

Rotations of first stars: need of a theory anchored on present-day observational constraints

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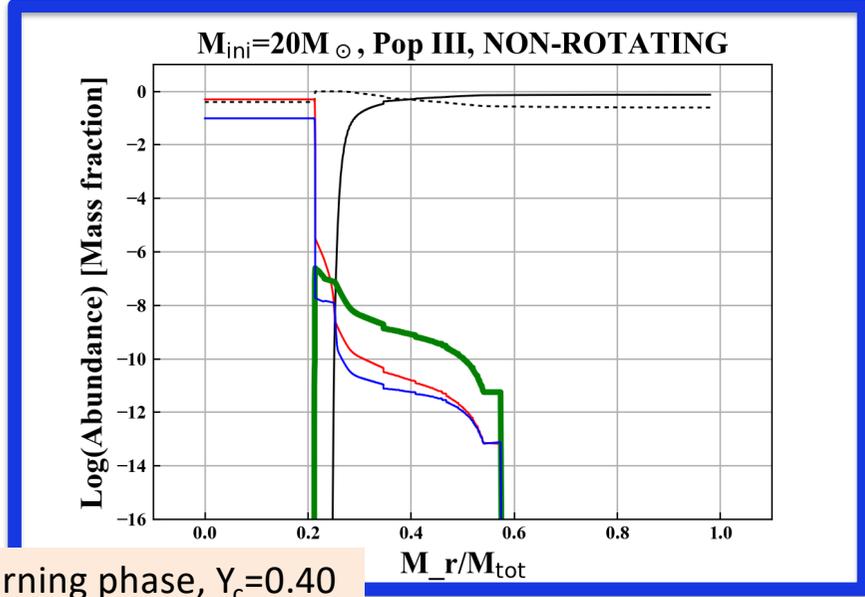
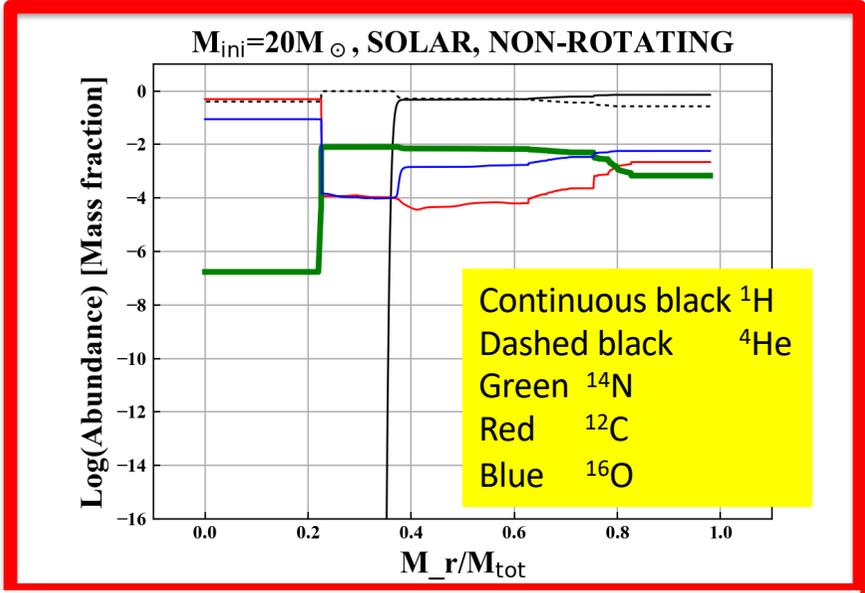
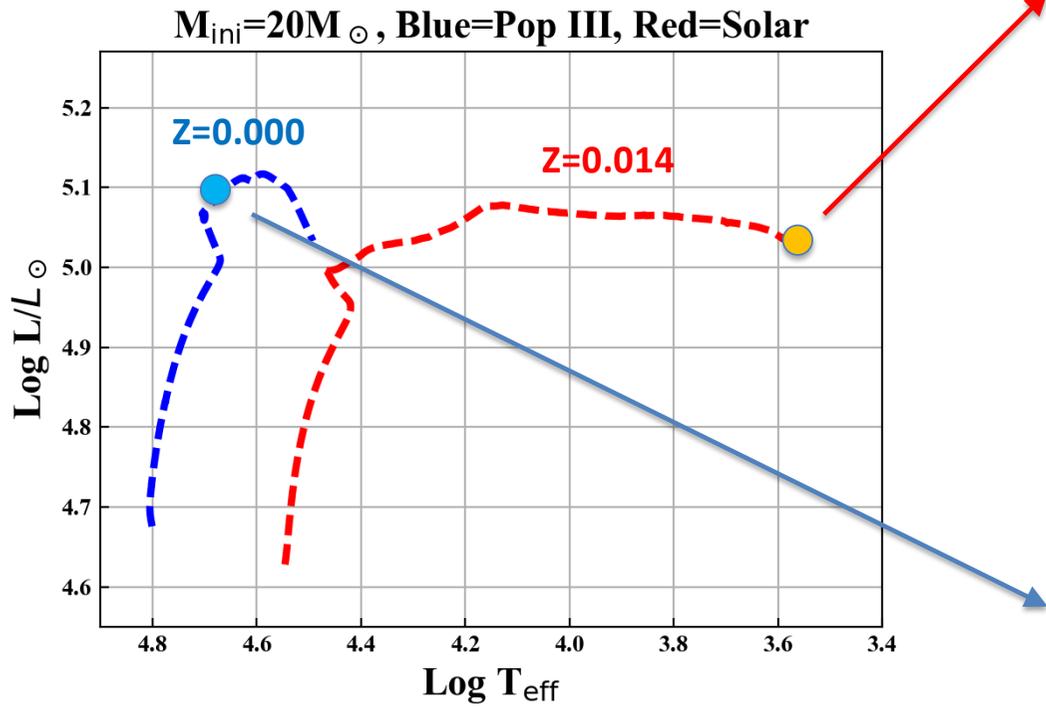


Laura Murphy
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**IMPACT OF A CHANGE OF METALLICITY
(NON-ROTATING MODELS)**

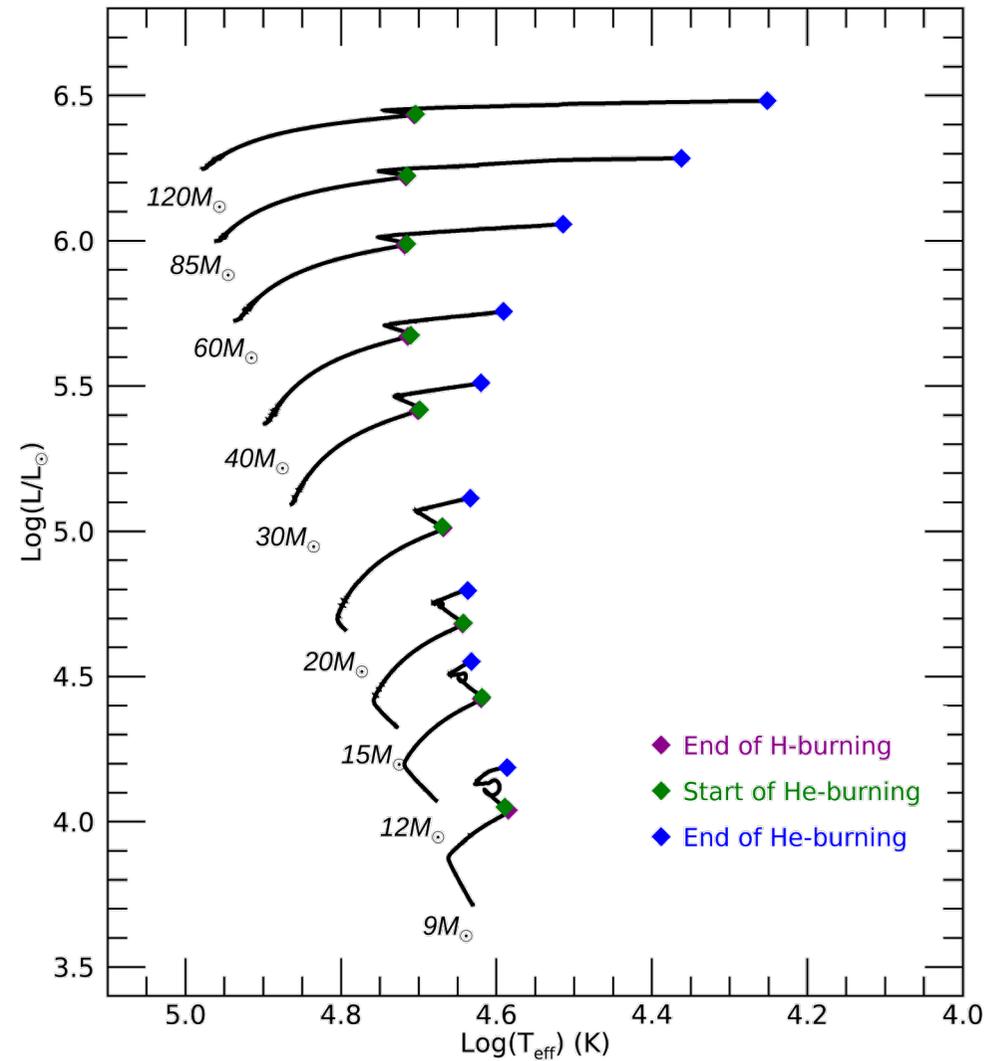


Core Helium burning phase, $Y_c=0.40$

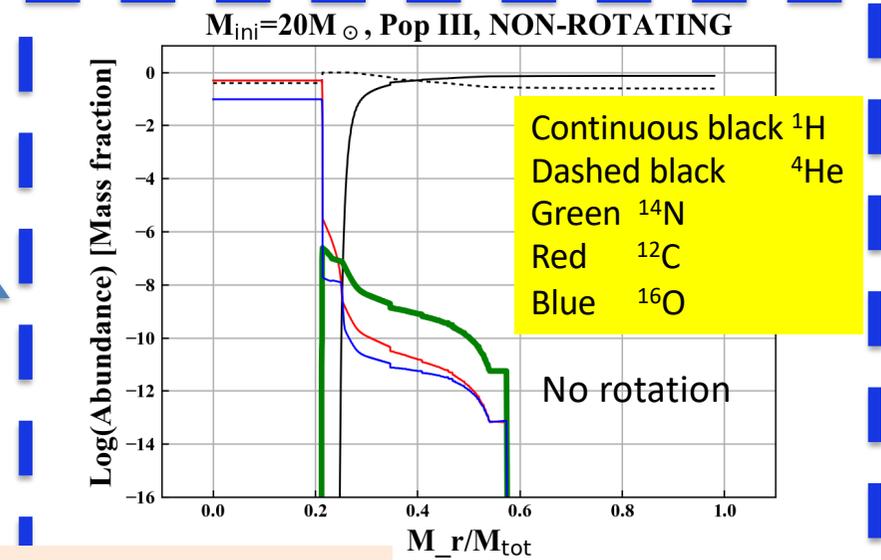
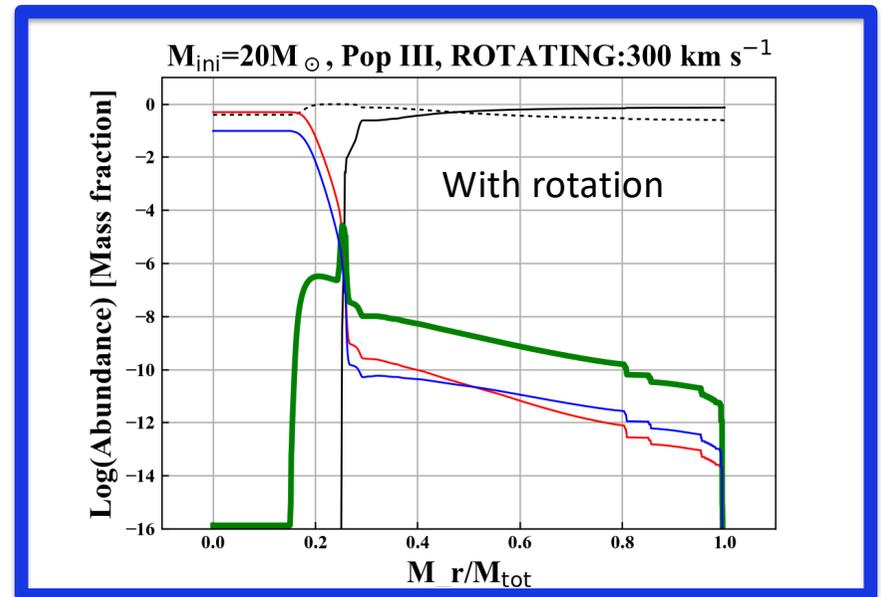
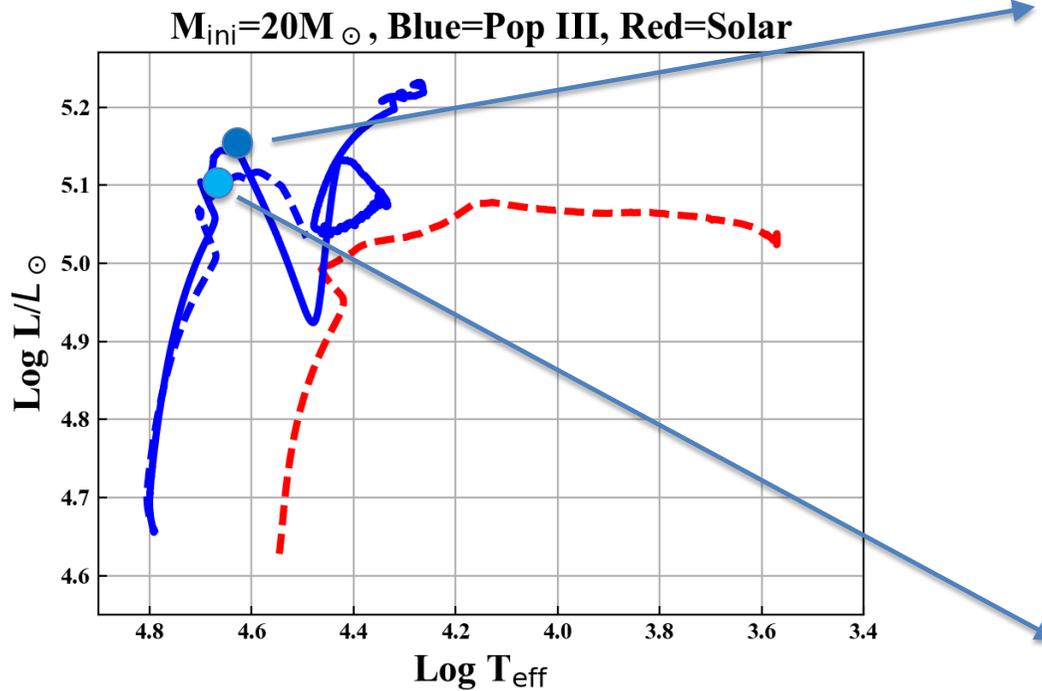
Grids of Stellar Models with Rotation V. Models from $9M_{\odot}$ to $120M_{\odot}$ at zero-metallicity

L. J. Murphy et al. in prep

- Initial contraction for lower mass models due to lack of CNO-elements
- Smooth transitions between burning phases due to high core temperatures
- Investigated for first time loop feature at start He-burning showing strength of H-burning shell
- Pop-III stars spend majority of life in blue, expect to produce many ionizing photons



**IMPACT OF ROTATION
(POP III MODELS-NON-DYNAMO MODELS)**

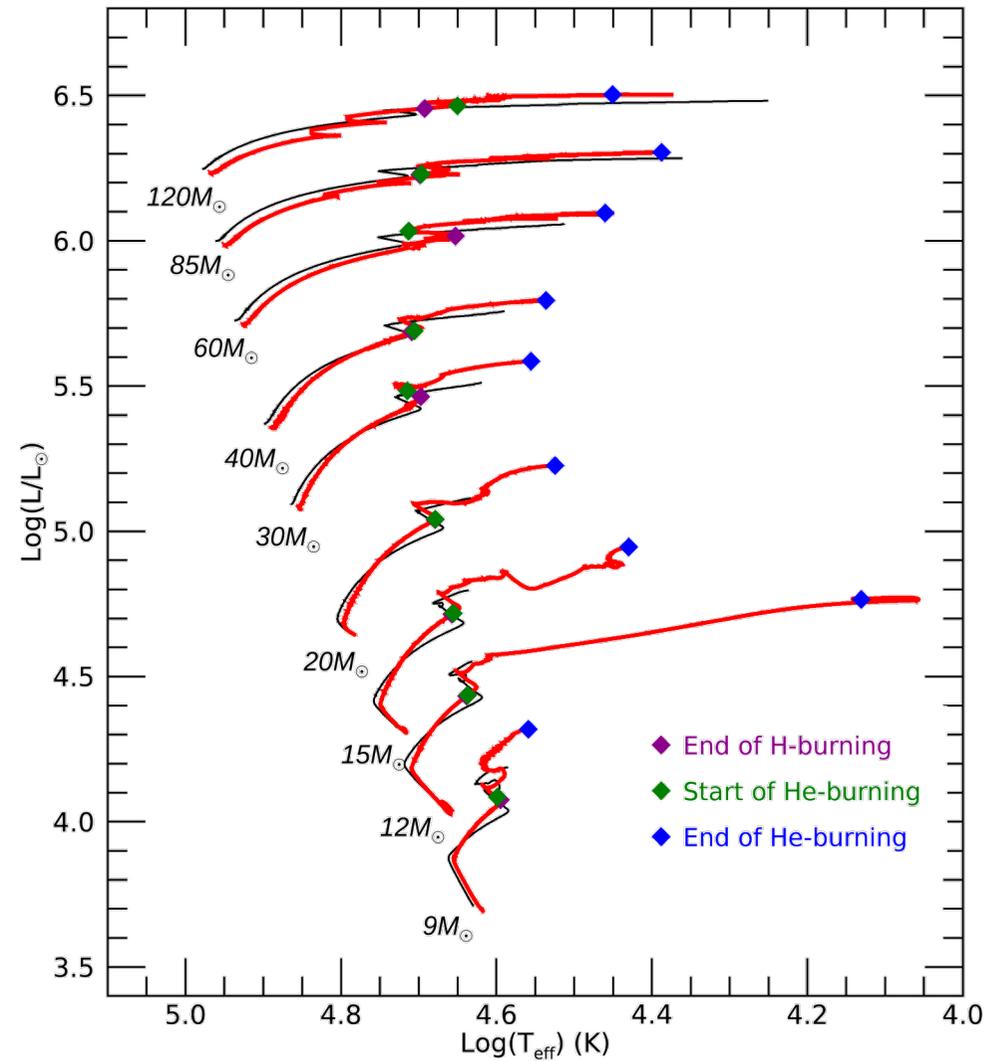


Core Helium burning phase

Grids of Stellar Models with Rotation V. Models from $9M_{\odot}$ to $120M_{\odot}$ at zero-metallicity

L. J. Murphy et al. in prep

- Rotation has little effect on MS surface evolution unless critical rotation reached
- Rotation has significant effect on He-burning for lower mass models
- Note vast difference in He-burning phase for $9, 12, 15M_{\odot}$ models, H-shell evolution dominates here

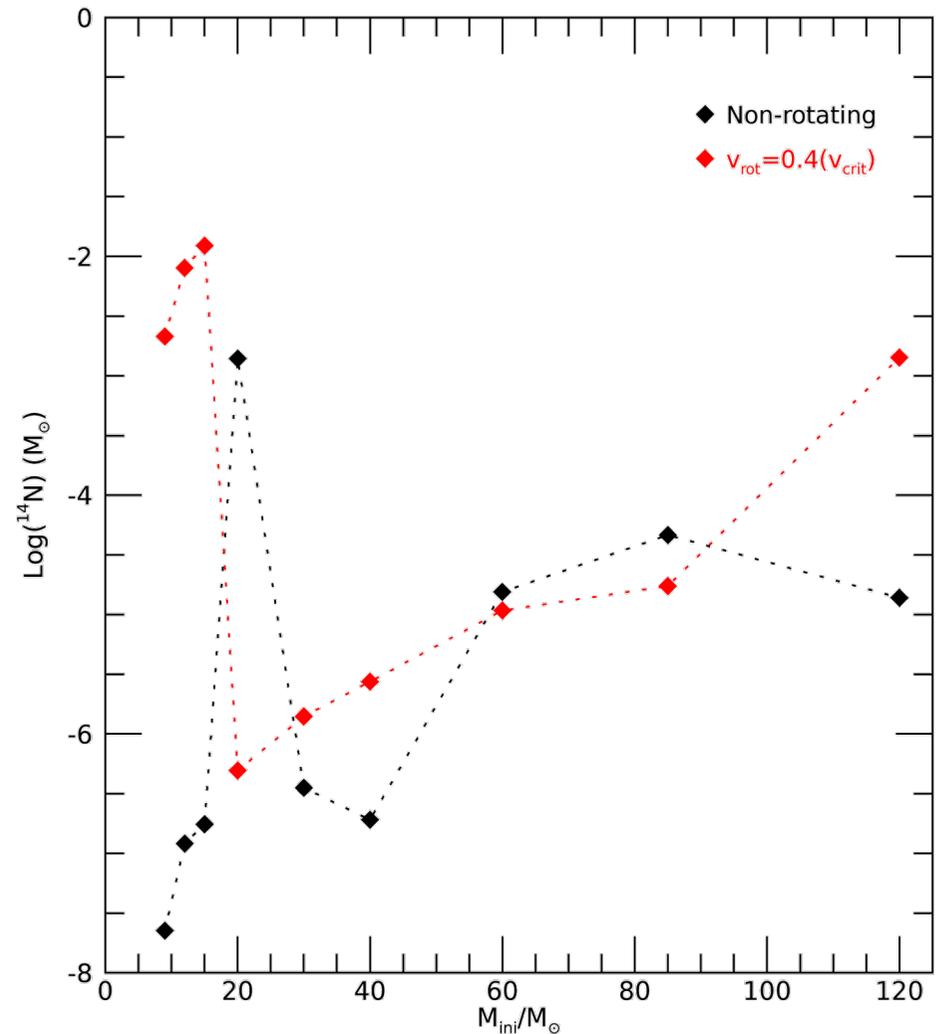


Grids of Stellar Models with Rotation

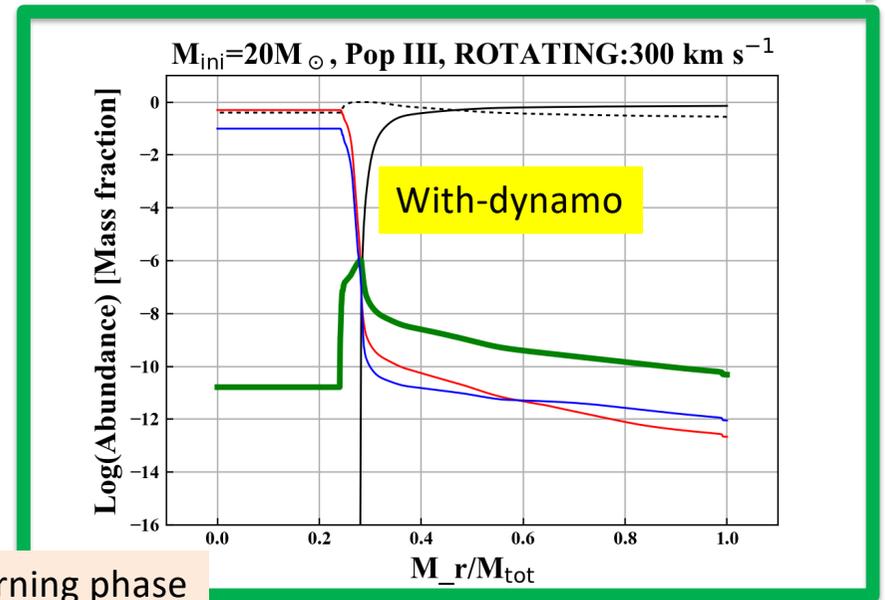
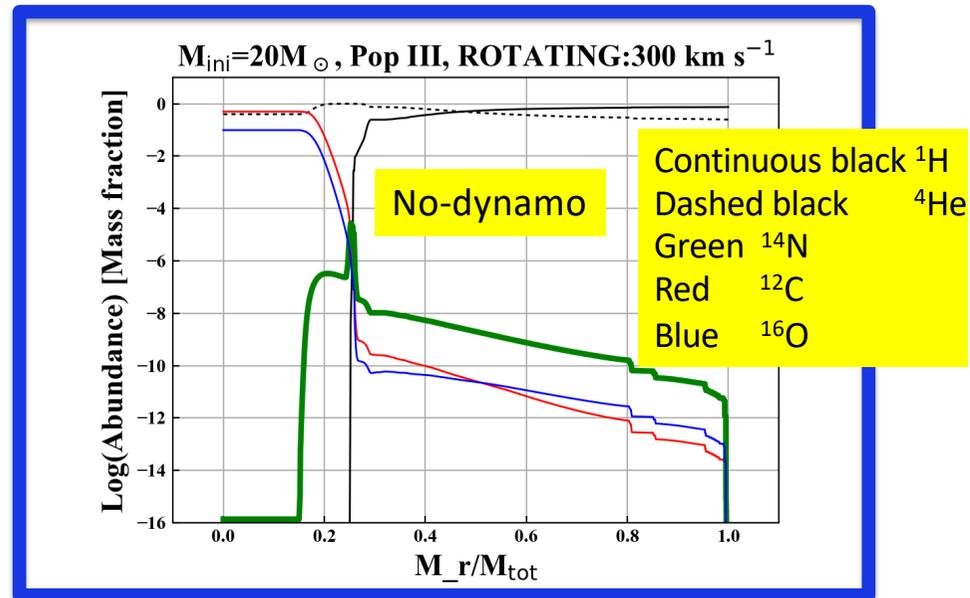
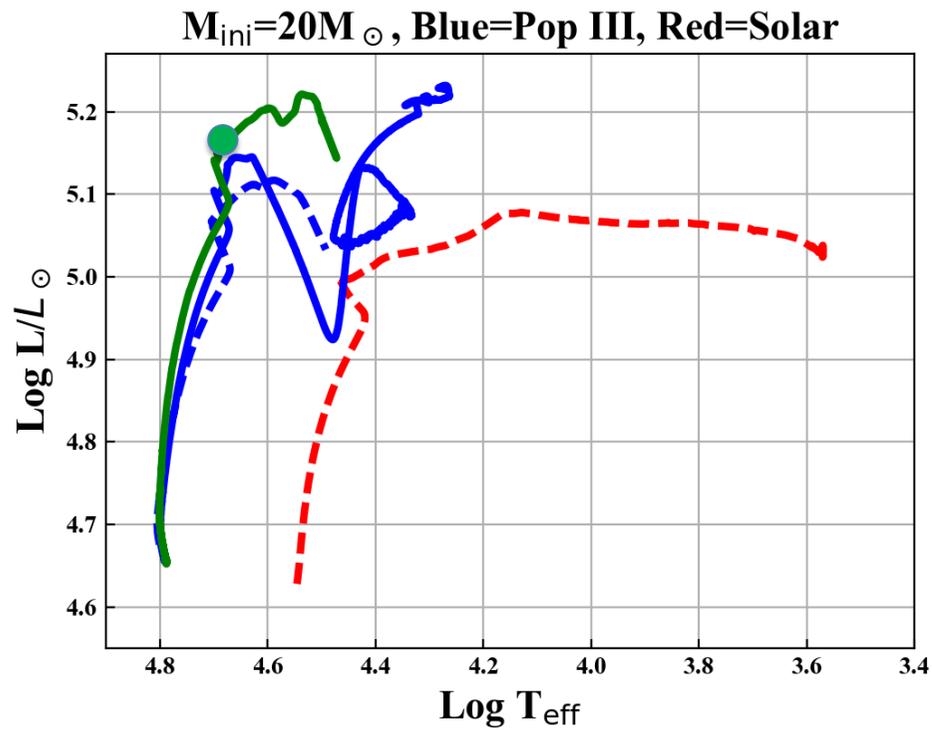
V. Models from $9M_{\odot}$ to $120M_{\odot}$ at zero-metallicity

L. J. Murphy et al. in prep

- N-production driven by strength of CNO boost
- $9, 12, 15M_{\odot}$ rotators experience strong CNO boost due to strength of H-burning shell
- Rotational mixing doesn't drive N-yields, affects surface N abundance not total N produced

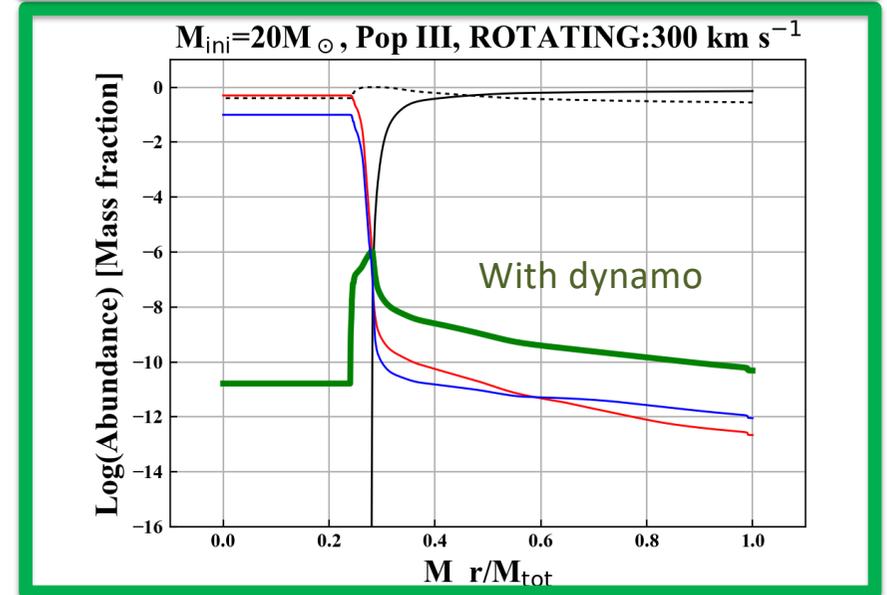
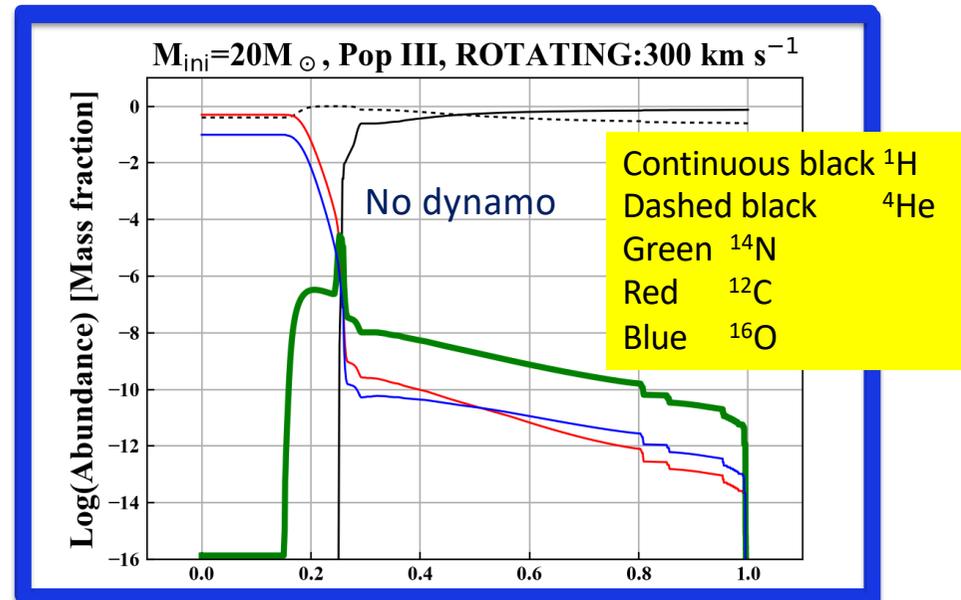
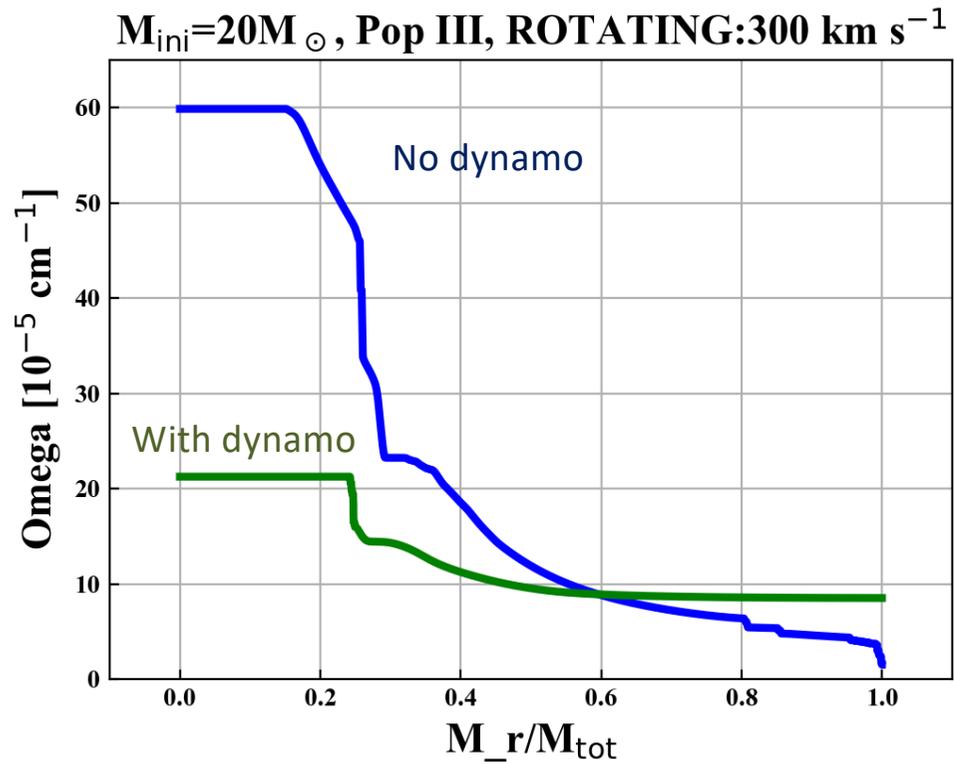


**IMPACT OF DYNAMO ON CHEMICAL STRUCTURE
(POP III MODELS)**



Core Helium burning phase

IMPACT OF DYNAMO ON INTERNAL ROTATION (POP III MODELS)



WHAT ARE THE OBSERVATIONAL CONSTRAINTS?

- 1) EVOLUTION OF THE SURFACE ROTATION-SURFACE ABUNDANCES (see Brott+2011ab, Ekström+ 2012)
- 2) HELIOSEISMOLOGY & ASTEROSEISMOLOGY (see Eggenberger+2019ab)
- 3) YOUNG PULSAR ROTATION RATES-WHITE DWARF SPIN (see Heger+2005; Georgy+2012; den Hartogh 2019)
- 4) SPIN OF MERGING BLACK HOLES (see Marchant+2016; Mandel & de Mink 2016; Qin+2018; Bavera+2019 Belczynski+2017)
- 5) SPIN OF BH IN X-Ray Binaries (see Qin+2019)

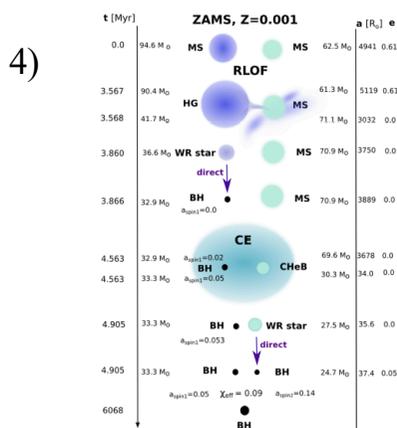
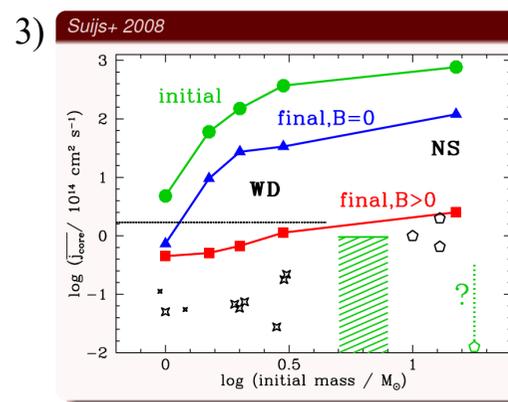
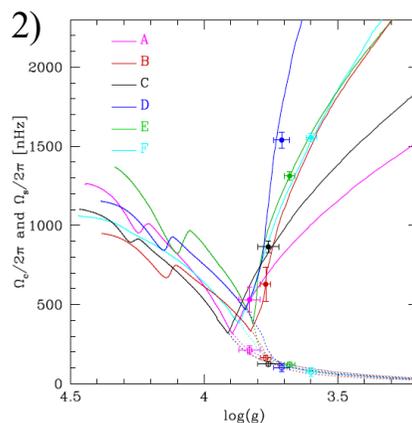
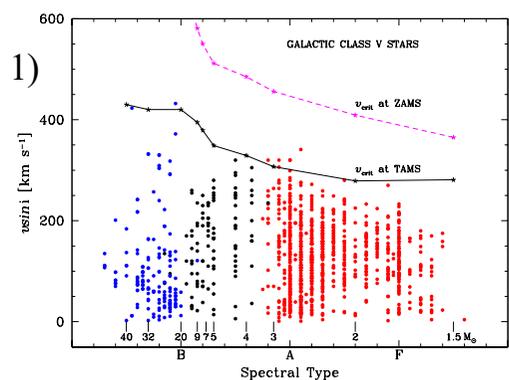
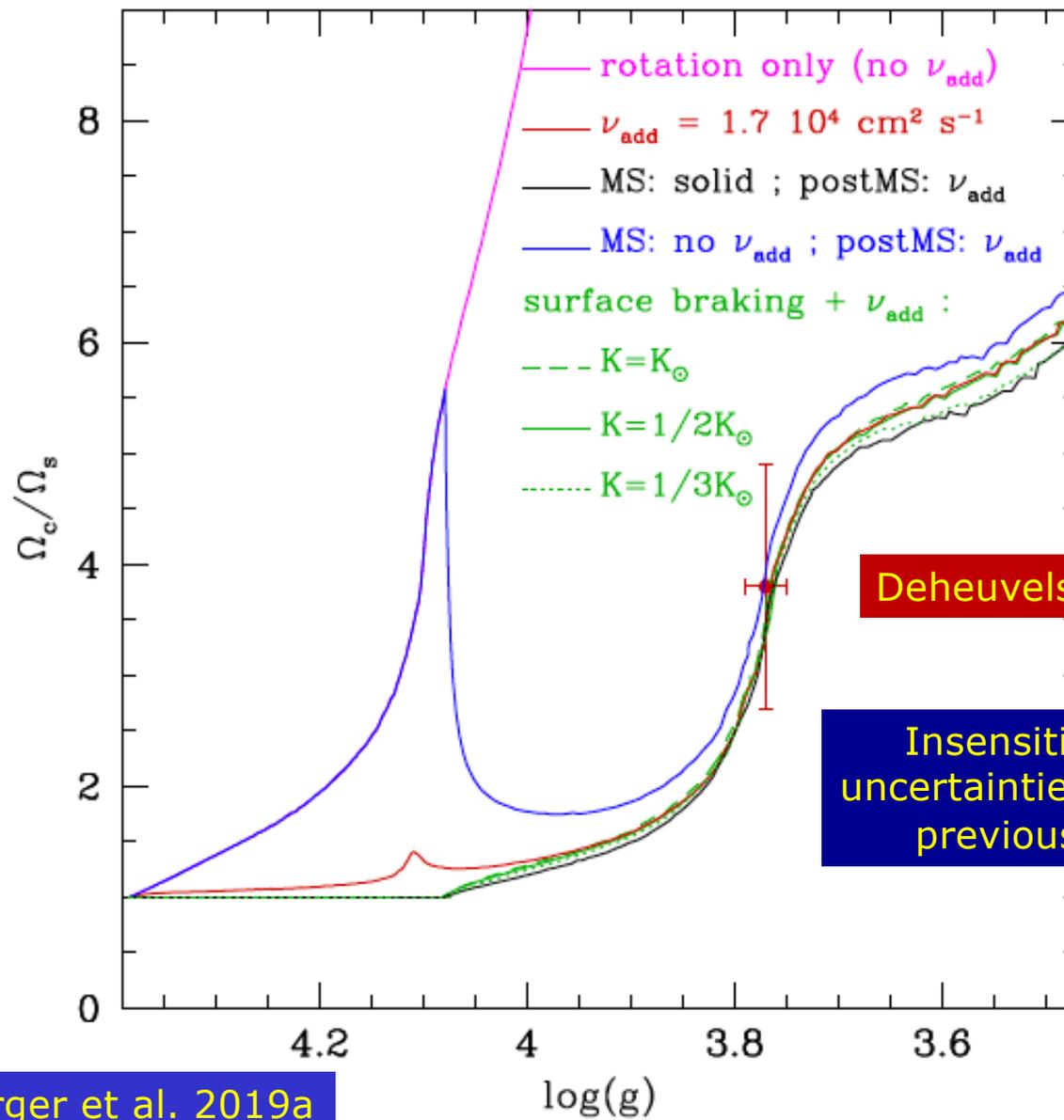


Table 1: BH spins via Continuum Fitting method

Sources	a_*	M/M_\odot	$P_{\text{orb}}/\text{days}$	References
HMXBs				
Cyg X-1	>0.983	14.8 ± 1.0	5.60	Gou et al. (2014)
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	3.91	Gou et al. (2009)
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	3.45	Liu et al. (2008, 2010)
LMXBs				
GRS 1915+105	>0.98	10.1 ± 0.6	33.9	McClintock et al. (2006)
4U 1543-47	0.80 ± 0.05	9.4 ± 1.0	1.12	Shafee et al. (2006)
GRO J1655-40	$0.70_{\pm 0.05}$	6.3 ± 0.5	2.26	Shafee et al. (2006)
XTE J1550-564	$0.34^{+0.20}_{-0.5}$	9.1 ± 0.6	1.54	Steiner et al. (2011)
LMC X-3	$0.25^{+0.13}_{-0.16}$	7.6 ± 2.6	1.70	Steiner et al. (2014a)
A0620-00	0.12 ± 0.19	6.6 ± 0.25	0.32	Gou et al. (2010)



Slowing the spins of stellar cores

MNRAS 2019

Jim Fuller,^{1★} Anthony L. Piro² and Adam S. Jermyn³

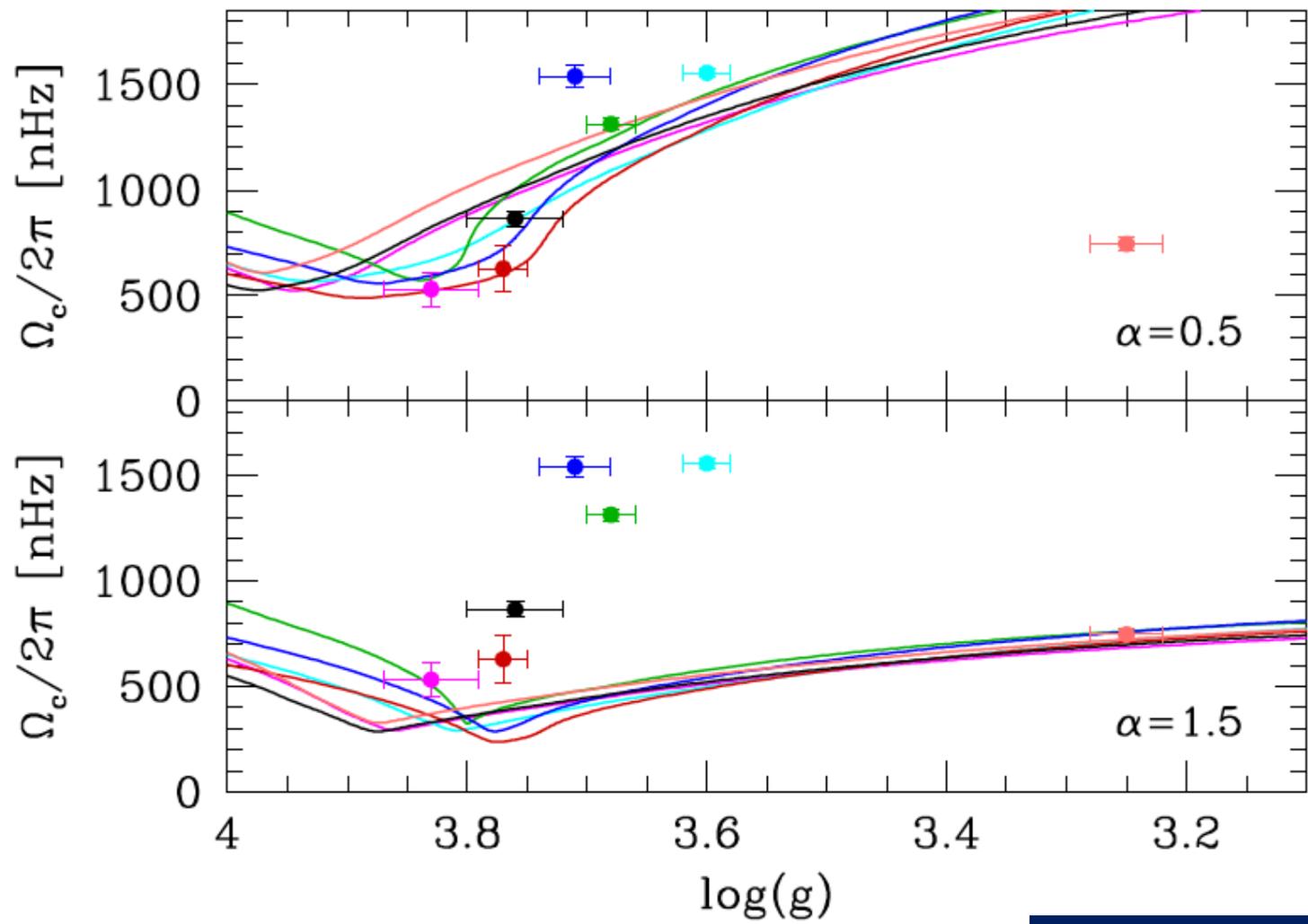
Magnetic Tayler instability saturates when turbulent dissipation of the perturbed magnetic field energy is equal to magnetic energy generation via winding.

According to Fuller et al 2019, the damping rate is much smaller than in the original Spruit theory

This allows stronger magnetic field to be reached and hence stronger coupling.

$$\nu_T = \alpha^3 r^2 \Omega \left(\frac{\Omega}{N_{\text{eff}}} \right)^2 \quad q_{\text{min}} = \alpha^{-3} \left(\frac{N_{\text{eff}}}{\Omega} \right)^{5/2} \left(\frac{\eta}{r^2 \Omega} \right)^{3/4}$$

$$N_{\text{eff}}^2 = \frac{\eta}{K} N_T^2 + N_\mu^2$$



CONCLUSIONS

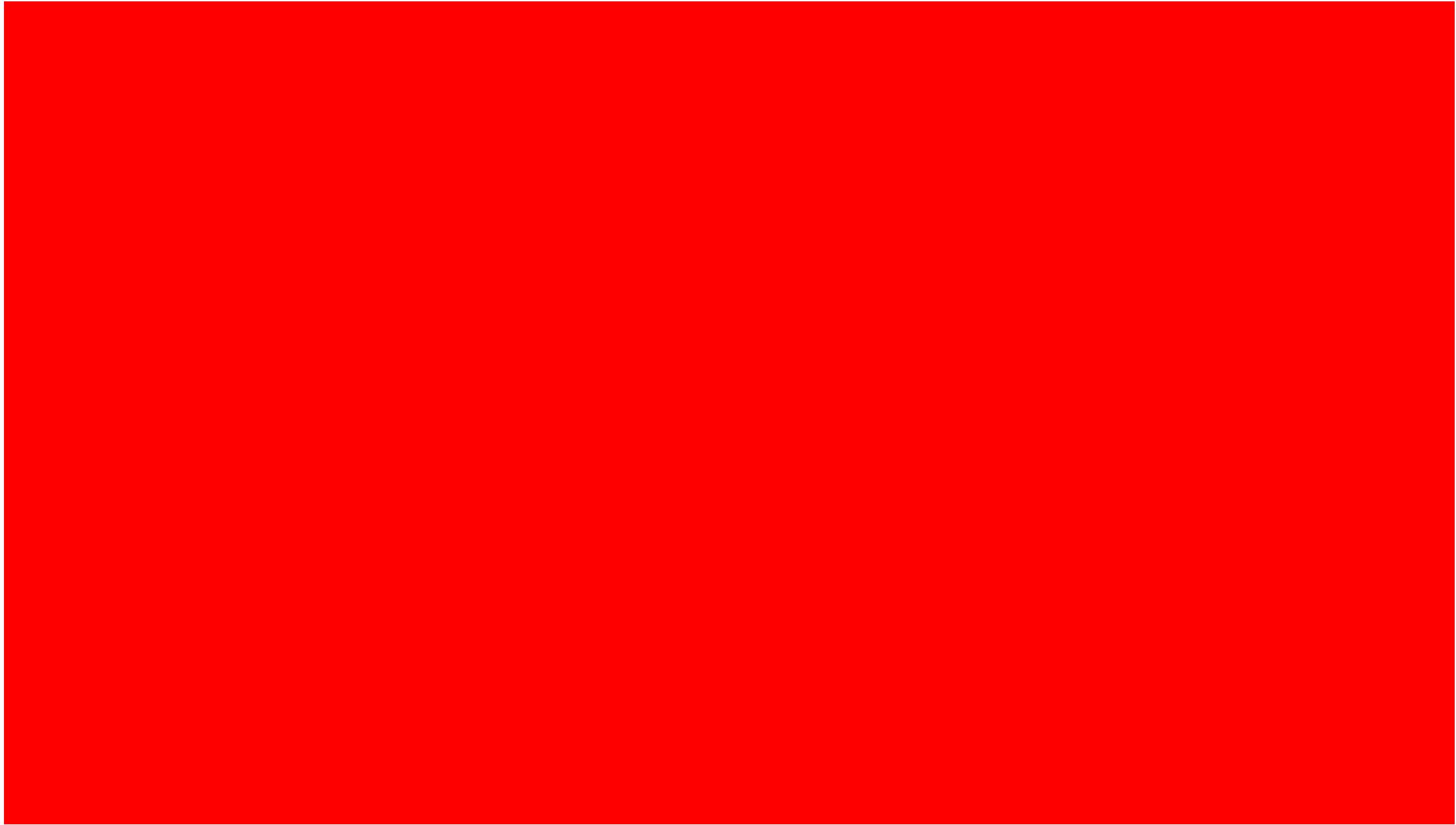
- Physics used to model stars that we cannot see should be tested on stars that we can observe.
- Helioseismology and asteroseismology have brought new key constraints on the angular momentum transport processes in stars.
- Still some work to be done for finding the best physics of the angular momentum transport in stars, but progresses are presently made.
- This physics has consequences for nucleosynthesis (link with CEMP stars), for ionizing luminosities, and for the transient (Supernovae, GW events) properties.



**The details are
making the
perfection and
the perfection is
not a detail.**

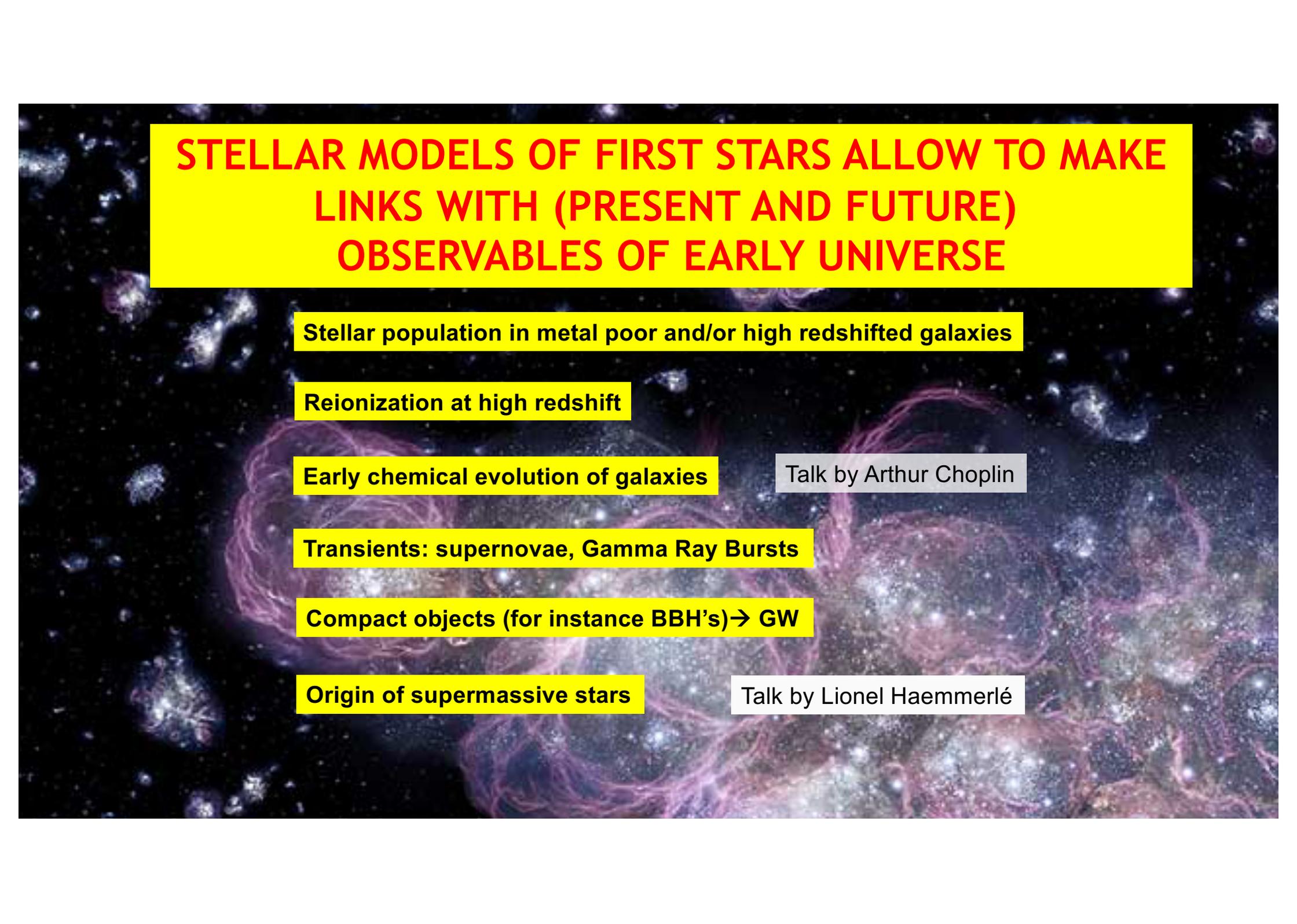
Léonard de Vinci

**Extrait des
carnets**



What we would like to know about the first stars

- Upper - lower stellar masses formed
- IMF
- Important physical ingredients
 - Formation
 - Rotation
 - Magnetic fields
 - Multiplicity
 - Impact of Dark Matter?
 - Change of fundamental constant?

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as glowing purple and blue structures against a black background, with numerous small, bright blue and white points representing galaxies and star-forming regions.

STELLAR MODELS OF FIRST STARS ALLOW TO MAKE LINKS WITH (PRESENT AND FUTURE) OBSERVABLES OF EARLY UNIVERSE

Stellar population in metal poor and/or high redshifted galaxies

Reionization at high redshift

Early chemical evolution of galaxies

Talk by Arthur Choplin

Transients: supernovae, Gamma Ray Bursts

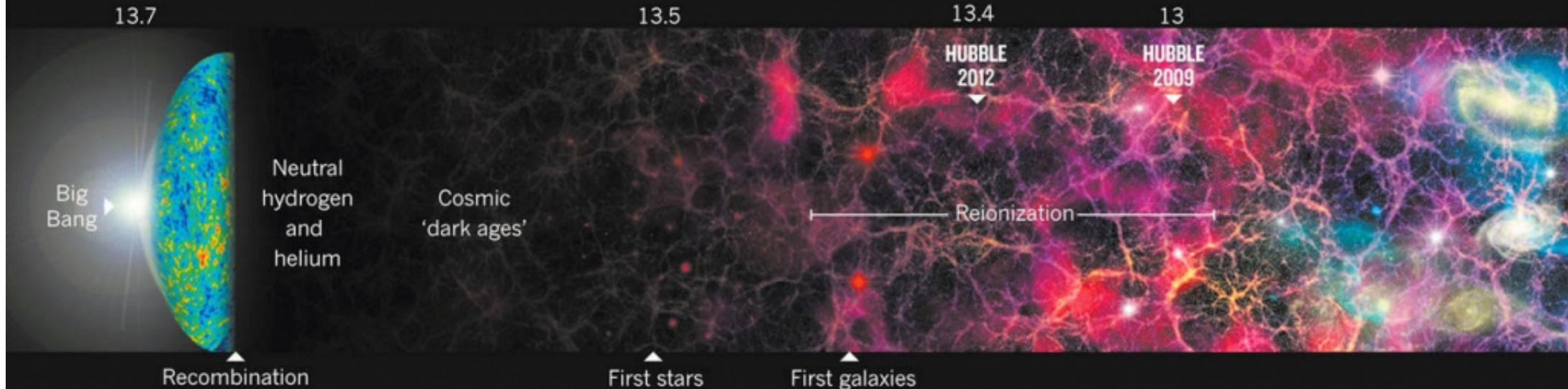
Compact objects (for instance BBH's) → GW

Origin of supermassive stars

Talk by Lionel Haemmerlé

THE PHYSICS THAT IS SUCCESSFUL FOR REPRODUCING OBSERVED FEATURES OF STARS IN THE PRESENT-DAY UNIVERSE SHOULD BE OUR FIRST CHOICE FOR MODELING THE EVOLUTION

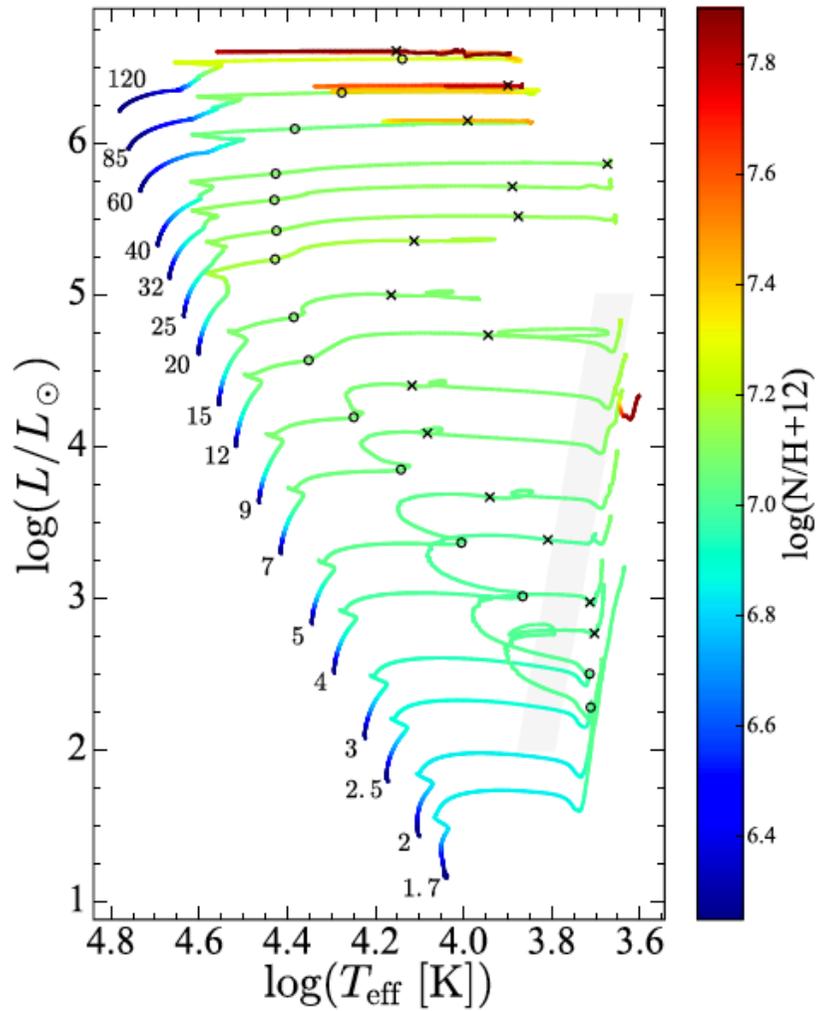
OF THE FIRST GENERATIONS OF STARS



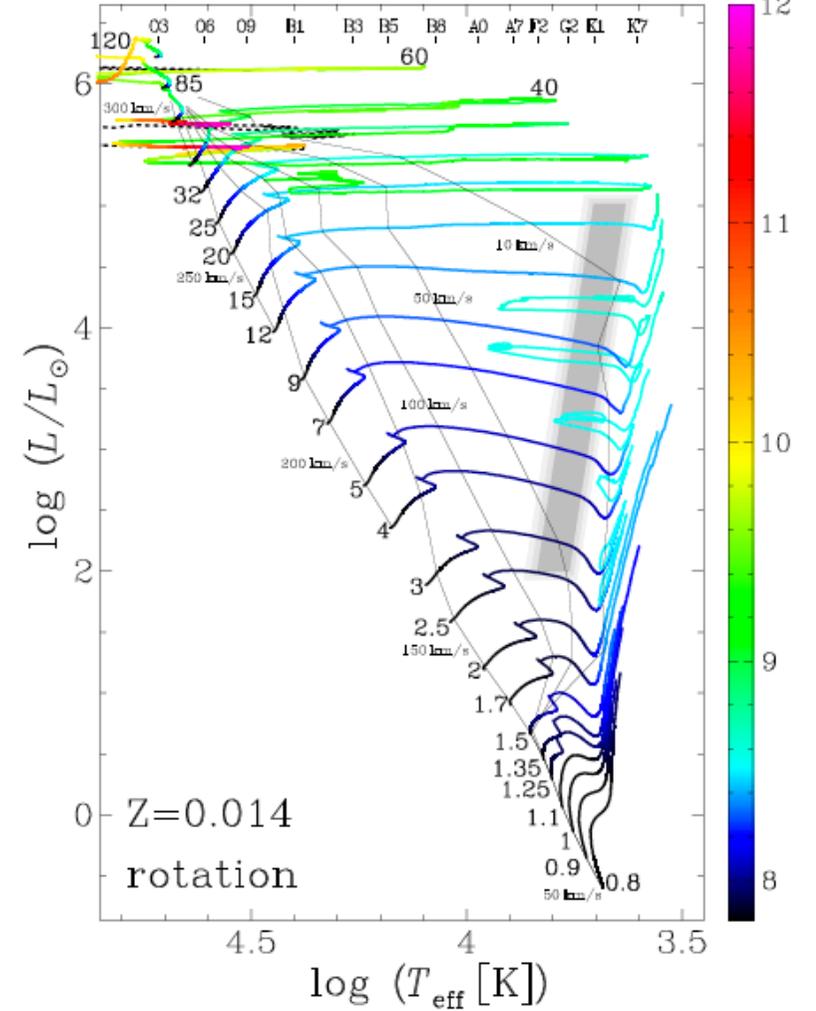
OUR TARGET:
UNVEILING THE
PROPERTIES OF
FIRST STARS

THE OBSERVED
CONSTRAINED
ARE IN THE PRESENT
DAY UNIVERSE

Z=0.0004 Groh et al. 2019



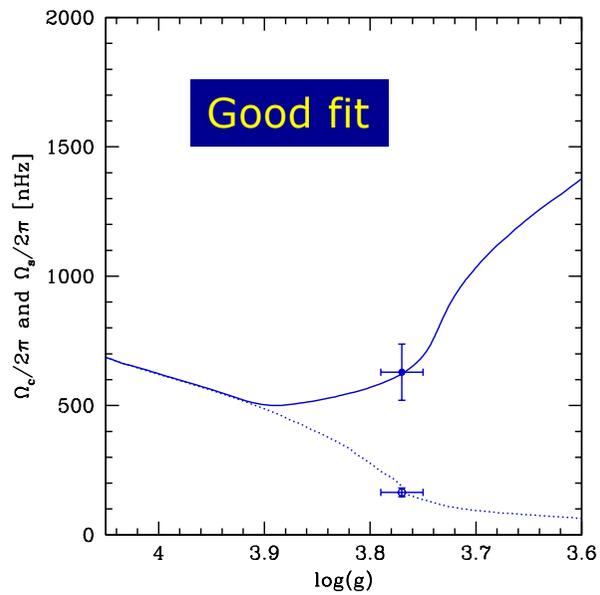
Z=0.014 Ekström et al. 2012 $\log(N/H)+12$



<https://www.unige.ch/sciences/astro/evolution/en/database/>

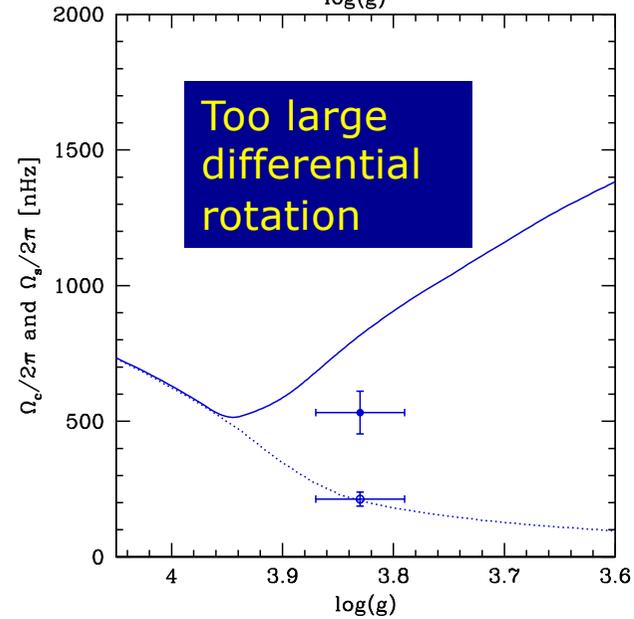
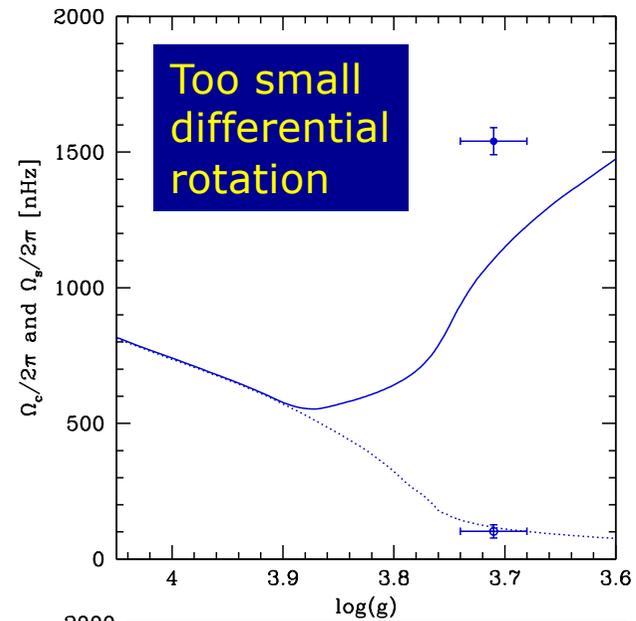
See also Georgy et al. 2013, Z=0.002, in preparation Z=0.000, 0.006, 0.020

Comparisons with subgiants
Using the Fuller's et al
prescription



2 stars over 6 correctly reproduced

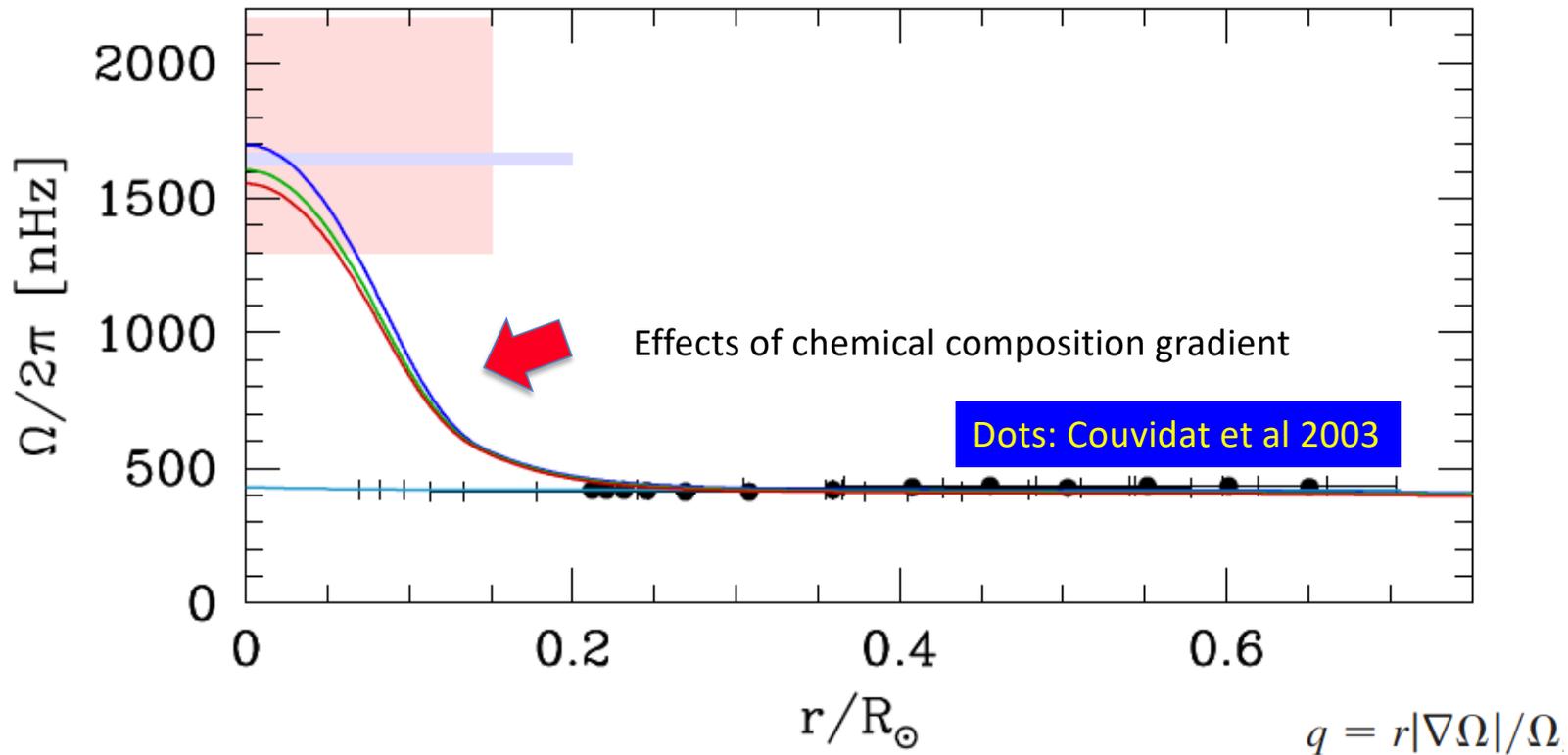
Observations: Deheuvels et al 2014
Eggenberger et al. In preparation



Rotation rate of the solar core as a key constraint to magnetic angular momentum transport in stellar interiors

P. Eggenberger¹, G. Buldgen¹, and S.J.A.J. Salmon²

2019



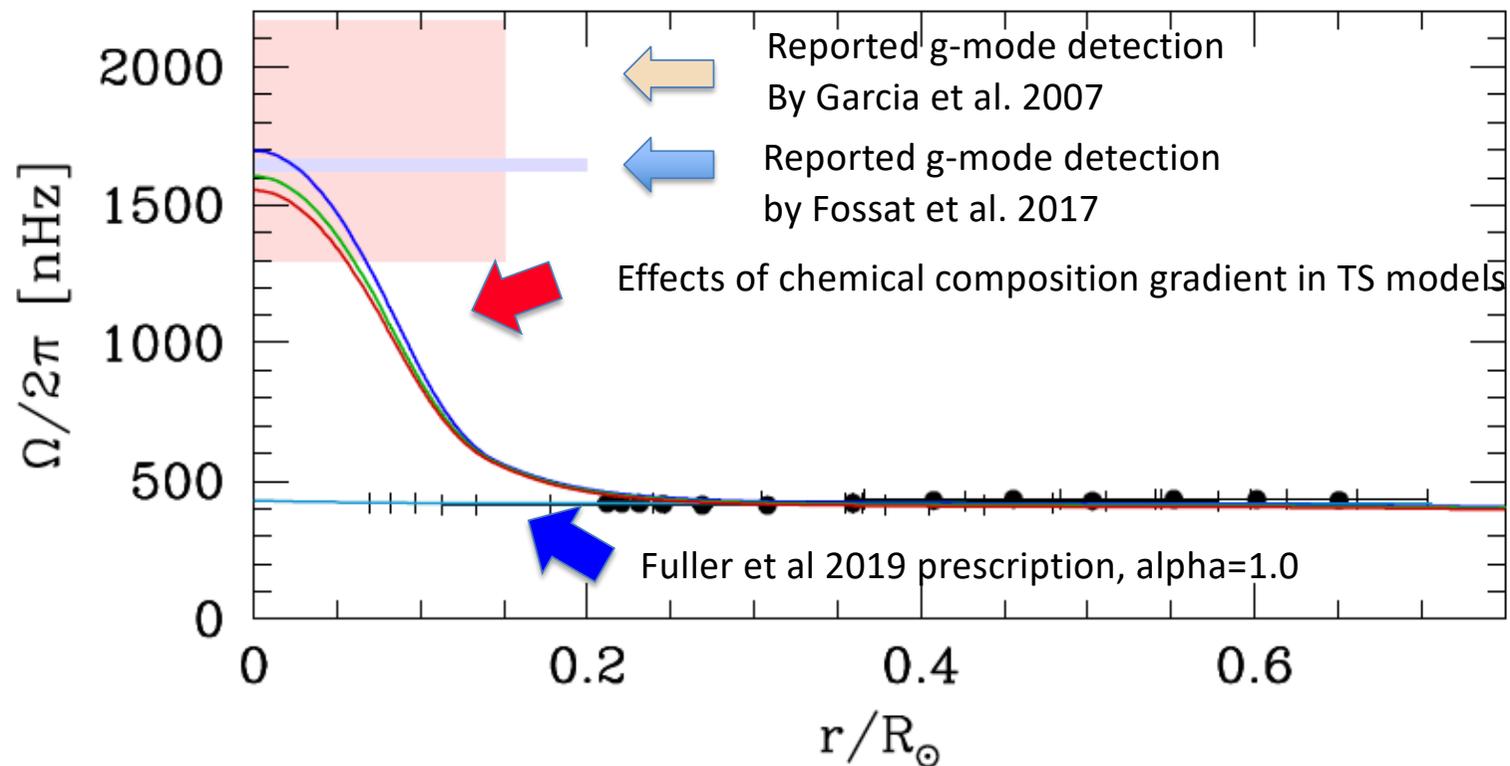
$$v_{\text{TS}} = r^2 \Omega q^2 \left(\frac{\Omega}{N_\mu} \right)^4 ; q_{\text{min}} = \left(\frac{N_\mu}{\Omega} \right)^{7/4} \left(\frac{\eta}{r^2 N_\mu} \right)^{1/4}$$

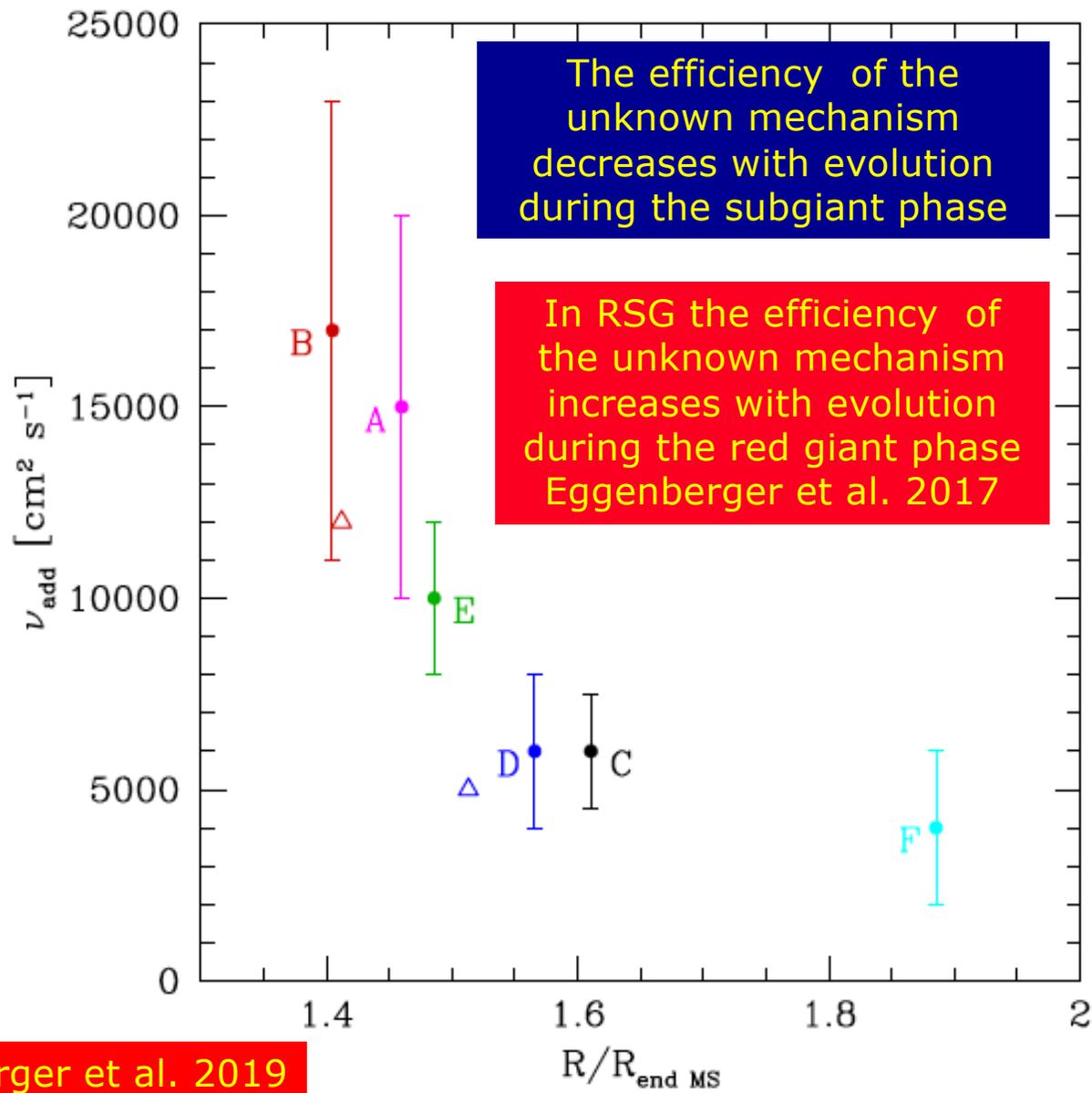
$v_{\text{TS}} \text{ prop to } N_\mu^{-1}$

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2019





Eggenberger et al. 2019