UV SPECTROSCOPY OF MASSIVE STARS

MIRIAM GARCIA

ULTRAVIOLET ASTRONOMY IN THE XXI CENTURY

GOBIERNO DE ESPAÑA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Instituto Nacional de Técnica Aeroespacial

MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

Acknowledging grants PID2019-105552RB-C41 and MDM-2017-0737 Unidad de Excelencia María de Maeztu - Centro de Astrobiología (CSIC-INTA), funded by MCIN/AEI/10.13039/501100011033

A LARGE TELESCOPE IN SPACE IS NEEDED FOR A FULL VIEW OF MASSIVE STARS ALONG COSMIC HISTORY

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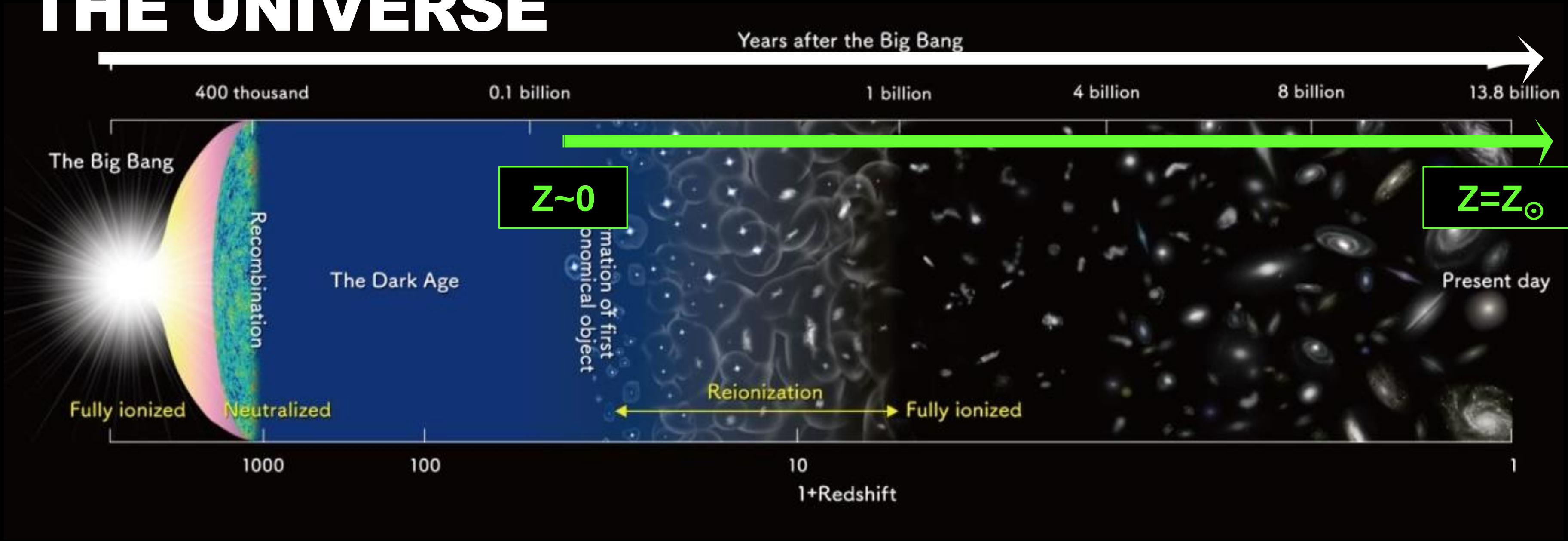
OUTLINE

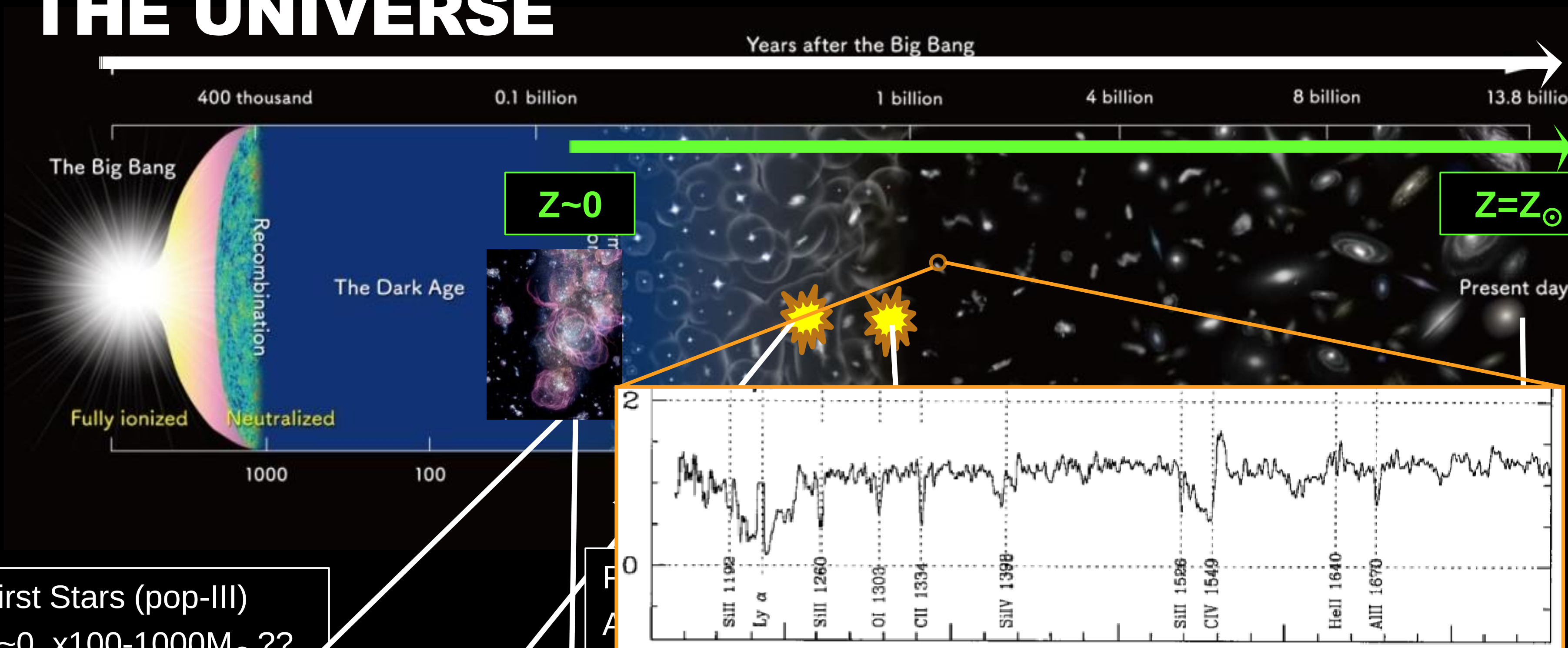
- **Introduction**
- **Winds of massive stars and UV spectroscopy**
- **Voyage 2050 proposal**
  - A metallicity ladder to look back in time
- **Conclusions**

INTRODUCTION

LOW-Z MASSIVE STARS AT KEY STAGES OF THE UNIVERSE



LOW-Z MASSIVE STARS AT KEY STAGES OF THE UNIVERSE

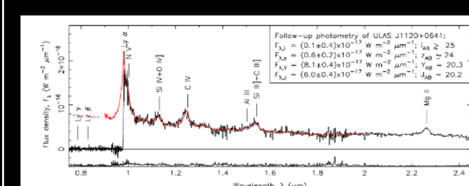


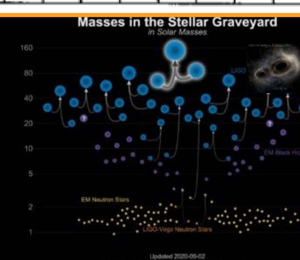
First Stars (pop-III)
Z~0, x100-1000$M_\odot$??
Bromm+ 2002,
Hirano+ 2015

Death events:
GRB,SNe,SLSNe,PISNe
Farthest GRB detected
redshift=9.4
Cucchiara+ 2011

Strong Ly, HeII1640 emission to be detected by JWST at Cosmic Dawn.
HeII4686/Hβ ratios.
e.g. Wofford+ 2014

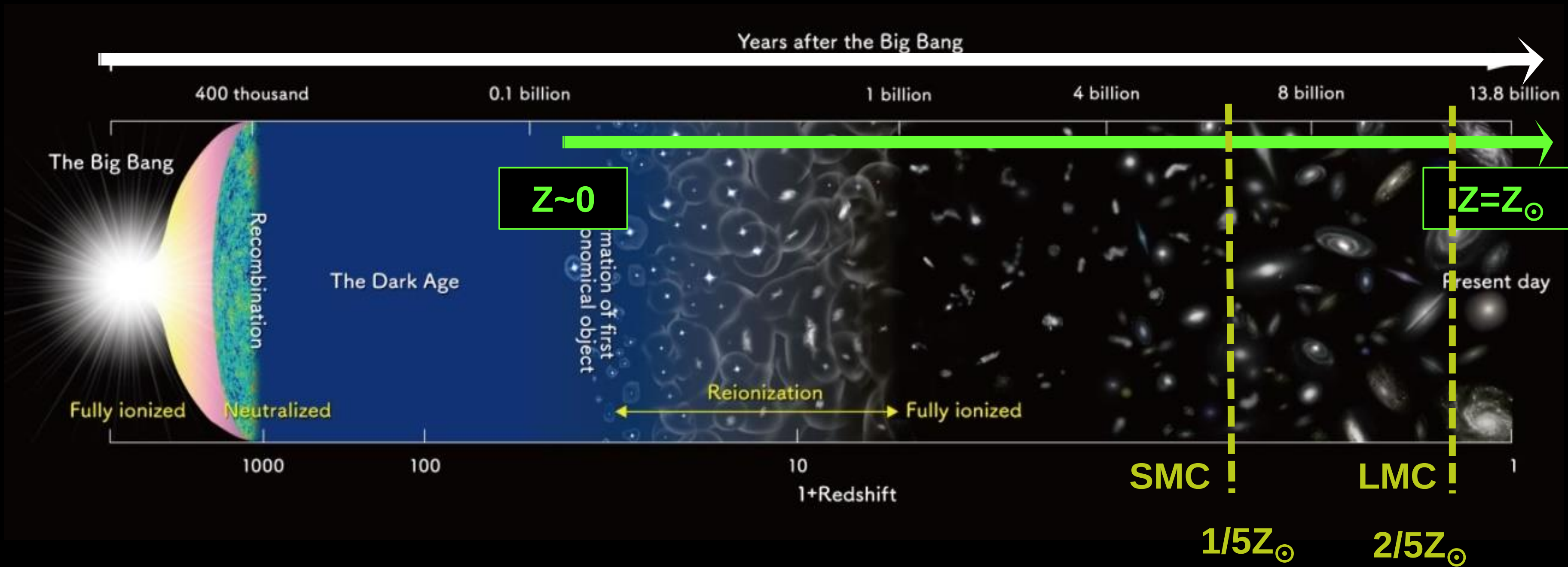
Early enrichment:
QSO at z = 7.085, with N, Si, C, O, Al, Mg
Mortlock+ 2011





Formation of >30$M_\odot$ black holes in binary systems (GW150914)
86+66 $M_\odot$
Abbott+ 2020

MASSIVE STARS ALONG COSMIC HISTORY

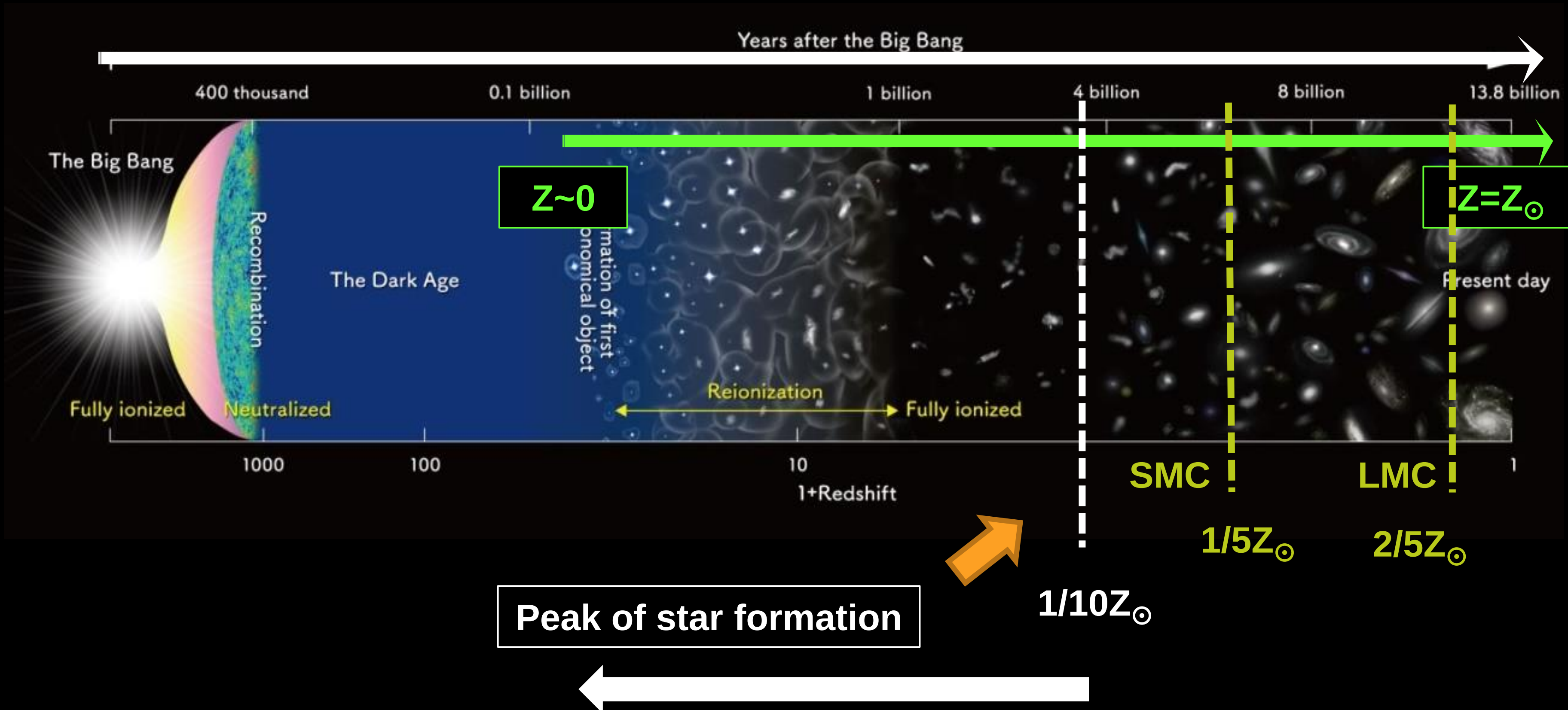


+1500 studied stars

(e.g. Bestenlehner+ 2020, Ramachandran+ 2019)


4MOST

MASSIVE STARS ALONG COSMIC HISTORY

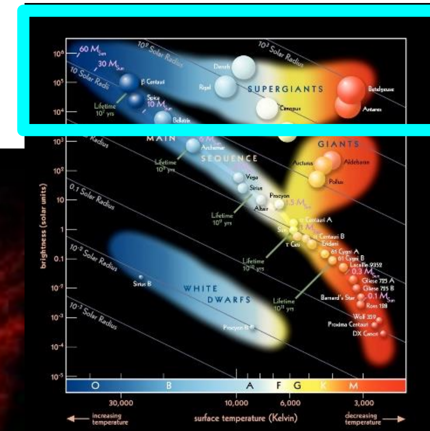


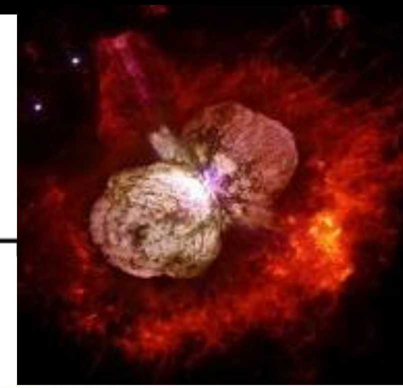
Only ~200 stars known (not analyzed)

Camacho+ 2016; Camacho PhD, 2017; Garcia, 2018; Garcia+ 2019; Evans+ 2019, Gull+ 2022, Lorenzo+ 2022

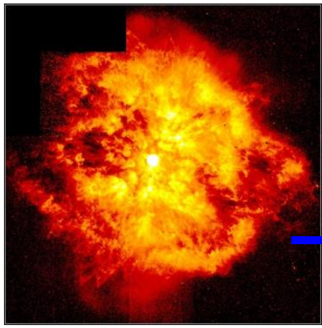
Observational evidence for the early-Universe is insufficient.

EVOLUTIONARY STAGES OF MASSIVE STARS

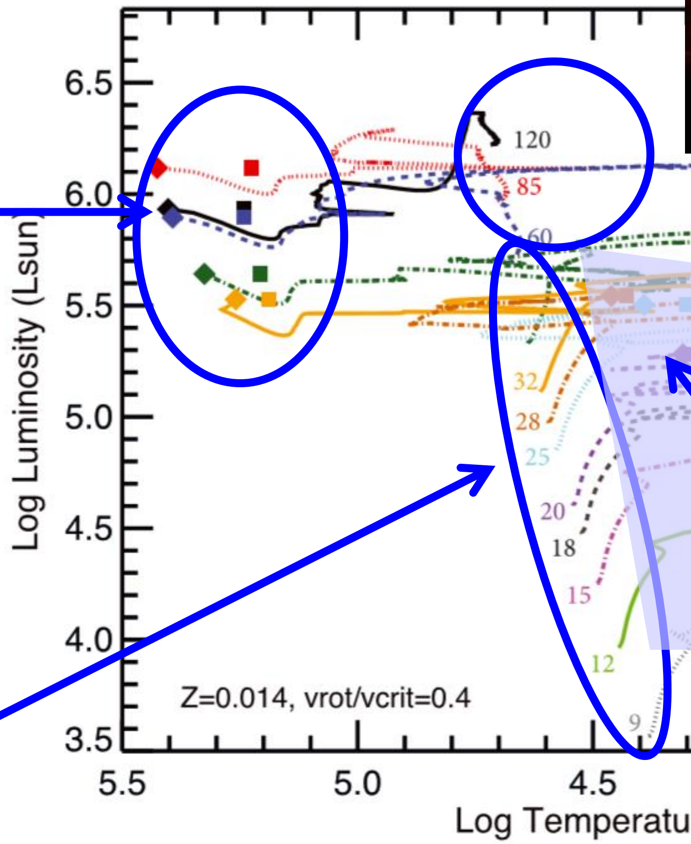


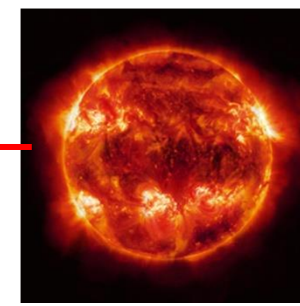


Luminous Blue Variables (LBV)



Wolf-Rayet (WR)





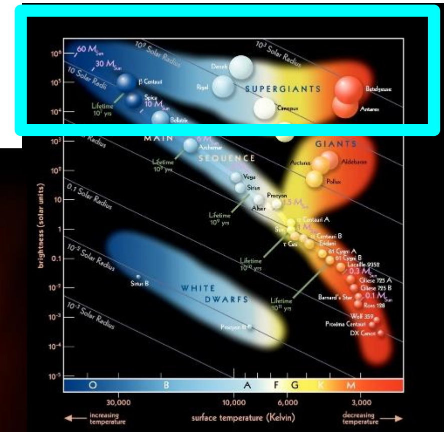
Red Supergiants (RSG)

Main sequence: OB-type stars

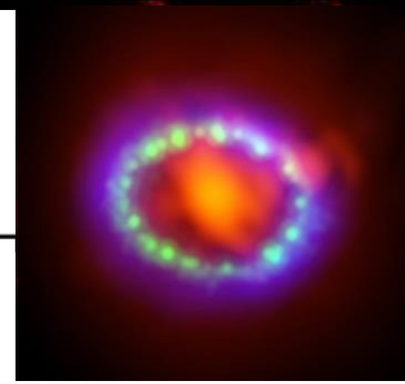
Groh et al. 2013

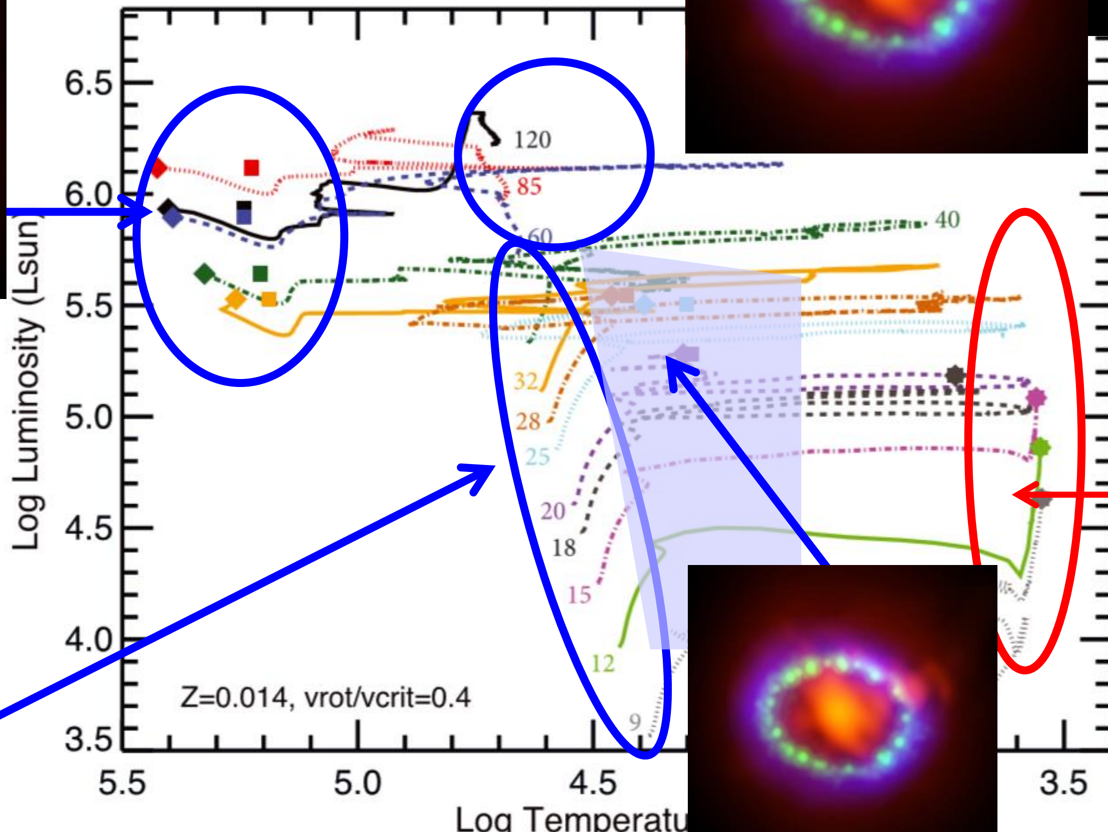
OB supergiants (BSG)

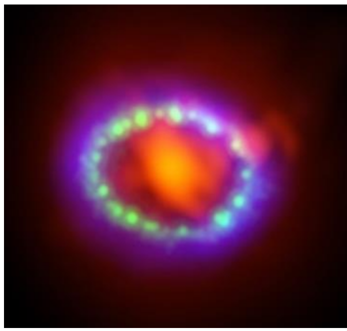
EVOLUTIONARY STAGES OF MASSIVE STARS



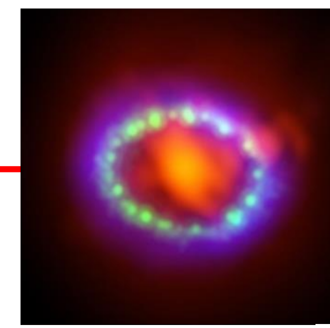
Luminous Blue Variables (LBV)







Wolf-Rayet (WR)



Red Supergiants (RSG)

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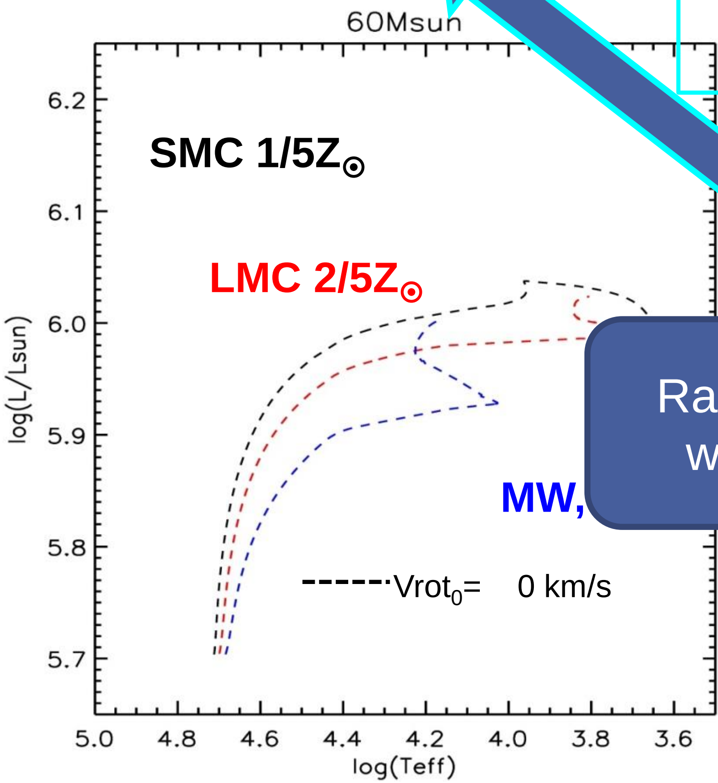
ROLE OF METALLICITY AND WINDS

<u>Evolutionary paths:</u>
Feedback

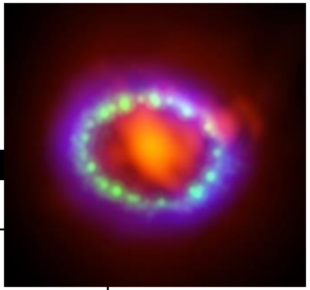
More ionizing photons



Radiation-driven winds at work

Tracks from Brott+ 2011

ROLE OF METALLICITY AND WINDS



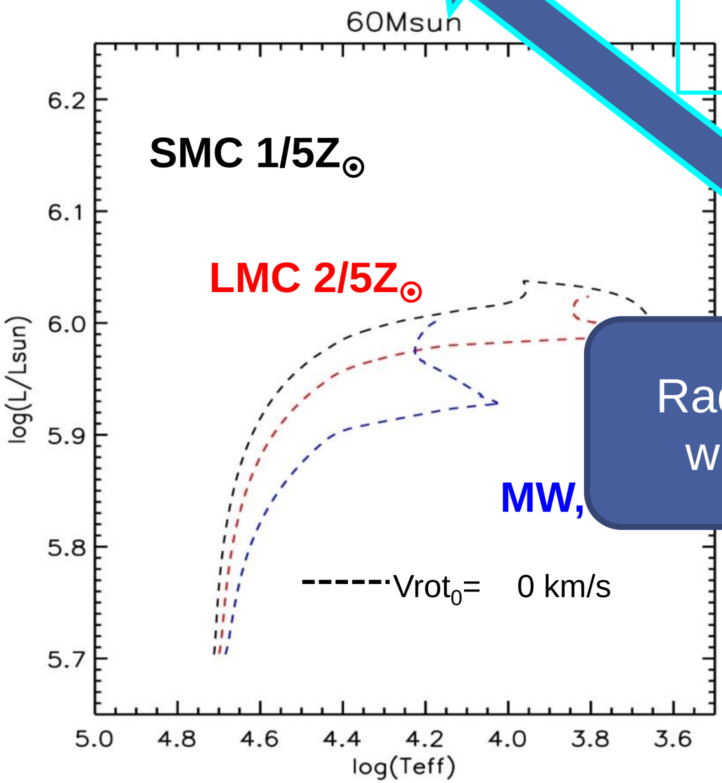
<u>Evolutionary paths:</u>

Feedback

<u>Final mass:</u>

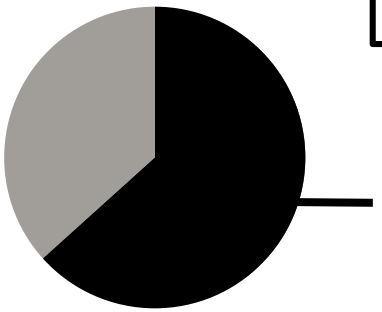
Type of SN. Remnant: NS/BH

More ionizing photons



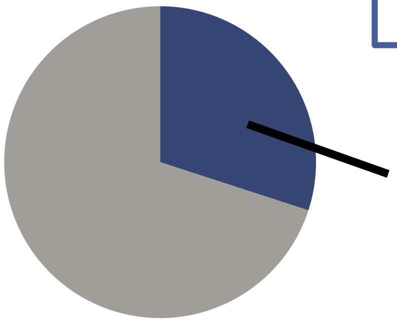
Radiation-driven winds at work

SMC: 1/5Z$_\odot$



38 M$_\odot$

MW: Z$_\odot$



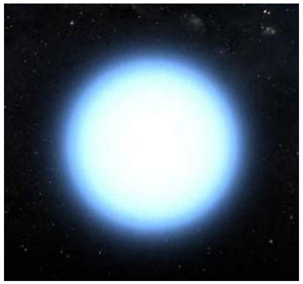
18 M$_\odot$

Tracks from Brott+ 2011

Groh+ (2019) , vrot=0 , M_{ini}=60 M$_\odot$

HIGH V*ROT* AND WEAK STELLAR WINDS: A NEW CHANNEL OF EVOLUTION AT LOW-Z

CHE = chemically homogeneous evolution



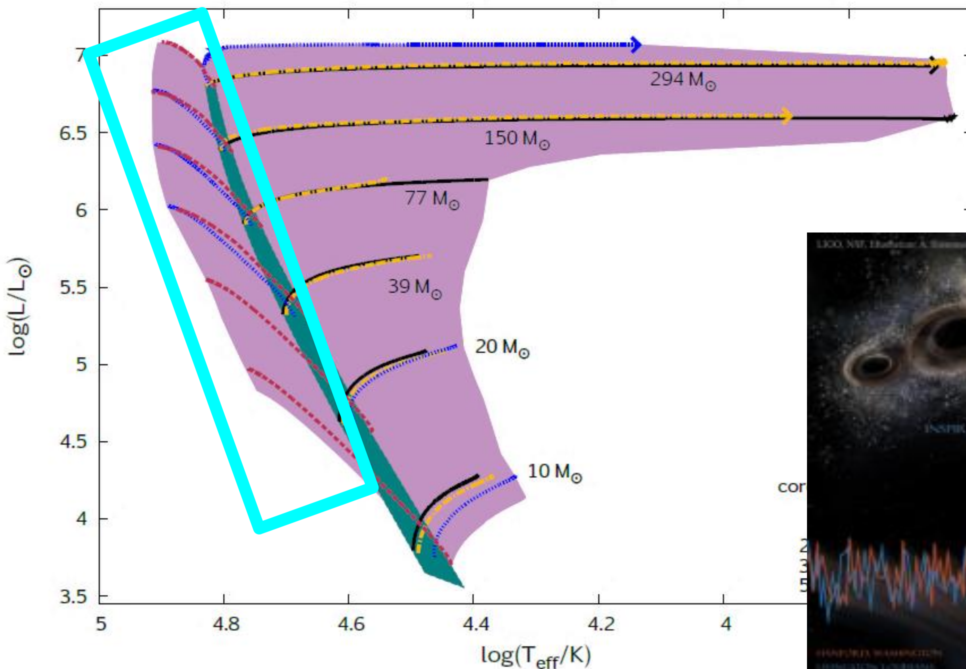
<u>TWUINs:</u>

90 000 K

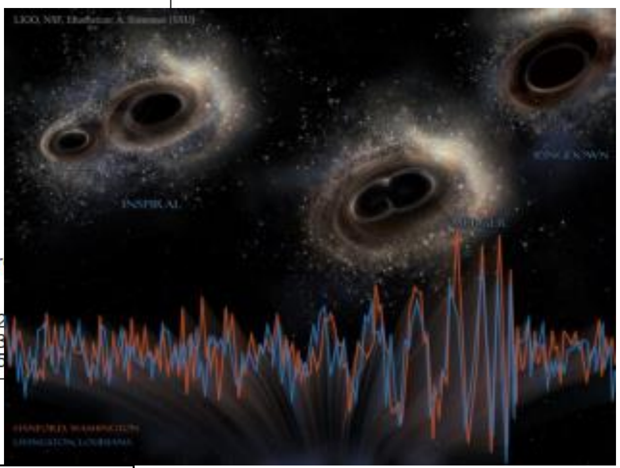
10-20 $R_\odot$

10 000 000 $L_\odot$

H-burning

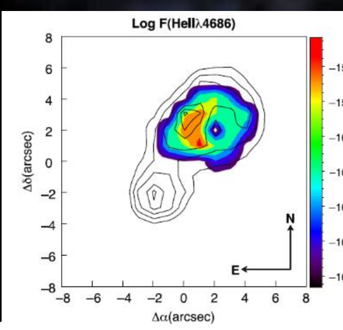


1/50 $Z_\odot$ tracks, Szécsi+ 2015 (also Schaerer 2002)



4x production of Ionizing photons of HeII

TWUINs have been invoked as ionizing sources to produce intense HeII4686 nebular emission in IZw18 (Kehrig+ 2015), CR7 (Sobral+ 2015)



Kehrig+ 2015

The evolution and death of metal-poor massive stars **($\leq 1/10 Z_{\odot}$)** can be very different from MW or Magellanic Clouds analogs, because of **their weaker winds**.

The characterization of the **winds of massive stars** at the **low metallicity regime** is crucial to compute realistic models of stellar evolution.

These, in turn, are needed to:

- Deciding if **CHE** is a feasible channel of evolution
- Estimating the production of **ionizing fluxes** of H and He
- Establishing the links between massive stars and GRB, SNe (**map of progenitors**)
- Determining how **massive stellar-size black holes** can form
- Extrapolating the physical properties of the **first**, metal-free **stars** of the Universe

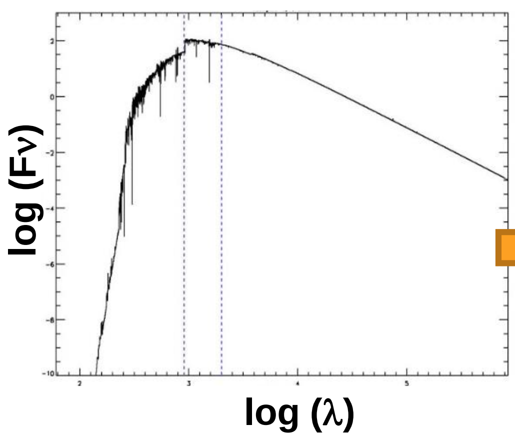
RADIATION-DRIVEN WINDS (RDW) AND UV SPECTROSCOPY

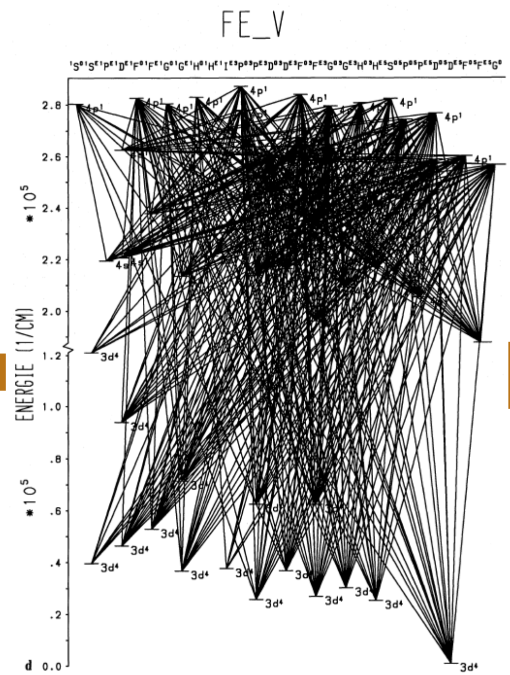
DRIVING MECHANISM

- **Photon scattering: absorption and re-emission of photons**

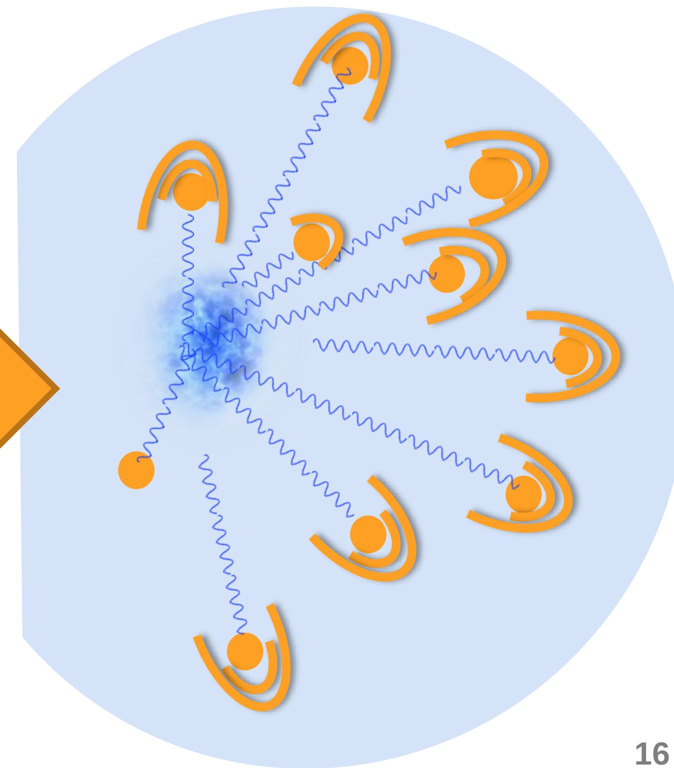
(Castor, Abbott & Klein 1975; Kudritzki & Puls 2000; Puls, Vink & Najarro 2008)

  - Intense UV radiation field
  - Momentum transfer to metal ions (Fe-group)





Pauldrach et al. 1994



DRIVING MECHANISM

- **Photon scattering: absorption and**

(Castor, Abbott & Klein 1975; Kudritzki & Puls 2

  - Intense UV radiation field
  - Momentum transfer to metal ions (F

- **Main parameters:**
  - Mass loss rate ($\dot{M}$)
  - Terminal velocity (v_∞)

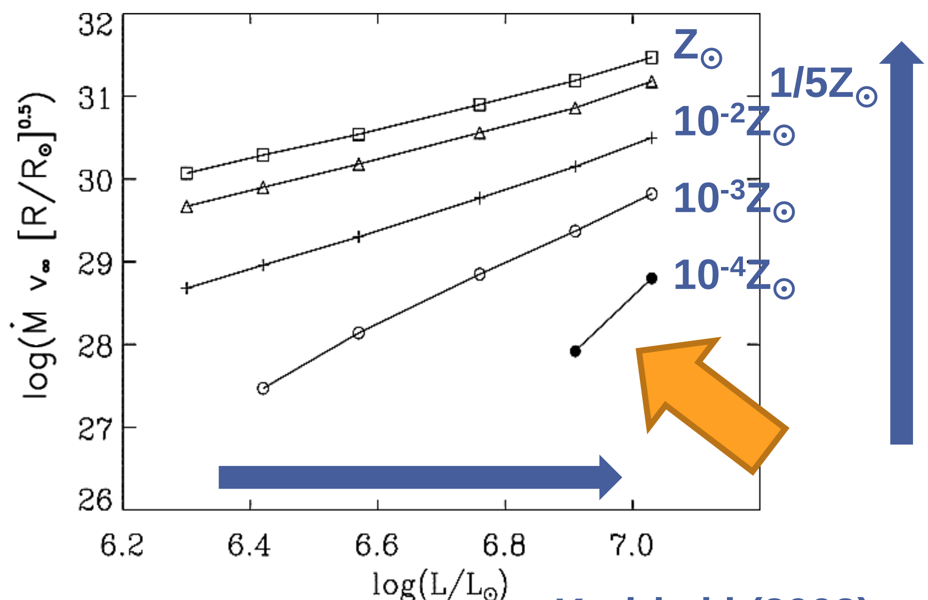
Very metal-poor massive stars can sustain winds as long as they are close to the Eddington limit: radiative acceleration ~ gravity.

See Gräfener+ (2011),

Bestenlehner (2020a)

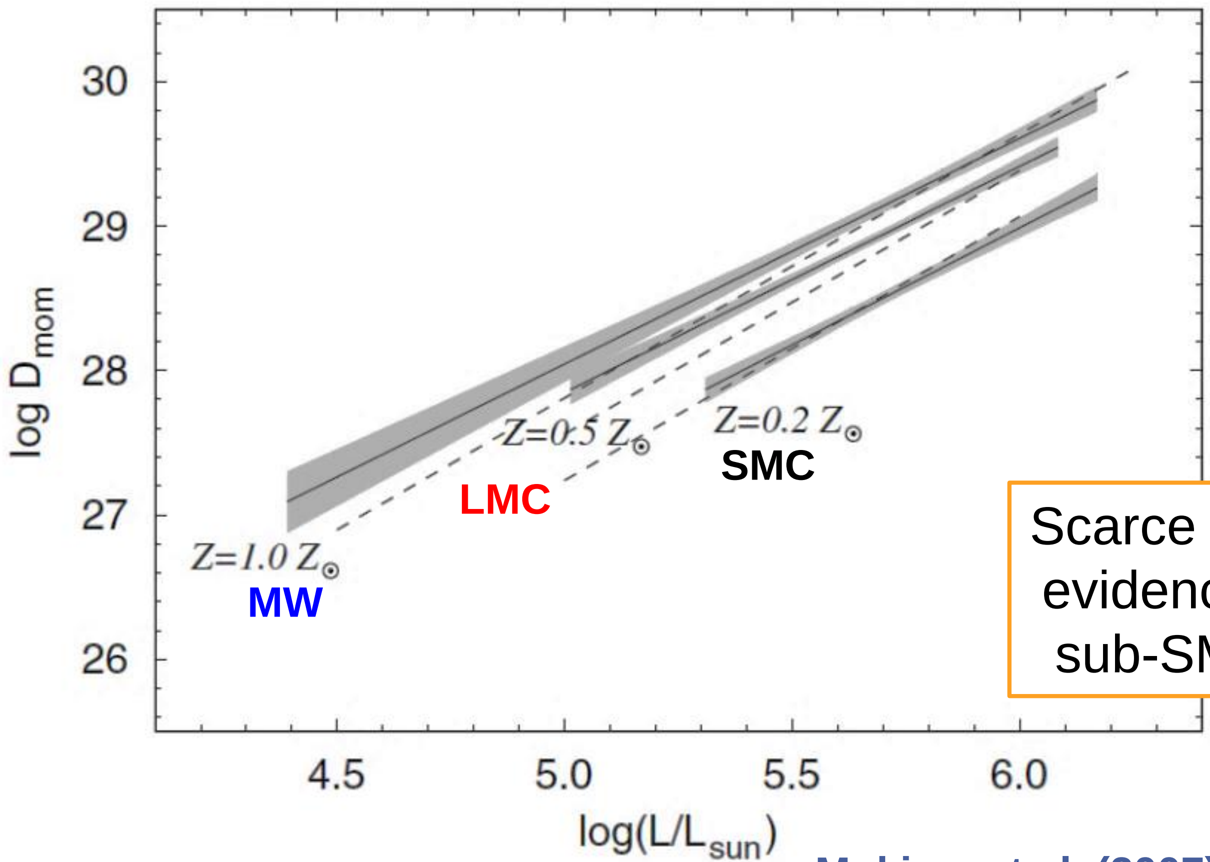
- **Wind momentum (D_{mom}) – Luminosity Relation (WLR):**

$$\log D_{mom} = \log D_0 + x \log(L/L_\odot)$$
$$D_{mom} = \dot{M}\, v_\infty\, (R_*/R_\odot)^{1/2}$$



Kudritzki (2002)

THE OBSERVATIONAL WLR



$\dot{M} \propto Z^{0.83}$

Scarce observational evidence in the very sub-SMC Universe

Mokiem et al. (2007)

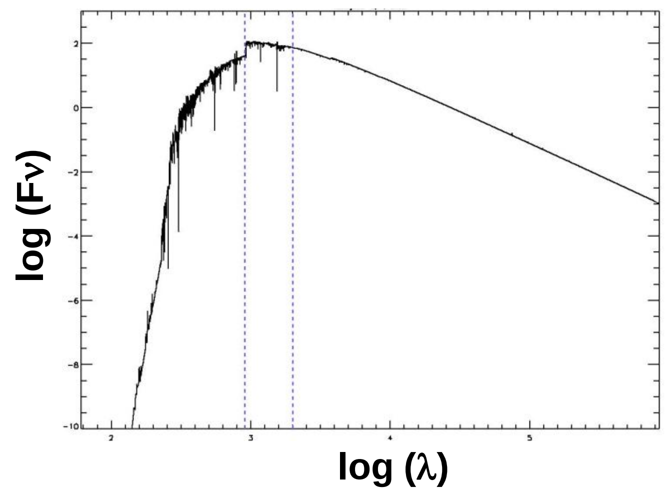
UV 900-2000 Å NEEDED TO STUDY LOW-Z WINDS

Optical range

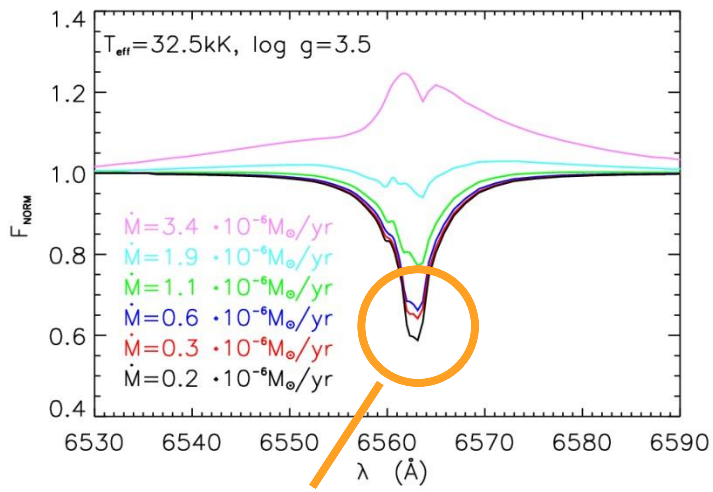
Ultraviolet (UV)

- No information on $\mathbf{v_\infty}$
- $v_\infty = 2.65\, v_{esc}$ Kudritzki & Puls 2000
- $v_\infty \propto Z^{0.13}$ Leitherer+ 1992

- Insensitive to low $\dot{M}$

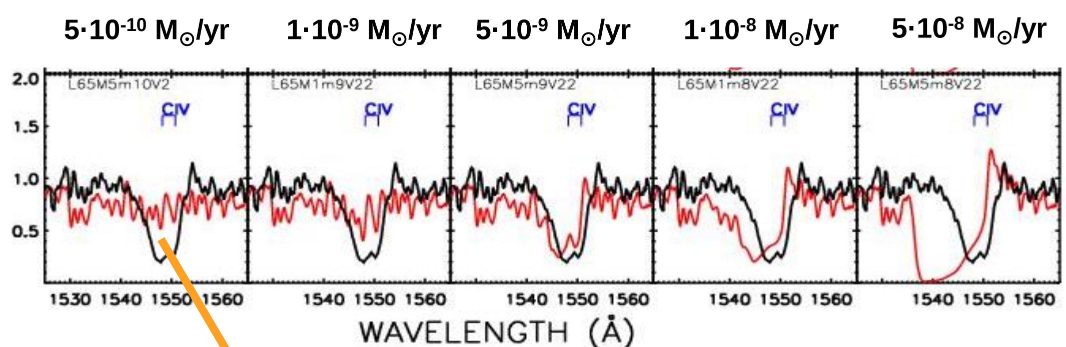


Hα 6563Å



Insensitive if $\dot{M}$ <6·10^{-7} M$_\odot$/yr

CIV 1550Å (UV) **Sensitive to low $\dot{M}$**

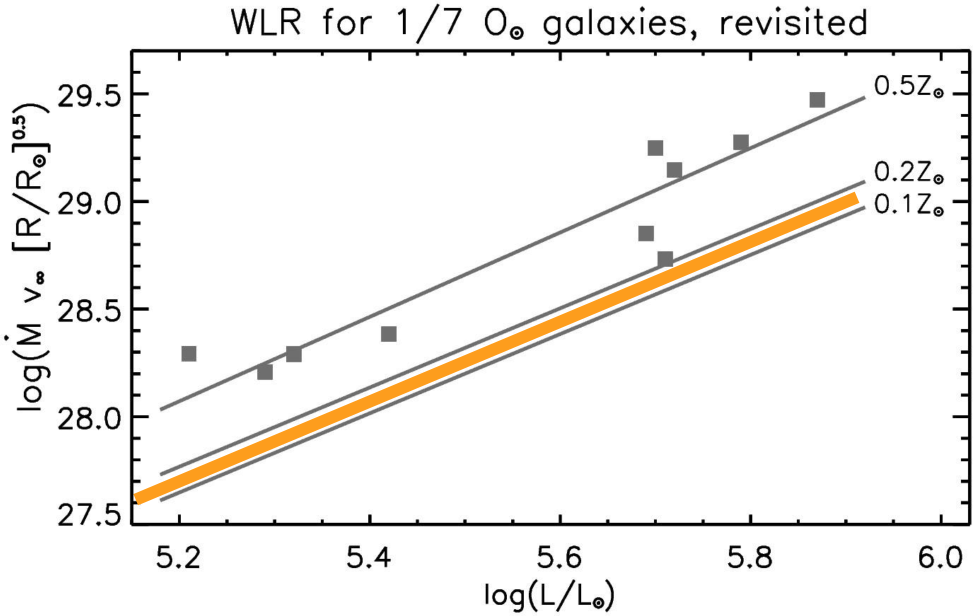


Constraints on $\mathbf{v_\infty}$

FIRST STUDIES OF WINDS IN LOW-Z MASSIVE STARS BEYOND THE SMC: IC1613

- **Analysis from the optical range (Hα):**
  - Winds are stronger than predicted by theory **(Tramper+ 2011, Herrero+ 2011)**

Tramper+ 2011, Herrero+ 2011

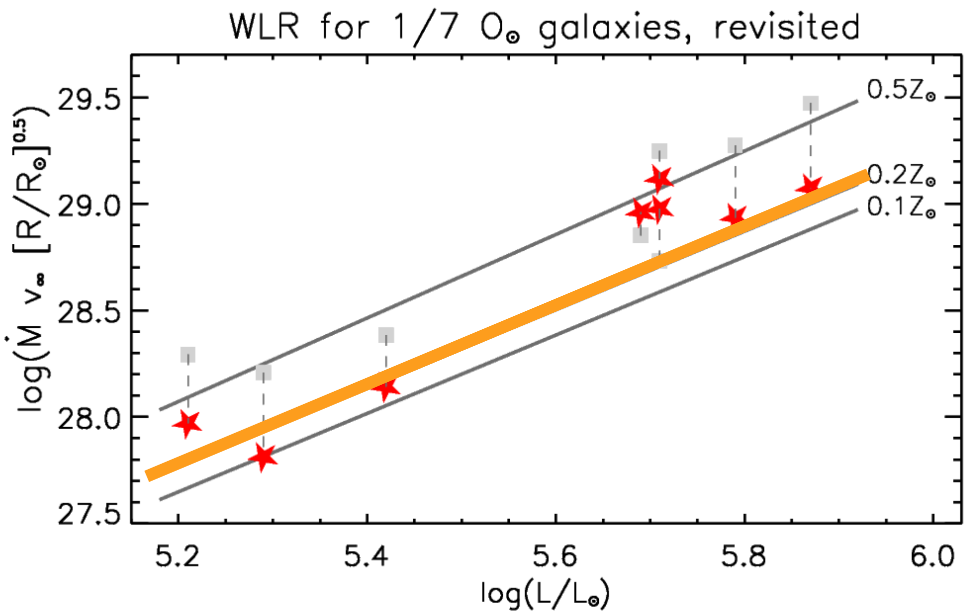


FIRST STUDIES OF WINDS IN LOW-Z MASSIVE STARS BEYOND THE SMC: IC1613

- **Analysis from the optical range (Hα):**
  - Winds are stronger than predicted by theory **(Tramper+ 2011, Herrero+ 2011)**
- **HST UV spectroscopy:**
  - IC1613 has a higher Fe-group content (≥1/5 $Fe_{\odot}$) than what would be scaled from nebular abundances (1/7 $O_{\odot}$)
  - Direct v_{∞} reconciles the tension **(Garcia+ 2014)**

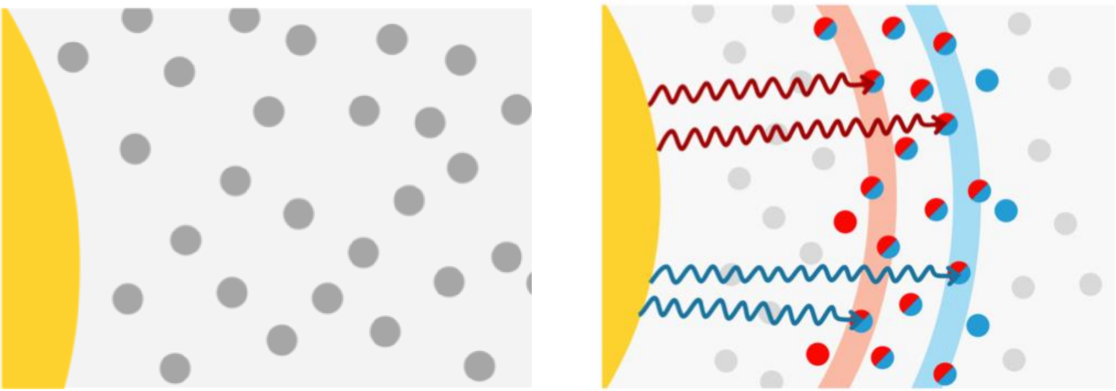
Tramper+ 2011, Herrero+ 2011

Garcia+ 2014



WIND INHOMOGENEITIES: CLUMPING

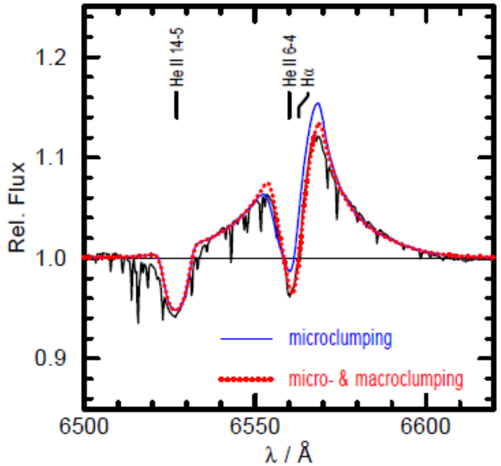
- Clumps coexist with the smooth wind.
- To be accounted for geometrically and in the velocity field

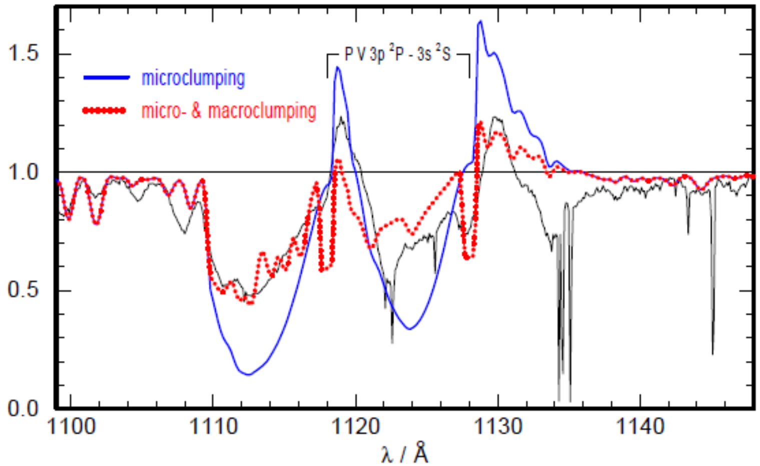


Brands+ 2022

(But see also Owocki+ 2004, Puls+ 2008, Najarro+ 2008, Sundqvist+ 2010,2011…)

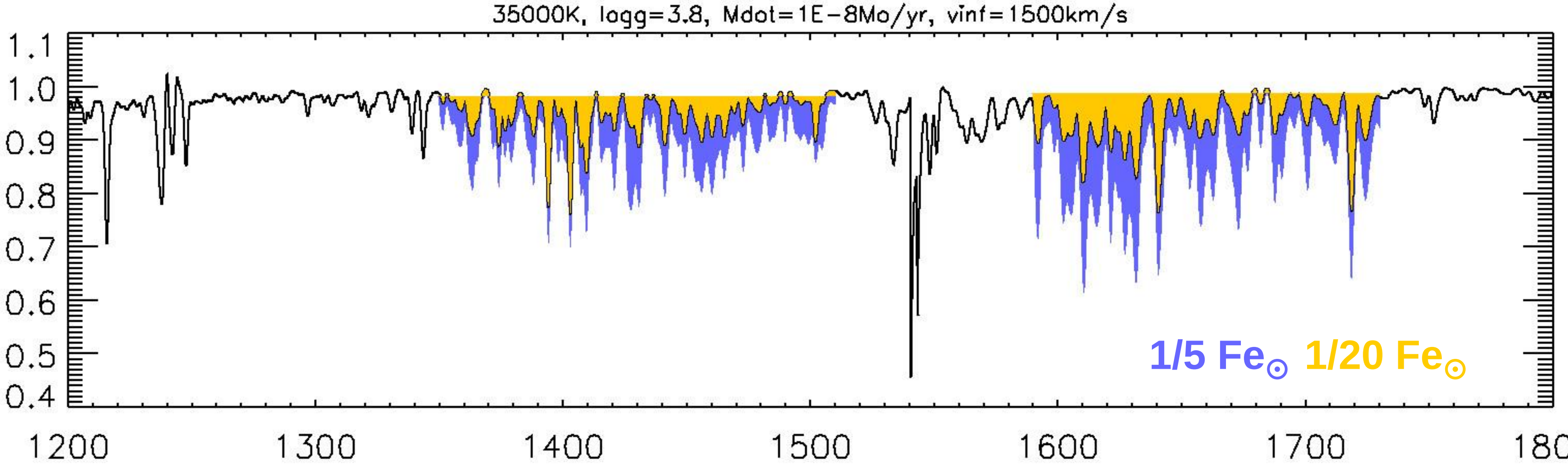
- **The UV scattering lines can trace the distribution of clumping**





Oskinova+ (2007)

ADDITIONAL DIAGNOSTICS IN THE UV-RANGE: FE-GROUP ABUNDANCES



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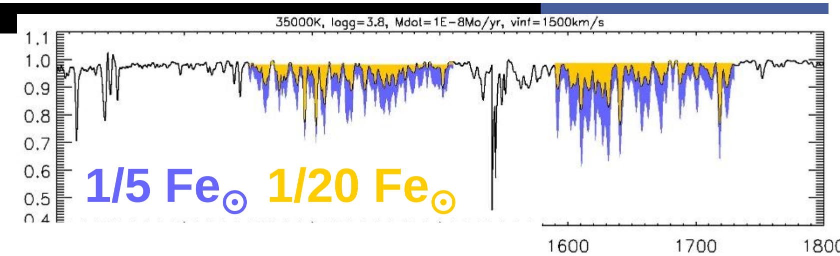
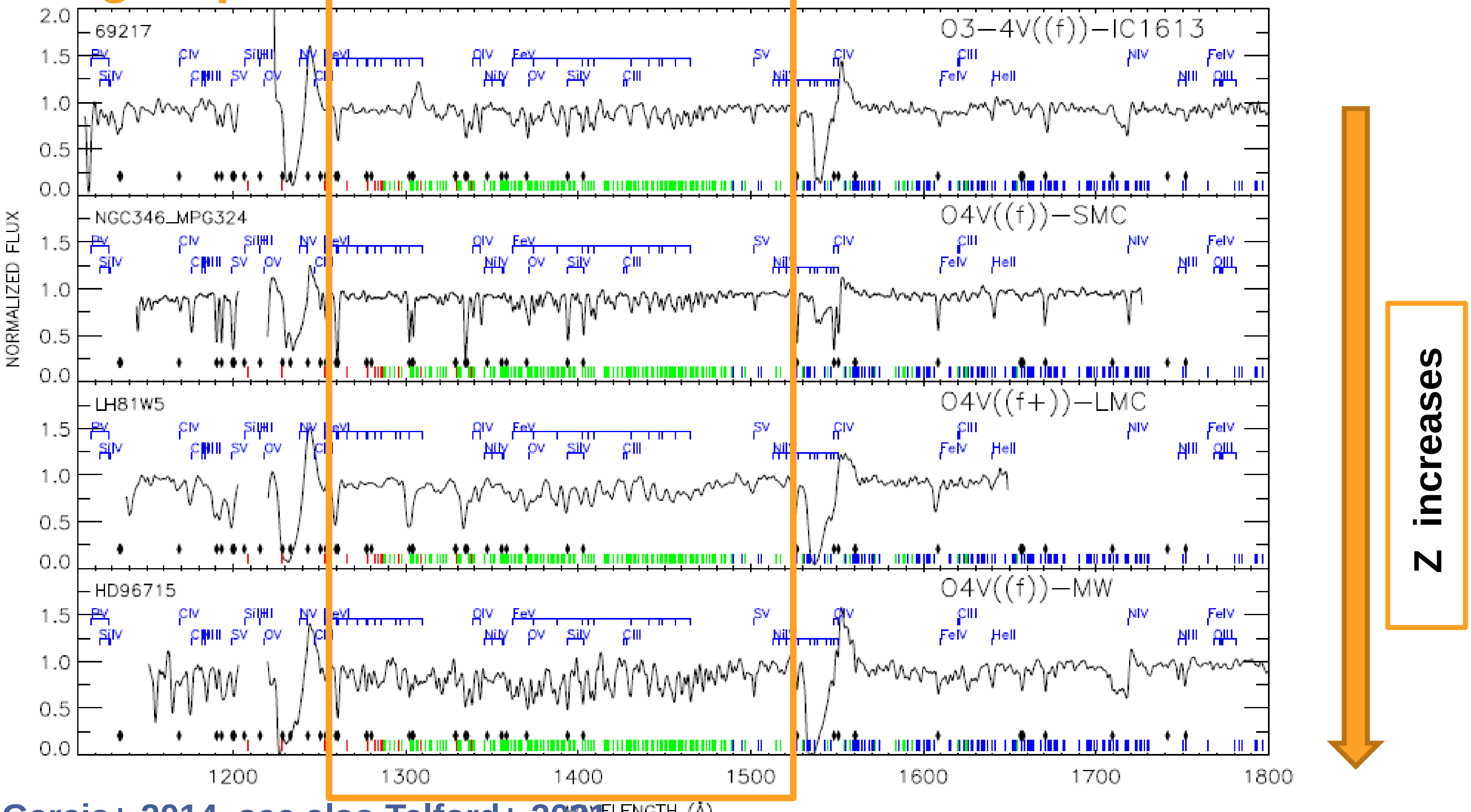
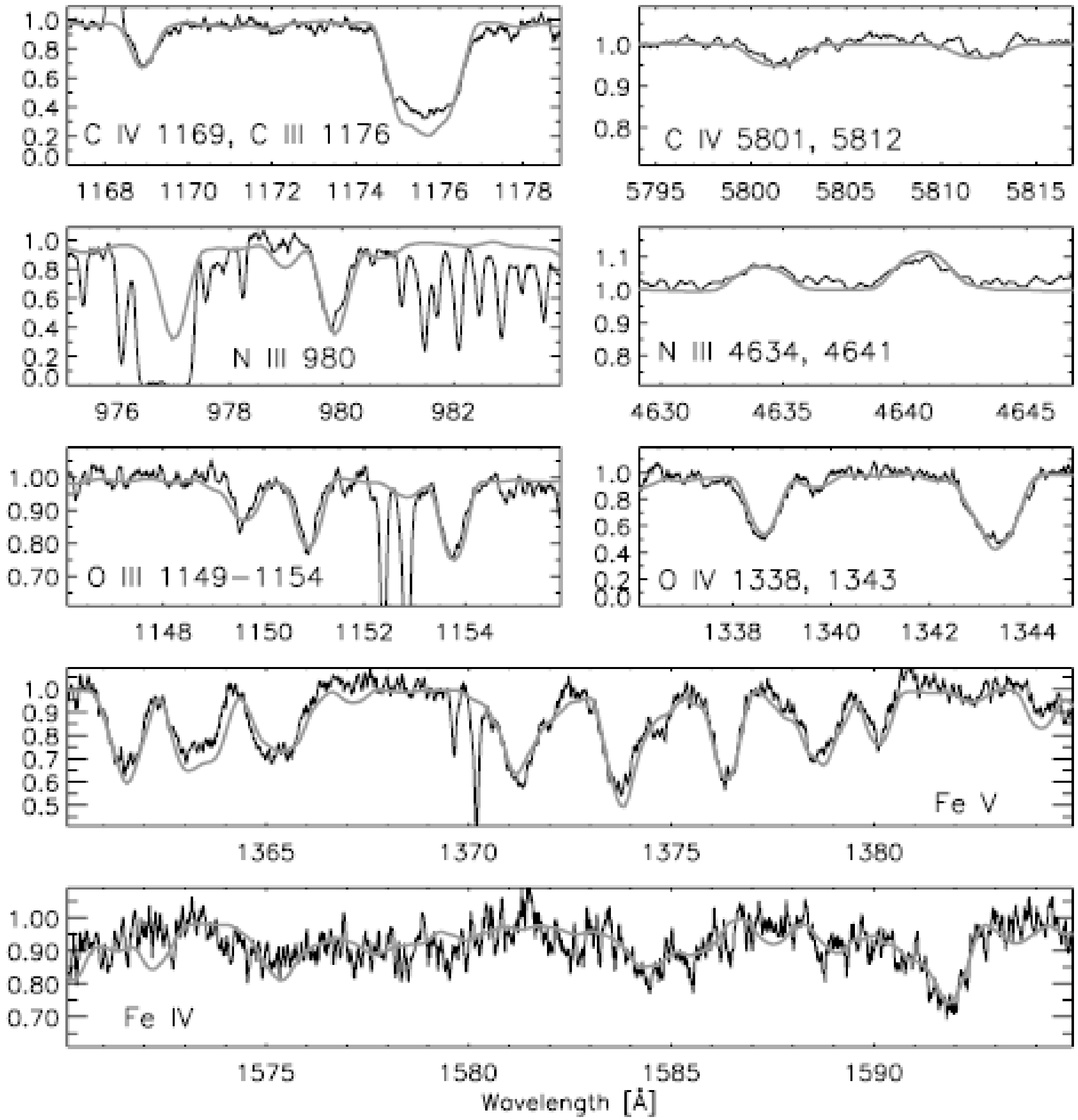


Fe-group



Garcia+ 2014, see also Telford+ 2021

ABUNDANCES OF OTHER ELEMENTS AND V*SINI*



Heap+. 2006

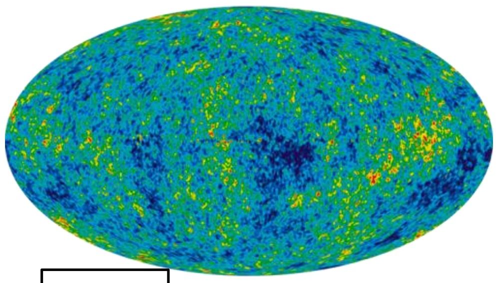
(See also Prinja+ 1990, Penny+ 1996, and works by Bouret+, Martins+).

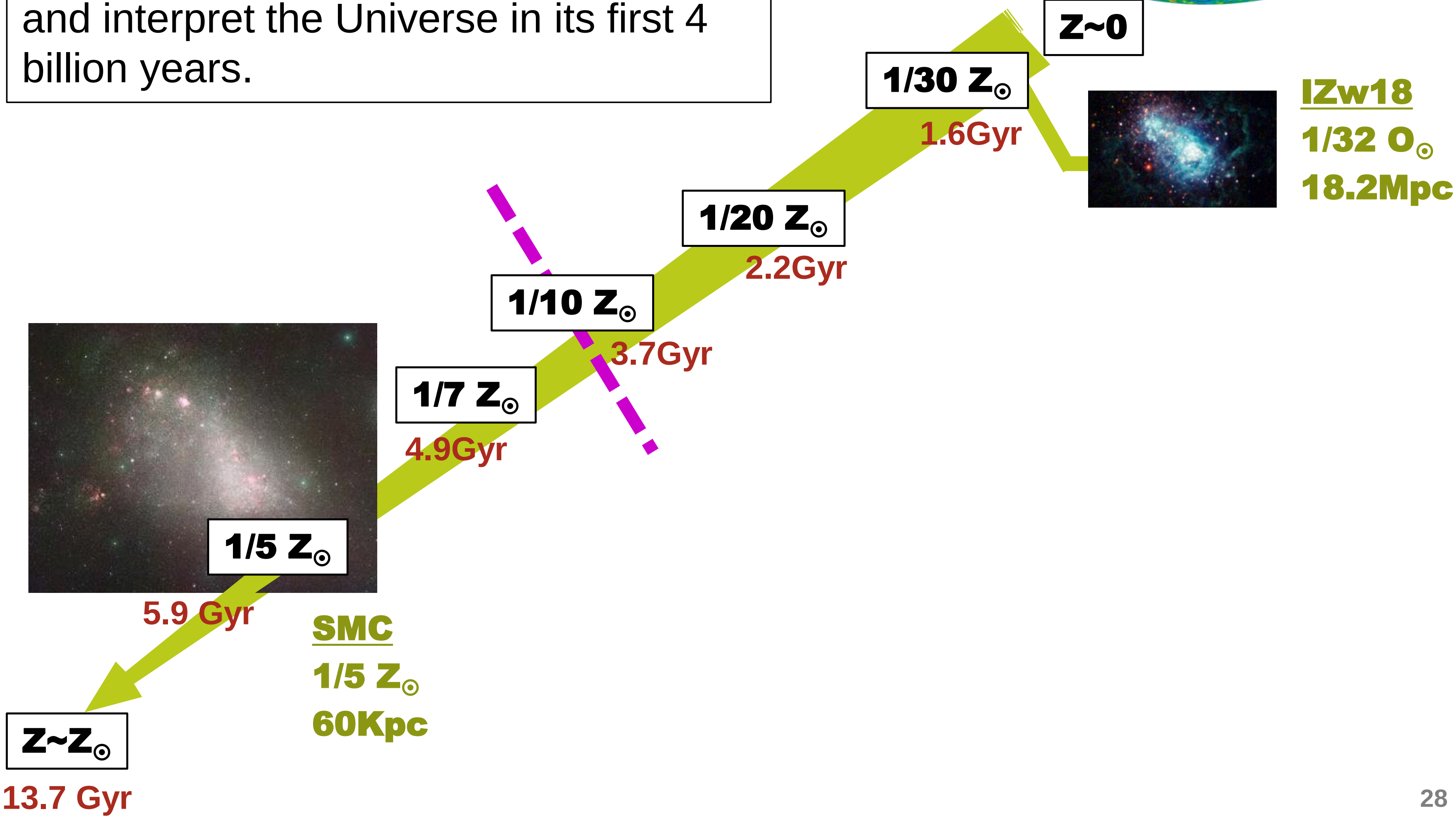
- The evolution and death of **metal-poor massive stars (≤1/10$Z_{\odot}$)** can be **very different** from MW or Magellanic Clouds analogs.
- The characterization of the **winds of massive stars** at the **low metallicity regime** is crucial to compute realistic stellar evolutionary tracks.
- Spectroscopy in space **UV (900-2000Å)** is needed to characterize **radiation-driven winds of low metallicity massive stars.**
- The UV contains **additional information**, some of it **exclusive to this range** (e.g. Fe-group abundances of O-type stars).

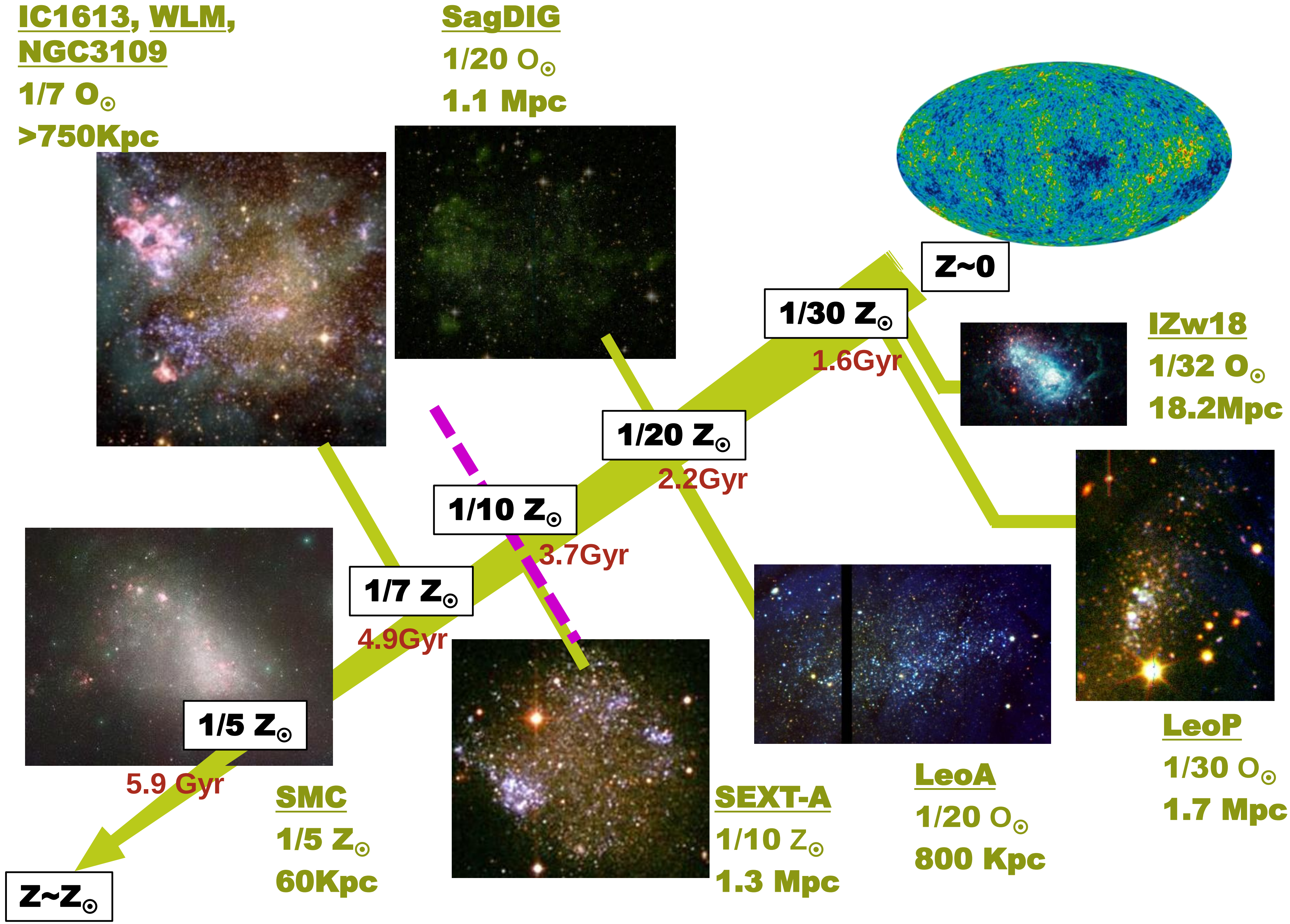
VOYAGE 2050 PROPOSAL

GOAL:

To study **NEARBY** massive stars and their winds in environs. of decreasing metal content that will help us model and interpret the Universe in its first 4 billion years.



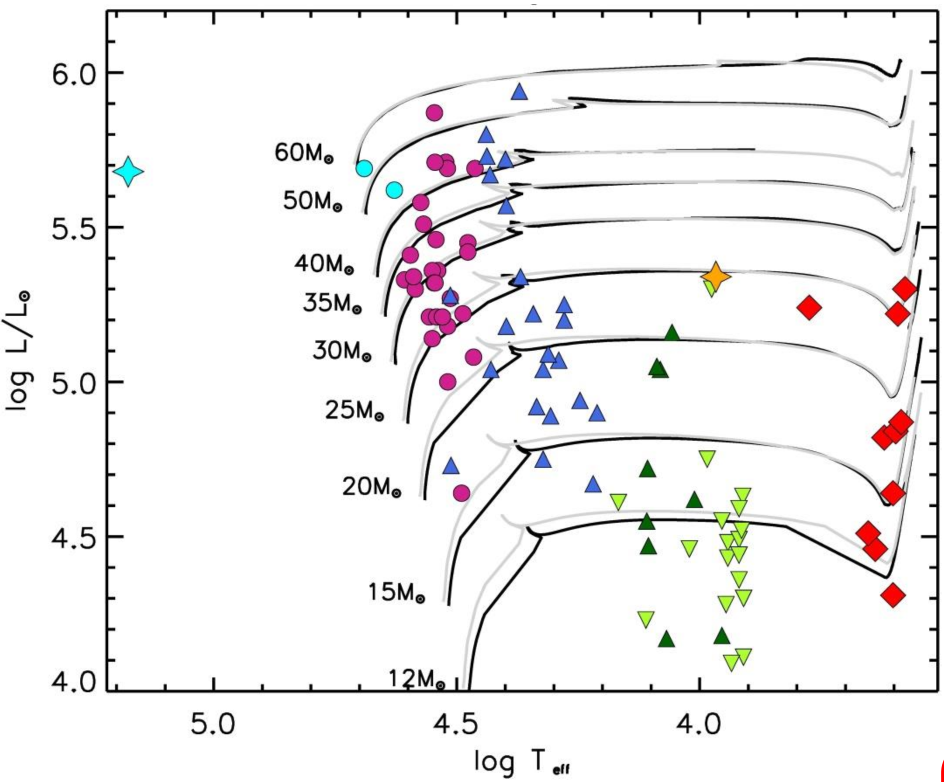


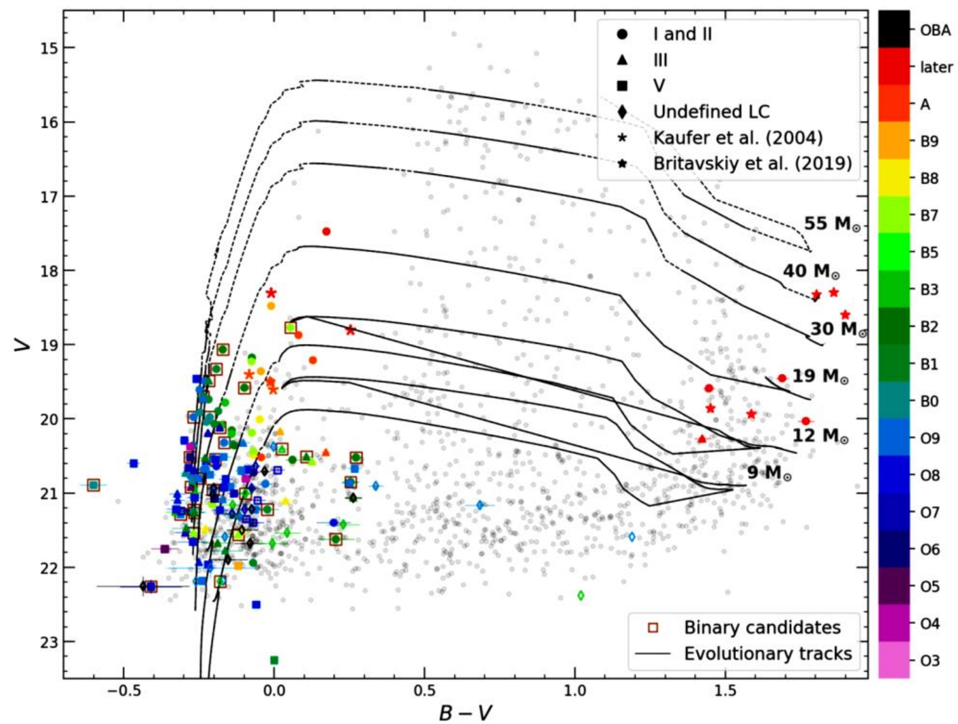

IC1613, WLM, NGC3109
1/7 O⊙
>750Kpc
SagDIG
1/20 O⊙
1.1 Mpc
Z~0
1/30 Z⊙
1.6Gyr
IZw18
1/32 O⊙
18.2Mpc
1/20 Z⊙
2.2Gyr
1/10 Z⊙
3.7Gyr
1/7 Z⊙
4.9Gyr
1/5 Z⊙
5.9 Gyr
Z~Z⊙
13.7 Gyr
SMC
1/5 Z⊙
60Kpc
SEXT-A
1/10 Z⊙
1.3 Mpc
LeoA
1/20 O⊙
800 Kpc
LeoP
1/30 O⊙
1.7 Mpc

PROGRESS: HR-DIAGRAM AT $Z<Z_{SMC}$

IC1613, WLM, NGC3109
1/7 $O_{\odot}$

Sextans A
1/10 $Z_{\odot}$

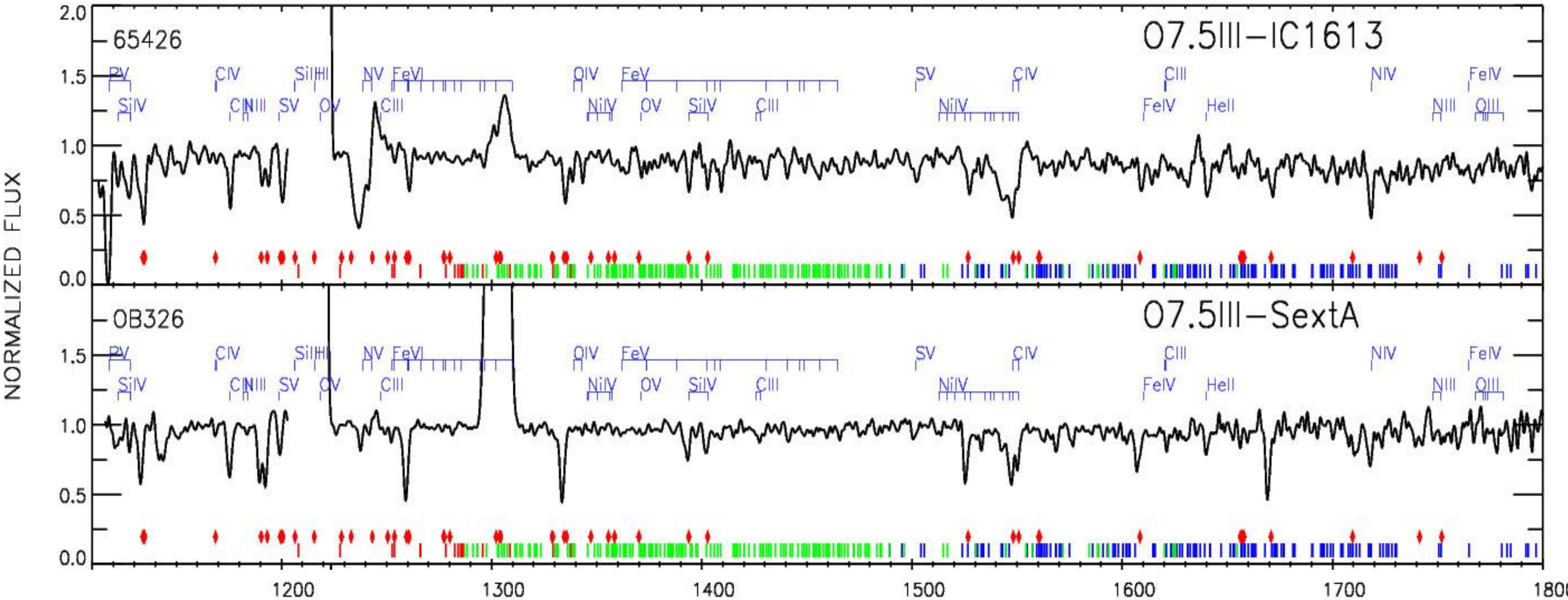




Only 6 **1/10 $Z_{\odot}$** O-type stars have been analyzed due to poor data quality

1/7 $O_{\odot}$: Bresolin+ 2007; Evans+ 2007; Tautvaisiene+ 2007; He
Hosek+ 2014; Bouret+ 2015; Camacho 2017, PhD thesis; Ber
prep.

1/10 $Z_{\odot}$: Camacho+ 2016; Britavskiy+ 2019, Kaufer+ 2004, Telford+ 2021, Lorenzo+2022


65426
O7.5III–IC1613
0B326
O7.5III–SextA
NORMALIZED FLUX
PV
SiIV
CIV
CIII
NIII
SiIII
SV
OV
NV
FeVI
OIV
NiIV
FeV
SiIV
FeIV
HeII
NIV
OIII

Garcia+ 2017

UV WIND STUDIES ARE SCARCER

- **10 OB-type stars to study winds at $Z \leq 1/10 Z_{\odot}$**

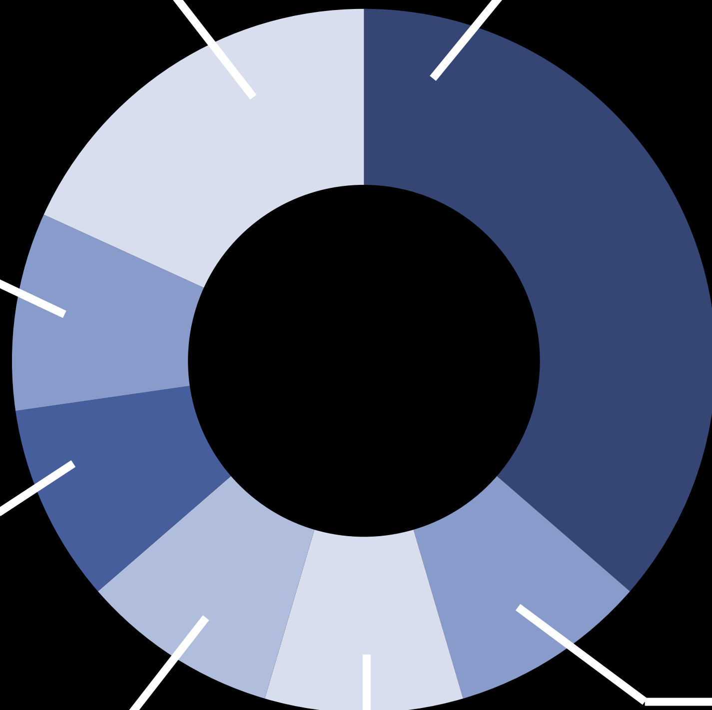
GALAXY	HST-COS SETTING	#targets	ORBITS
IC1613 NGC3109	G140L	5 O-stars + 3 B-superg 2 O-stars + 1 B-superg	23 orbits (PI M. Garcia) 18 orbits **ULLYSES**
IC1613, WLM	G130M+G160M G130M+G160M	3 O-stars 1 O-star	18 orbits (PI Lanz) 9 orbits (PI Chisholm)
SEXT-A	G140L	4 O-stars + 1 B-superg 2 O-stars + 1 B-superg	26 orbits (PI M. Garcia) **ULLYSES**
SEXT-A	G130M+G160M	1 O-star	14 orbits (PI Chisholm)
Leo P	G130M+G160M	1 O-star	26 orbits (PI Chisholm)
IZw18	G130M, G160M, G185M	Unresolved (4 max.)	~35 orbits (PIs Green -x2-, Aloisi, Wofford)

$Z \leq 1/10 Z_{\odot}$

MASSIVE STARS IN EXTREMELY METAL-POOR GALAXIES: A WINDOW INTO THE PAST

White Paper submitted to ESA's Voyage 2050 call

M. Garcia coordinator



Low-metallicity :
- M. García
- C. J. Evans
- N. Castro
- F. Tramper

Binaries:
- S. E. de Mink
- H. Sana

Stellar evolution:
- D. Szecsi
- J. Th. van Loon
- I. Negueruela

Star formation:
- M. Gieles

Population synthesis :
- A. Wofford
- M. Cerviño

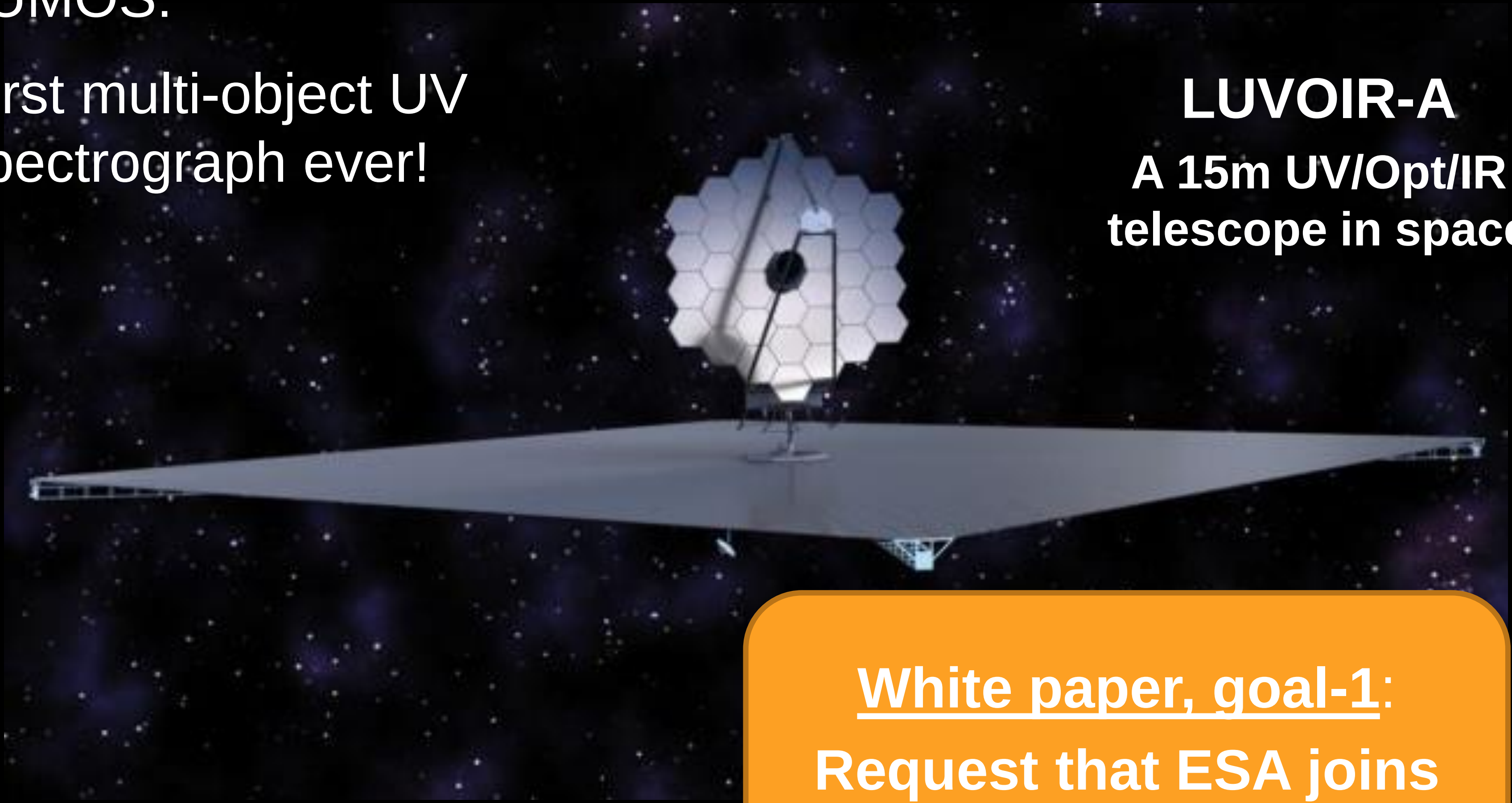
Spectral modelling:
- M. García
- F. Najarro
- A. Herrero
- D. J. Lennon
- S. Simón-Díaz
- F. Martins
- J. Bestenlehner
- A. de Koter
- J. Vink

UV spectroscopy:
- M. García
- J.C. Bouret
- A. W. Fullerton

2040's:
THE ERA OF LARGE TELESCOPES IN SPACE

LUMOS:

First multi-object UV spectrograph ever!



LUVOIR-A

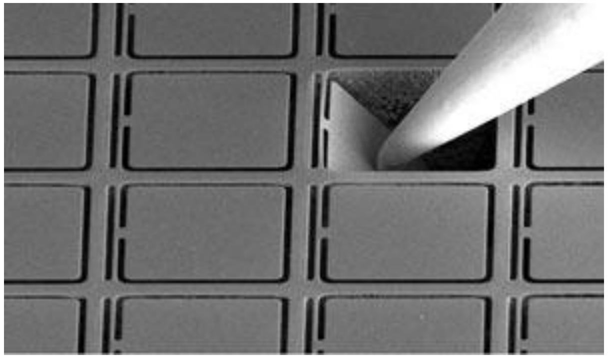
A 15m UV/Opt/IR telescope in space

<u>White paper, goal-1</u>:

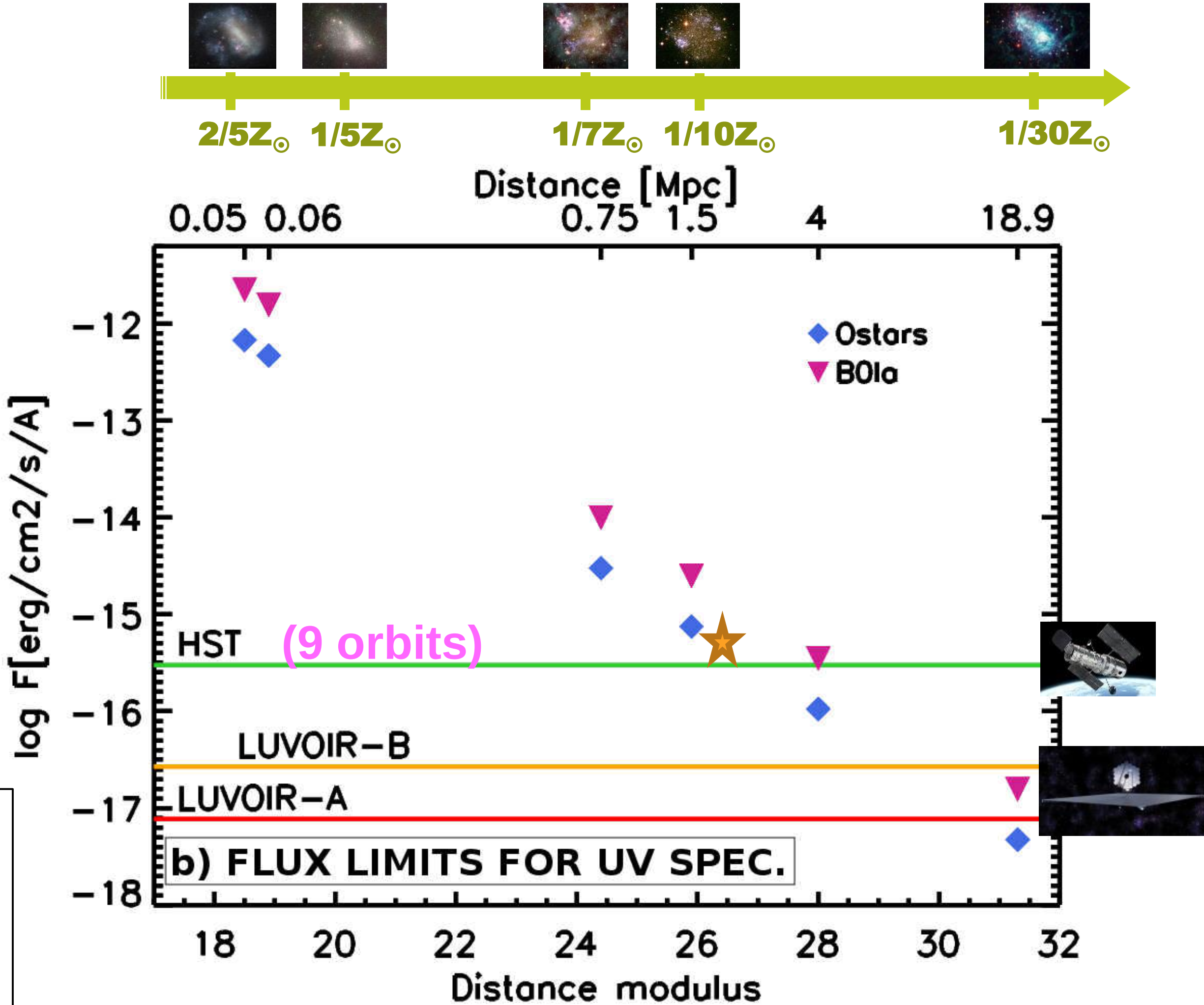
Request that ESA joins NASA in this enterprise

LUMOS: LUVOIR ULTRAVIOLET MULTI OBJECT SPECTROGRAPH

First UV multi-object spectrograph

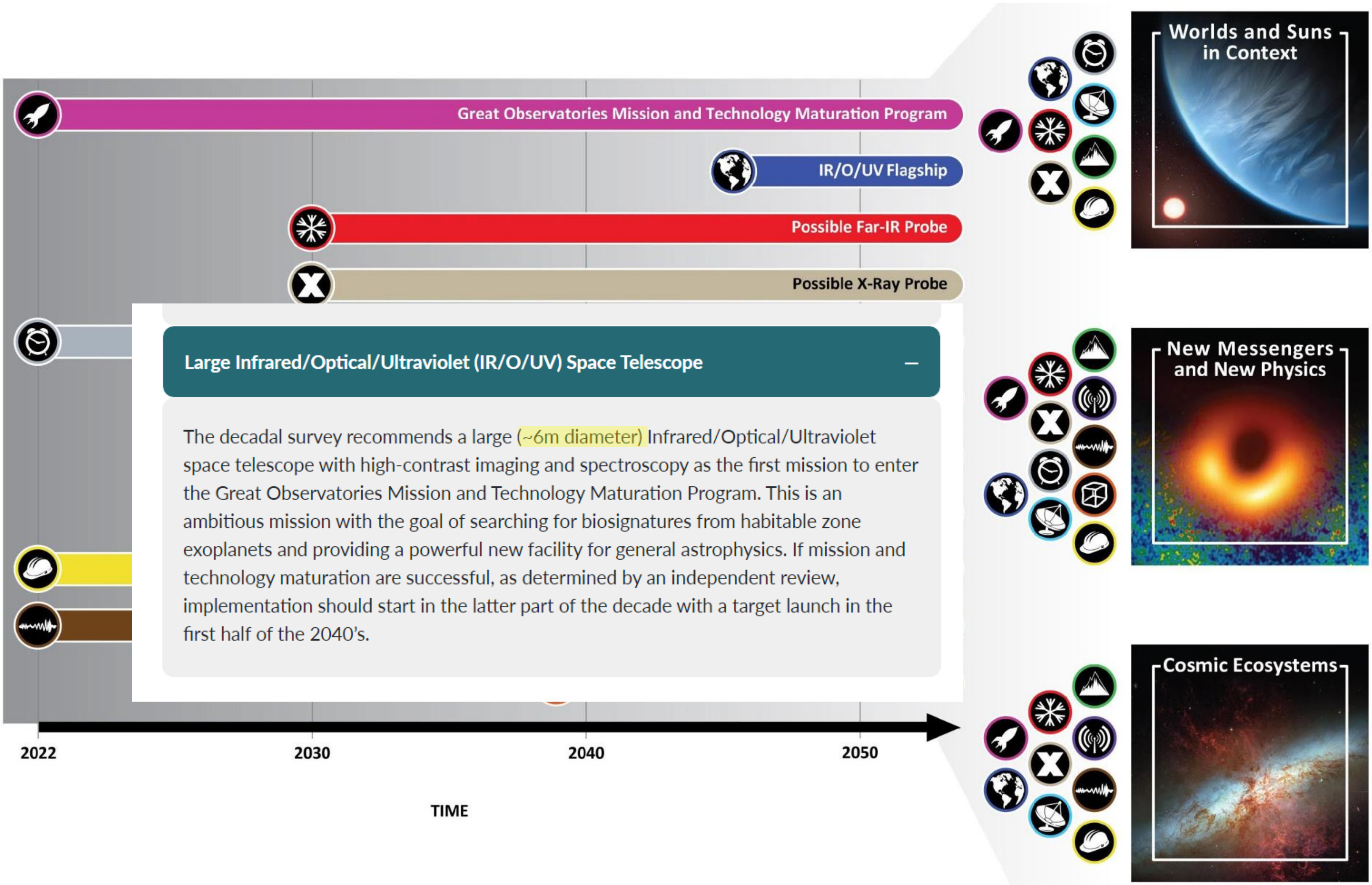


Winds of known metal-poor Local Group OB-stars in 30 hours. UV-brightest sources in IZw18 in 11.5h (100-hour highlight #3, **France+ 2017**)



Garcia+ 2021, white paper for Voyage 2050

ASTRO2020 DECADAL SURVEY RESULTS



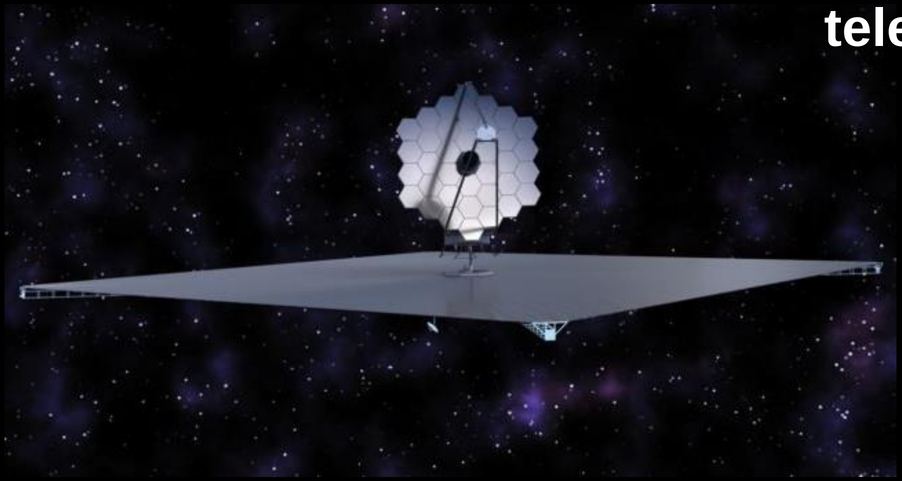
Large Infrared/Optical/Ultraviolet (IR/O/UV) Space Telescope –

The decadal survey recommends a large (~6m diameter) Infrared/Optical/Ultraviolet space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program. This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040's.

2040's:
THE ERA OF LARGE TELESCOPES IN SPACE

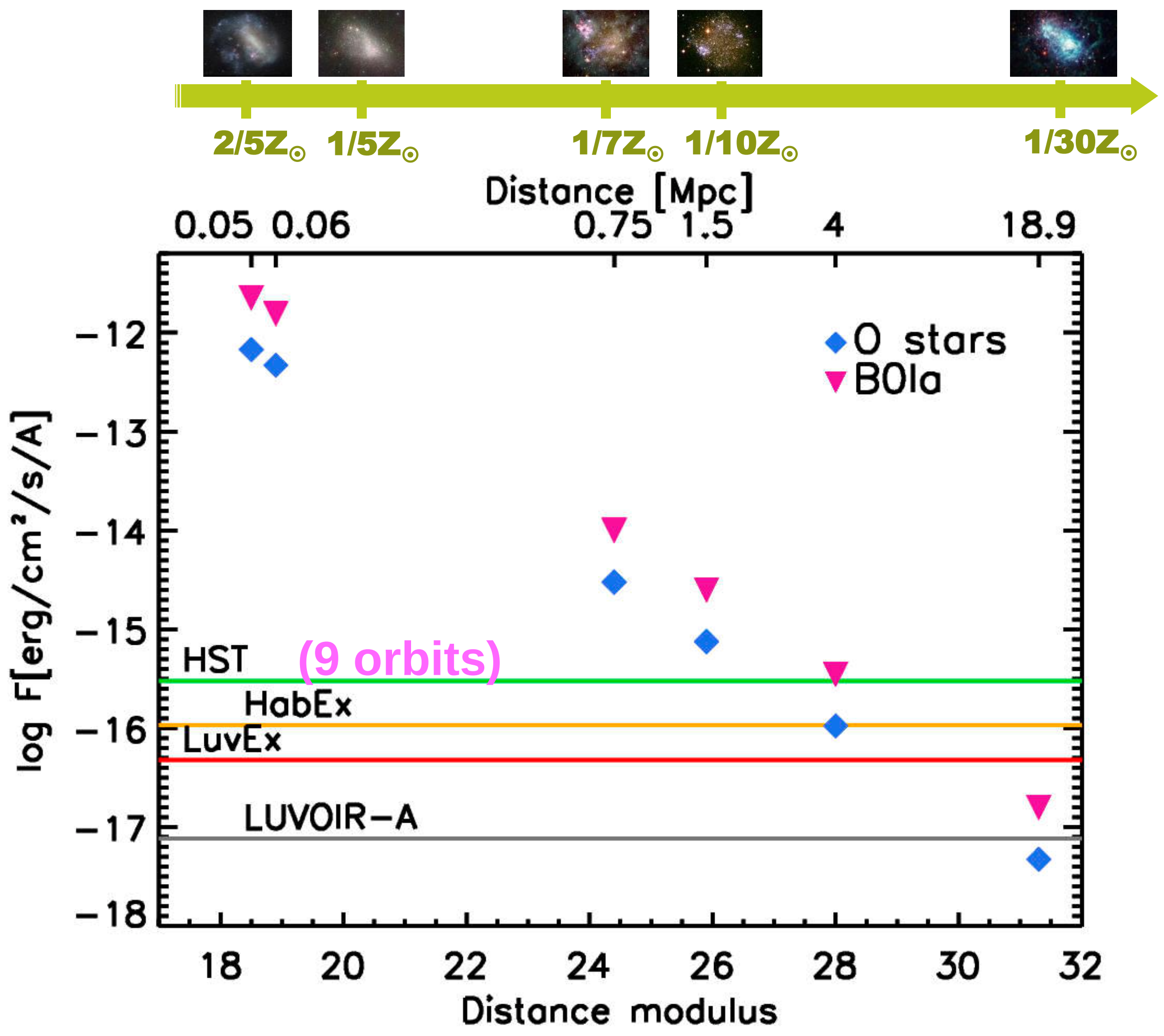
LUVEX (!?)

A 6m UV/Opt/IR telescope in space



LUVEX will reach moderately reddened O-stars **in the Local Group and nearby groups.**

Improving the detector sensitivity could compensate the mirror downsizing.



WHITE PAPER GOAL-2:
PROPOSE AN OPTICAL SPECTROGRAPH FOR LUVOIR

Optical range multi-object spectrograph to profit from LUVOIR's excellent image quality in the **optical range, over a large field of view**.

This will not be accessible to 30m telescopes + AO.

Table 1: *Level-zero technical specifications for an optical spectrograph onboard LUVOIR.*

Parameter	Value	Justification
Wavelength coverage	3600-7 000Å	Coverage for Balmer jump, optical diagnostic lines and $H\alpha$
Resolving power ($\lambda/\Delta\lambda$)	1 000	Massive stars beyond the Local Group (≥4 Mpc)
	8 000	Massive stars in the Local Group (≤1.5 Mpc)
	5 0000	Other (e.g. SB2 disentangling)
Faint limit, R=1 000	V=25	Bright O-stars in I Zw18
R=8 000	V=21	Faint O-stars in Sextans A
Field of view	$3' \times 1.6'$	To match the field of view of LUMOS FUV-MOS
Observing modes	Single-object Multi-object	
MOS-multiplex	>10. 50 optimal	Density of targets in Local Group dIrrs

Garcia+ 2021, white paper for Voyage 2050

CONCLUSIONS

- **Metal-poor massive stars** at the early epochs of the Universe may evolve very differently from massive stars today, with potentially great **impact on feedback** along cosmic history.
- **Observational evidence** for this problem is extremely **scarce**.
- **Ultraviolet spectroscopy** is critical to constrain their radiation-driven **winds**, which in turn make a fundamental part of evolution.
- A **6m, UV-optimized space telescope with a multi-object UV spectrograph** will characterize the winds of metal-poor massive stars, from moderately-reddened analogs in the Local Group.
- An **optical spectrograph (4000-5000Å)** to profit from the excellent image quality is needed to completely characterize metal-poor massive stars in crowded regions, a niche **inaccessible to AO** from the ground.

Thank you!