Stars at the extreme

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European Research Council

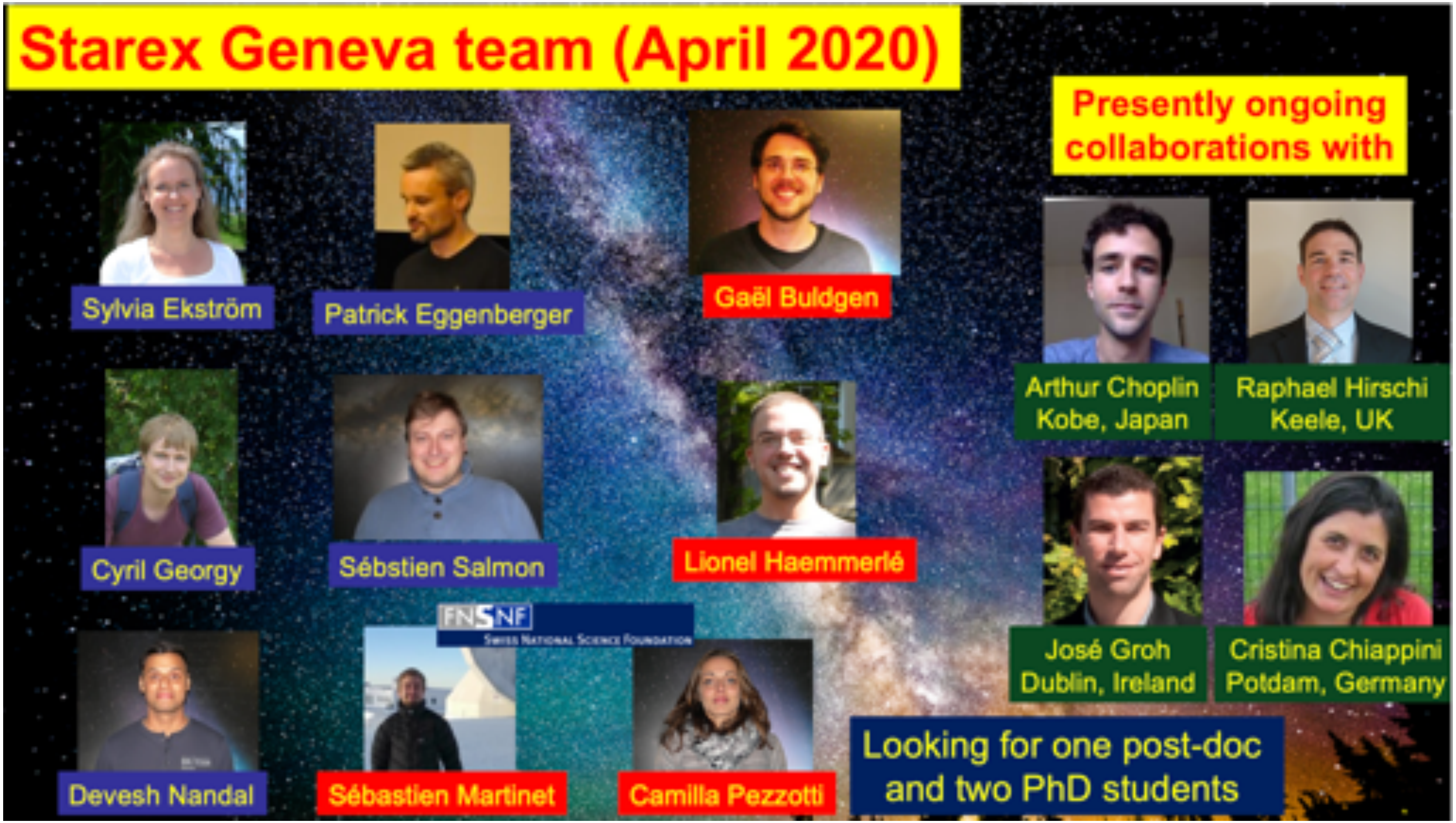
Established by the European Commission

STAREX

2020-2024

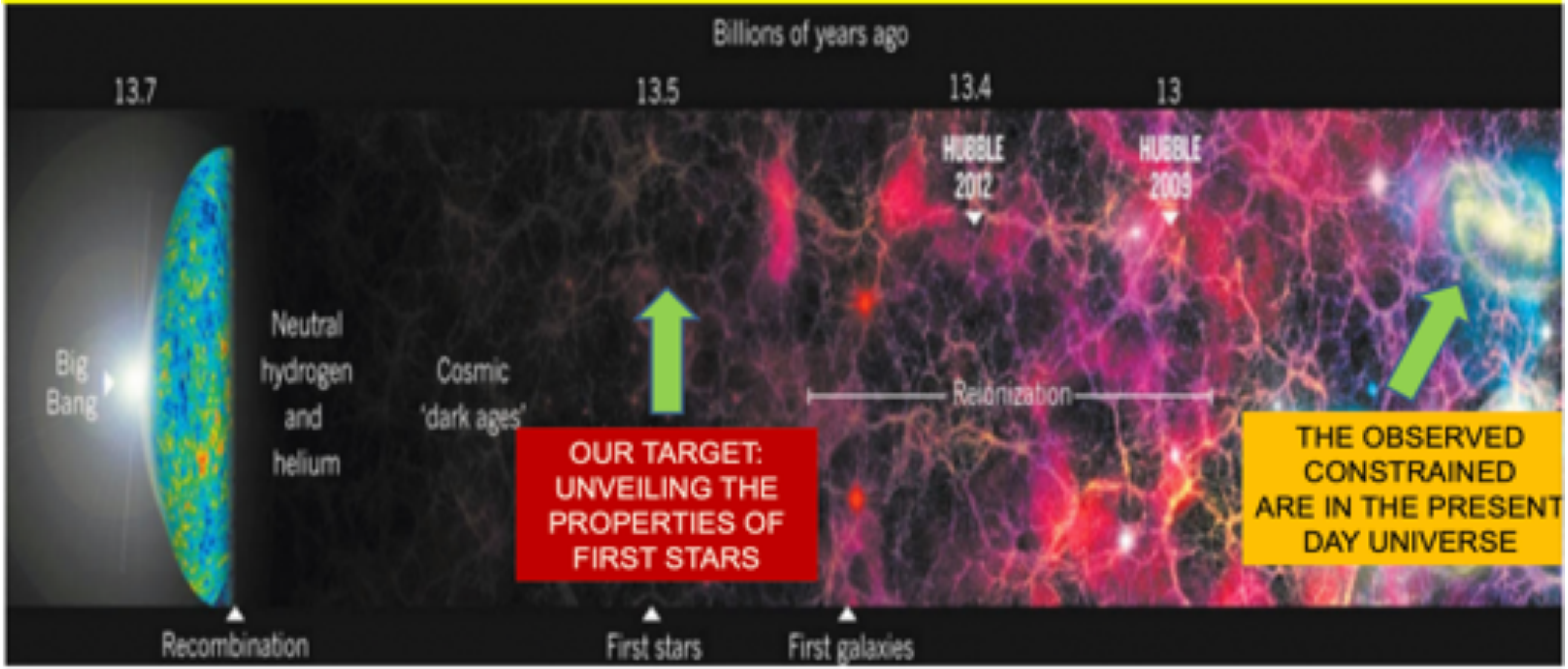
I am walking to know where I am going.
Goethe

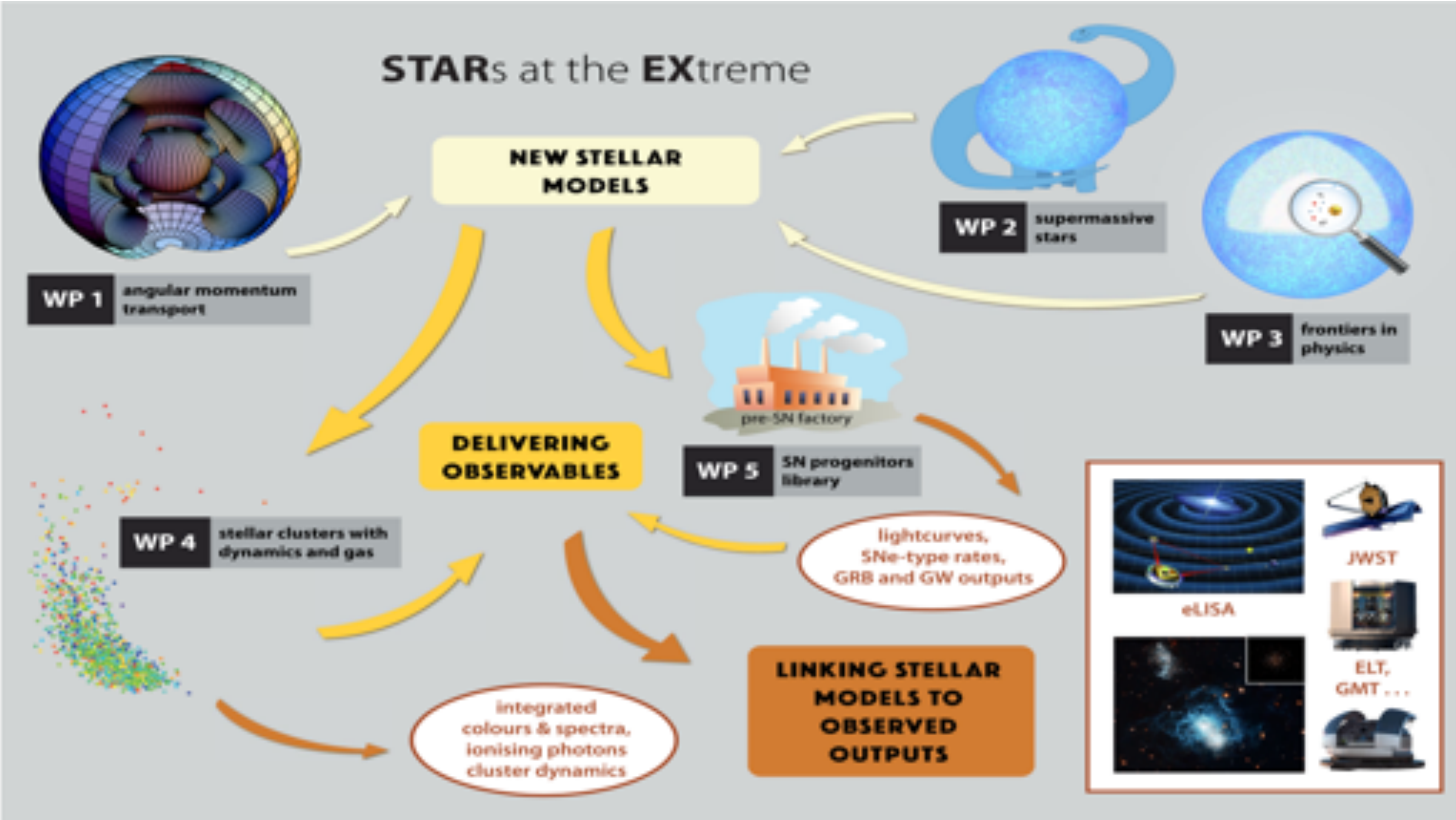
…We are doing research to know what we are looking for.


Starex Geneva team (April 2020)
Presently ongoing collaborations with
Sylvia Ekström
Patrick Eggenberger
Gaël Buldgen
Arthur Choplin
Kobe, Japan
Raphael Hirschi
Keele, UK
Cyril Georgy
Sébstien Salmon
Lionel Haemmerlé
José Groh
Dublin, Ireland
Cristina Chiappini
Potdam, Germany
FNSNF
Swiss National Science Foundation
Devesh Nandal
Sébastien Martinet
Camilla Pezzotti
Looking for one post-doc and two PhD students

From normal stars to extreme stars…

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



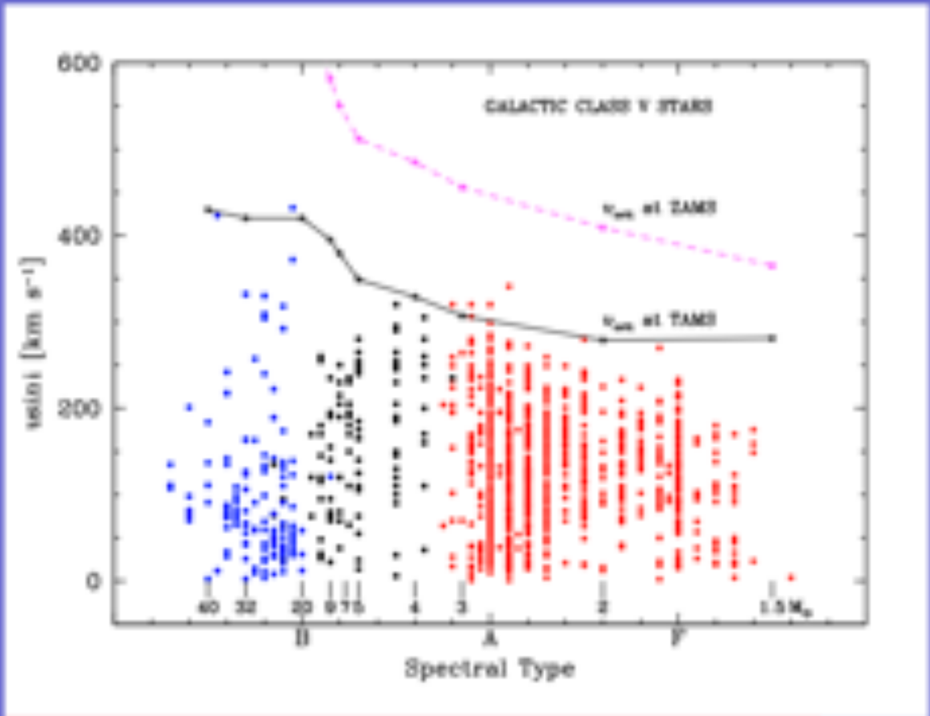


STARs at the EXtreme
NEW STELLAR MODELS
WP 1 angular momentum transport
WP 2 supermassive stars
WP 3 frontiers in physics
pre-SN factory
WP 5 SN progenitors library
DELIVERING OBSERVABLES
WP 4 stellar clusters with dynamics and gas
lightcurves, SNe-type rates, GRB and GW outputs
integrated colours & spectra, ionising photons cluster dynamics
LINKING STELLAR MODELS TO OBSERVED OUTPUTS
eLISA
JWST
ELT, GMT . . .

THE CONTEXT

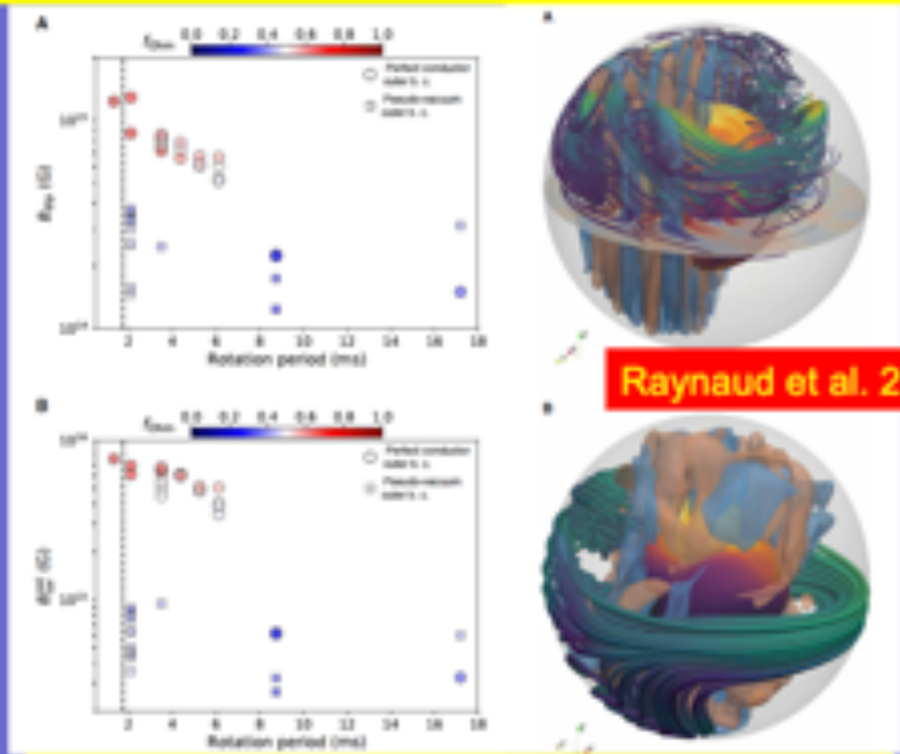
Stars have angular momentum

Importance of being able to trace its evolution



Howarth et al. 97,Dufton et al. 2006, Hunter et al. 2009, Zorec and Royer 2012

First three-dimensional simulations of a convective dynamo based on a protoneutron star interior model



Raynaud et al. 2020

Protomagnetar models of gamma-ray burst and superluminous supernova central engines

THE CHALLENGES

Many interacting processes

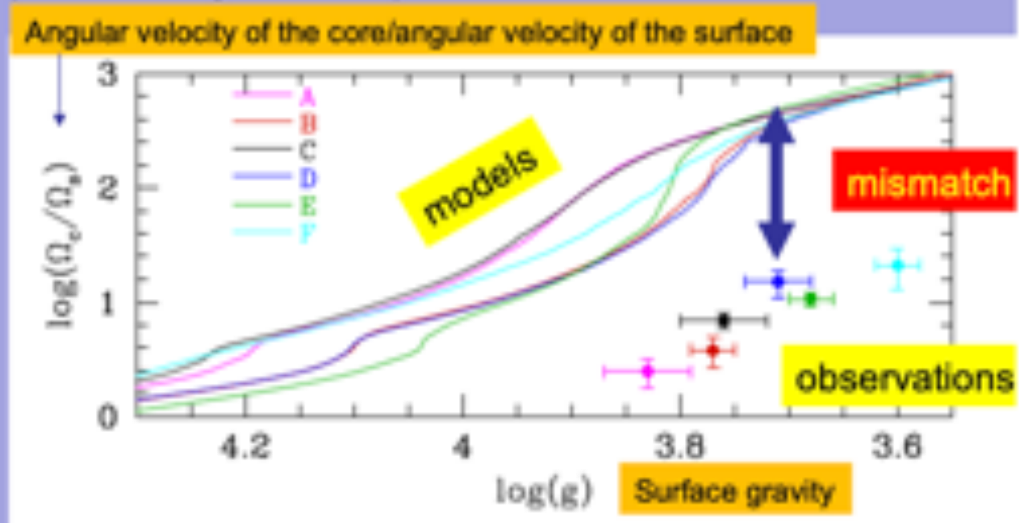
The missing angular momentum transport

Single and close binary stars

- **INTERNAL ANGULAR MOMENTUM TRANSPORT (internal magnetic field)**
- MASS LOSSES BY LINE DRIVEN WINDS (surface magnetic field)
- MECHANICAL MASS LOSSES

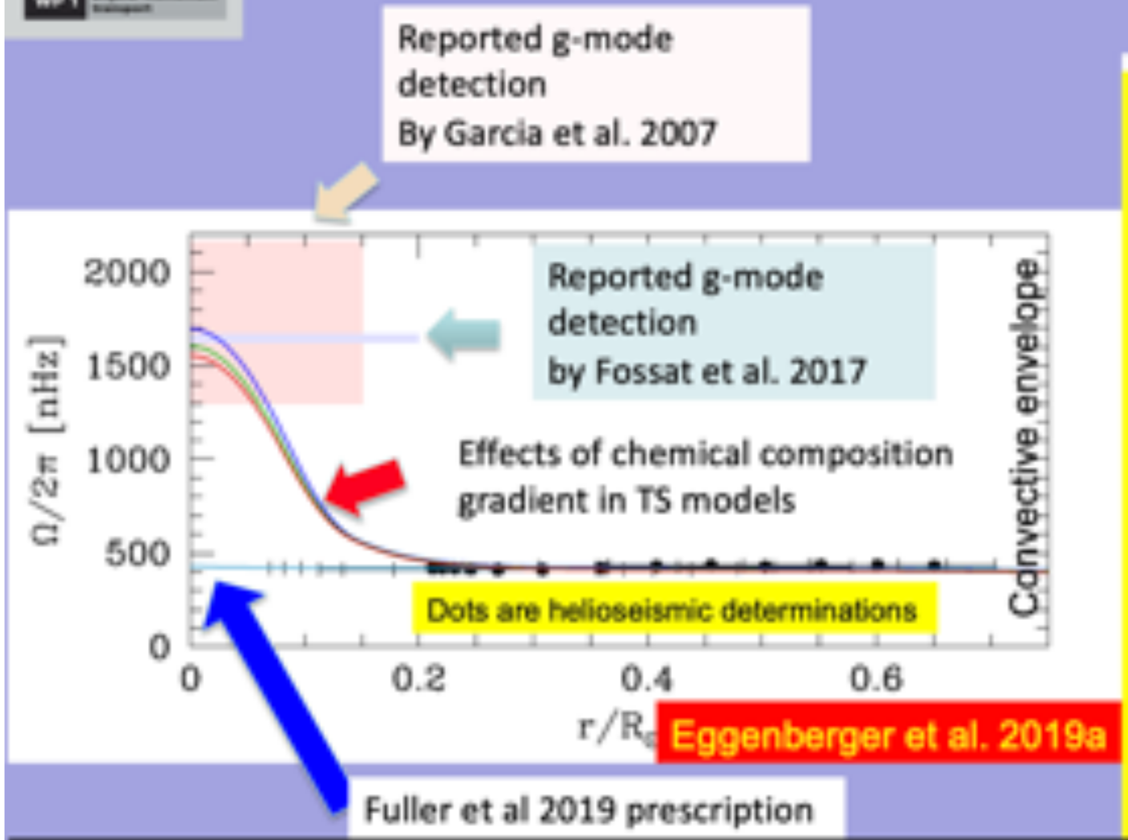
Close binary stars

- TIDAL INTERACTIONS
- MASS TRANSFER IN CLOSE BINARIES
- COMMON ENVELOPE PHASE
- MERGING



Shellular models: Eggenberger et al. 2019b
→Masses : 1.15-1.4 M_{sol},
→V_{rot}(ZAMS): 4-8 km s^{-1}
Observations: Deheuvels et al 2014

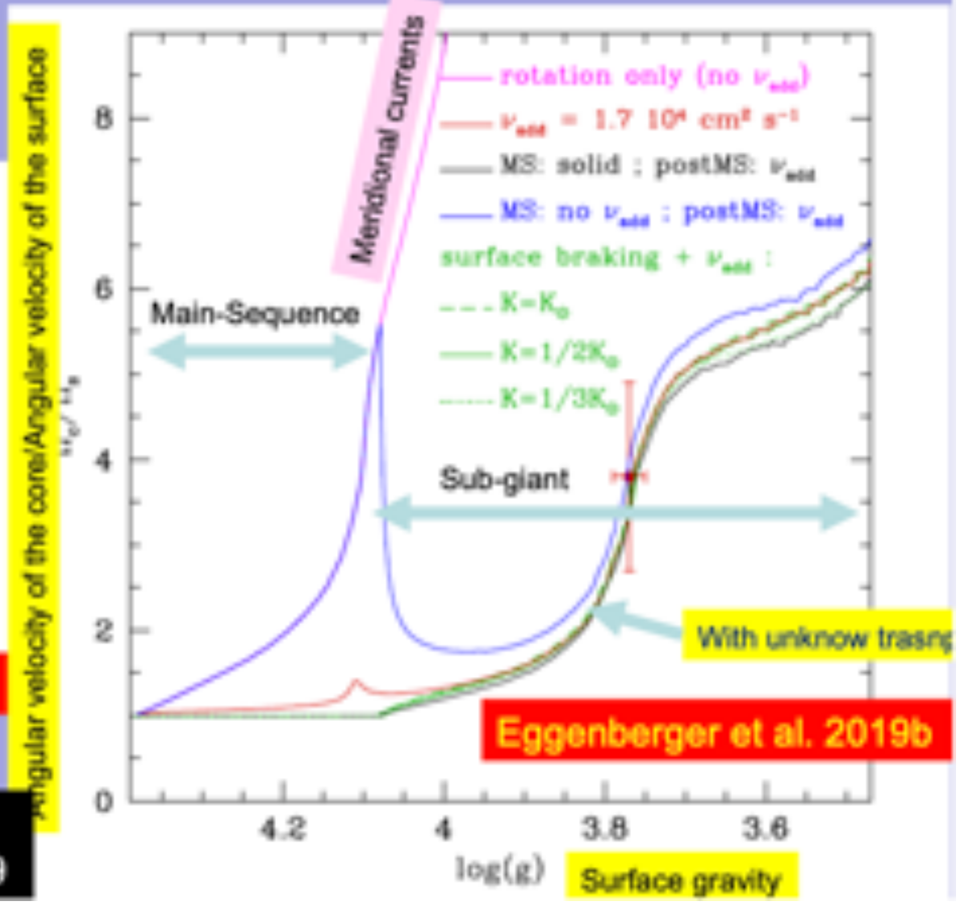
WHAT HAS BEEN DONE SO FAR



Physics of the instability
Zahn 1992; Maeder & Zahn 1998; Spruit 2002; Fuller et al. 2019

Impact of different prescriptions

Properties of the missing transport

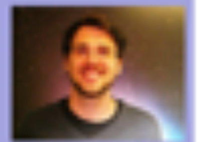


WHAT WE PLAN TO DO

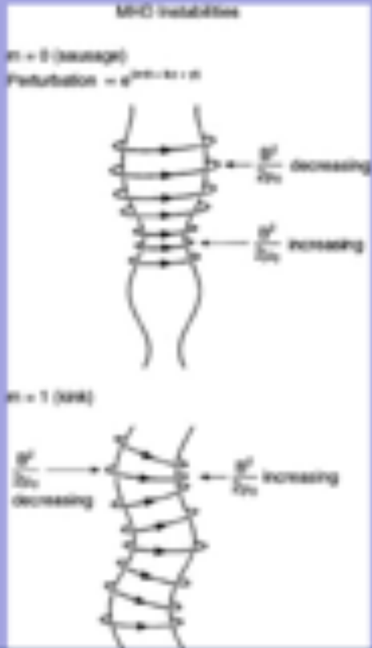
Analytical expressions for new processes to be tested with asteroseismic constraints

Interactions between hydrodynamical and magneto-hydrodynamical processes

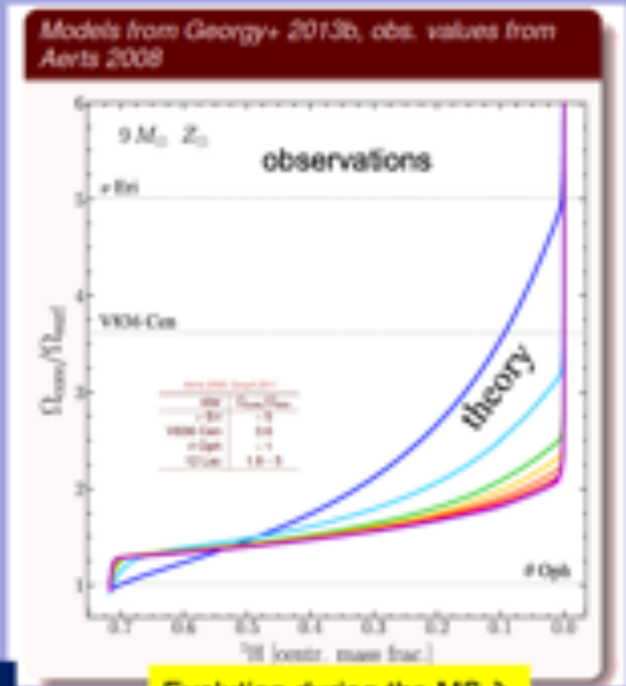
Core Team on WP 1



In non stratified regions:
Magneto-Rotational-instabilities
https://mri.pppl.gov/physics.html



In stratified regions
Tayler-instability



Evolution during the MS→

Beta Cephei stars
Also with solar-type oscillators

THE CONTEXT

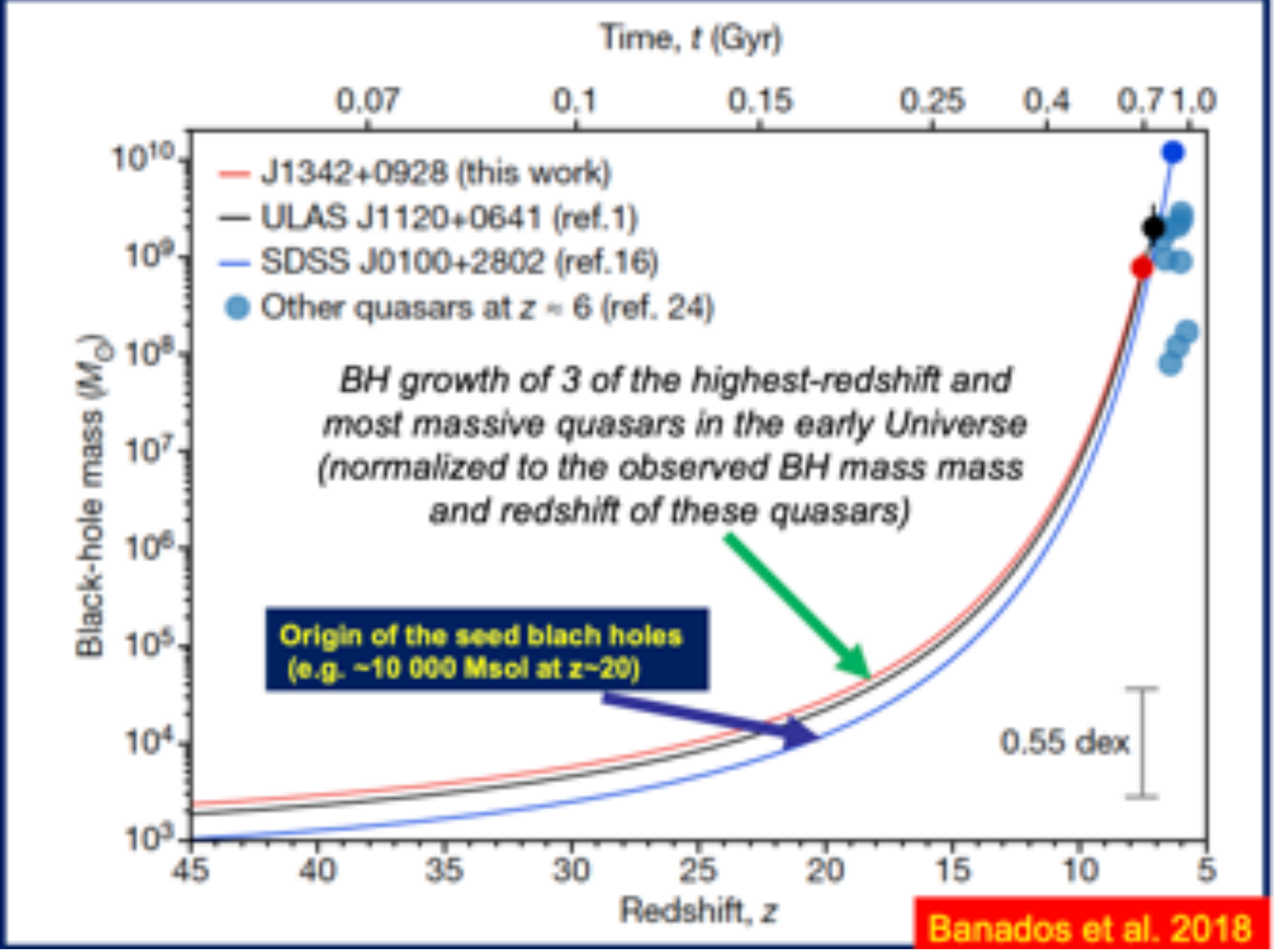
Origin of supermassive black holes at high redshift

Formation and physics of supermassive stars

Most distant quasar

J1342-0928

Z=7.54 (Age Uni. 690My)
$L=4\ 10^{13}\ L_{sol}$
$M=0.8\ GM_{sol}$



Banados et al. 2018

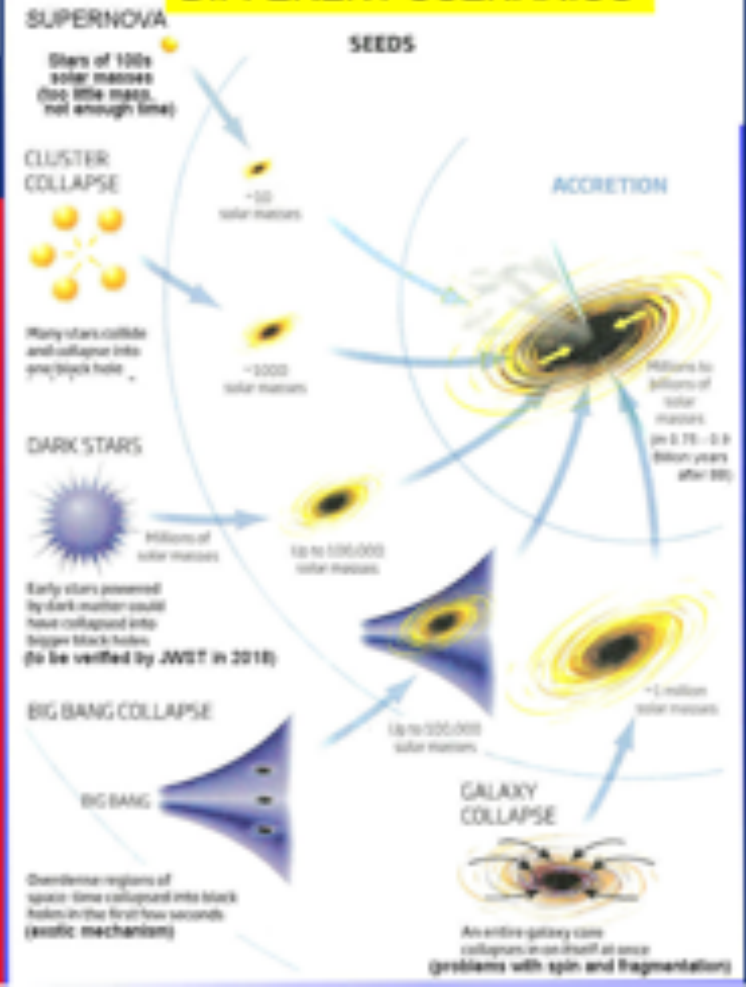
THE CHALLENGES

WP 2 supermassive stars

Different scenarios with a complex physics

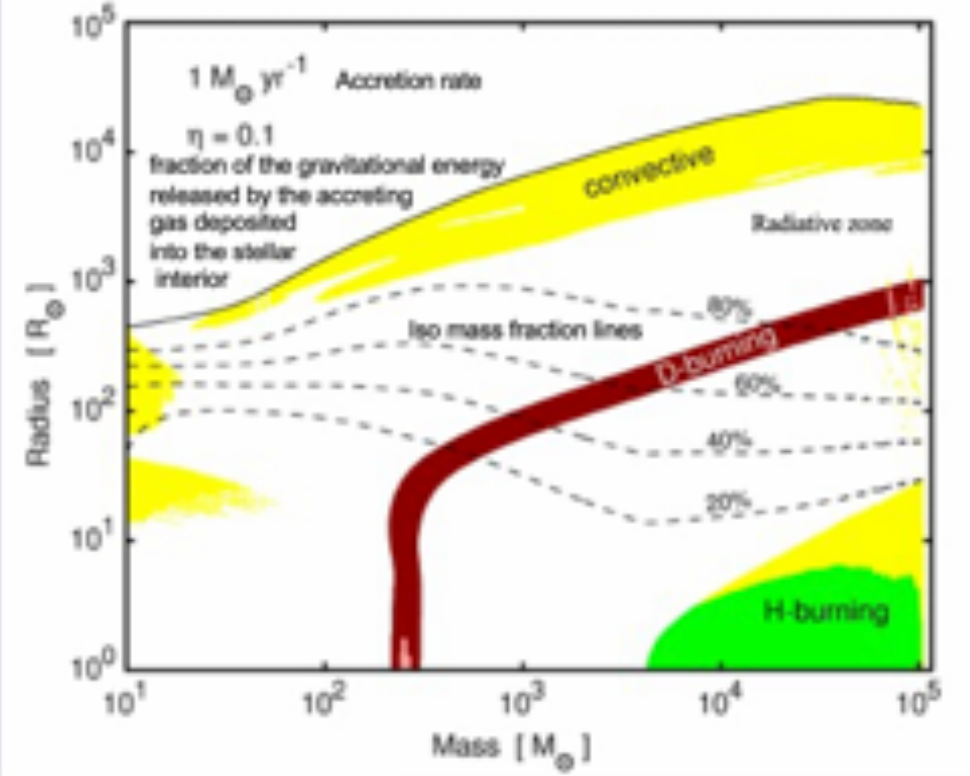
Which are those preferred by Nature?

DIFFERENT SCENARIOS



http://universe-review.ca/I05-14-superbh.jpg

FORMATION OF SUPERMASSIVE STARS



Hosokawa et al. 2013

WHAT HAS BEEN DONE

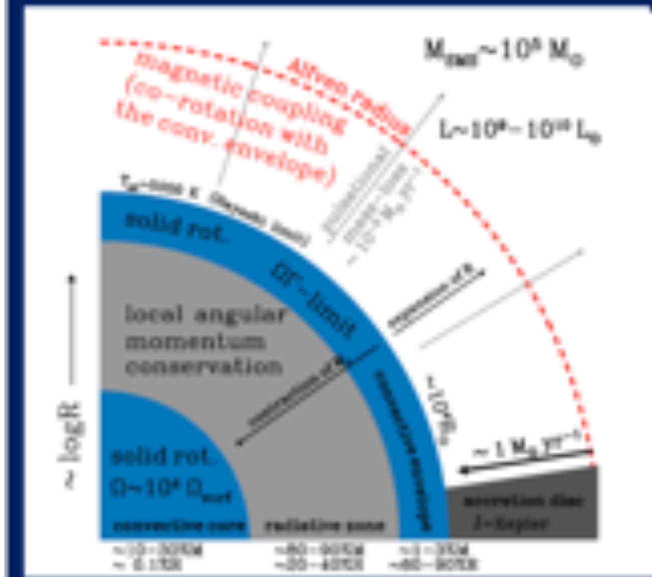
WP 2 supermassive stars

Models for rotating supermassive stars

Models with very high accretion rates

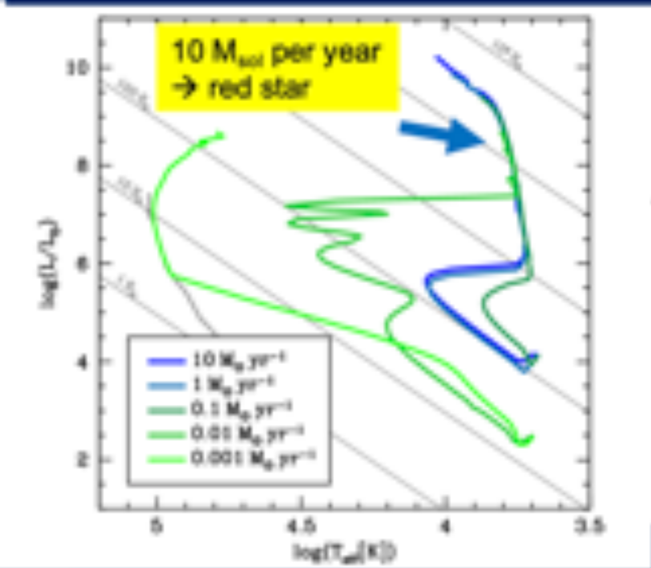
The tool: GENEC stellar evolution code with accretion and rotation and the GR instability criterion

Structure of an accreting SMS



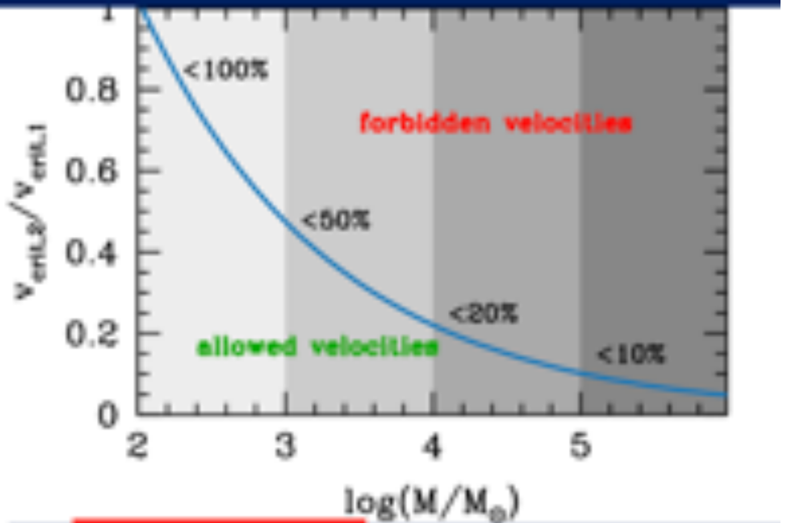
Haemmerlé & Meynet 2019

Evolution in the HR diagram



Haemmerlé et al. 2017

Rotation



Haemmerlé et al. 2018

Other Models for supermassive stars

[Hosokawa et al. 2013; Sakurai et al. 2015,2016; Umeda et al. 2016; Woods et al. 2017; Haemmerlé et al. 2018; Haemmerlé & Meynet 2019] Gieles et al.; 2018; Martins et al. 2020

WHAT WE PLAN TO DO

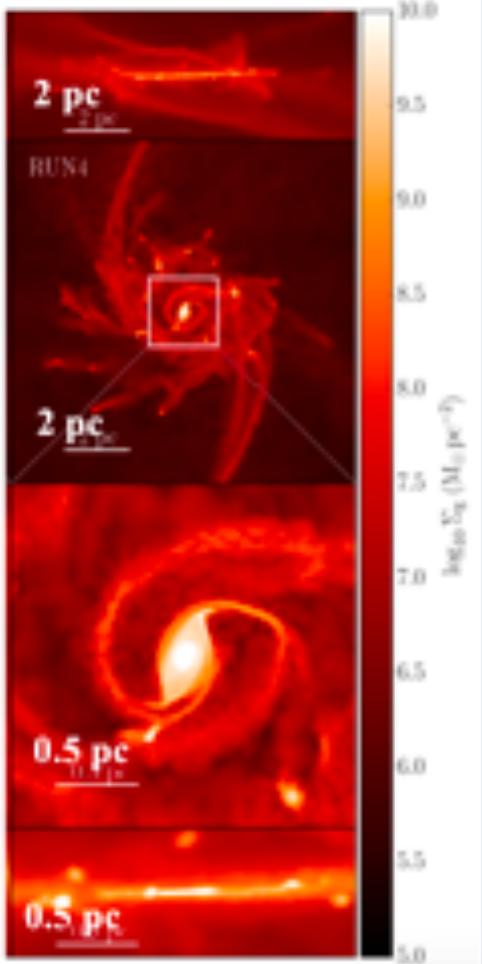
→ Need of hydrodynamics

SMS formation in merging galaxies

Impact of rotation at the collapse to the BH

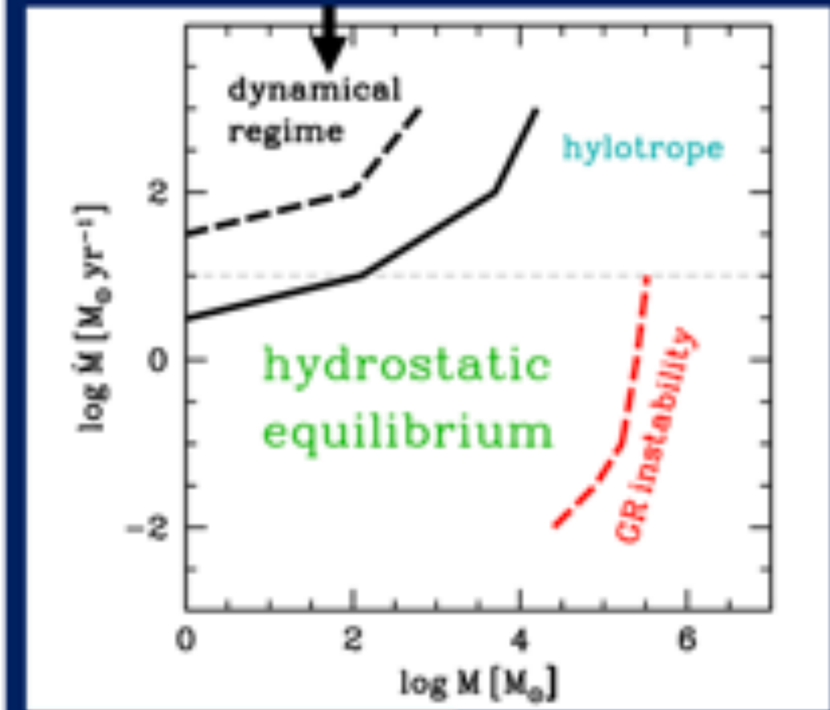
Face-on/edge-on projected gas density map of the nuclear region of a merger of central cores 5000 years after the merging

A compact disk-inner core is formed



Mayer & Bonoli 2019

Accretion timescale shorter than the sound wave crossing time



Haemmerlé et al. 2020

Core Team on WP 2

THE CONTEXT

Do physical constants have varied during the cosmic history?

Does dark matter exist?

Dimensionless number can be constructed from fundamental physical constants

All large numbers of the order of 10^{39} …10^{78} , are apart from simple numerical coefficients, just equal to *t*, t^2,.. where *t* is the present epoch expressed in atomic units $e^2/(m_e c^3)$

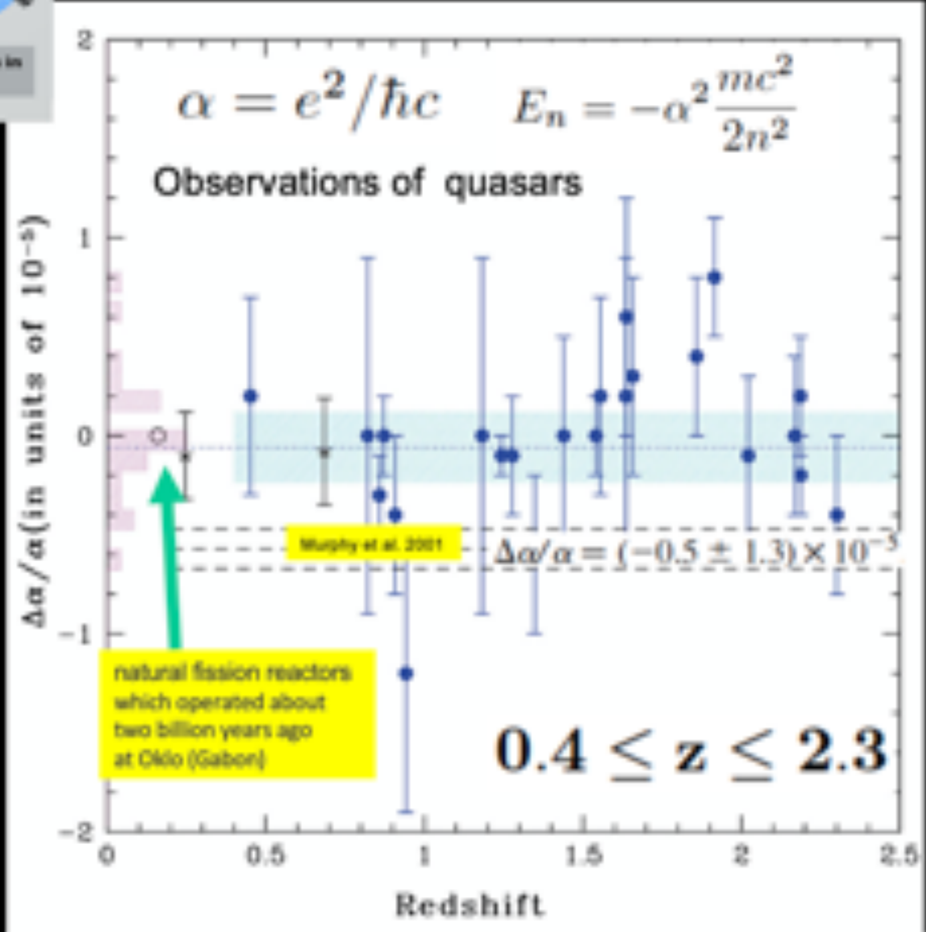
Dirac 1937

https://physics.aps.org/articles/v11/48

THE CHALLENGES

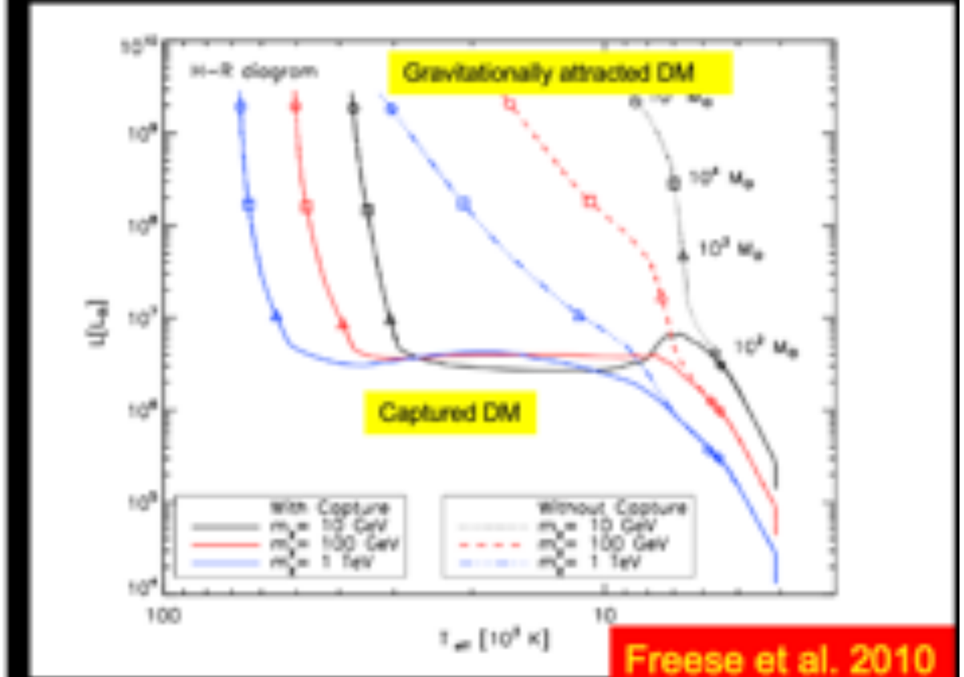
Observational challenge

Undirect probes



Srianand et al. 2004 $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$

Massive and SMS formation with DM



Freese et al. 2010

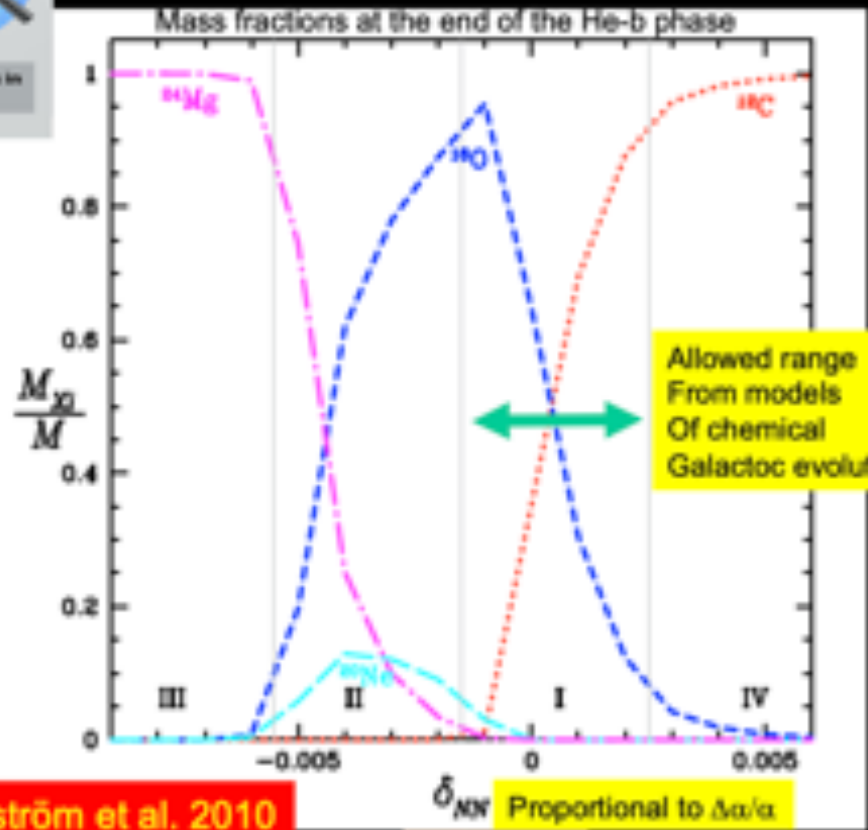
According to models, the first stars to form in the universe are made almost entirely of baryons with only 10^{-3} of the mass made of dark

WHAT HAS BEEN DONE

Impact of fine structure constant variation on the 3 alpha reaction rate and pop III star nucleosynthesis

WIMPS annihilation in Pop III stars

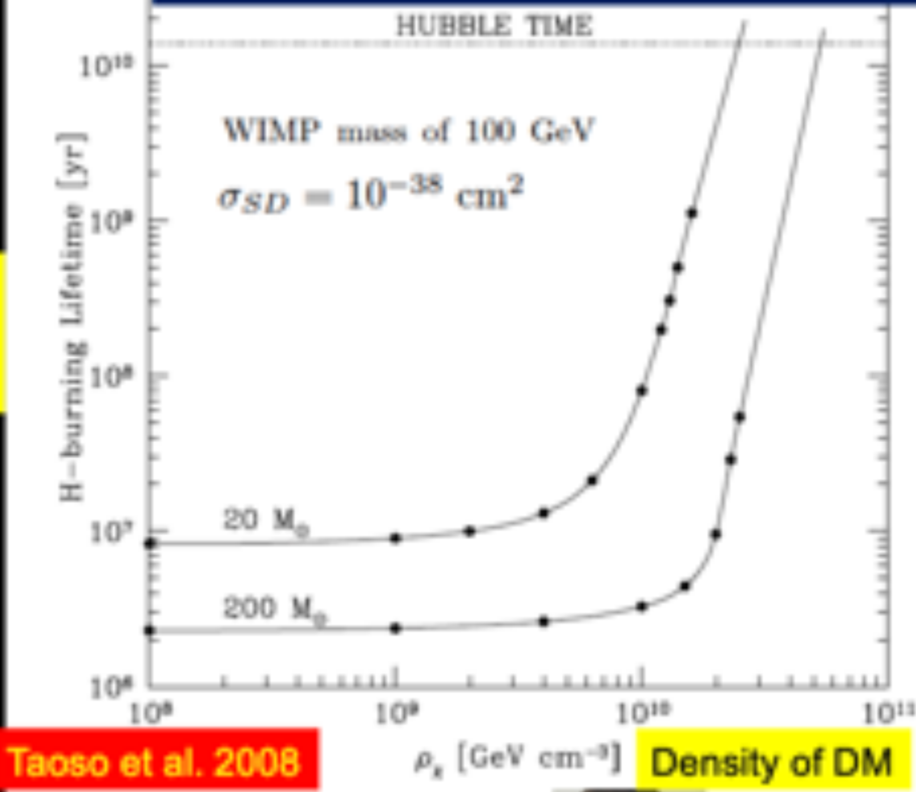
15 M_{sol}
Pop III
Z ~15-20



Ekström et al. 2010

$$-3.5\times10^{-5} < \frac{\Delta\alpha_{em}}{\alpha_{em}} < +1.8\times10^{-5}.$$

Pierre Descouvemont,
ULB, Begium



Taoso et al. 2008

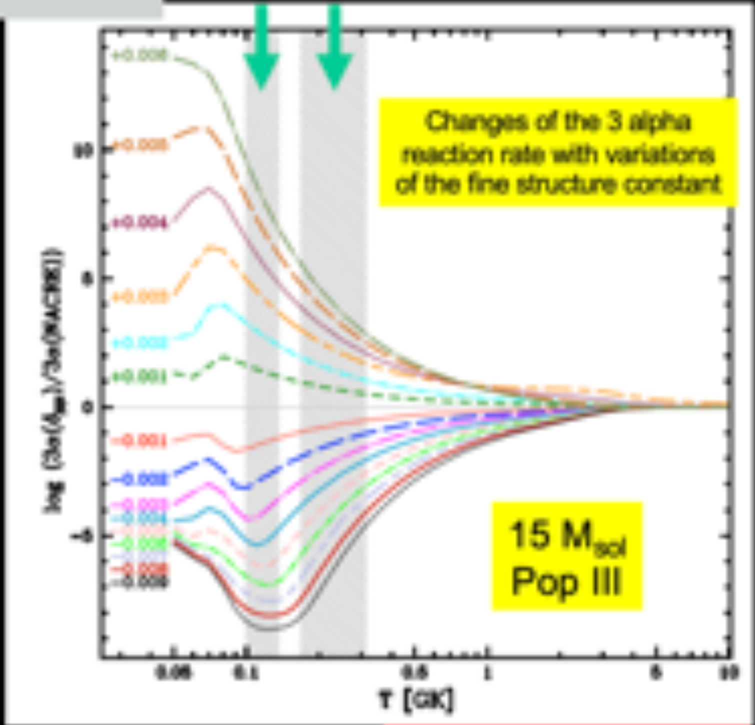
Marco Toaso
INFN, Torino
Italy

WHAT WE PLAN TO DO

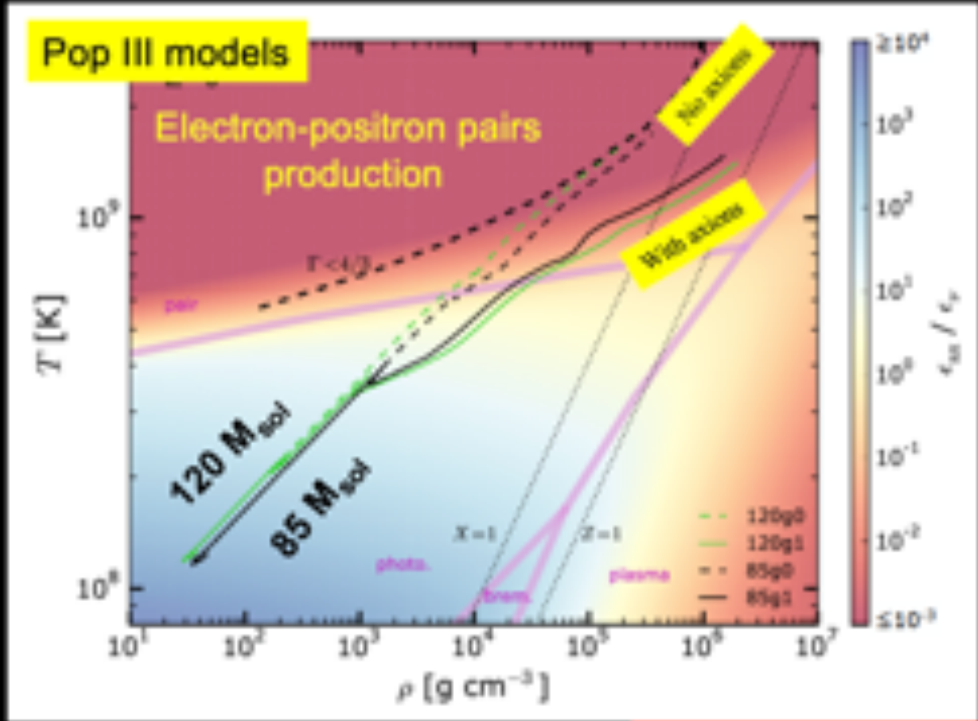
Impact of fine structure constant variation on the $^{12}C(alpha,gamma)^{16}O$ reaction rate

New DM particles in supermassive stars

Central tempratures in
core H He –burning



Ekström et al. 2010



Choplin et al. 2017

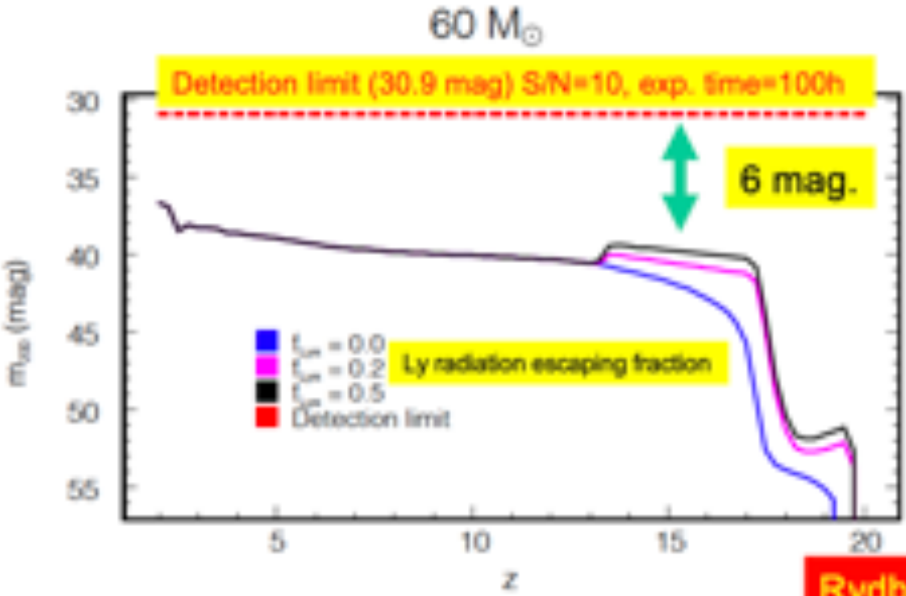
Core Team on WP 3

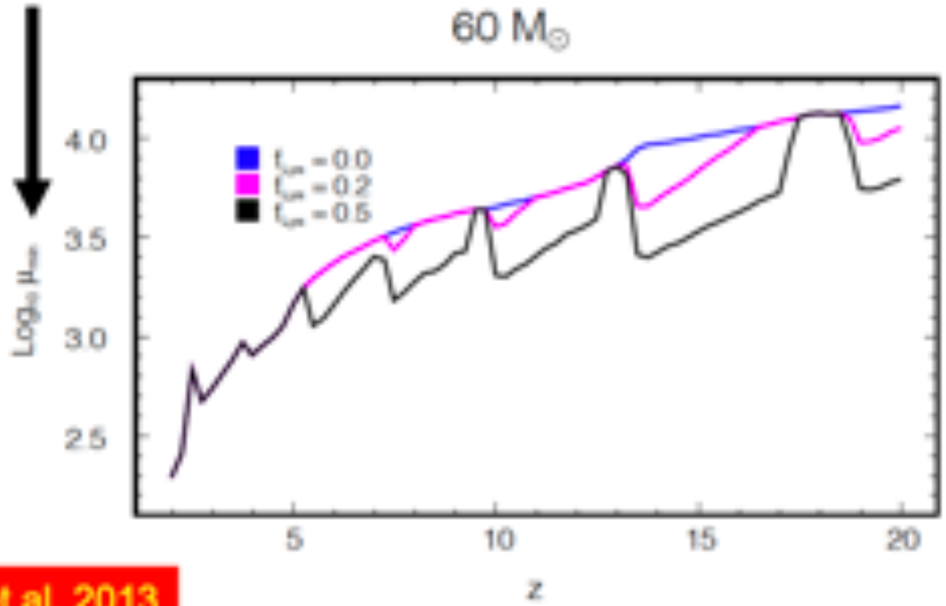
THE CONTEXT

No individual Pop III massive star detectable

Even if lensed, lensing factor too high needed

Minimum gravitational magnification required





Rydberg et al. 2013

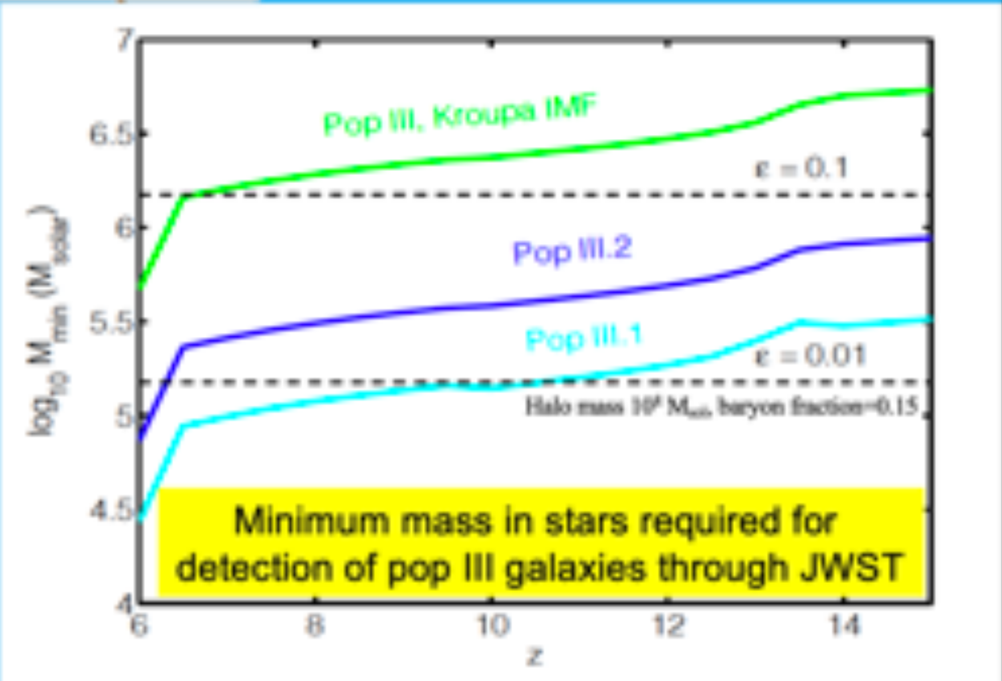
NIRCam/F200W AB magnitude

For each redshift, the filter resulting in the lowest necessary magnification is selected in the calculation of μ_{min}.

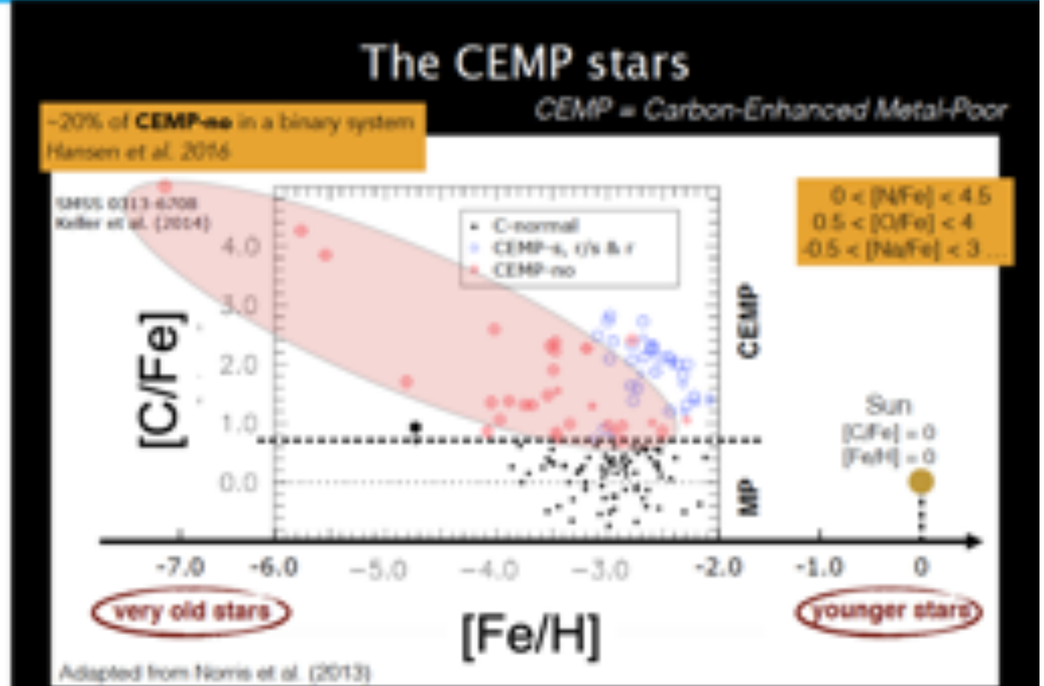
THE CHALLENGES

Direct detection only possible for a population of stars

Indirect hints on the nature of first stars



Zackrisson 2012



Norris et al. 2013, viewgraph from Arthur Choplin

100 h JWST exposures per filter, 10sigma detection in at least one JWST filter, 1 Myr old galaxies and no leakage of ionizing radiation into the intergalactic medium.

Cyan extremely top heavy IMF/Blue moderately top IMF/Green, normal IMF

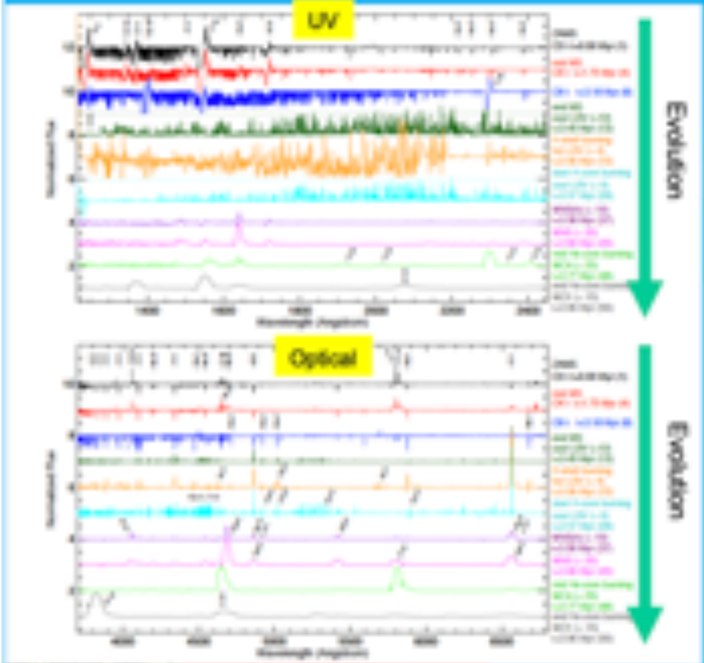
WHAT HAS BEEN DONE

Spectral evolution

Population synthesis of rotating stars

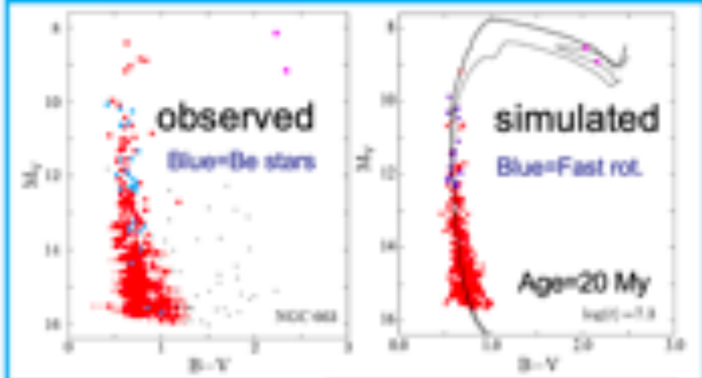
Imoact of rotation on nucleosynthesis

Non-rotating 60 Msol

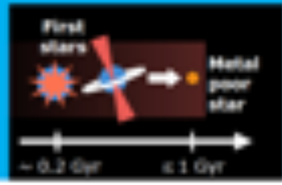


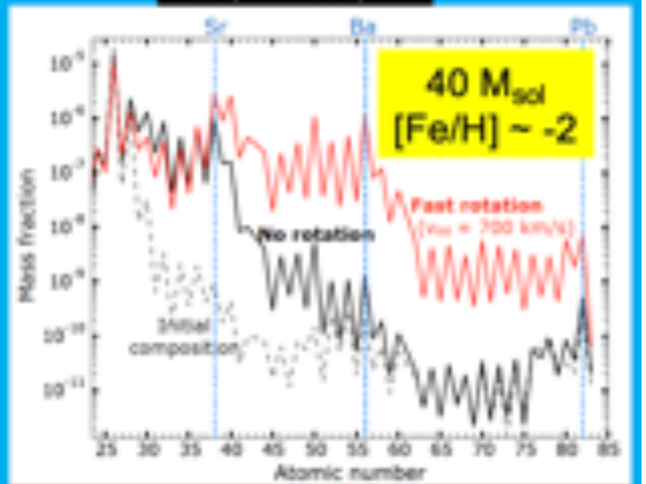
Groh et al. 2014

NGC 663



Georgy et al. 2014





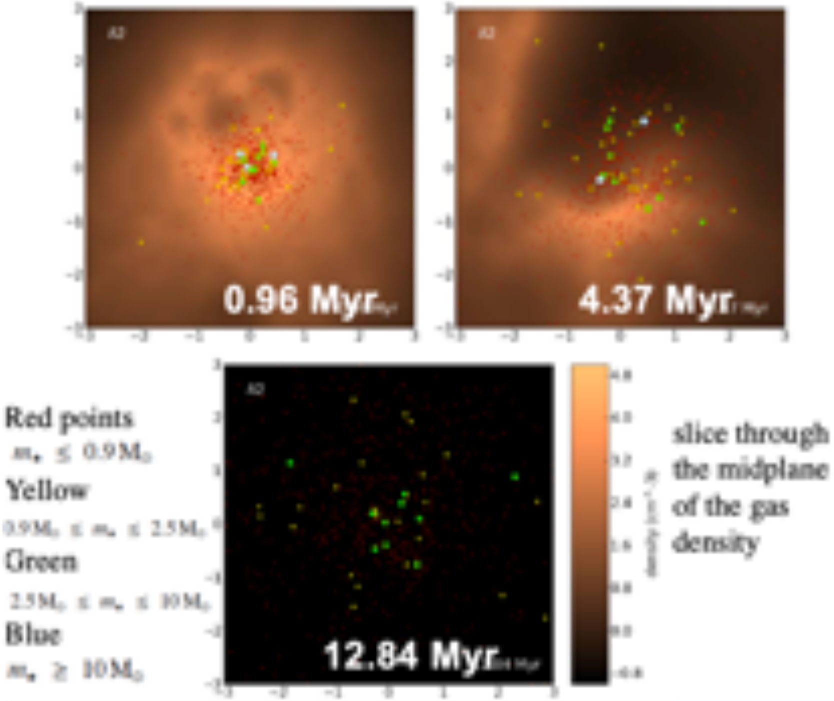
Choplin et al. 2016, 2017ab, 2018

First interior+atmopshere models, spectroscopic diagnostic of Pop III stars→Schaerer 1995, 2002, 2003

WHAT WE PLAN TO DO

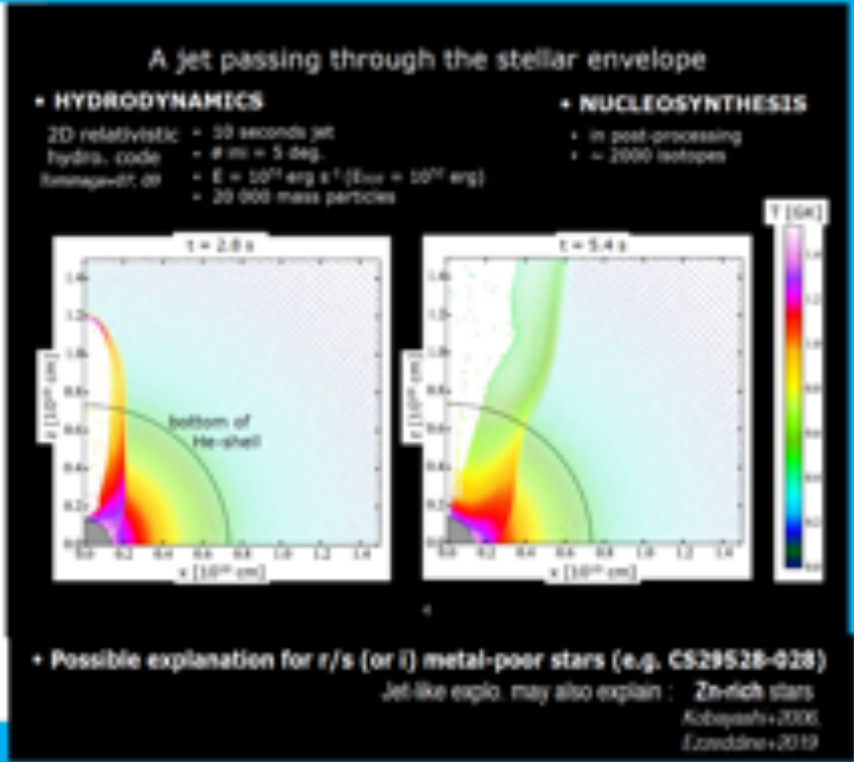
Connection to AMUSE

Explosive nucleosynthesis



Pelupessy and Portegies Zwart 2012

Astrophysical Multi-purpose Software Environment



Choplin et al. In preparation, slide from Choplin

Core Team on WP 4

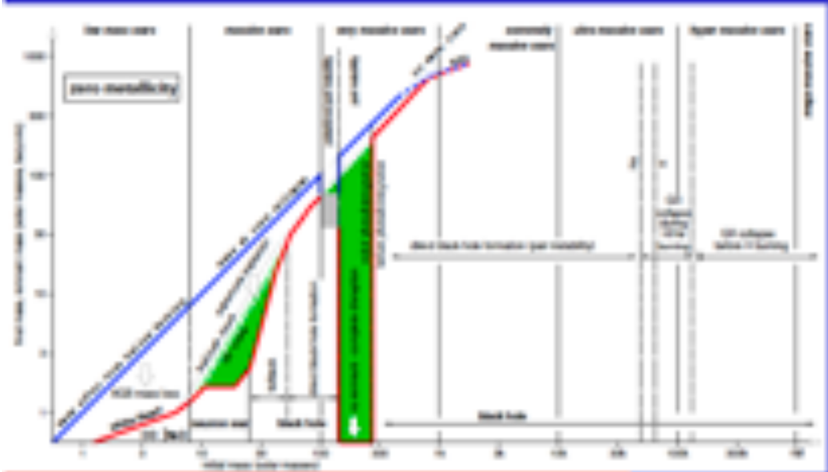
THE CONTEXT

Transient objects, nature and properties of remnants

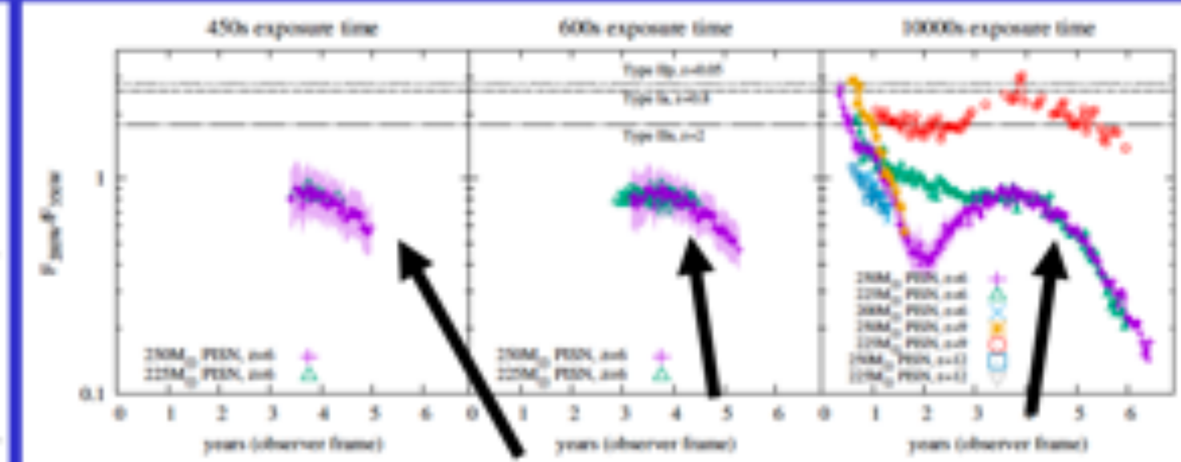
Detectability of transients

8-130 M_{sol} → possible SN explosion

Most promising 2-filter diagnostic for different exposure times.



Woods, Heger & Haemmerlé 2020



Hartwig et al. 2018

Detection with S/N >10 in both filters

Purple shaded purple area illustrates the observational uncertainty of < 0,14 mag (only for the 250M_{sol} PISN at z = 6).

Exposure times of < 1 ks are sufficient to detect the brightest PISNe at z = 6,

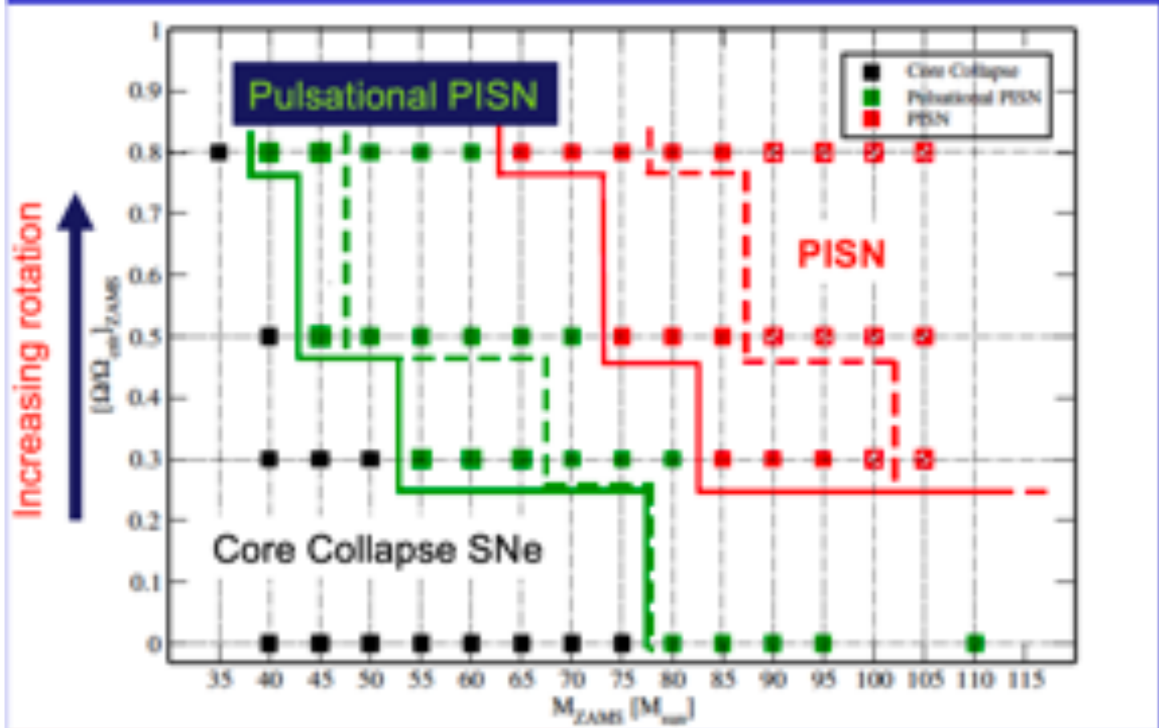
For t_{exp} > 10 ks, PISNe at z > 12 are detectable.

THE CHALLENGES

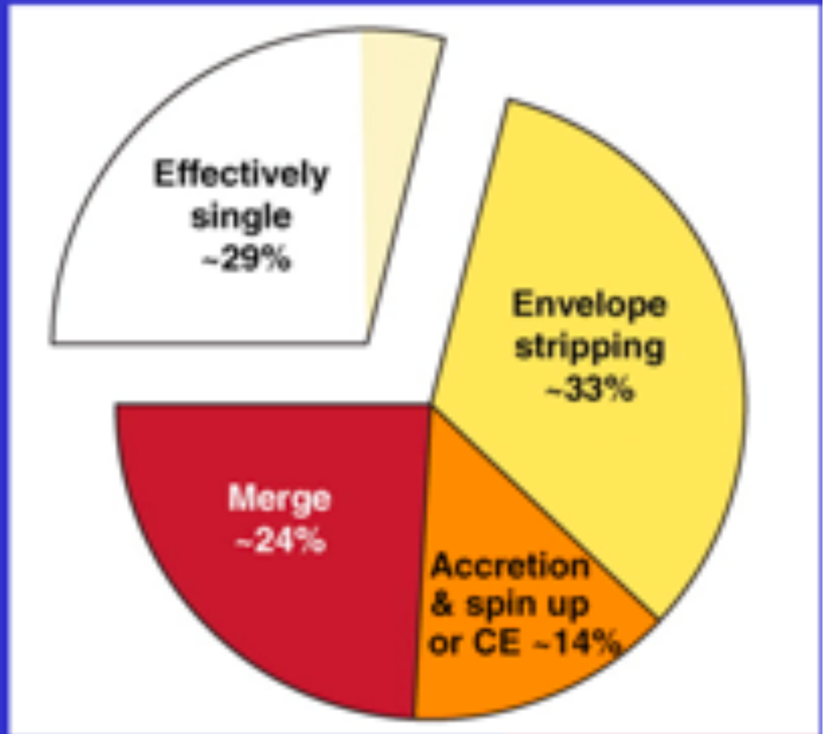
Impact of rotation

Impact of multiplicity

Z=0 models, continuous→ no mass loss
dashed → with mass loss



Chatzopoulos & Wheeler 2012

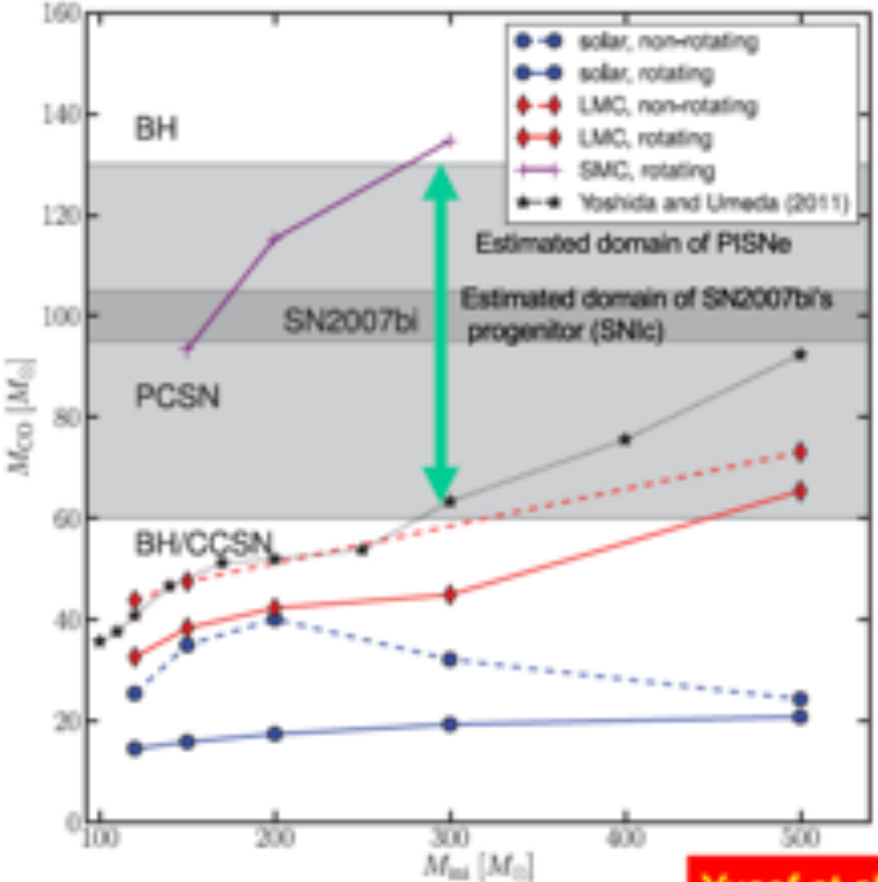


Sana et al. 2012

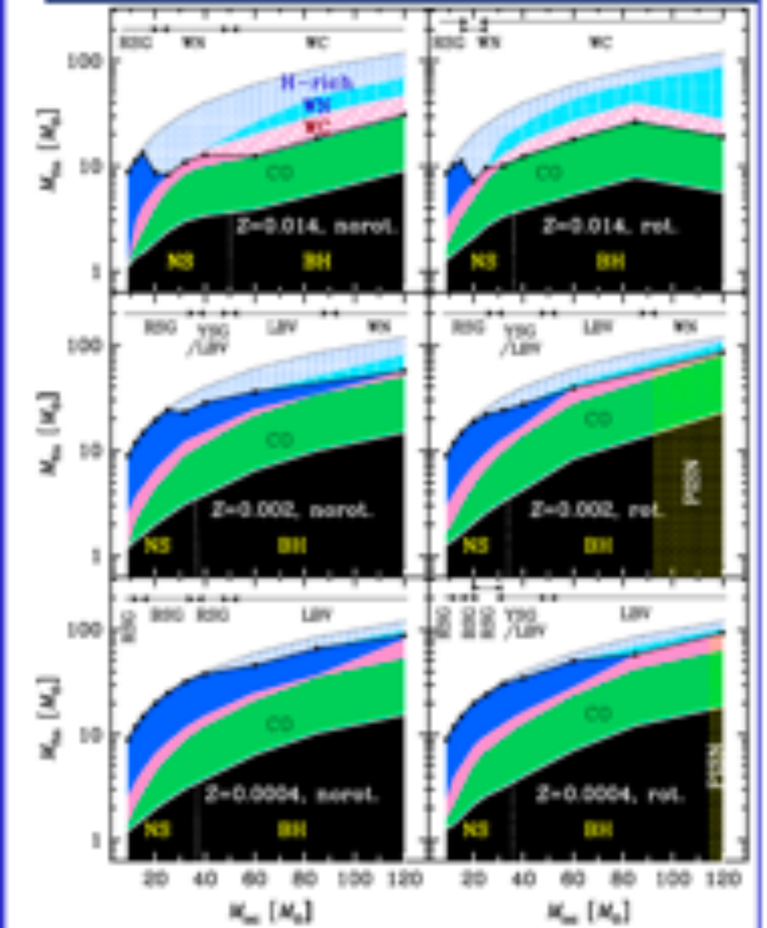
WHAT HAS BEEN DONE

Impact of rotation on PISNe progenitors

Progenitor,s ejecta, remnants

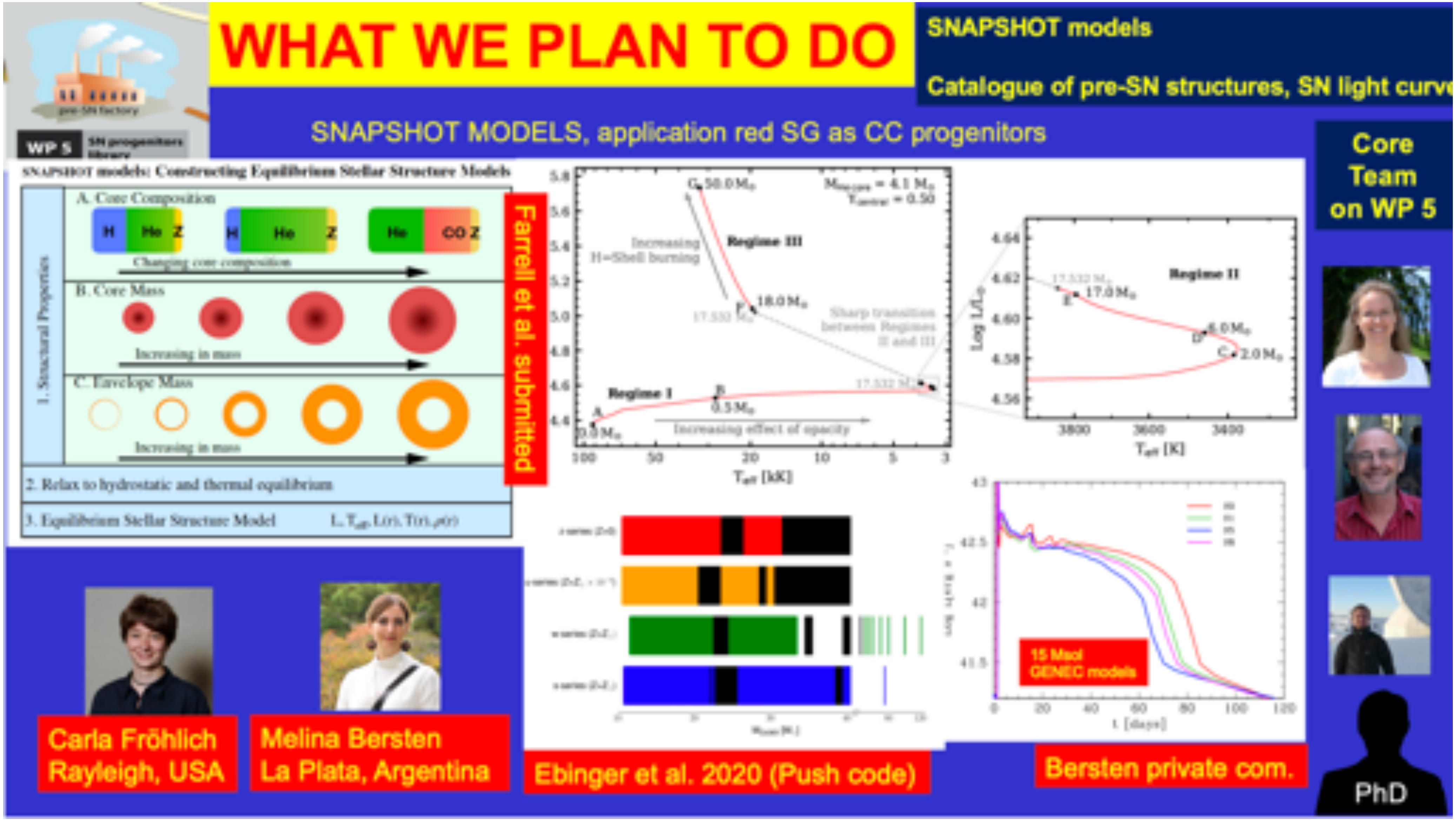


Yusof et al. 2013



Groh et al. 2019

Close binary evolution→see Bavera et al. 2020; Qin et al. 2018

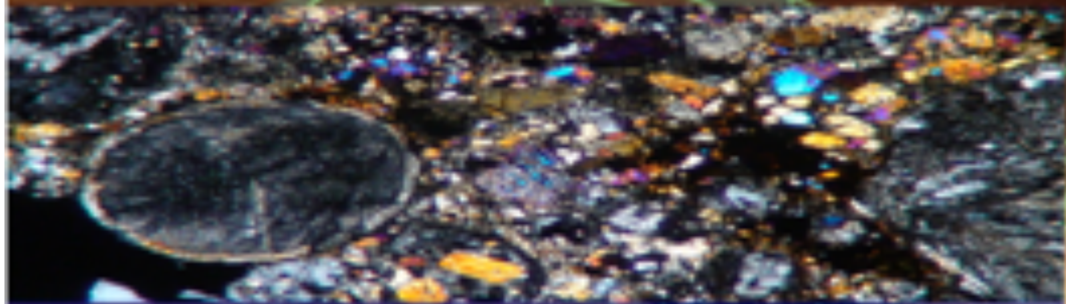

WHAT WE PLAN TO DO
SNAPSHOT models
Catalogue of pre-SN structures, SN light curve
WP 5
SNAPSHOT MODELS, application red SG as CC progenitors
Core Team on WP 5
SNAPSHOT models: Constructing Equilibrium Stellar Structure Models
A. Core Composition
Changing core composition
B. Core Mass
Increasing in mass
C. Envelope Mass
Increasing in mass
1. Structural Properties
2. Relax to hydrostatic and thermal equilibrium
3. Equilibrium Stellar Structure Model
Farrell et al. submitted
Regime III
Regime II
Regime I
Increasing H-Shell burning
Sharp transition between Regimes II and III
Increasing effect of opacity
Log L/L☉
15 Msol GENEC models
t [days]
Carla Fröhlich
Rayleigh, USA
Melina Bersten
La Plata, Argentina
Ebinger et al. 2020 (Push code)
Bersten private com.
PhD

CONCLUSIONS

Stupidity consists in wanting to conclude   Flaubert

STARS → Age and distance in the Universe,

STARS → Physics laboratories



The understanding of stellar evolution is required to understand structures as small as dust grains and large scale structure as the galaxies .