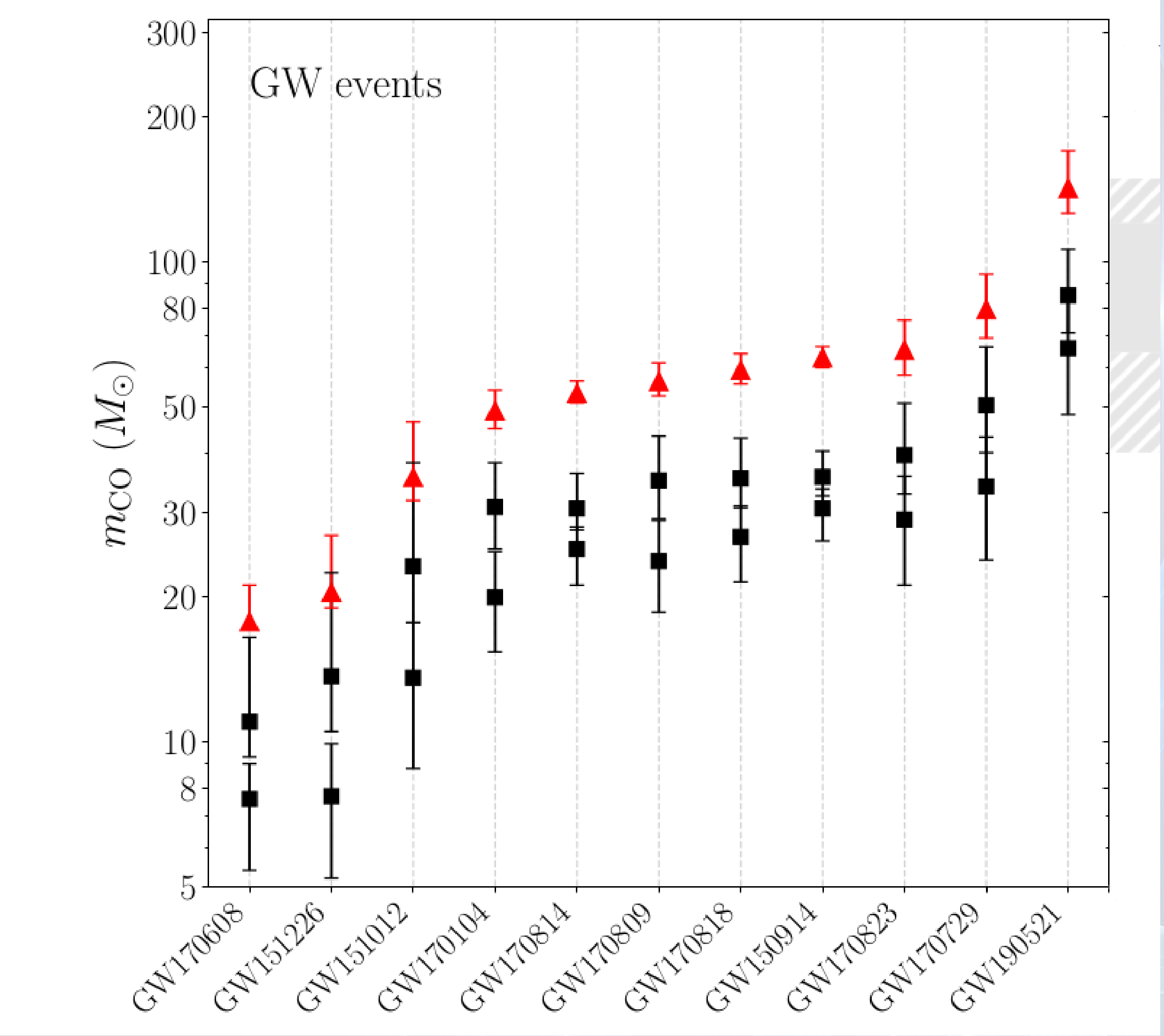
direct fall-in into
a black hole
(of mass ~20-40 $M_\odot$)

Consequence #2:



pair-instabiliy developing, leading to
a PISN (or maybe a pPISN)
or again to direct fall-in to a BH
(but this will be a very heavy BH with >150 $M_\odot$)

The BHs of GW190521 shouldn't exist…



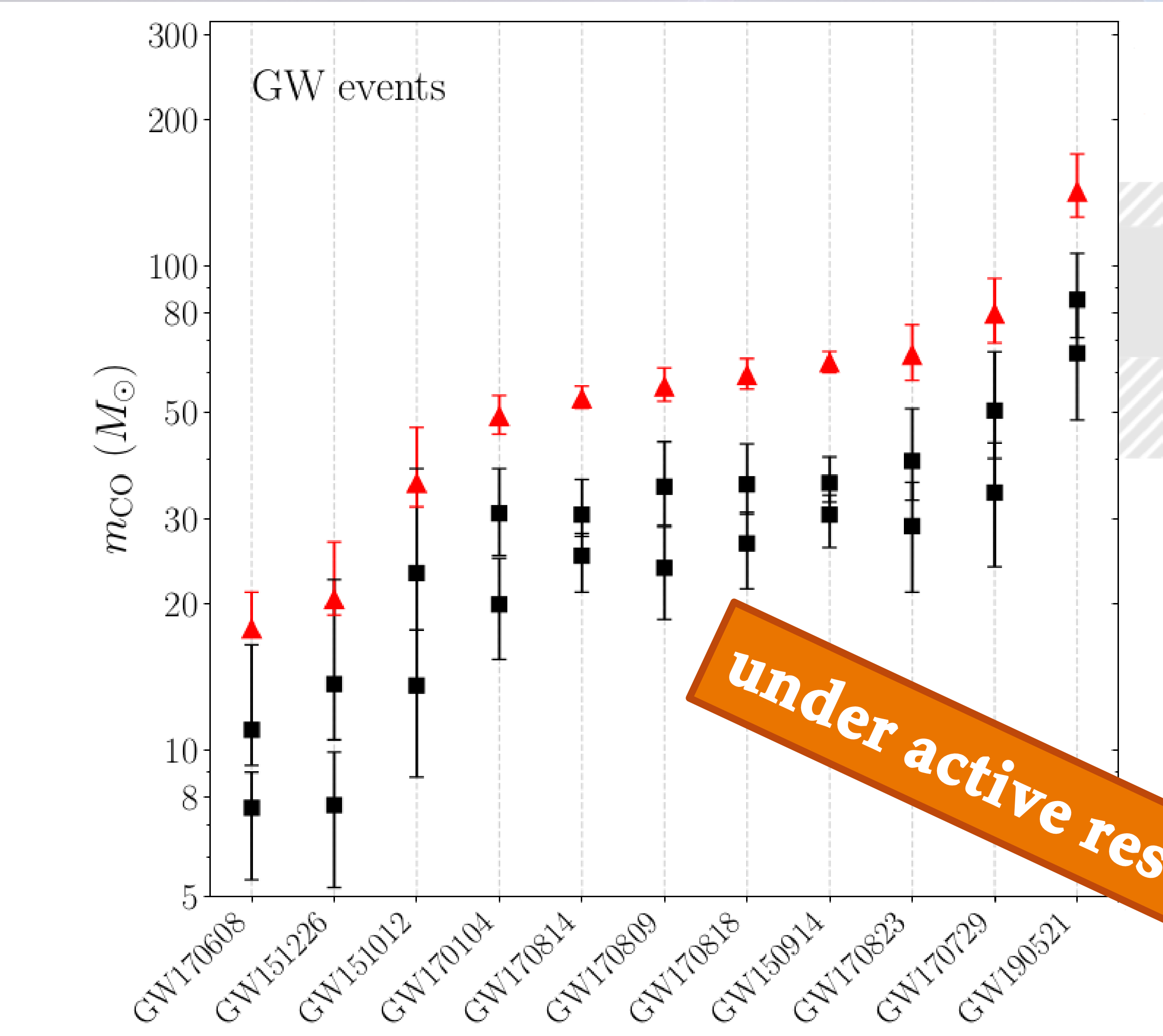
BH no go zone

GW190521:

m1 = 85 (+21/−14) Msun

m2 = 66 (+17/−18) Msun

The BHs of GW190521 shouldn't exist…



under active research

BH no go zone

GW190521:

m1 = 85 (+21/−14) Msun

m2 = 66 (+17/−18) Msun