Progress and Promise in Understanding Massive Stars

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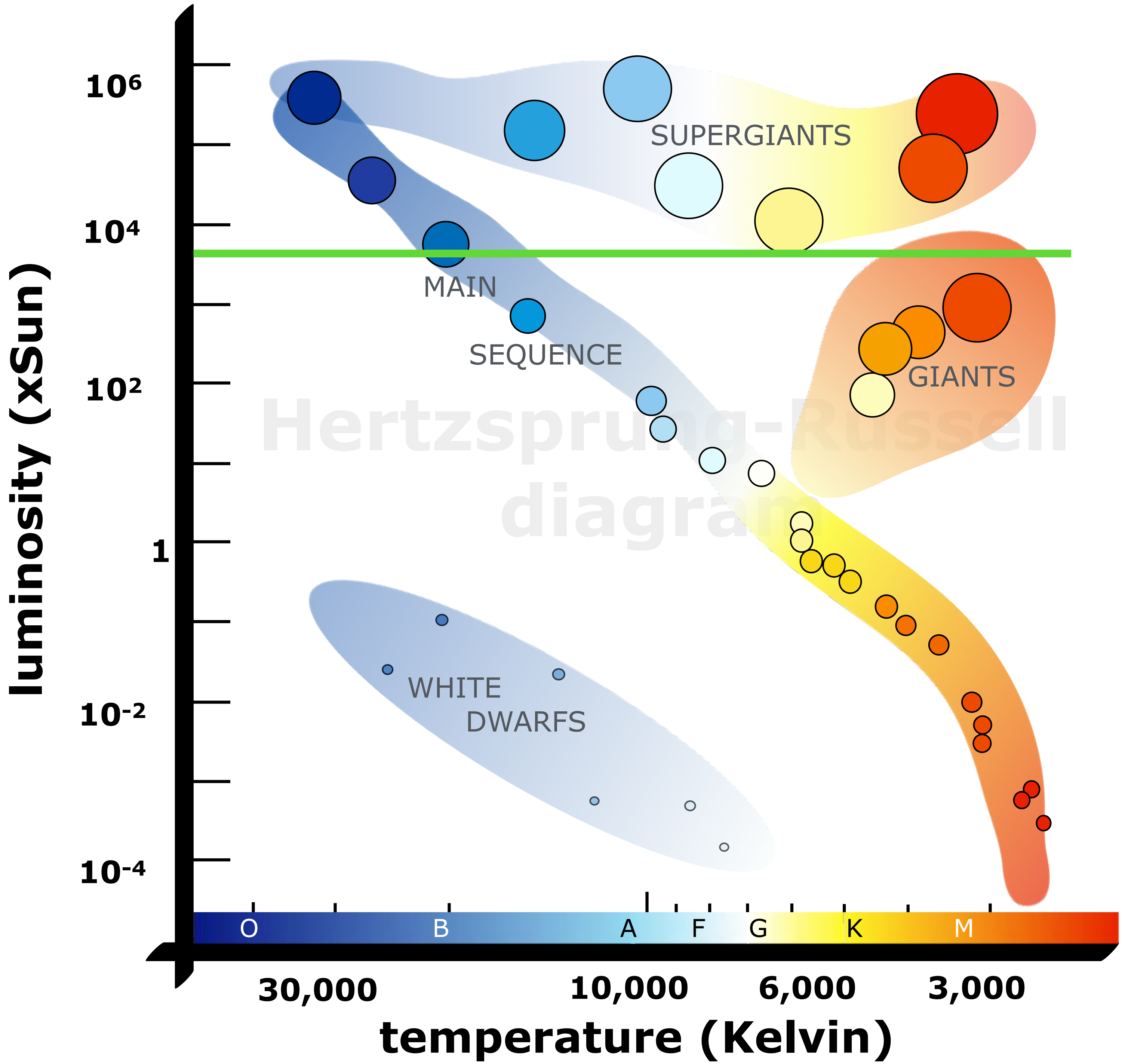
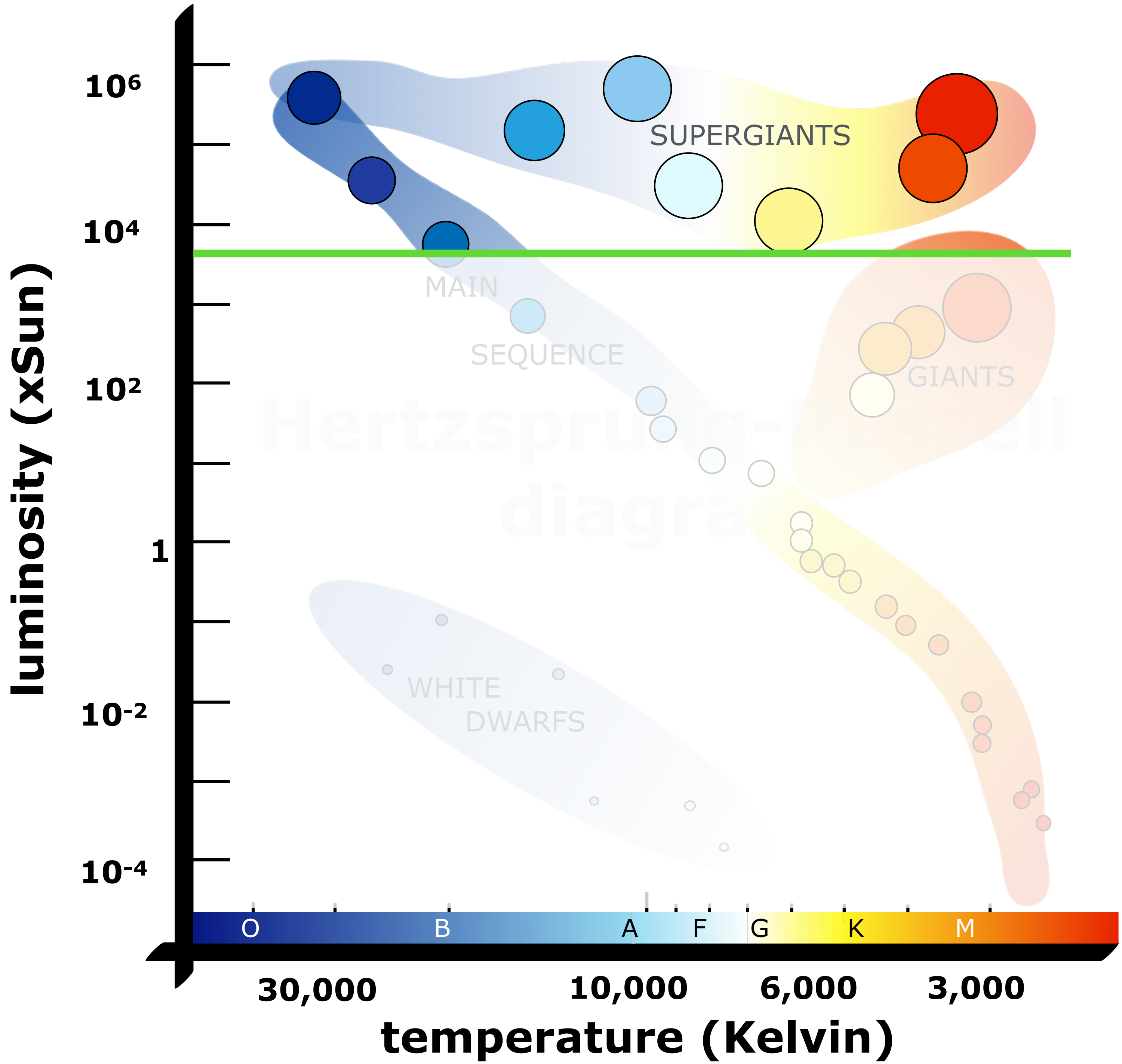
Big Questions in Massive Stars



Big Questions in Massive Stars



— short lifetimes ($\sim 10^6$ y)

— cores are convective, not (yet) degenerate

— cores capable of fusing H, He, C, O…

—dying (mostly) as core-collapse SNe

—*not* only main sequence (red & yellow supergiants, Wolf-Rayet stars, LBVs…)

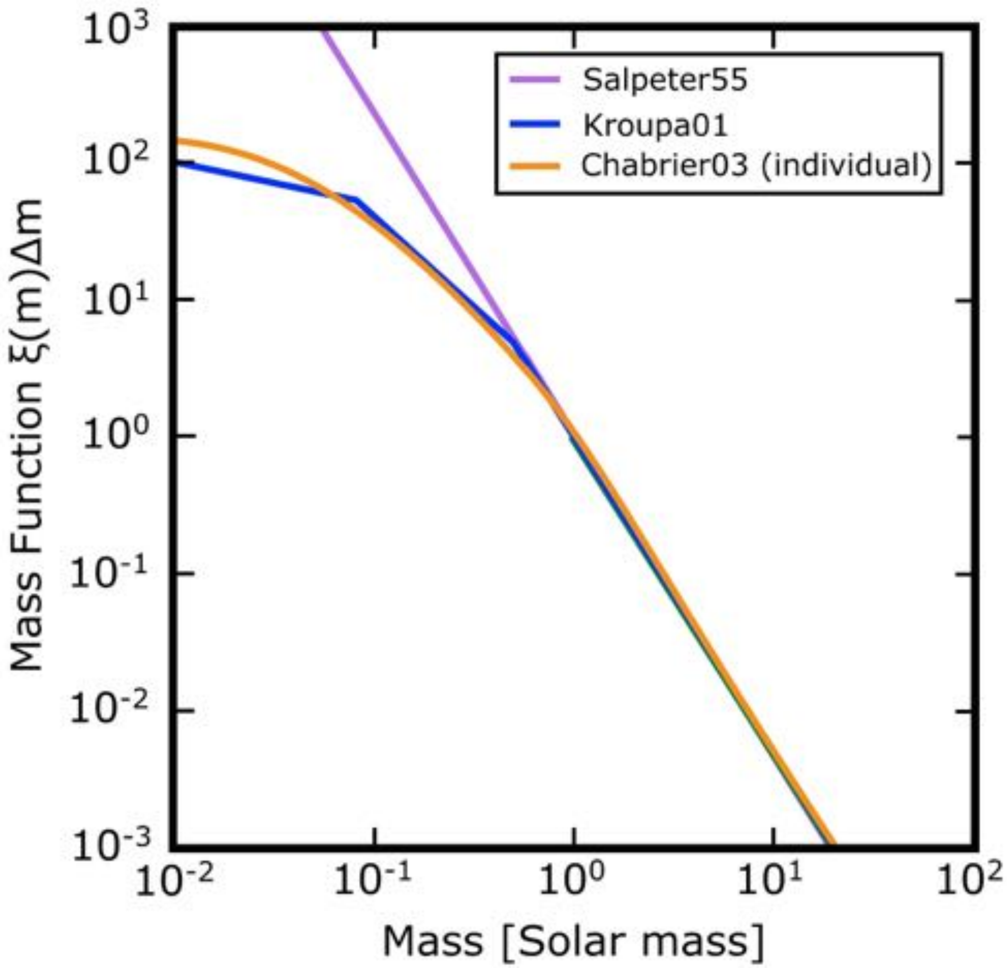
—*not* giant stars (RGB and AGB stars have very distinct evolution!)

Big Questions in Massive Stars

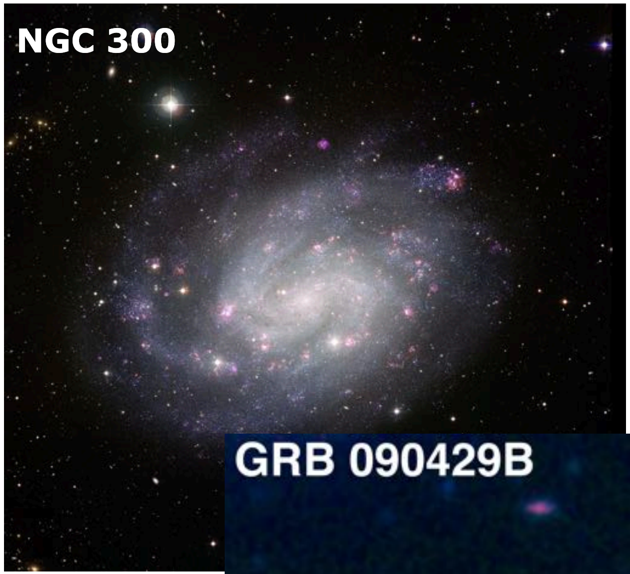
The role of massive stars

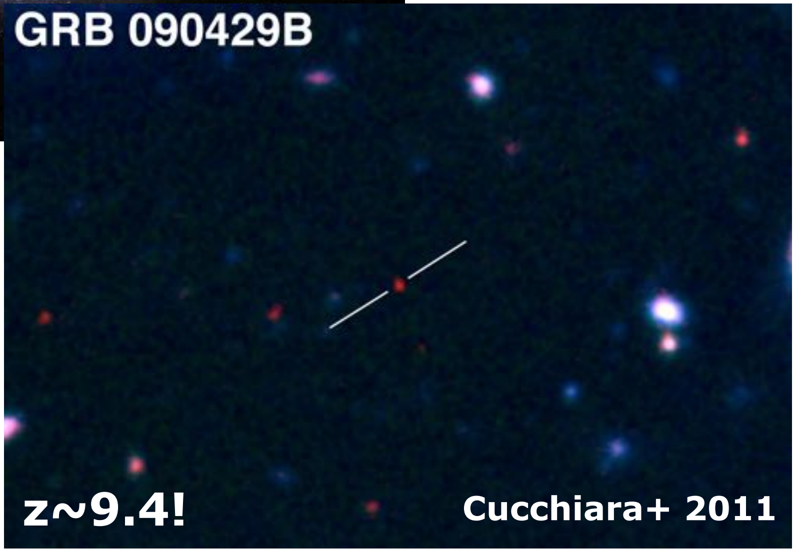
— Massive stars are (relatively) rare; studying the stars themselves in large (N~1000+) or “big-data-esque” quantities is very challenging.

— However, their luminosities and deaths give them a unique reach…



Lamers & Levesque 2017

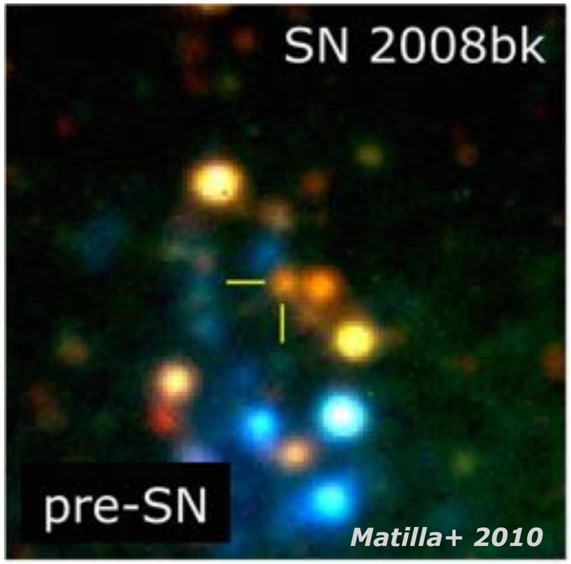




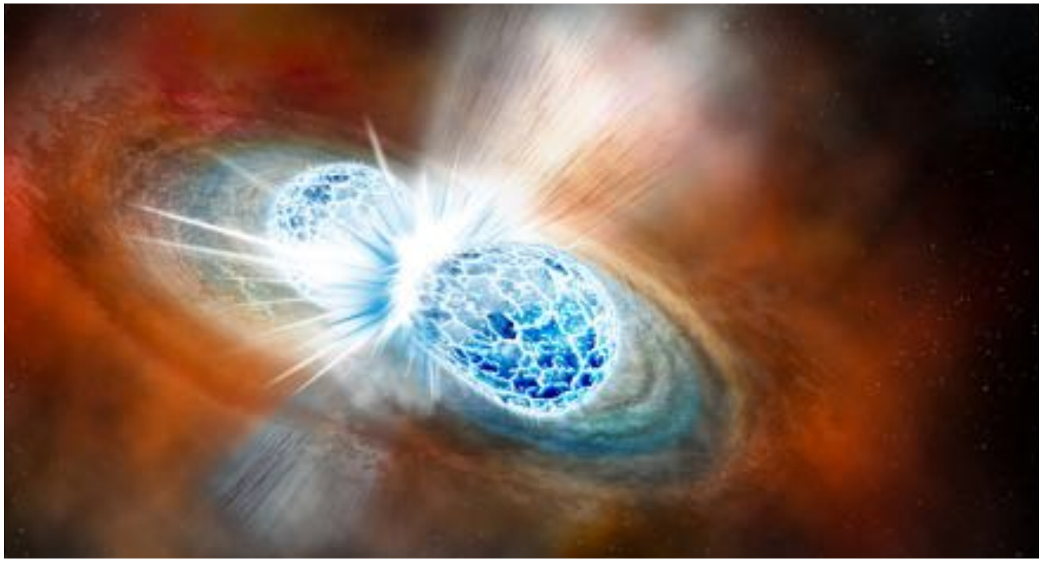
Big Questions in Massive Stars

The role of massive stars

core-collapse supernovae



gravitational wave progenitors



young stellar populations

extragalactic stars

Big Questions in Massive Stars

The role of massive stars

- — how do they contribute to ionizing flux?
- — can we connect specific progenitors to supernovae?
- — what kinds of compact objects do massive stars produce?
- — how do massive stars contribute to chemical enrichment?

How do the physical properties of massive stars impact their evolution?

Big Questions in Massive Stars

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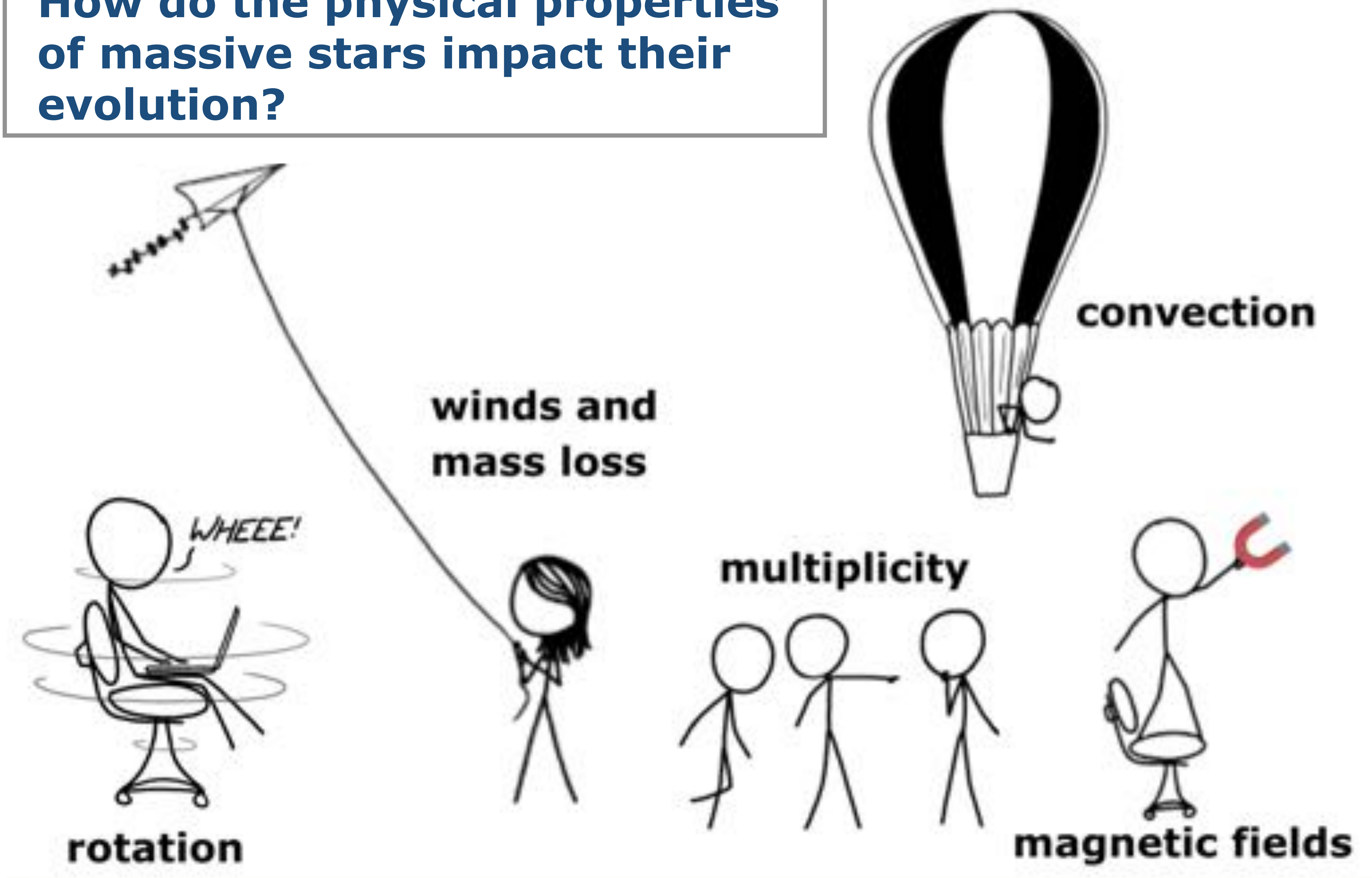


Major strides since 2010

Binaries

Binary interaction is a **common** and **crucial** ingredient in massive star evolution.

Common:

— estimates of potentially interacting massive binaries have gone as high as 70%-100% (Sana+ 2012)

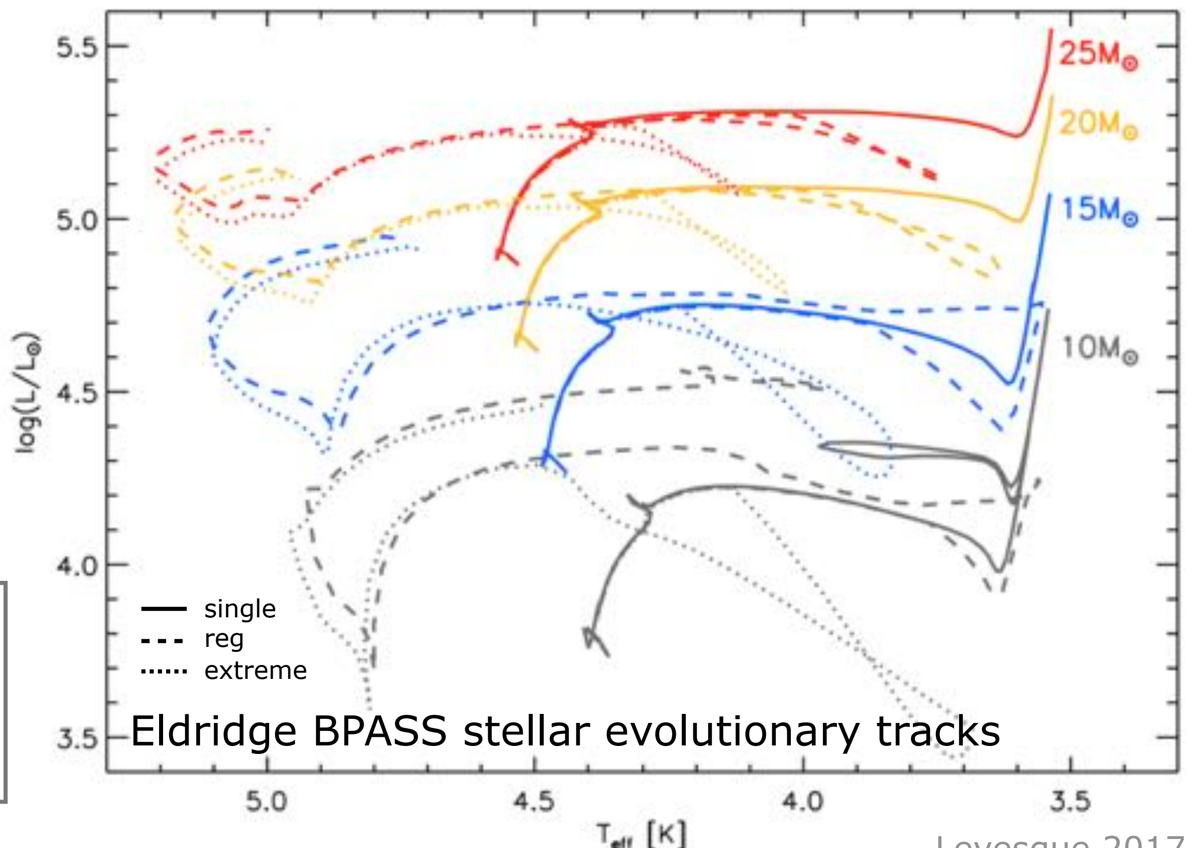
— the observed short-period binary fraction of O stars *and* Wolf-Rayet stars is 35% (Sana+ 2012, Neugent & Massey 2014)

Crucial:

— first binary evolution tracks predict substantial effects from binary interactions (e.g. Eldridge+ 2013)

— we can simulate common envelope evolution and its observable signatures (e.g. Ivanova 2017)

Binaries impact massive star and ionizing populations, supernova progenitor imaging and evolution, and compact object systems.



Eldridge BPASS stellar evolutionary tracks

Levesque 2017

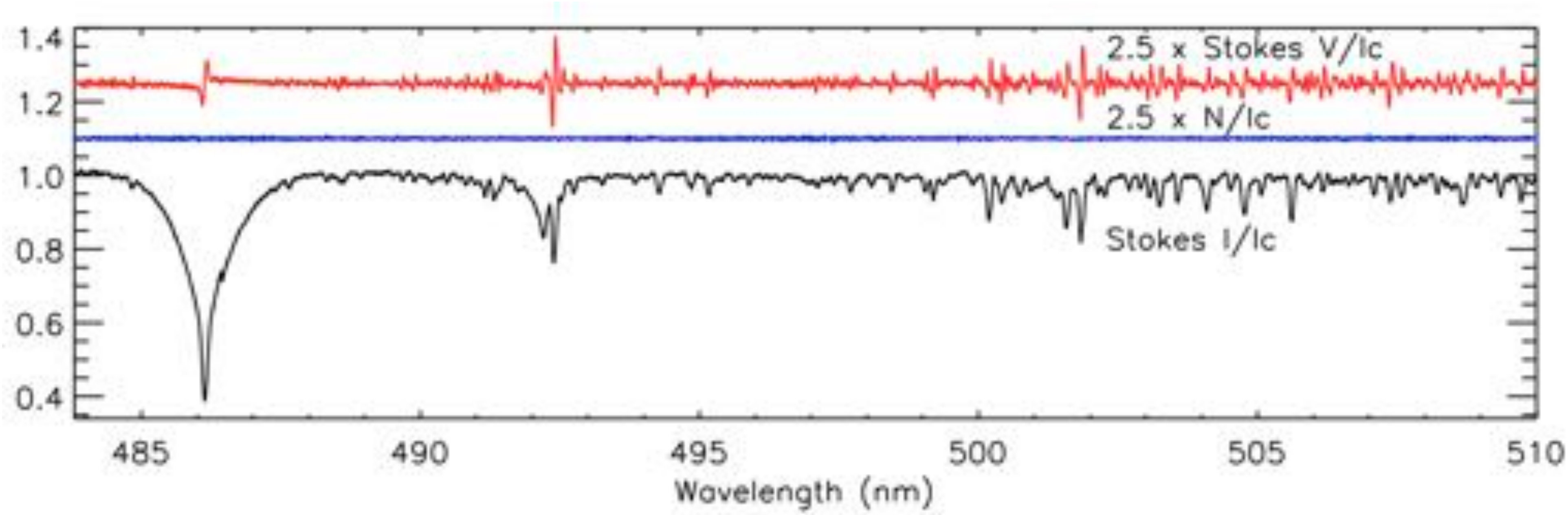
Major strides since 2010

Magnetic Fields

A **significant fraction** of MS massive stars have **strong surface B-fields**.

Significant fraction:
— spectropolarimetric surveys have found magnetic fields in ~10% of O and early-B type massive stars (e.g. Wade+, Grunhut+, Morel+, Neiner+, Oksala+)

Strong surface B-fields:
— typical fields are ~0.3-20 kG (e.g. Wade+ 2012, Morel+ 2015, Neiner+ 2017, Oksala+ 2017)
— B-fields and their effects persist even when stars leave the MS



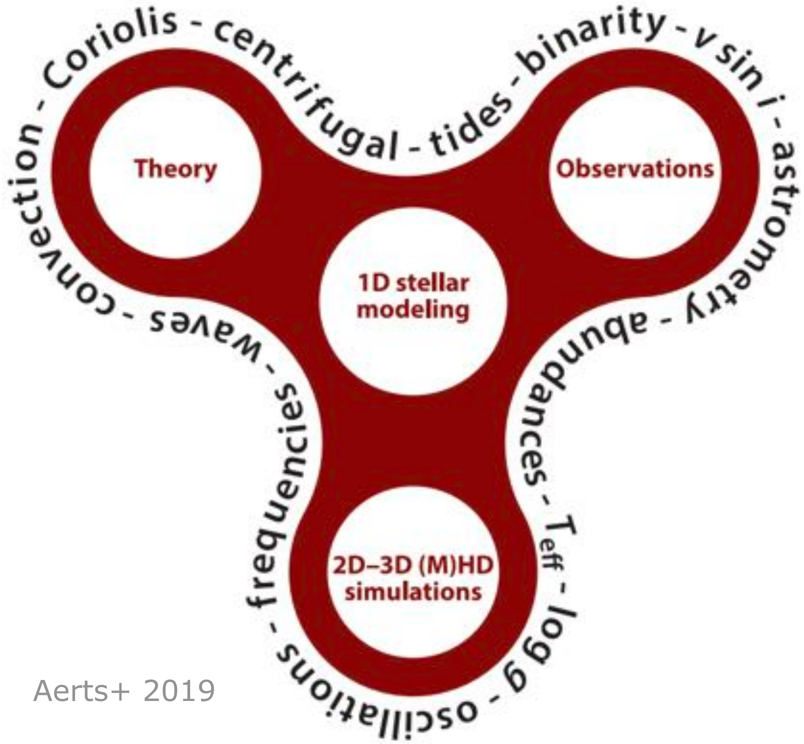
Surface B-fields produce orientation-dependent effects on observed spectra and impact the stars' physical properties (luminosity, rotation rates, etc.)

Major strides since 2010

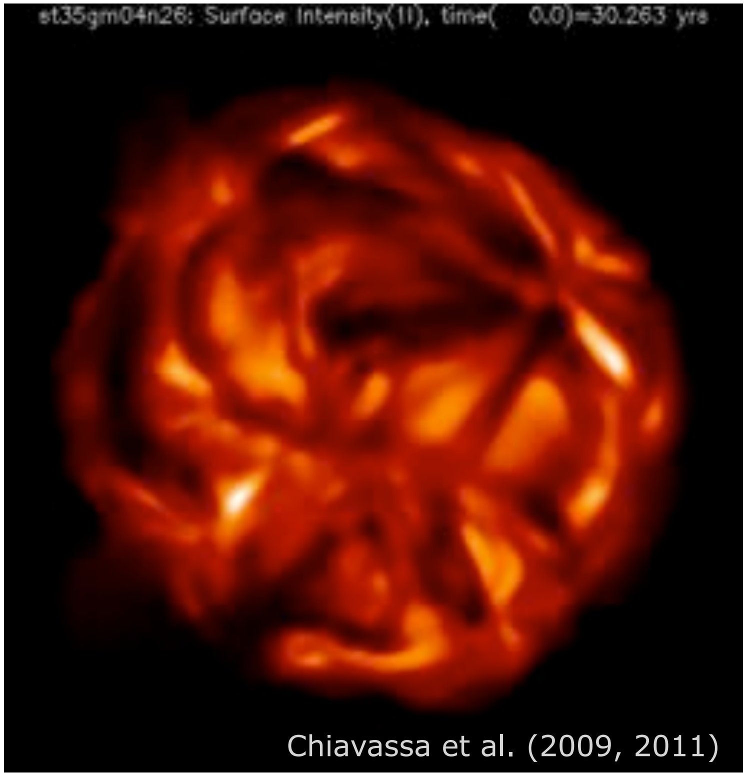
Interiors

Asteroseismology of massive stars is now possible thanks to space missions like CoRoT, Kepler, and TESS.

— evidence of internal gravity waves in young massive stars (e.g. Aerts+ 2015)
— signs of surprisingly large convective cores (e.g. Johnston+ 2019)
— ongoing explorations of internal/core magnetic fields
— convective cores *and* outer layers after massive stars leave the main sequence! (e.g. Chiavassa+ 2009, 2011)



Aerts+ 2019



Chiavassa et al. (2009, 2011)

Massive star interiors are complex, but today's photometric surveys have given us the ability to study them.

Major strides since 2010

Mass Loss

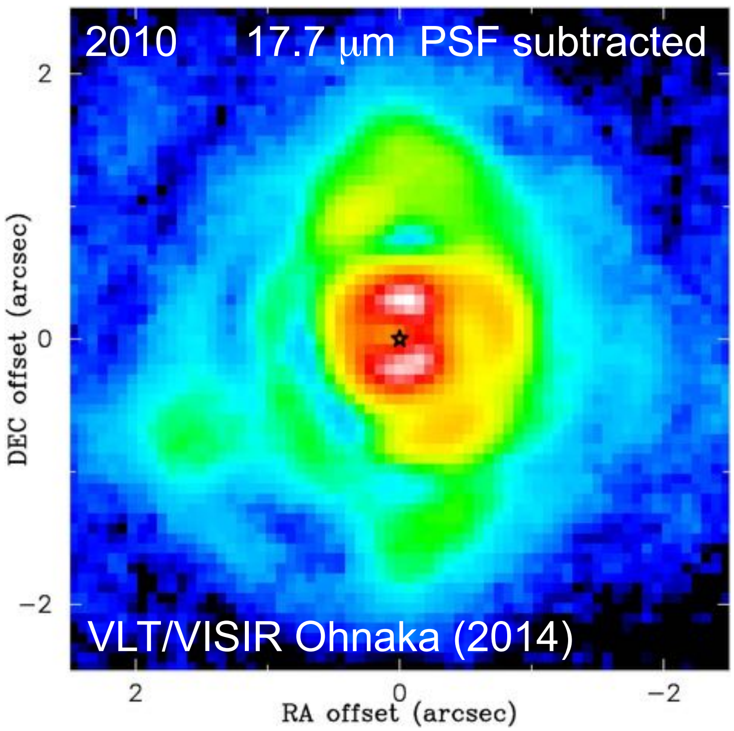
Massive stars experience **mass loss** both on and after the main sequence.

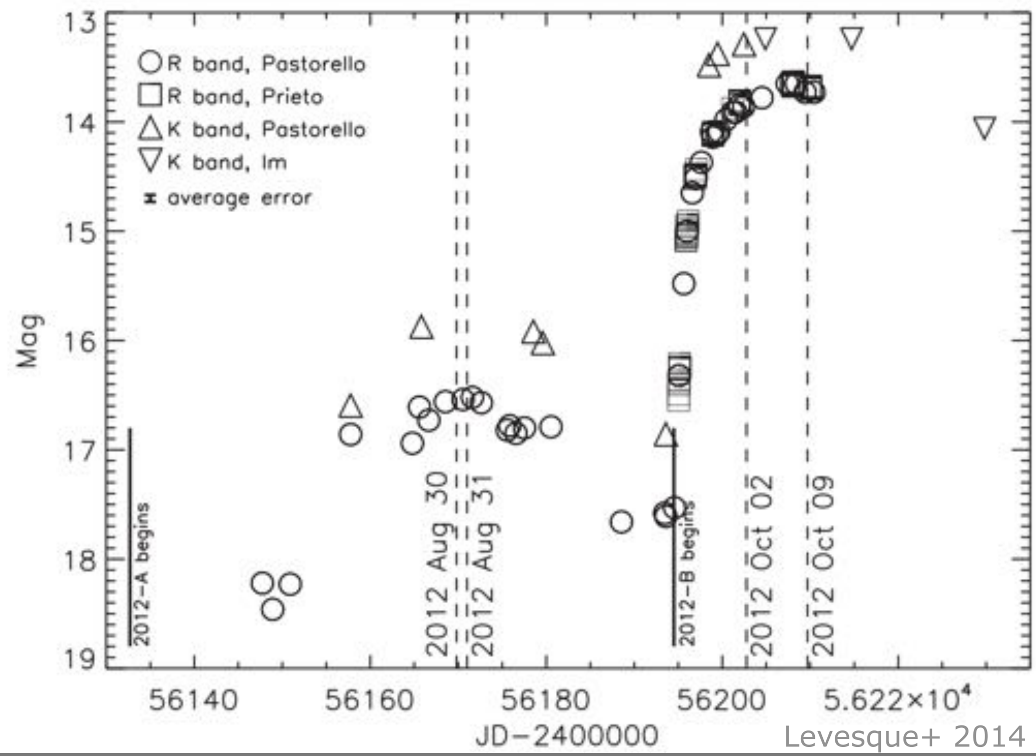
— ten years ago we had good estimates of hot star mechanisms and Z-dependence

— current work on clumping, porosity, hot spots are updating mass loss rates (e.g. Gräfener & Hamman 2016)

— model and empirical mass loss rates for cool stars and dust-driven mass loss are still ongoing (e.g. Ohnaka+, Lomax+, van Loon+, Bonanos+, Mauron & Josselin+)

— extreme and episodic mass loss has been observed in variables, SN progenitors (e.g. Ofek+ 2014, Margutti+ 2014)





Mass loss impacts massive stars' observable signatures, angular momentum evolution, dust production, and deaths.

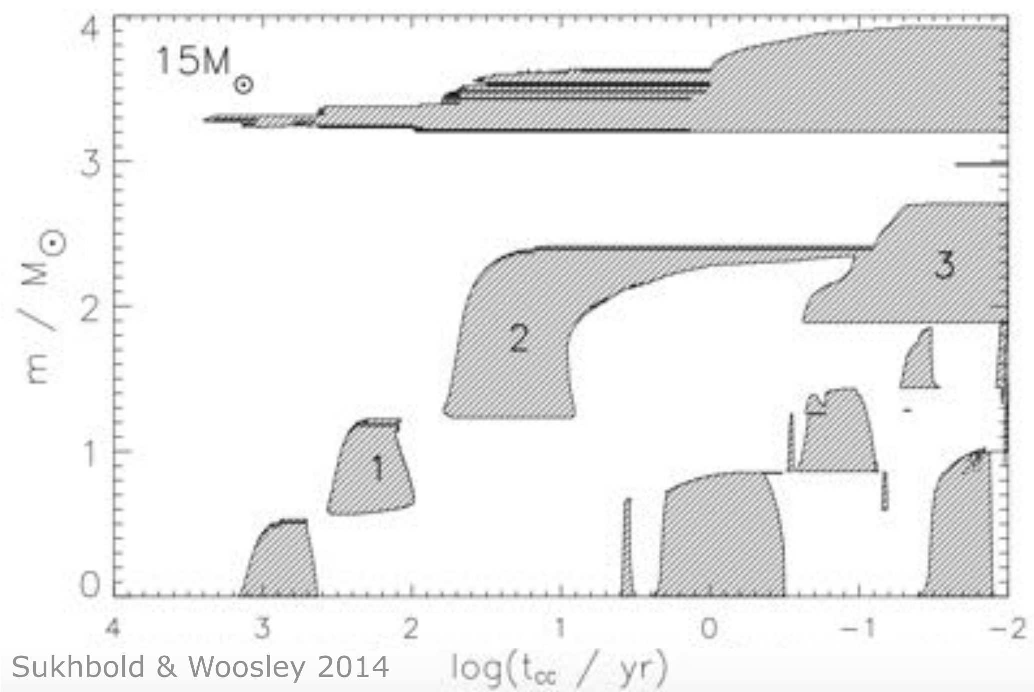
Major strides since 2010

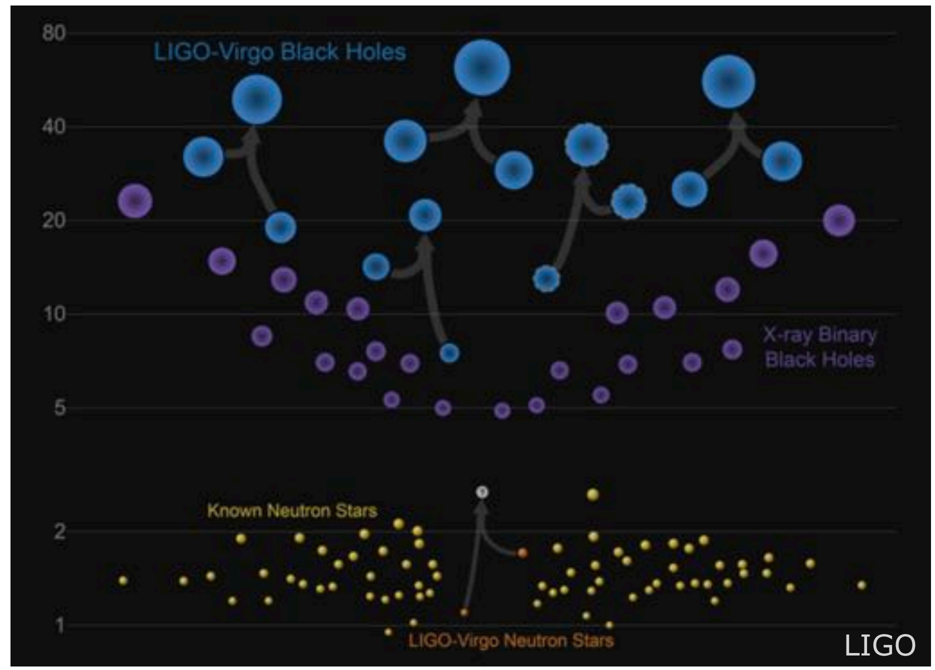
Compact object formation

Stellar evolution impacts the type and mass of the compact object left behind.

— core-collapse models depend on our understanding of the star's physical properties just before compact object formation

— LIGO proved that very massive stellar black holes can form and merge!



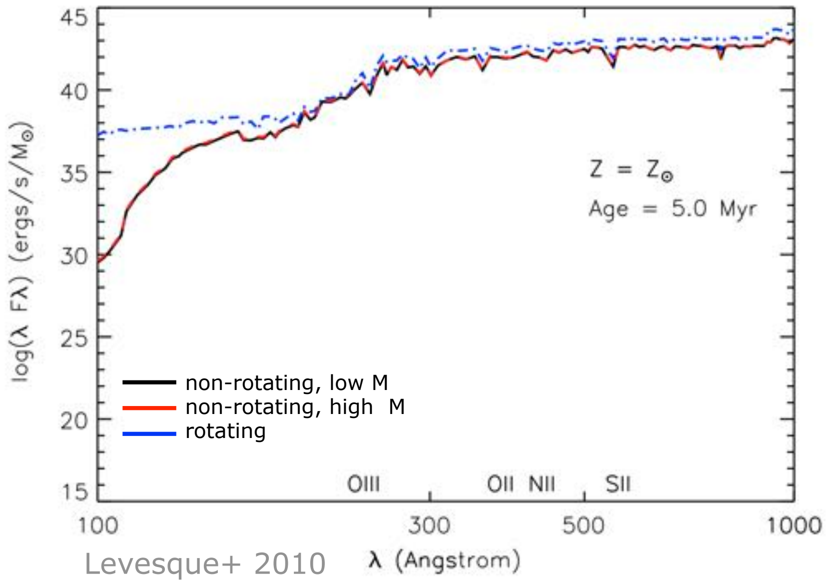


The physical properties of massive stars directly impact the numbers, masses, and populations of compact objects that they produce.

Major strides since 2010

Massive star populations

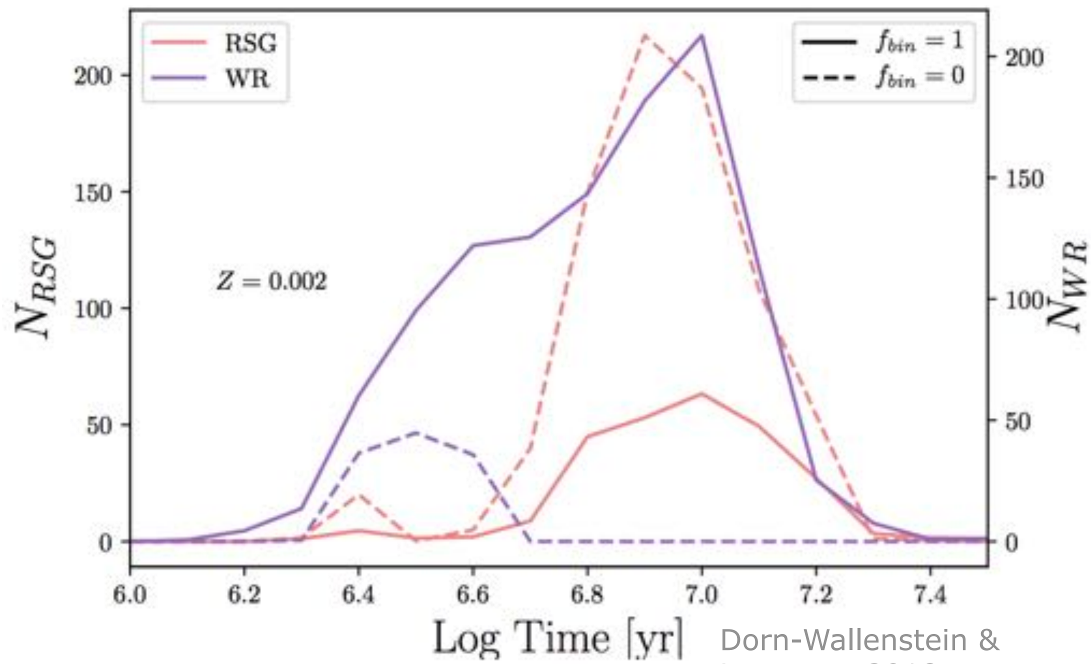
Stellar population synthesis **strongly** depends on models of massive star evolution.



Levesque+ 2010

Since 2010:
— new models of binary evolution
— new models of evolution with rotation
— models with updated treatments of MS and post-MS mass loss
— new observations constraining the ionizing output from massive stars

Since 2010:
— observations of extragalactic massive stars can constrain our picture of their populations (e.g. LGGS, VLT-FLAMES)
— we've started to predict population-scale diagnostics of massive star evolution



Dorn-Wallenstein & Levesque 2018

Modeling young stellar populations both depends on and can help constrain massive star evolution.

Priorities for 2030

~~Binary~~ multiple evolution

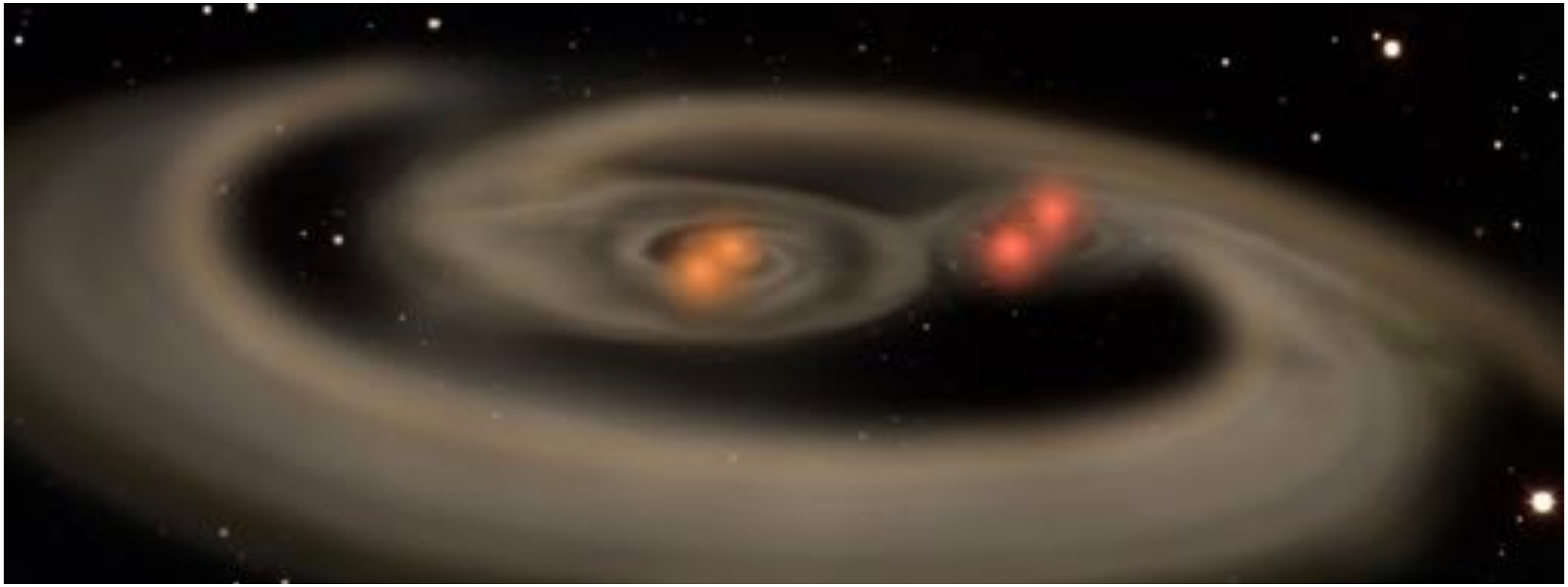
— quantify the multiple fraction and interactive multiple fraction both on and off the main sequence

— improve models of multiple interaction, common envelope evolution, end products

— improve our observations of massive stars in multiple systems

— refine predictions for interacting stellar populations and compare with observations

— understand metallicity dependence



Priorities for 2030

Mass loss and eruptions

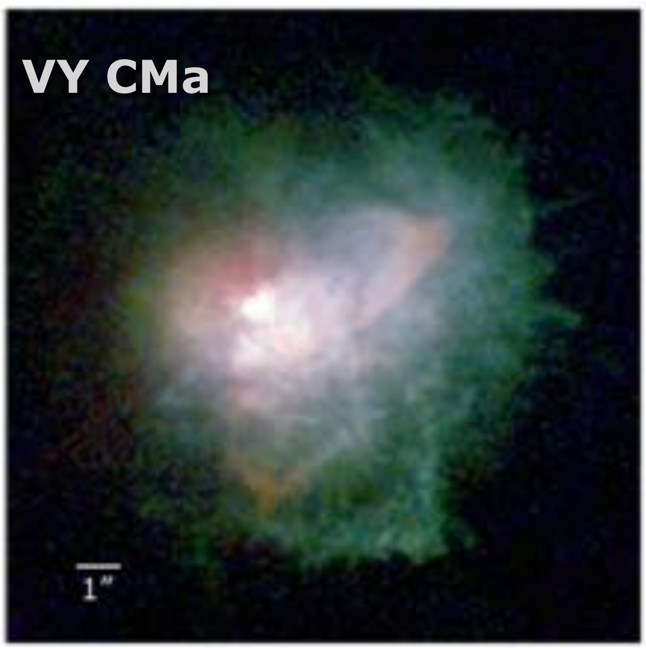
— continue refining our picture of hot star/line-driven mass loss (including post-main-sequence objects like Wolf-Rayet stars)

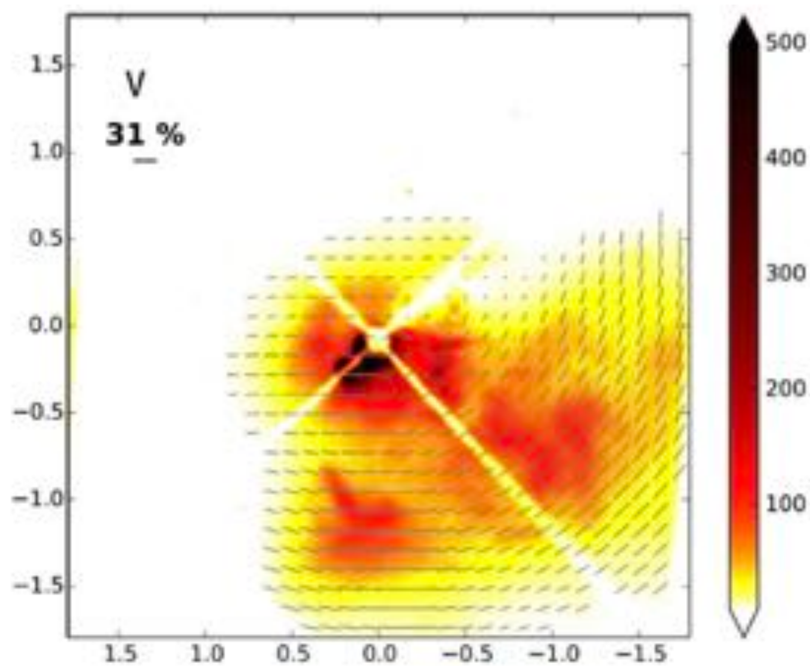
— quantify and explain red and yellow supergiant mass loss

— unravel photometric signatures of mass loss (continuous, sporadic, eruptive…)

— model how mass loss impacts observable signatures and terminal stages

— understand metallicity dependence





Smith 2001, Scicluna+ 2015, Levesque 2017

Priorities for 2030

Interiors

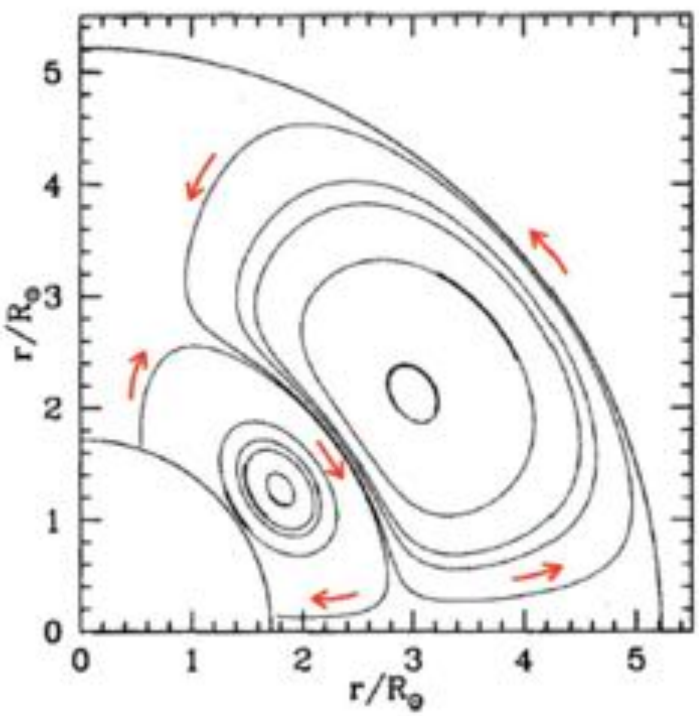
— improve our models of how rotation and angular momentum impact stellar interiors, from core to envelope

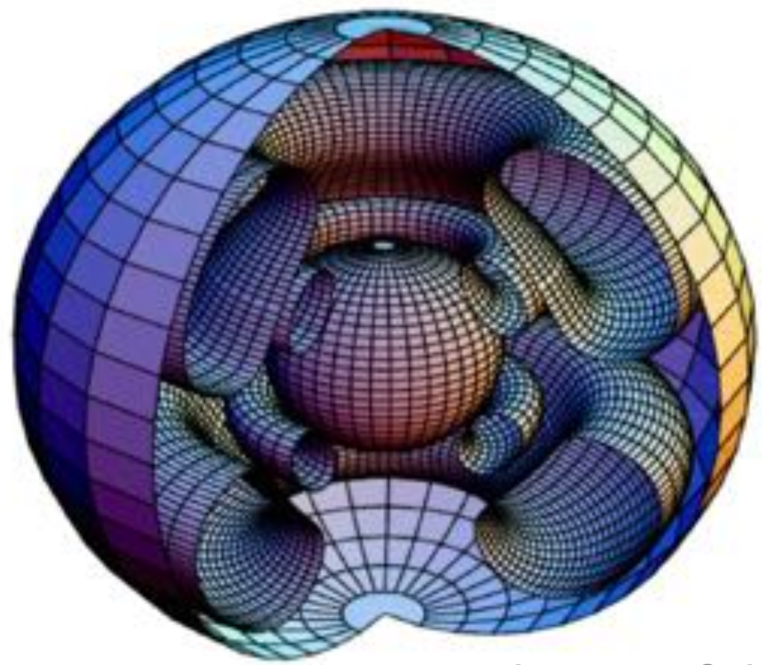
— improve models of mixing in massive stars (and consequences for feedback)

— continue exploring models and signatures of interior magnetic fields

— connect theories of massive star interiors with potential observables

— understand metallicity dependence





Lamers & Levesque 2017

Priorities for 2030

Mass range, distribution, and ionizing population

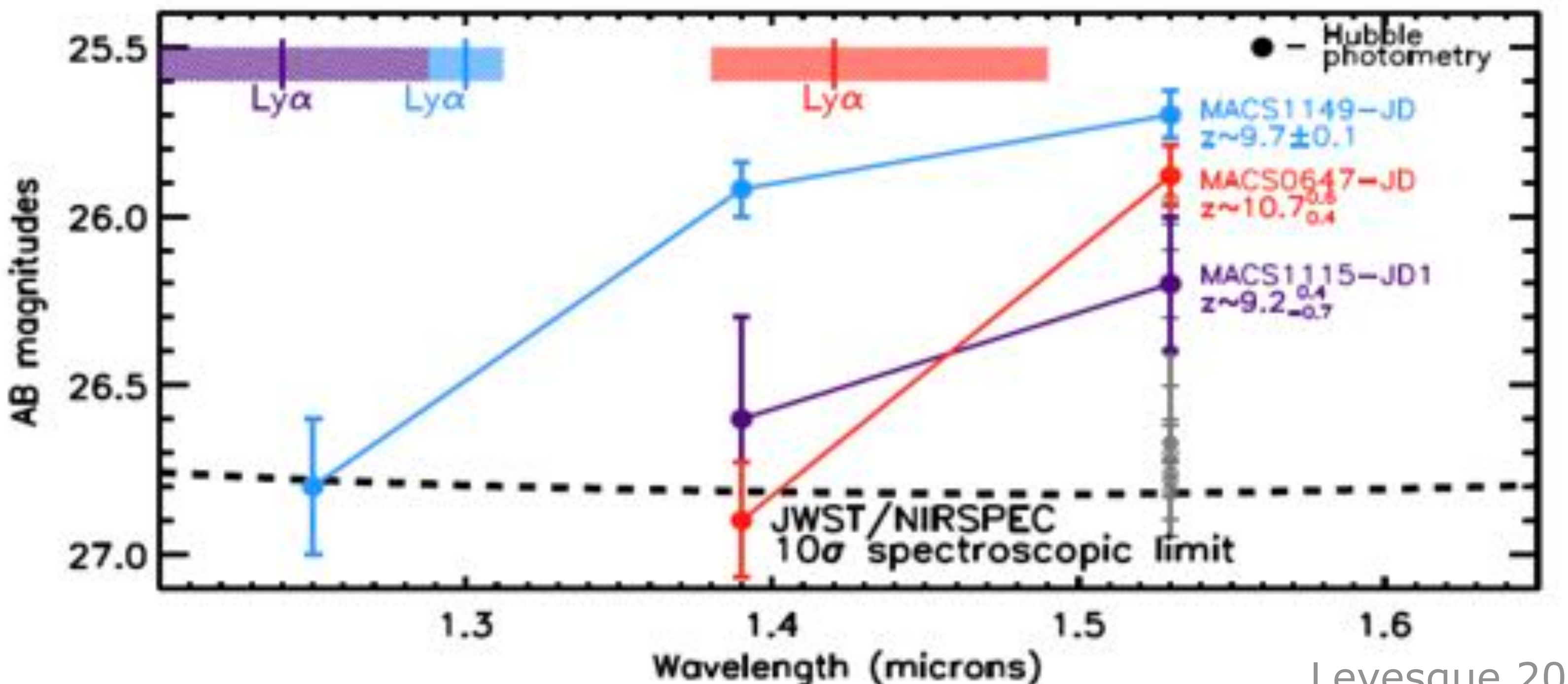
— constrain the upper mass limit of massive stars

— constrain the IMF and star formation histories of nearby massive star populations

— improve our diagnostics of massive star physical properties (which in turn impact our available tools for measuring masses)

— quantify the ionizing flux produced by different populations of hot massive stars

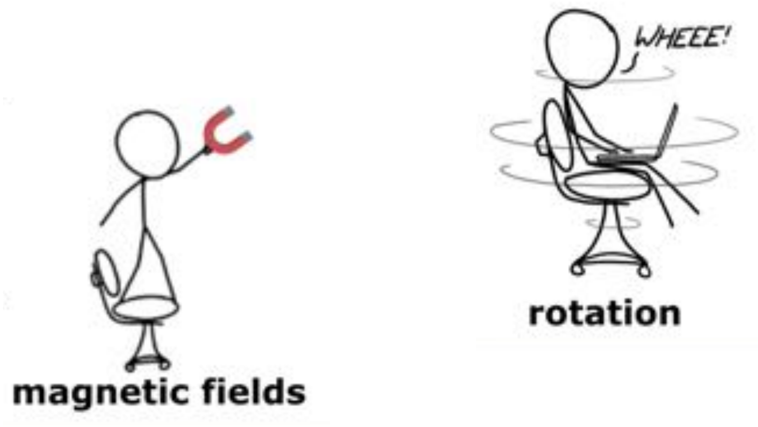
— understand metallicity dependence

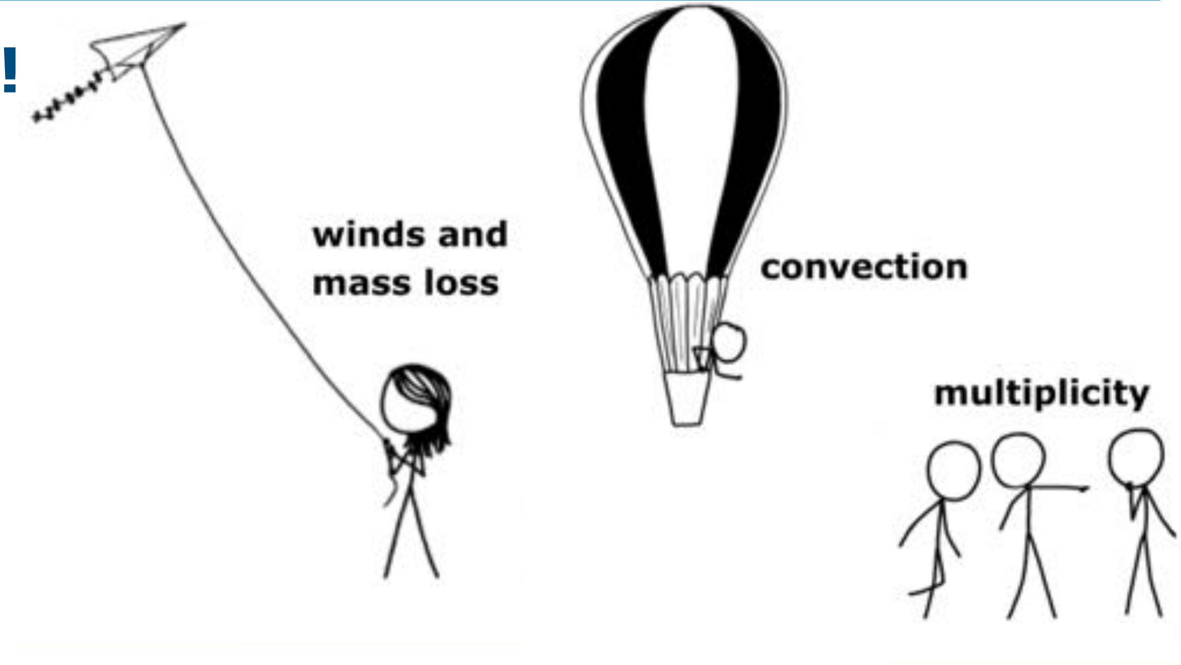


Levesque 2015

Priorities for 2030

Interplay of parameters!





Big Questions in Massive Stars...

— how do they contribute to ionizing flux?

— can we connect specific progenitors to supernovae?

— what kinds of compact objects do massive stars produce?

— how do massive stars contribute to chemical enrichment?

...combine all the big puzzles

— all parameters are interdependent

— fundamental concepts (mixing, energy transport involve all five parameters)

— metallicity matters broadly to apply what we learn about massive stars across the cosmos

— puzzled must be approached in parallel

Priorities for 2030

Observational needs

Massive star research will continue to benefit enormously from:
— photometry, particularly time-domain (variability, transients, asteroseismology)
— infrared observations (cool stars, dust production, high-redshift stellar population and host galaxies)

However, **massive stars *NEED* spectroscopy and ultraviolet/blue observations!!**
— UV and blue observatories are critical for studying stellar winds, young stellar populations, binaries, etc. LUVOIR!: “these are the spectral windows where stellar winds leave their imprint”. LUVOIR!
— need visible spectroscopy from the ELTs and other large campaigns (broadband photometry is not enough to answer the questions we're currently grappling with!)