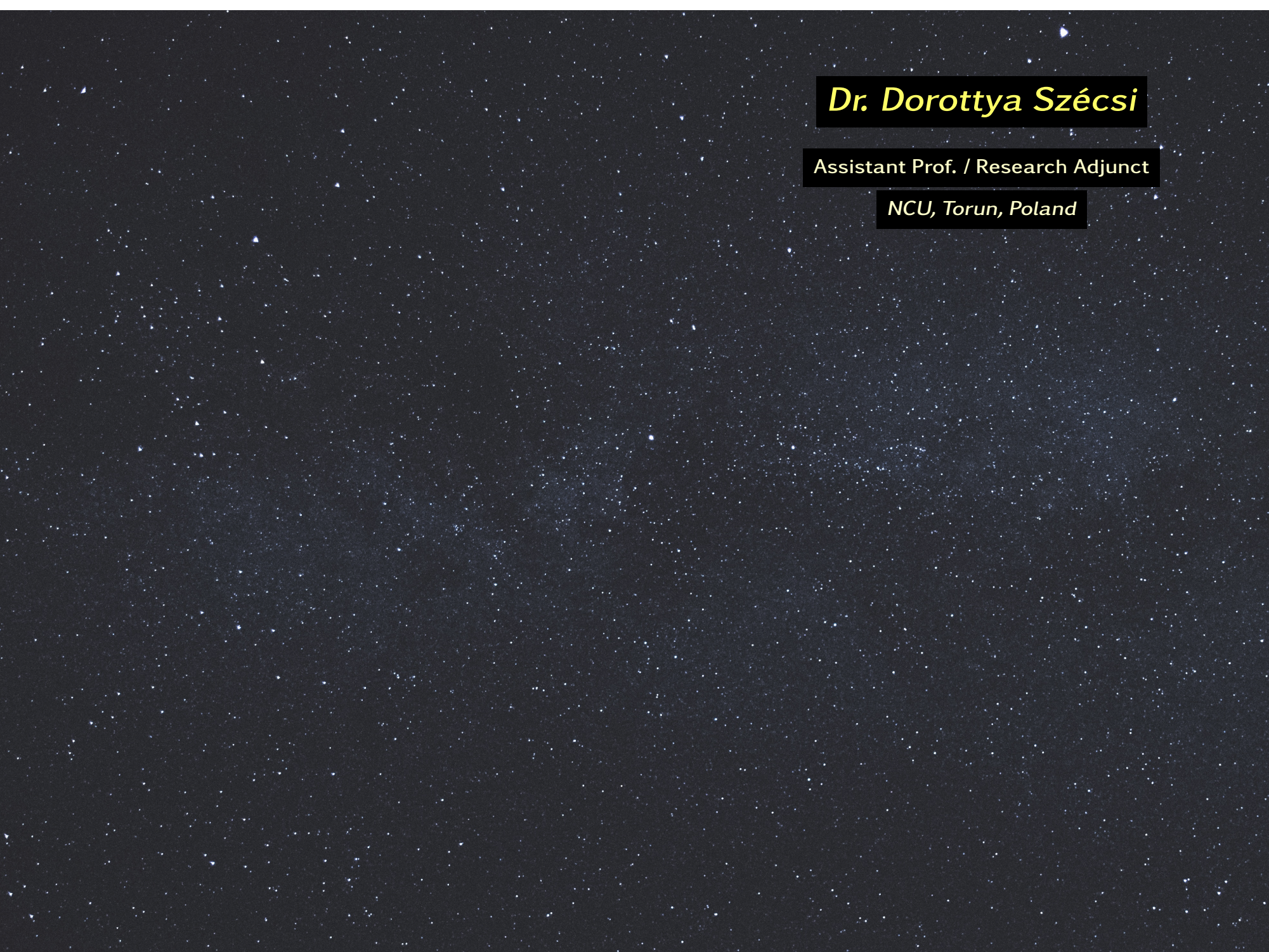
The theory linking gravitational waves, star-formation and the dawn of the Universe

Dr. Dorottya Szécsi

Assistant Professor / Research Adjunct
Nicolaus Copernicus University, Poland

Torun, 30th November 2020



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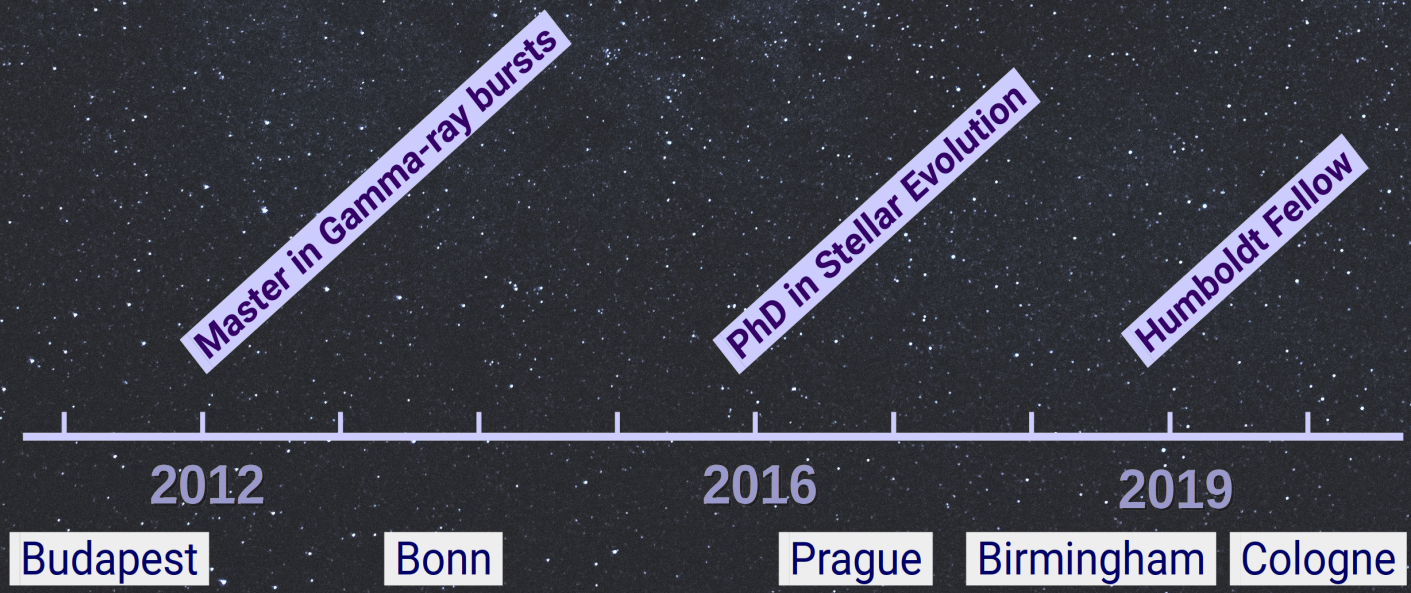

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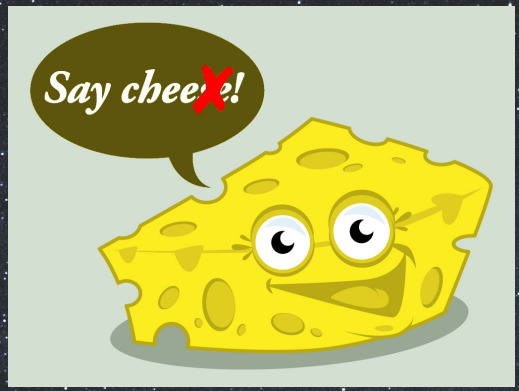


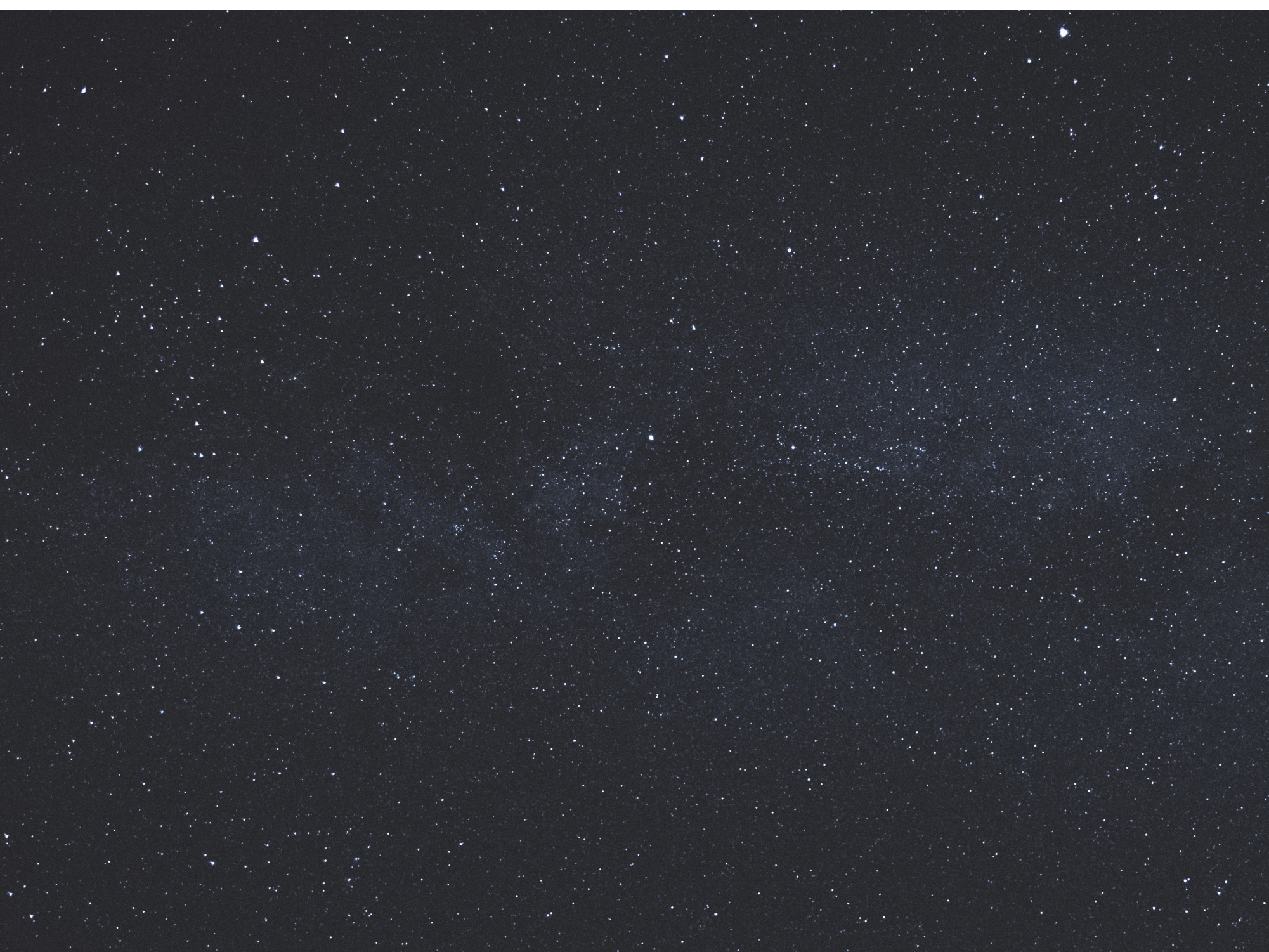
Master in Gamma-ray bursts

PhD in Stellar Evolution

Humboldt Fellow

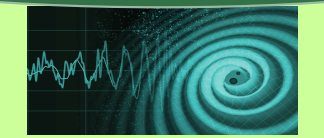
2012 — 2016 — 2019

Budapest — Bonn — Prague — Birmingham — Cologne



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)

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

★ ionizing flux is strong due to chemically homogeneous evolution

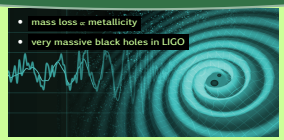
★ *current work:* 3D hydro simulations of star-forming regions

★ 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; Walch & Szécsi (in prep.);

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

★ supervising PhD student Poojan Agrawal (Melbourne)

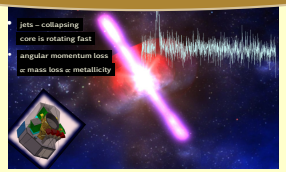
e.g. Watts +08,+09; Kruckow, Szécsi +16; Vigna-Gómez, Szécsi +18; Wijers '18 Broekgaarden +19; Neijssel, Szécsi +19; Stevenson, Szécsi +19;

High-redshift Univ.

- 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; Szécsi '17a; Szécsi '17b; Japelj +18; Stratta, Szécsi +18; Amati, Szécsi +18;

Globular clusters

- metal-poor low-mass stars
- previous generation: massive stars

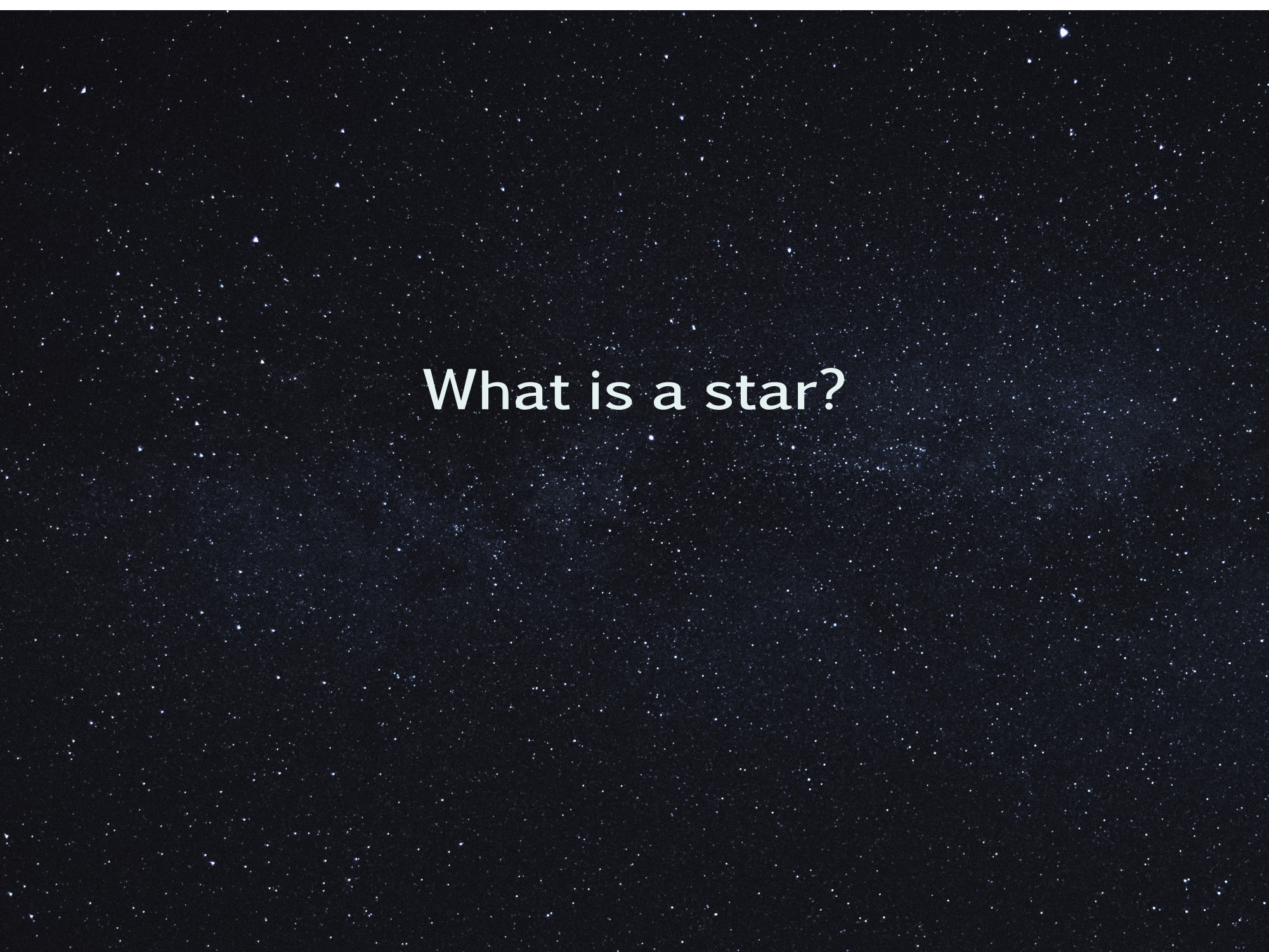
★ *post-doc in Prague:* metal-poor luminous supergiants play a key role

★ 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.)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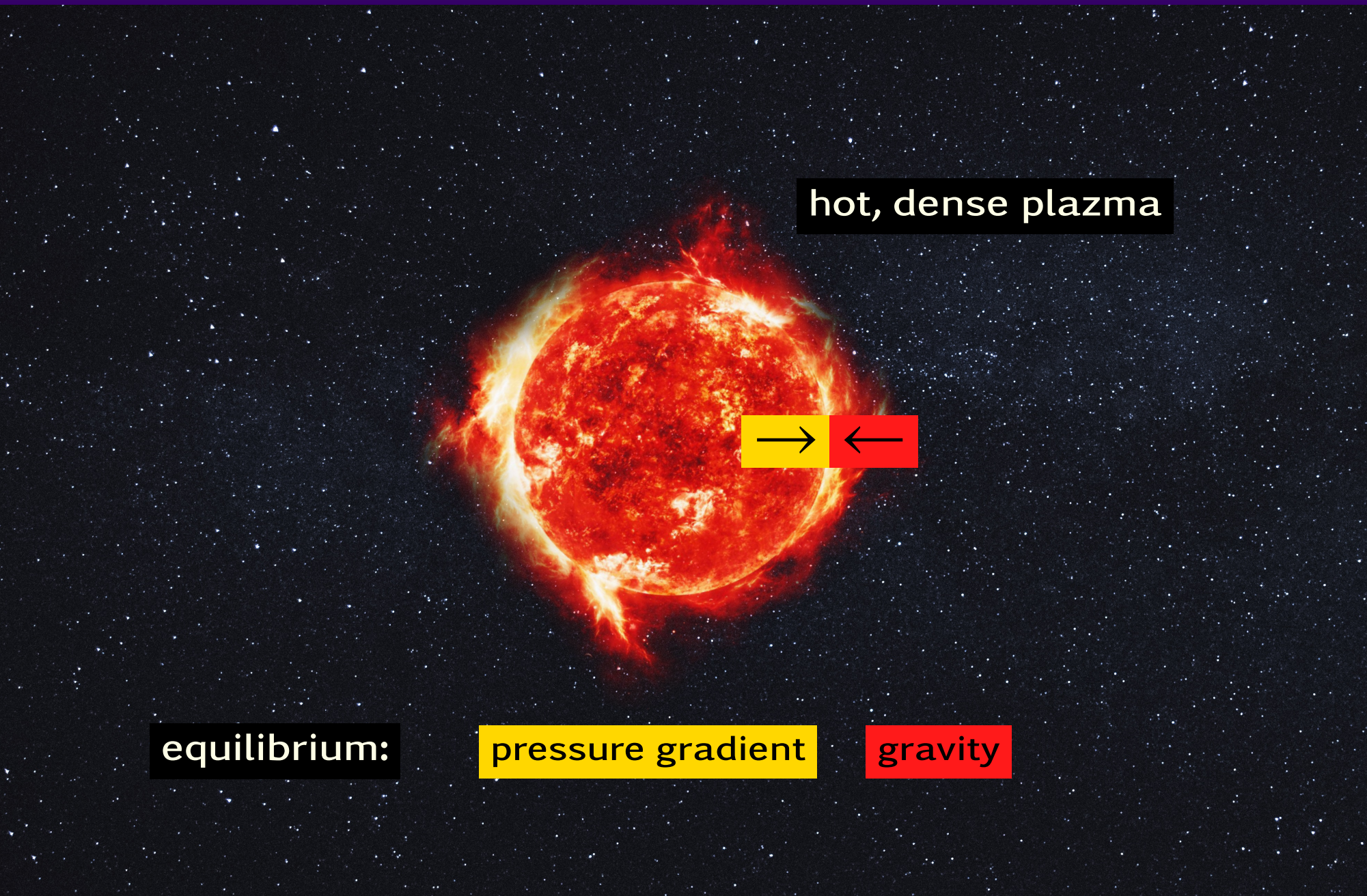

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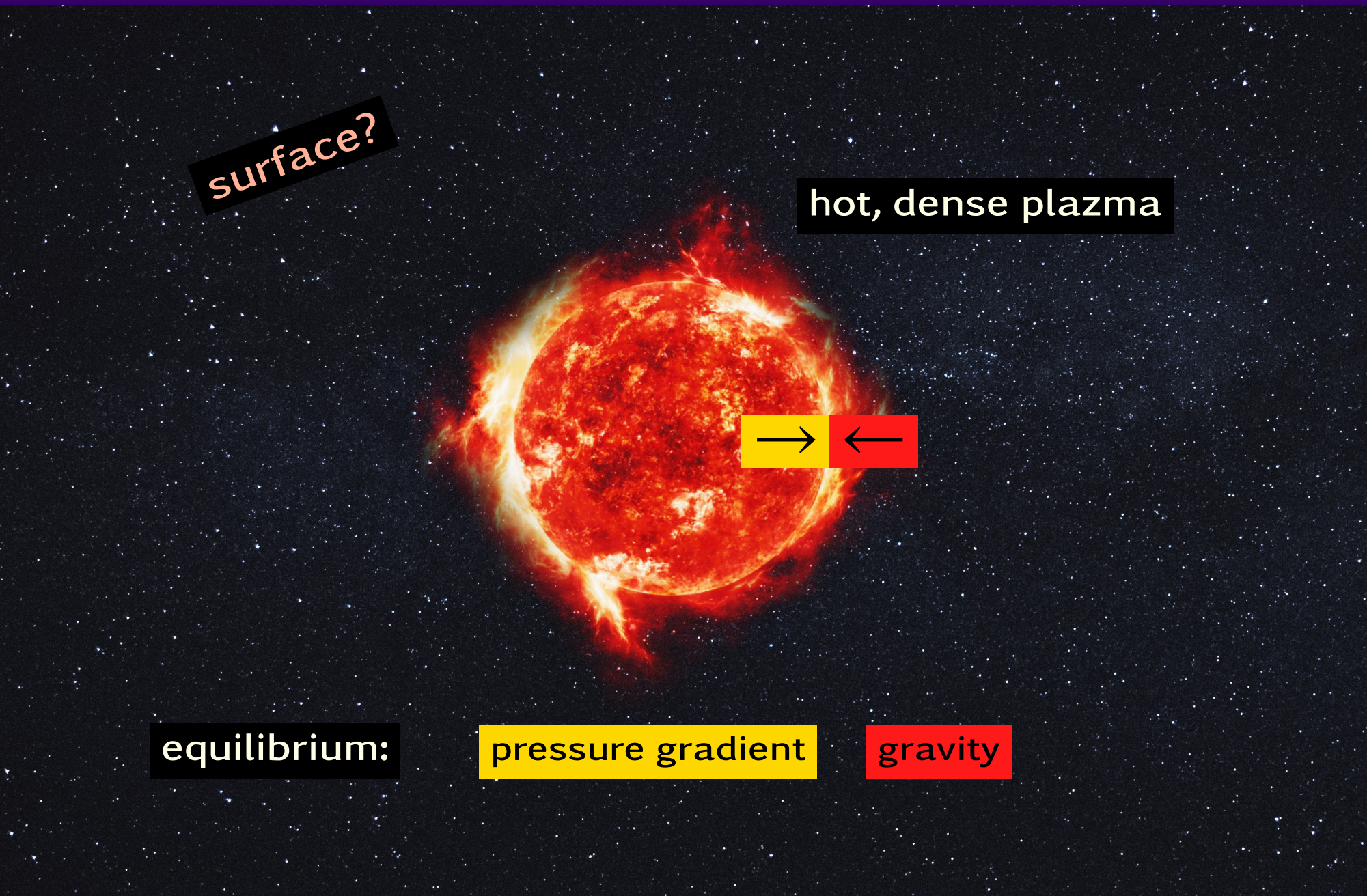
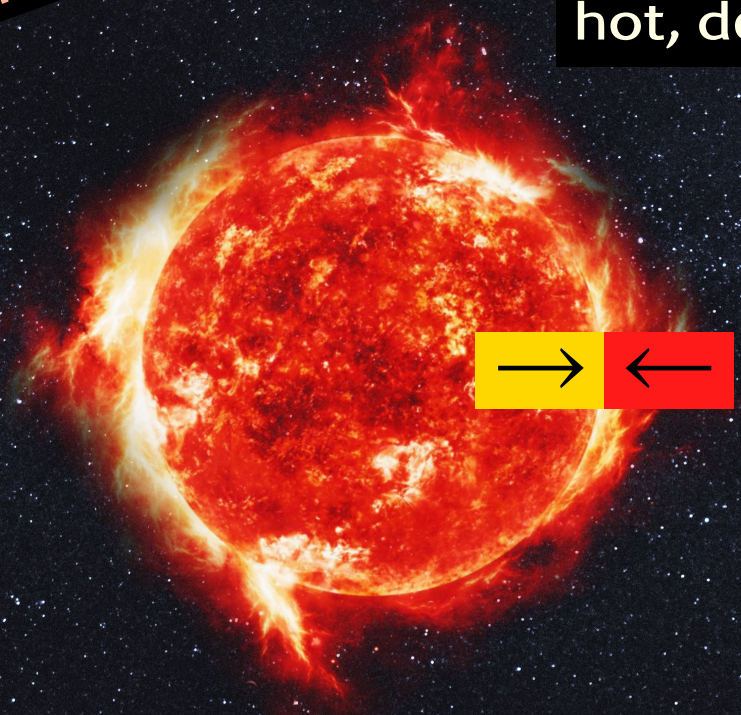


What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



equilibrium: pressure gradient gravity

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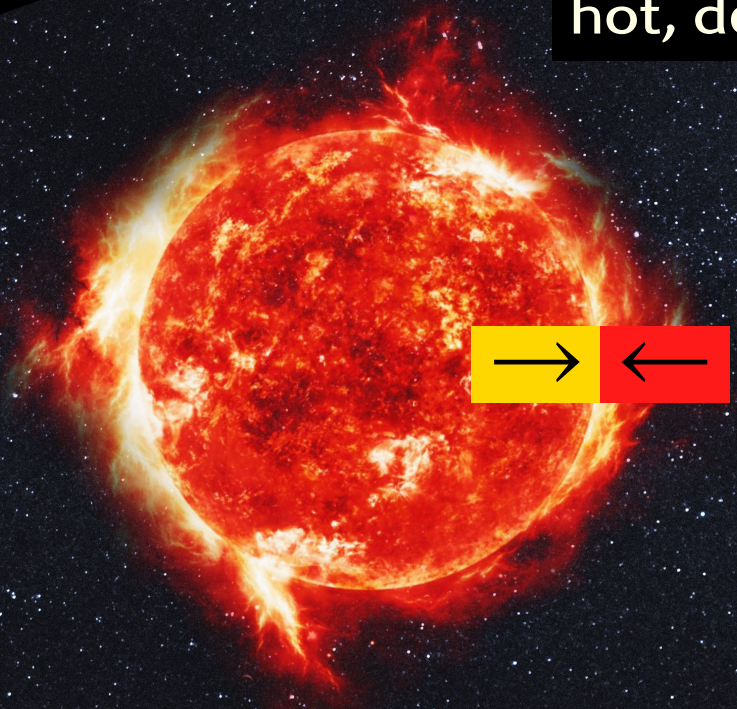

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What is inside?

→ ←

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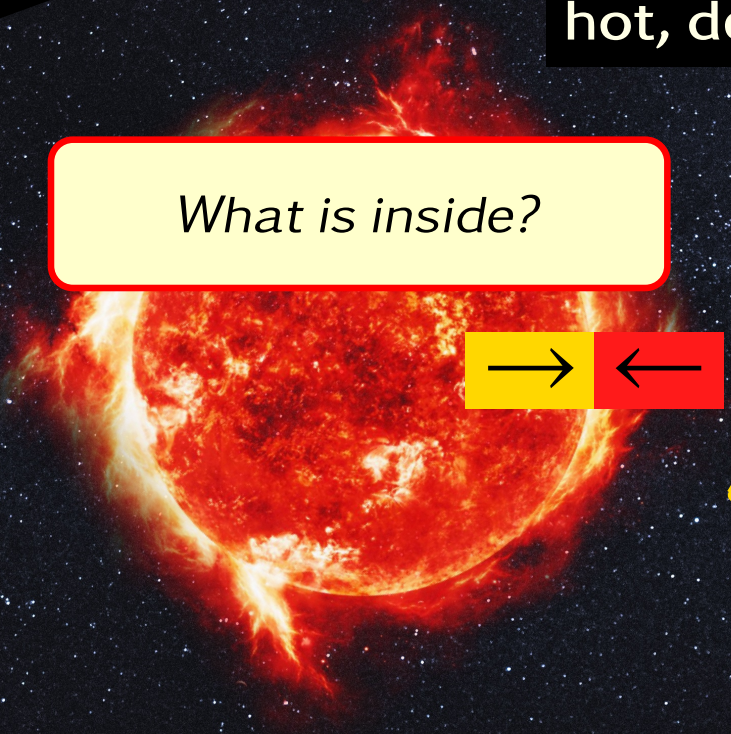
What is inside?



→ ←

theoretical modelling of the stellar structure

equilibrium: pressure gradient gravity

Theoretical modelling of the stellar structure

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

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

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

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

Guilera+ 11

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Guilera+ 11

composition change due to nuclear burning:

Theoretical modelling of the stellar structure

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mass conservation

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$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad (3)$$

energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (4)$$

transport of energy

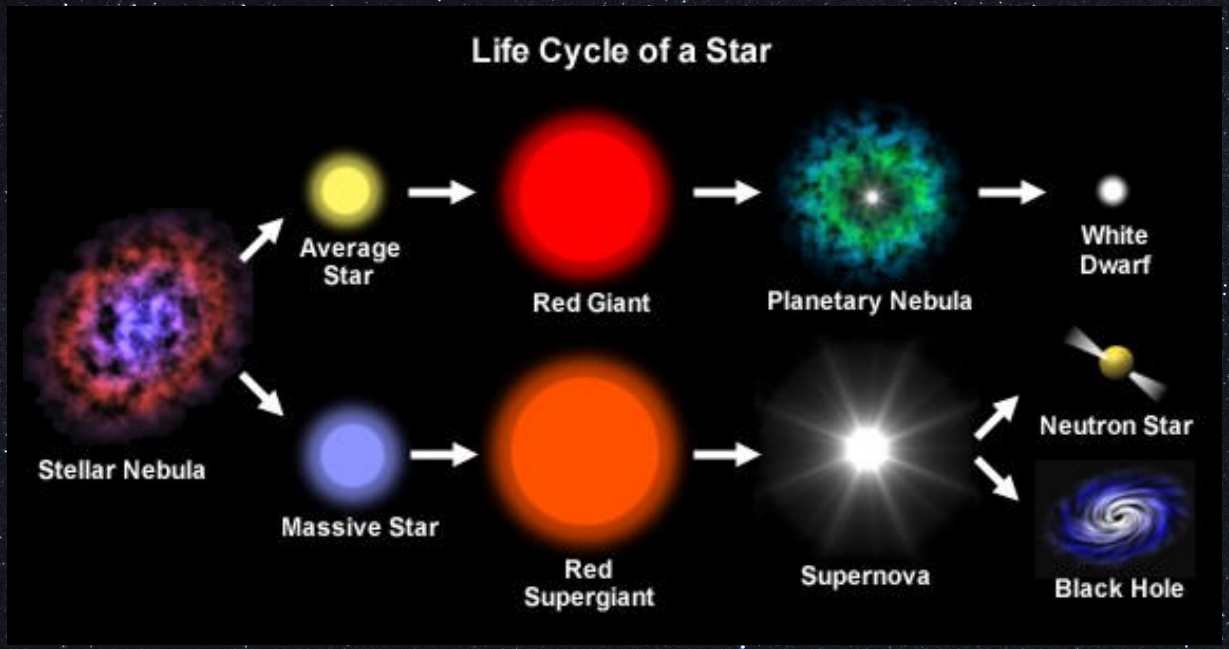
Guilera+ 11

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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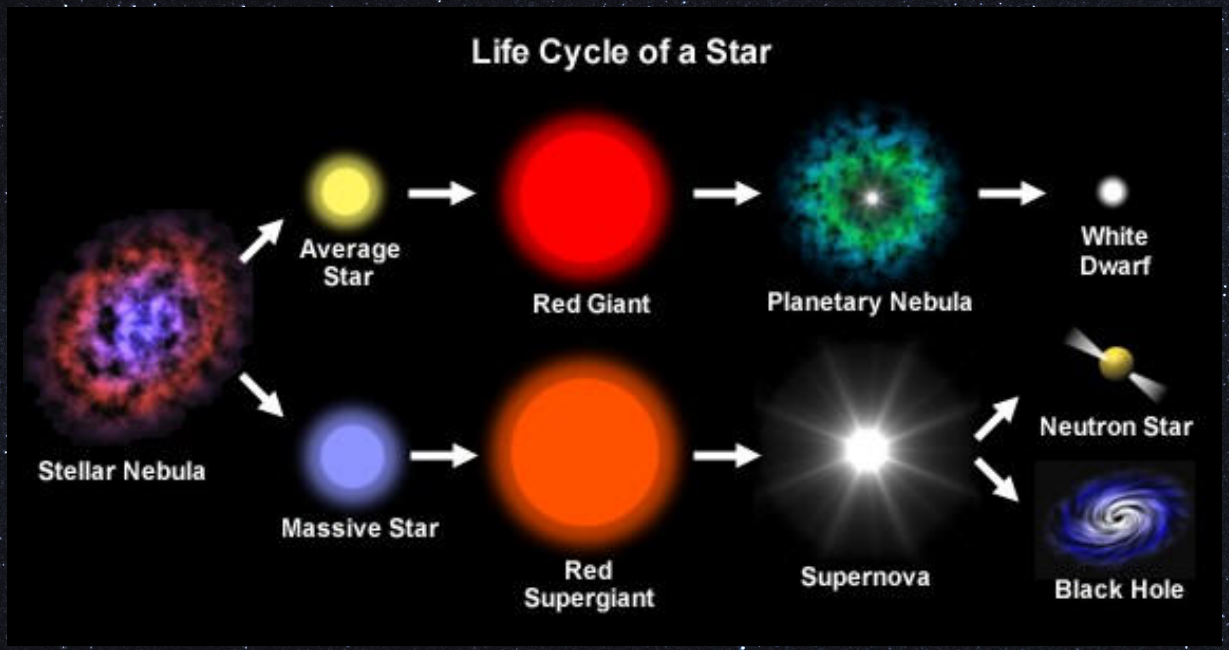

- Metallicity
- Rotation
- Binarity

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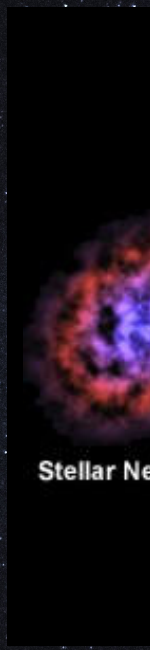

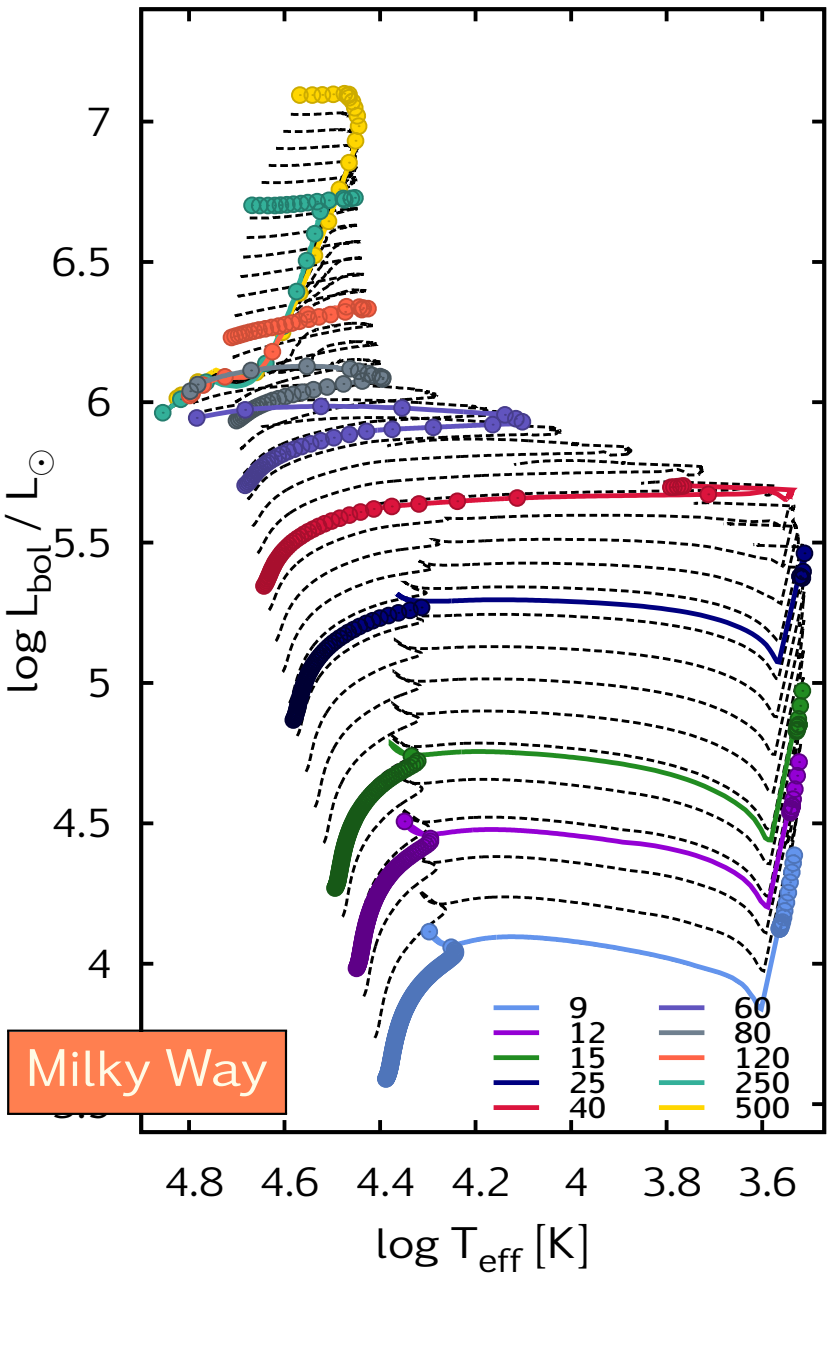

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Brott+ 11 (< 60 $M_\odot$),

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

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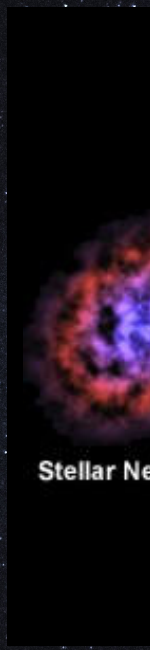

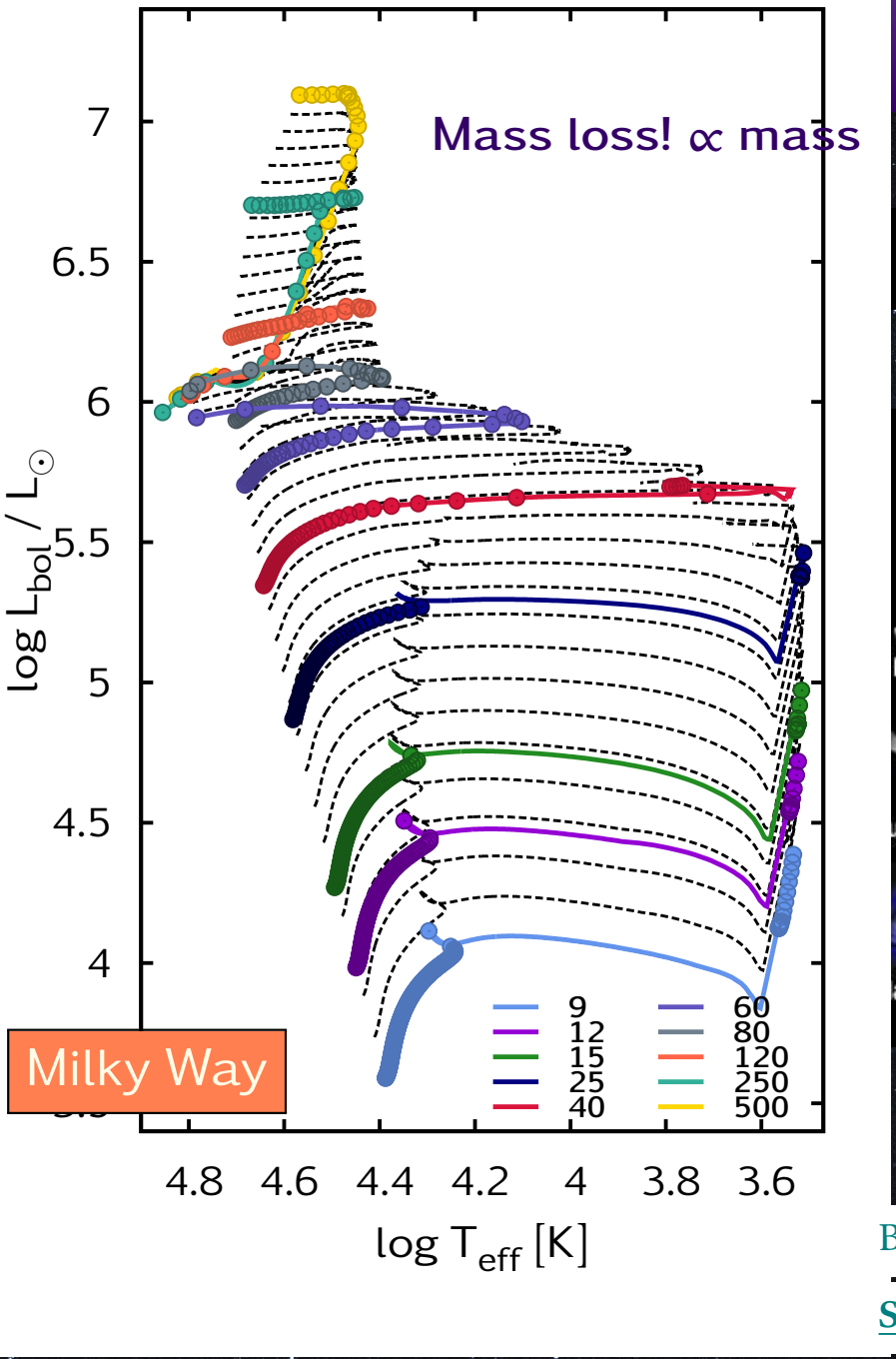

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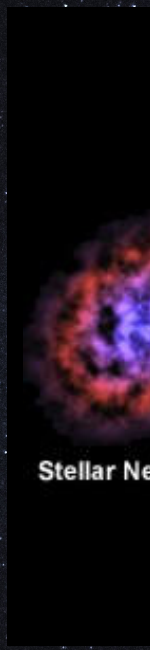

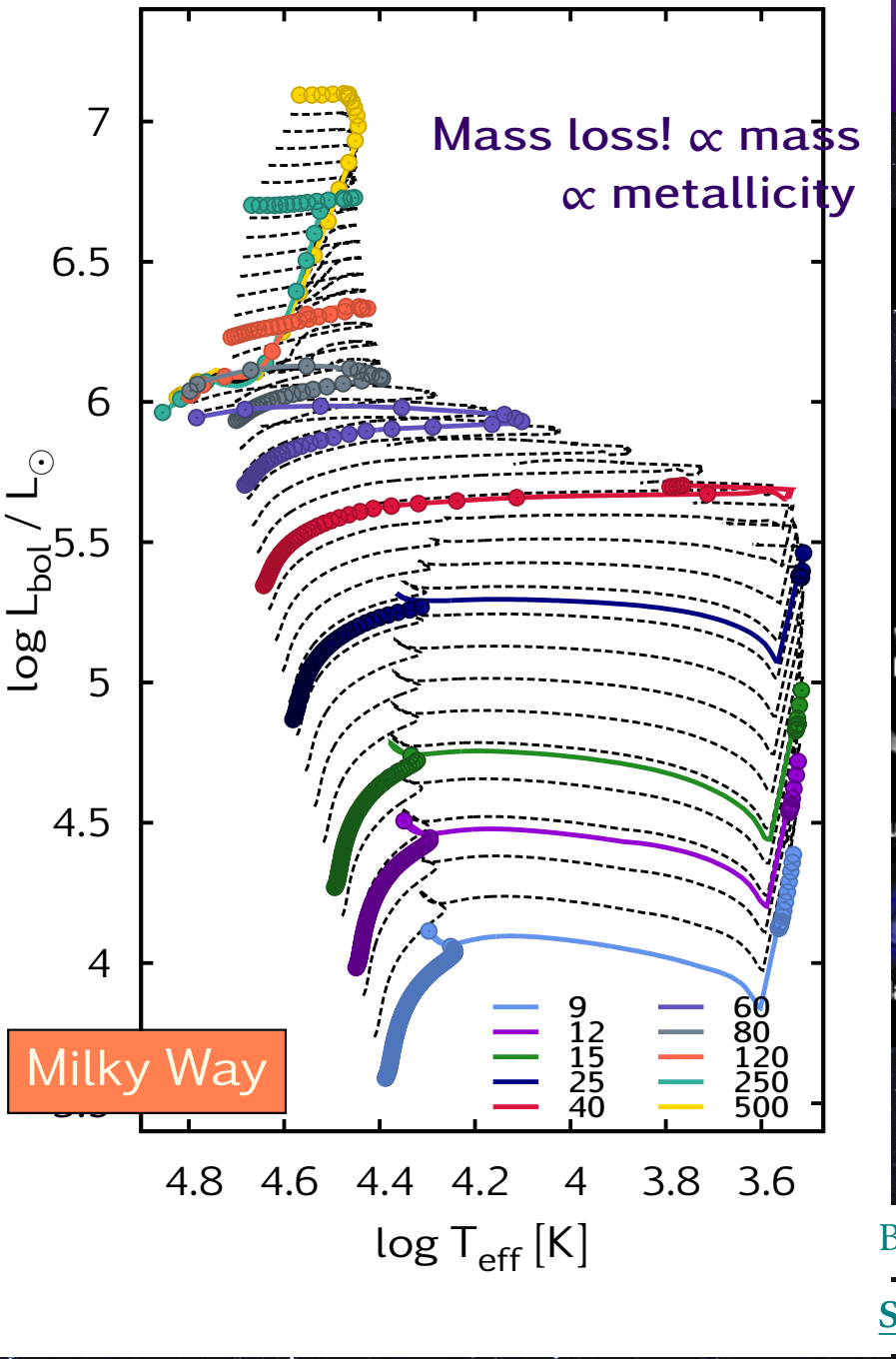

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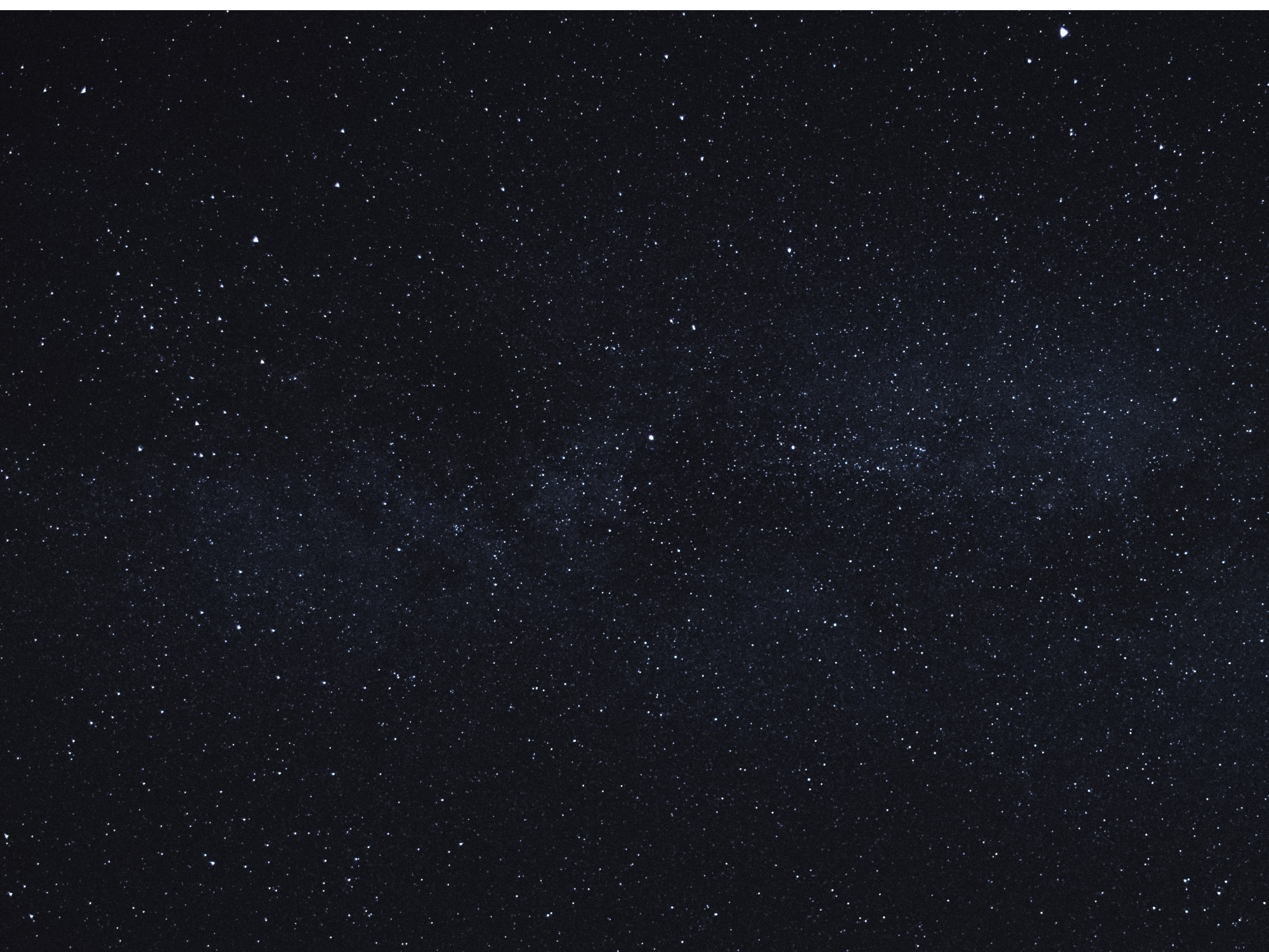
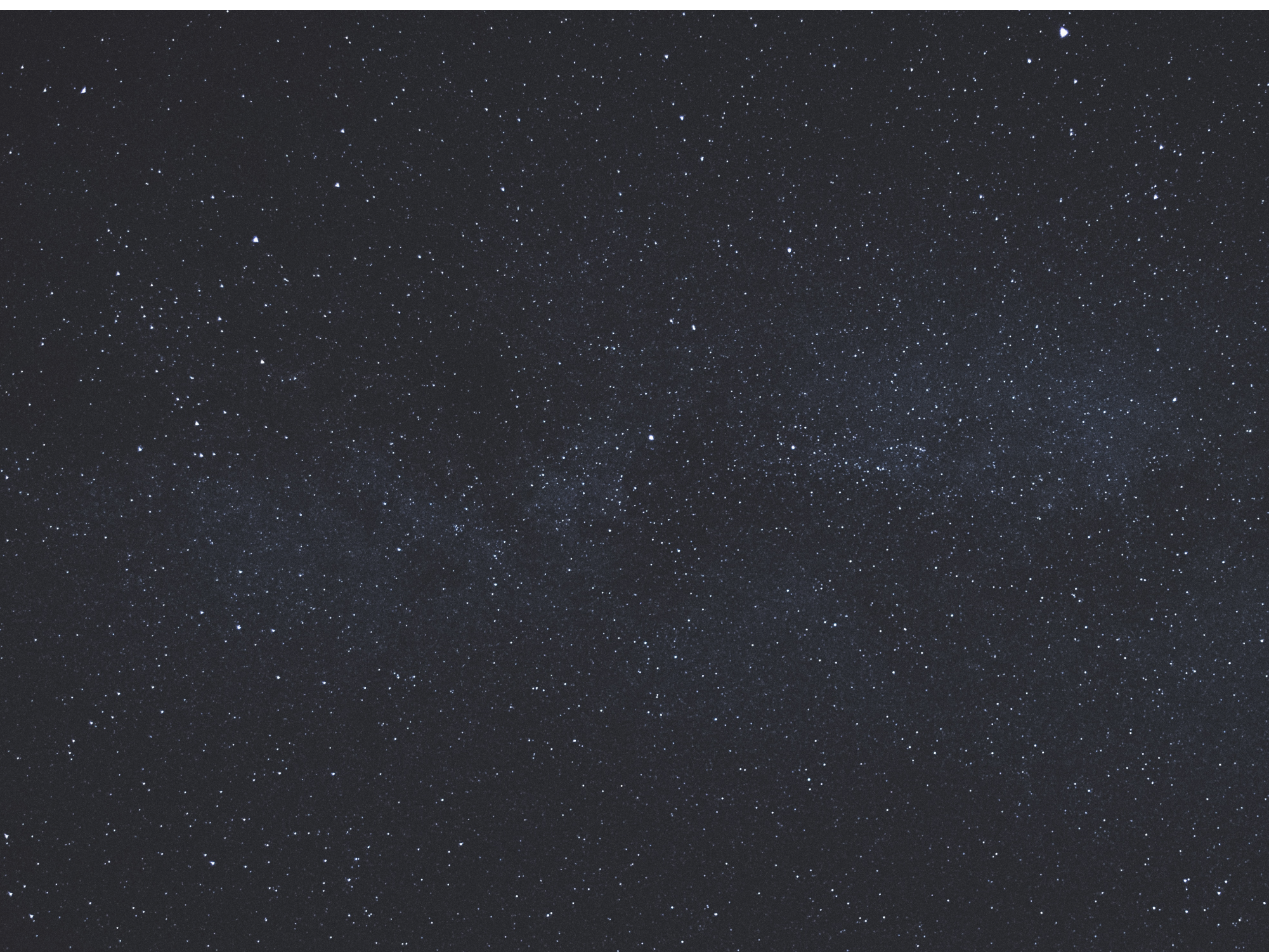
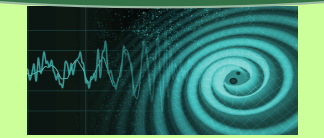




Dwarf galaxies

Gravitational waves



High-redshift Univ.

Metal-poor massive stars

Gamma-ray bursts

Globular clusters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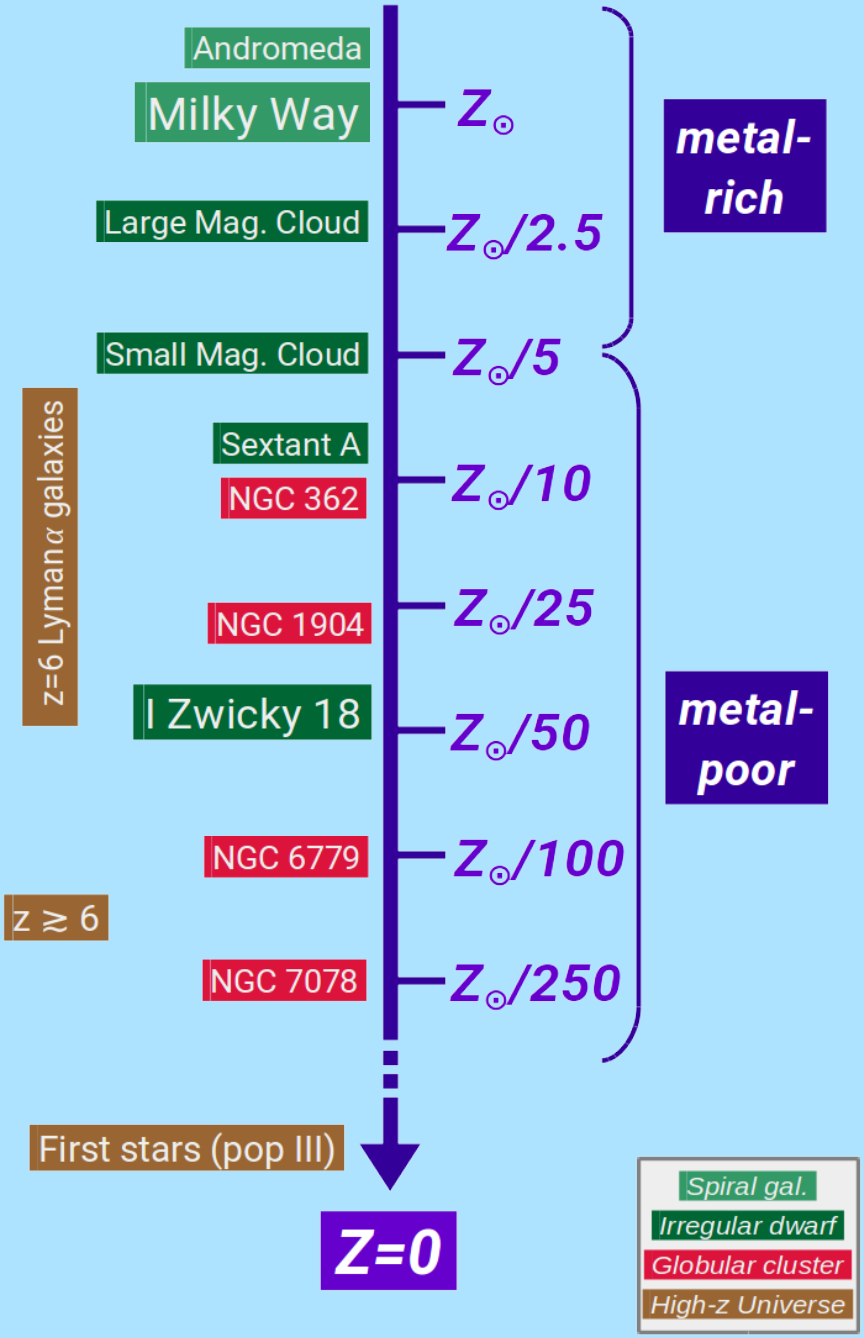
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z ≳ 6
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metal-rich
metal-poor
First stars (pop III)
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Spiral gal.
Irregular dwarf
Globular cluster
High-z Universe

Andromeda

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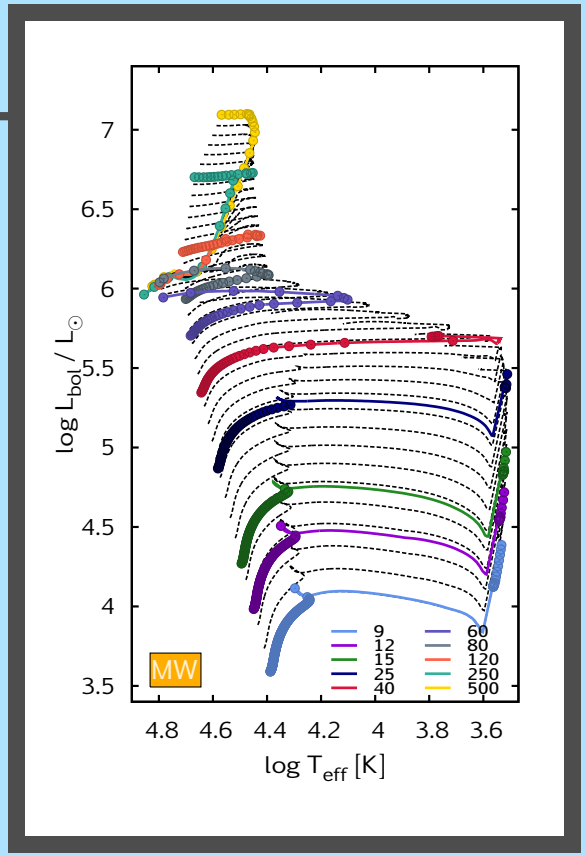

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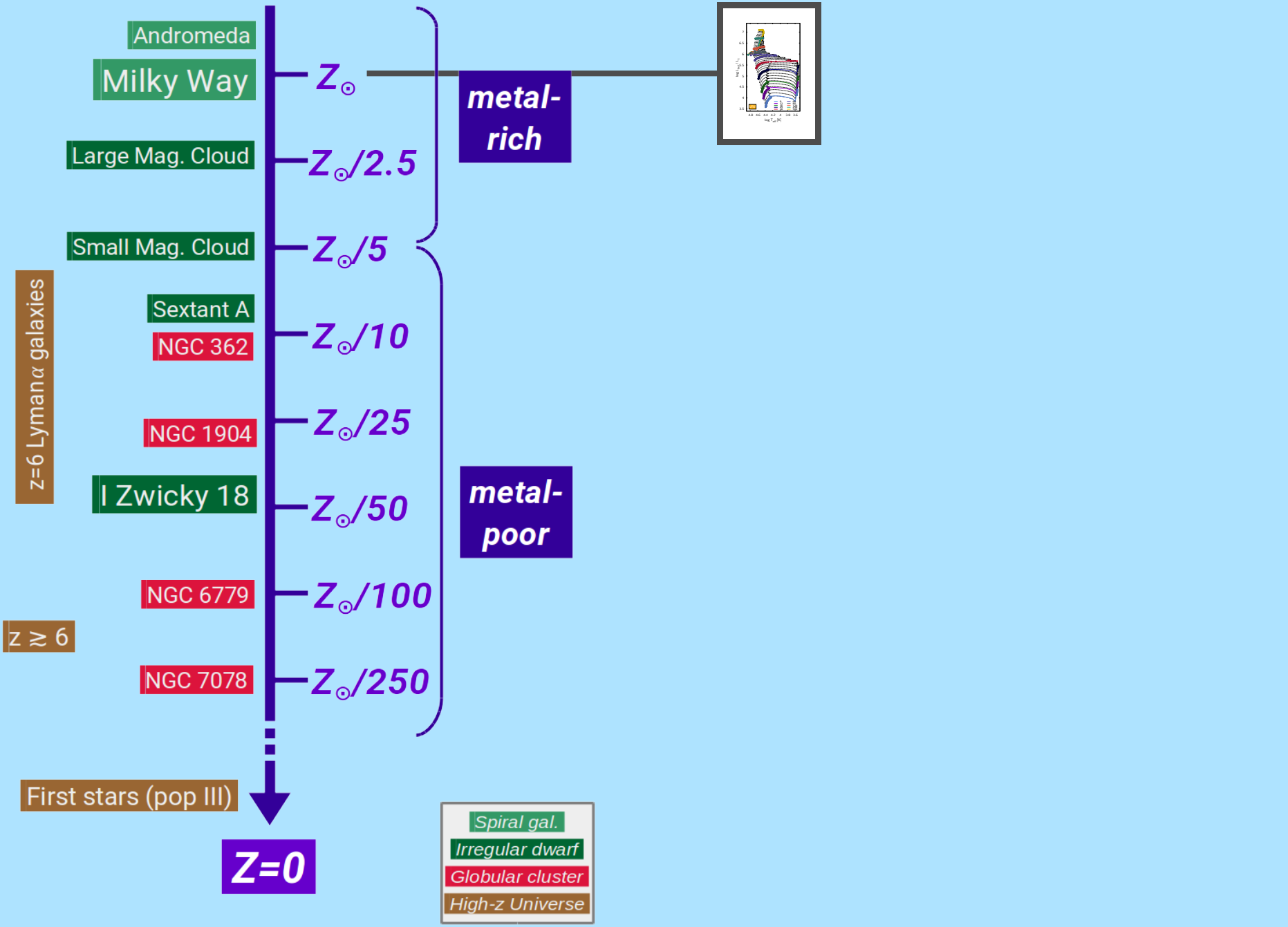
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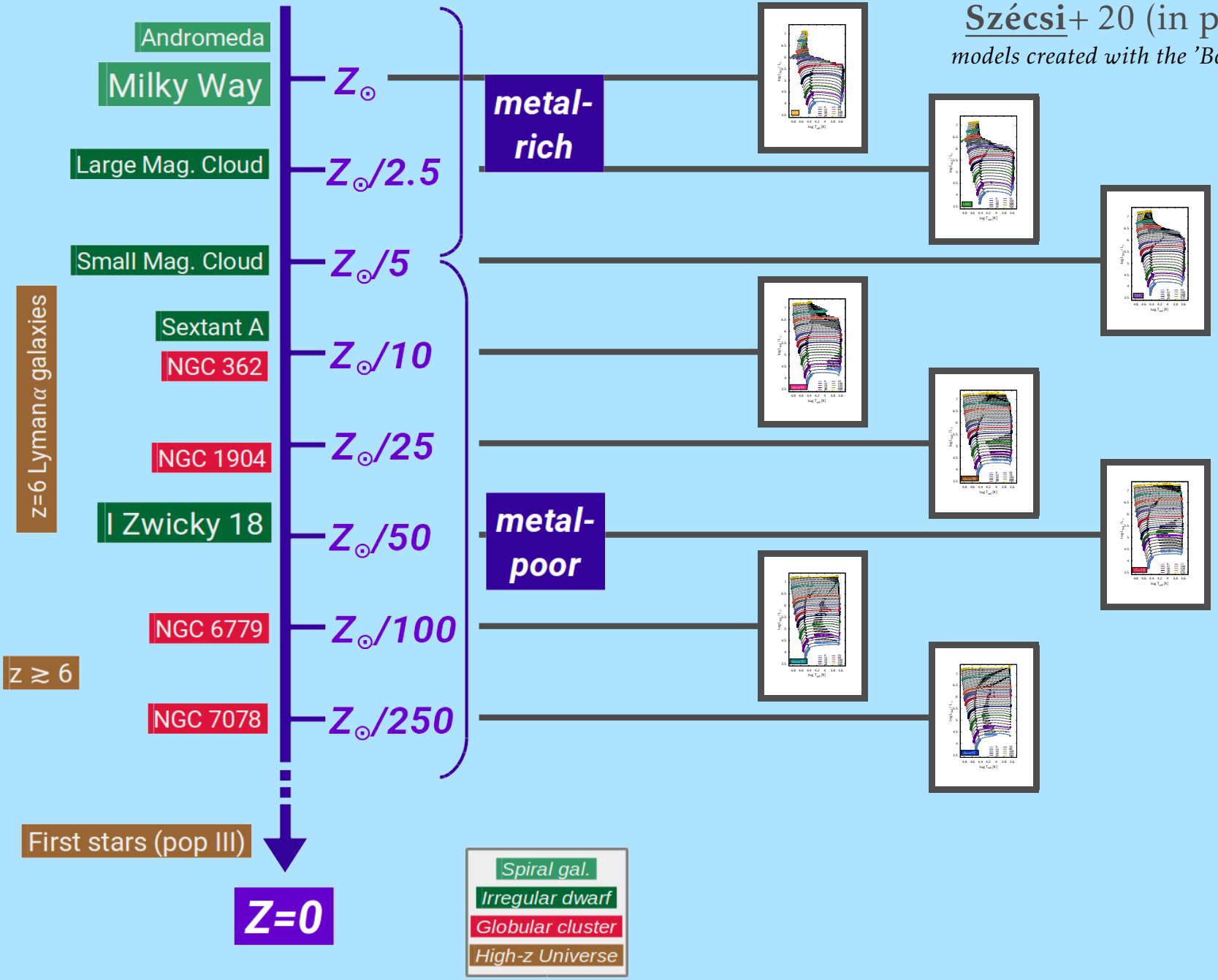
Szécsi+ 20 (in prep.)
models created with the 'Bonn' code
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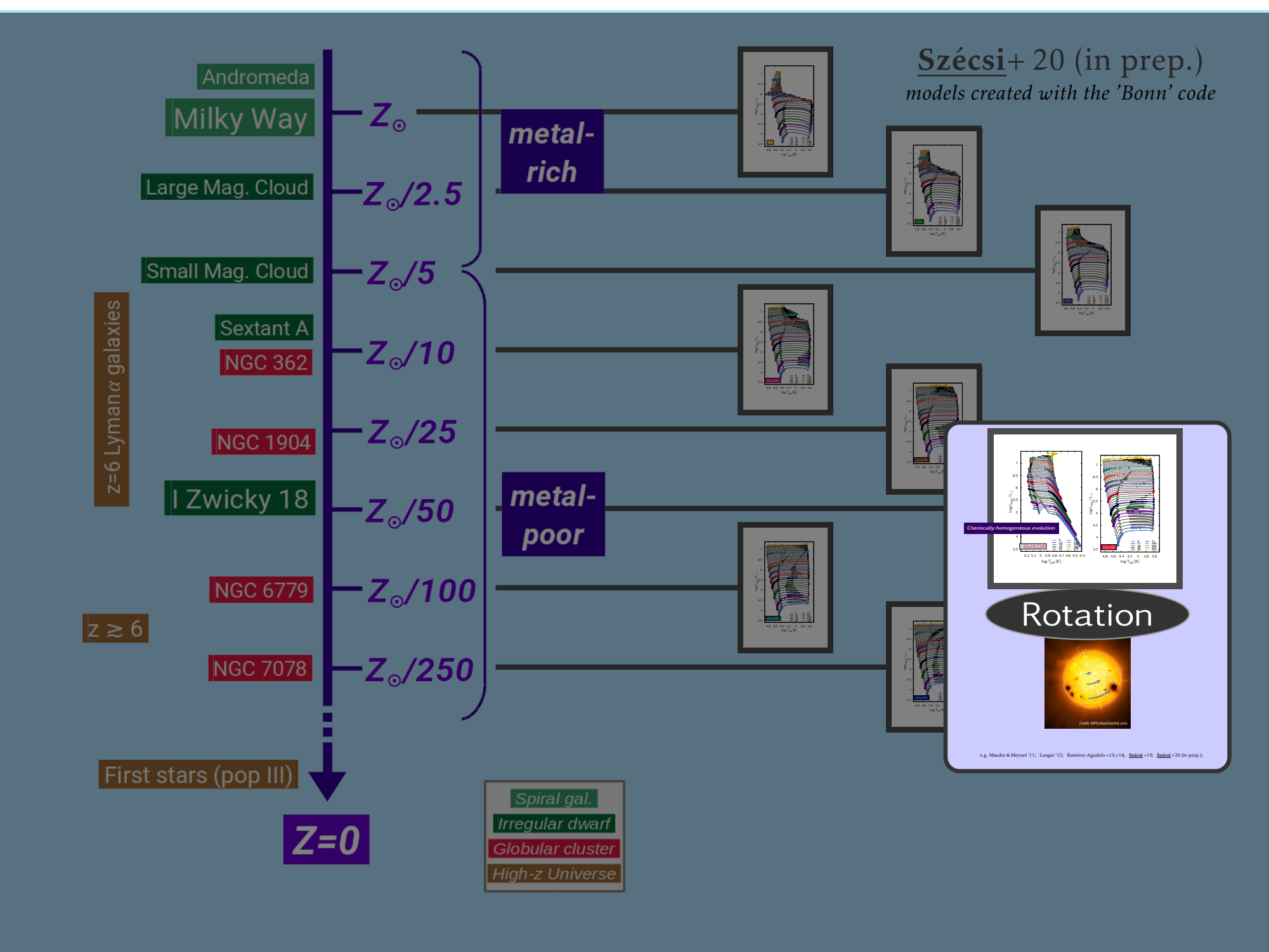
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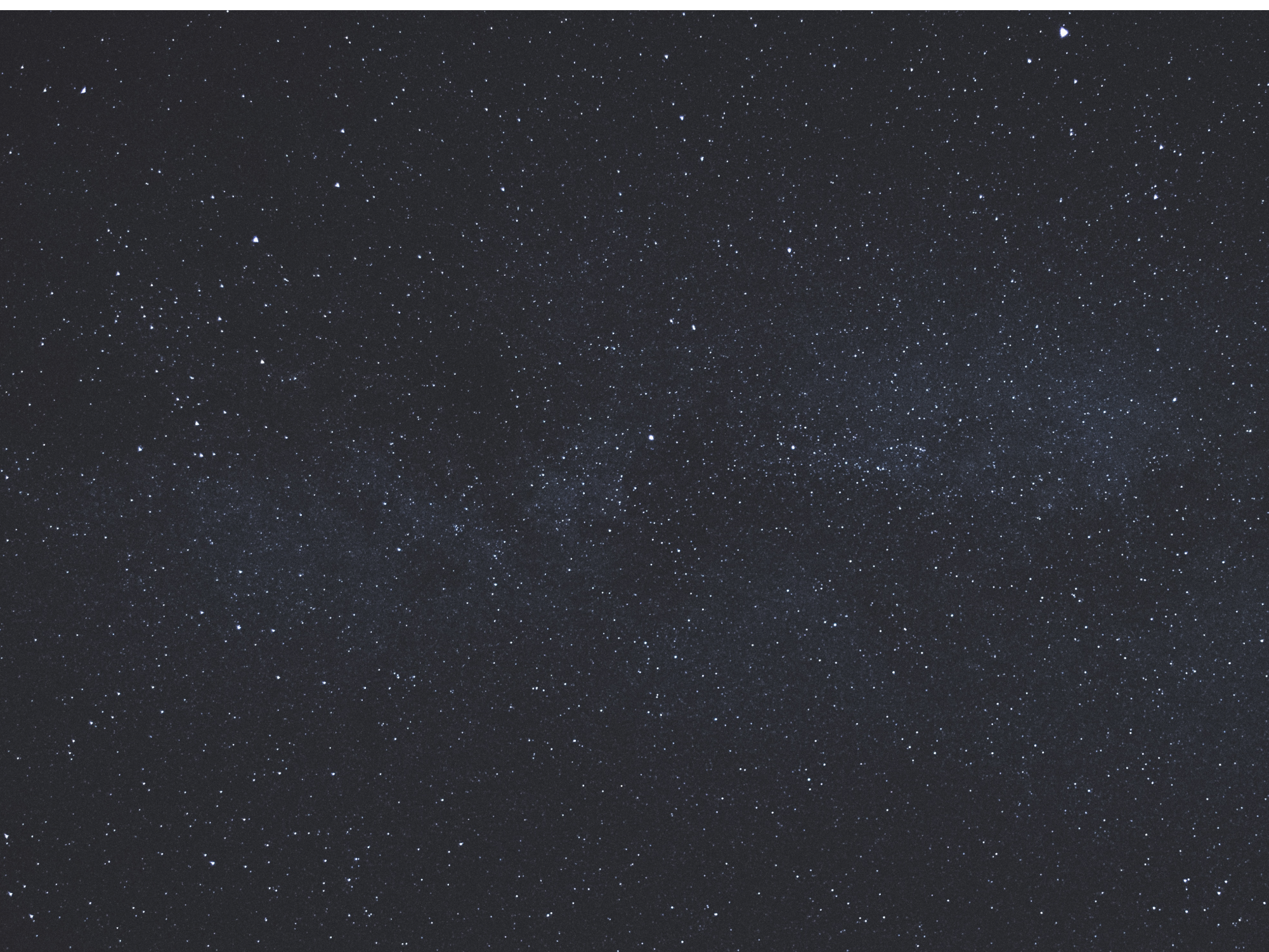

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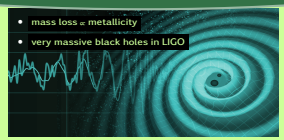

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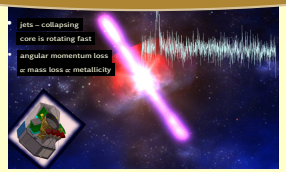

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e.g. Szécsi +13; Leventis +14; Schulze +14; Szécsi '16; Bagoly & Szécsi +16; Szécsi '17a; Szécsi '17b; Japelj +18; Stratta, Szécsi +18; Amati, Szécsi +18;

Globular clusters

- metal-poor low-mass stars
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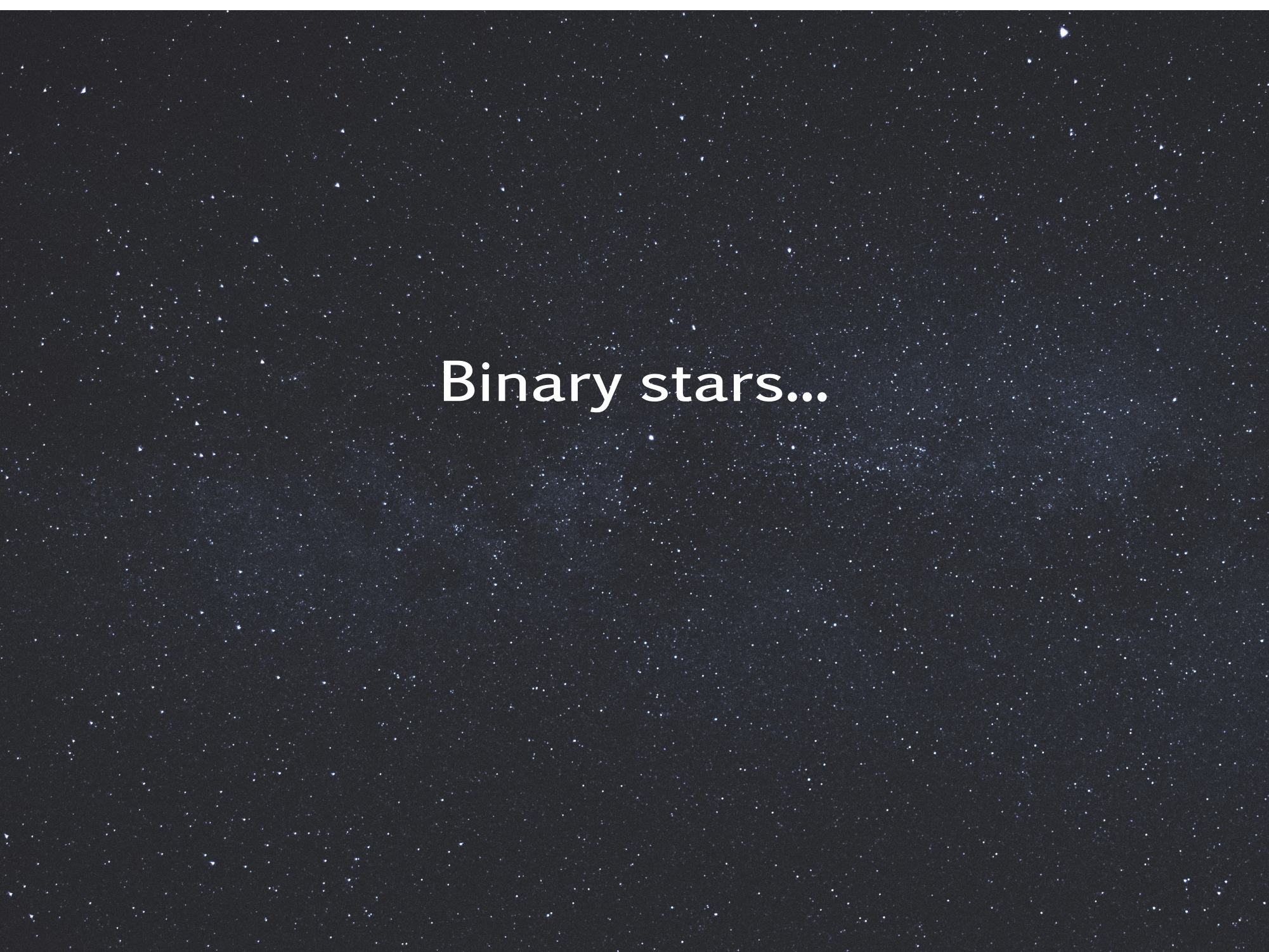
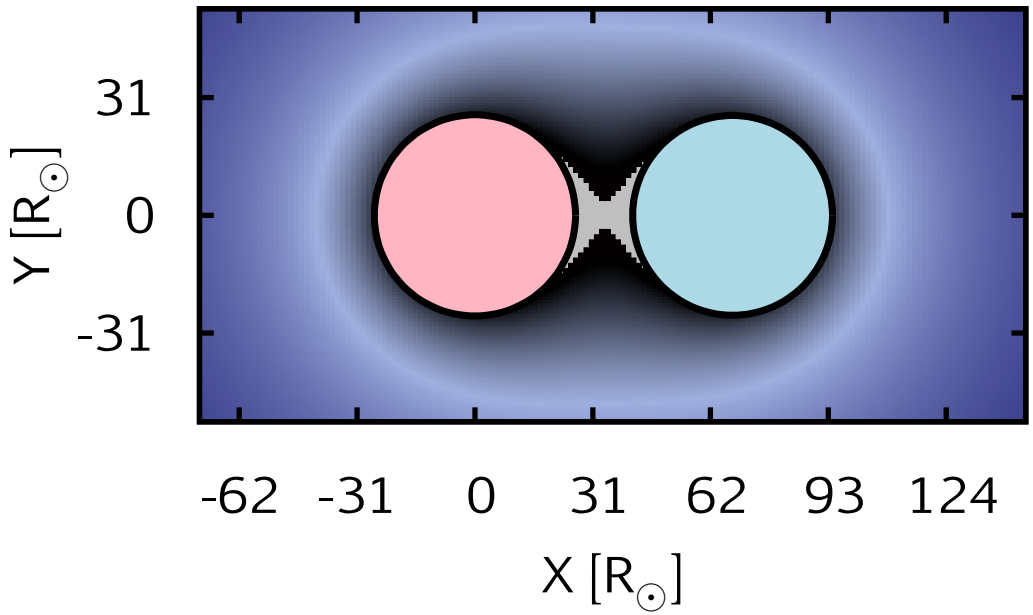
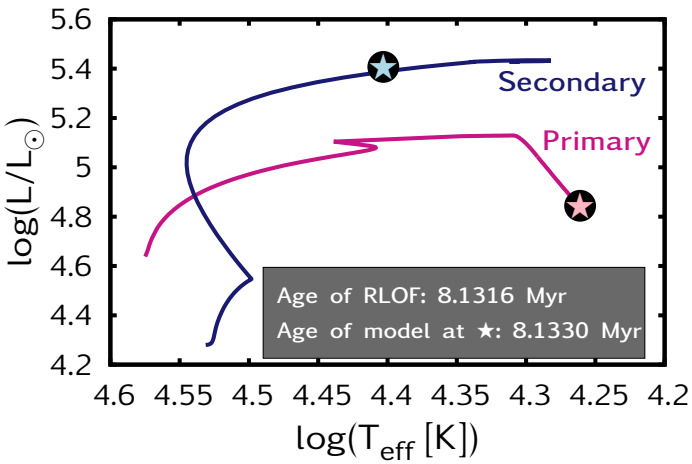
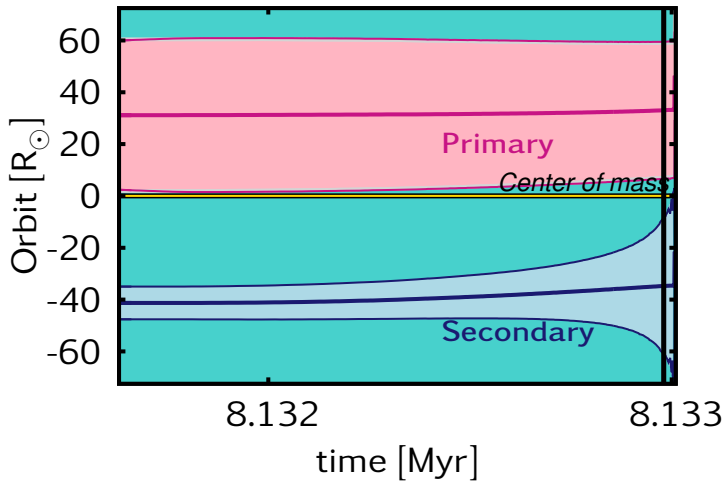

Binary stars...

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

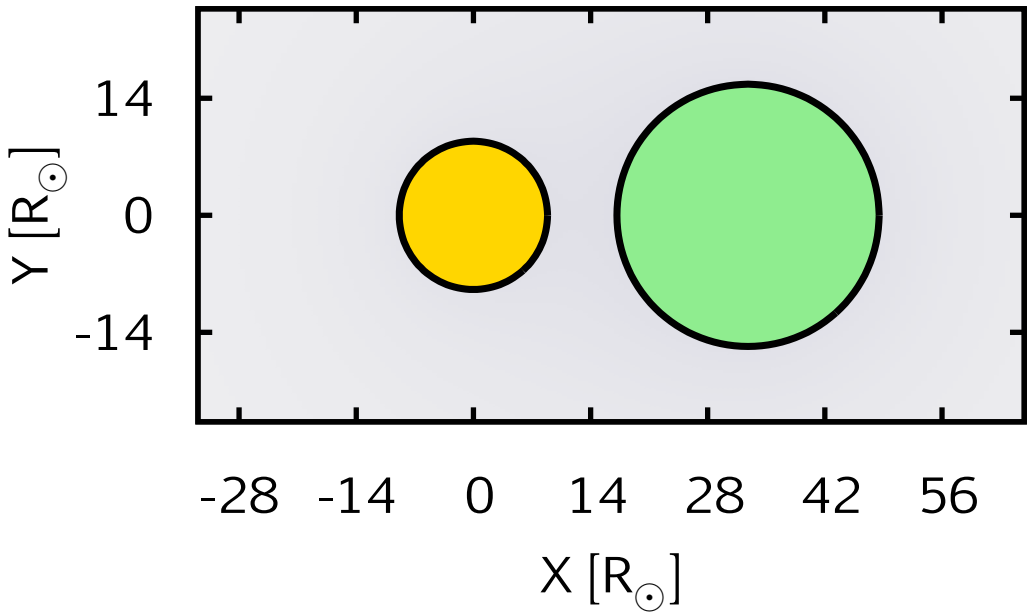


de Mink +09, **Szécsi** +14

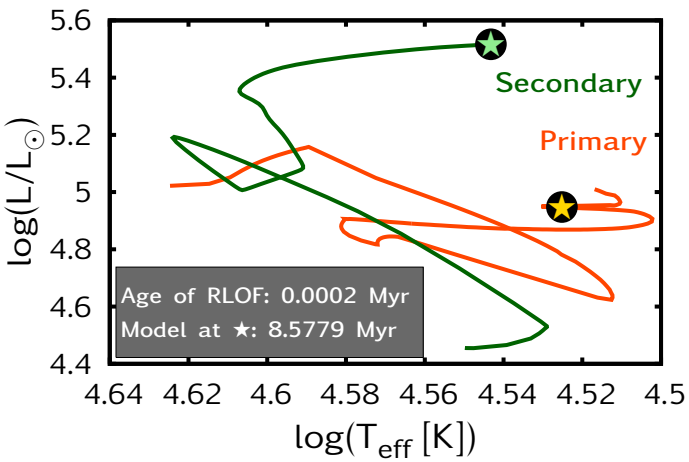


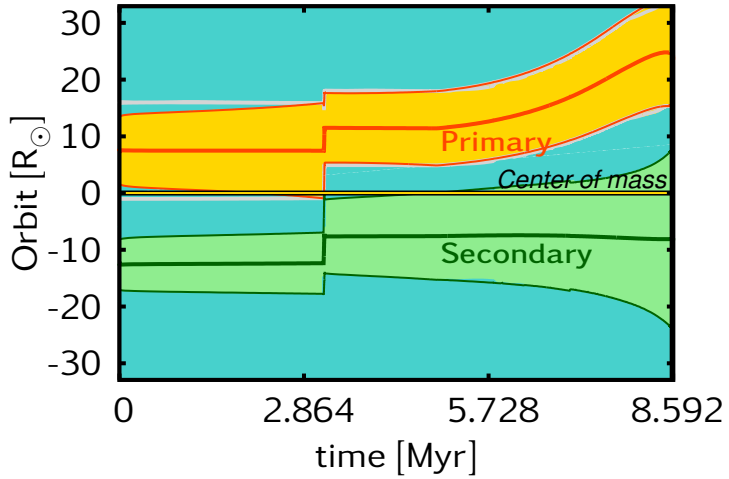


System: 29 $M_\odot$ + 17 $M_\odot$ + 1.5 d Age: 8.5779 Myr



Menon & **Szécsi** +20 (in prep.)





Metal-poor massive stars

Dwarf galaxies

- low metallicity ($Z \sim 1/10$–$1/50\ Z_\odot$)
- active star-formation → massive stars (but often embedded)

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

★ ionizing flux is strong due to chemically homogeneous evolution

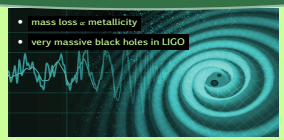
★ *current work:* 3D hydro simulations of star-forming regions

★ 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; Walch & Szécsi (in prep.);

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

★ supervising PhD student Poojan Agrawal (Melbourne)

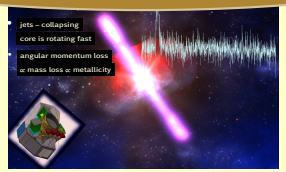
e.g. Watts +08,+09; Kruckow, Szécsi +16; Vigna-Gómez, Szécsi +18; Wijers '18 Broekgaarden +19; Neijssel, Szécsi +19; Stevenson, Szécsi +19;

High-redshift Univ.

- First stars: metal-free
- Subsequent generations: metal-poor

Gamma-ray bursts

- jets – collapsing core is rotating fast
- angular momentum loss ∝ mass loss ∝ metallicity



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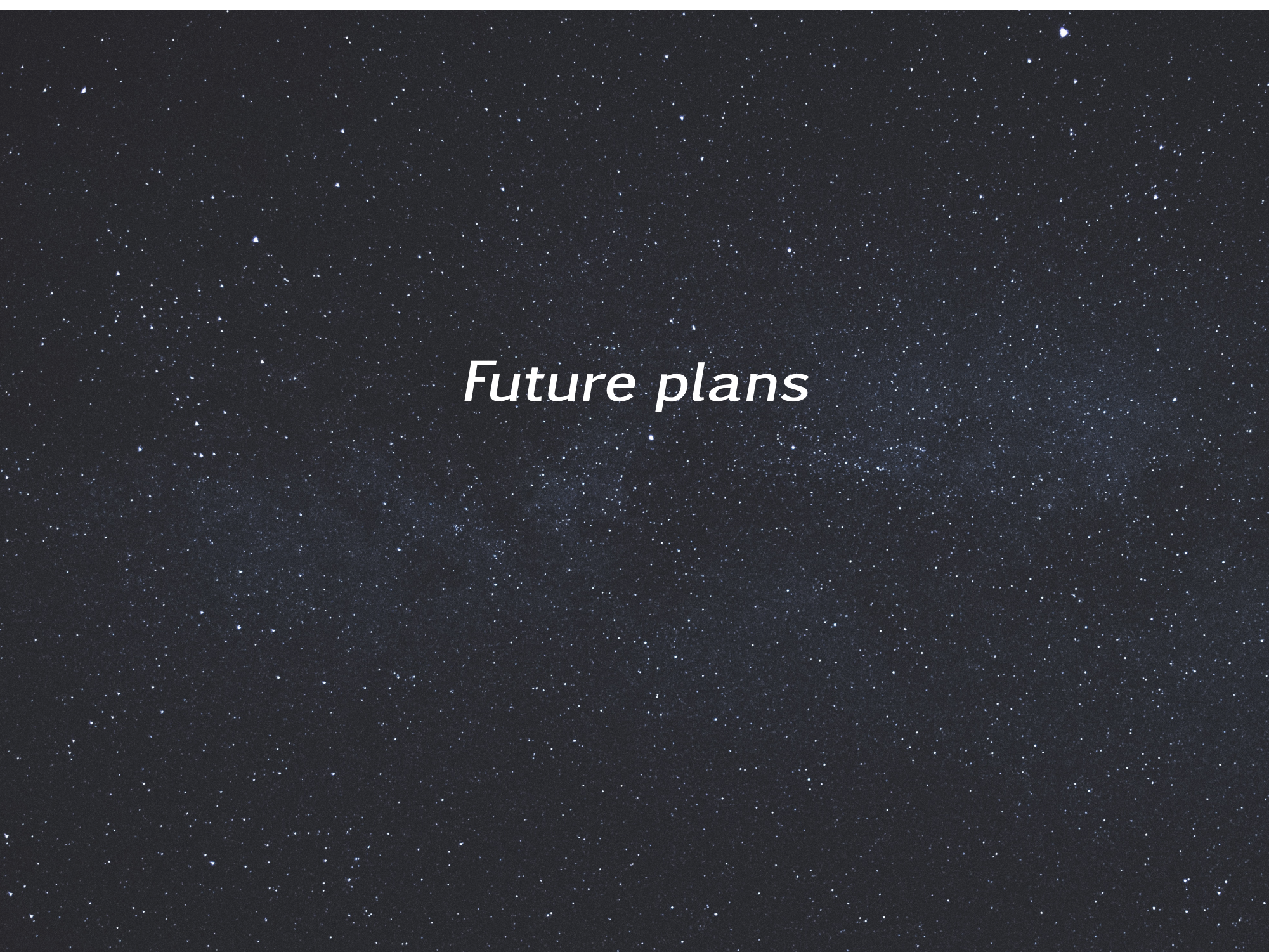
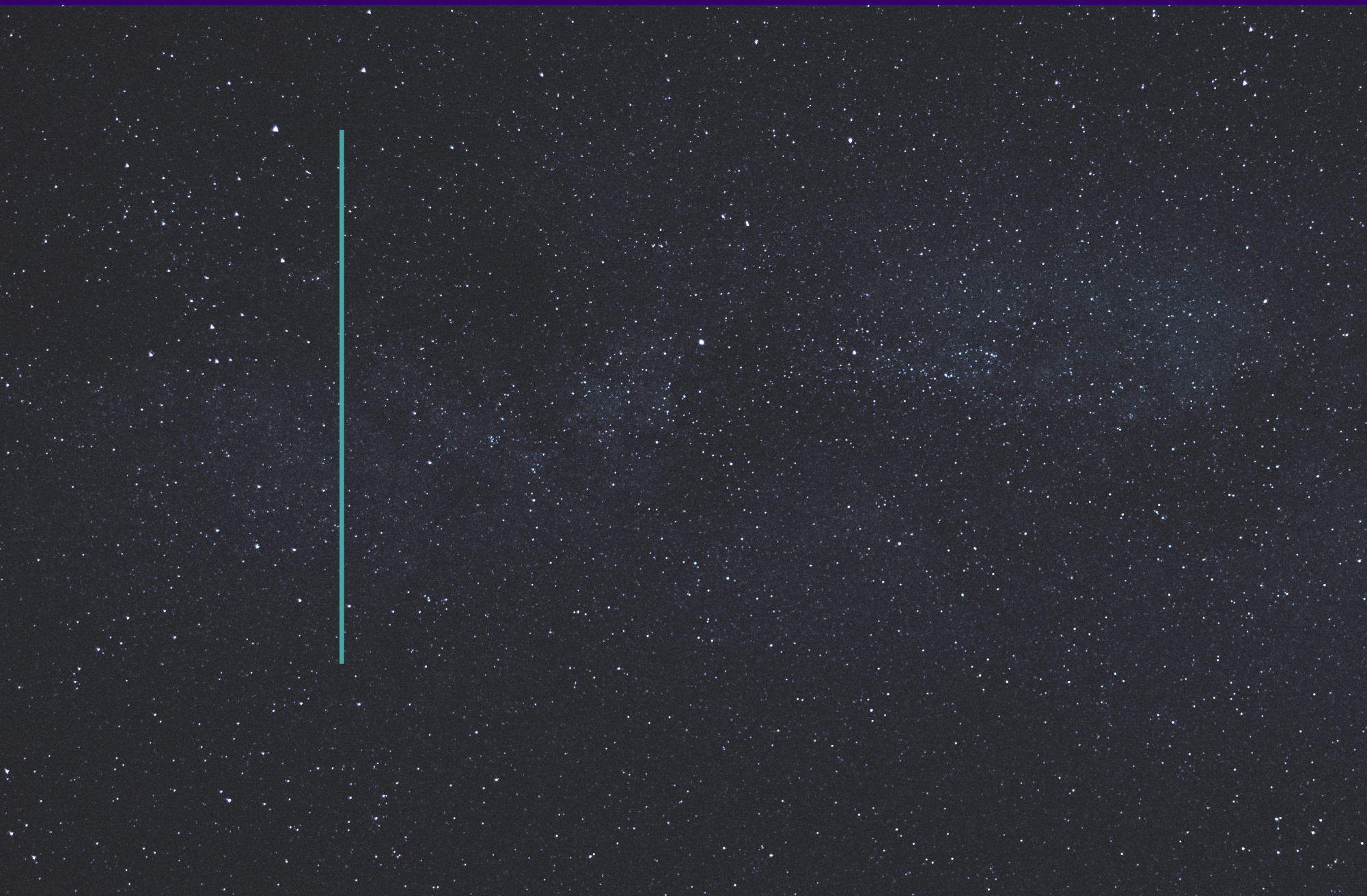

Future plans

How well do we understand metal-poor massive stars?



How well do we understand metal-poor massive stars?

Theory

Metal-*rich* massive stars

↓

"assumptions"

↓

Metal-poor massive stars

How well do we understand metal-poor massive stars?

Theory

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Metal-poor massive stars

Observations

spectroscopy (good resolution, large samples)

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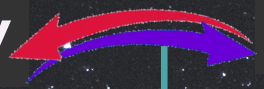

Theory

Observations

Metal-*rich*
massive stars

↓

"assumptions"

↓

Metal-poor
massive stars

spectroscopy
(good resolution,
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How well do we understand metal-poor massive stars?

Theory ⇄ **Observations**

Metal-*rich* massive stars

↓

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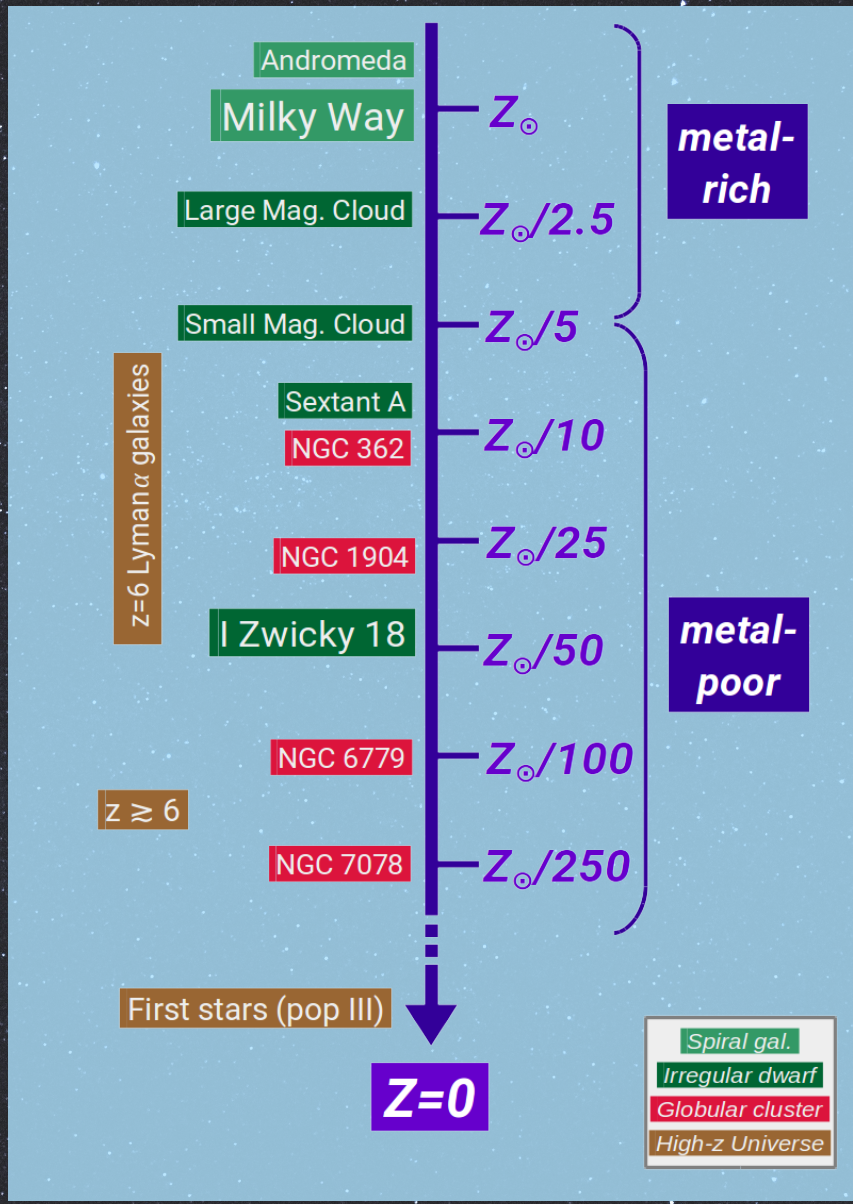
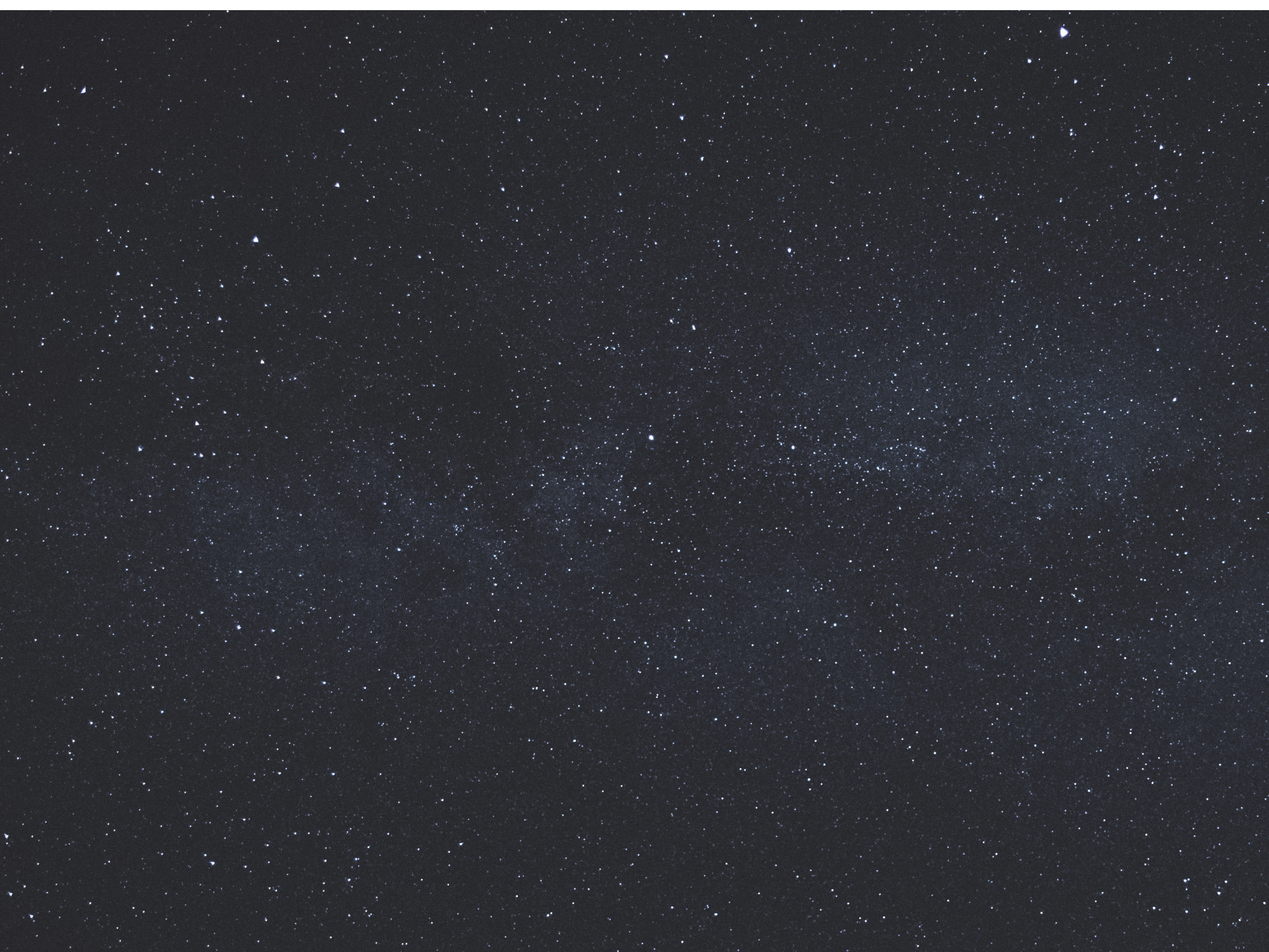
Metal-poor massive stars

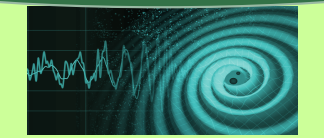
spectroscopy (good resolution, large samples)





Dwarf galaxies

Gravitational waves

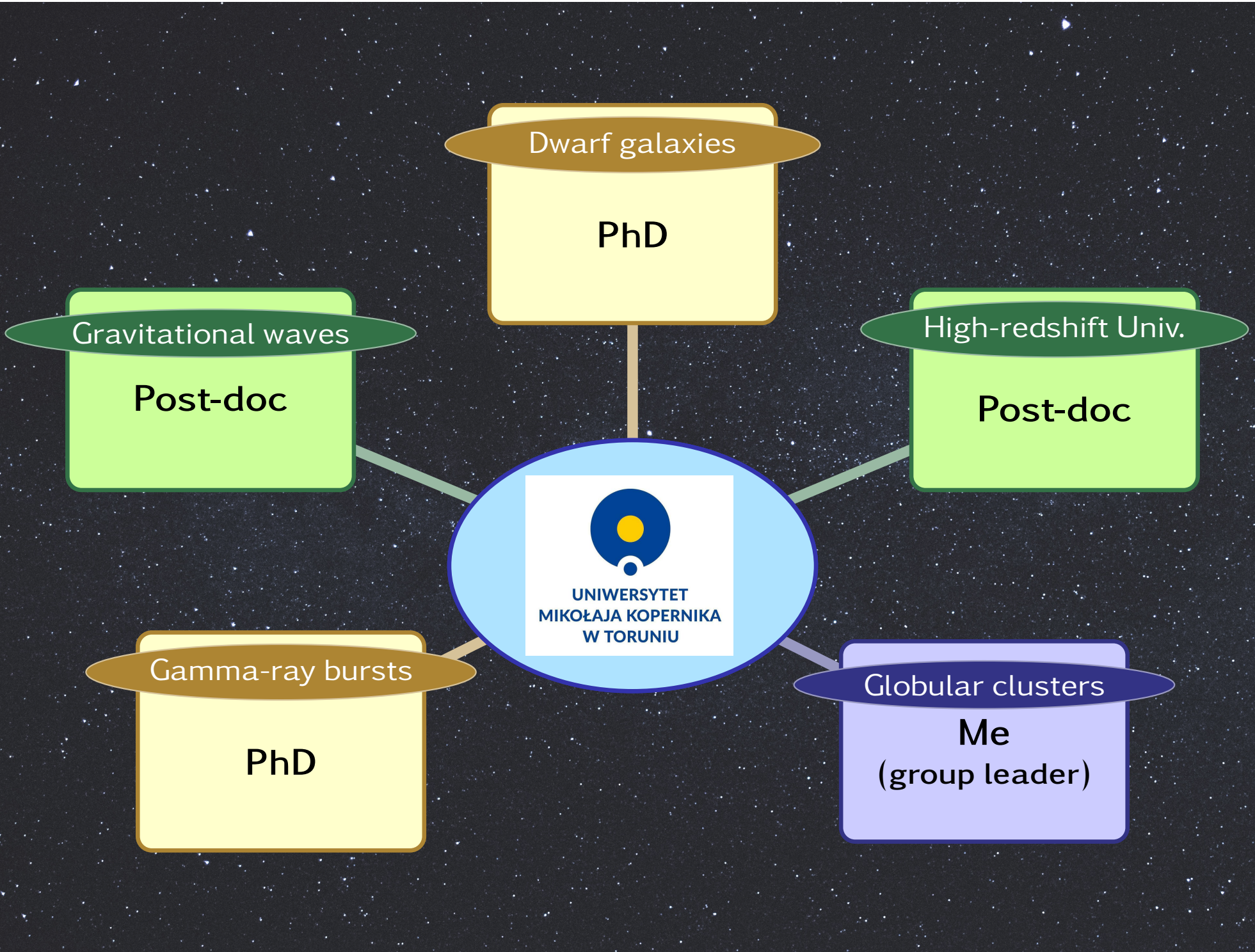


High-redshift Univ.

Metal-poor massive stars

Gamma-ray bursts

Globular clusters


Dwarf galaxies
PhD
Gravitational waves
Post-doc
High-redshift Univ.
Post-doc
UNIWERSYTET
MIKOŁAJA KOPERNIKA
W TORUNIU
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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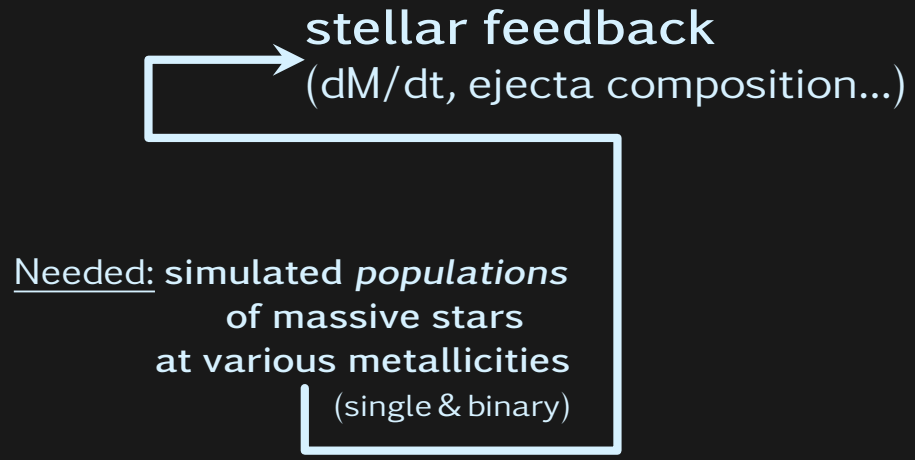

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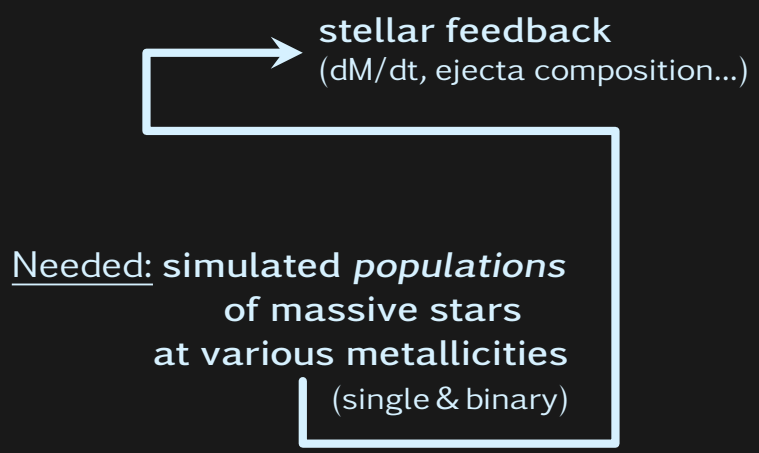

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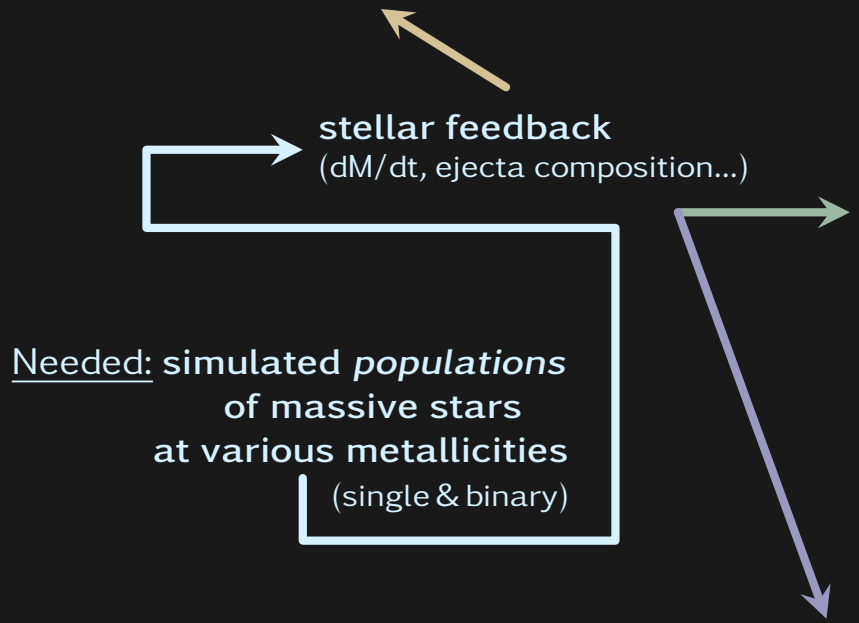

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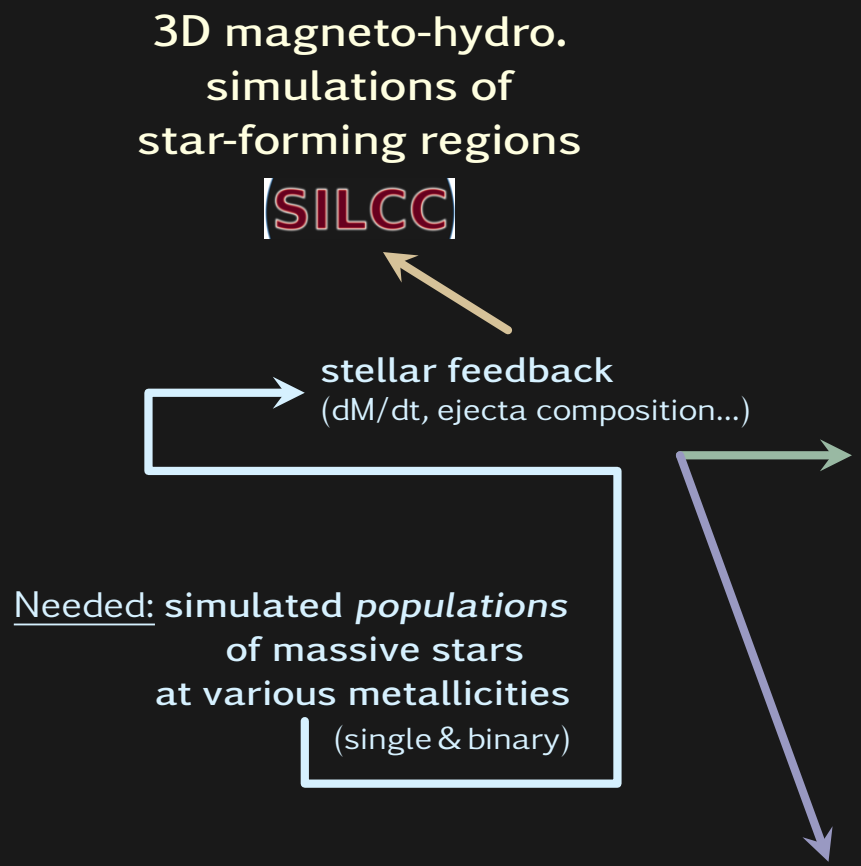

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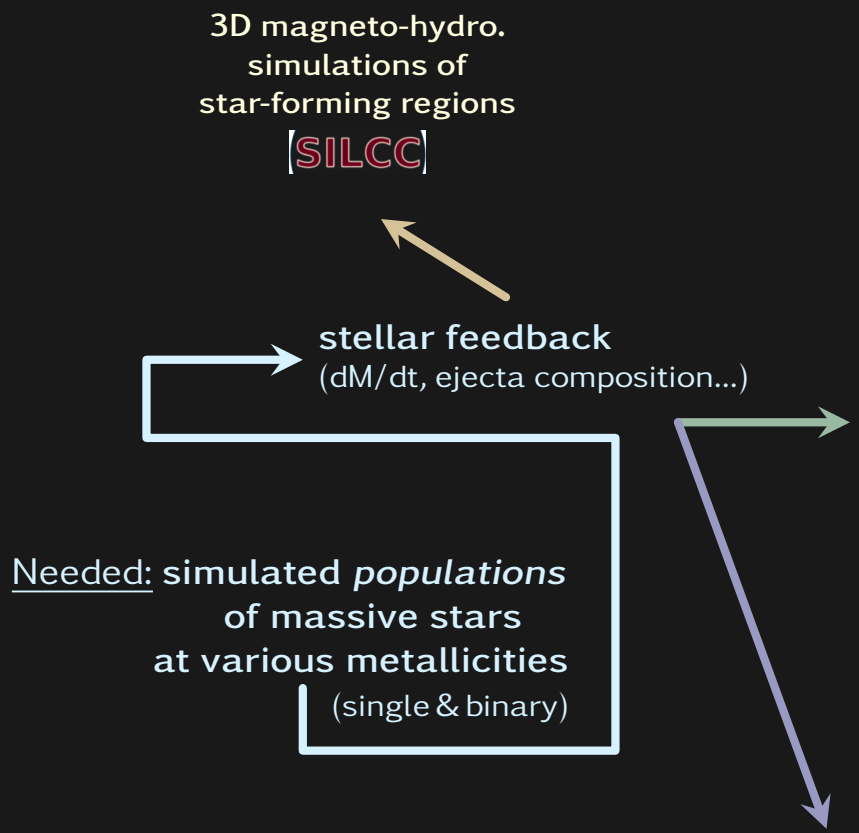

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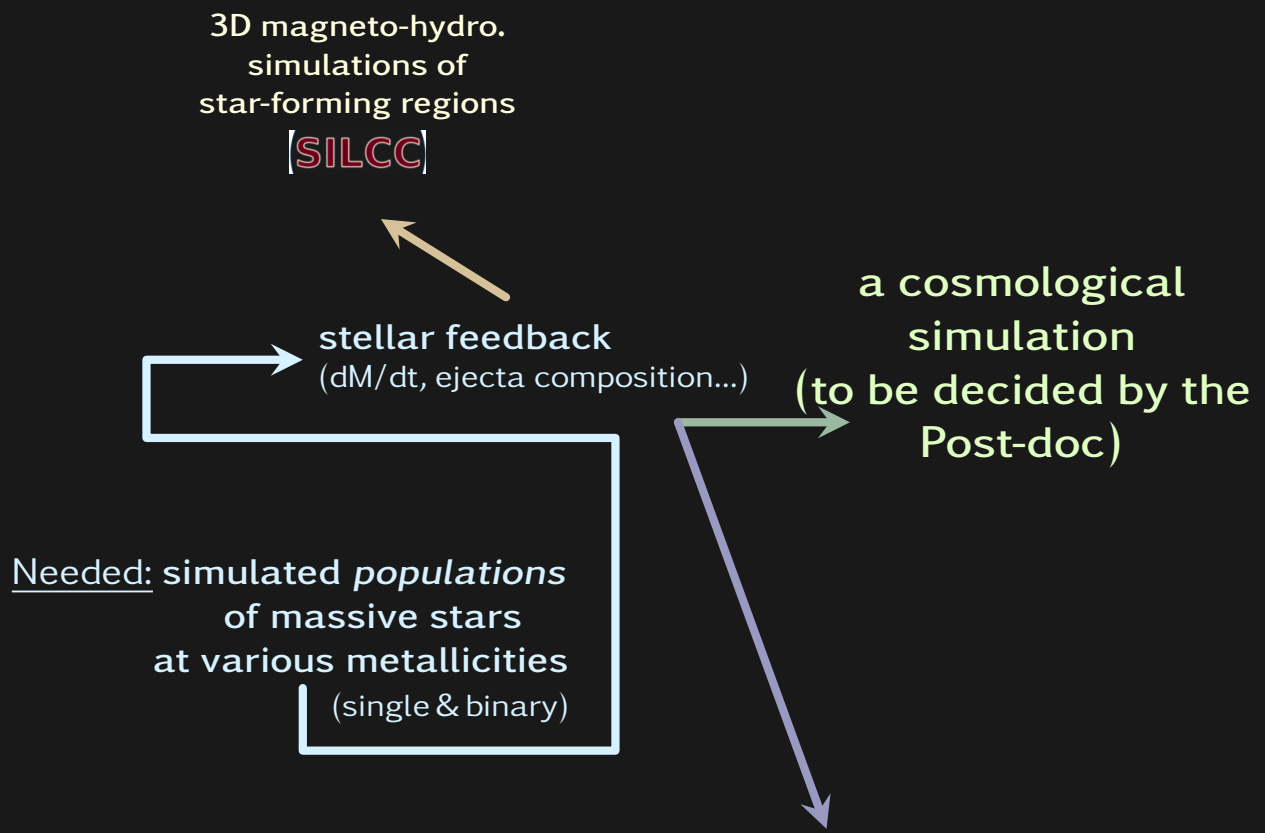

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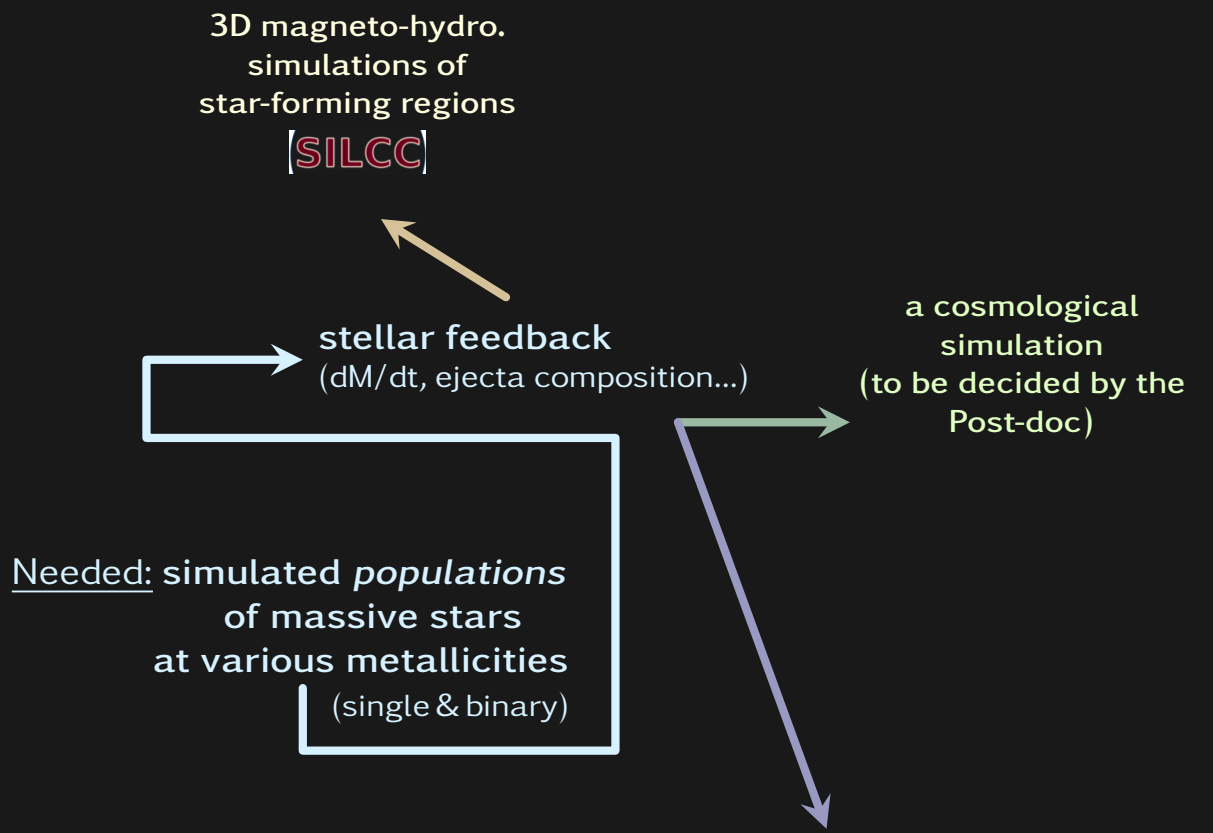

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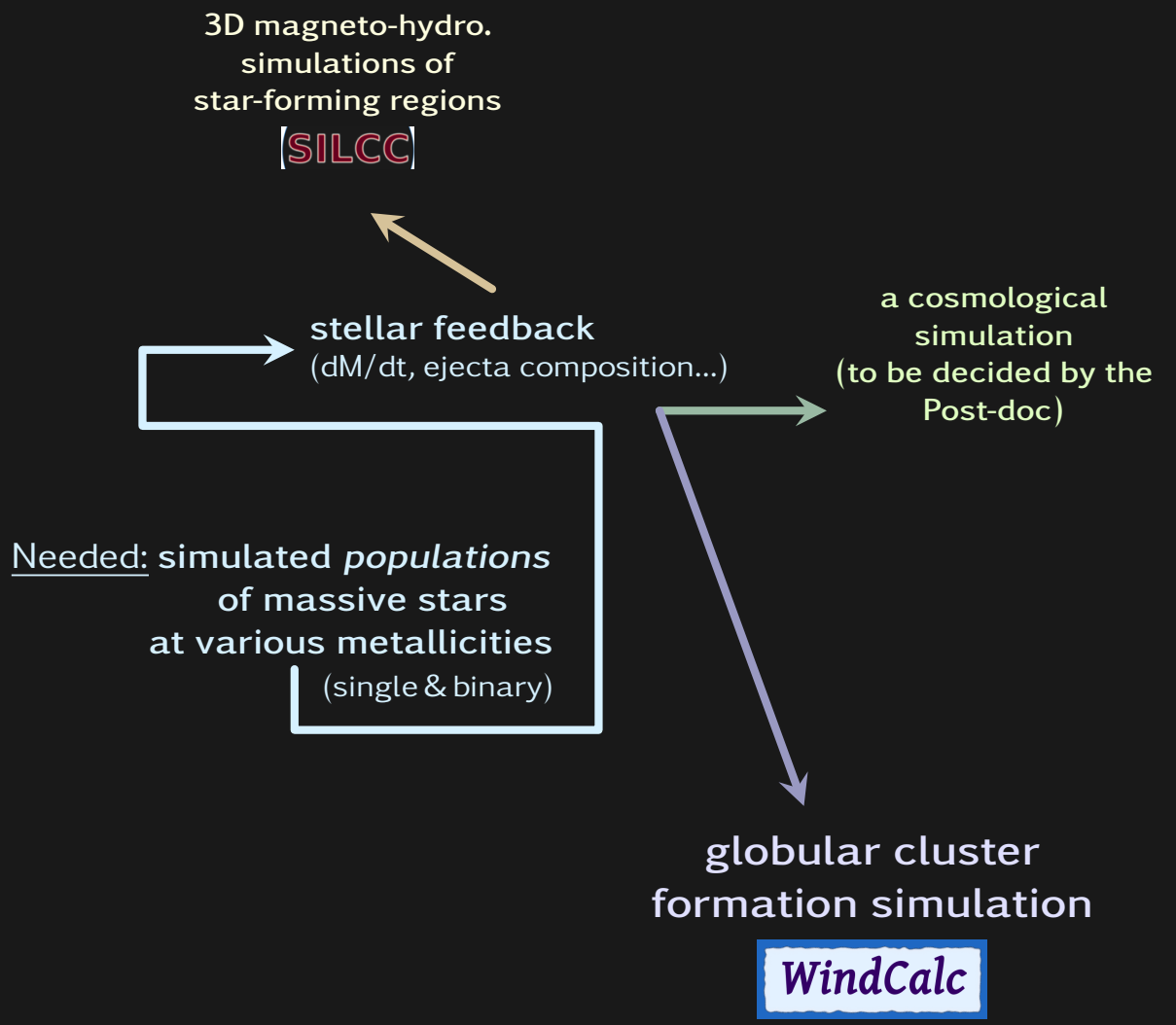

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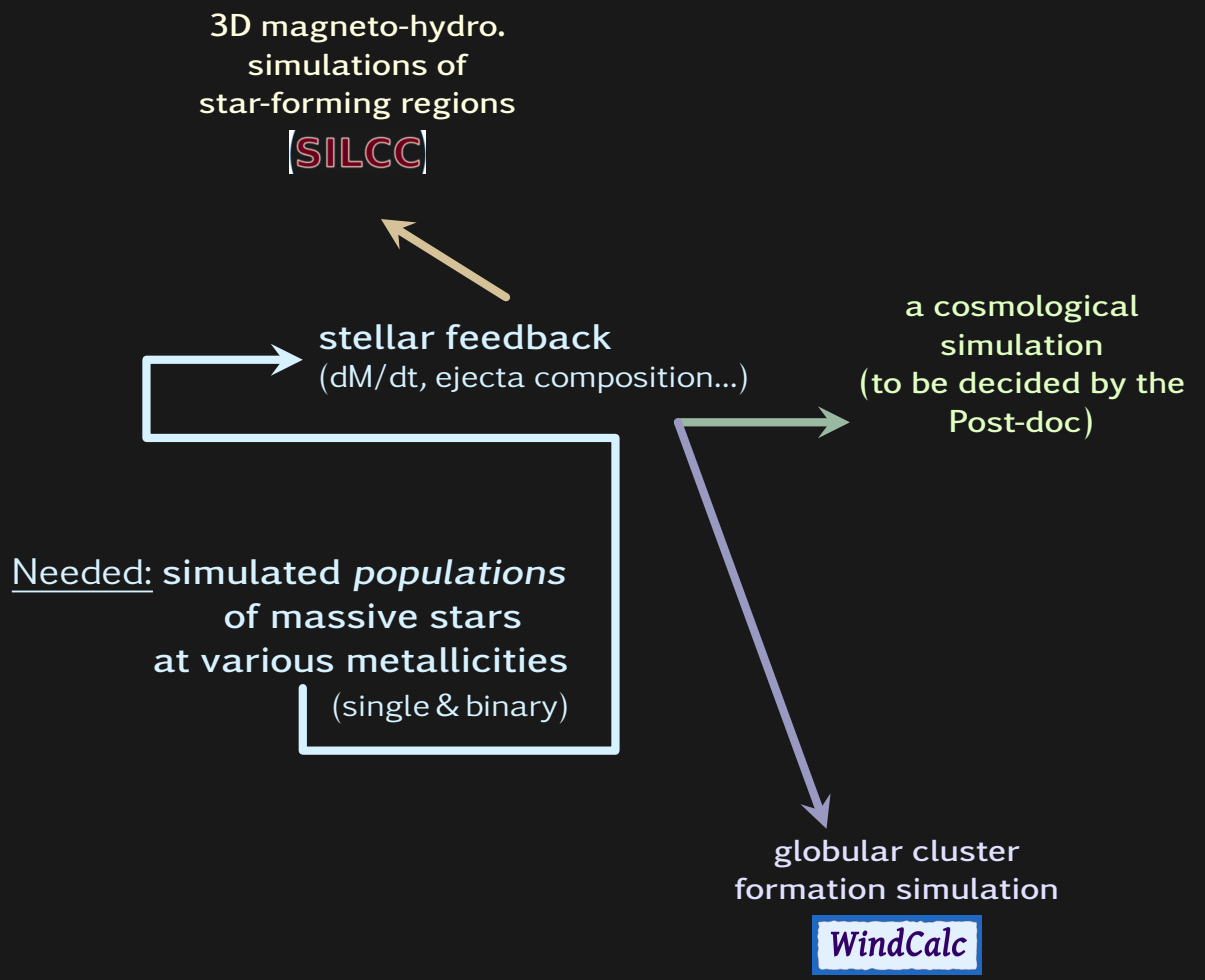

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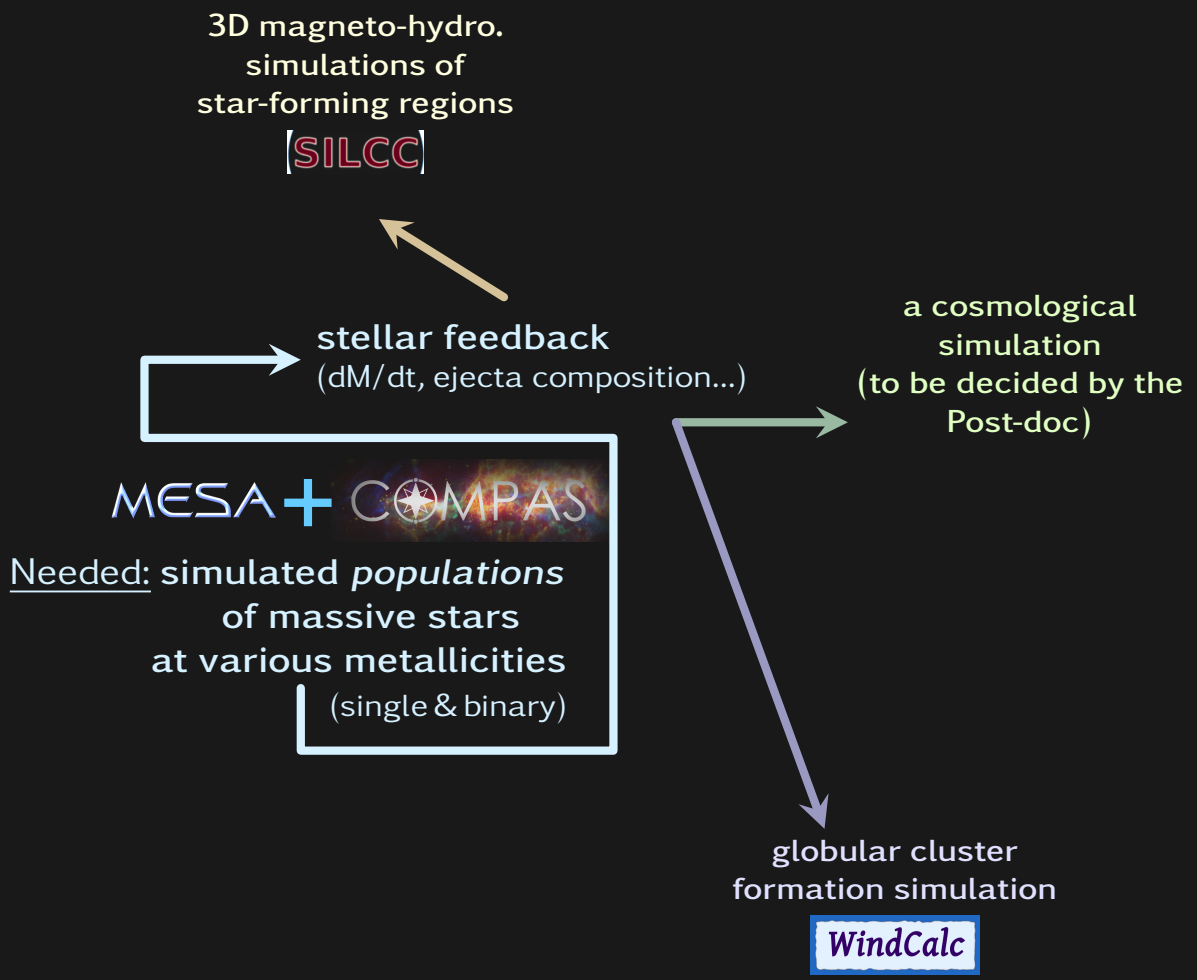

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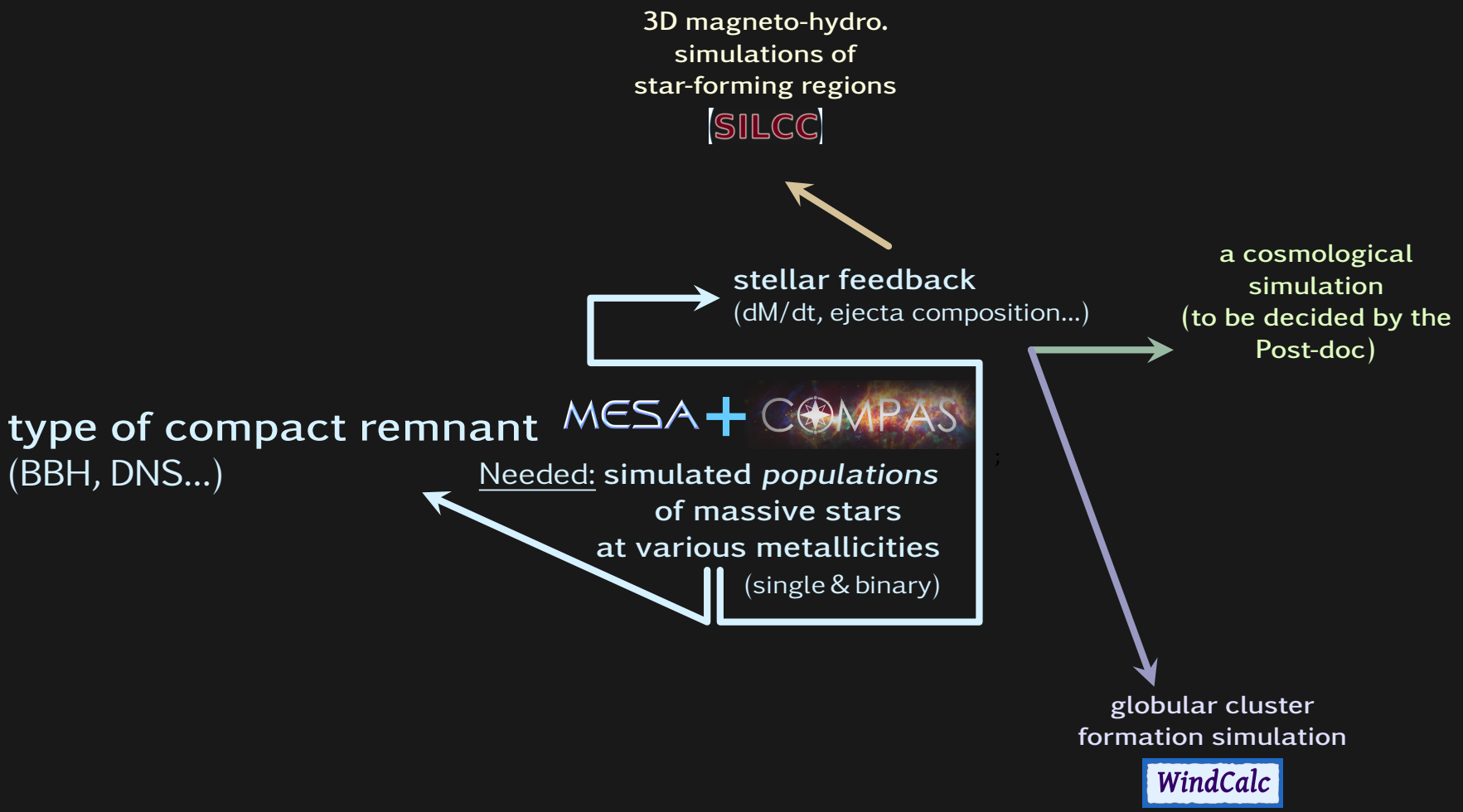

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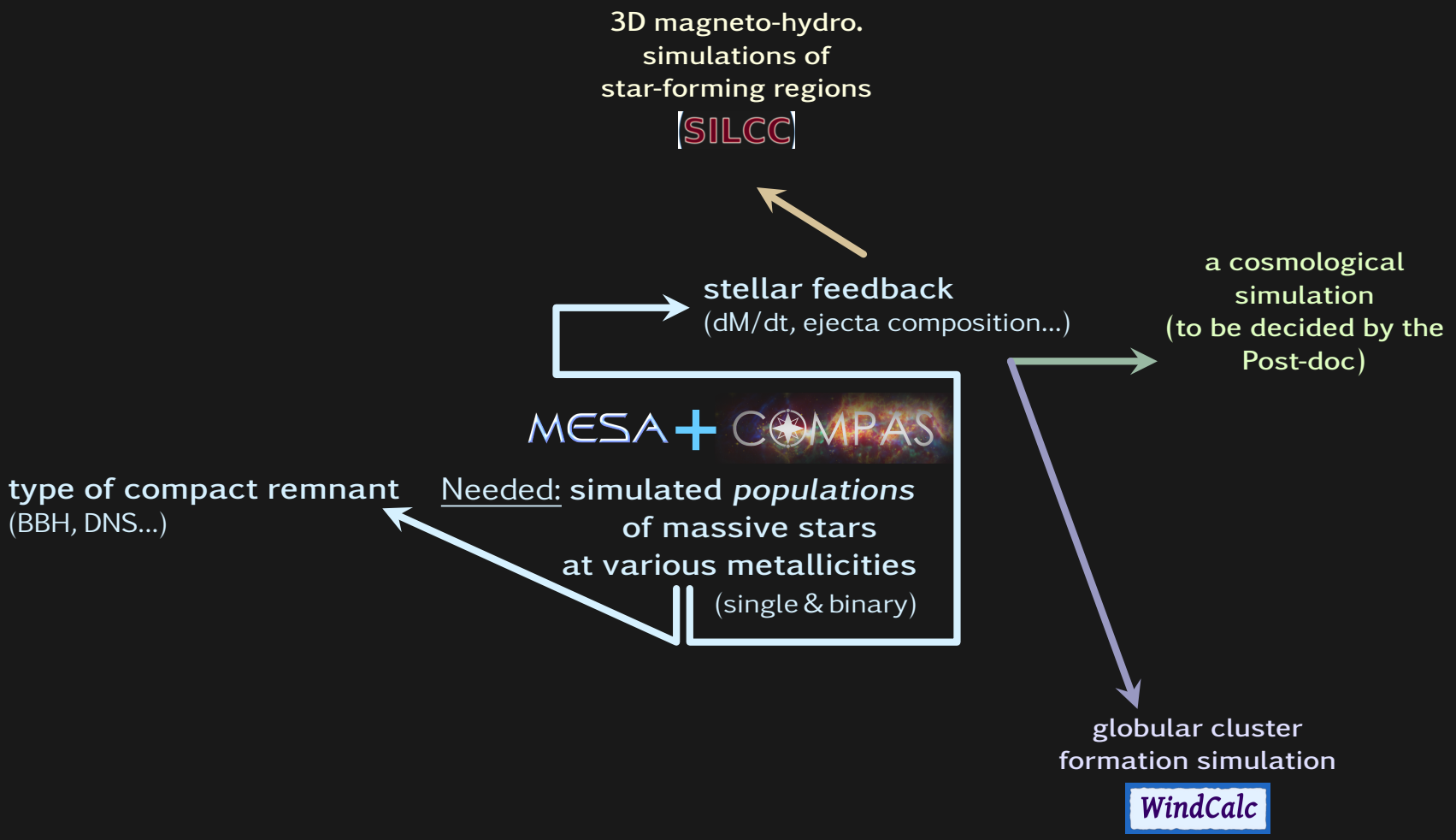

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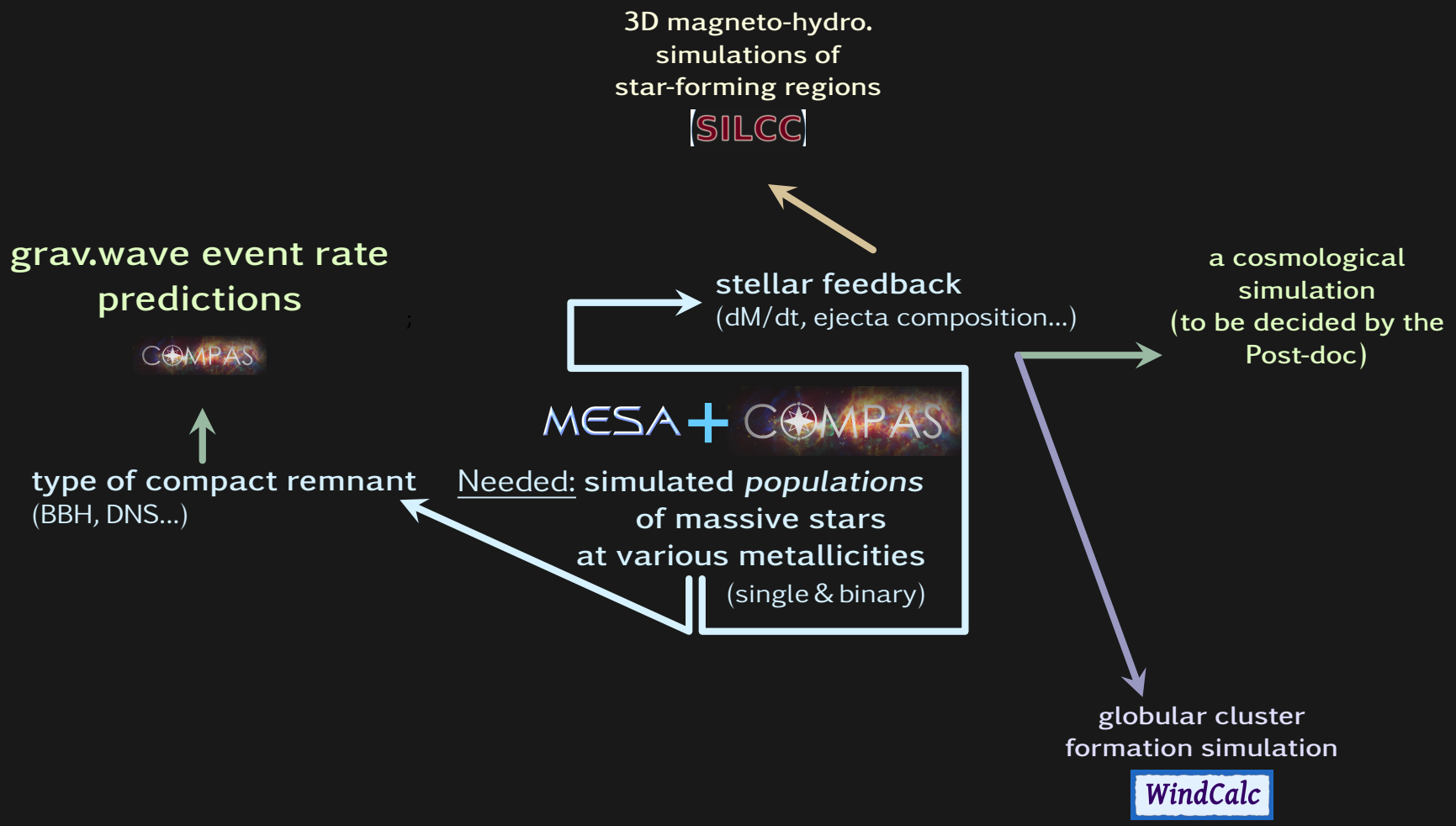

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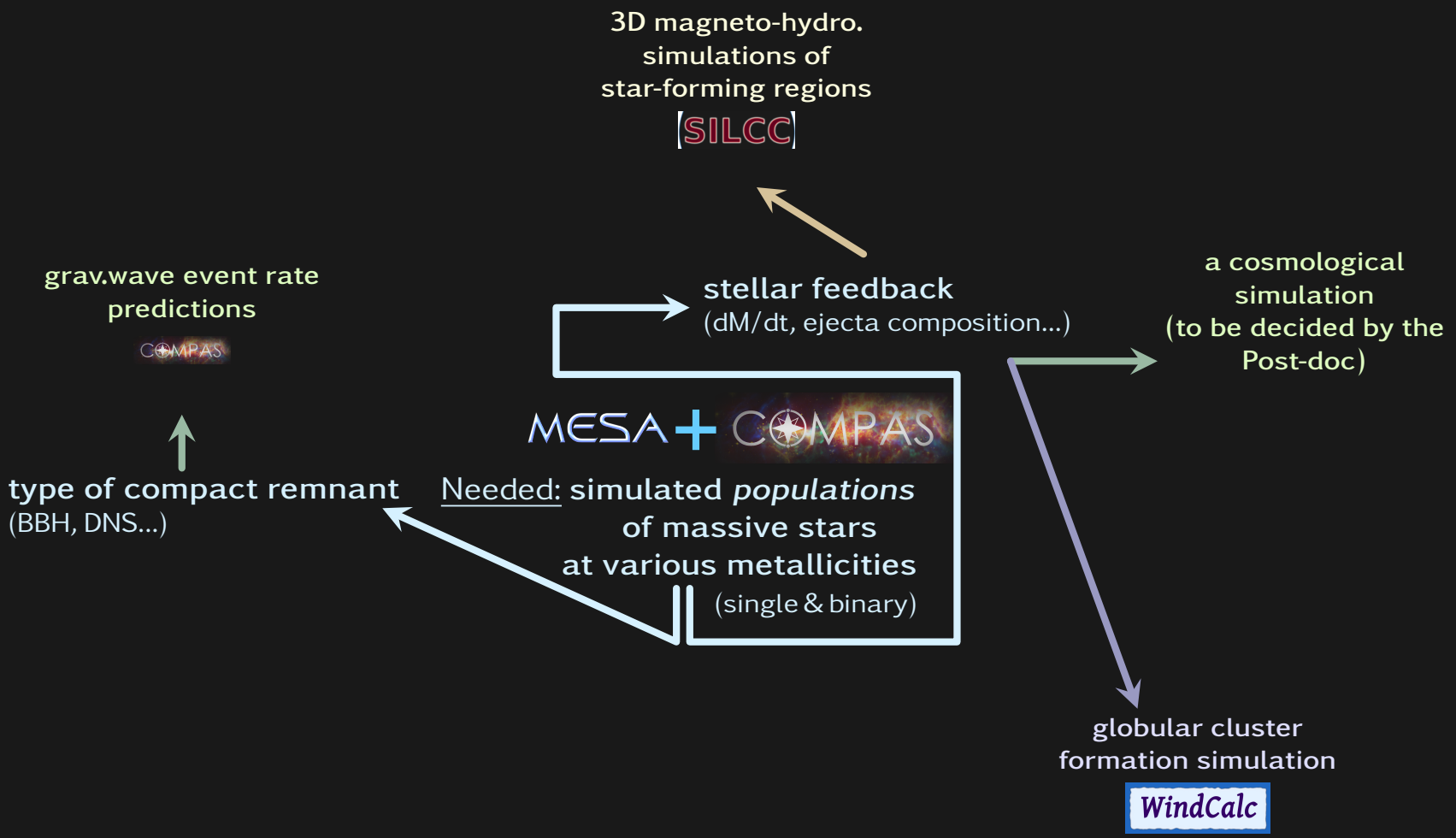

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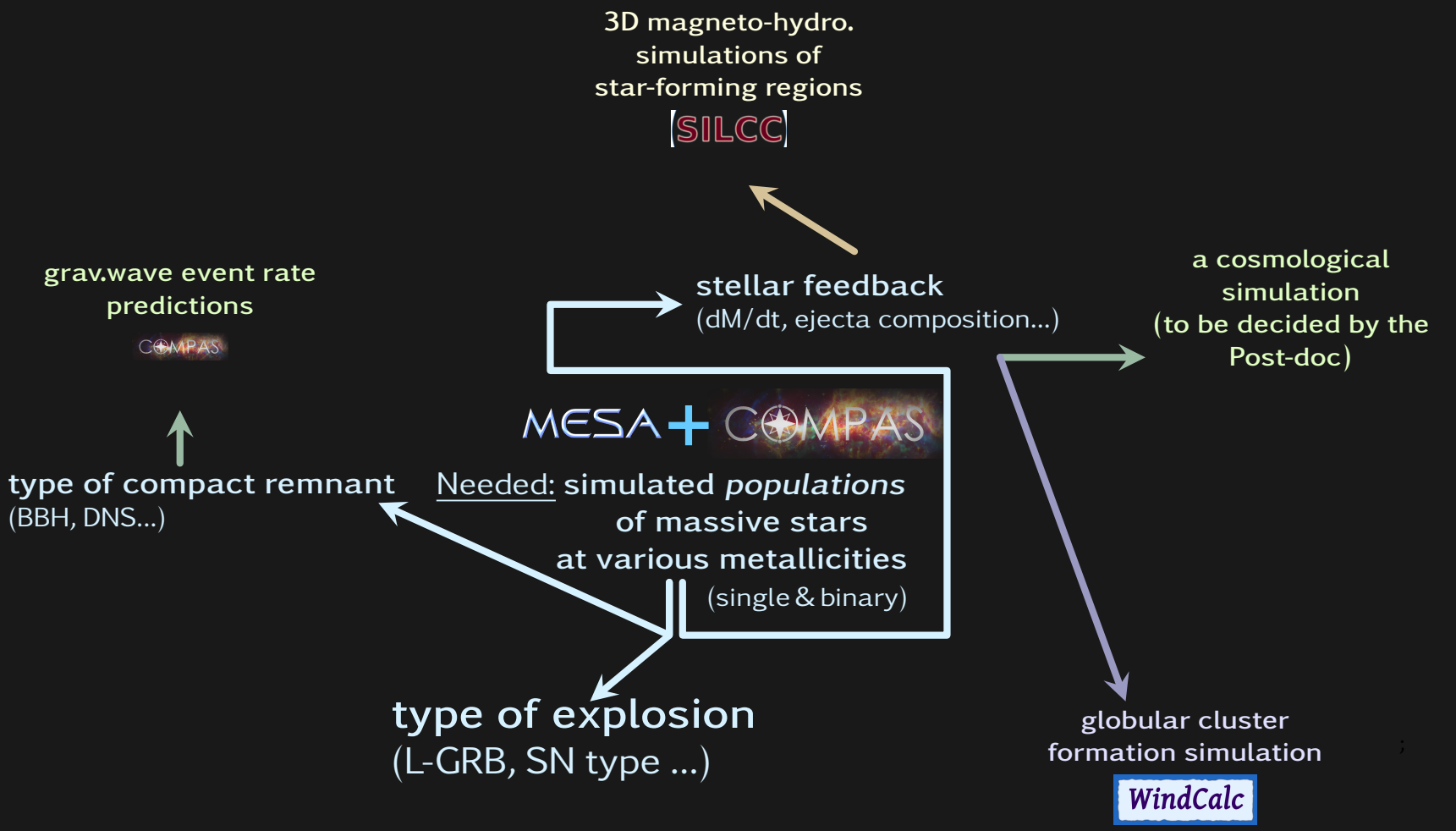

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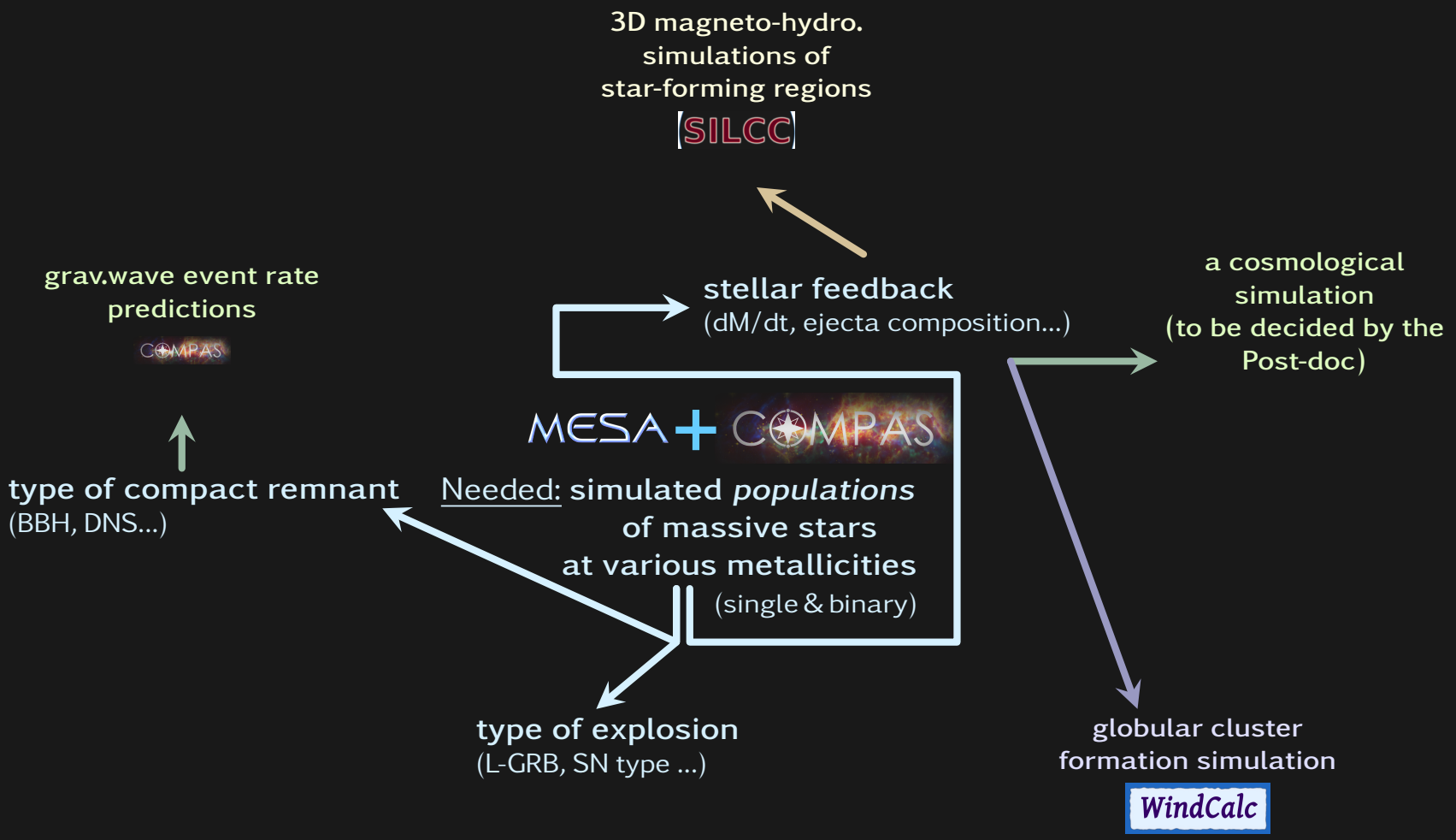

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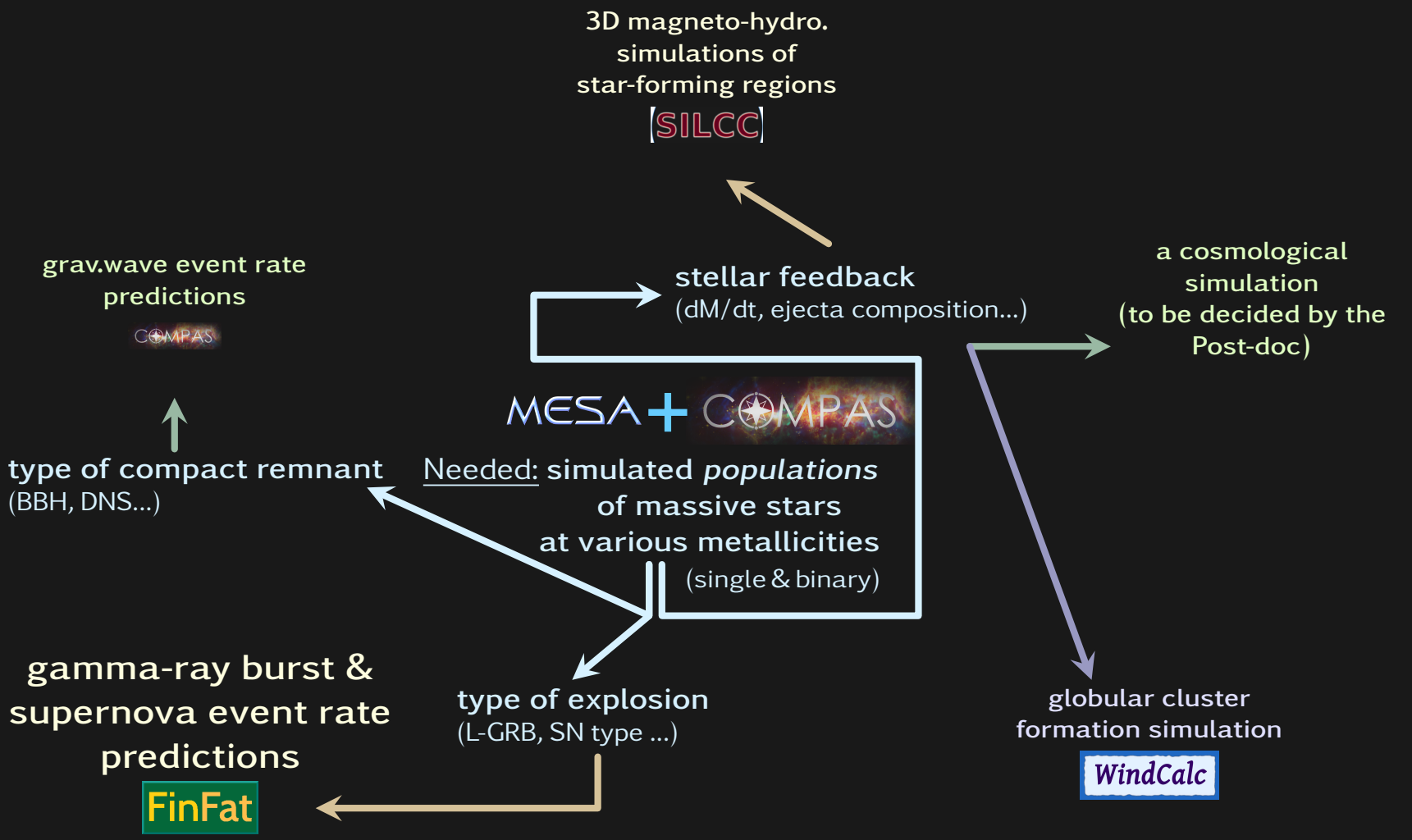

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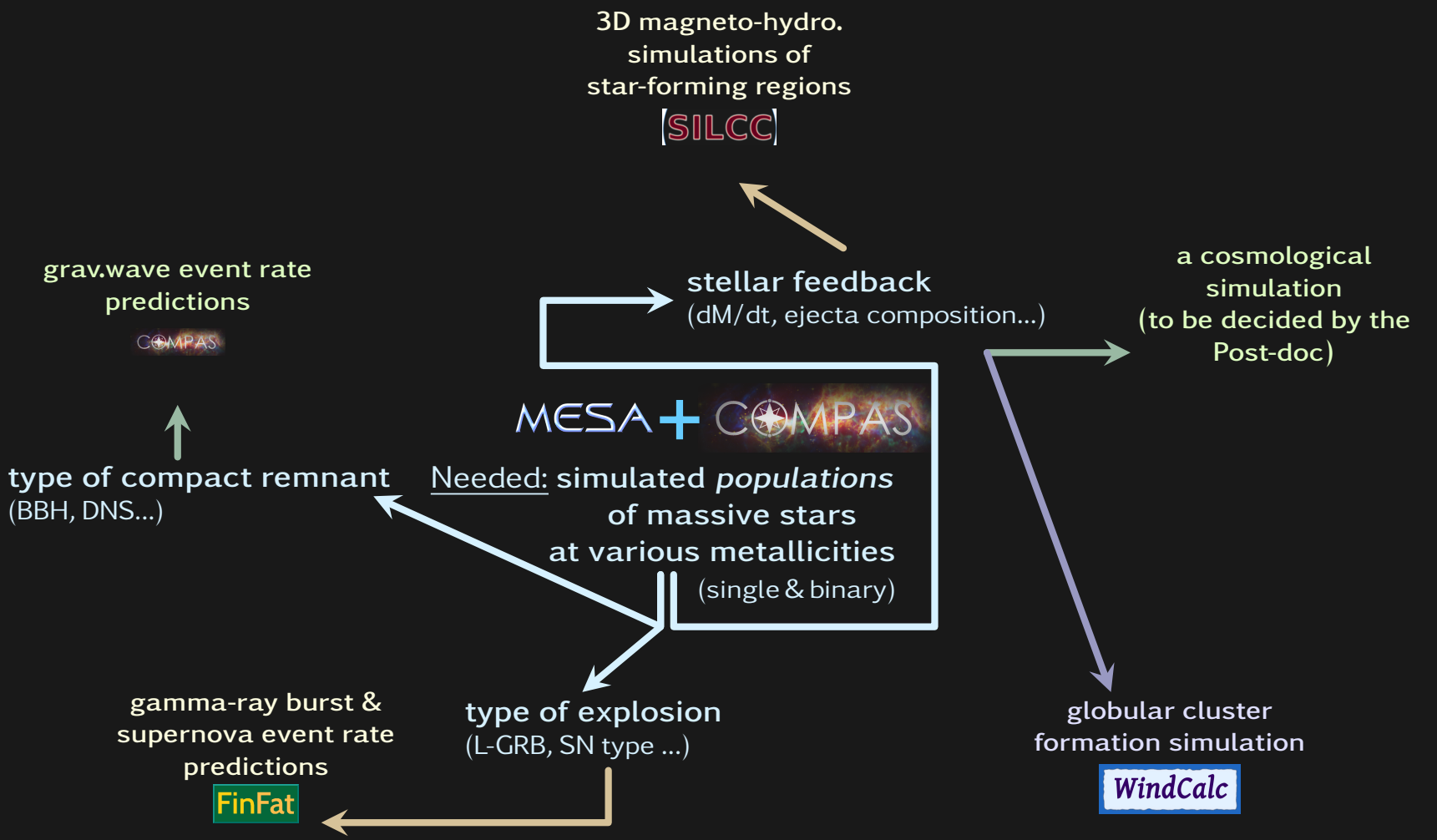

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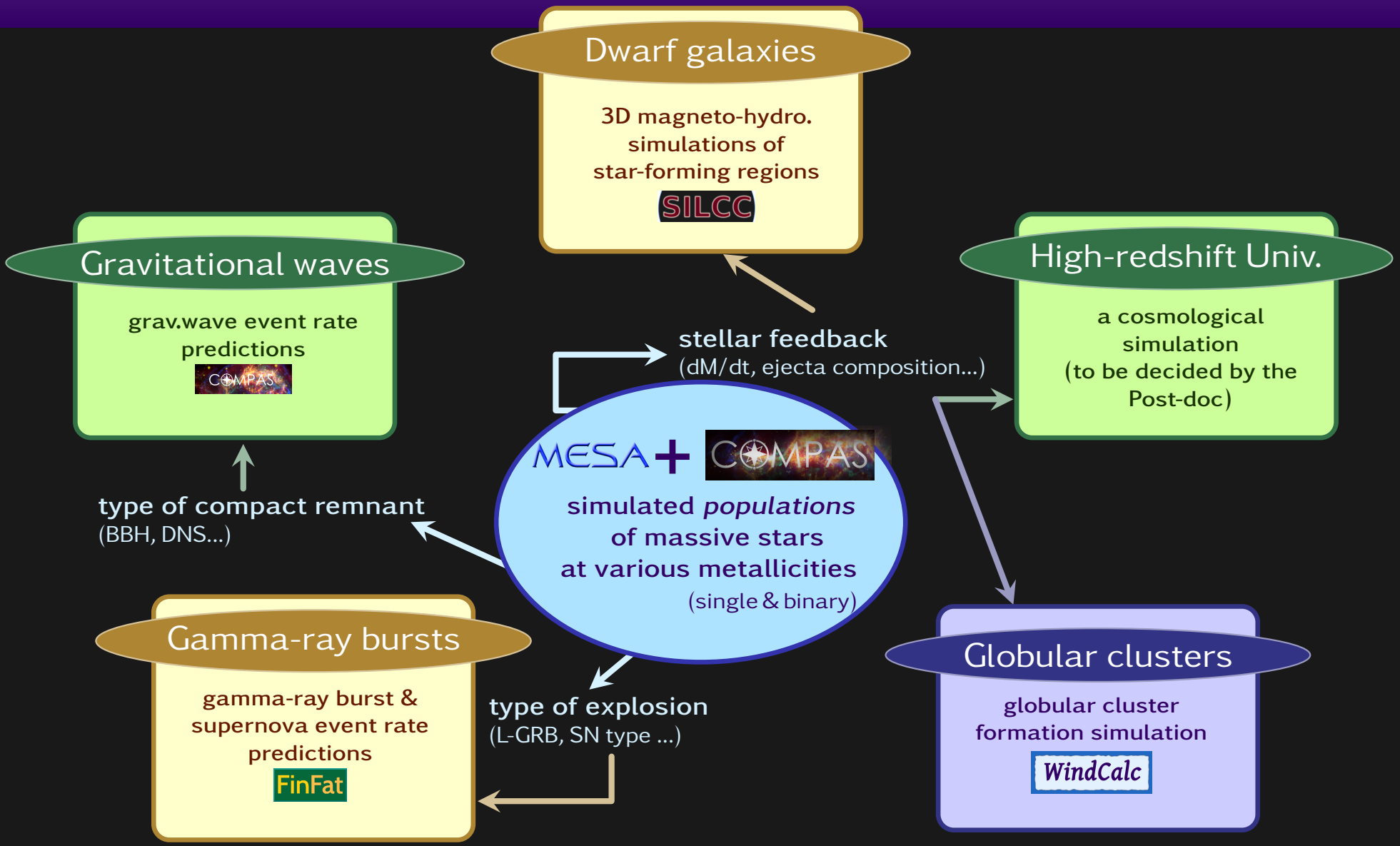


Technical details...

Dwarf galaxies

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

SILCC

Gravitational waves

grav.wave event rate predictions

COMPAS

High-redshift Univ.

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

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

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

MESA + COMPAS

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

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

Gamma-ray bursts

gamma-ray burst & supernova event rate predictions

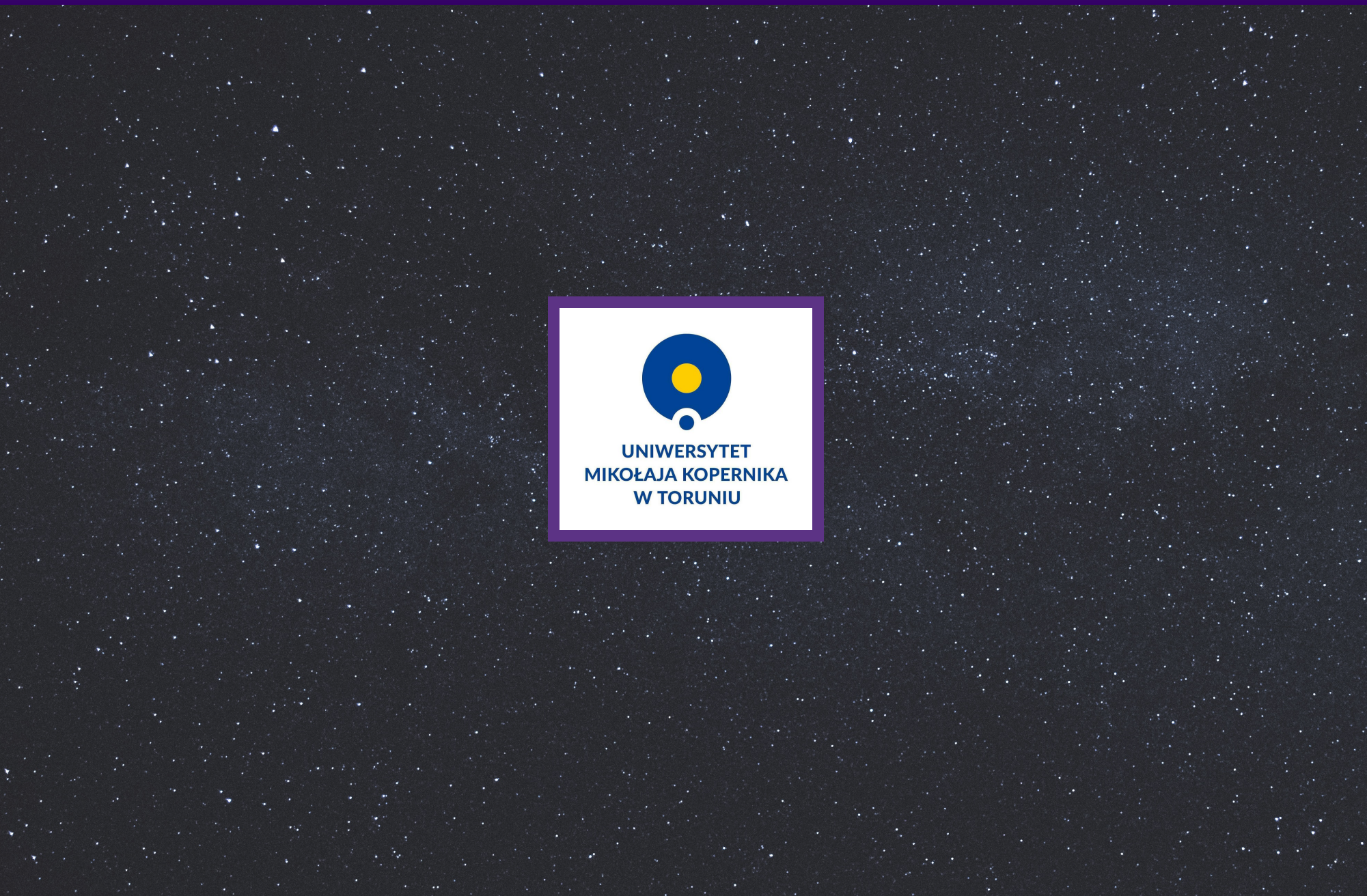
FinFat

Globular clusters

globular cluster formation simulation

WindCalc

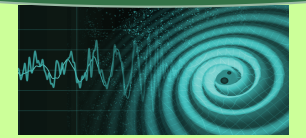
Future plans...



Future plans...

Dwarf galaxies

Gravitational waves

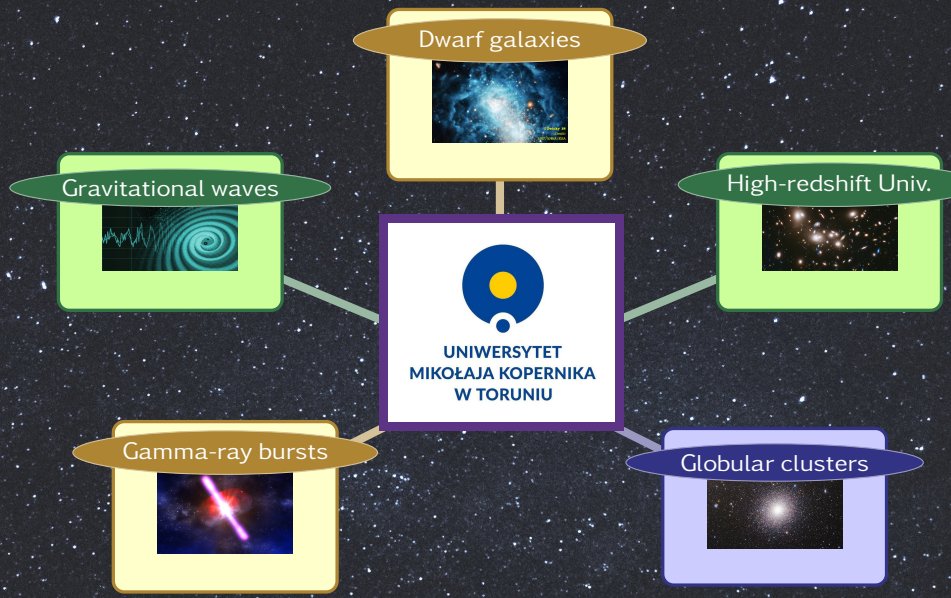


High-redshift Univ.

UNIWERSYTET
MIKOŁAJA KOPERNIKA
W TORUNIU

Gamma-ray bursts

Globular clusters


Dwarf galaxies
Gravitational waves
High-redshift Univ.
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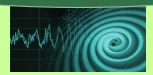


High-redshift Univ.

UNIWERSYTET MIKOŁAJA KOPERNIKA W TORUNIU

Gamma-ray bursts

Globular clusters

Master in Gamma-ray bursts

PhD in Stellar Evolution

Humboldt Fellow

ERC Starting Grant application

Leading my own research group on metal-poor massive stars

2012 — Budapest

Bonn

2016 — Prague

2019 — Birmingham, Cologne

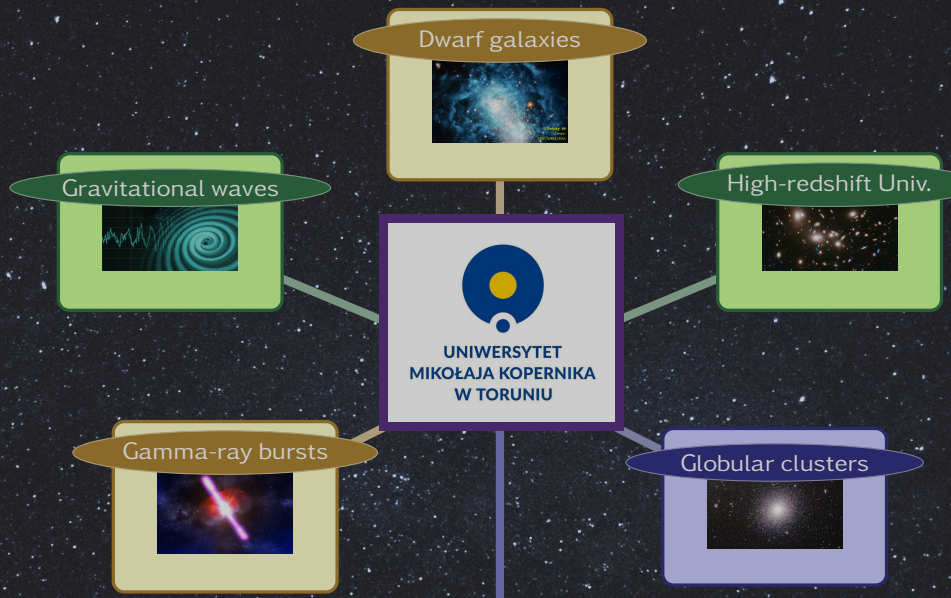
2021 — Torun

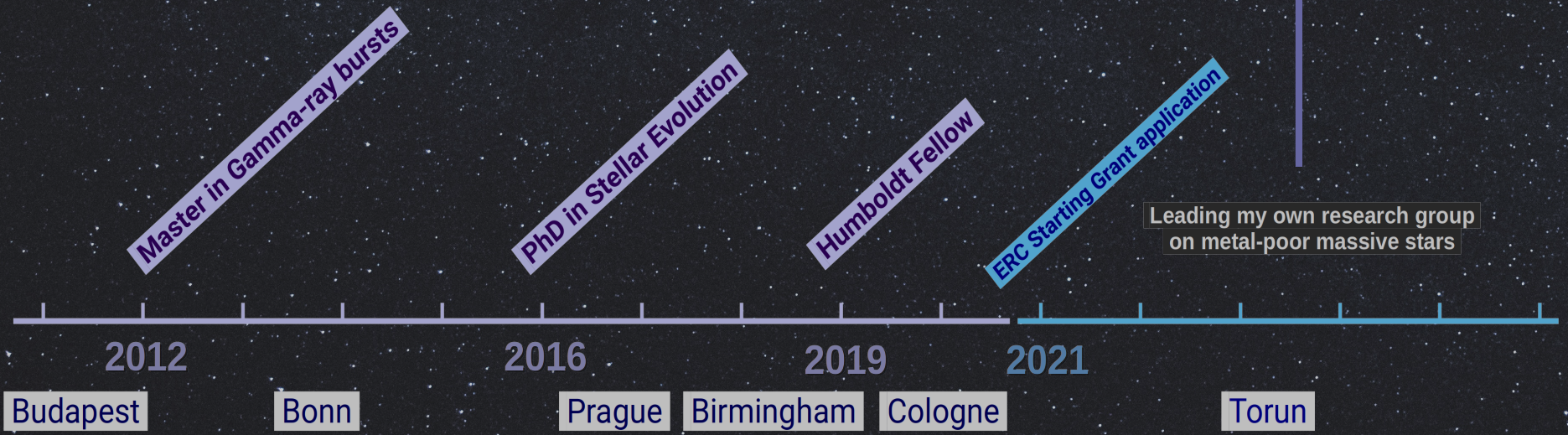
The theory linking gravitational waves, star-formation and the dawn of the Universe

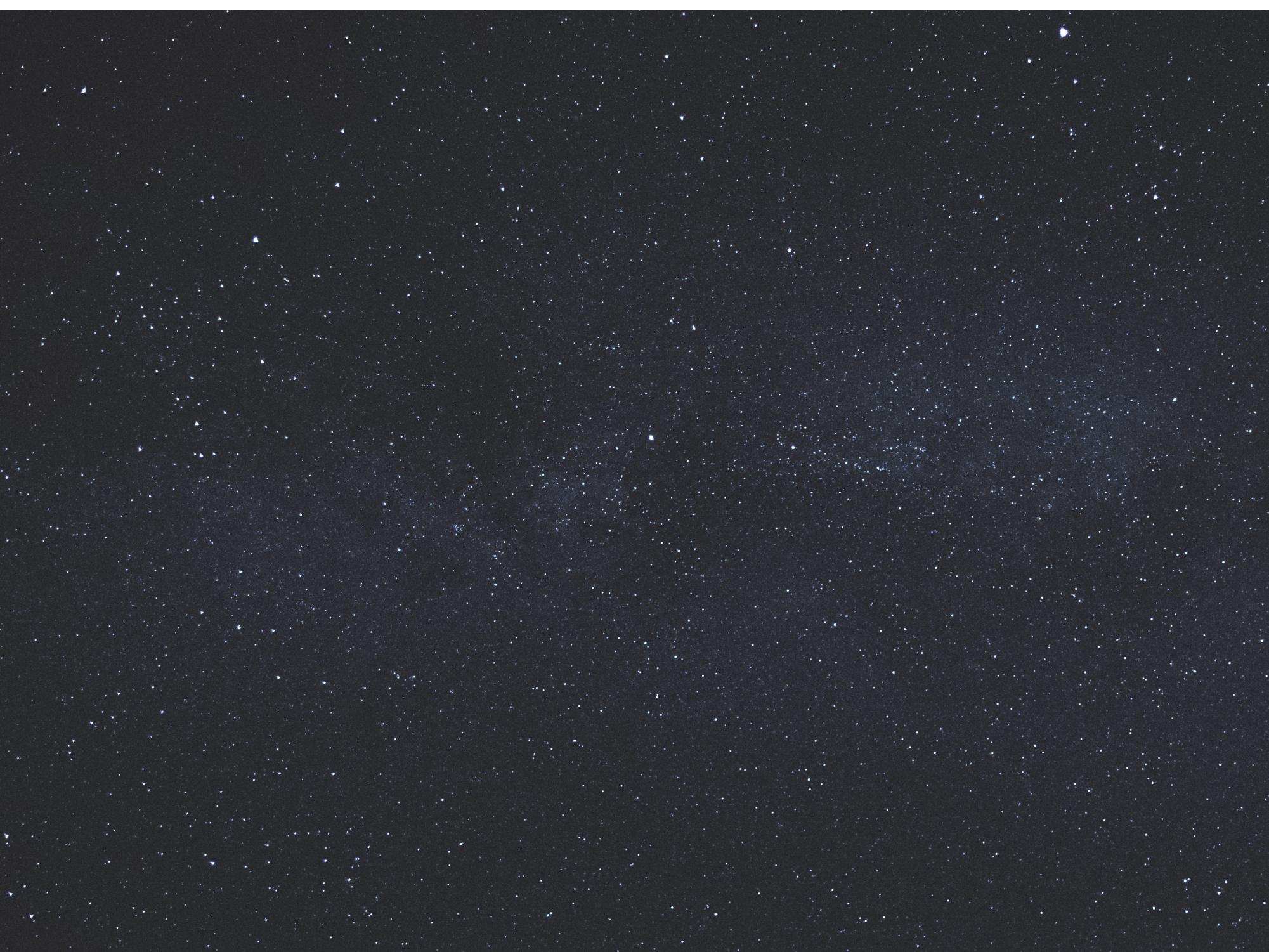
Dr. Dorottya Szécsi

Assistant Prof. / Research Adjunct
NCU, Torun, Poland

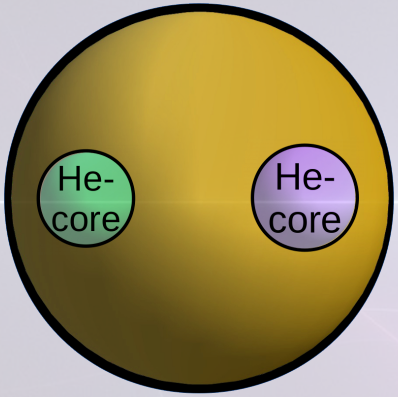
Thank you for your attention!







3 GW progenitor theories



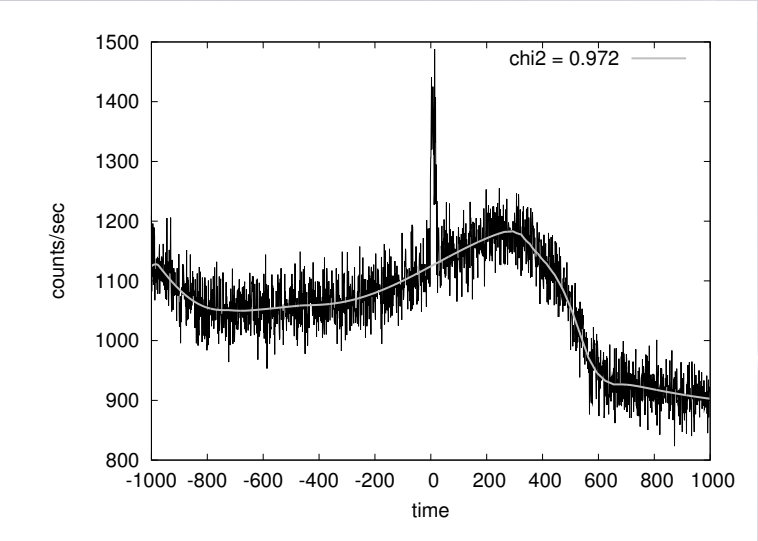
Common envelope
in a binary

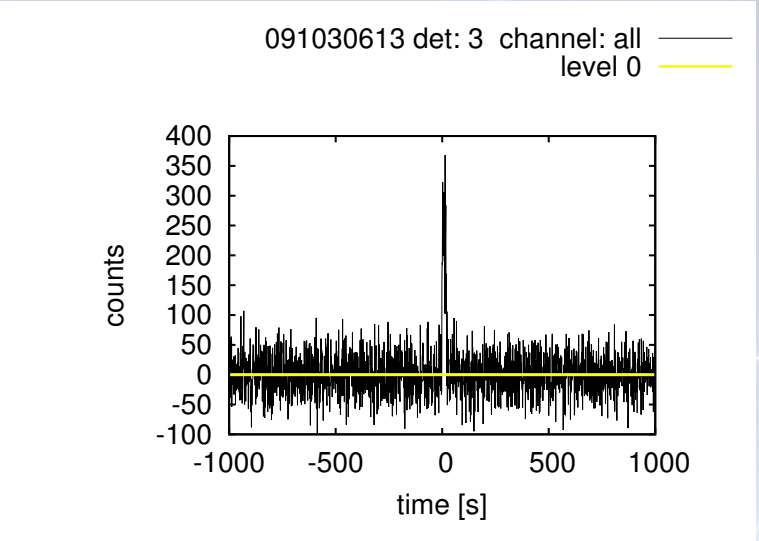
Chemically-
homogeneous
evolution
in a binary

Dynamics in
dense clusters

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

Direction dependent background fitting



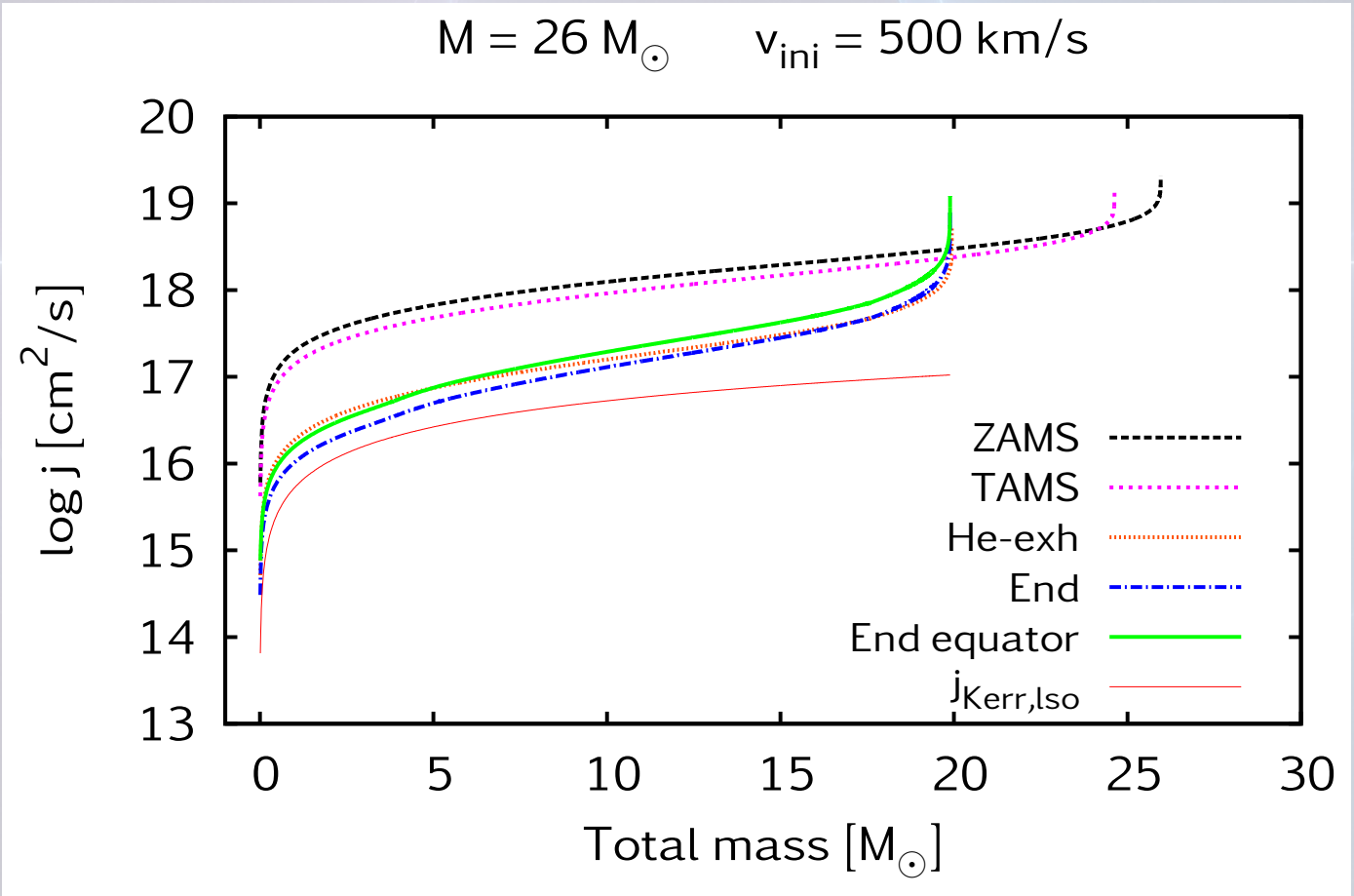


- The new model takes into account:
  - angle between detector and burst
  - angle between Sun and detector
  - Earth uncovering
- Numerical fitting
- Lightcurve without background → further analyses

Szécsi +12a,b, Szécsi +13

A long-duration GRB progenitor model

(1/50 $Z_\odot$)



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