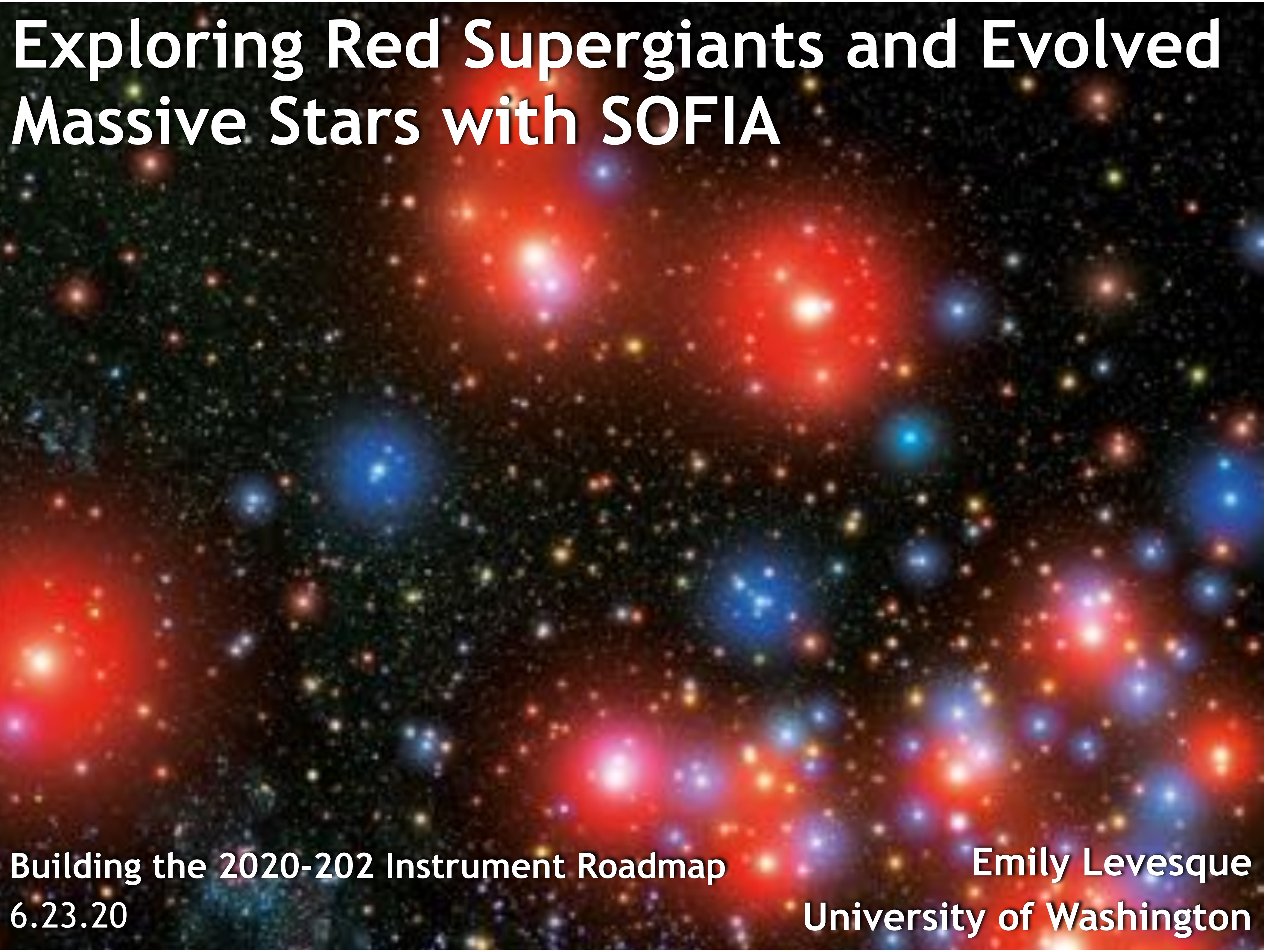
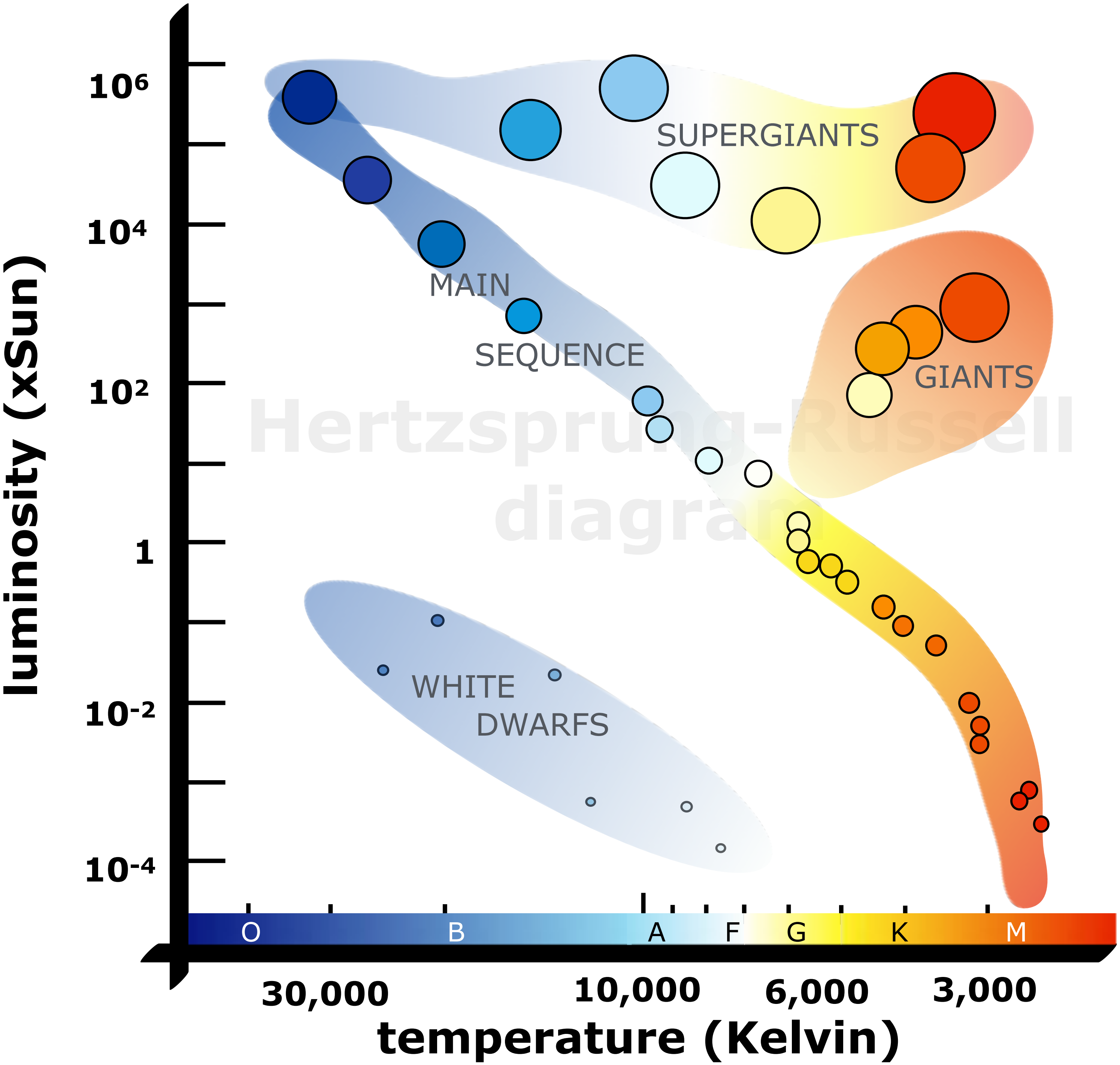
Exploring Red Supergiants and Evolved Massive Stars with SOFIA



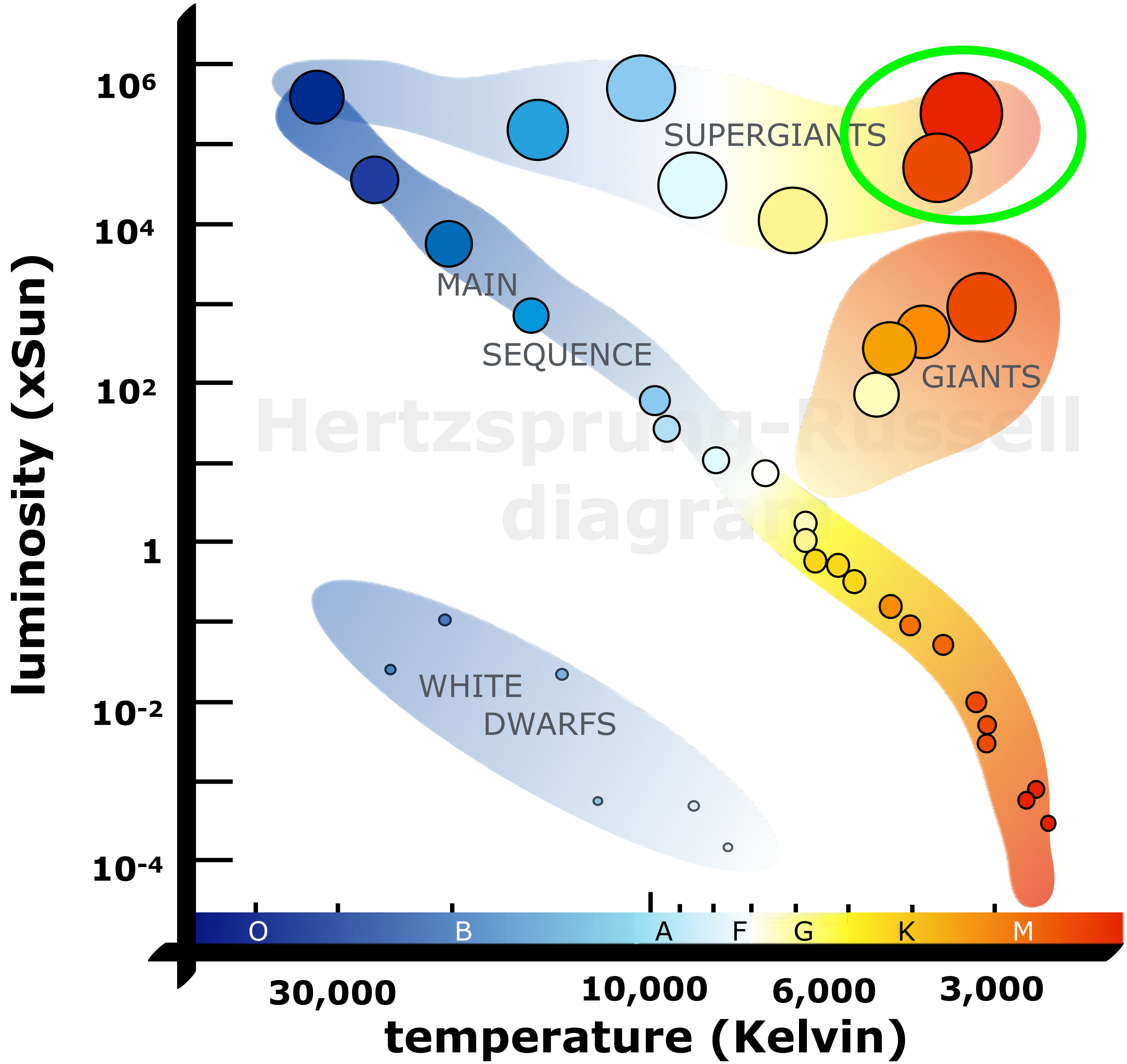
Building the 2020-202 Instrument Roadmap
6.23.20

Emily Levesque
University of Washington

Red supergiants…

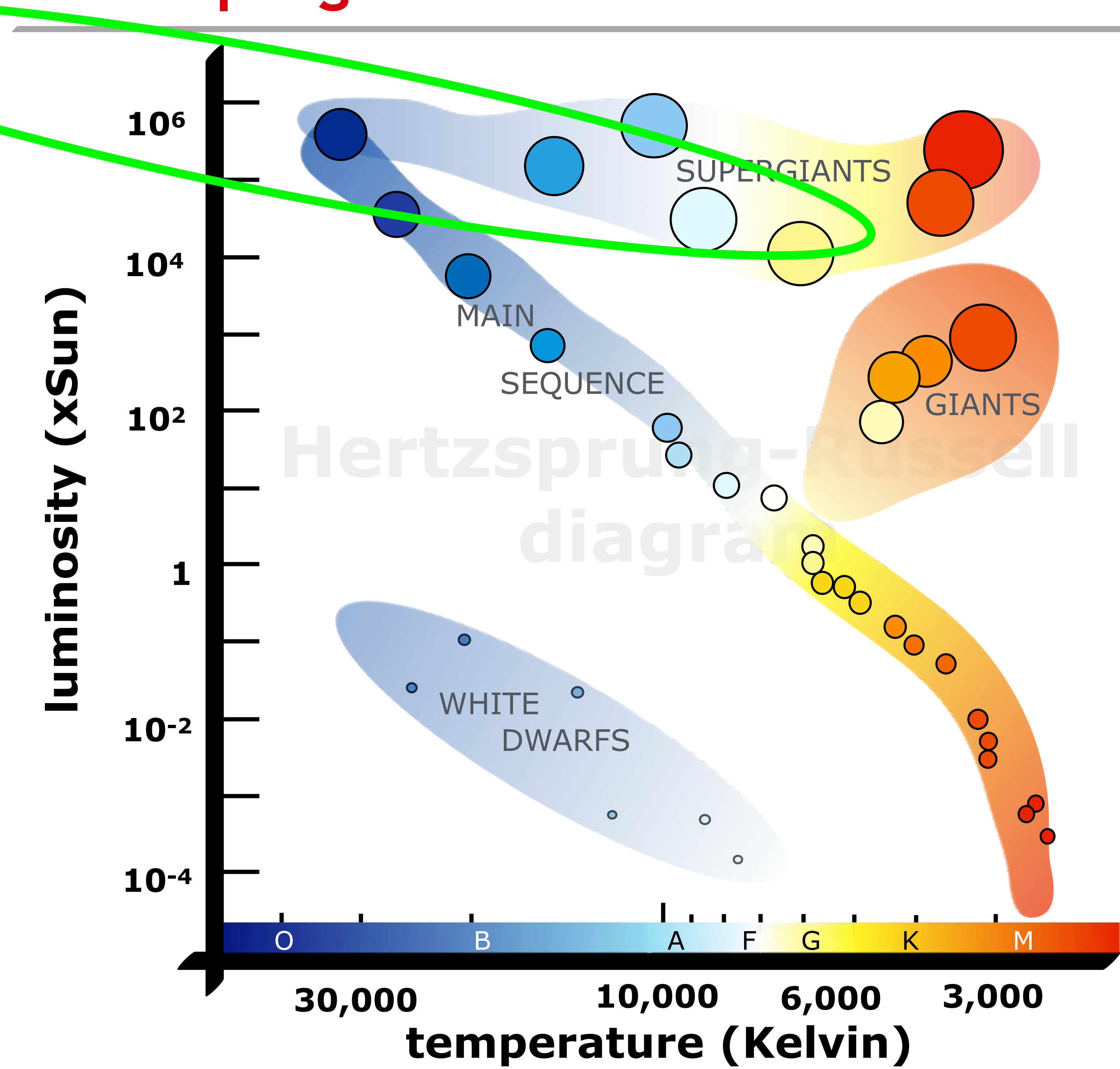


Red supergiants...



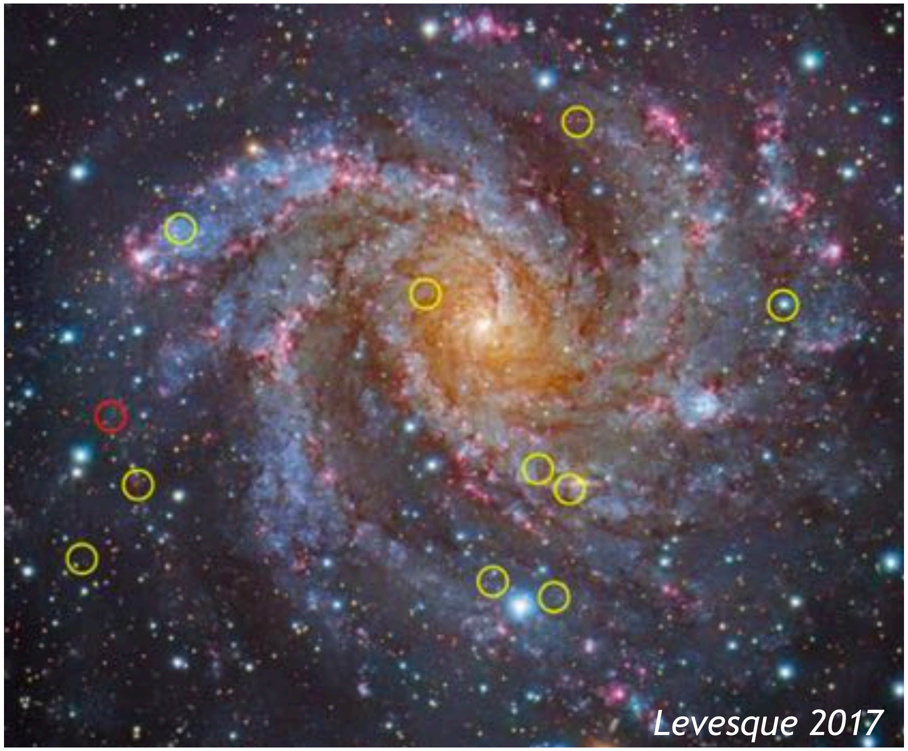
- **red supergiants**: cold, large, dusty phase of evolution for ~8-30M☉ stars

Red supergiants…and evolved massive stars



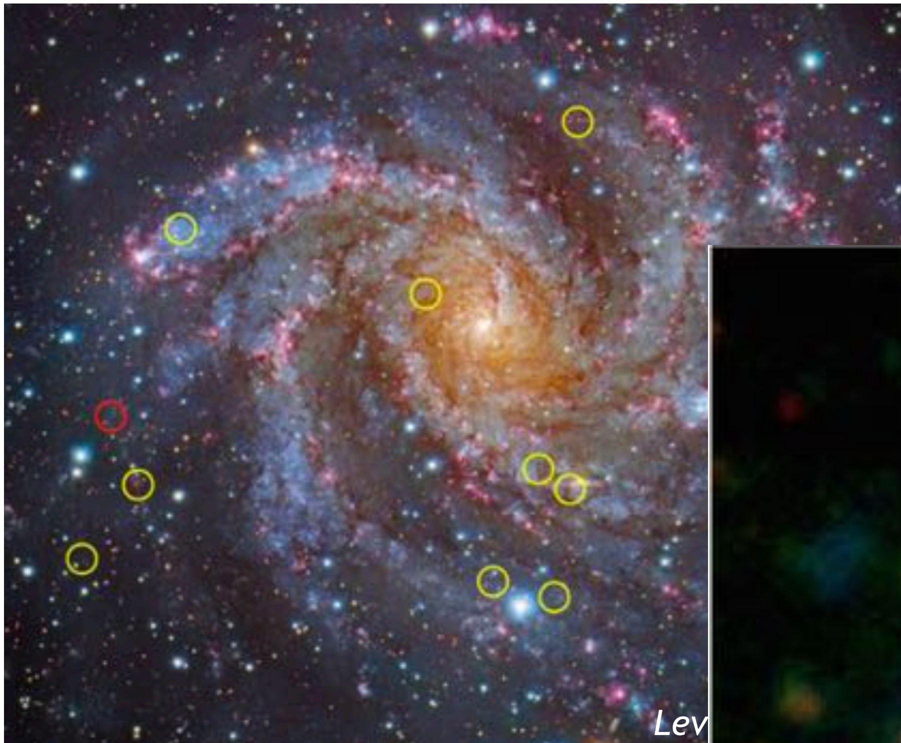
- **red supergiants**: cold, large, dusty phase of evolution for ~8-30$M_\odot$ stars
- **yellow supergiants**: rare post-MS (*and post-RSG?*) phase with mass loss, pulsations
- **Wolf-Rayet stars**: post-MS hot stripped-envelope stars
- **LBVs**: high-mass evolved variables with substantial sporadic mass loss

Who *cares* about red supergiants?

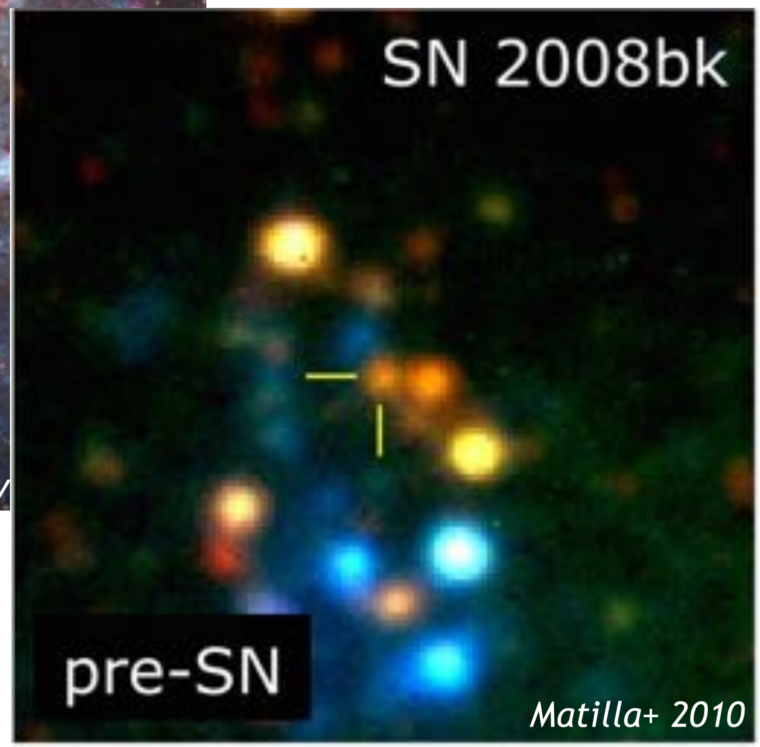


ideal extragalactic targets

Who *cares* about red supergiants?

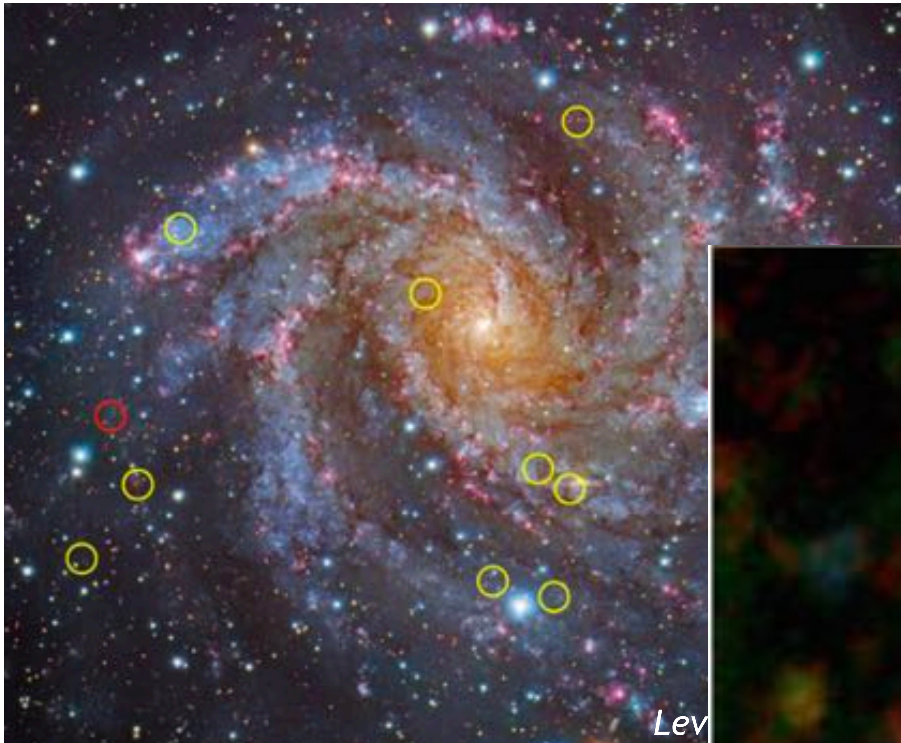


ideal extragalactic targets

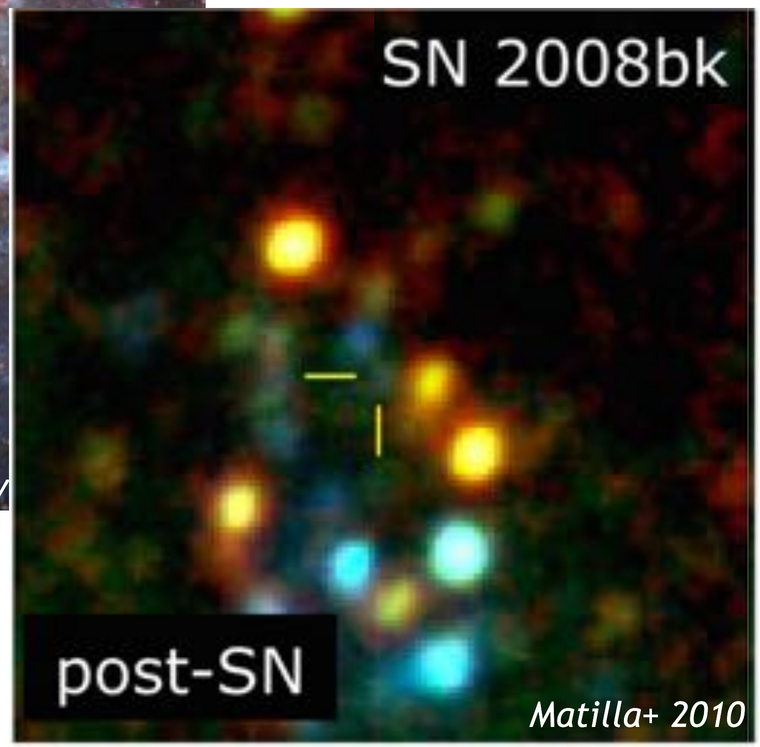


core-collapse progenitors

Who *cares* about red supergiants?

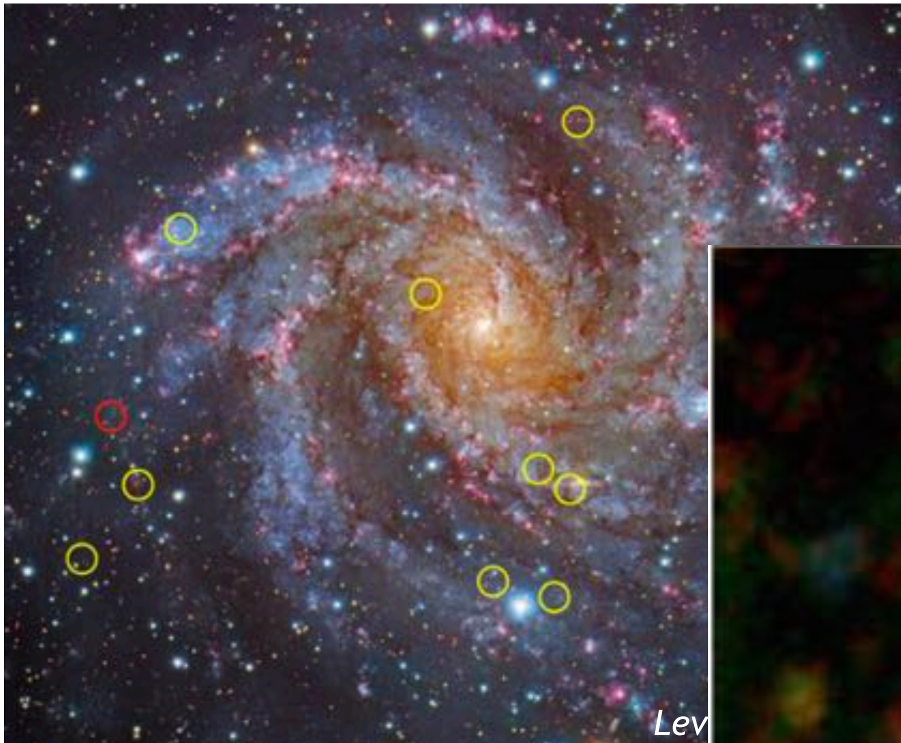


ideal extragalactic targets

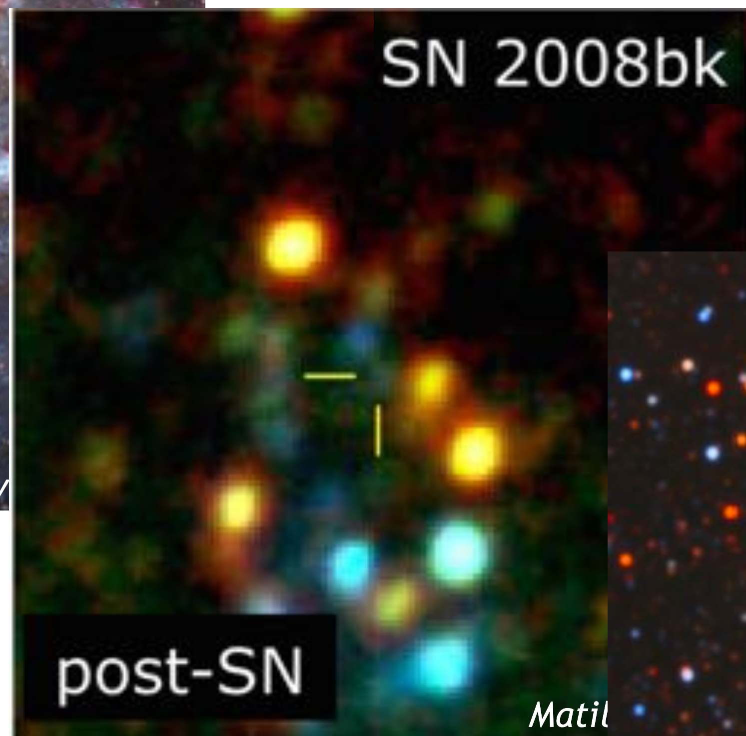


core-collapse progenitors

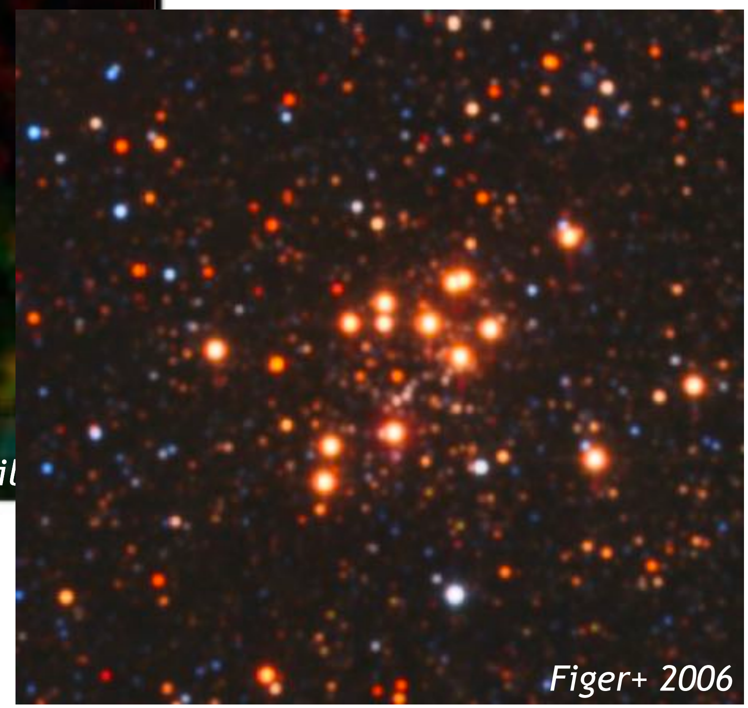
Who *cares* about red supergiants?



ideal extragalactic targets

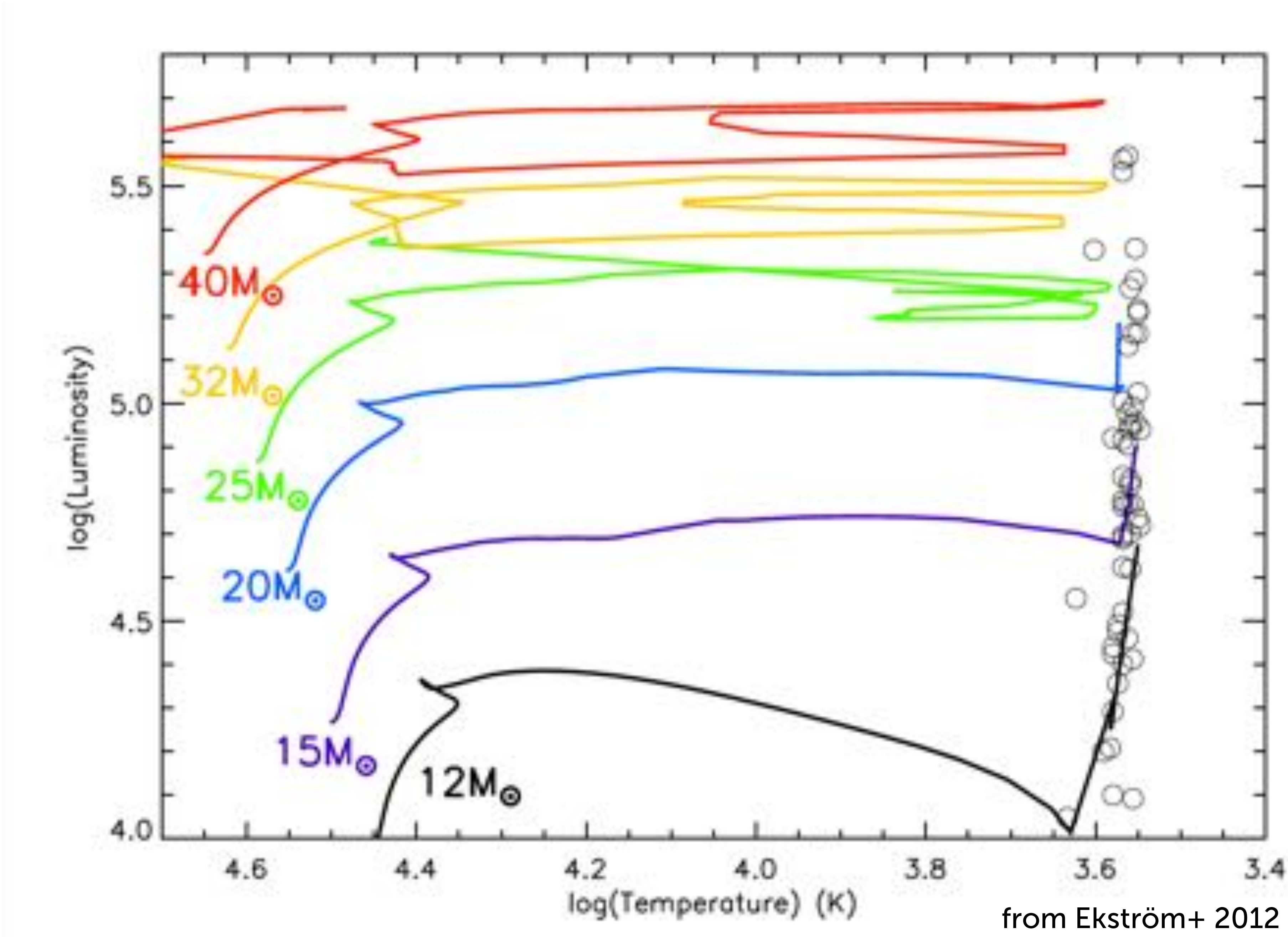


core-collapse progenitors



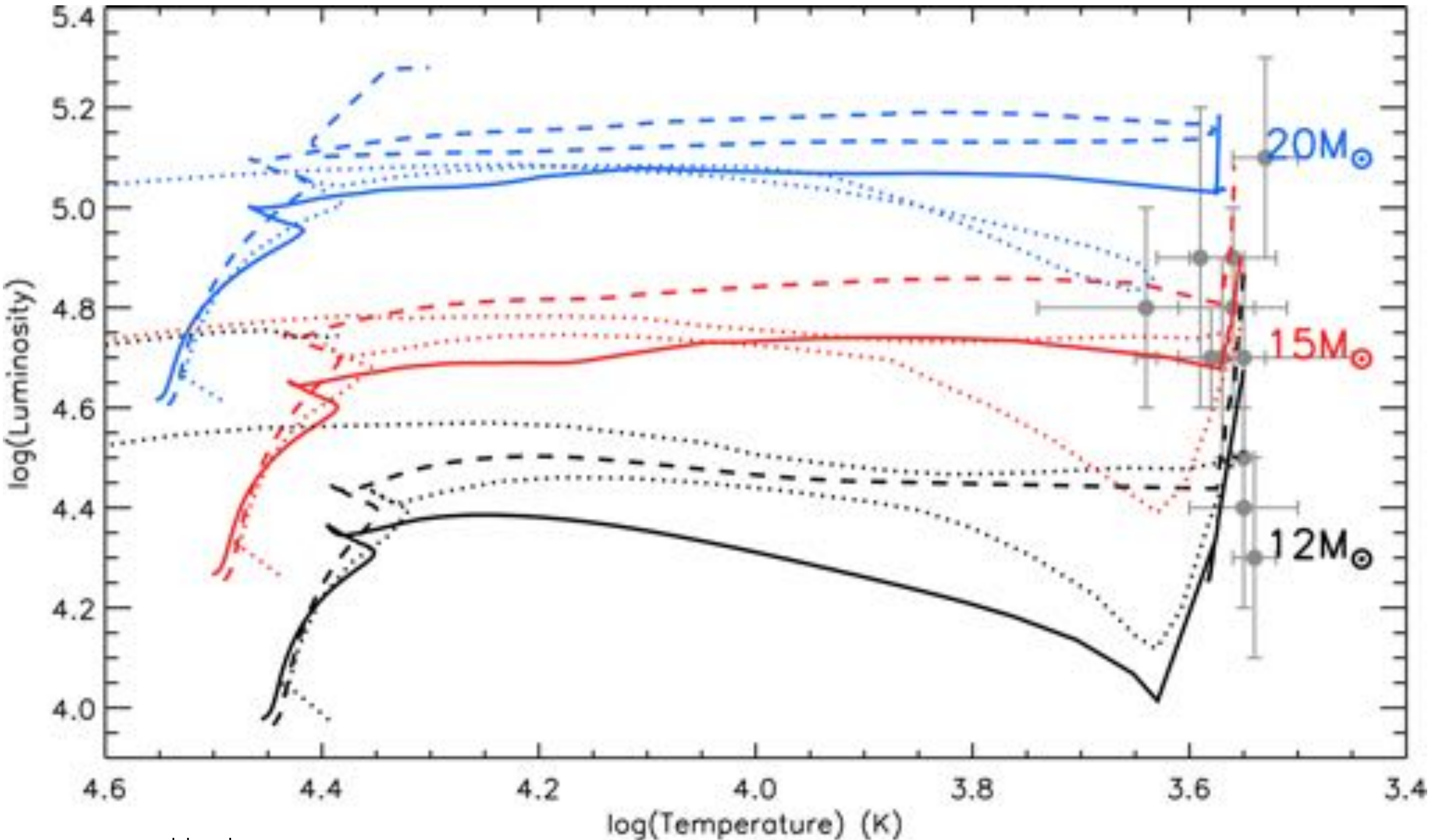
"magnifying glasses"
for massive star evolution

Challenges: RSG physical properties



from Ekström+ 2012
from Levesque+ 2005

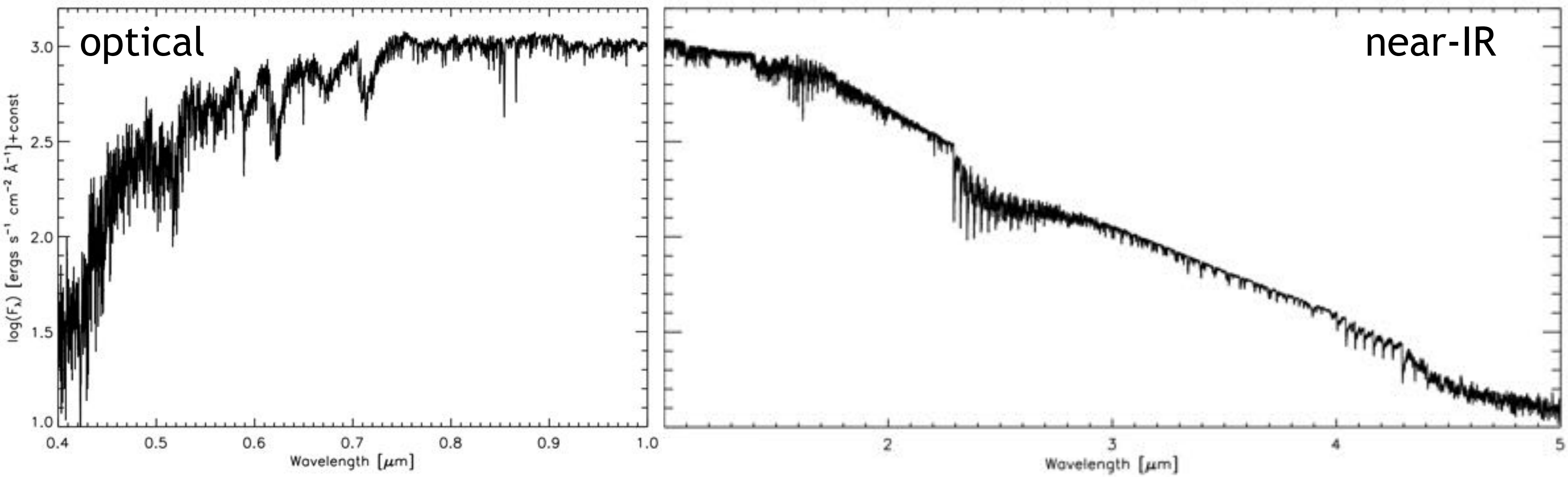
Challenges: RSG physical properties



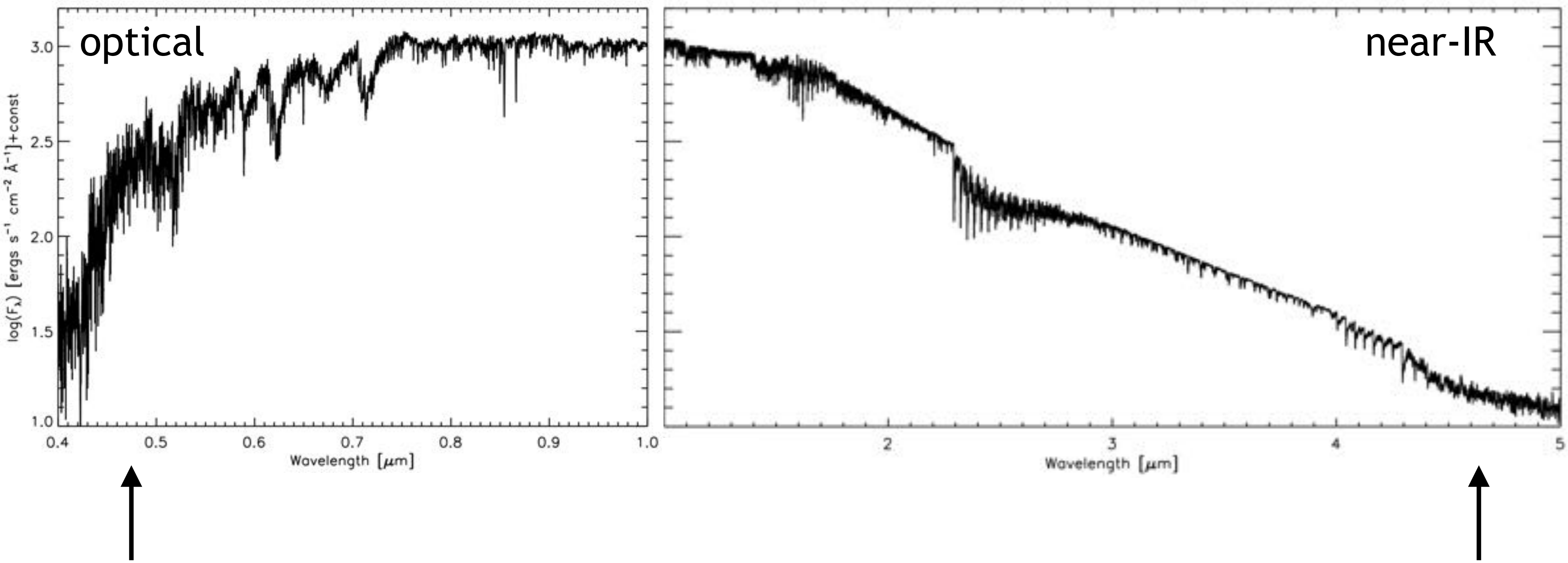
binaries
rotating
single

from Levesque 2017

Challenges: RSG physical properties



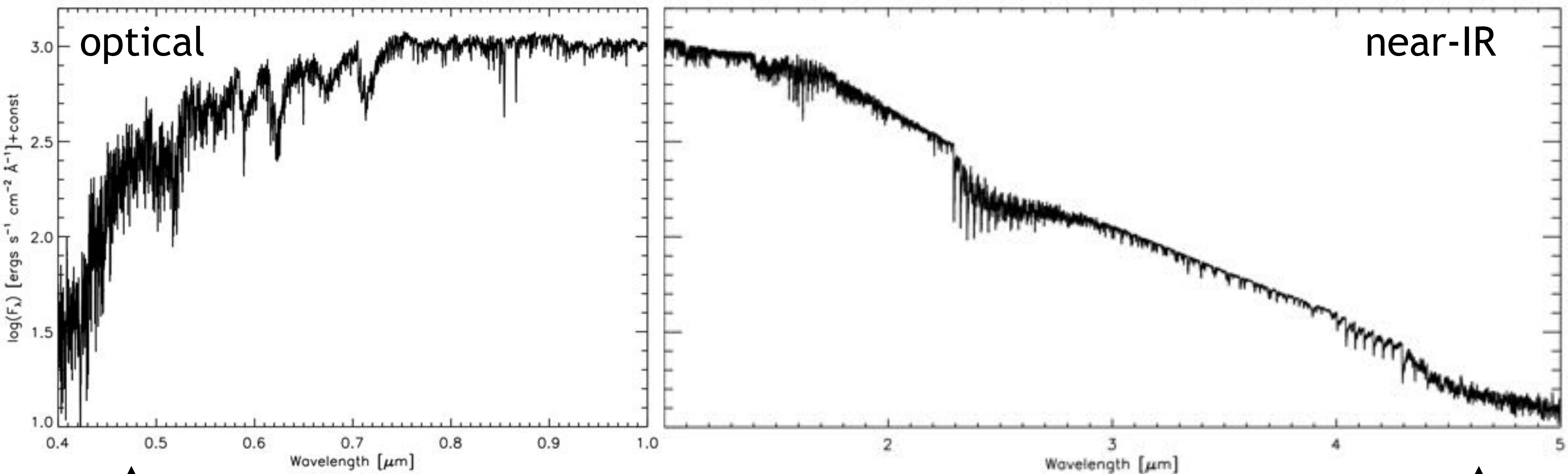
Challenges: RSG physical properties



TiO molecular bands
atomic lines?

other molecular bands?
atomic lines?

Challenges: RSG physical properties



TiO molecular bands
atomic lines?

other molecular bands?
atomic lines?

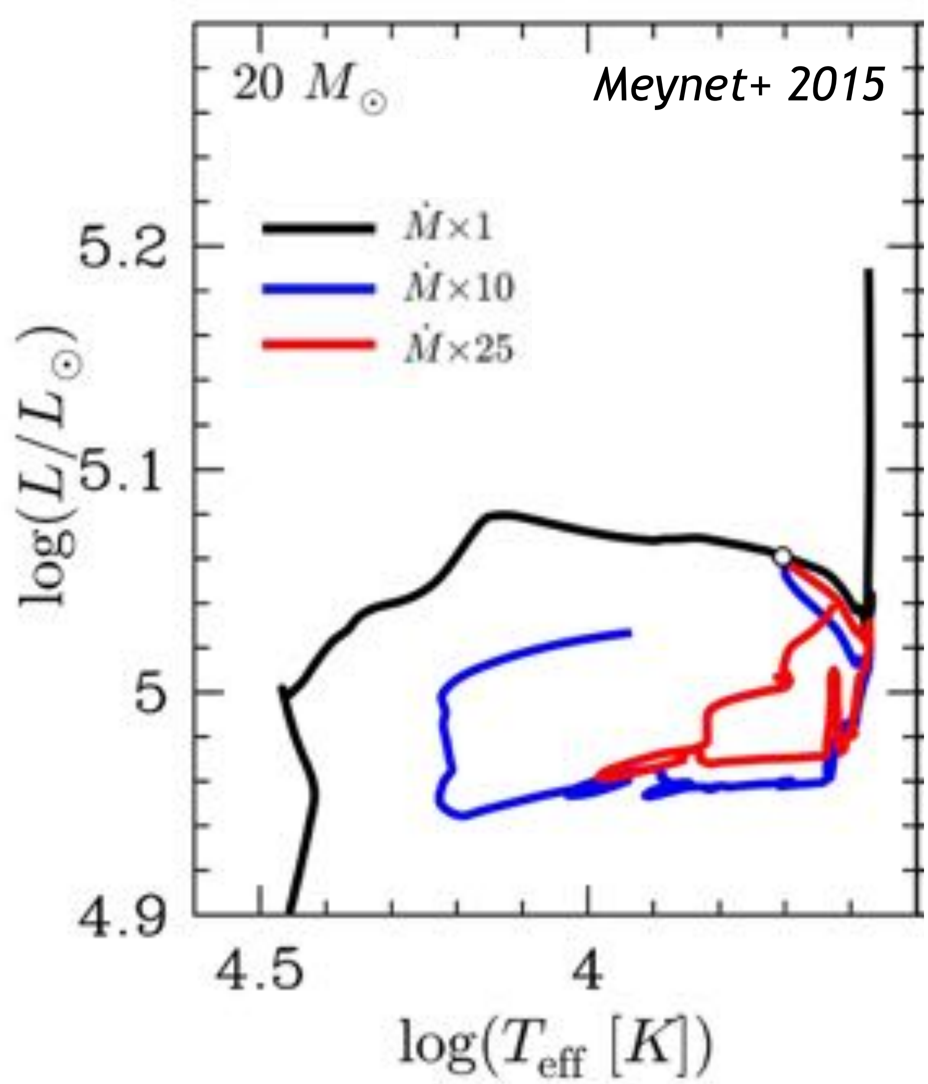
- temperature also crucial for luminosities because of bolometric corrections
- mass is *strongly* degenerate with luminosity
- binary, merger, and mass loss effects all complicate interpretation

Challenges: RSG mass loss

RSGs shed an enormous amount of mass from their outer layers during their lifetimes…

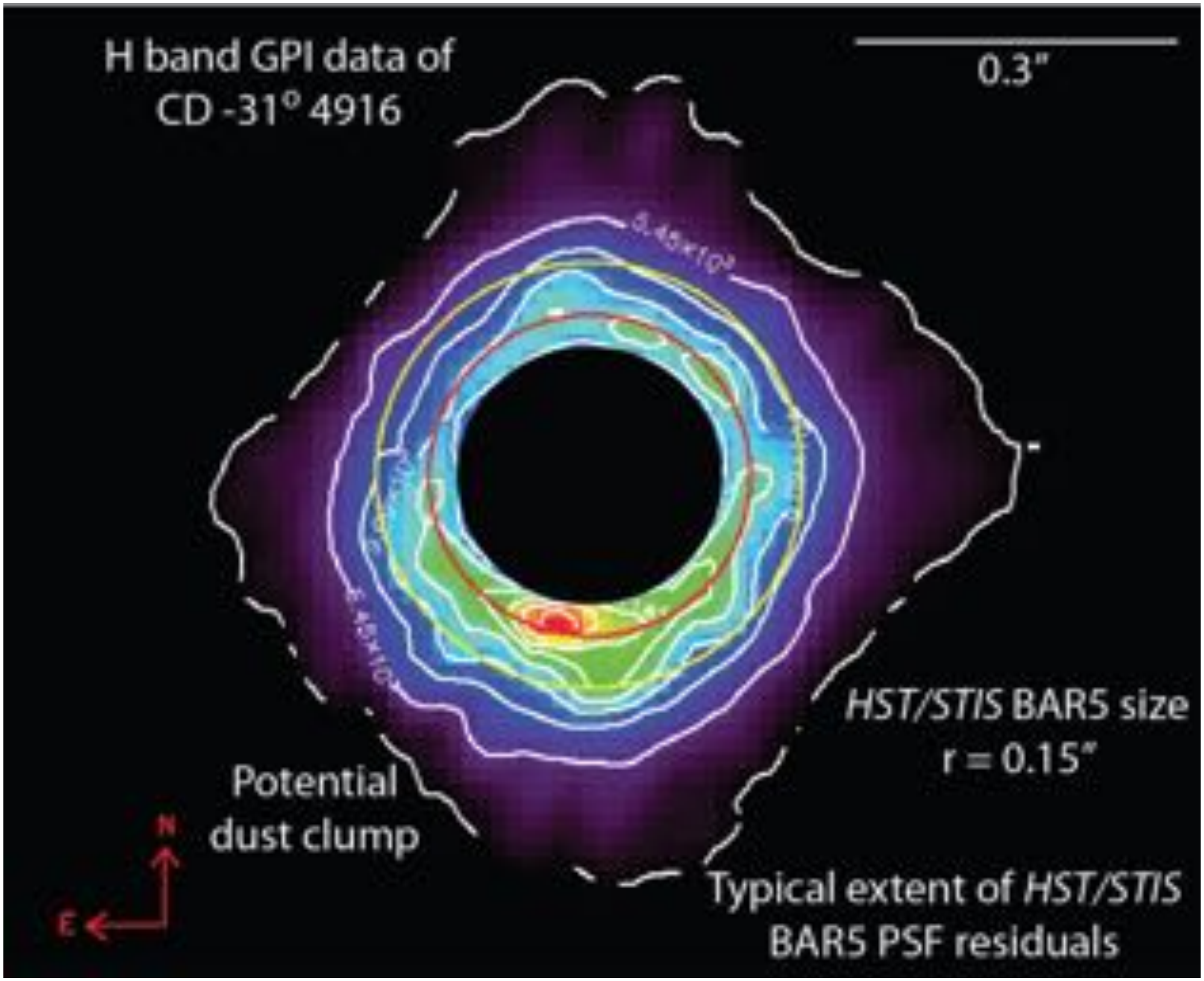
Challenges: RSG mass loss

RSGs shed an enormous amount of mass from their outer layers during their lifetimes…impact their evolution, observables, and ISM contribution.



Challenges: RSG mass loss

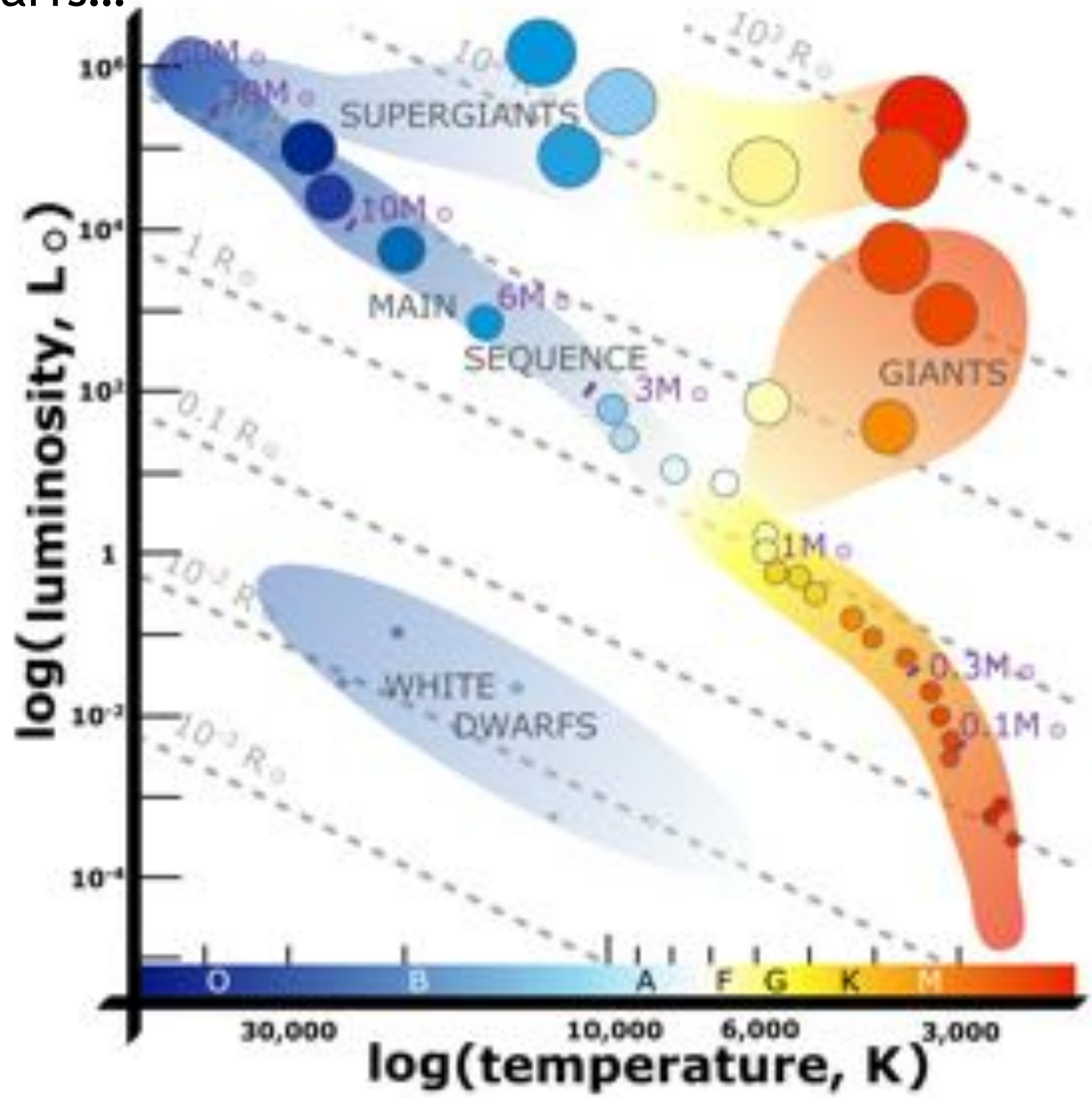
RSGs shed an enormous amount of mass from their outer layers during their lifetimes…impact their evolution, observables, and ISM contribution.



Lomax & Levesque in prep

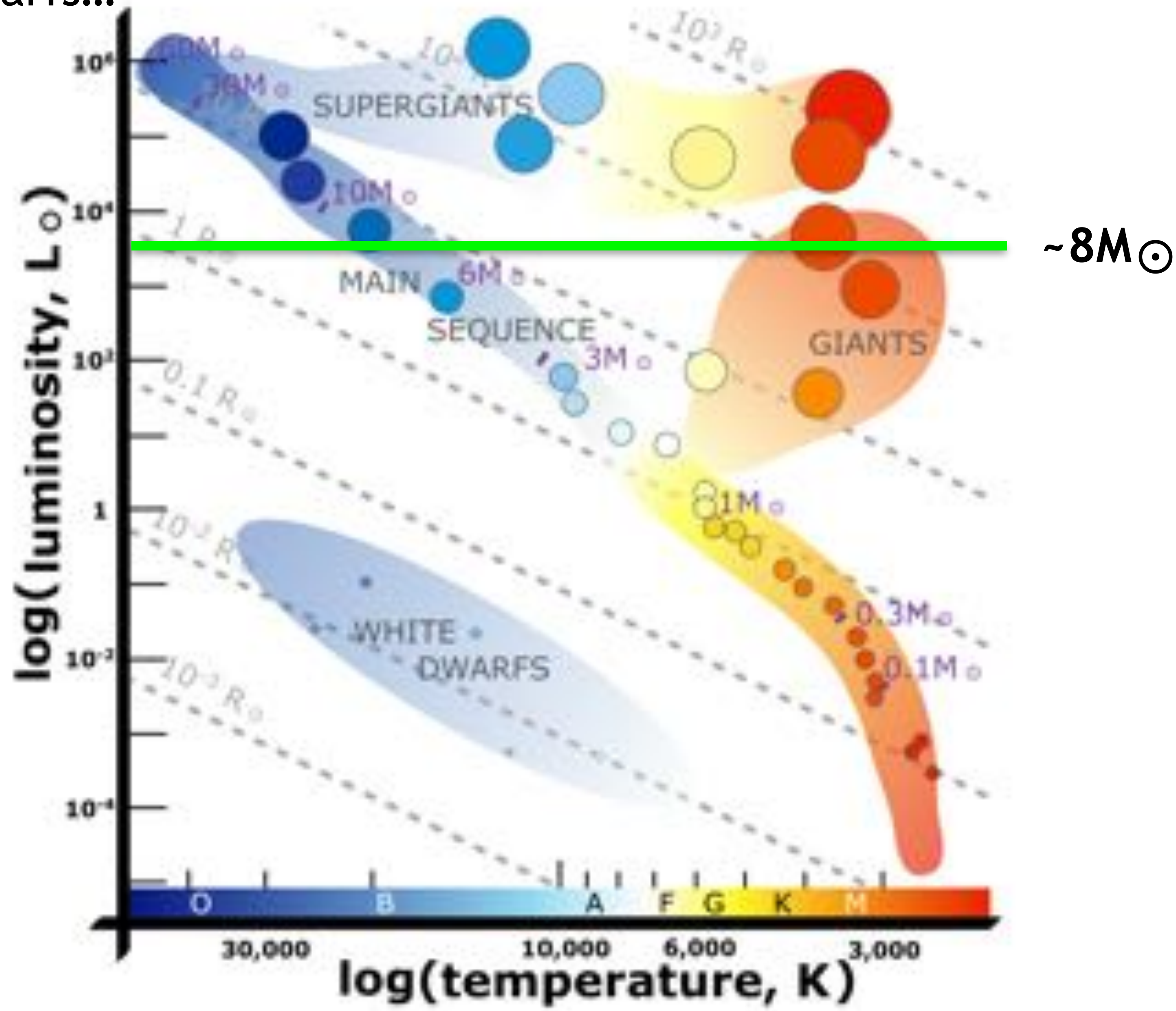
Challenges: Low-mass contaminants

Tools like GAIA and surface gravity effects can distinguish RSGs and foreground dwarfs…



Challenges: Low-mass contaminants

Tools like GAIA and surface gravity effects can distinguish RSGs and foreground dwarfs…

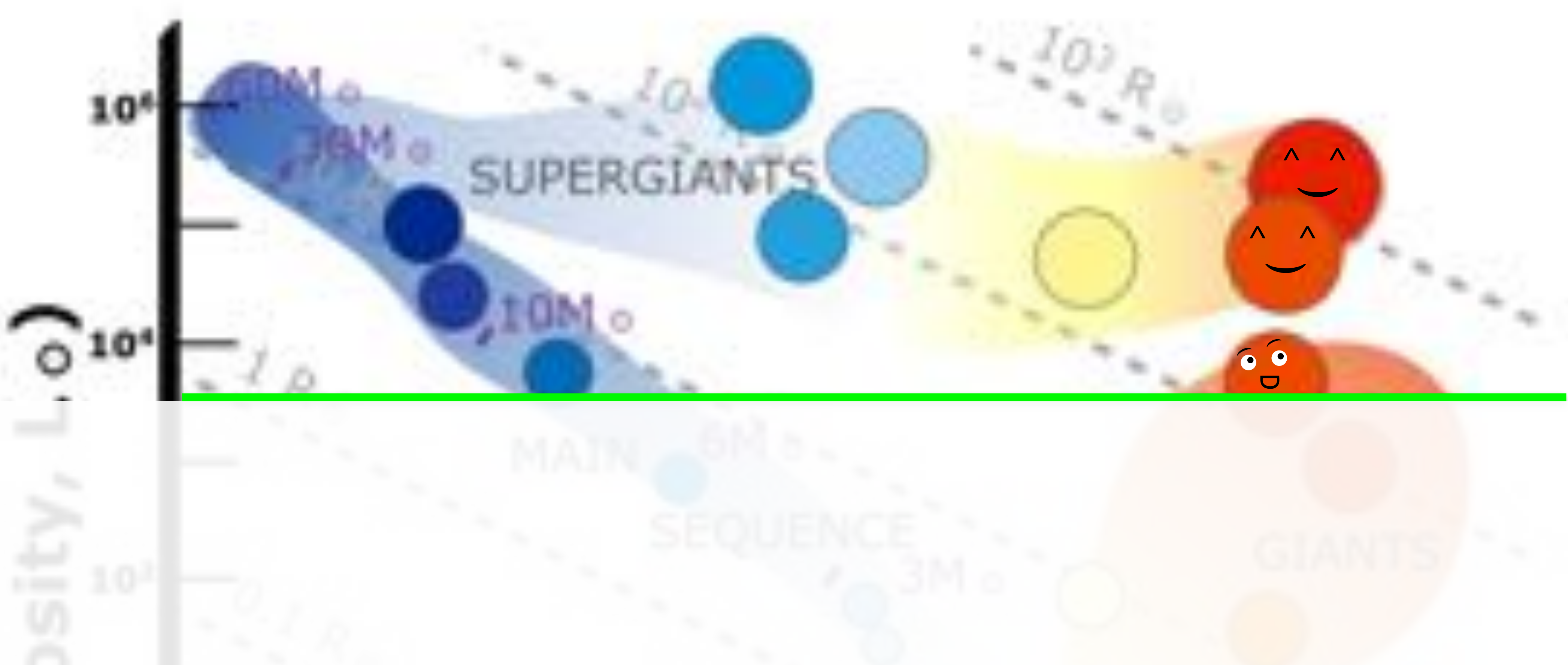


Challenges: Low-mass contaminants

Tools like GAIA and surface gravity effects can distinguish RSGs and foreground dwarfs…

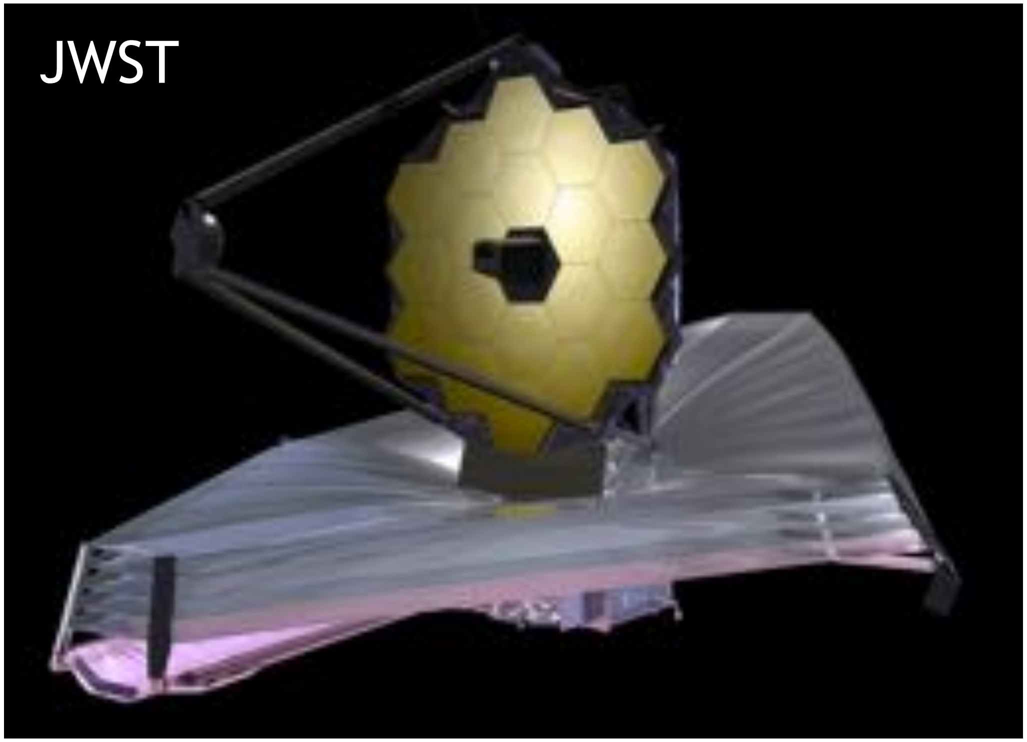
…but contamination from RGB and AGB stars becomes a problem.

- lower M_i
- longer lifetimes
- different evolutionary pathways
- different interior structures
- different nucleosynthesis processes
- different mass loss processes



RSGs in the infrared

Upcoming space telescopes will be focused on IR observations…



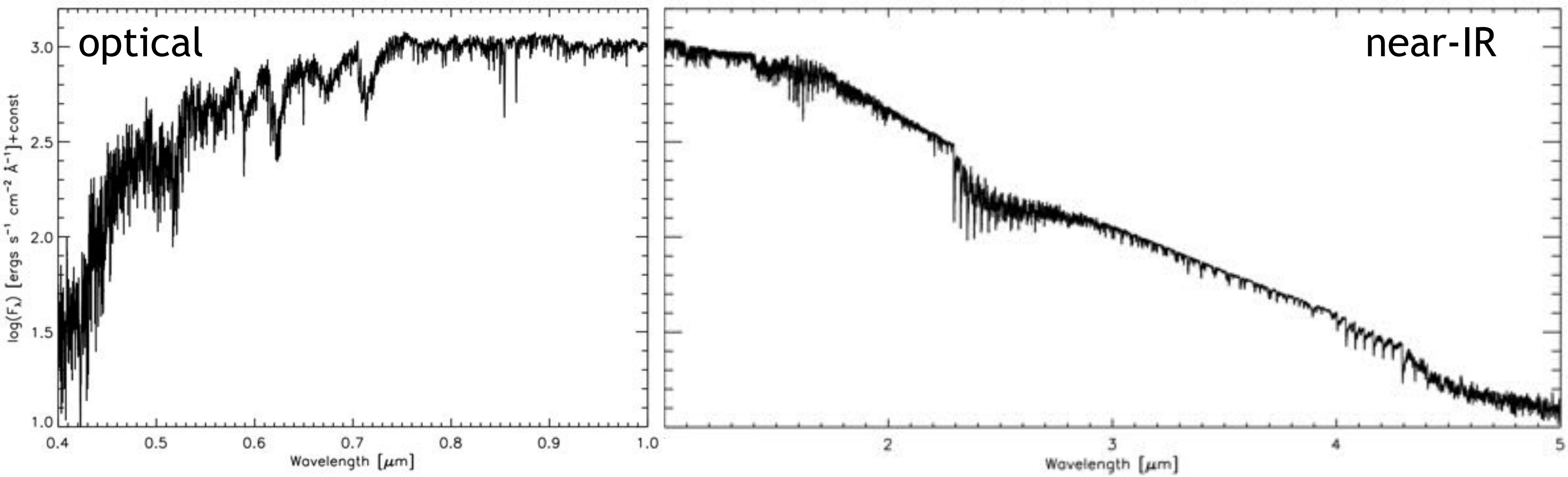
Ideal for:

- local and extragalactic RSG populations
- "fixing" our large error bars on pre-explosion imaging of SN progenitors…
- observing RSG mass loss and dust production

RSGs in the infrared

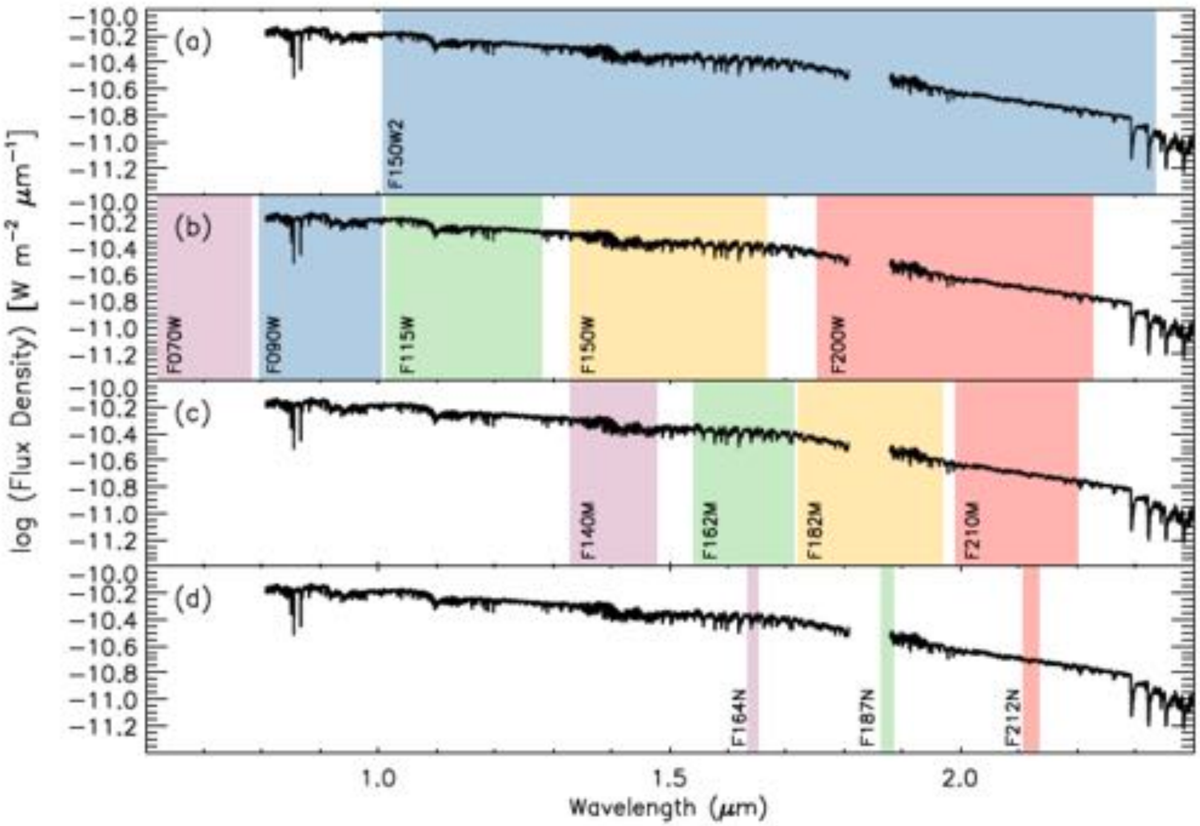
Upcoming space telescopes will be focused on IR observations…

…and RSGs are ideal (but under-studied!) targets in the IR.



RSGs in the infrared

We can improve this in the JWST era using IR models and observations of RSGs to…

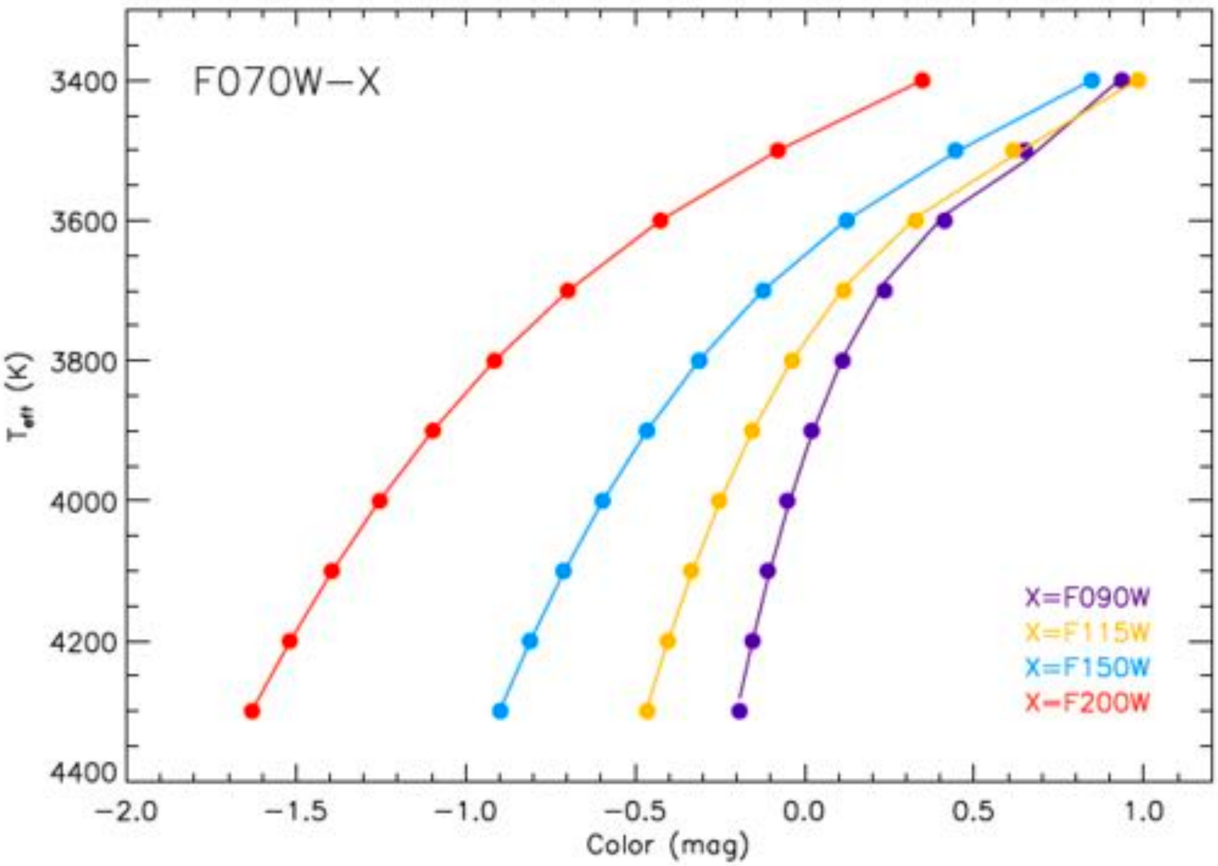


–simulate JWST photometry

Levesque 2018

RSGs in the infrared

We can improve this in the JWST era using IR models and observations of RSGs to…

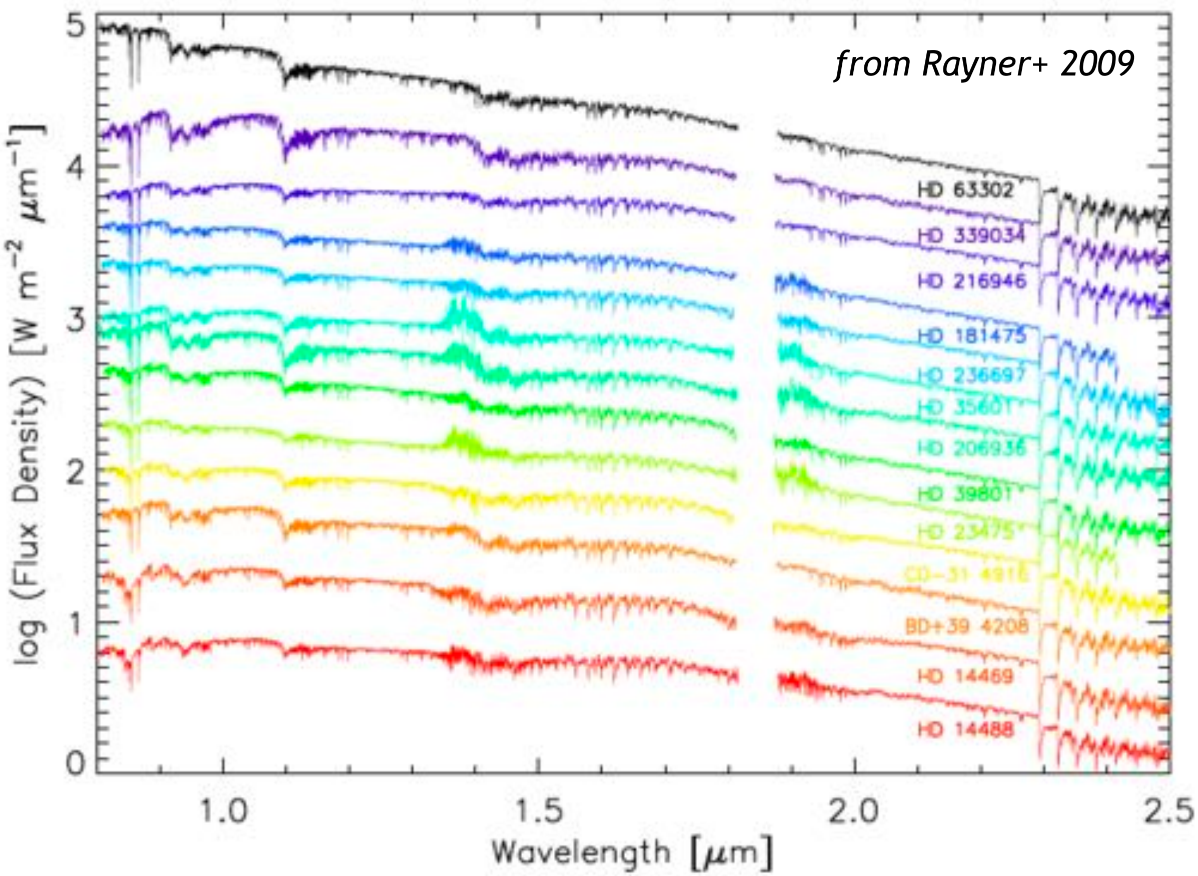


—simulate JWST photometry

Levesque 2018

RSGs in the infrared

We can improve this in the JWST era using IR models and observations of RSGs to…



—simulate JWST photometry

—use spectra to ID features sensitive to T_{eff}, M_{bol}, surface gravity, etc.

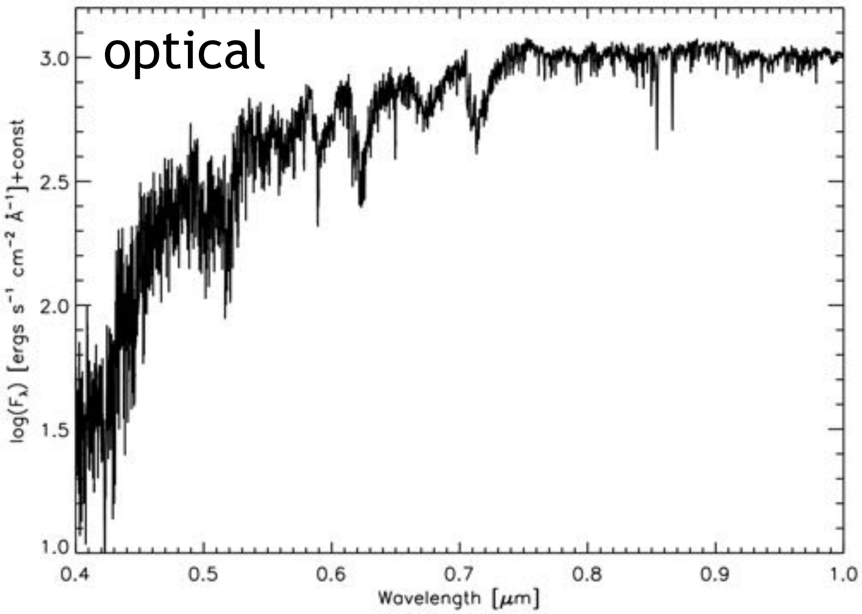
But currently this work is limited to near-IR (<5μm)!

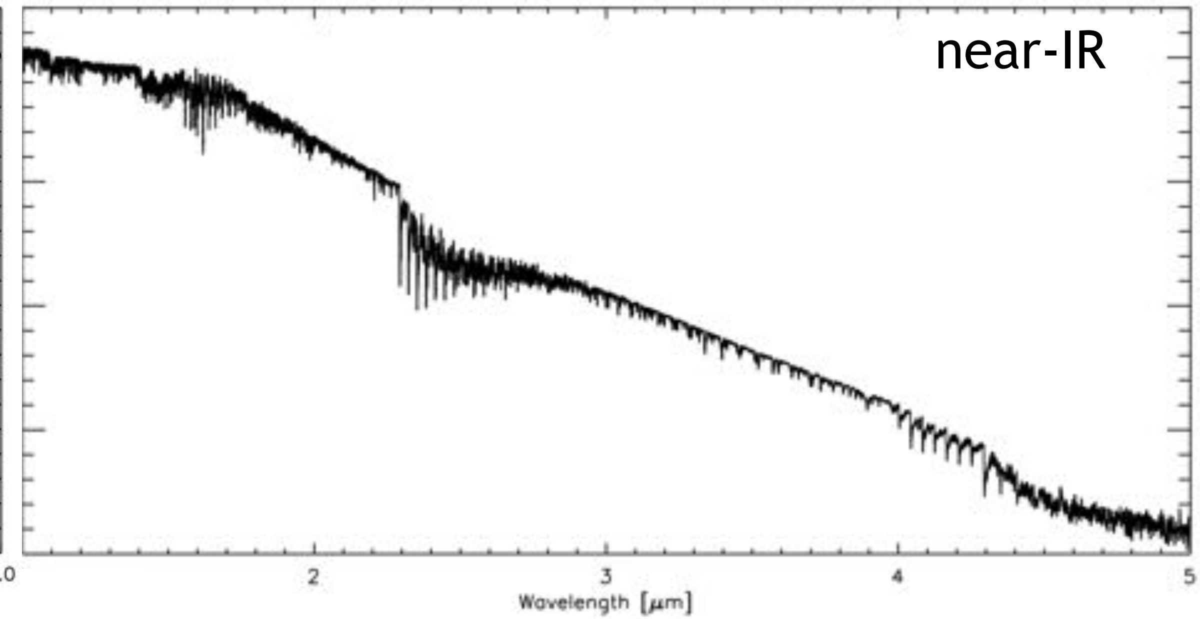
Dicenzo & Levesque, in prep

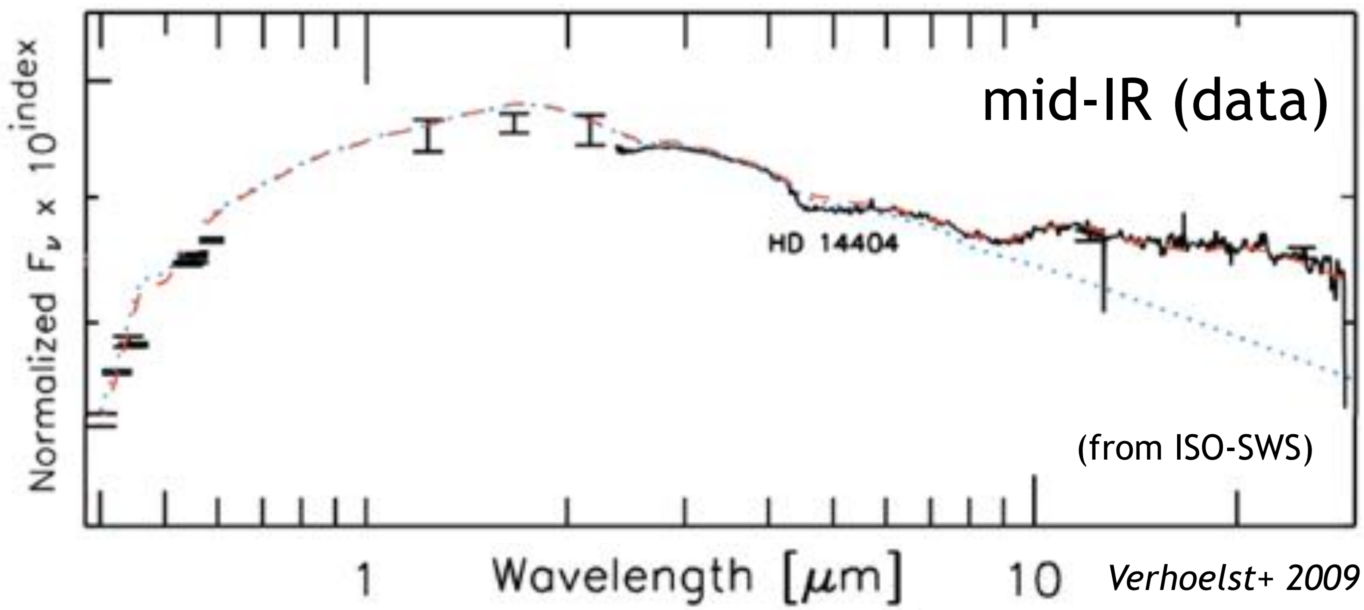
RSGs in the infrared

Upcoming space telescopes will be focused on IR observations…

…and RSGs are ideal (but under-studied!) targets in the IR.





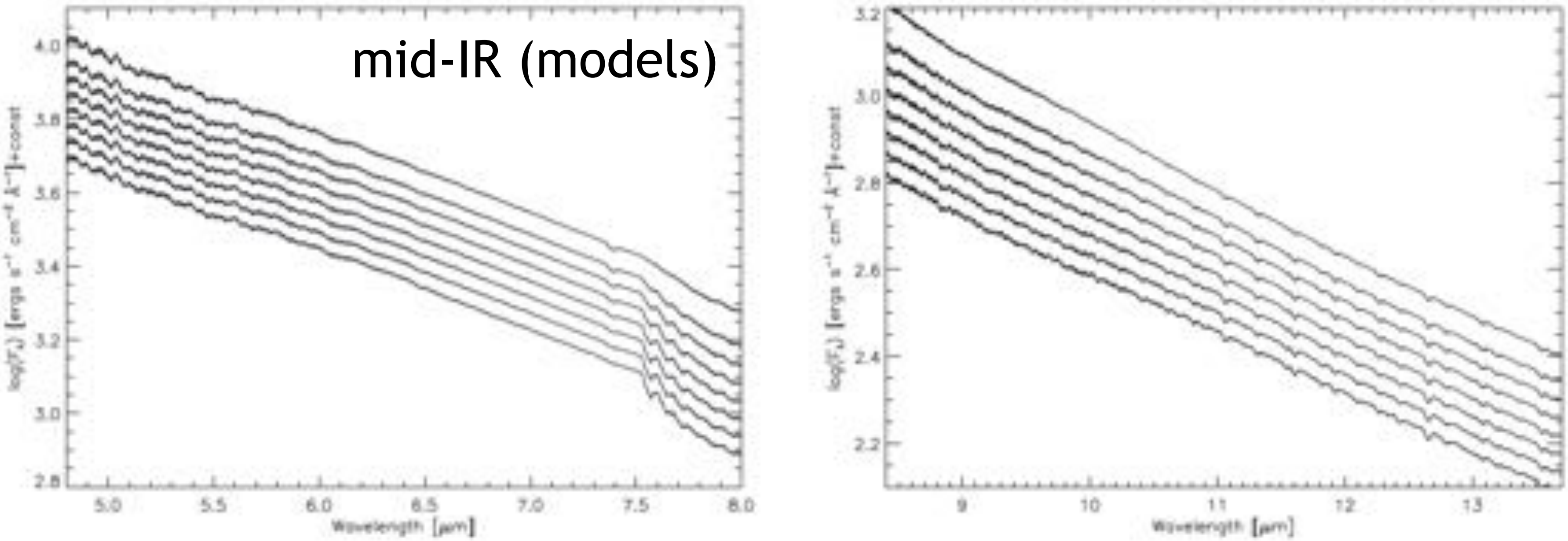


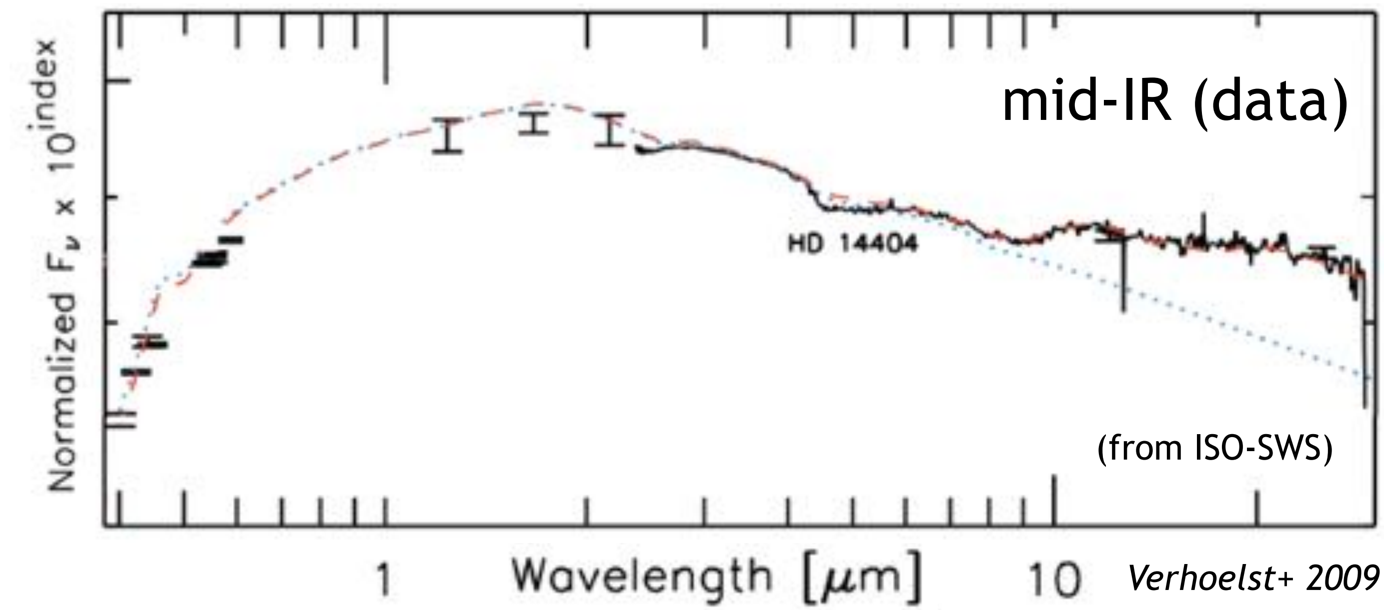
Verhoelst+ 2009

RSGs in the infrared

Upcoming space telescopes will be focused on IR observations…

…and RSGs are ideal (but under-studied!) targets in the IR.

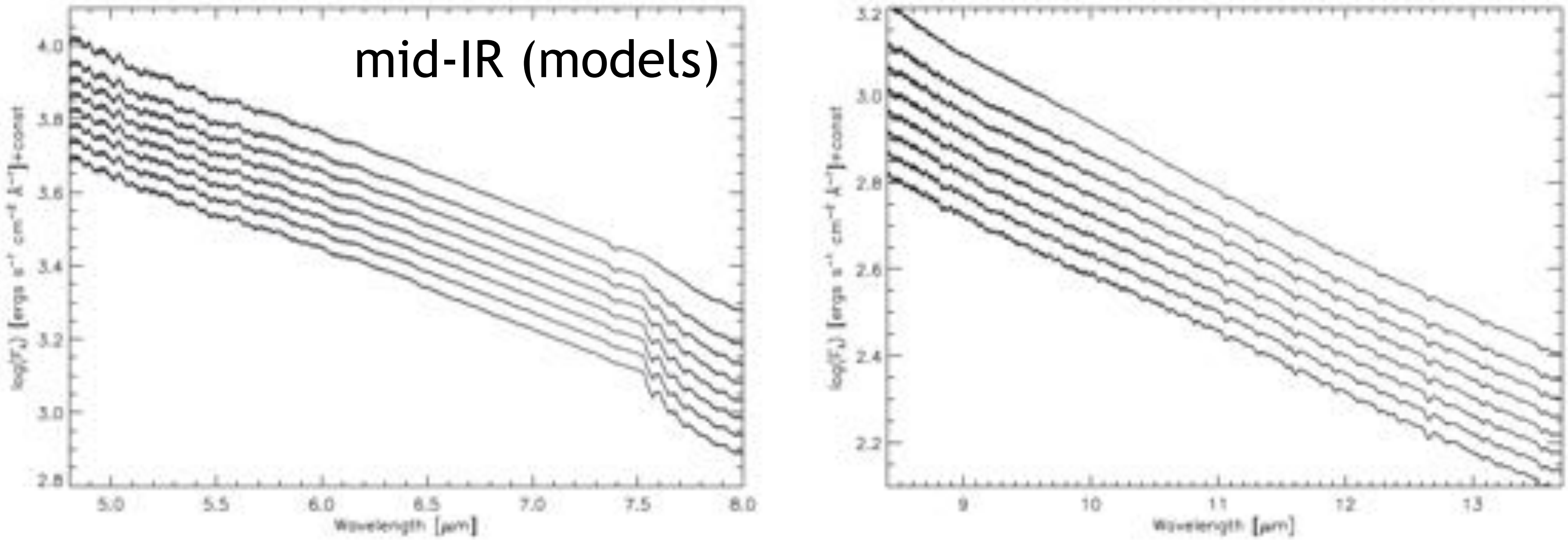




Verhoelst+ 2009

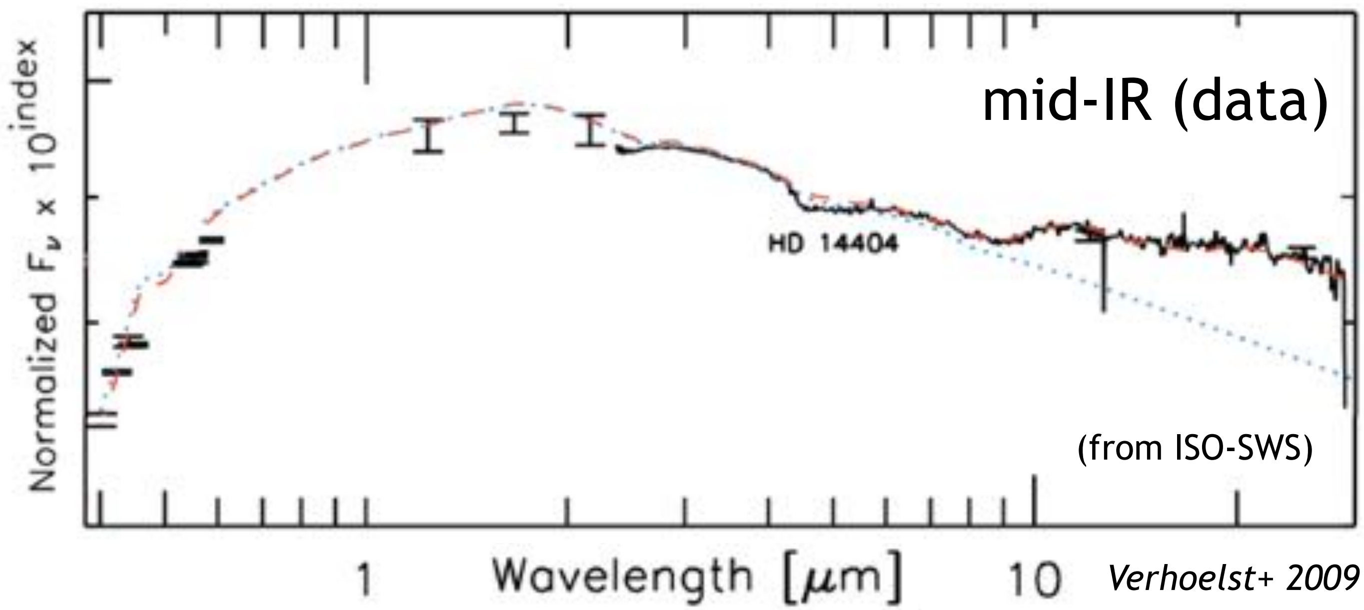
RSGs in the infrared

Upcoming space telescopes will be focused on IR observations…
…and RSGs are ideal (but under-studied!) targets in the IR.



With mid-IR RSG spectra we can:

- estimate physical properties (e.g. Britavskiy et al.)
- potentially ID RSGs vs. giants
- quantify mass loss
- determine circumstellar dust quantity, composition



Verhoelst+ 2009

RSGs with SOFIA

Stratospheric Observatory for Infrared Astronomy (SOFIA)

FORCAST as a SOFIA spectrograph:

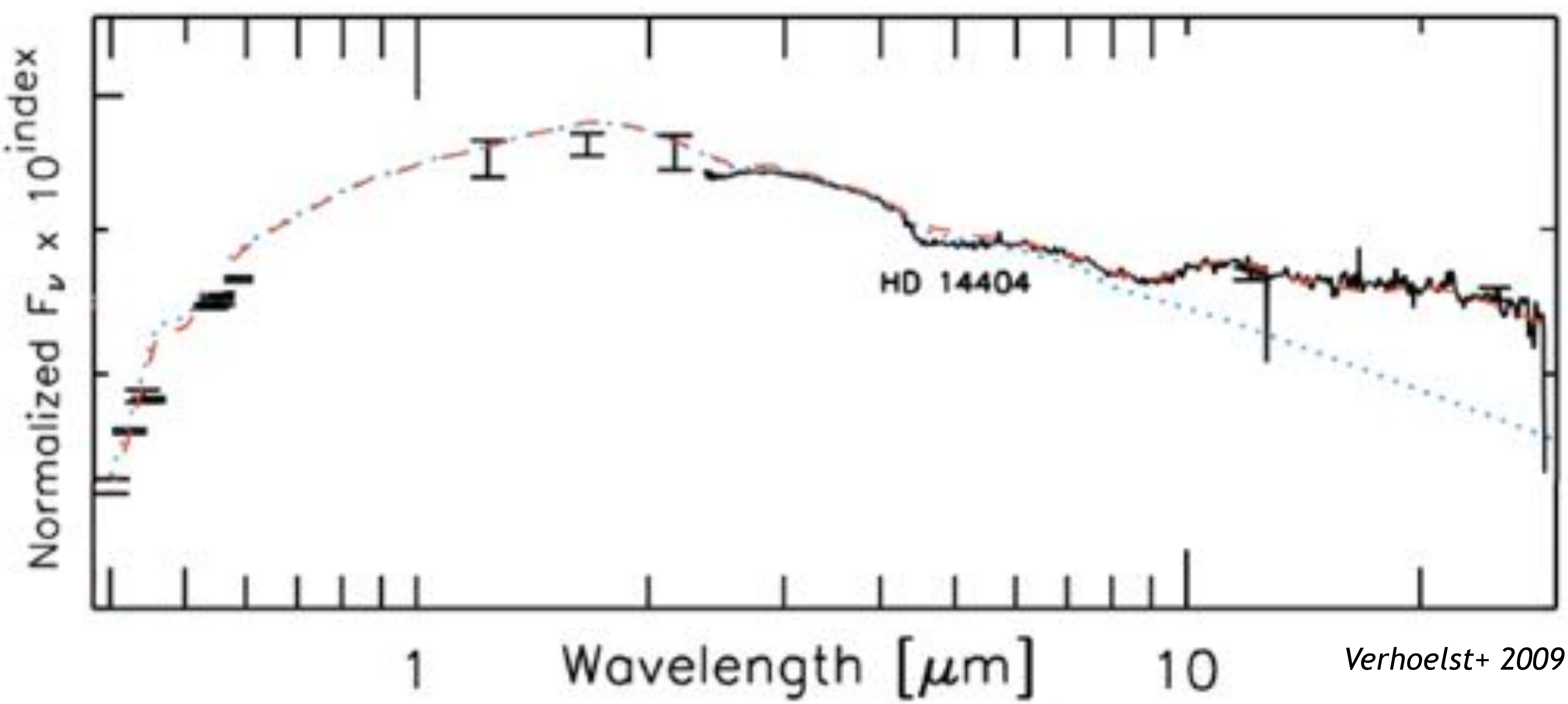
- grisms cover from 4.8-40μm
- 2.4″ slit yields R~130-300 (comparable to resolution of MIRI on JWST!)
- for Galactic RSGs, S/N ≥ 100 at 5μm, ≥ 5 at 13μm (but it can handle bright targets!)

RSGs with SOFIA

Unique advantages of SOFIA/FORCAST RSG SWC spectra:

- 5-8μm: can quantify precise continuum where dust overtakes photospheric emission
- 5-13μm: can identify discrete emission features from dust species (alumina, melilite, olivine, MgFeO)
- identify new diagnostics (photometric, spectroscopic) for RSGs
- short exposure times = large Galactic RSG sample!

Mid-IR spectral library of RSGs for JWST era!



Verhoelst+ 2009

RSGs with SOFIA

SOFIA Cycle 7 observations

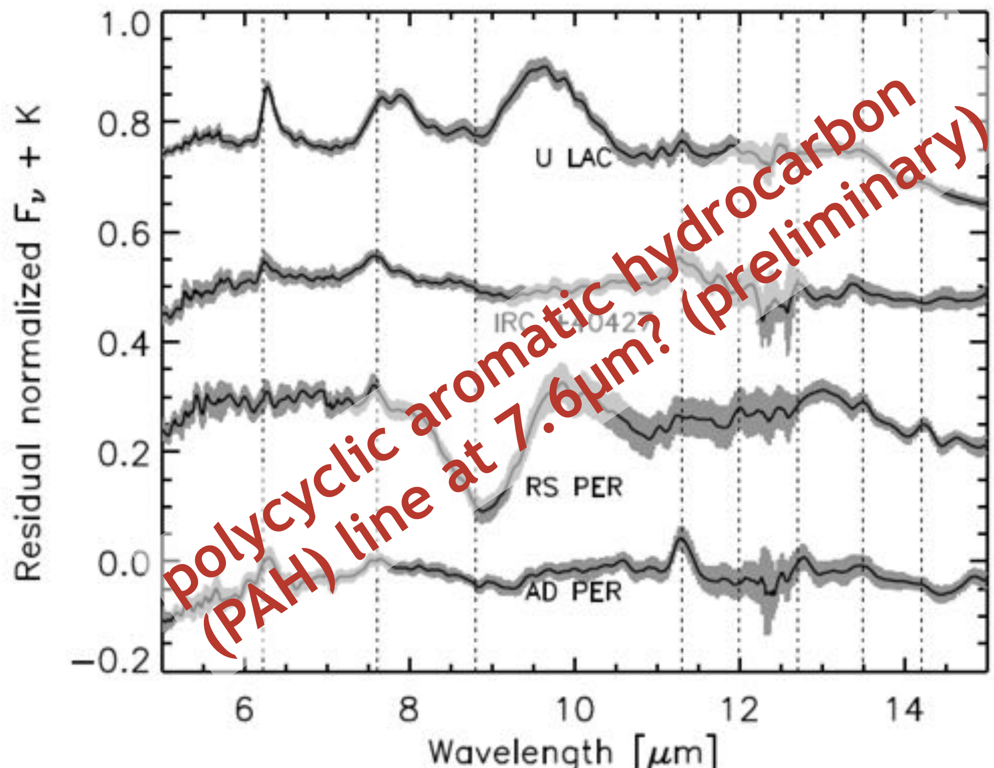
- ~70 potential targets = “survey mode” (like popular HST/SNAP)
- ~20 observed so far during Christchurch (July 2019) and Palmdale (Oct 2019) flights

(also flying on SOFIA is *so incredibly cool*…)

RSGs with SOFIA

SOFIA Cycle 7 observations

- ~70 potential targets = "survey mode" (similar to HST/SNAP!)
- ~20 observed so far during Christchurch (July 2019) and Palmdale (Oct 2019) flights



Verhoelst+ 2009

(*extremely*) preliminary results!

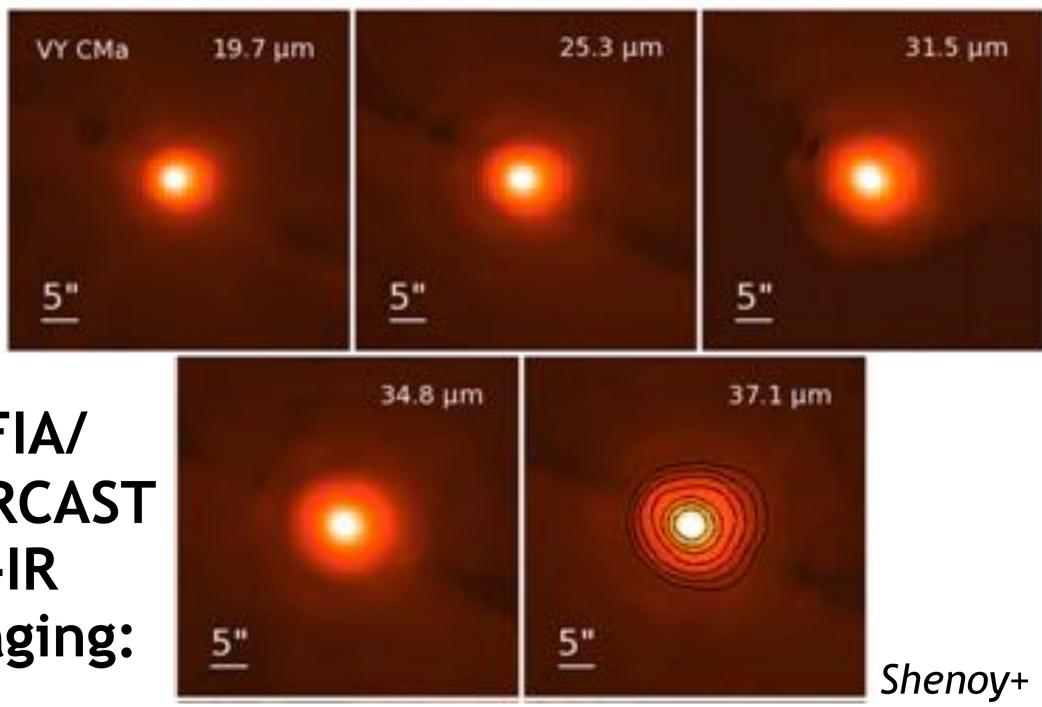
RSGs with SOFIA

SOFIA Cycle 7 observations

- ~70 potential targets = "survey mode" (similar to HST/SNAP!)
- ~20 observed so far during Christchurch (July 2019) and Palmdale (Oct 2019) flights

Other potential RSG applications:

- imaging the circumstellar environments of dusty RSGs (including polarimetry!)



SOFIA/ FORCAST far-IR imaging:

Shenoy+ 2016

RSGs with SOFIA

SOFIA Cycle 7 observations

- ~70 potential targets = "survey mode" (similar to HST/SNAP!)
- ~20 observed so far during Christchurch (July 2019) and Palmdale (Oct 2019) flights

Other potential RSG applications:

- imaging the circumstellar environments of dusty RSGs (including polarimetry!)
- direct comparisons with RGB/AGB samples

RSGs with SOFIA

SOFIA Cycle 7 observations

- ~70 potential targets = "survey mode" (similar to HST/SNAP!)
- ~20 observed so far during Christchurch (July 2019) and Palmdale (Oct 2019) flights

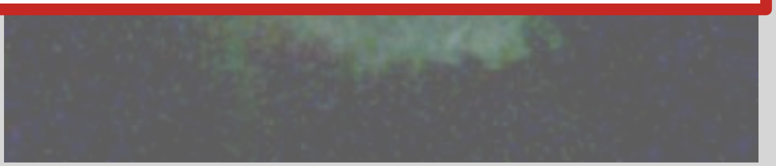
Other potential RSG applications:

- imaging the circumstellar environments of dusty RSGs (including polarimetry!)
- direct comparisons with RGB/AGB samples
- short exposure times and "survey" suitability of targets make it possible to study variability…

RSGs with SOFIA

SOFIA Cycle 7 observations

Betelgeuse!

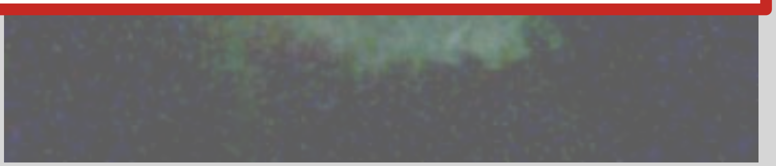


RSGs with SOFIA

SOFIA Cycle 7 observations

C

Betelgeuse!

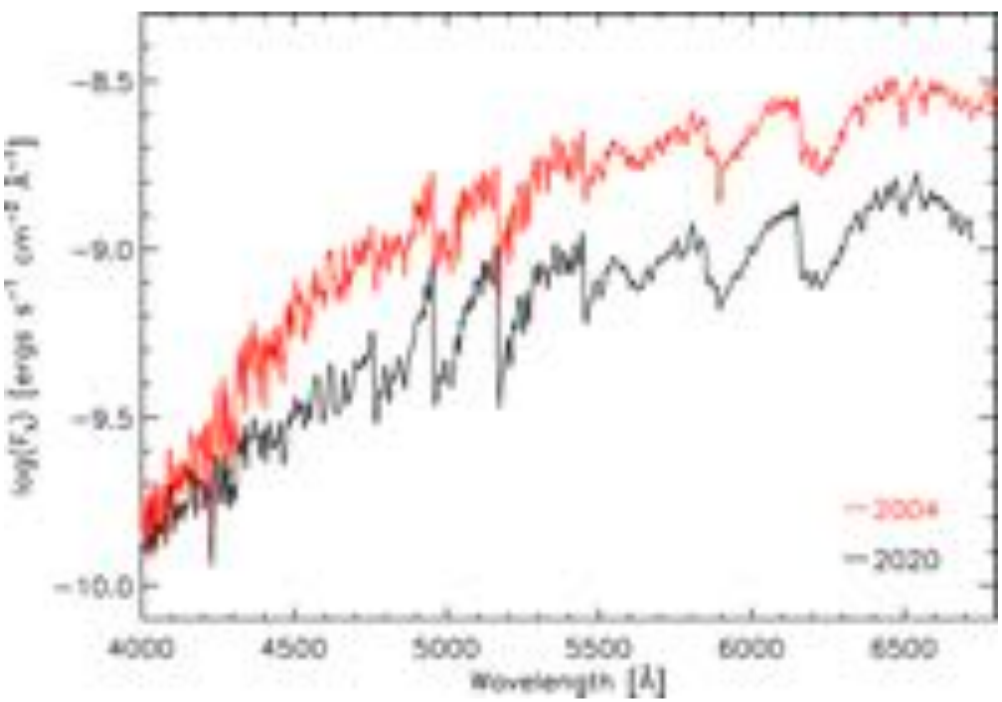


RSGs with SOFIA

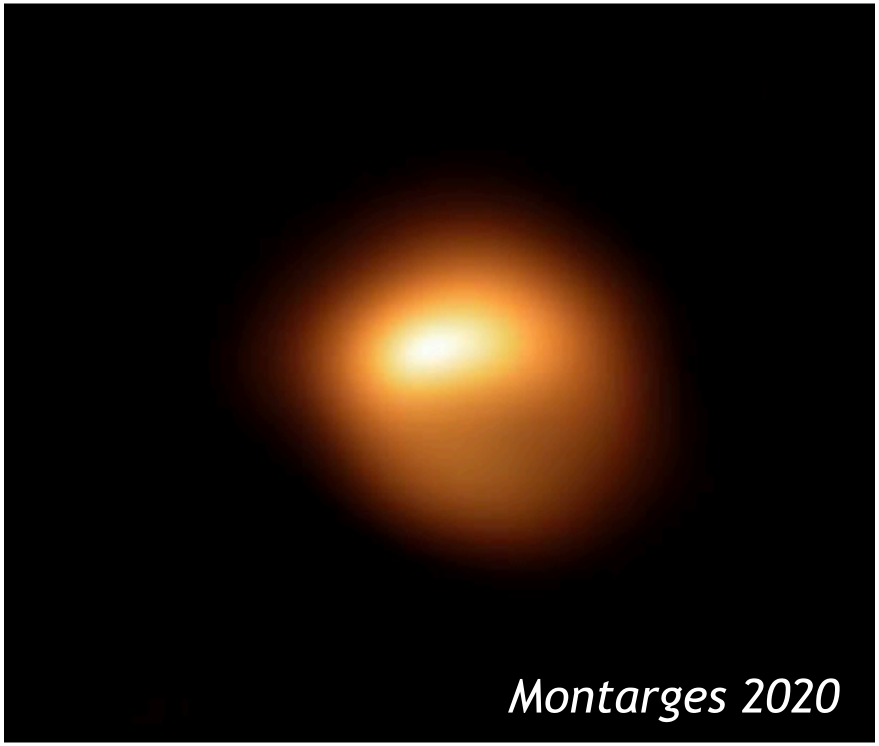
SOFIA Cycle 7 observations

Betelgeuse!

Dimming in optical (but not in near-IR) *suggested* dust…



Levesque & Massey 2020



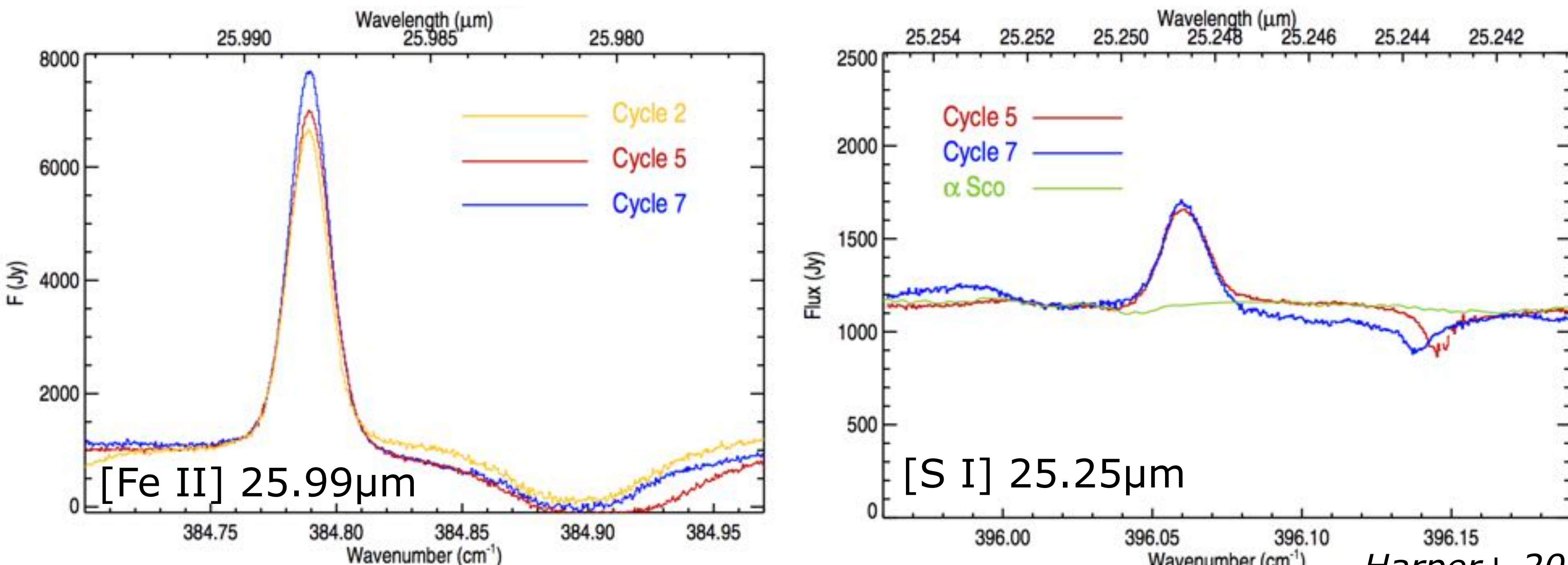
Montarges 2020

RSGs with SOFIA

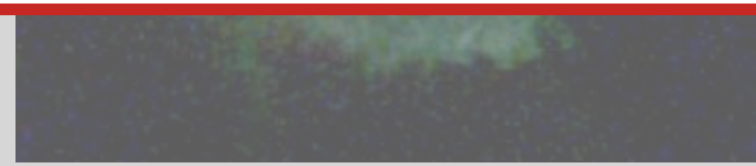
SOFIA Cycle 7 observations

Betelgeuse!

Dimming in optical (but not in near-IR) *suggested* dust…
…and SOFIA/EXES observations saw minimal changes in (some) circumstellar gas velocities and line profiles



Harper+ 2020

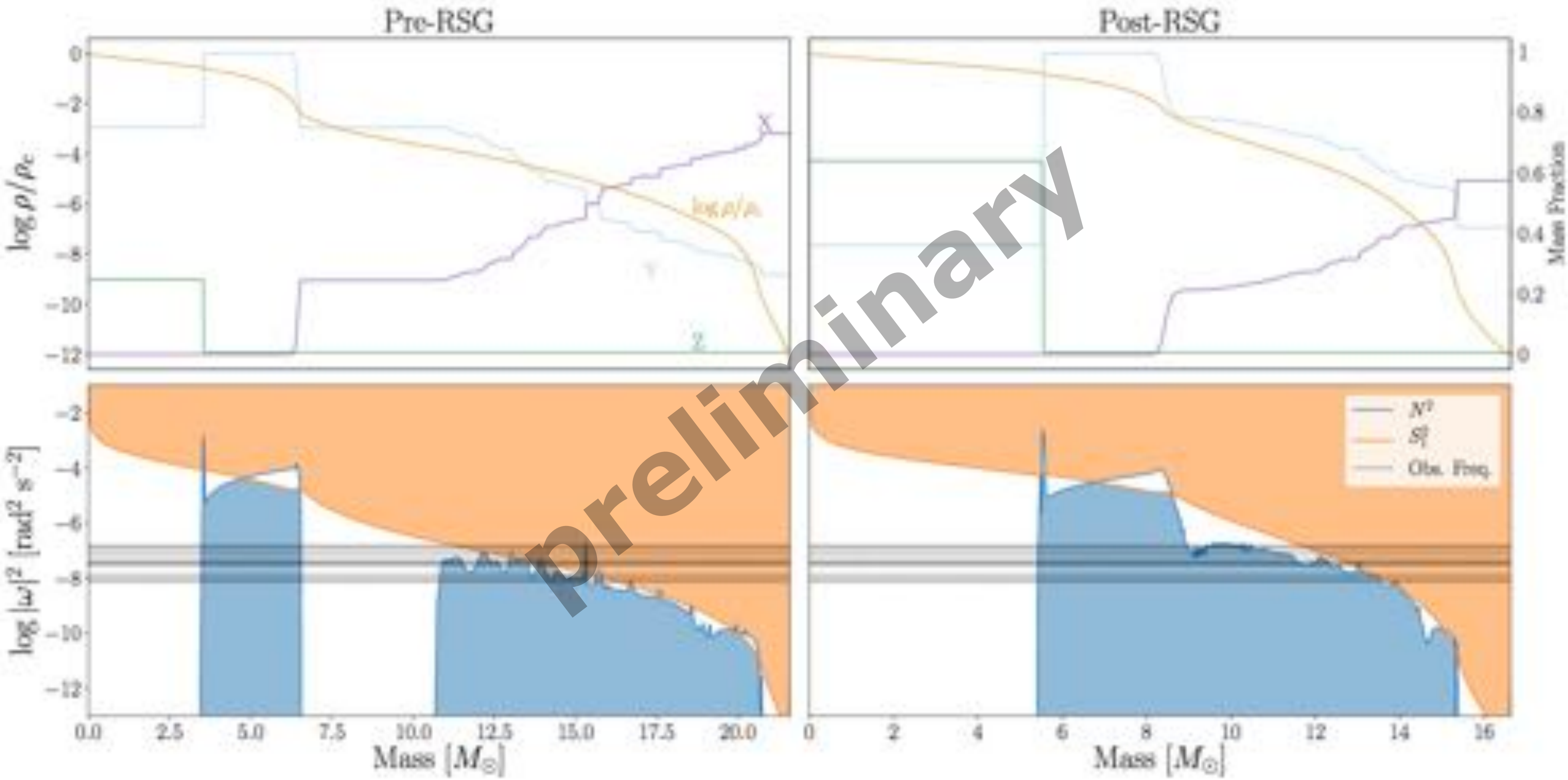


Evolved Massive Stars with SOFIA

Yellow Supergiants

- pre- and post-SN states are hard to distinguish
- evidence of both fast- and long-period pulsations

SOFIA imaging, spectroscopy, and polarimetry in mid-IR could probe mass loss geometry and composition in a poorly-understood (and nearby!) dataset



Dorn-Wallenstein *+ 2020 (submitted)*

Evolved Massive Stars with SOFIA

Yellow Supergiants

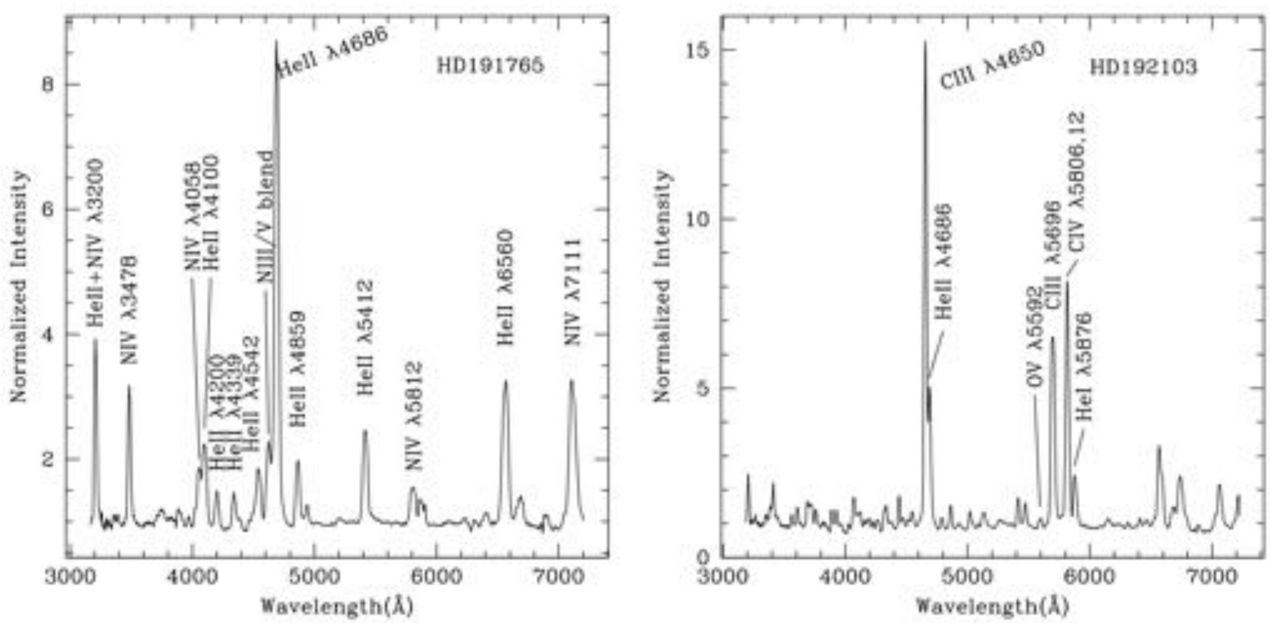
- pre- and post-SN states are hard to distinguish
- evidence of both fast- and long-period pulsations

SOFIA imaging, spectroscopy, and polarimetry in mid-IR could probe mass loss geometry and composition in a poorly-understood (and nearby!) dataset

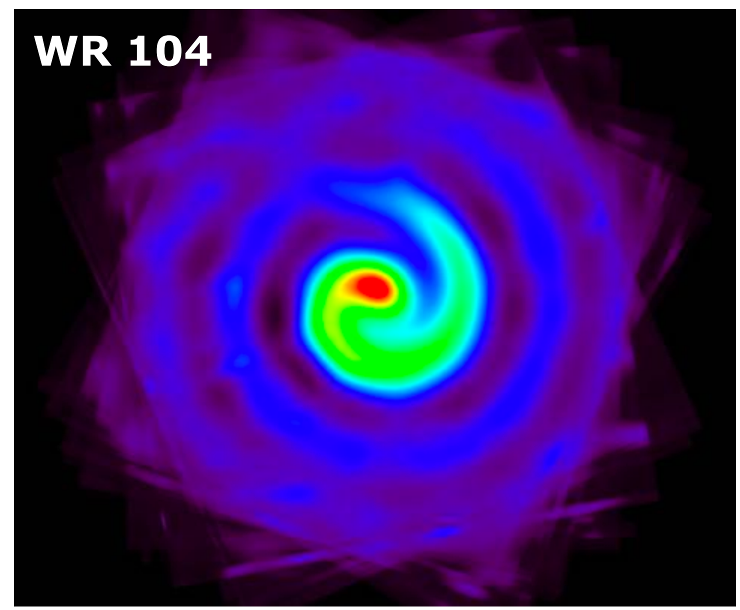
Wolf-Rayet stars

- formation channels for these stars are unclear (binaries? strong winds?)
- expected SN progenitors and sources of interstellar enrichment

SOFIA observations of Wolf-Rayet-specific dust, circumstellar geometries, and wind interactions with ISM could probe these stars' evolution



Neugent & Massey 2019



Tuthill+ 2000

Evolved Massive Stars with SOFIA

Yellow Supergiants

- pre- and post-SN states are hard to distinguish
- evidence of both fast- and long-period pulsations

SOFIA imaging, spectroscopy, and polarimetry in mid-IR could probe mass loss geometry and composition in a poorly-understood (and nearby!) dataset

Wolf-Rayet stars

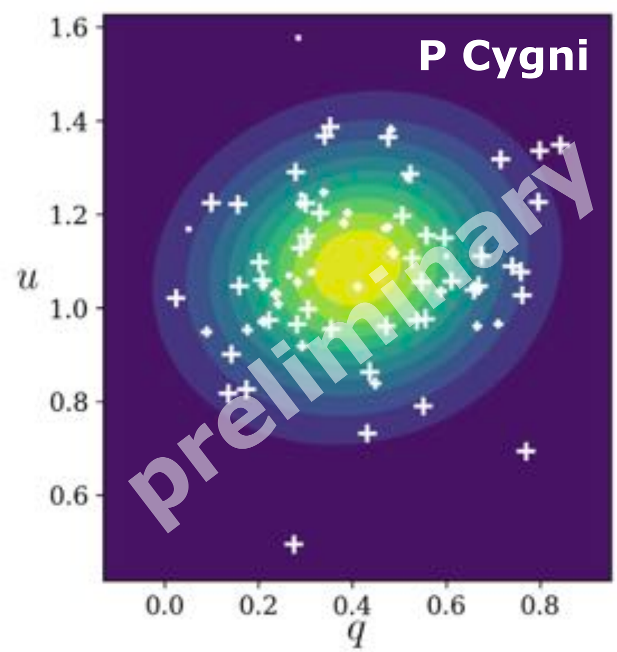
- formation channels for these stars are unclear (binaries? strong winds?)
- expected SN progenitors and sources of interstellar enrichment

SOFIA observations of Wolf-Rayet-specific dust, circumstellar geometries, and wind interactions with ISM could probe these stars' evolution

Luminous Blue Variables

- are just *weird*
- poorly-understood post-MS and pre-SN where mass loss is key

SOFIA mid-IR imaging and polarimetry offers a unique tool for studying the small sample of bright and "well-understood" LBVs



Gootkin+ 2020 (submitted)

Evolved Massive Stars with SOFIA

Yellow Supergiants

- pre- and post-SN states are hard to distinguish
- evidence of both fast- and long-period pulsations

SOFIA imaging, spectroscopy, and polarimetry in mid-IR could probe mass loss geometry and composition in a poorly-understood (and nearby!) dataset

Wolf-Rayet stars

- formation channels for these stars are unclear (binaries? strong winds?)
- expected SN progenitors and sources of interstellar enrichment

SOFIA observations of Wolf-Rayet-specific dust, circumstellar geometries, and wind interactions with ISM could probe these stars' evolution

Luminous Blue Variables

- are just *weird*
- poorly-understood post-MS and pre-SN where mass loss is key

SOFIA mid-IR imaging and polarimetry offers a unique tool for studying the small sample of bright and "well-understood" LBVs

Exciting potential SOFIA capabilities in mid-IR:

- high(er)-res spectroscopy
- high-contrast imaging for nearby/luminous stars
- imaging polarimetry and spectropolarimetry

Summary

- The post-main-sequence is a **crucial phase** of massive star evolution and ideal science for future IR missions; we can study these stars' evolution, mass loss, dust production, circumstellar envrionments, and supernovae

- We **need more data in the mid-IR** to fully utilize the capabilities of future IR missions for studying massive stars

- **SOFIA is the ideal observatory** for getting mid-IR spectra and other observations of evolved massive stars, which can:
  - quantify diagnostics for these stars' physical properties
  - distinguish supergiant and giant populations
  - probe dust chemistry and crucial mass loss behavior
  - quantify pre-SN stages of stellar evolution