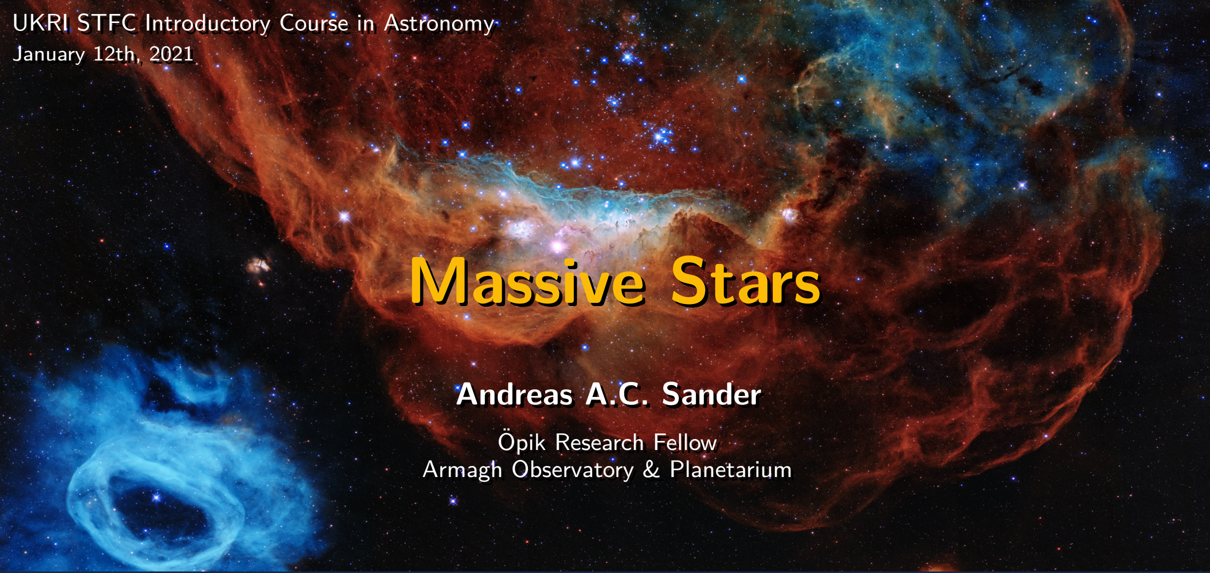

UKRI STFC Introductory Course in Astronomy
January 12th, 2021

Massive Stars

Andreas A.C. Sander

Öpik Research Fellow
Armagh Observatory & Planetarium

Armagh Observatory & Planetarium

What you might spot at night...

Credits: DSS, ESA/ESO/NASA FITS Liberator

What you might spot at night...

Orion Constellation
(Credit: Rogelio Bernal Andreo)

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What you might spot at night...

Orion Constellation
(Credit: Rogelio Bernal Andreo)

We see a lot of massive stars in the night sky
(e.g. all bright stars in Orion)

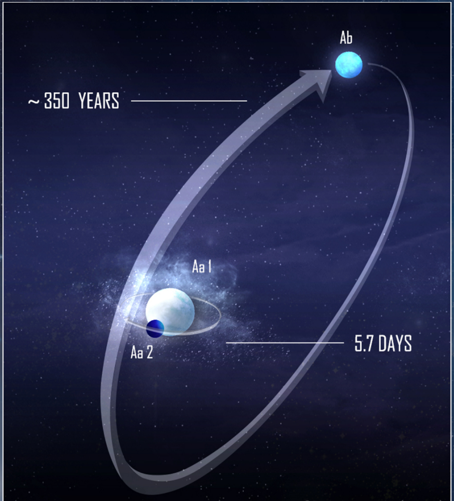
$\Rightarrow$ effect of their enormous luminosity

Massive stars are...

- actually rare in absolute numbers
- often in binaries or hierarchical systems

Credits: DSS, ESA/ESO/NASA FITS Liberator

What you might spot at night...



Shenar et al. (2015)

Credits: DSS, ESA/ESO/NASA FITS Liberator

What do we mean by massive?

Massive = high initial mass

- sometimes: $M_{\mathrm{init}} > 3\,M_\odot$
  - $\rightarrow$ in contrast to "low-mass stars"
  - $\rightarrow$ $2 \ldots 8\,M_\odot$: intermediate mass
- usually: $M_{\mathrm{init}} > 8 \ldots 10\,M_\odot$
  - $\rightarrow$ model uncertainties
  - $\rightarrow$ C ignition ($\sim 7.5\,M_\odot$)
  - $\rightarrow$ Ne ignition ($\sim 10\,M_\odot$)
  - $\Rightarrow$ eventual core collapse
- much shorter lifetimes
  - $\rightarrow$ stronger gravitational force
  - $\rightarrow$ higher core temperatures
  - $\rightarrow$ much faster nuclear burning
- Luminous: $L > 20\,000\,L_\odot$

Credits: NASA, ESA, and STScI

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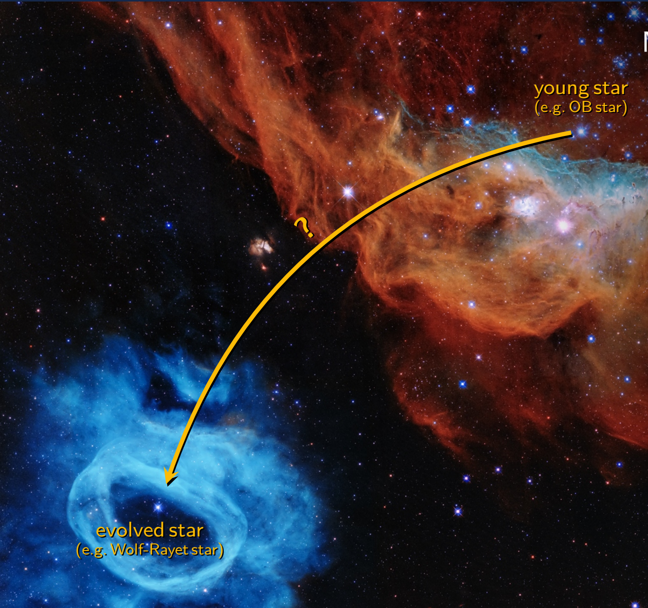

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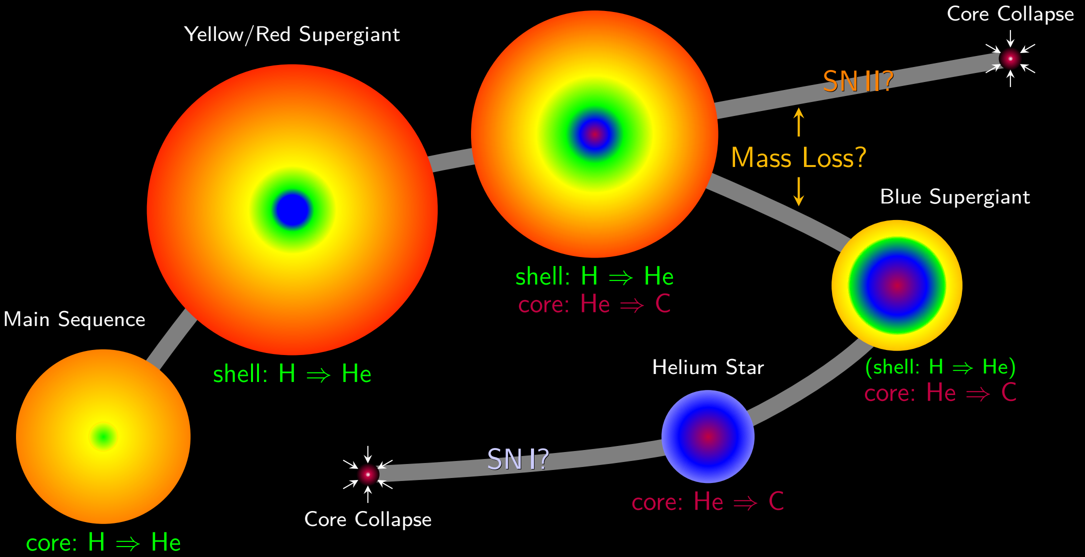
The fate of massive stars



The fate of massive stars

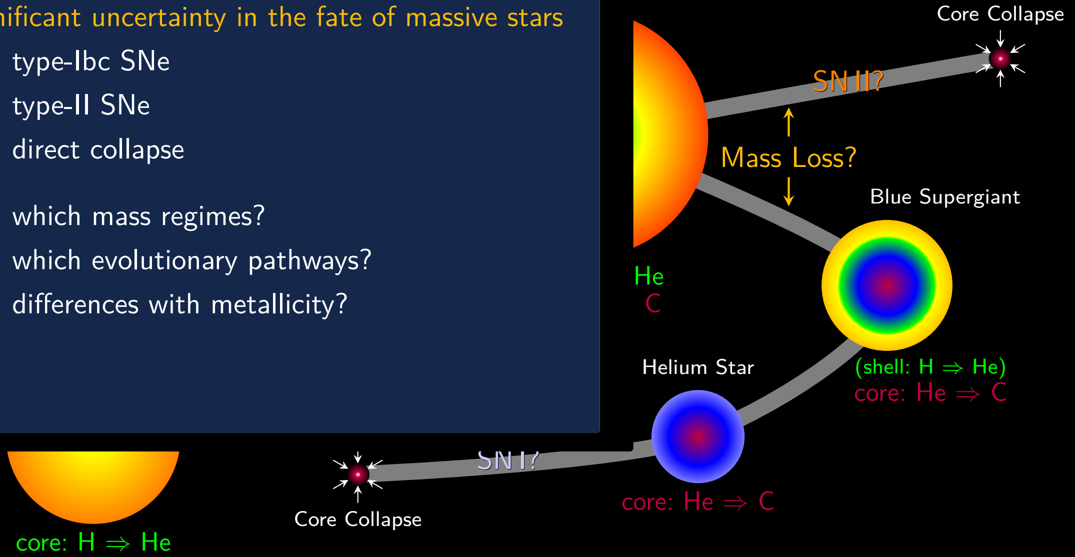
Significant uncertainty in the fate of massive stars

- type-Ibc SNe
- type-II SNe
- direct collapse

→ which mass regimes?

→ which evolutionary pathways?

→ differences with metallicity?



The fate of massive stars

Significant uncertainty in the fate of massive stars

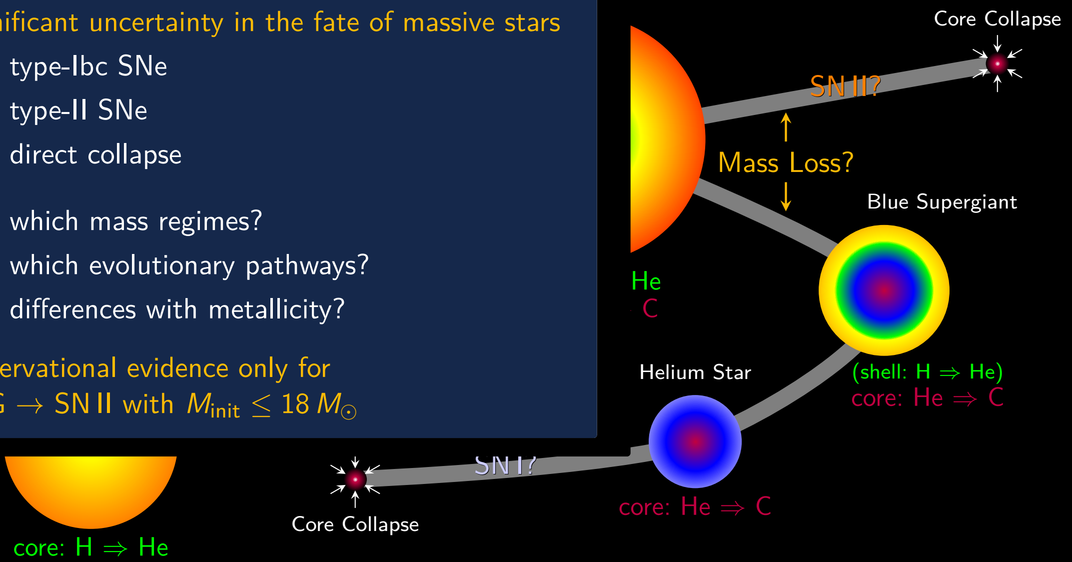
- type-Ibc SNe
- type-II SNe
- direct collapse

→ which mass regimes?

→ which evolutionary pathways?

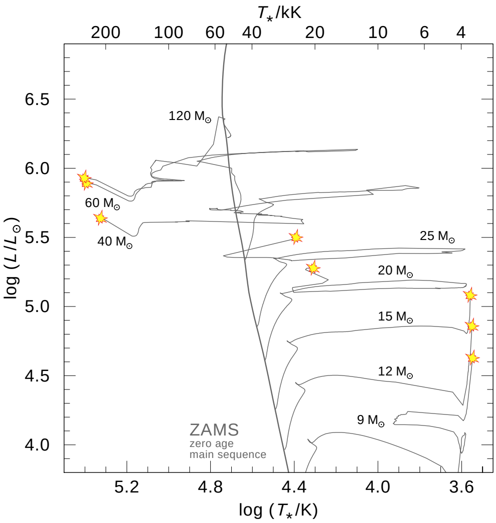
→ differences with metallicity?

Observational evidence only for RSG → SN II with $M_{\mathrm{init}} \leq 18\,M_{\odot}$



Massive star evolution

Important stages of massive star evolution:



HRD example for $Z_\odot$, evolutionary tracks by Ekström et al. (2012)

Massive star evolution

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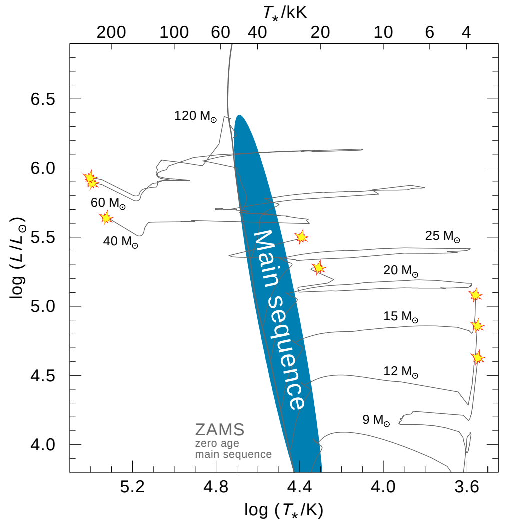
- Main Sequence (O, B)



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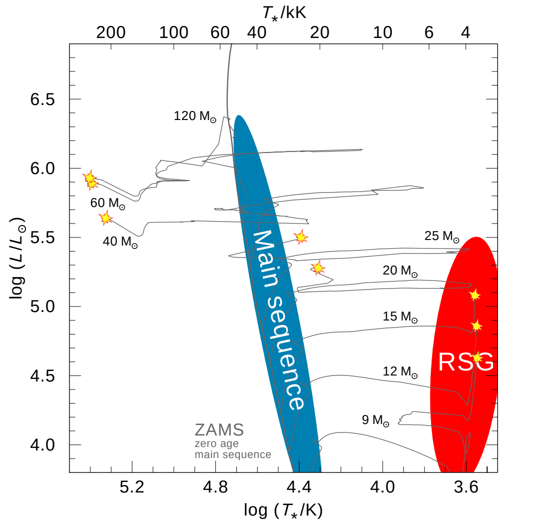

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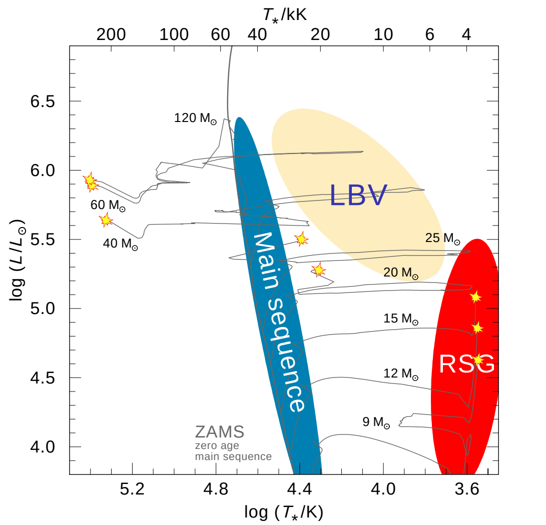

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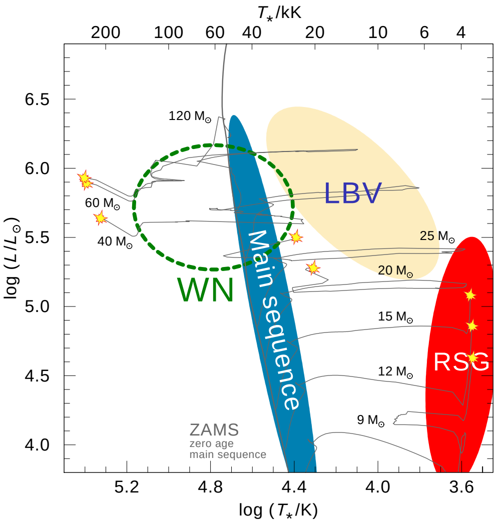

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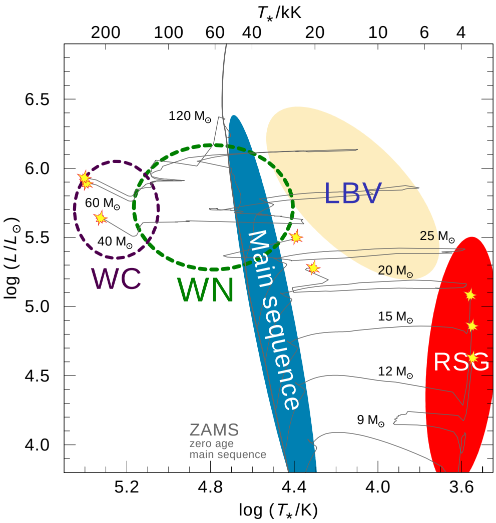

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Massive star evolution

Important stages of massive star evolution:

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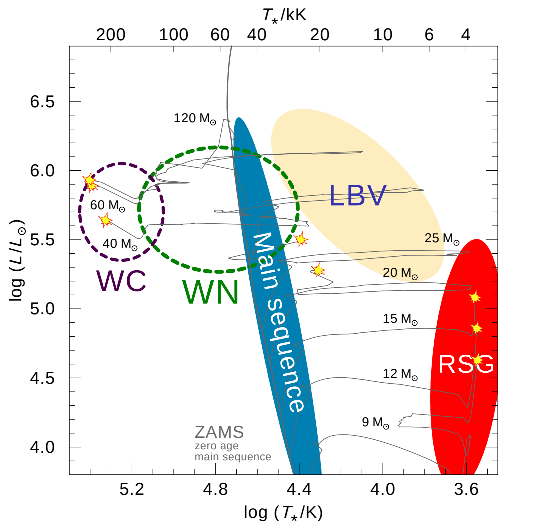
Observations yield:

M_{init}		M_{final}
$40\,M_\odot$	$\rightarrow$	$\sim 10\,M_\odot$
$120\,M_\odot$	$\rightarrow$	$\sim 30\,M_\odot$

$\Rightarrow \sim 75\%$ of mass removed



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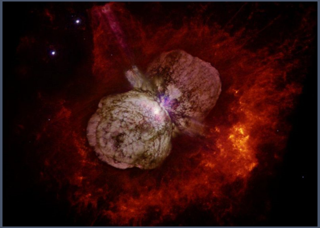
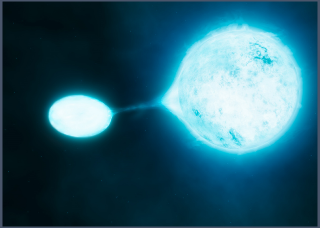
Changing the life of a massive star

Massive stars can lose their outer layers in various ways:

Credit: NASA, JPL-Caltech, Spitzer



Credit: NASA, N. Smith



Credit: ESA/NASA, L. Calcada, S. de Mink

Stellar Winds
→ continuous

Outbursts
→ episodic

Binary Interaction
→ episodic/continuous

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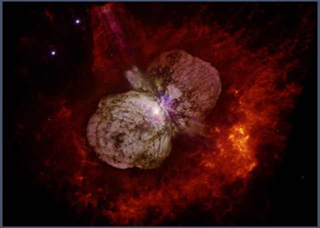

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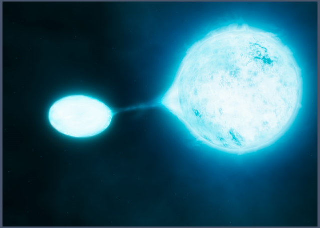

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Stellar Winds
→ continuous

Outbursts
→ episodic

Binary Interaction
→ episodic/continuous

+ additional, more exotic scenarios
(e.g. rotationally induced mass loss)

→ which channels are common/typical?

Massive Stars in the Carina Nebula Region

Panoramic View of the Carina Nebula Region (Credit: ESO)

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Massive Stars in the Carina Nebula Region

η Car

Luminous Blue Variable

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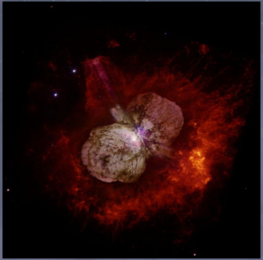
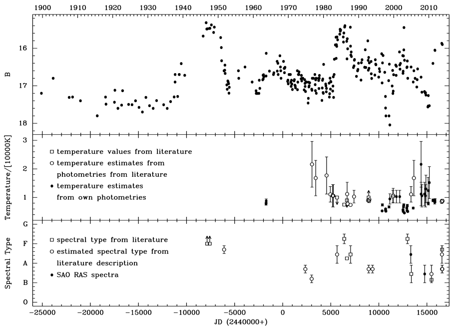


Credit: NASA, N. Smith

Luminous Blue Variables

diverse class of hot and variable objects

- S-Dor cycles
  $\hookrightarrow$ quasi-periodic T_{eff} (and L) changes



Burggraf et al. (2015)

Massive Stars in the Carina Nebula Region

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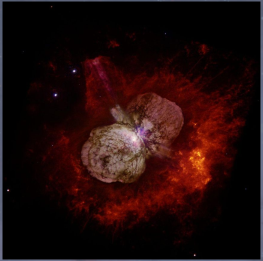


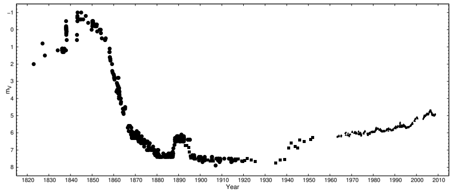
Credit: NASA, N. Smith

Luminous Blue Variable

Luminous Blue Variables

diverse class of hot and variable objects

- S-Dor cycles
  $\hookrightarrow$ quasi-periodic T_{eff} (and L) changes
- giant eruptions (supernova impostors?)



Fernández-Lajús et al. (2009)

Panoramic View of the Carina Nebula Region (Credit: ESO)

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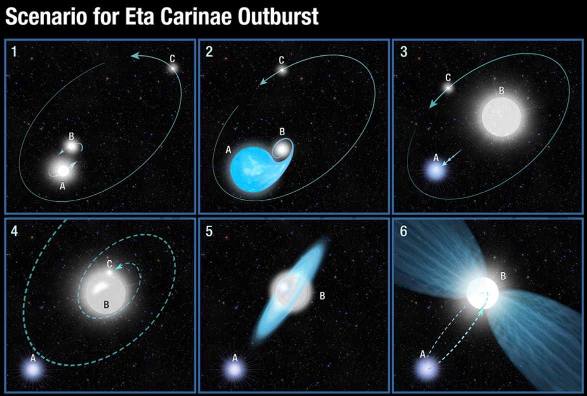


Credit: NASA, ESA, and A. Feild (STScI)

Merger scenario for η Car outburst?

(e.g. Smith et al. 2018, Ryosuke et al. 2020)

General Problem:

How to handle LBVs and outbursts in stellar evolution?

- what is intrinsic?
- core vs. envelope origin?
  (e.g. Grassitelli et al. 2020)

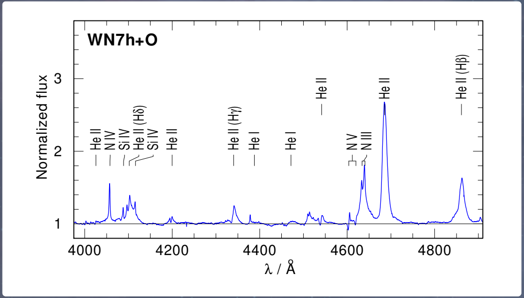
Panoramic View of the Carina Nebula Region (Credit: ESO)

Massive Stars in the Carina Nebula Region

Wolf-Rayet (WR) Stars

emission-line stars discovered in 1867

- named after French astronomers Charles Wolf and Georges Rayet
- dense, persistent matter outflow



Credit: 2MASS, NASA/IPAC

WR 22

(hydrogen-rich)
Wolf-Rayet Star

Panoramic View of the Carina Nebula Region (Credit: ESO)

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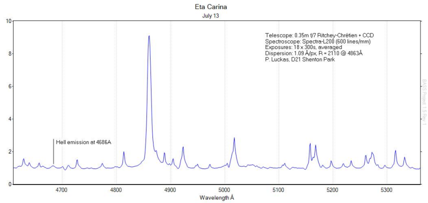

Credit: Paul Luckas, Shenton Park Observatory

Credit: 2MASS, NASA/IPAC

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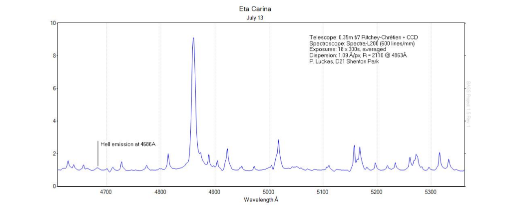

Credit: Paul Luckas, Shenton Park Observatory

Credit: 2MASS, NASA/IPAC

WR 22

(hydrogen-rich)
Wolf-Rayet Star

- η Car not classified as WR, but "similar"
- evidence for LBV $\leftrightarrow$ WR connection (various quiescent LBVs show WR spectrum)

Panoramic View of the Carina Nebula Region (Credit: ESO)

Wolf-Rayet stars

Officially defined by their *spectral* appearance

- Mass loss up to $1 \ldots 10\,M_\odot$ in $10\,000\,\mathrm{yr}$
- Wind velocities up to ≈ 5000 km/s
- Subclasses based on non-He lines: WN, WC, WO

Thor's Helmet (NGC 2359) around WR 7 (Credit: Rogelio Bernal Andreo, Ray Gralak)

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- Wind velocities up to $\approx 5000\,\mathrm{km/s}$
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Wolf-Rayet (WR) stars come in two (main) flavours:

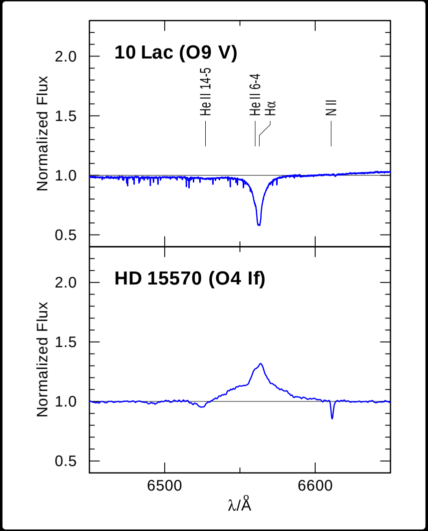
- classical WR stars: core He-burning, evolved
  $\hookrightarrow$ partially or completely depleted in hydrogen
- very massive WNh stars: core H-burning, barely evolved
  $\hookrightarrow$ extension of the main sequence (“O stars on steroids”)

For the experts:
Low-mass analogue for some central stars of Planetary Nebula, denoted as [WR]

Thor’s Helmet (NGC 2359) around WR 7 (Credit: Rogelio Bernal Andreo, Ray Gralak)

Spectral signatures of stellar winds

Spectral signatures of mass-loss beyond Wolf-Rayet stars:



Optical:

- opt. thin wind: absorption lines
  $\hookrightarrow$ we mainly see the star
- opt. thick wind: emission lines
  $\hookrightarrow$ we (mainly) see the wind

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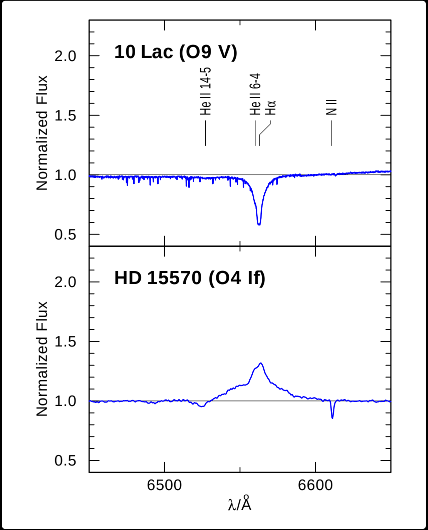

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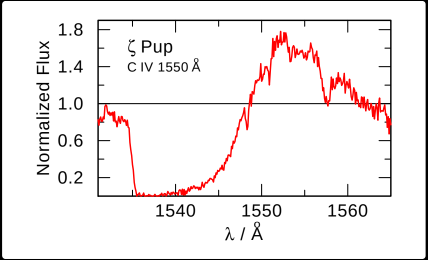
UV: P Cygni Profiles



Spectral signatures of stellar winds

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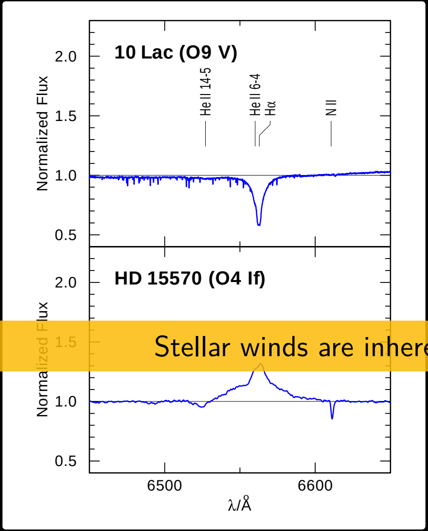

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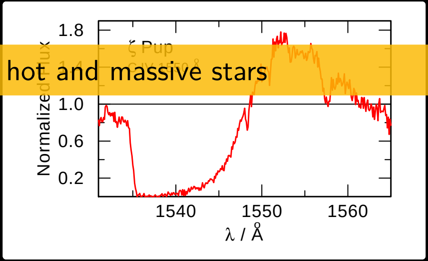
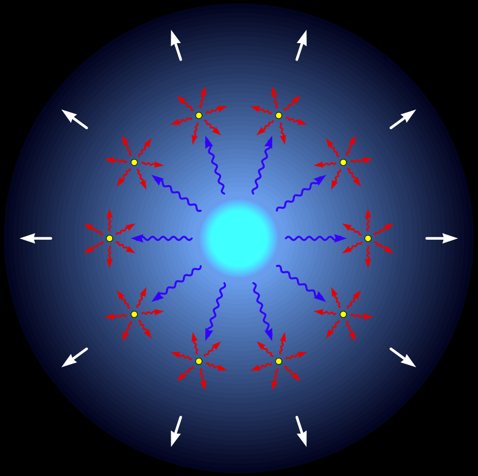
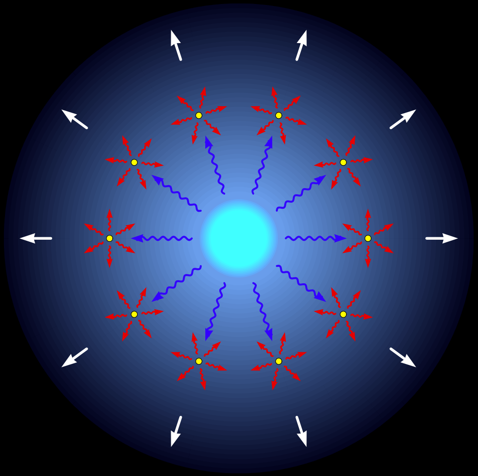


Stellar winds are inherent to all hot and massive stars



Hot star winds are line-driven:

→ Main acceleration due to electron scattering plus line absorption



Hot star winds are line-driven:

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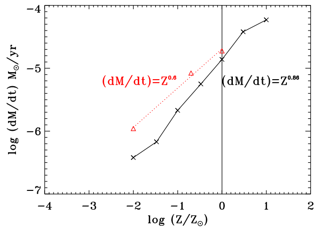
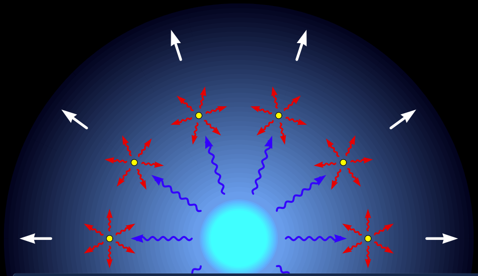
→ inherent metallicity dependence



Puls, Vink, & Najarro (2008)

Stellar winds in hot massive stars



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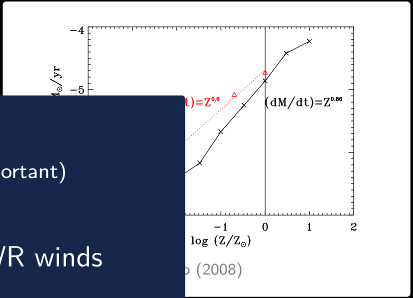


Radiation-driven winds of hot stars:

- general mechanism known (→ line opacities important)
- lots of details still unclear (e.g. multi-D effects)
- fundamental differences between OB and WR winds

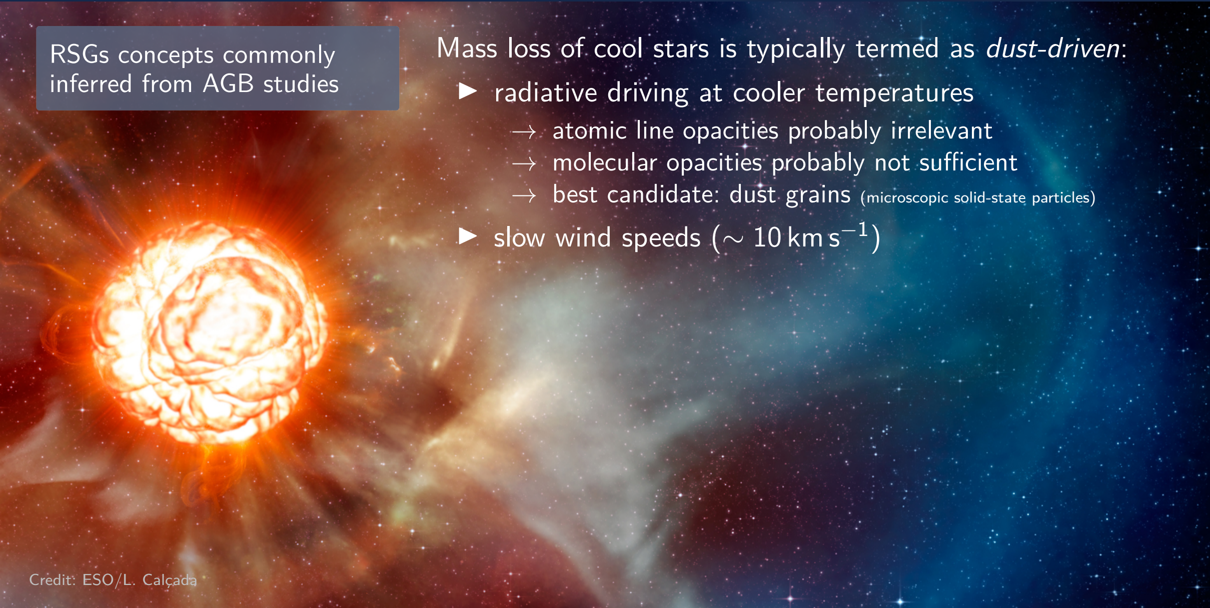
⇒ *uncertain, but reasonably constrained*

Stellar winds in cool massive stars

RSGs concepts commonly inferred from AGB studies

Mass loss of cool stars is typically termed as *dust-driven*:

- radiative driving at cooler temperatures
  - → atomic line opacities probably irrelevant
  - → molecular opacities probably not sufficient
  - → best candidate: dust grains (microscopic solid-state particles)
- slow wind speeds ($\sim 10\,\mathrm{km\,s^{-1}}$)



Credit: ESO/L. Calçada

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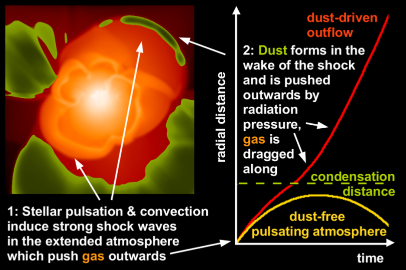
Standard scenario:

PEDDRO

Pulsation-**E**nhanced **D**ust-**DR**iven **O**utflow

e.g. Höfner & Olofsson (2018)

→ requires pulsation to levitate atmospheric material

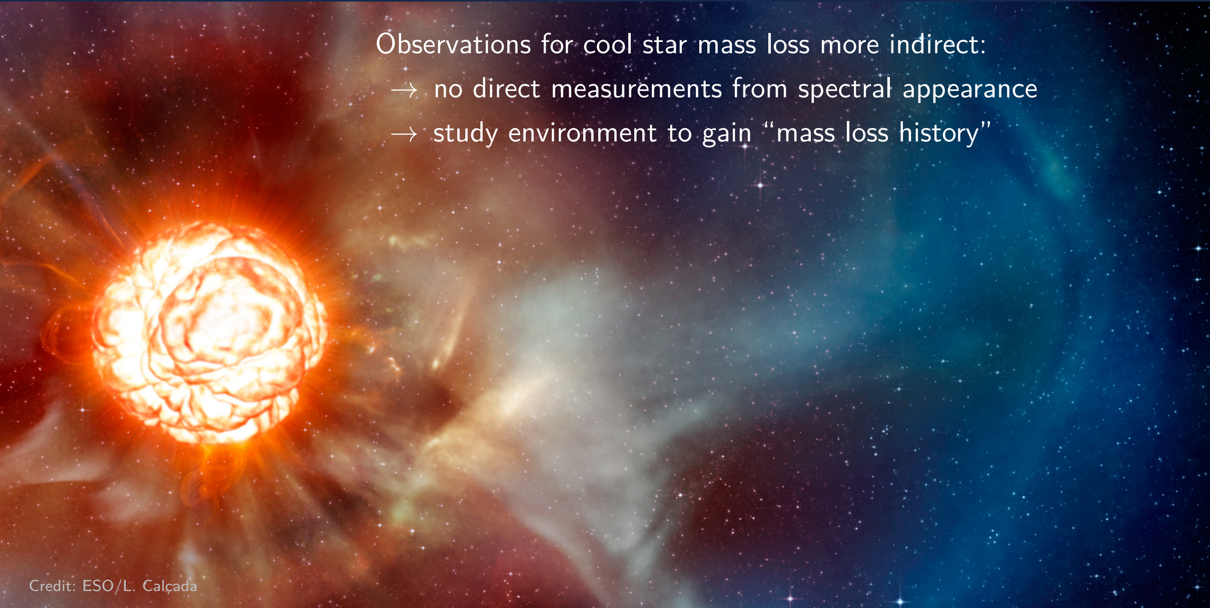


Stellar winds in cool massive stars

Observations for cool star mass loss more indirect:

→ no direct measurements from spectral appearance

→ study environment to gain “mass loss history”



Credit: ESO/L. Calçada

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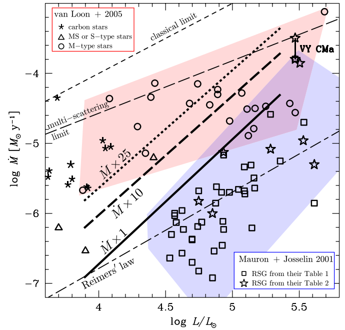
⇒ how to treat RSGs in stellar evolution?



Meynet et al. (2015)

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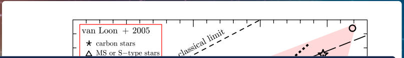


Radiation-driven winds of cool stars:

- standard, but not confirmed mechanism (→ dust opacities important)
- unclear if mass loss actually episodic or continuous
- some scenarios imply metallicity-dependence (e.g. due to C-O dependence)
- so far no mass-loss predictions from first principles

⇒ *more uncertain and less constrained than hot-star regime*

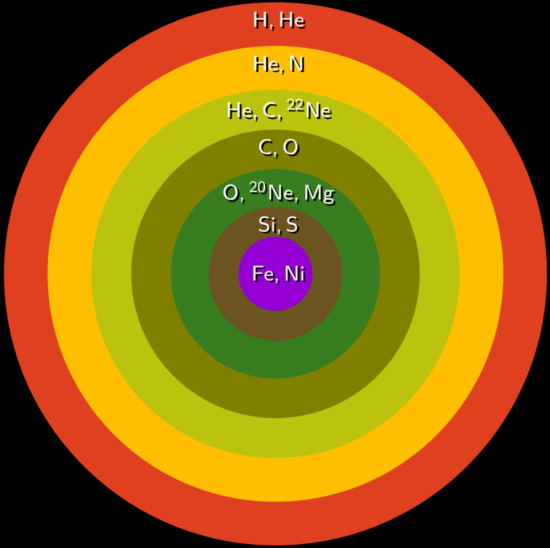
Meynet et al. (2015)

Credit: ESO/L. Calçada

Nucleosynthesis

The yields of massive stars:

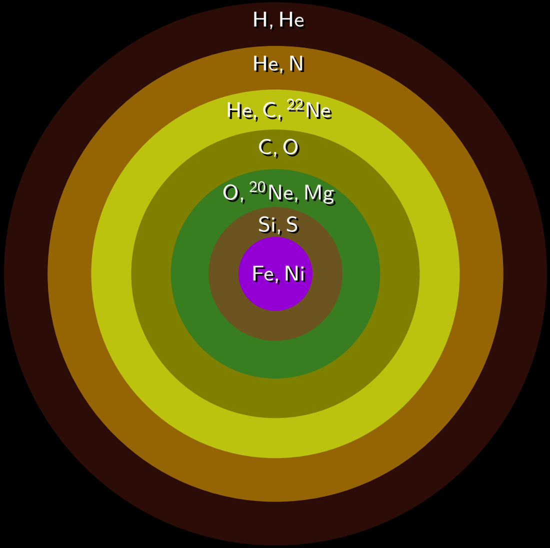
- from mass loss and SN explosion
- onion-like structure before core collapse



Nucleosynthesis

The yields of massive stars:

- from mass loss and SN explosion
- onion-like structure before core collapse
- mass loss could remove outermost layers, thereby altering
  - $\rightarrow$ further evolution
  - $\rightarrow$ ionizing fluxes
  - $\rightarrow$ stellar winds
  - $\Rightarrow$ overall yields



Nucleosynthesis

The yields of massive stars:

- from mass loss and SN explosion
- onion-like structure before core collapse
- mass loss could remove outermost layers, thereby altering
  - $\rightarrow$ further evolution
  - $\rightarrow$ ionizing fluxes
  - $\rightarrow$ stellar winds
  - $\Rightarrow$ overall yields
- + uncertainty of reaction rates

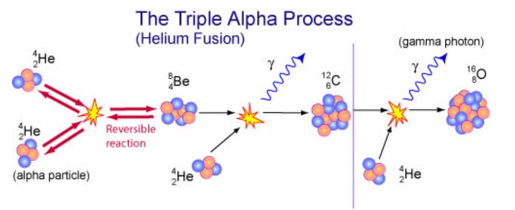
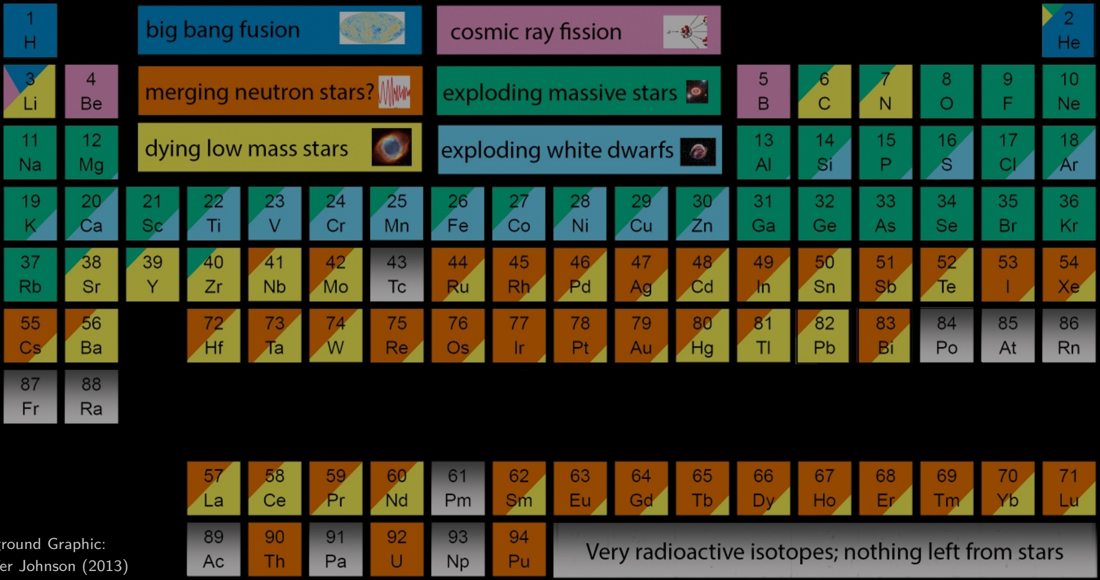


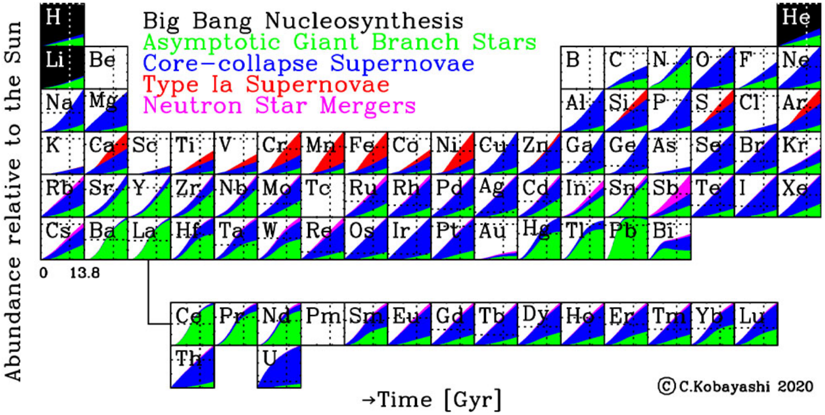
Image Credit: CSIRO ATNF

The Origin of the Elements



Background Graphic:
Jennifer Johnson (2013)

The Origin of the Elements



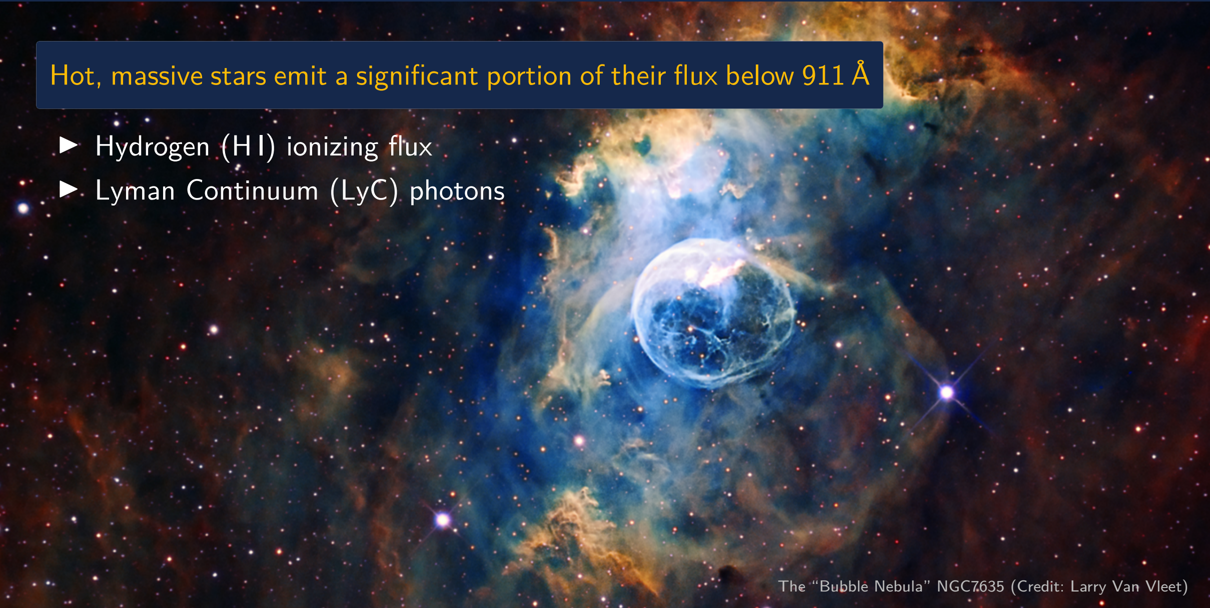
Kobayashi et al. (2020)

Background Graphic:
Jennifer Johnson (2013)

Ionizing fluxes

Hot, massive stars emit a significant portion of their flux below 911 Å

- Hydrogen (H I) ionizing flux
- Lyman Continuum (LyC) photons



The “Bubble Nebula” NGC7635 (Credit: Larry Van Vleet)

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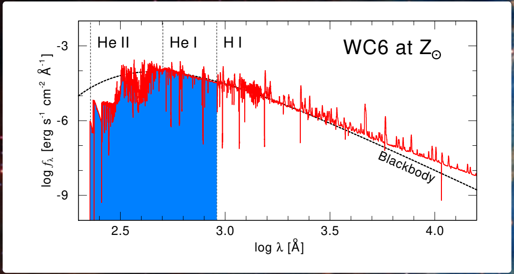
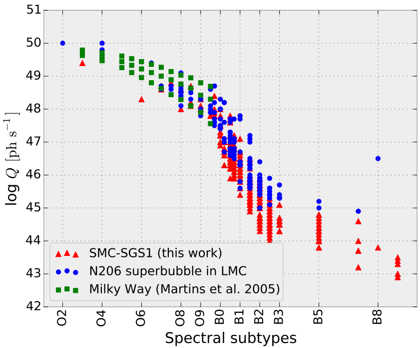


- (hot) stars are not blackbodies → winds shift flux from UV to IR

The "Bubble Nebula" NGC7635 (Credit: Larry Van Vleet)

Ionizing fluxes

Earliest spectral types dominate the flux budget in a stellar population:
$\rightarrow$ do not miss these few stars!



Ramachandran et al. (2019)

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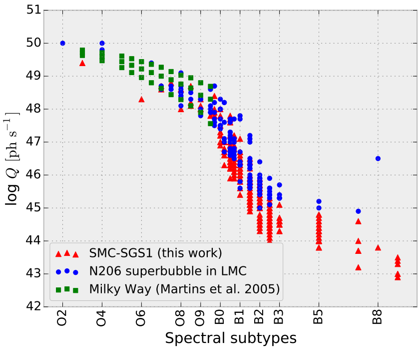
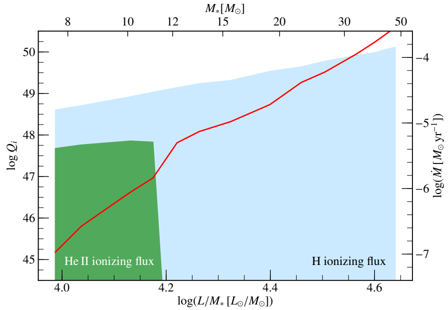


Ramachandran et al. (2019)

He II ionizing flux

- hydrogen-free stars can emit below 227 Å
- strong metallicity dependence
  $\rightarrow$ released by He stars with weak winds
  $\rightarrow$ more common in the early Universe



Sander & Vink (2020), Fig. from Vink (2020)

Ionizing fluxes

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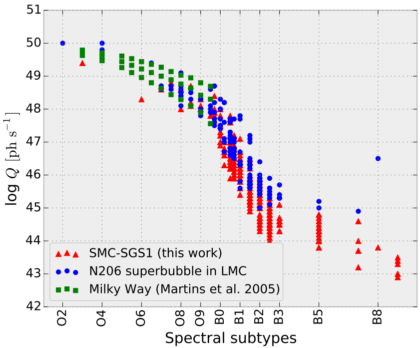

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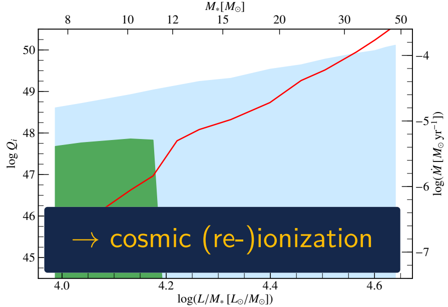
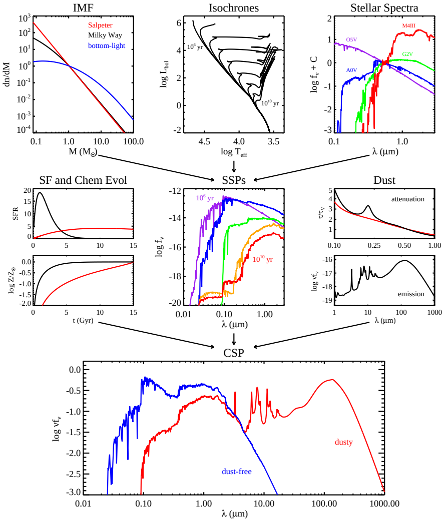


→ cosmic (re-)ionization

Sander & Vink (2020), Fig. from Vink (2020)

The imprint of massive stars on populations

Studying the integrated light of galaxies with stellar population models



Conroy (2013)

Image Credit: ESA/Hubble & NASA, D. Leonard

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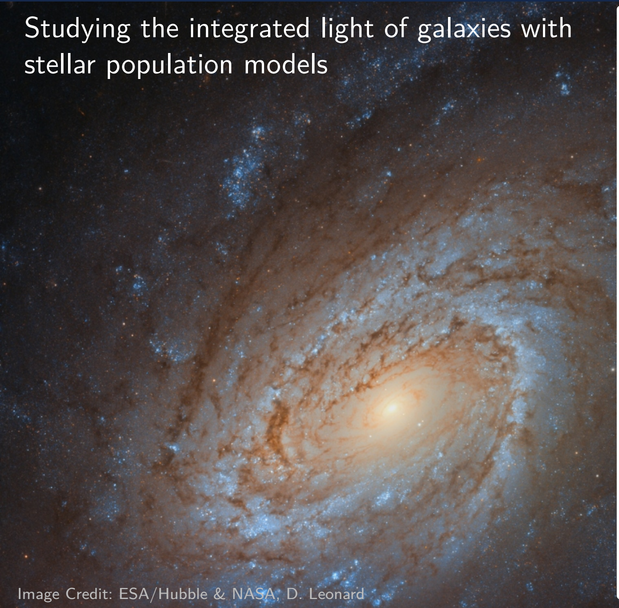

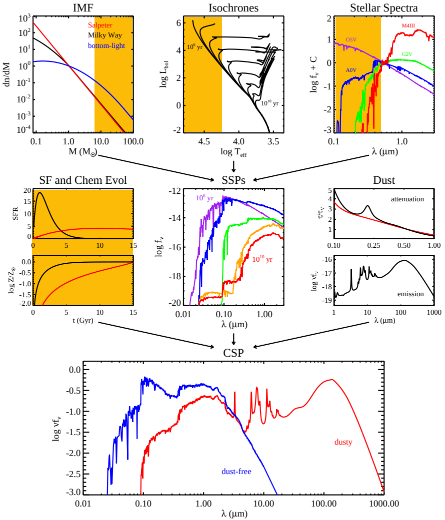

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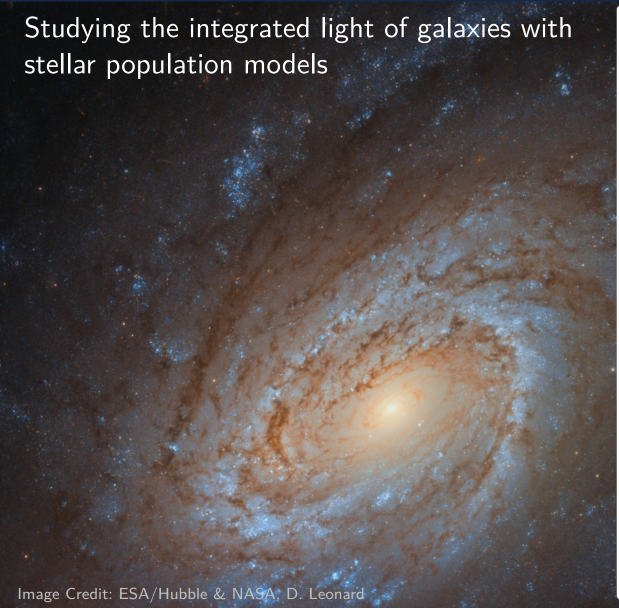

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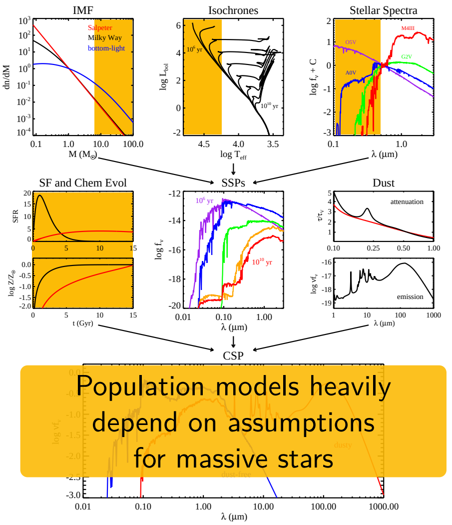

Population models heavily depend on assumptions for massive stars

Conroy (2013)

The imprint of massive stars on populations

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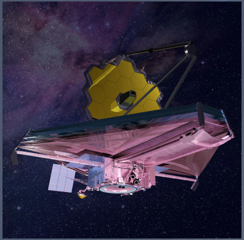
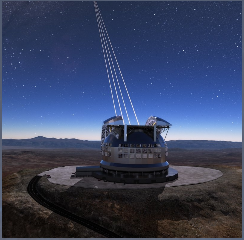


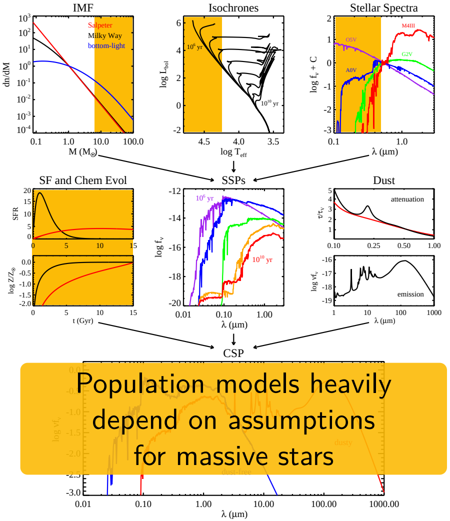
Credit: NASA



Credit: ESO/L. Calçada

Next-gen. telescopes: integrated light from massive stars in the Early Universe

→ are current predictions reliable?



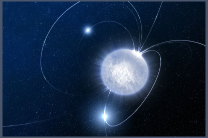
Population models heavily depend on assumptions for massive stars

Conroy (2013)

Image Credit: ESA/Hubble & NASA, D. Leonard

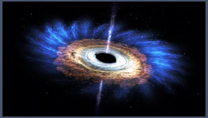
The fate of massive stars

Neutron Star



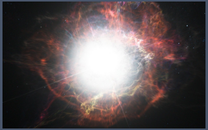
Credit: ESO/L. Calçada

Black Hole



Credit: NASA GSFC/CI Lab

No Remnant



Credit: ESO/M. Kornmesser

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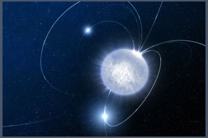

Credit: ESO/L. Calçada

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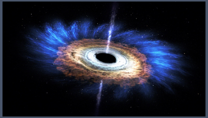

Credit: NASA GSFC/CI Lab

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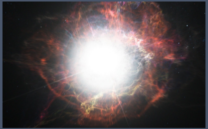

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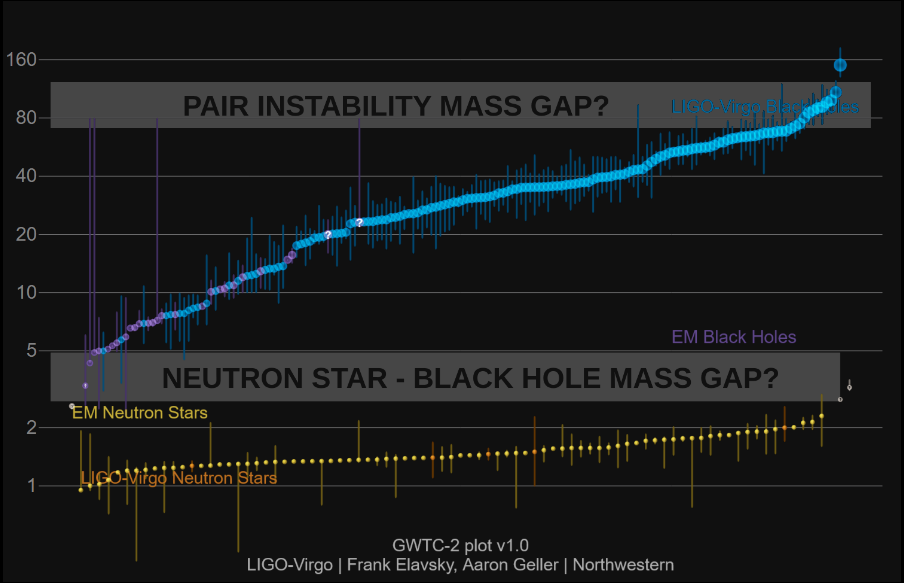

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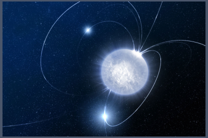

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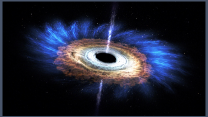

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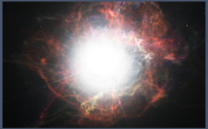

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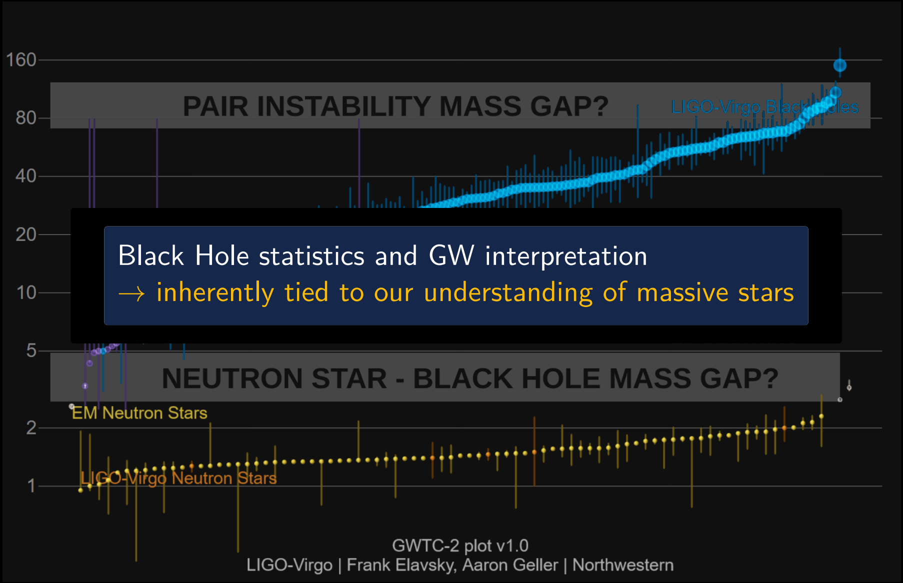
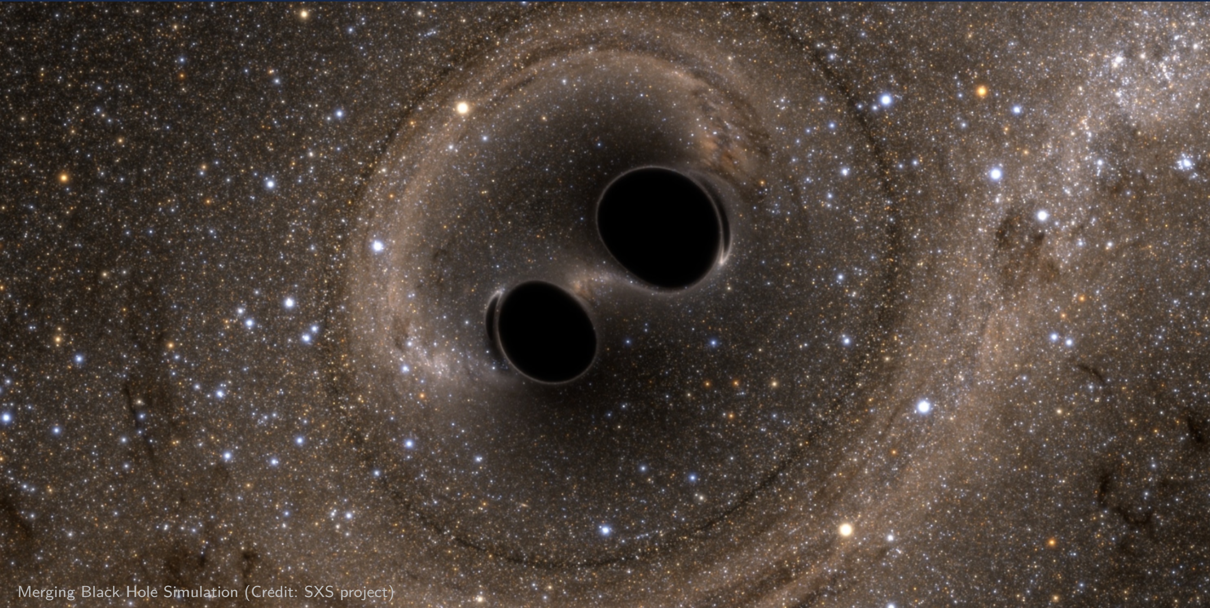


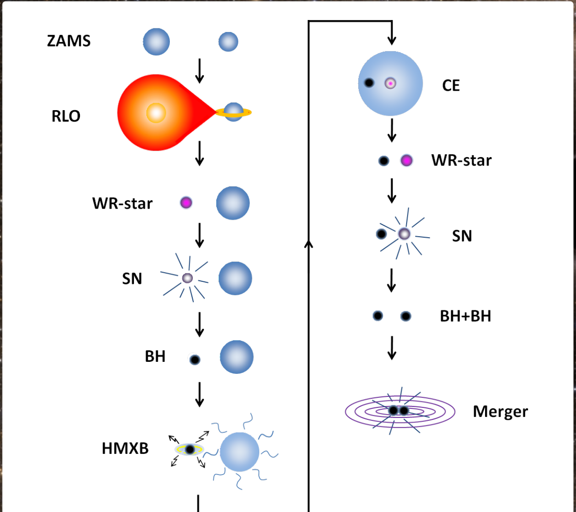
Black Hole statistics and GW interpretation
→ inherently tied to our understanding of massive stars

The uncertain route to Gravitational Waves



Merging Black Hole Simulation (Credit: SXS project)

The uncertain route to Gravitational Waves



Marchant et al. (2016)

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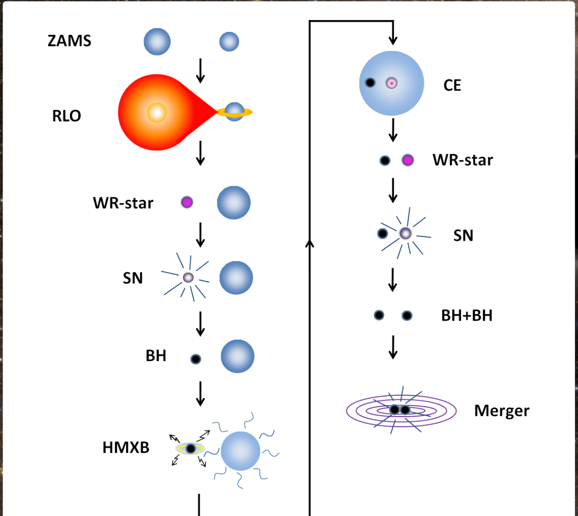

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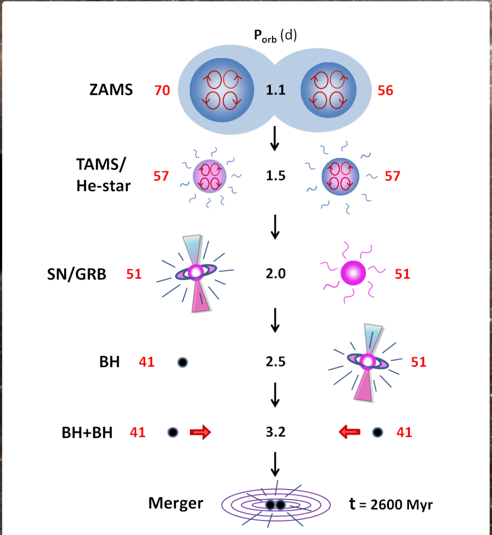

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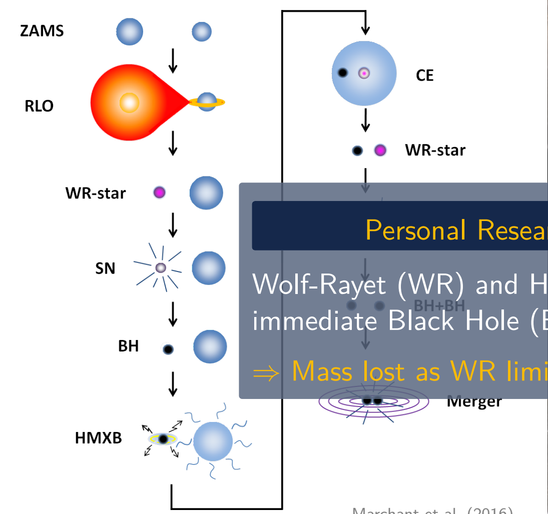

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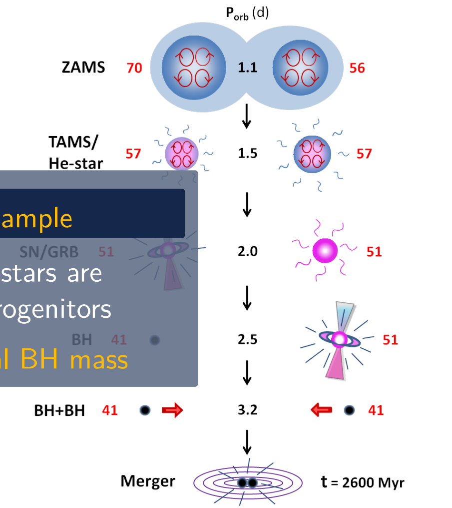

Marchant et al. (2016)

Personal Research Example

Wolf-Rayet (WR) and Helium stars are immediate Black Hole (BH) progenitors

$\Rightarrow$ Mass lost as WR limits final BH mass

Merging Black Hole Simulation (Credit: SXS project)

Translating Observations into Physics

How do we study
hot, massive stars?

Thor's Helmet (NGC 2359) around WR 7 (Credit: Rogelio Bernal Andreo, Ray Gralak)

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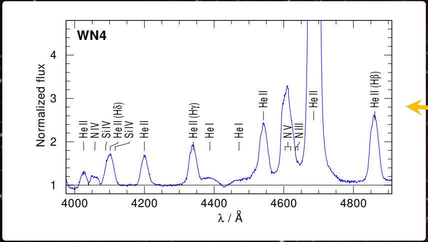

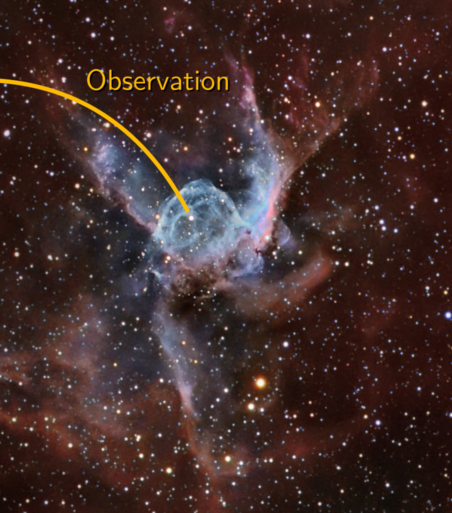

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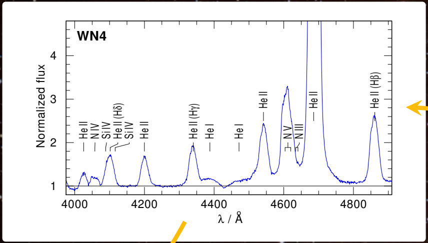
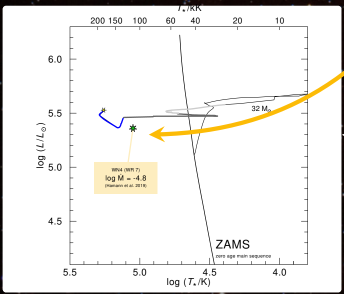


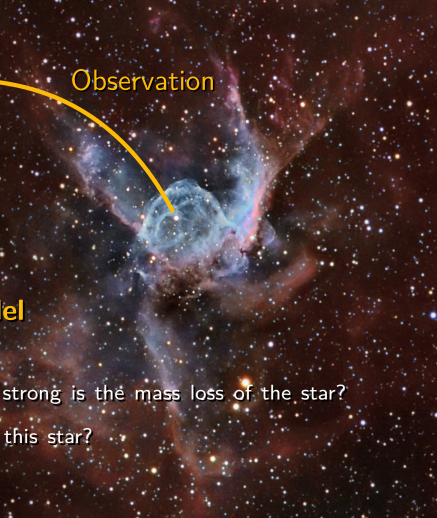
Observation

Stellar Atmosphere Model



How strong is the mass loss of the star?

In which stage of its life cycle is this star?
(Hertzsprung Russell Diagramm)



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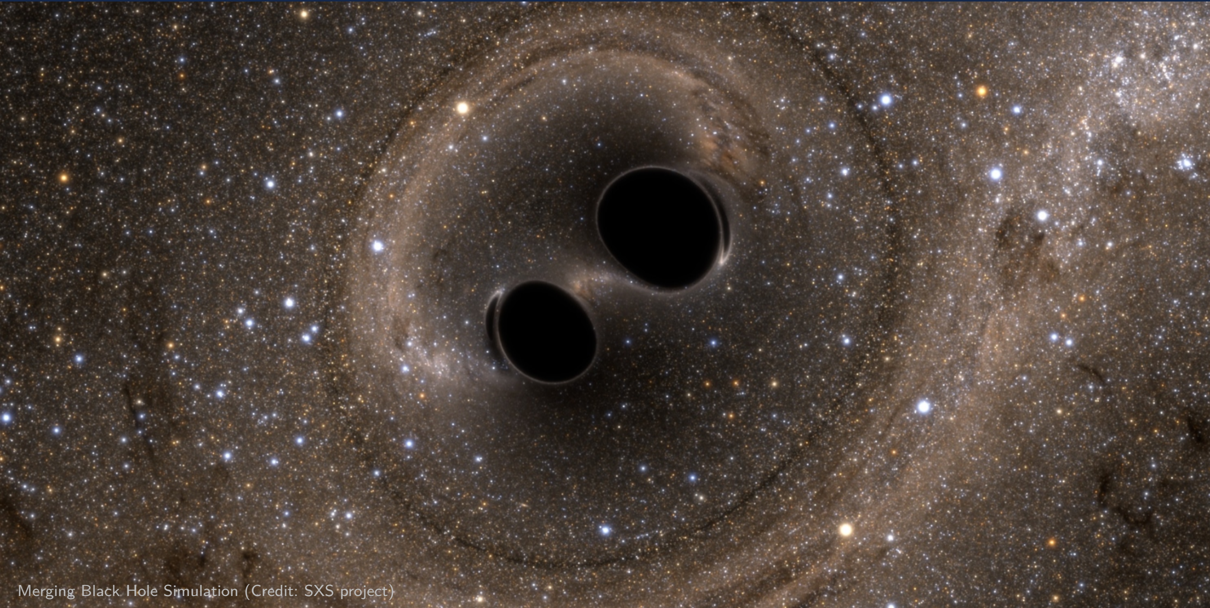
My Research: Use model atmospheres to study mass loss



Merging Black Hole Simulation (Credit: SXS project)

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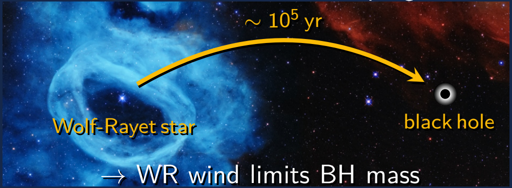
Reminder: WRs are direct BH progenitors



Personal research example:

- Aim: Derive hot star wind mass loss from first principles
- Method: Dynamically-consistent model atmospheres (→ map full complexity)
- Outputs: Mass loss, wind structure, ionizing fluxes, stellar spectra

→ Sander et al. (2020); Sander & Vink (2020); Higgins et al. (2021)

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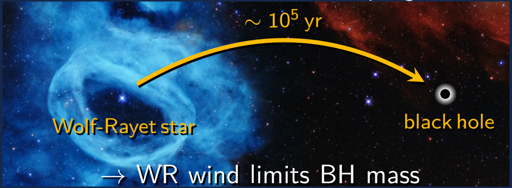

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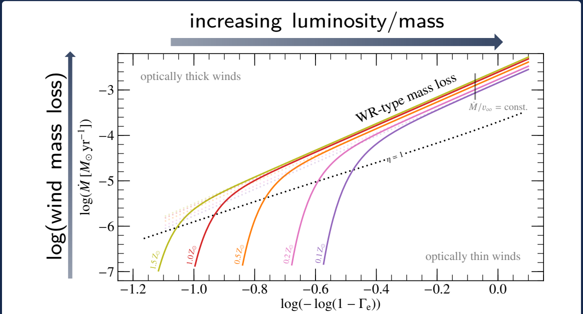
Pioneering insights:

- first theoretical description of WR winds



Sander & Vink (2020)

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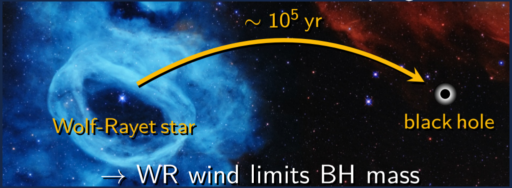

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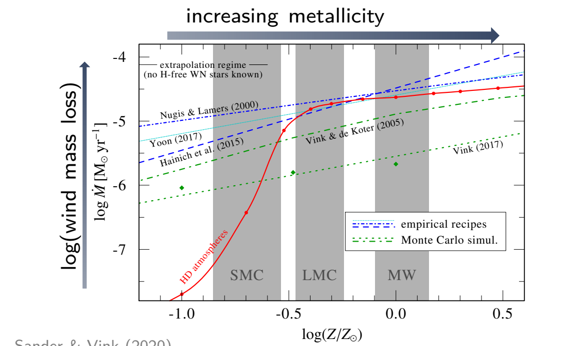
Pioneering insights:

- first theoretical description of WR winds
- wind strongly mass- and "metal"-dependent
  → not mapped in previous descriptions



Sander & Vink (2020)

Merging Black Hole Simulation (Credit: SXS project)

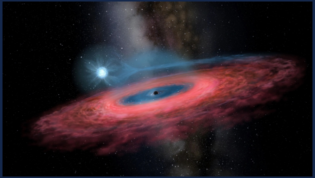
We are only at the beginning...

We are just discovering the true properties of massive stars

$\rightarrow$ wide-range impact across the field of astrophysics

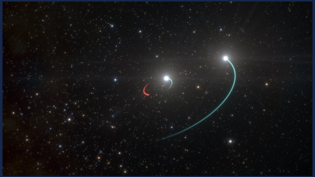
We are only at the beginning...

70 $M_\odot$ BH in our Galaxy



Credit: Jingchuan YU/Beijing Planetarium

Closest BH to Earth



Credit: ESO/L. Calçada

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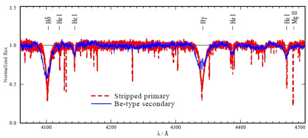
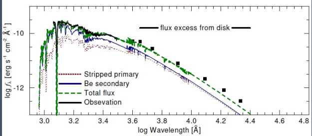


No BH: stripped B + Be

Shenar et al. (2020)

~~Closest BH to Earth~~



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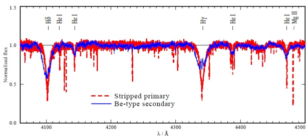

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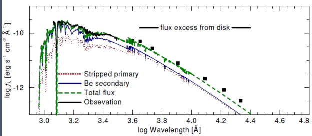

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Bodensteiner et al. (2020)

We are just discovering the true properties of massive stars

$\rightarrow$ wide-range impact across the field of astrophysics

- Quantitative spectroscopy requires expertise and experience
- Stellar evolution should not considered to be "known"
- We need better insights on stellar winds and feedback

However:

Uncertainty does not mean we can arbitrarily change parameters!

Our knowledge about massive stars already gives a multitude of insights, constraints, and theoretical understanding.

Summary: The fundamental role of massive stars

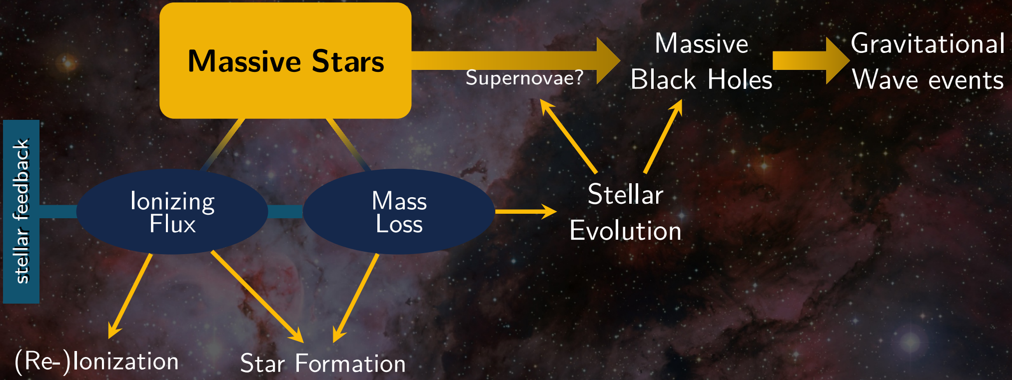
Massive Stars → Massive Black Holes → Gravitational Wave events

Background image: ESO

Summary: The fundamental role of massive stars

Background image: ESO

Summary: The fundamental role of massive stars



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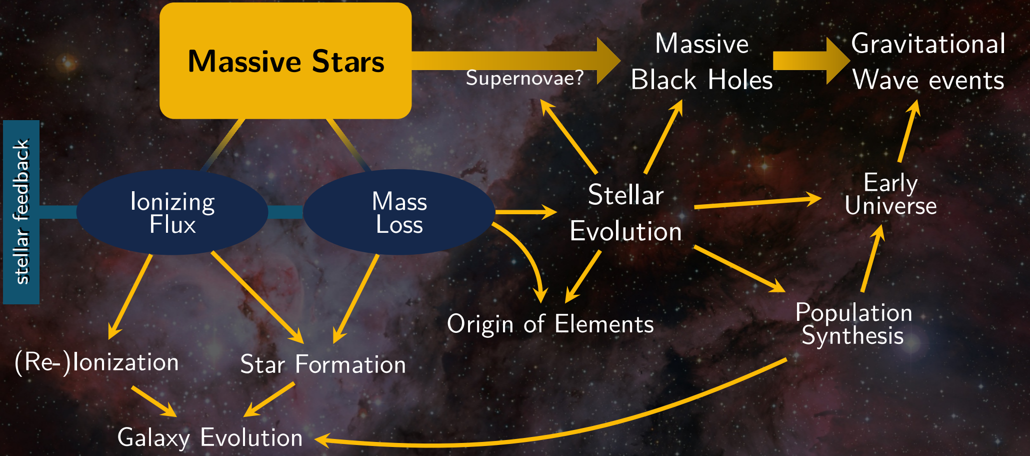
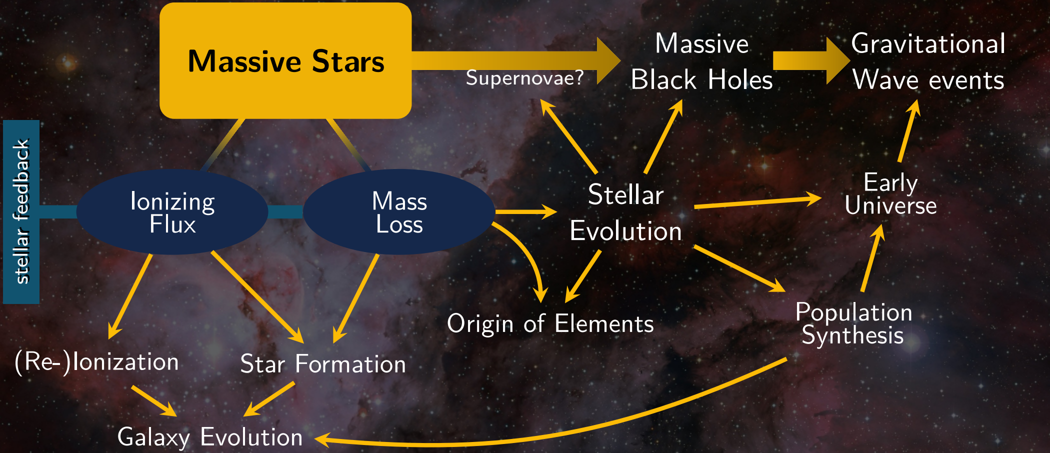
Summary: The fundamental role of massive stars



Background image: ESO

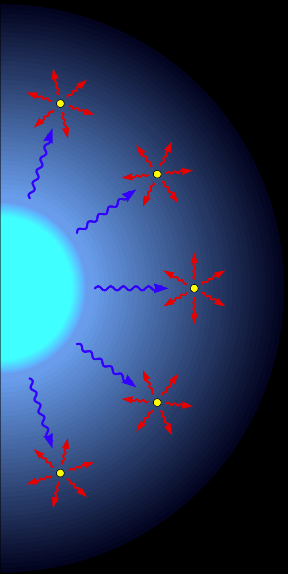
Summary: The fundamental role of massive stars



Massive stars are a keystone in astrophysics with complex interdependencies
$\Rightarrow$ frontier of current research to uncover their parameters, evolution, and impact

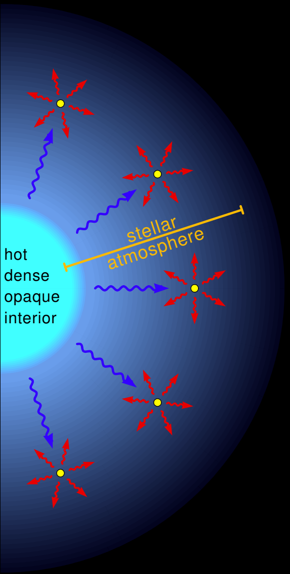
Appendix

Modelling the outermost layers of a star



Stars are giant balls of gas:

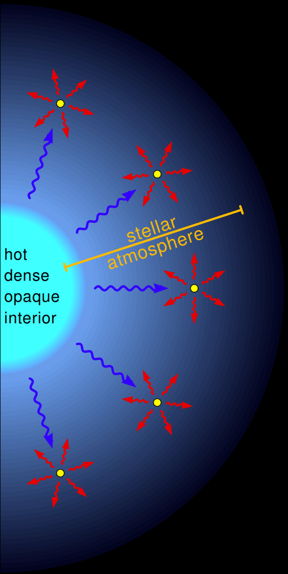
Modelling the outermost layers of a star



Stars are giant balls of gas:

- no hard boundary (→ non-trivial radius definition)
- spectrum stems from a transition layer: *stellar atmosphere*

Modelling the outermost layers of a star



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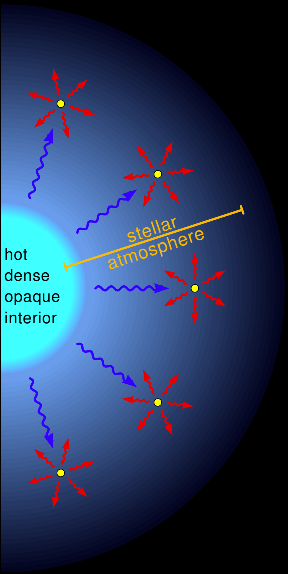
stellar atmosphere models
=
fundamental tool of astrophysics

Modelling the outermost layers of a star



Stars are giant balls of gas:

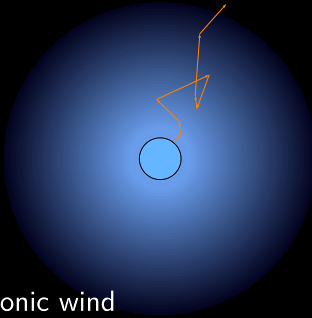
- no hard boundary (→ non-trivial radius definition)
- spectrum stems from a transition layer: *stellar atmosphere*

stellar atmosphere models = fundamental tool of astrophysics

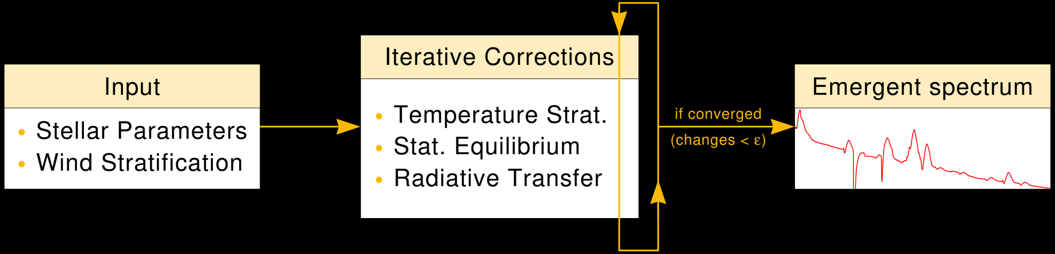
Modelling challenges for hot stars:

- outside of thermodynamic equilibrium
- radiative transfer in expanding atmosphere
- connection from hydrostatic layers to supersonic wind
- model atoms for H, He, C, N, O, Fe, ...

\+ many further physical and numerical issues



My Technique: Next-Generation Stellar Atmosphere Models



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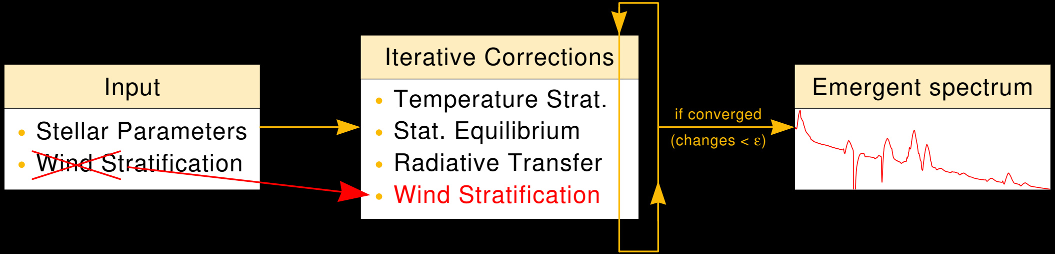

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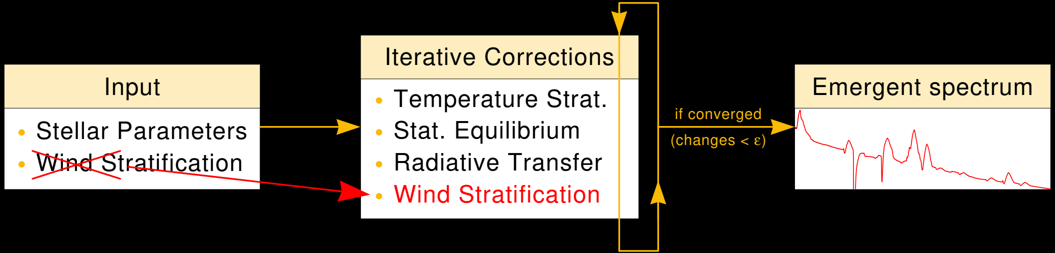

Stellar atmospheres with local hydrodynamical consistency

→ Sander et al. (2015, 2017, 2018, 2020)

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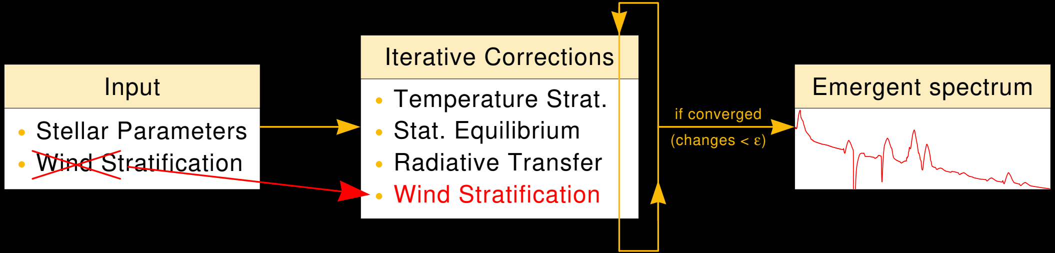


Stellar atmospheres with local hydrodynamical consistency

→ Sander et al. (2015, 2017, 2018, 2020)

- applicable to various kinds of hot stars (WR, OB, LBV...)

My Technique: Next-Generation Stellar Atmosphere Models

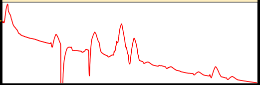
Input
- Stellar Parameters
- ~~Wind Stratification~~

Iterative Corrections
- Temperature Strat.
- Stat. Equilibrium
- Radiative Transfer
- Wind Stratification

if converged

(changes < ε)

Emergent spectrum



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→ Sander et al. (2015, 2017, 2018, 2020)

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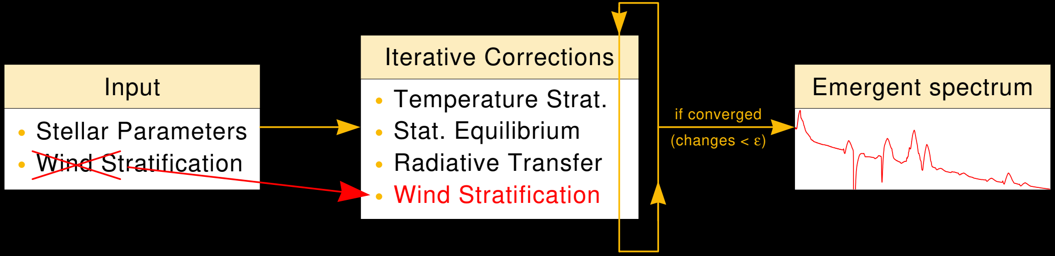

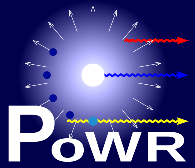

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→ Sander et al. (2015, 2017, 2018, 2020)

- applicable to various kinds of hot stars (WR, OB, LBV...)
- consistent prediction of spectrum, mass loss, & ionizing flux
- enables unprecedented insights into stellar wind driving