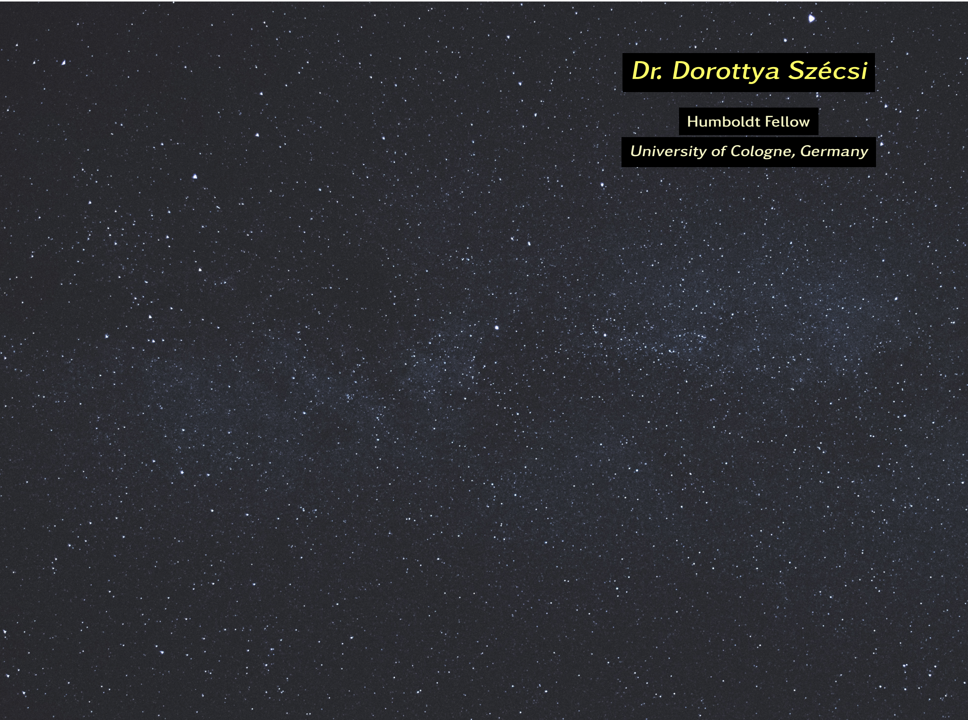
The theory linking gravitational waves, star-formation and the dawn of the Universe

Dr. Dorottya Szécsi

Humboldt Fellow
University of Cologne, Germany

Amsterdam, 11th March 2020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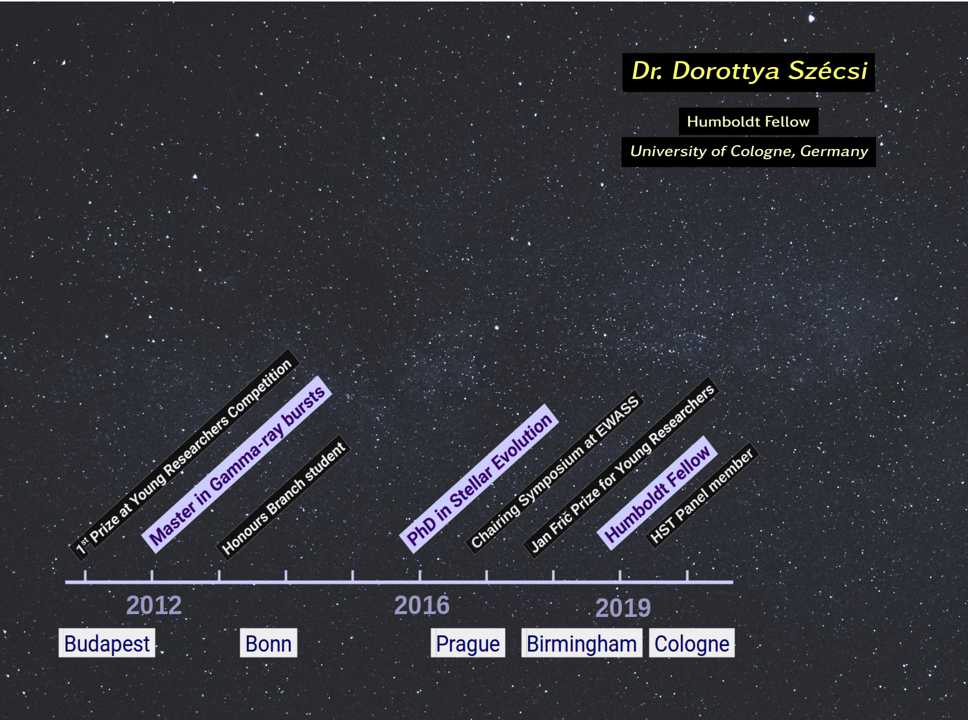
Dr. Dorottya Szécsi
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1st Prize at Young Researchers Competition
Master in Gamma-ray bursts
Honours Branch student
PhD in Stellar Evolution
Chairing Symposium at EWASS
Jan Frič Prize for Young Researchers
Humboldt Fellow
HST Panel member
2012
2016
2019
Budapest
Bonn
Prague
Birmingham
Cologne

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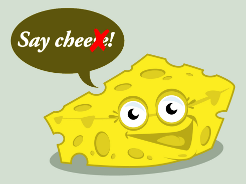

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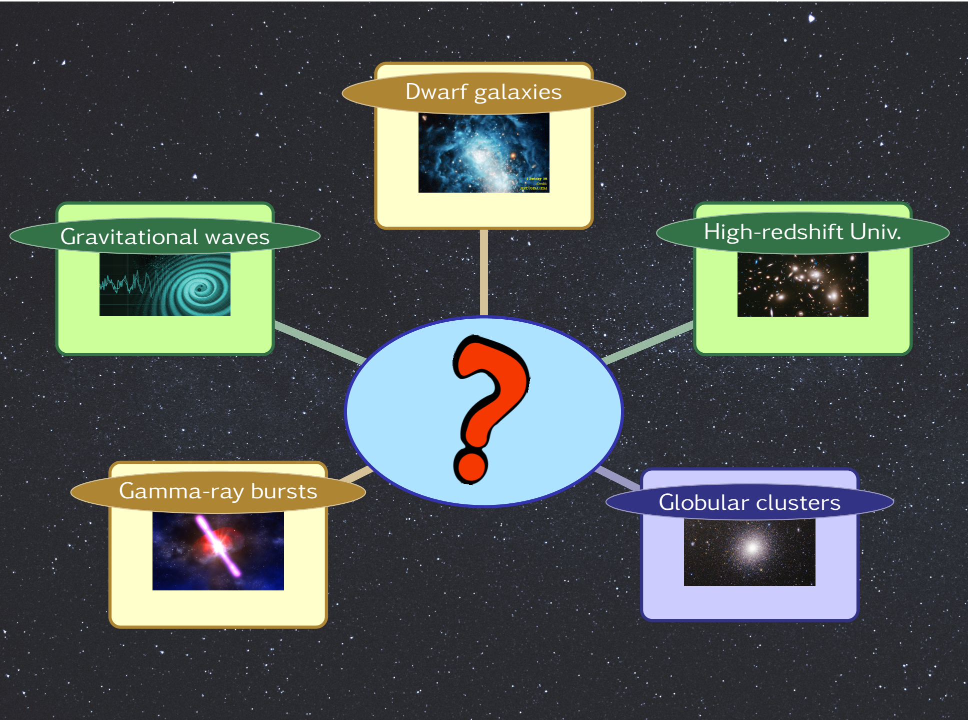
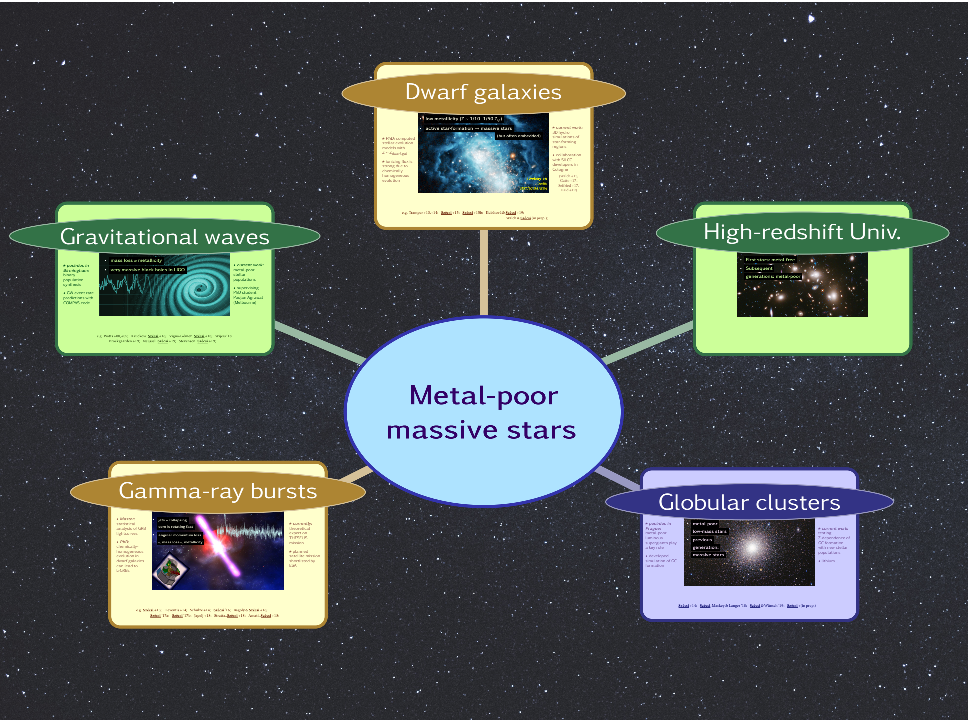

Dwarf galaxies
Gravitational waves
High-redshift Univ.
Gamma-ray bursts
Globular clusters


Metal-poor massive stars
Dwarf galaxies
• low metallicity ($Z \sim 1/10$–$1/50\ Z_{\odot}$)
• active star-formation → massive stars
(but often embedded)
I Zwicky 18
Credit: HST/NASA/ESA
★ PhD: computed stellar evolution models with $Z \sim Z_{dwarf.gal}$
★ ionizing flux is strong due to chemically homogeneous evolution
★ current work: 3D hydro simulations of star-forming regions
★ collaboration with SILCC developers in Cologne
(Walch +15, Gatto +17, Seifried +17, Haid +19)
e.g. Tramper +13,+14; Szécsi +15; Szécsi +15b; Kubátová & Szécsi +19;
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Gravitational waves
• mass loss ∝ metallicity
• very massive black holes in LIGO
★ post-doc in Birmingham: binary population synthesis
★ GW event rate predictions with COMPAS code
★ current work: metal-poor stellar populations
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e.g. Watts +08,+09; Kruckow..Szécsi +16; Vigna-Gómez..Szécsi +18; Wijers '18
Broekgaarden +19; Neijssel..Szécsi +19; Stevenson..Szécsi +19;
High-redshift Univ.
• First stars: metal-free
• Subsequent generations: metal-poor
Gamma-ray bursts
• jets – collapsing core is rotating fast
• angular momentum loss ∝ mass loss ∝ metallicity
★ Master: statistical analysis of GRB lightcurves
★ PhD: chemically-homogeneous evolution in dwarf galaxies can lead to L-GRBs
★ currently: theoretical expert on THESEUS mission
★ planned satellite mission shortlisted by ESA
e.g. Szécsi +13; Leventis +14; Schulze +14; Szécsi '16; Bagoly & Szécsi +16;
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Globular clusters
• metal-poor low-mass stars
• previous generation: massive stars
★ post-doc in Prague: metal-poor luminous supergiants play a key role
★ developed simulation of GC formation
★ current work: testing Z-dependence of GC formation with new stellar populations
★ lithium...
Szécsi +14; Szécsi, Mackey & Langer '18; Szécsi & Wünsch '19; Szécsi +(in prep.)

What is a star?

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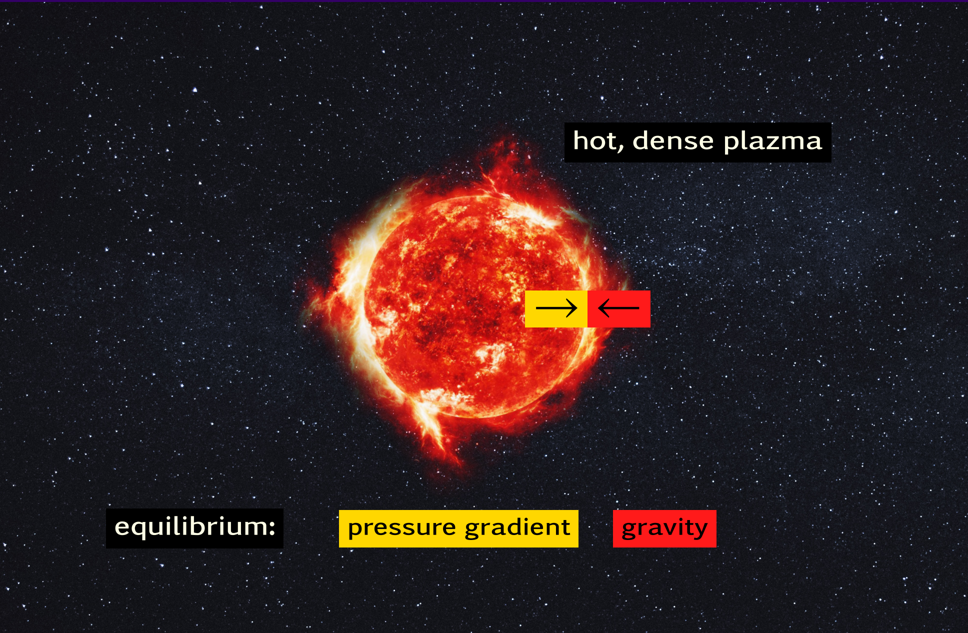

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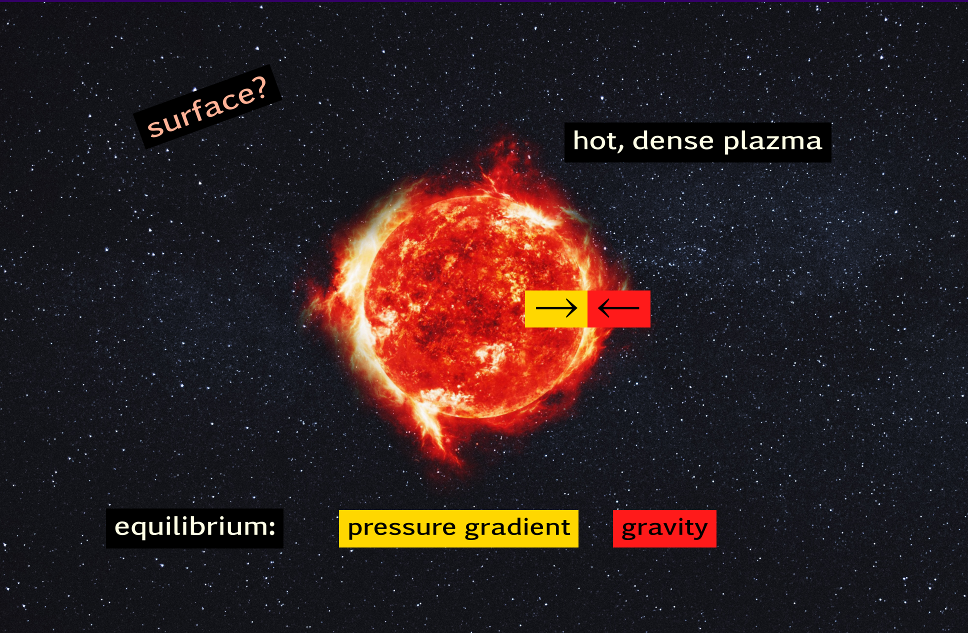
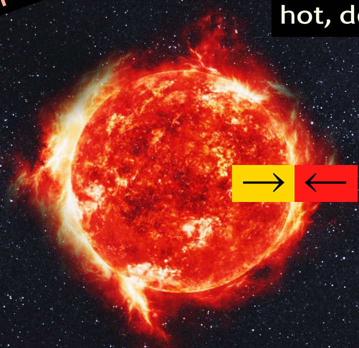


What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



equilibrium: pressure gradient gravity

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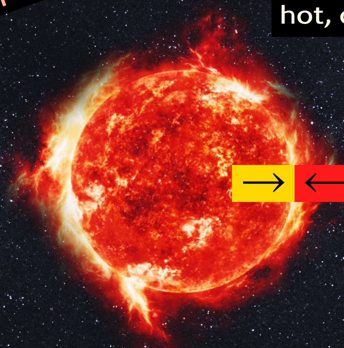

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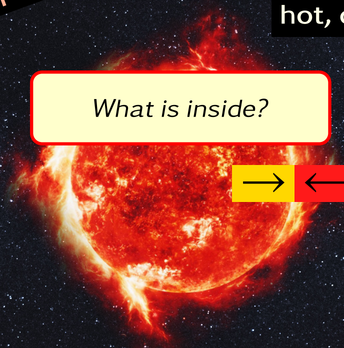

What is inside?

→ ←

equilibrium: pressure gradient gravity

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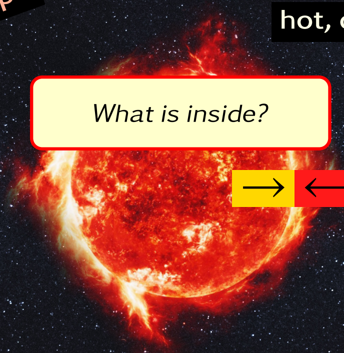

What is inside?

→ ←

theoretical modelling of the stellar structure

equilibrium: pressure gradient gravity

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \quad \text{equation of definition of mass} \quad (1)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \quad \text{equation of hydrostatic equilibrium} \quad (2)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \quad (3)$$

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \quad \text{equation of energy transport,} \quad (4)$$

Guilera+ 11

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$$ mass conservation (1)

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transport of energy

Guilera+ 11

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Guilera+ 11

composition change due to nuclear burning:

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transport of energy

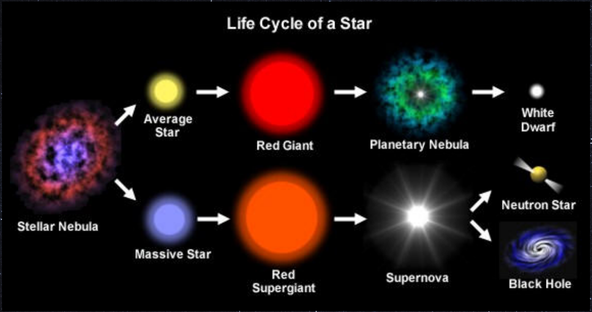
Guilera+ 11

composition change due to nuclear burning:

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \qquad (5)$$

Massive vs. low-mass stars

Massive stars: $\gtrsim$ 9 times the Sun ($\gtrsim 9\ M_\odot$)



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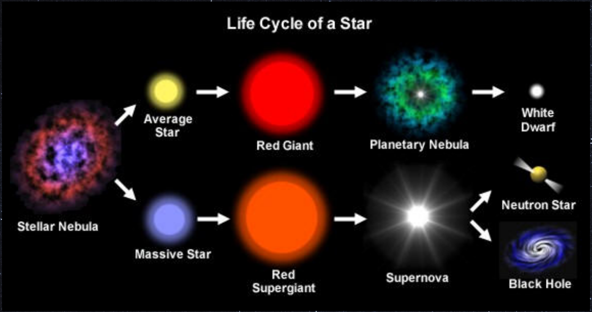


- Metallicity
- Rotation
- Binarity

Massive vs

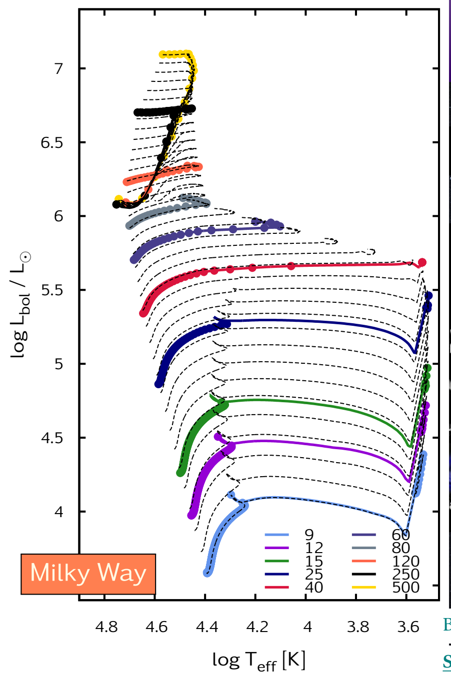
Massi… 9 $M_\odot$)

Stellar Ne

White Dwarf

utron Star

ack Hole



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Brott+ 11 (< 60 $M_\odot$),

Szécsi+ 20 (> 60 $M_\odot$ & interpol.)

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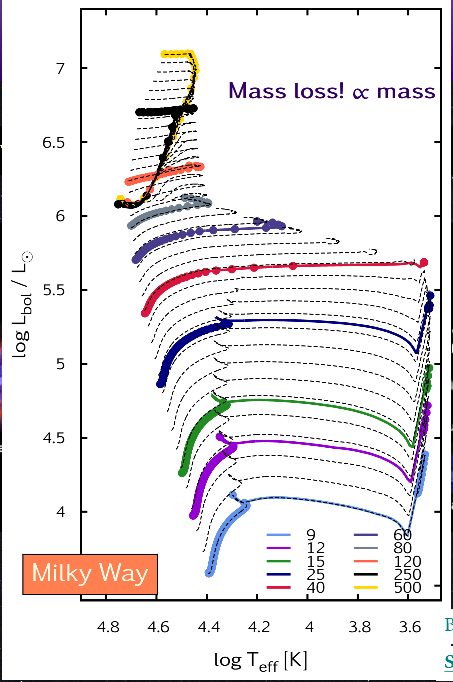

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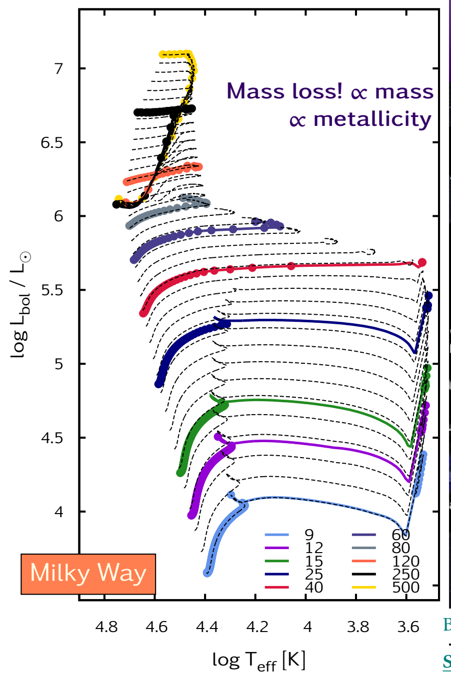

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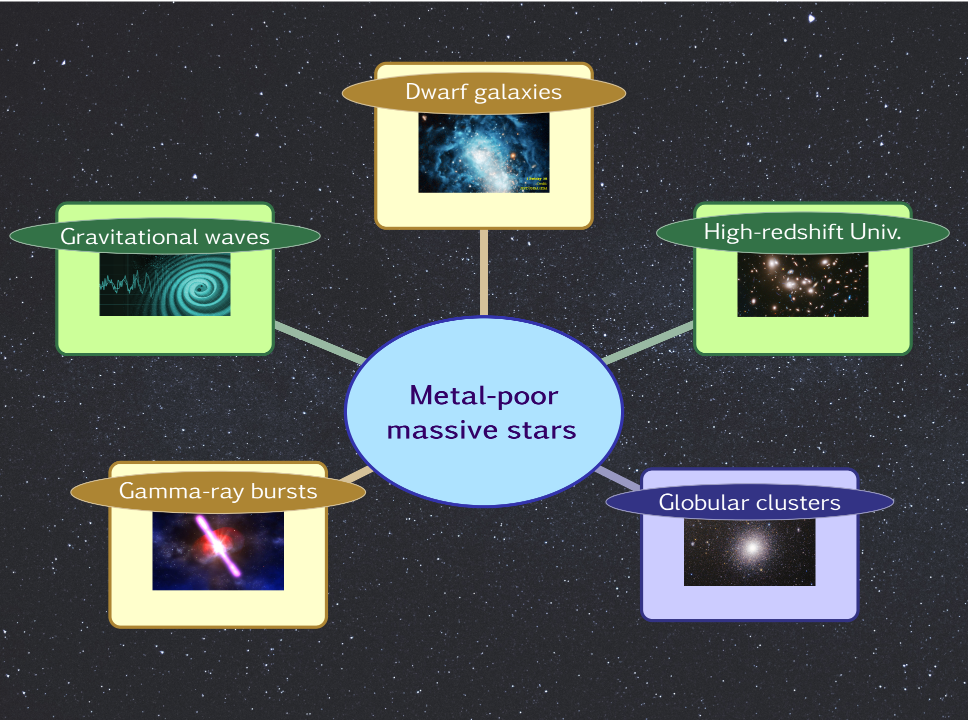

Dwarf galaxies
Gravitational waves
High-redshift Univ.
Metal-poor
massive stars
Gamma-ray bursts
Globular clusters

Metal-poor
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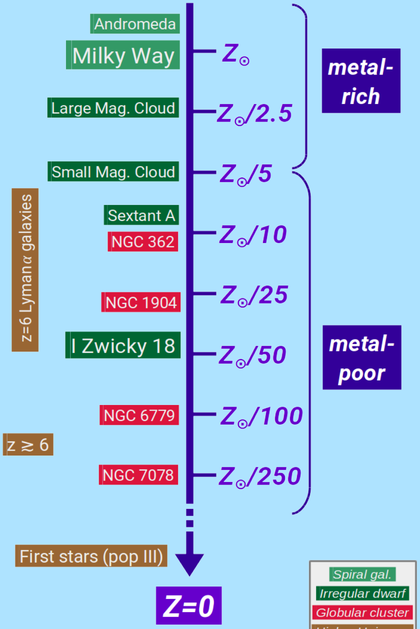
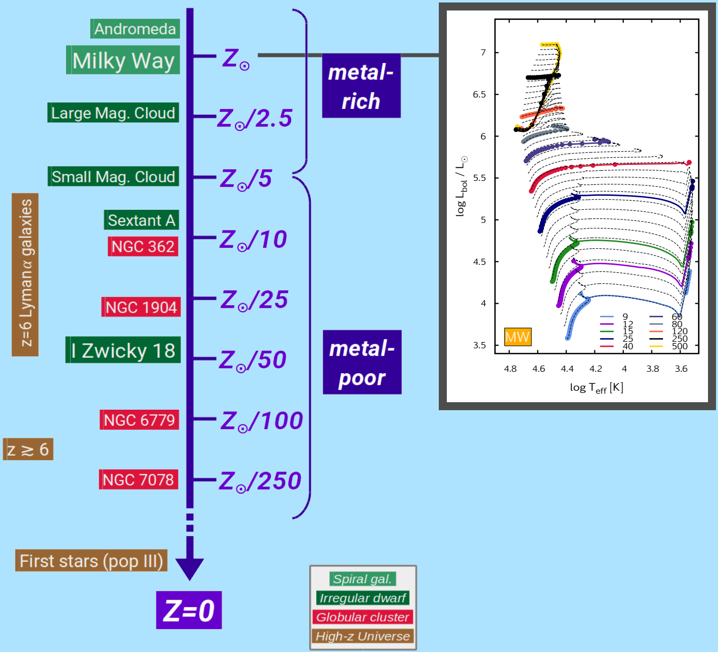


Andromeda
Milky Way
Large Mag. Cloud
Small Mag. Cloud
Sextant A
NGC 362
NGC 1904
I Zwicky 18
NGC 6779
NGC 7078
z=6 Lymanα galaxies
z ≳ 6
First stars (pop III)
$Z_\odot$
$Z_\odot/2.5$
$Z_\odot/5$
$Z_\odot/10$
$Z_\odot/25$
$Z_\odot/50$
$Z_\odot/100$
$Z_\odot/250$
Z=0
metal-rich
metal-poor
Spiral gal.
Irregular dwarf
Globular cluster
High-z Universe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metal-rich
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log L_bol / L⊙
log T_eff [K]
MW
9
12
15
25
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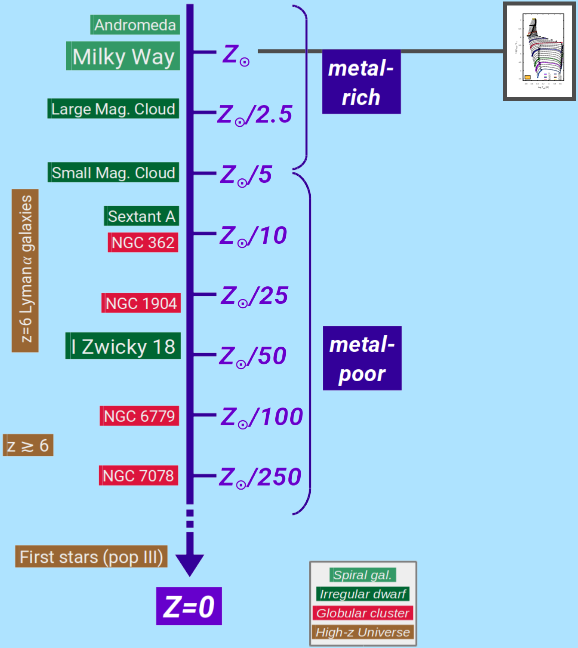
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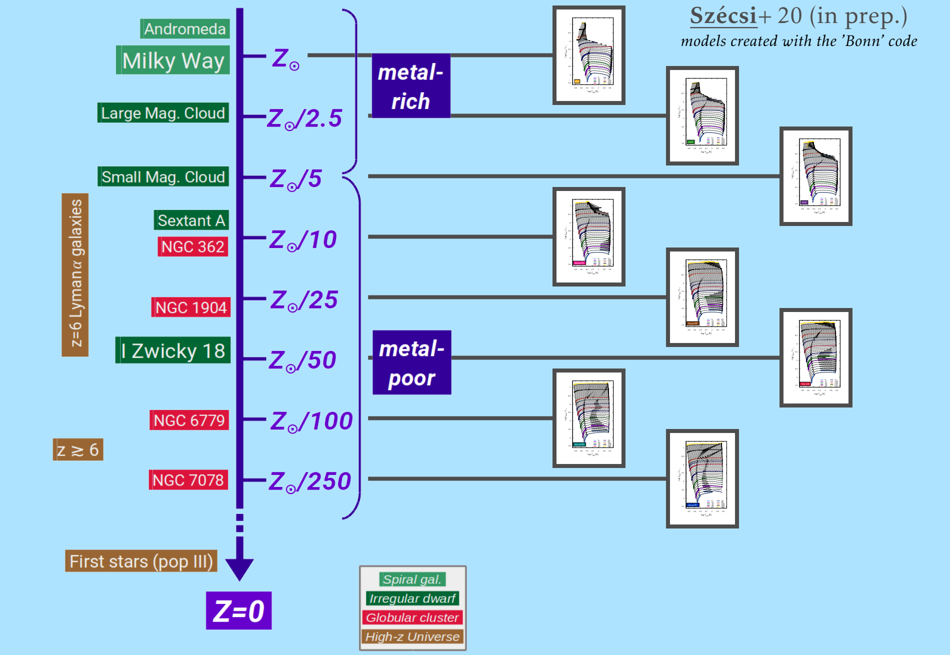

Szécsi+ 20 (in prep.)
models created with the 'Bonn' code
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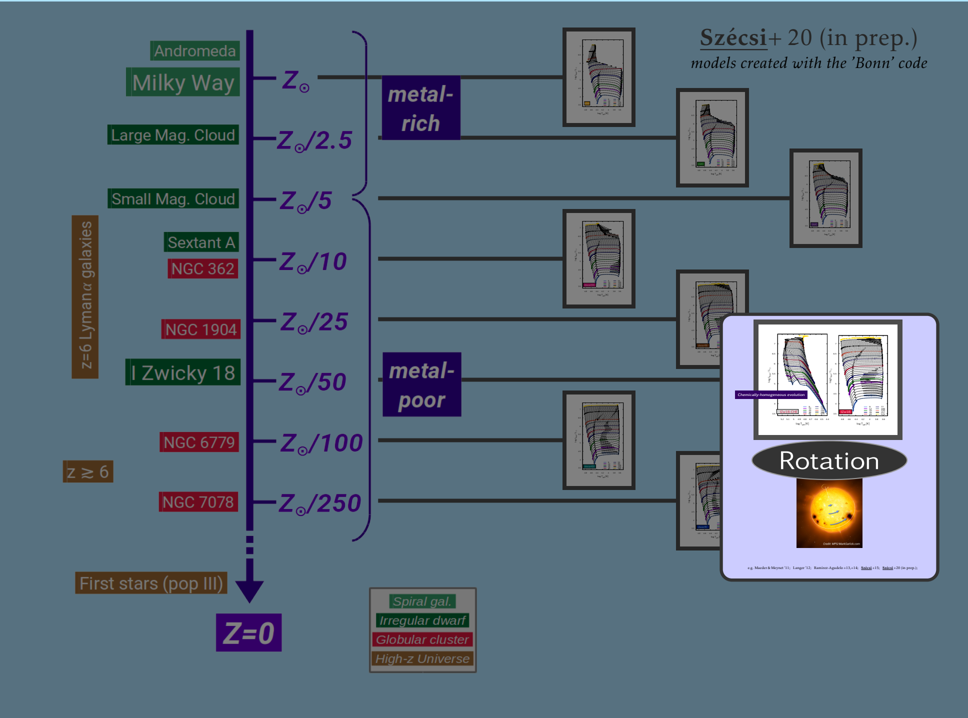

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⋆ *PhD:* computed stellar evolution models with $Z \sim Z_{dwarf.gal}$

⋆ ionizing flux is strong due to chemically homogeneous evolution

⋆ *current work:* 3D hydro simulations of star-forming regions

⋆ collaboration with SILCC developers in Cologne (Walch +15, Gatto +17, Seifried +17, Haid +19)

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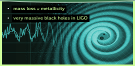
Gravitational waves



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High-redshift Univ.

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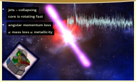

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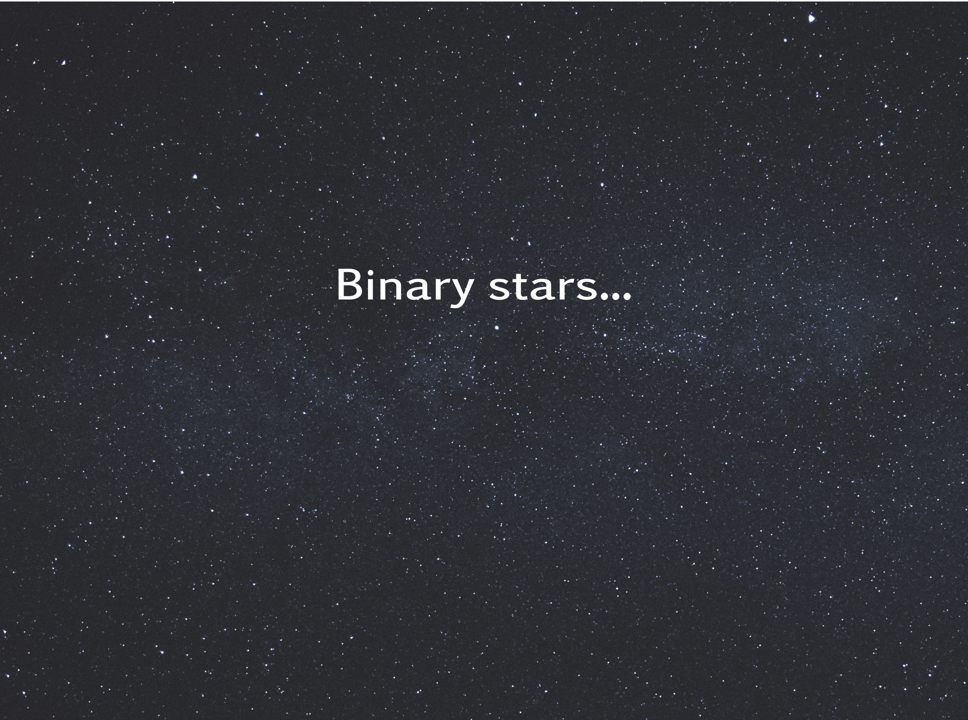
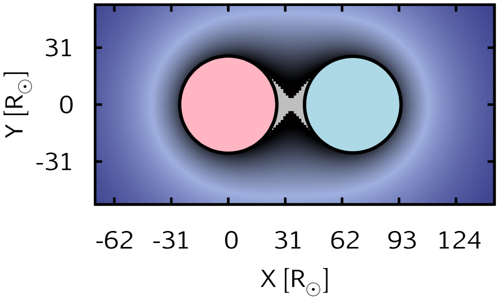
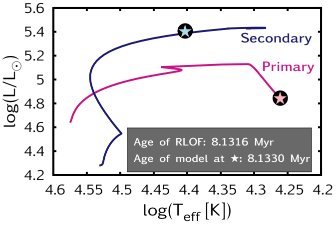
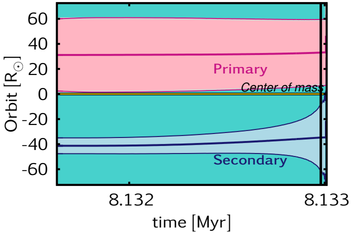

Binary stars...

System: 20 $M_\odot$ + 15 $M_\odot$ + 12 d Age: 8.1330 Myr

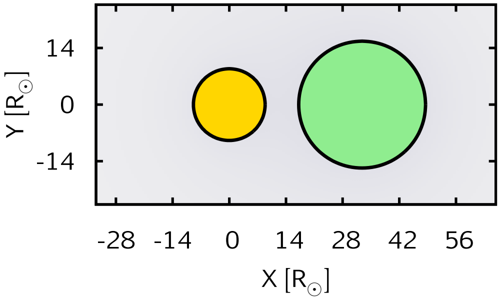


de Mink +09, **Szécsi** +14

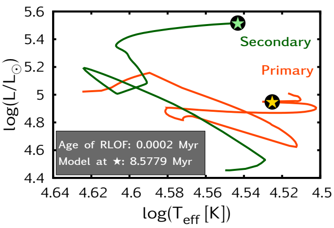


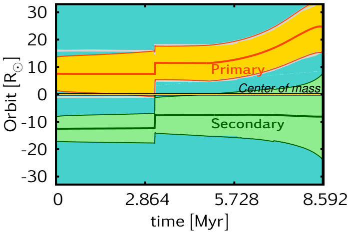


System: 29 $M_\odot$ + 17 $M_\odot$ + 1.5 d   Age: 8.5779 Myr



Menon & **Szécsi** +20 (in prep.)





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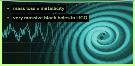

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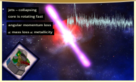
★ *current work:* metal-poor stellar populations

★ supervising PhD student Poojan Agrawal (Melbourne)

e.g. Watts +08,+09; Kruckow..**Szécsi** +16; Vigna-Gómez..**Szécsi** +18; Wijers '18 Broekgaarden +19; Neijssel..**Szécsi** +19; Stevenson..**Szécsi** +19;

High-redshift Univ.

Gamma-ray bursts



★ *Master:* statistical analysis of GRB lightcurves

★ *PhD:* chemically-homogeneous evolution in dwarf galaxies can lead to L-GRBs

★ *currently:* theoretical expert on THESEUS mission

★ planned satellite mission shortlisted by ESA

e.g. **Szécsi** +13; Leventis +14; Schulze +14; **Szécsi** '16; Bagoly & **Szécsi** +16; **Szécsi** '17a; **Szécsi** '17b; Japelj +18; Stratta..**Szécsi** +18; Amati..**Szécsi** +18;

Globular clusters

★ *post-doc in Prague:* metal-poor luminous supergiants play a key role

★ developed simulation of GC formation

★ *current work:* testing Z-dependence of GC formation with new stellar populations

★ lithium...

Szécsi +14; **Szécsi**, Mackey & Langer '18; **Szécsi** & Wünsch '19; **Szécsi** +(in prep.)

Future plans

How well do we understand metal-poor massive stars?

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Theory

Metal-*rich*
massive stars
↓
"assumptions"
↓
Metal-poor
massive stars

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Observations

spectroscopy
(good resolution,
large samples)

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How well do we understand metal-poor massive stars?

Theory ⇄ **Observations**

Metal-*rich*
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↓
"assumptions"
↓
Metal-poor
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spectroscopy
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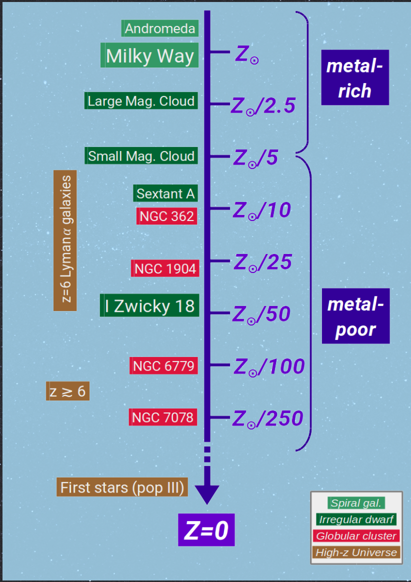
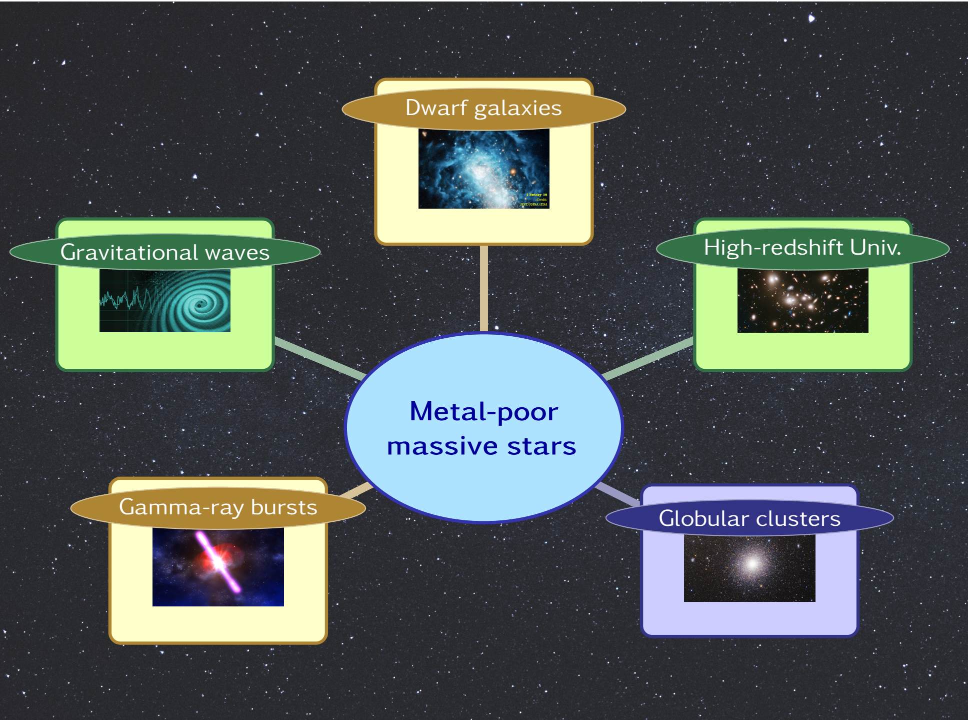
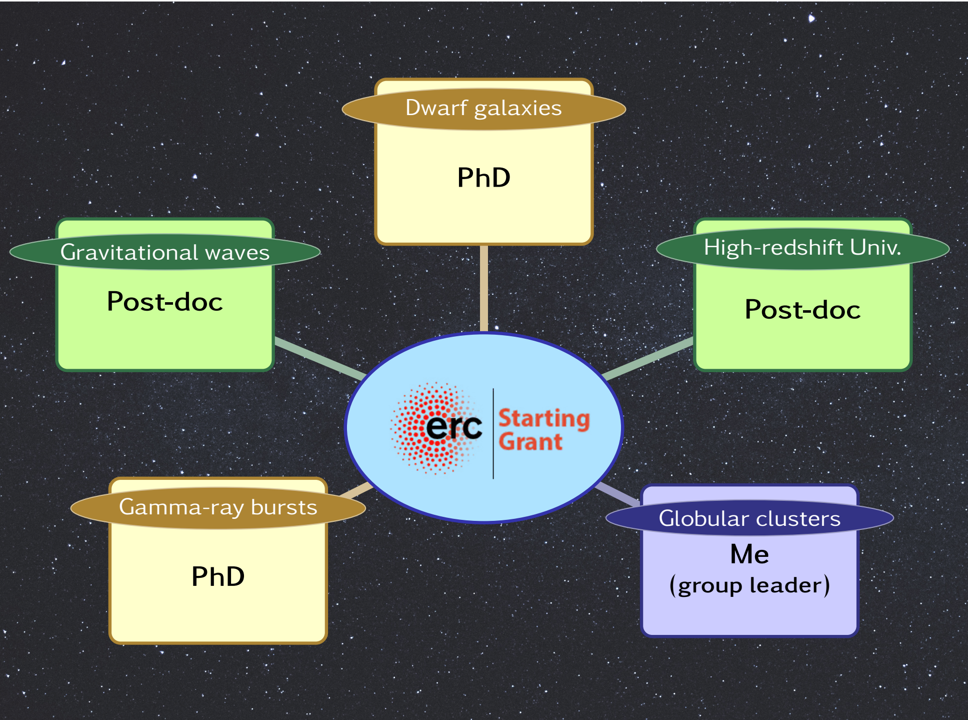



Dwarf galaxies
Gravitational waves
High-redshift Univ.
Metal-poor massive stars
Gamma-ray bursts
Globular clusters


Dwarf galaxies
PhD
Gravitational waves
Post-doc
High-redshift Univ.
Post-doc
erc
Starting Grant
Gamma-ray bursts
PhD
Globular clusters
Me
(group leader)

Technical details…

Needed: **simulated *populations***
of massive stars
at various metallicities
(single & binary)

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3D magneto-hydro. simulations of star-forming regions

[SILCC]

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globular cluster
formation simulation
WindCalc

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grav.wave event rate
predictions
COMPAS

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(L-GRB, SN type ...)

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[SILCC]

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SILCC

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MESA + COMPAS

type of compact remnant
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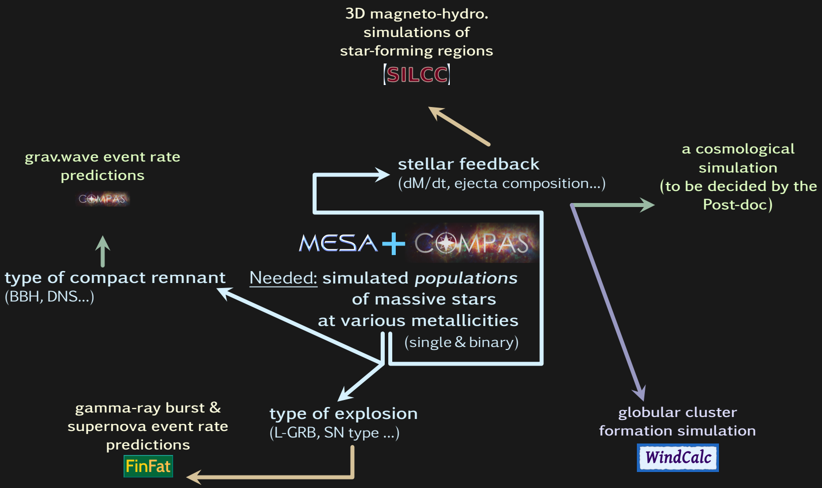
gamma-ray burst &
supernova event rate
predictions
FinFat

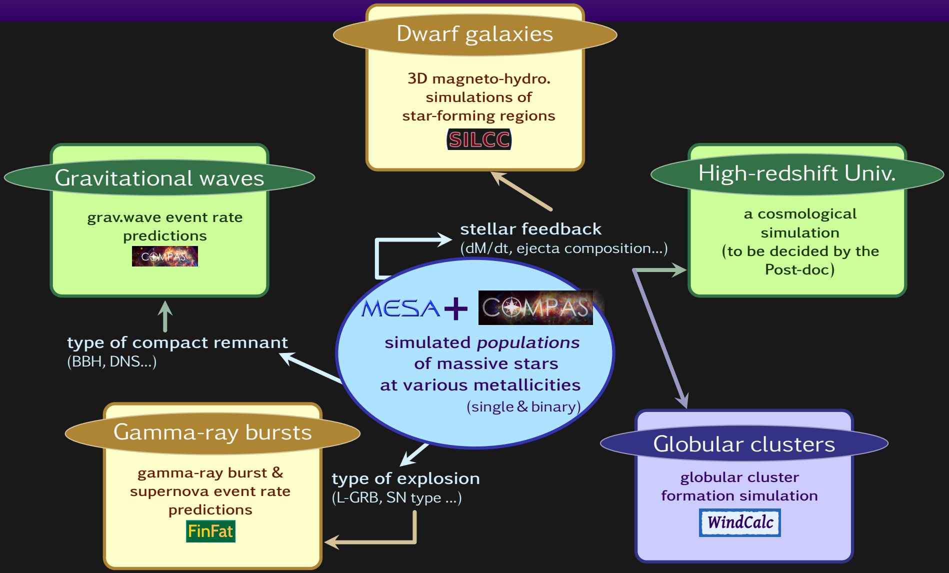
type of explosion
(L-GRB, SN type ...)

globular cluster
formation simulation
WindCalc

Technical details...



Technical details...



Technical details...

Dwarf galaxies

3D magneto-hydro. simulations of star-forming regions

SILCC

stellar feedback
(dM/dt, ejecta composition...)

Gravitational waves

grav.wave event rate predictions

COMPAS

type of compact remnant
(BBH, DNS...)

High-redshift Univ.

a cosmological simulation
(to be decided by the Post-doc)

MESA + COMPAS

simulated *populations* of massive stars at various metallicities
(single & binary)

Gamma-ray bursts

gamma-ray burst & supernova event rate predictions

FinFat

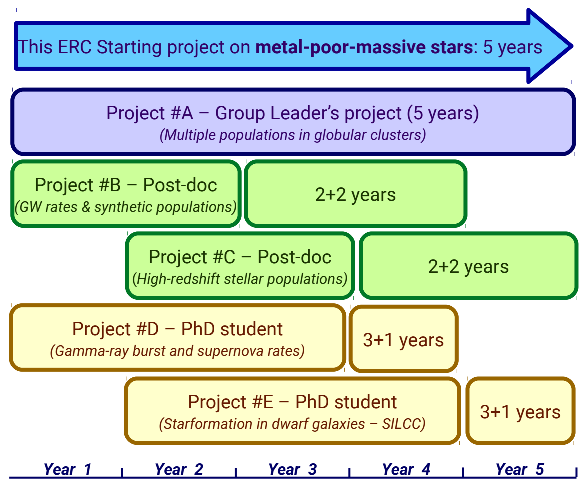
type of explosion
(L-GRB, SN type ...)

Globular clusters

globular cluster formation simulation

WindCalc

Timelines


This ERC Starting project on **metal-poor-massive stars**: 5 years
Project #A – Group Leader's project (5 years)
(Multiple populations in globular clusters)
Project #B – Post-doc
(GW rates & synthetic populations)
2+2 years
Project #C – Post-doc
(High-redshift stellar populations)
2+2 years
Project #D – PhD student
(Gamma-ray burst and supernova rates)
3+1 years
Project #E – PhD student
(Starformation in dwarf galaxies – SILCC)
3+1 years
Year 1
Year 2
Year 3
Year 4
Year 5

The host...

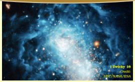
The host...

ANTON PANNEKOEK
INSTITUTE

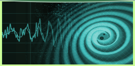
UNIVERSITY OF AMSTERDAM

The host…

Dwarf galaxies



Gravitational waves

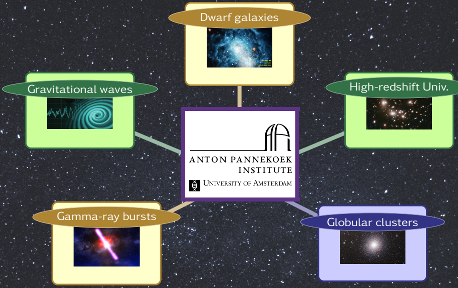


High-redshift Univ.

ANTON PANNEKOEK INSTITUTE
UNIVERSITY OF AMSTERDAM

Gamma-ray bursts

Globular clusters


Dwarf galaxies
Gravitational waves
High-redshift Univ.
ANTON PANNEKOEK INSTITUTE
UNIVERSITY OF AMSTERDAM
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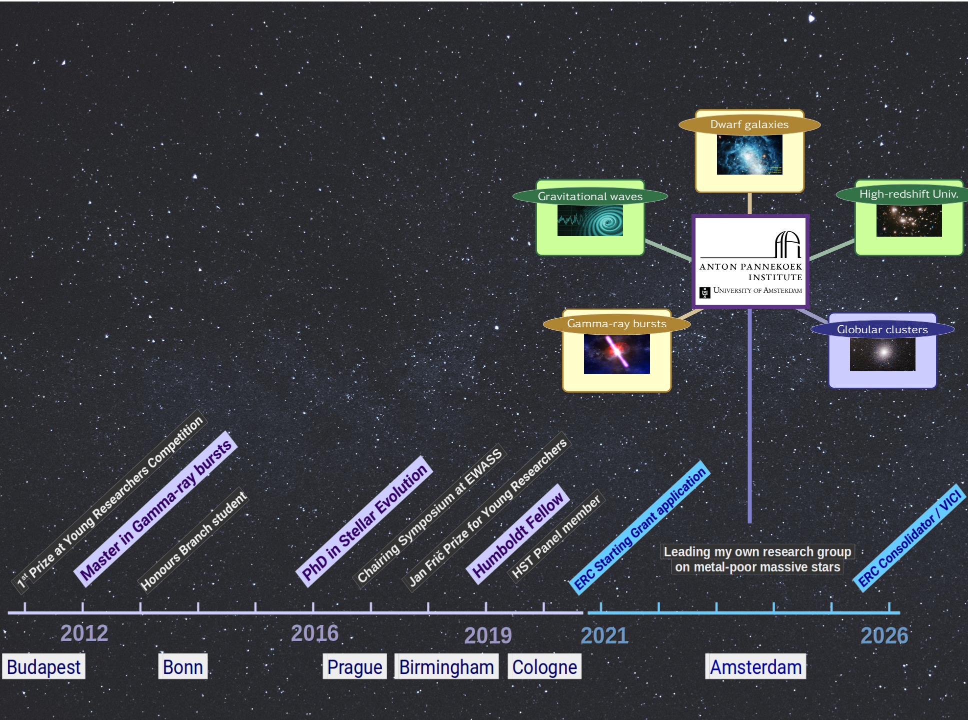
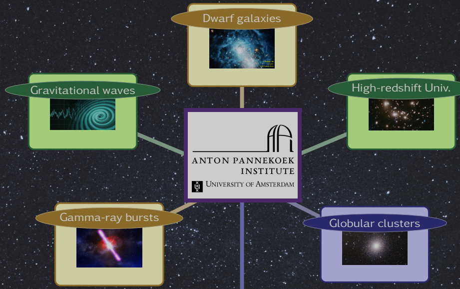

Dwarf galaxies
Gravitational waves
High-redshift Univ.
ANTON PANNEKOEK INSTITUTE
UNIVERSITY OF AMSTERDAM
Gamma-ray bursts
Globular clusters
1st Prize at Young Researchers Competition
Master in Gamma-ray bursts
Honours Branch student
PhD in Stellar Evolution
Chairing Symposium at EWASS
Jan Frič Prize for Young Researchers
Humboldt Fellow
HST Panel member
ERC Starting Grant application
Leading my own research group
on metal-poor massive stars
ERC Consolidator / VICI
2012
2016
2019
2021
2026
Budapest
Bonn
Prague
Birmingham
Cologne
Amsterdam

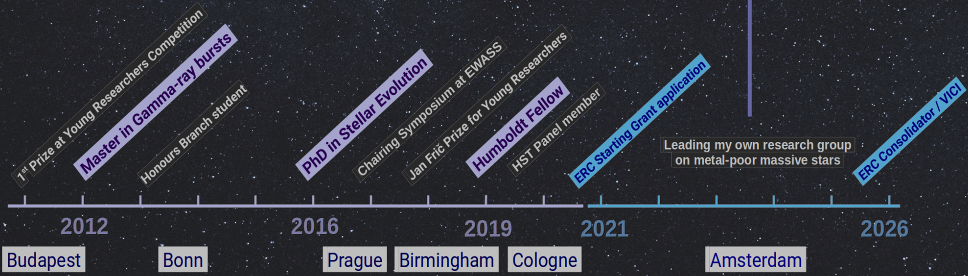
The theory linking gravitational waves, star-formation and the dawn of the Universe

Dr. Dorottya Szécsi

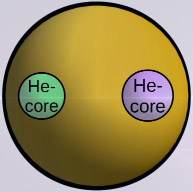
Humboldt Fellow
University of Cologne, Germany

Thank you for your attention!

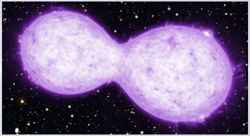




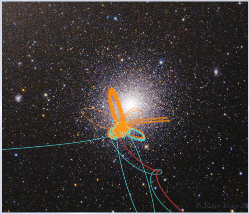
3 GW progenitor theories



Common envelope
in a binary



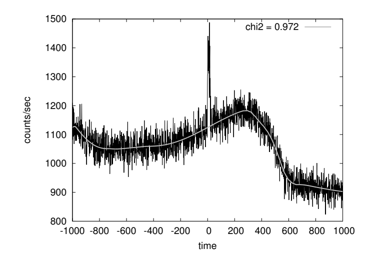
Chemically-
homogeneous
evolution
in a binary

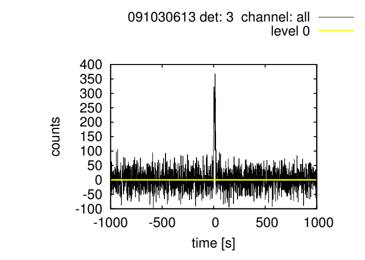


Dynamics in
dense clusters

e.g. Vigna-Gómez..**Szécsi**+18; **Szécsi**’17a,b; **Szécsi**&Wünsch’19

Direction dependent background fitting



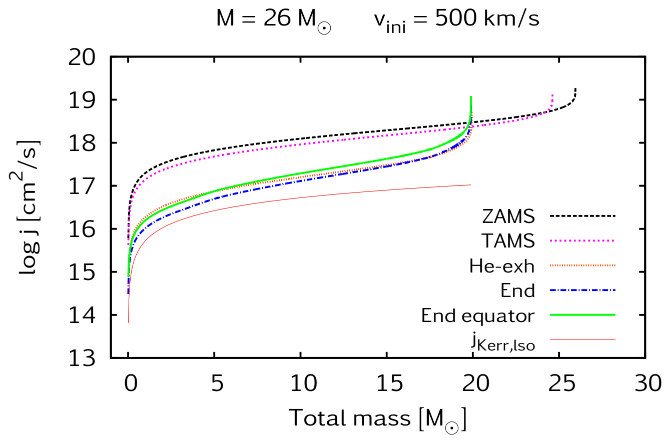


- The new model takes into account:
  - angle between detector and burst
  - angle between Sun and detector
  - Earth uncovering
- Numerical fitting
- Lightcurve without background → further analyses

Szécsi +12a,b, **Szécsi** +13

A long-duration GRB progenitor model

(1/50 $Z_\odot$)



Szécsi'16