The Stellar Modeler's Toolkit

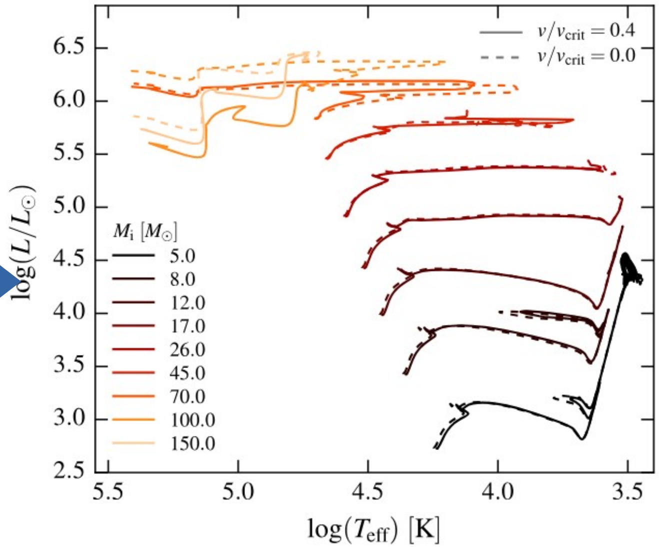
Pablo Marchant

UNIVERSITEIT GENT

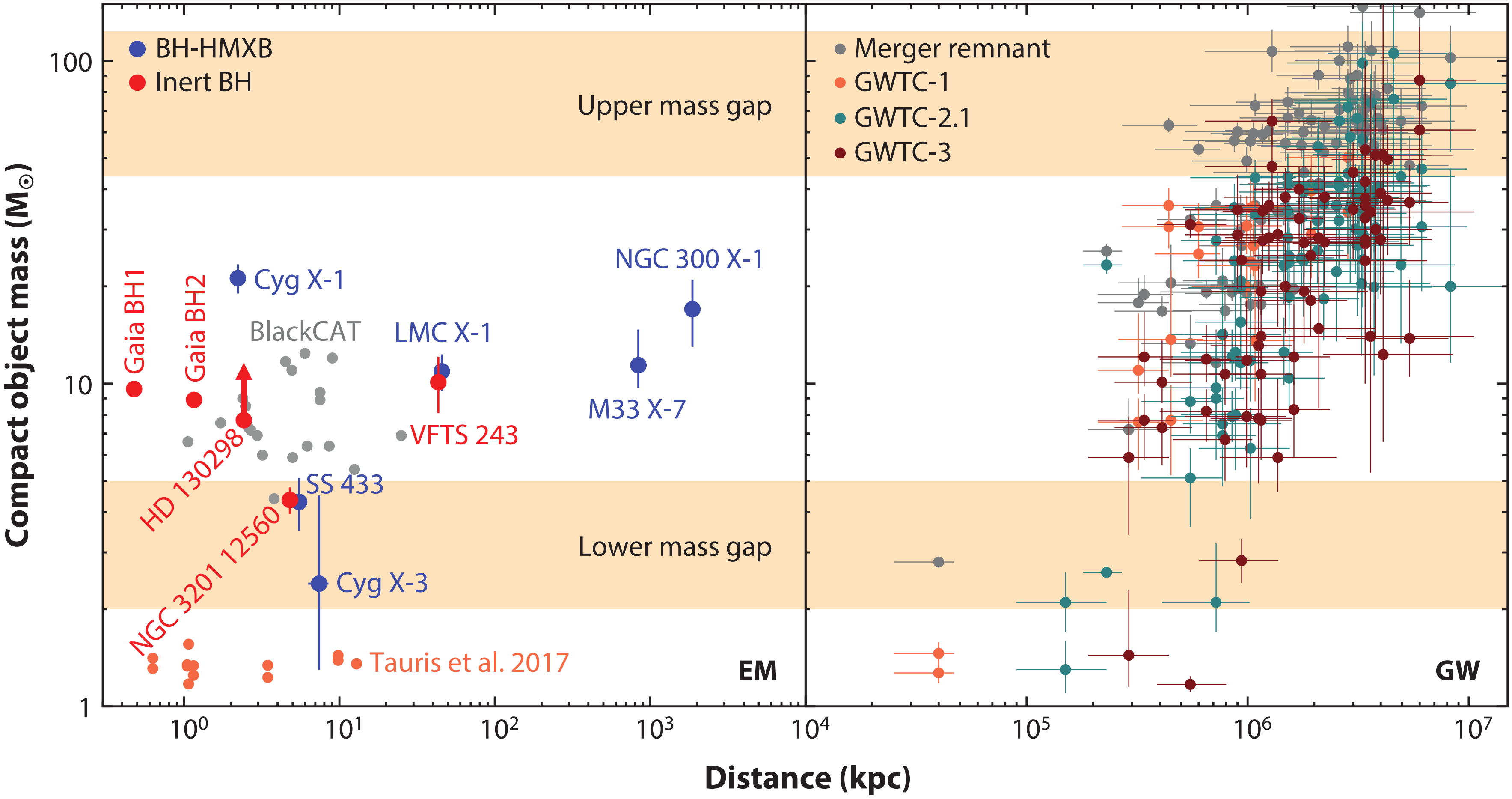
The stellar evolution black box

$$\mathrm{M}_{\mathrm{initial}},\ v_{\mathrm{rot}}/v_{\mathrm{crit}}$$

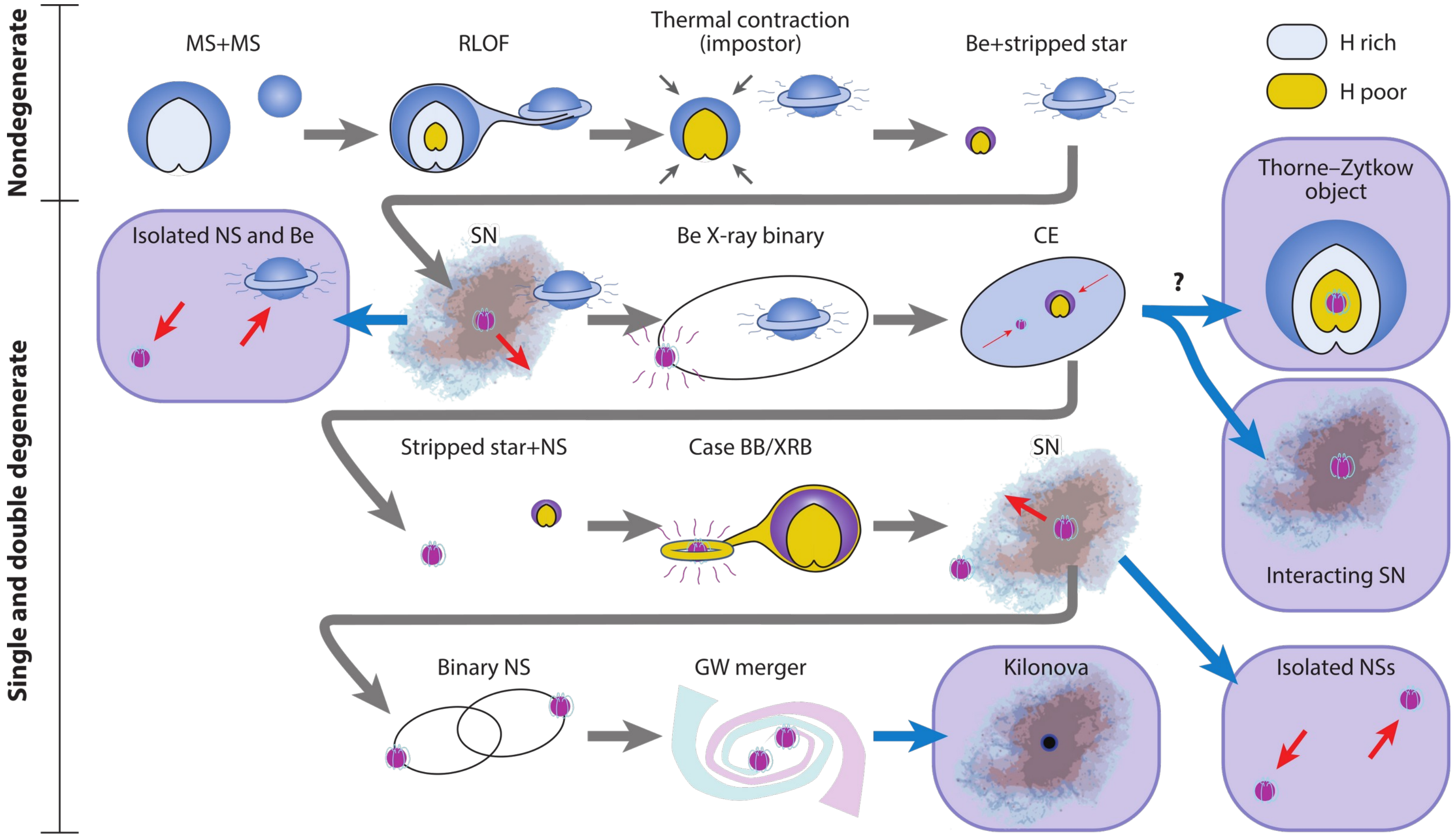
Choi et al. (2016)



Gravitational wave sources



Zooming in on binary evolution

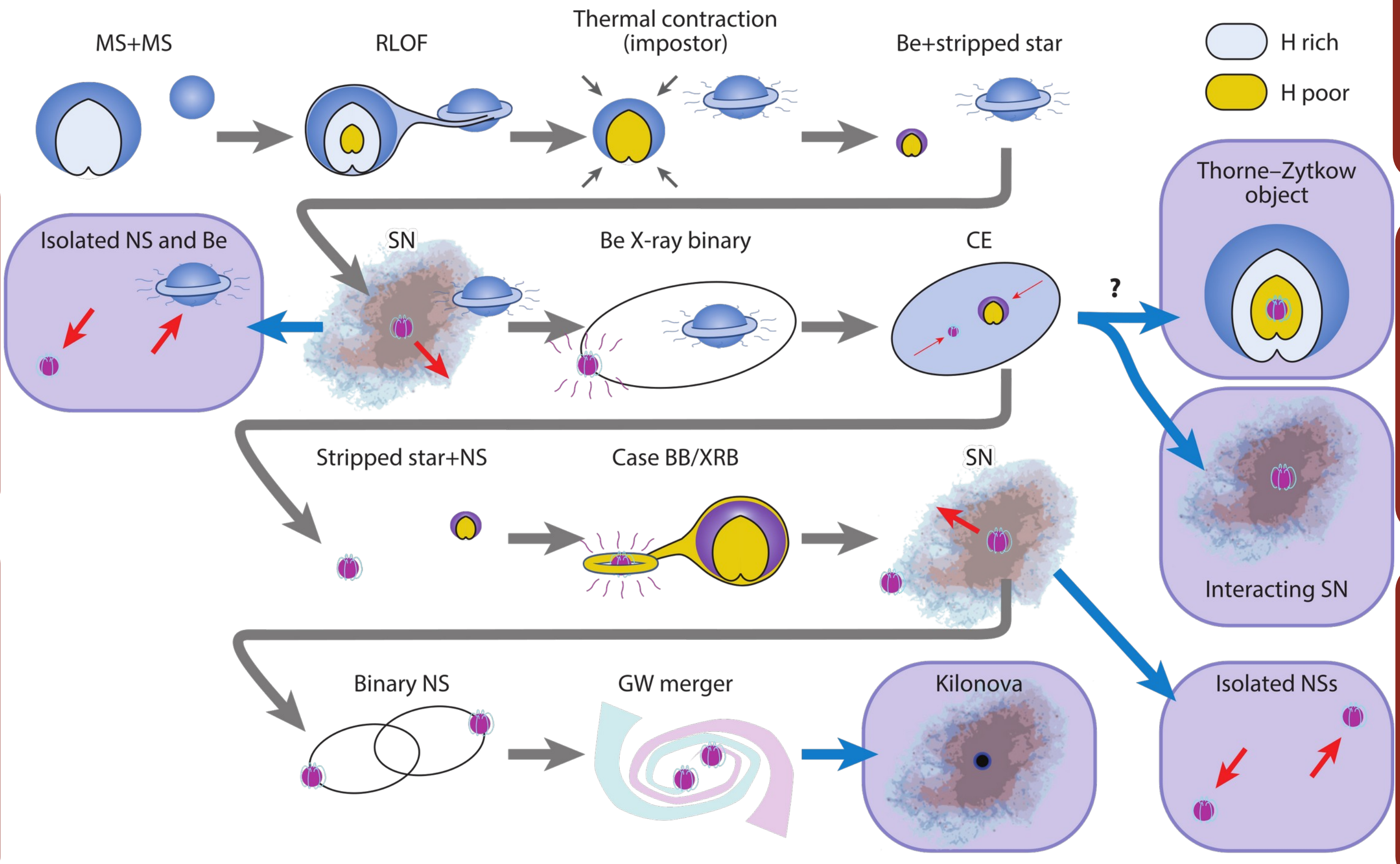


ng in on binary evolution

Matthias Fabry

Reinhold Willcox

Ritavash Debnath

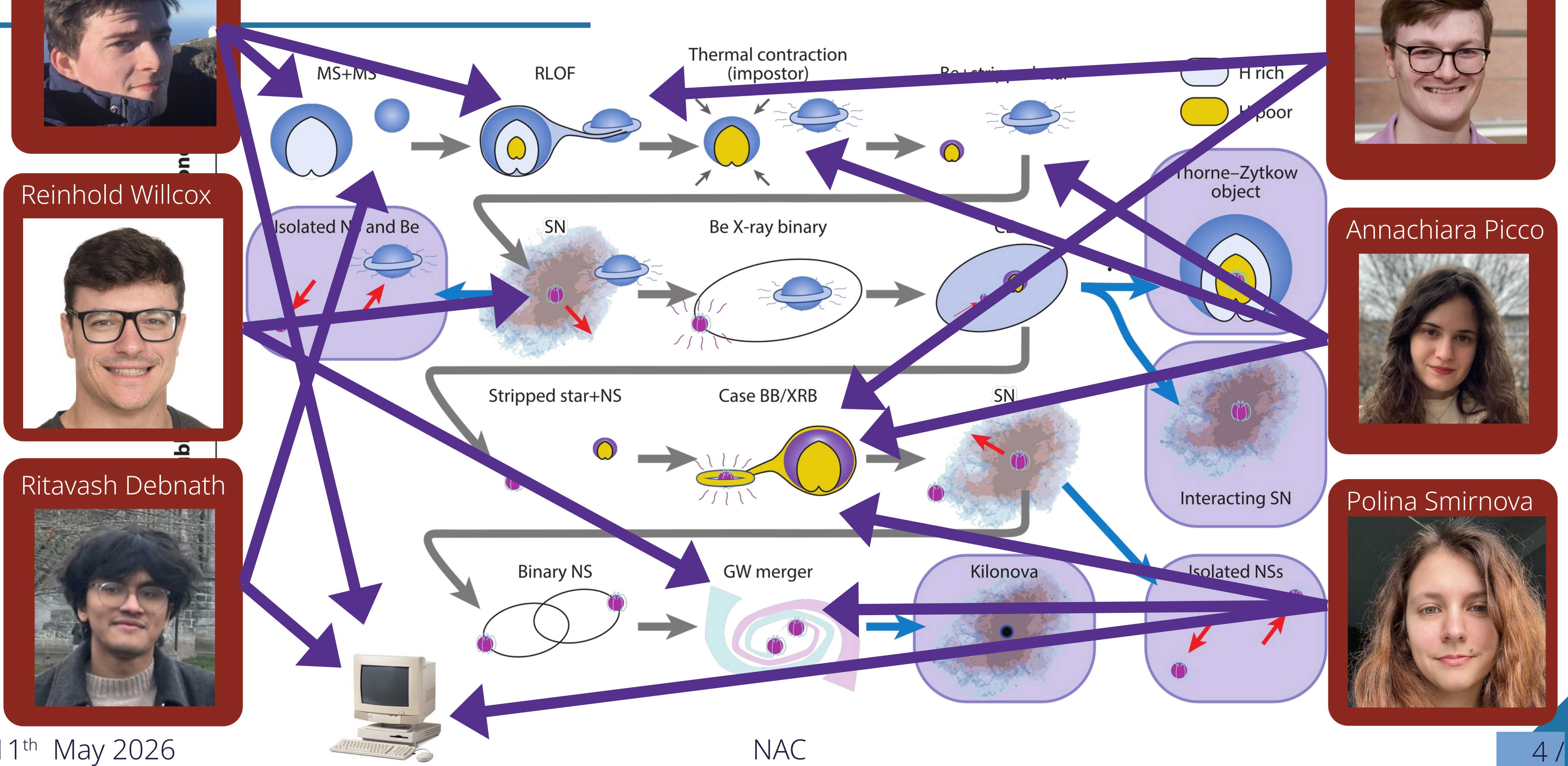


Davey Dickson

Annachiara Picco

Polina Smirnova

ng in on binary evolution



The first computer calculations

Extract from an interview to Martin Schwarzschild

https://repository.aip.org/node/128579

Weart:

One more question before we break for lunch: what are your general feelings about the impact of computers on astronomy? I mean their impact on our knowledge has been very clear, but on the way astronomers approach problems, or just the social patterns that take place in astronomy? Have computers had an impact?

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Schwarzschild:

I don't really see the computers as all that different from new really major tools on the observational side.

The problem of stellar evolution

$$\frac{\mathrm{d}r}{\mathrm{d}m} = \frac{1}{4\pi r^2 \rho}, \quad \text{Continuity equation}$$

$$\frac{\mathrm{d}P}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4}, \quad \text{Hydrostatic equilibrium (HSE)}$$

$$\frac{\mathrm{d}L}{\mathrm{d}m} = \varepsilon_{\mathrm{nuc}}, \quad \text{Energy equation}$$

$$\frac{\mathrm{d}T}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4}\frac{T}{P}\nabla, \quad \nabla = \begin{cases} \nabla_{\mathrm{rad}}, & \nabla_{\mathrm{rad}} < \nabla_{\mathrm{ad}} \\ \nabla_{\mathrm{ad}}, & \nabla_{\mathrm{rad}} > \nabla_{\mathrm{ad}} \end{cases}$$

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Analytical solutions are rarely available :(

Time for computer simulations!

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4} \rightarrow \frac{P_i - P_{i-1}}{(\Delta m)_i} = -\frac{Gm_i}{4\pi r_i^4}$$

We do the same for the rest and find a way to numerically solve them

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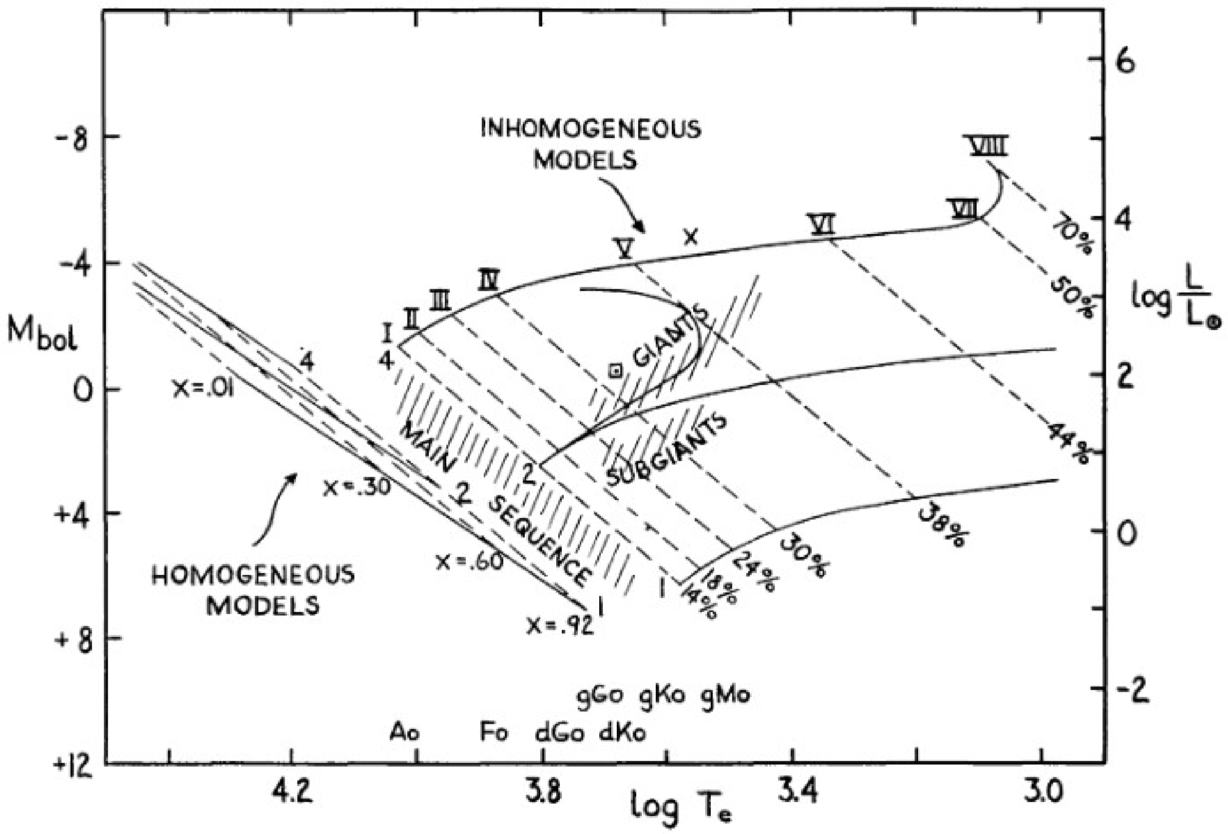
We do the same for the rest and find a way to numerically solve them

$$R_{2,i} = \frac{P_i - P_{i-1}}{(\Delta m)_i} + \frac{Gm_i}{4\pi r_i^4} = 0$$

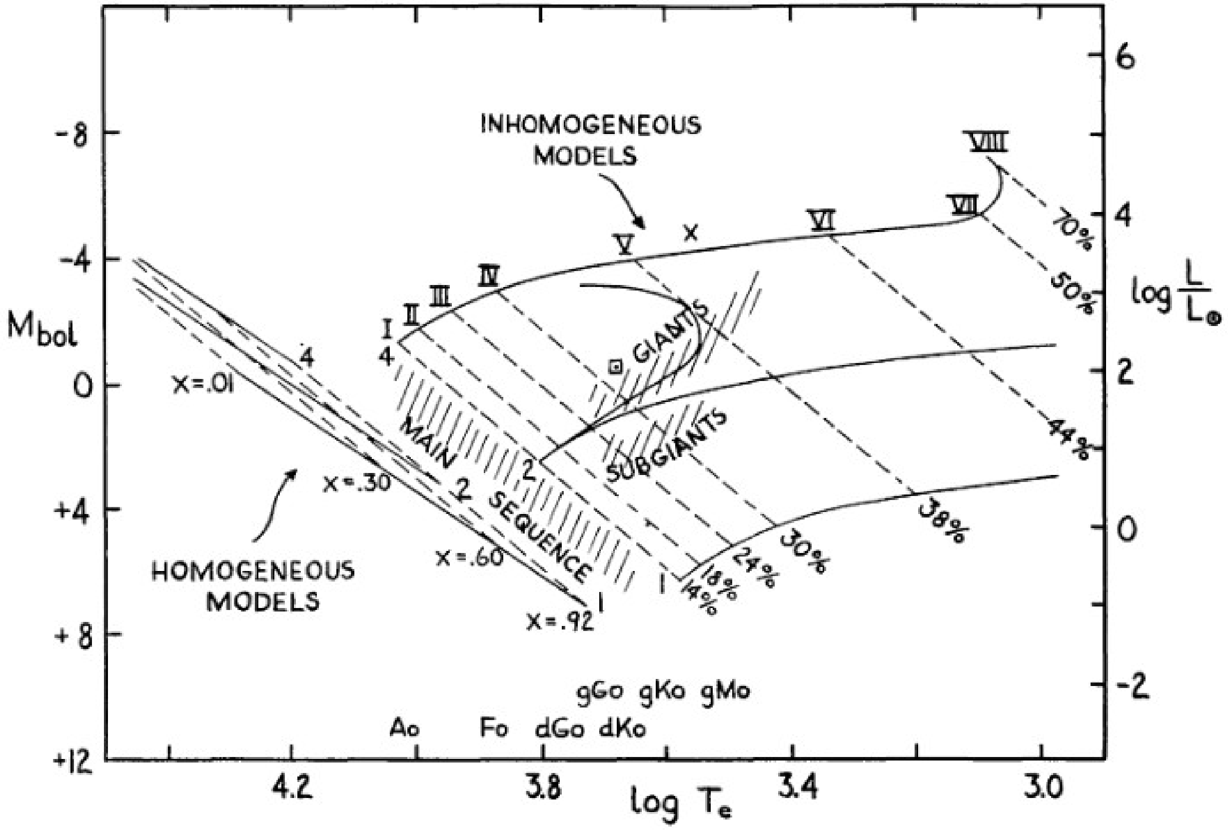
The first computer calculations



Oke & Schwarzschild (1952)

Why do stars evolve into red giants?

The first computer calculations



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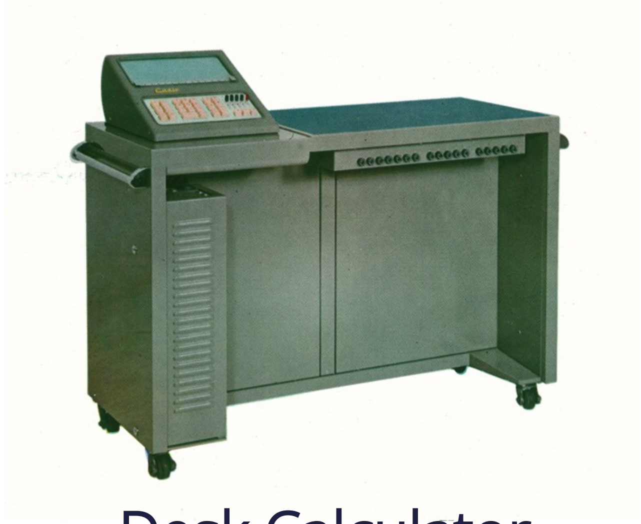
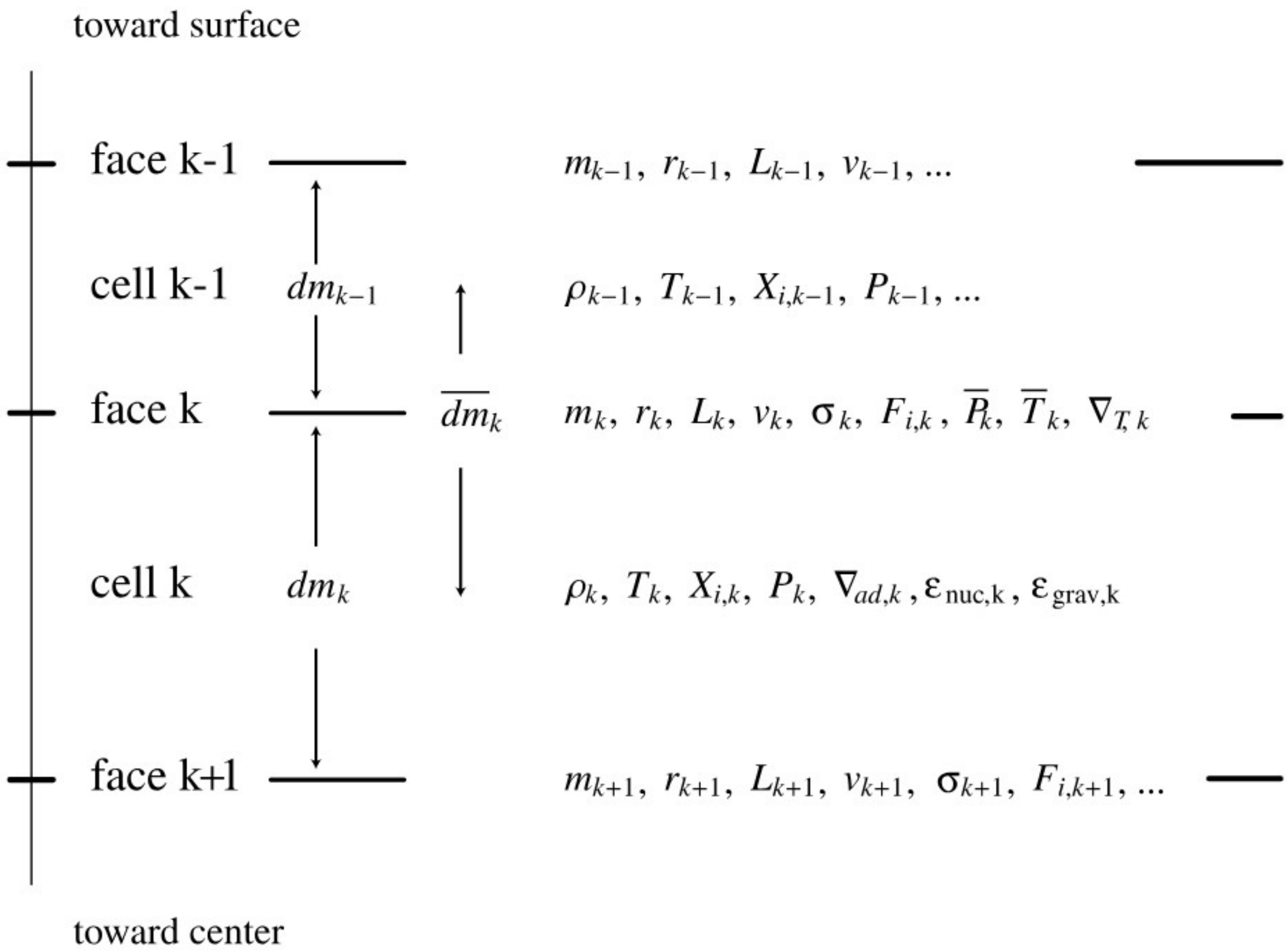


Desk Calculator

Modern tools are VERY similar

Paxton et al. (2011)

Paxton et al. (2015, incl PM)



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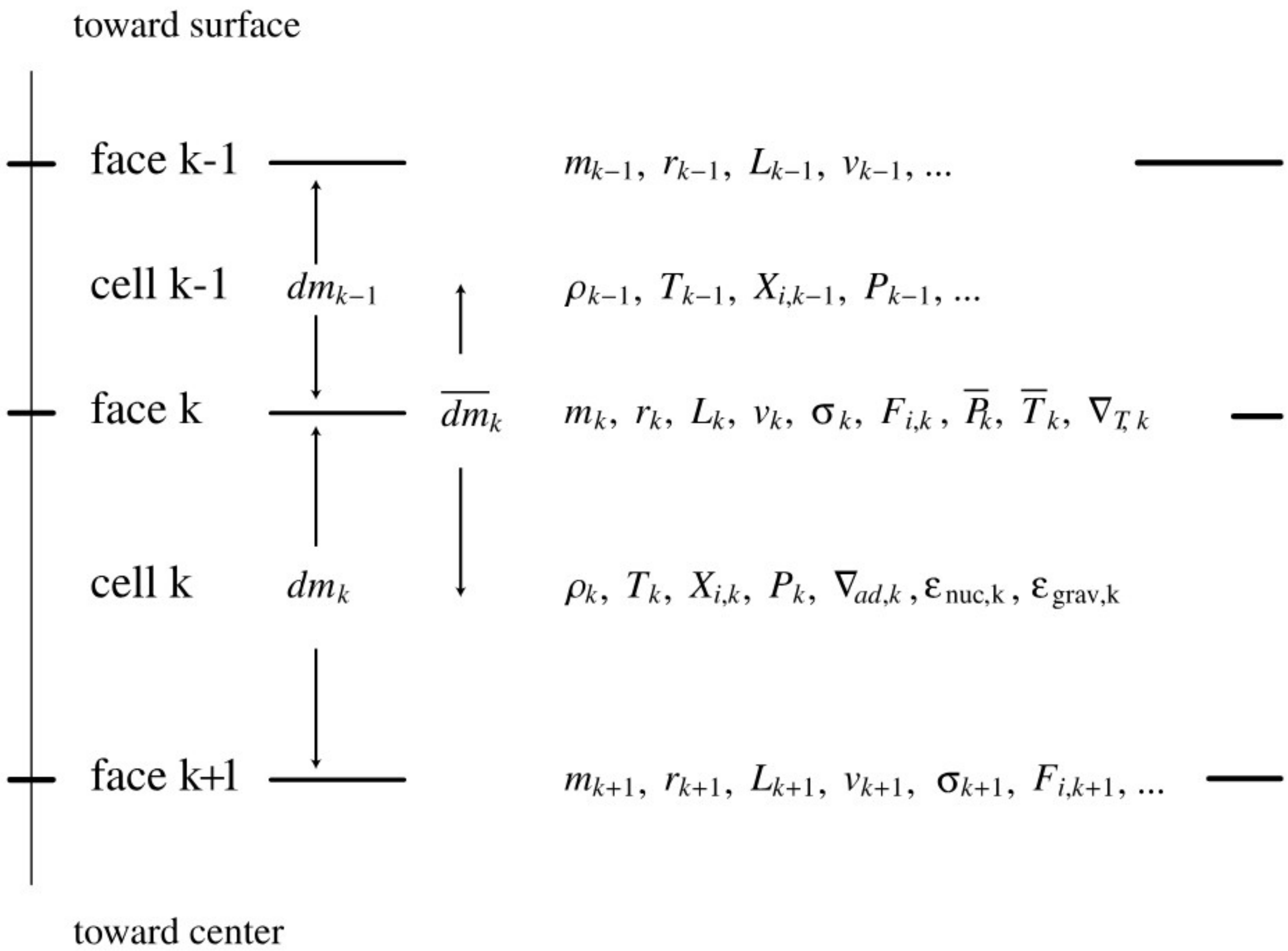

MESA

So, problem solved?

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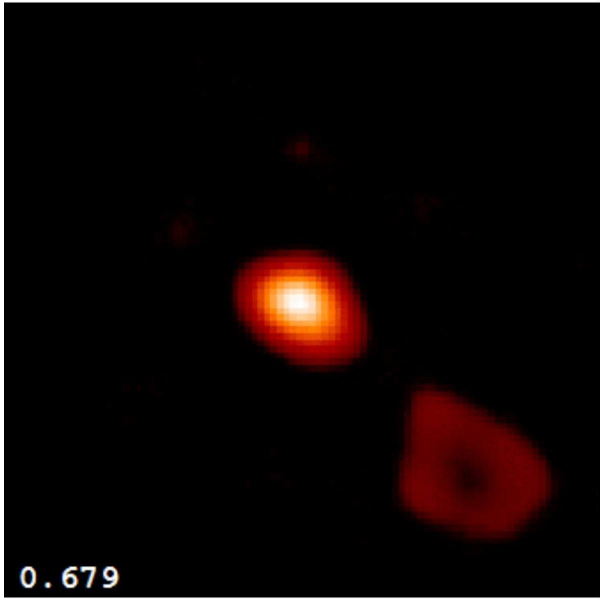
Hydrodynamics

So, problem solved?

Hydrodynamics

Binarity



Baron et al. (2012)

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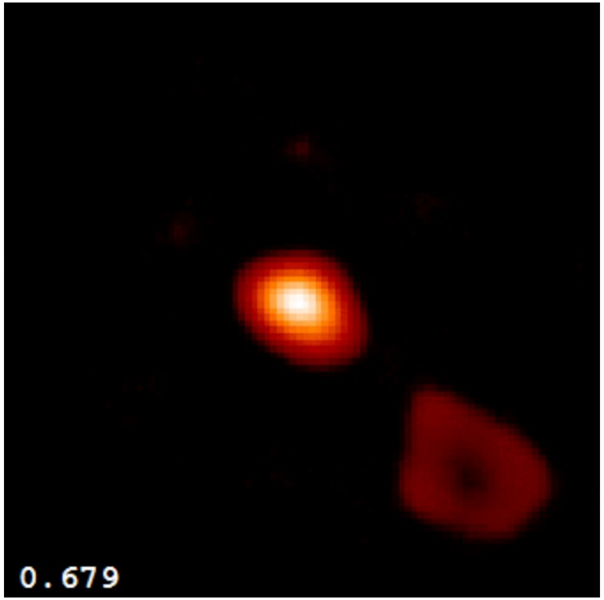


Baron et al. (2012)

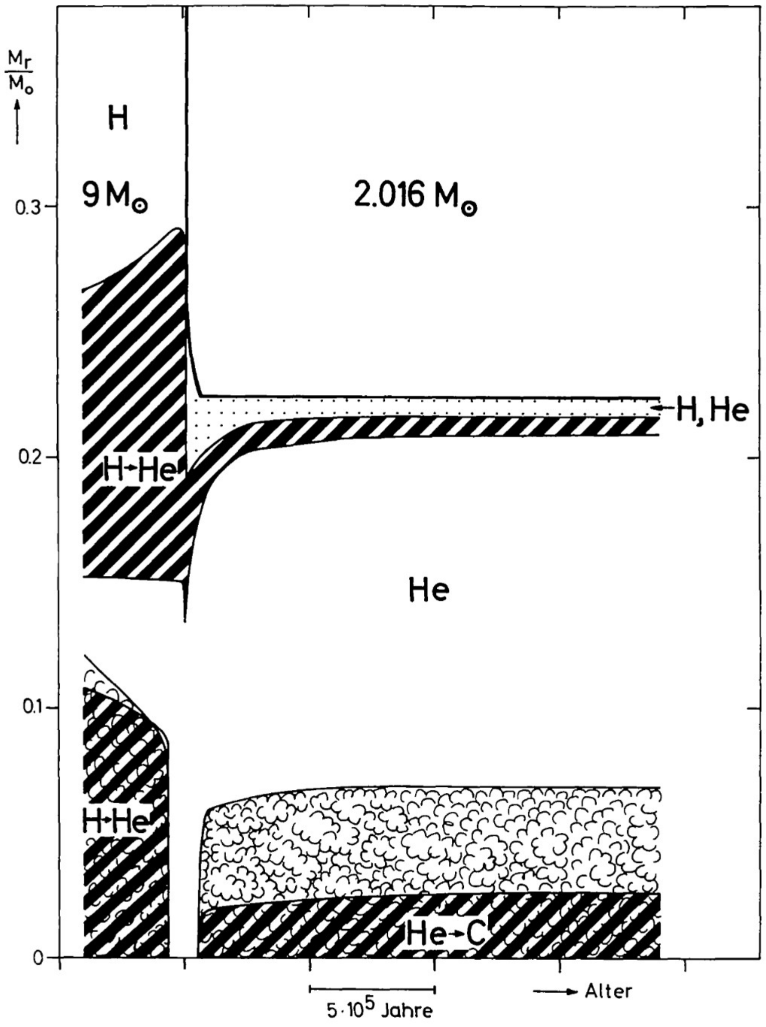
Populations

Evolutionary models

Current modelling efforts go into three “tiers”:

- Rapid pop-synth: Semi-analytical, e.g. the BSE code, Hurley et al (2002) [<second].
- 1D stellar structure and evolution e.g. MESA, Paxton, Marchant et al. (2015) [~core hours].
- 3D hydro, e.g. AREPO, Springel (2010) [can exceed 1M core hours]

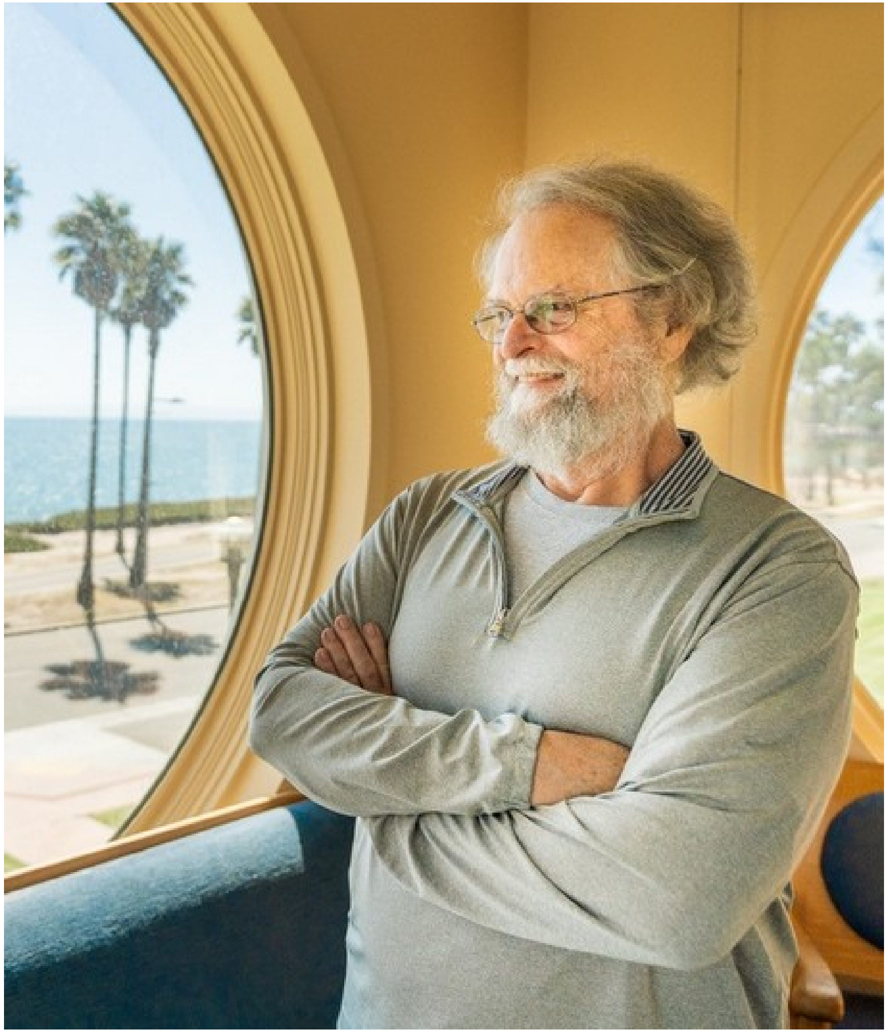
Kippenhahn & Weigert (1967)



The MESA project

Paxton et al. (2011)

- **M**odules for **E**xperiments in **S**tellar **A**strophisics (Paxton et al. 2011)
- OPEN SOURCE!
- OPEN SCIENCE!
  https://zenodo.org/communities/mesa/records
- Support for binary evolution, Paxton, Marchant et al. (2015).




Eoin Farrell


Adam Jermyn

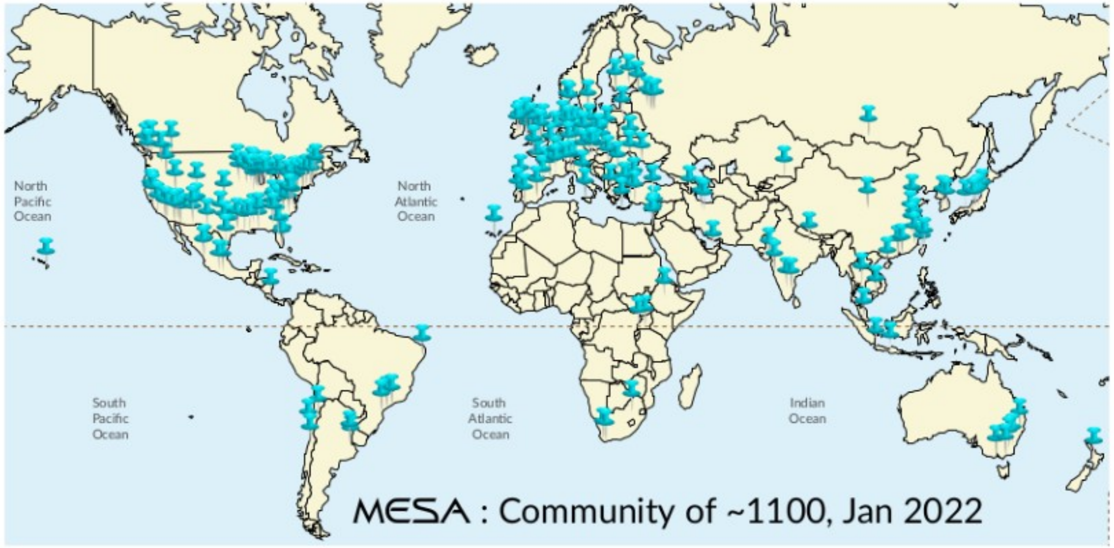

Meridith Joyce


Evan Bauer


Earl Bellinger


Anne Thoul


Radek Smolec




Bill Wolf

Outdated list!


Rob Farmer


Pablo Marchant


Warrick Ball


Aaron Dotter


Rich Townsend

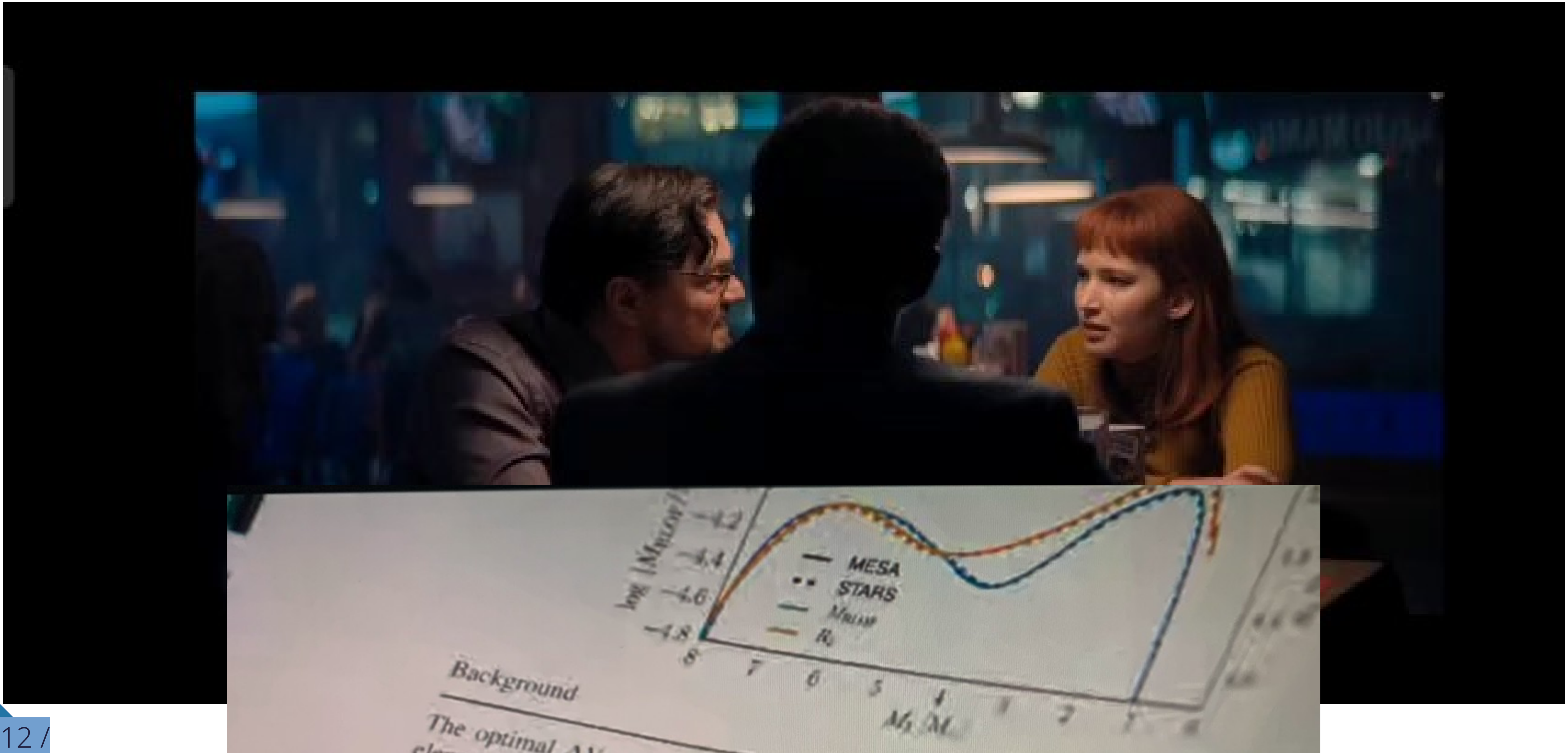

Frank Timmes


Lars Bildsten


Matteo Cantiello

The MESA project

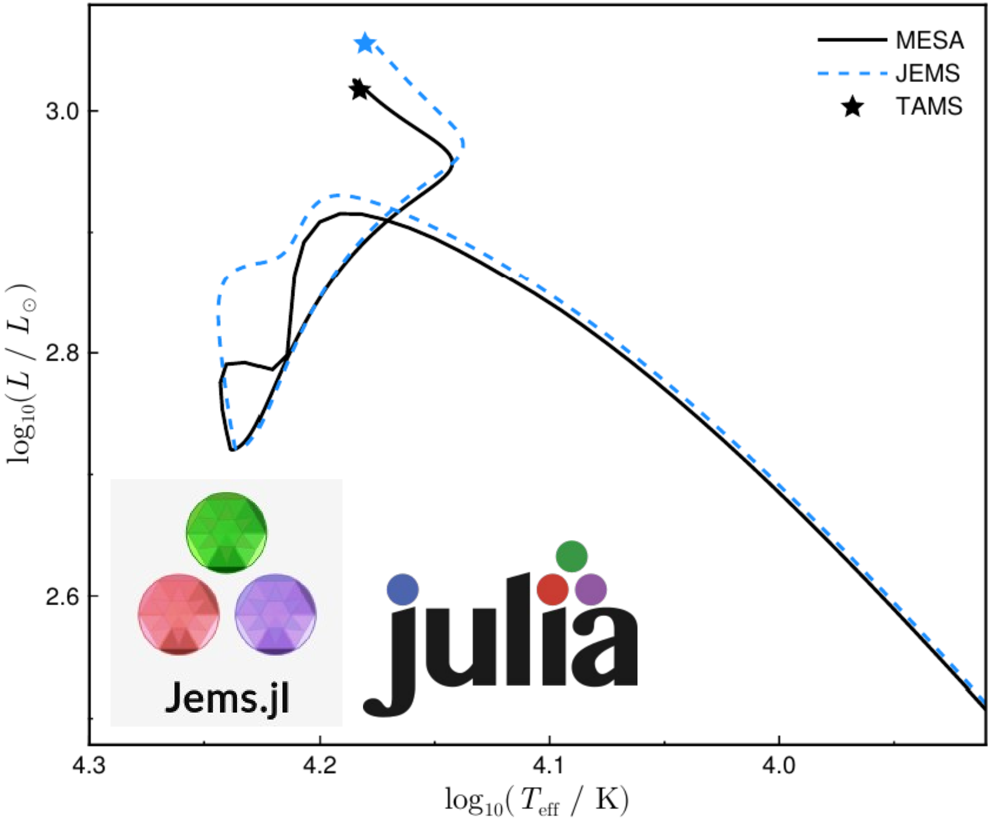
“This is next generation cutting edge technology” Leonardo di Caprio



The next generation of stellar evolution models

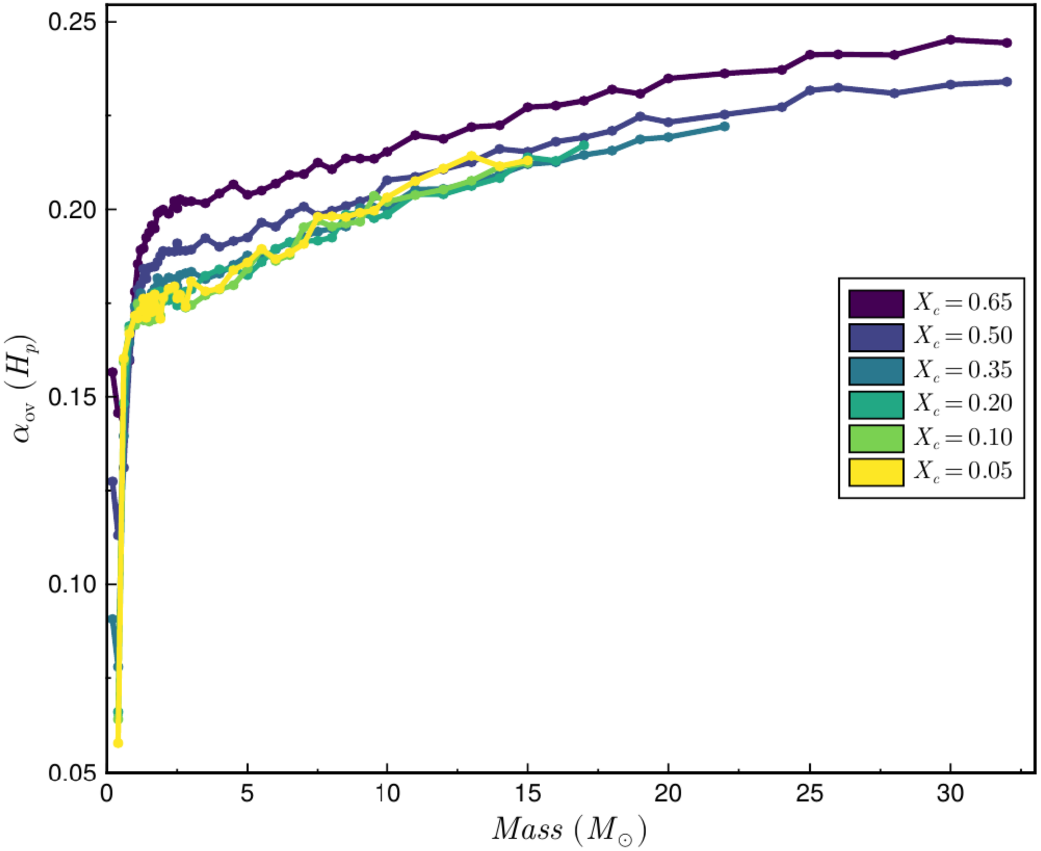
https://jems-jl.github.io/Jems.jl

- Brand new stellar evolution code developed in julia (core contributions from PhD student Ritavash Debnath).
- Development of efficient population synthesis methods (led by PhD student Polina Smirnova).
- Full adoption of automatic differentiation.
- Complete flexibility to adjust equations/physics/discretization.



Easy inclusion of new equations

Debnath, Marchant et al. (in prep)



What if we want a better model of convection to succeed mixing length theory, including its time dependence?

$$\frac{\partial \omega}{\partial t} = \frac{\nabla_{\rm ad} T \Lambda \alpha_{\rm s} c_{\rm p}}{H_{\rm p}^2} \sqrt{\omega}(\nabla - \nabla_{\rm ad}) - \frac{C_{\rm D}}{\Lambda}\omega^{3/2} - \frac{\omega}{\tau_{\rm rad}} - \mathcal{F}_\omega \,.$$

Kuhfuss et al. (1986), Braun et al. (2024)

A flexible code with automatic differentiation makes this straightforward to implement!

Fabry et al. (in prep)

Differentiable stellar evolution

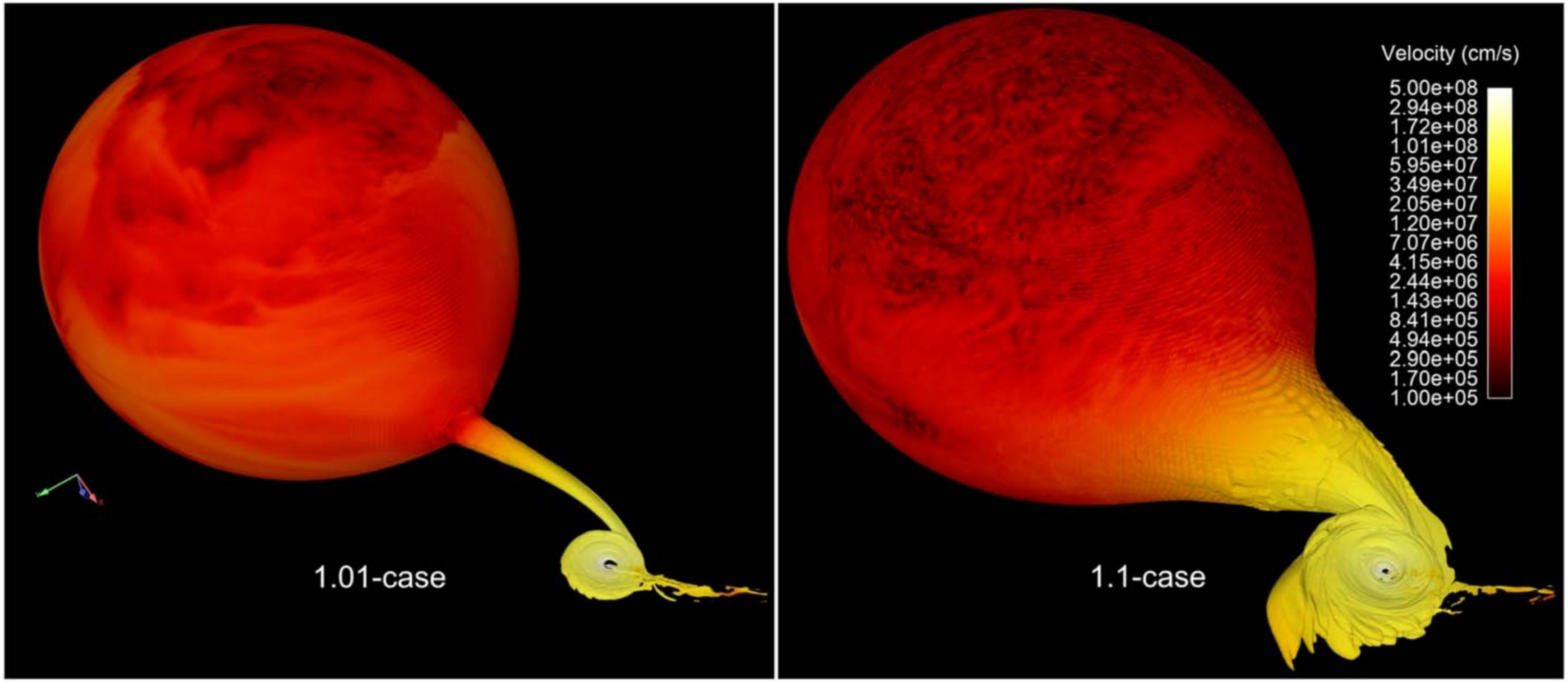
M_{initial} →  → $L(M_{\mathrm{initial}}, t)$

M_{initial} →  → $L(M_{\mathrm{initial}}, t) + \frac{dL}{dM_{\mathrm{initial}}}(M_{\mathrm{initial}}, t)$

What about 3D?

Aiming to model long-lived 3D processes

See more about this on Wednesday at 10:30!



Dickson (2024)

Davey Dickson

Parting thoughts

Software as an instrument

Most cited astro papers of 2015

1. 2015CQGra..32b4001A 2015/01 cited: 3953
   Advanced Virgo: a second-generation interferometric gravitational wave detector
   Acernese, F.; Agathos, M.; Agatsuma, K. *and 231 more*
2. 2015CQGra..32g4001L 2015/04 cited: 3783
   Advanced LIGO
   LIGO Scientific Collaboration; Aasi, J.; Abbott, B. P. *and 699 more*
3. 2015MNRAS.446..521S 2015/01 cited: 3546
   The EAGLE project: simulating the evolution and assembly of galaxies and their environments
   Schaye, Joop; Crain, Robert A.; Bower, Richard G. *and 19 more*
4. 2015ApJS..220...15P 2015/09 cited: 3116
   Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and Explosions
   Paxton, Bill; Marchant, Pablo; Schwab, Josiah *and 10 more*
5. 2015ApJS..219...12A 2015/07 cited: 2374
   The Eleventh and Twelfth Data Releases of the Sloan Digital Sky Survey: Final Data from SDSS-III
   Alam, Shadab; Albareti, Franco D.; Allende Prieto, Carlos *and 301 more*

Open science (good for you, good for everyone)

Draft version March 30, 2026
Typeset using LaTeX **twocolumn** style in AASTeX7

The YREC Stellar Evolution Code: Public Data Release

Marc H. Pinsonneault[1,2] Jennifer L. van Saders[3] Lyra Cao[4] Jamie Tayar[5] Franck Delahaye[6] Leslie M. Morales[5] Rachel A. Patton[7] Matthew C. Rendina[1] Joel C. Zinn[8] Zachary R. Claytor[9] Amanda L. Ash[1] Susan Byrom[5] Kaili Cao[2,10] and Vincent A. Smedile[1,2]

README GPL-3.0 license

GENEC

Welcome to the Geneva stellar evolution code.

To copy the code to your computer, run:

git clone git@github.com:GESEG/GENEC.git

git tutorials can be found here: https://www.atlassian.com/git/tutorials/

But beware, software is NOT reality

But beware, software is NOT reality

Weart:

You don't feel that it changes the way an astronomer regards himself or his subject.

Schwarzschild:

No, but every tool always brings with it a balance; you can fall in love with a tool and forget about astronomy, and overdo the use of the tool and not do the maximum science, or you can also be overcautious and be on the conservative side and start using the new tool too late. So with a powerful tool like a computer, that danger always exists and you always see the whole spectrum. But that's not peculiar to computers.

Want to learn more about binaries?

Marchant & Bodensteiner (2024)

Marchant (2025)

ANNUAL REVIEWS

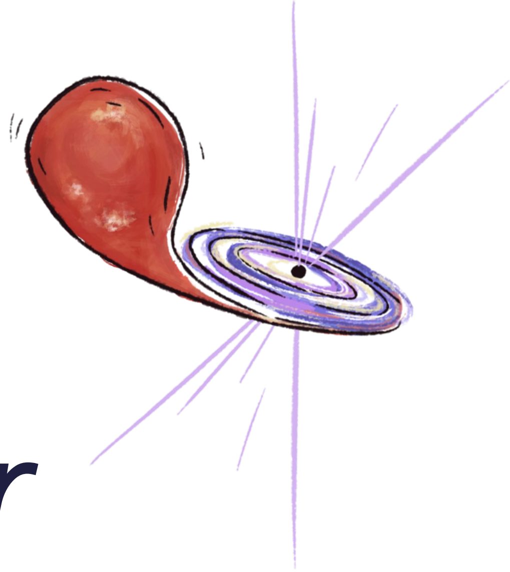
Annual Review of Astronomy and Astrophysics

The Evolution of Massive Binary Stars

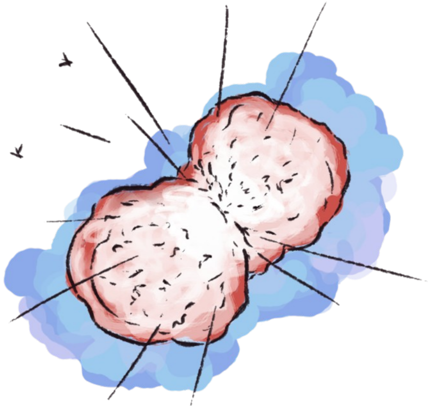
Pablo Marchant[1] and Julia Bodensteiner[2]

[1]Institute of Astronomy, KU Leuven, Leuven, Belgium; email: pablo.marchant@kuleuven.be

[2]European Organisation for Astronomical Research in the Southern Hemisphere (ESO), Garching, Germany; email: julia.bodensteiner@eso.org



Thanks for your attention!



Extra slides

Klement et al (2025)

Automatic differentiation

Basics of dual number arithmetic

$$x = a_1 + b_1\epsilon,\ y = a_2 + b_2\epsilon,\ \epsilon^2 = 0$$

$$xy = a_1 + a_2 + (a_1 b_2 + a_2 b_1)\epsilon$$

This enables the calculation of derivatives through operator overloading

$$x = f(z_0) + \left.\frac{df}{dz}\right|_{z=z_0}\epsilon,\ y = g(z_0) + \left.\frac{dg}{dz}\right|_{z=z_0}\epsilon$$

$$xy = (f(z_0) + g(z_0)) + \left(f(z_0)\left.\frac{dg}{dz}\right|_{z=z_0} + g(z_0)\left.\frac{df}{dz}\right|_{z=z_0}\right)\epsilon$$

Automatic differentiation

Basics of dual numbe

$$x = a_1 + b_1\epsilon, \; y =$$

$$xy = a_1 + a_2 + ($$

$$J(f)_{\vec{x}-\vec{x}_0} = \begin{pmatrix} \mathbf{D}^1 & \mathbf{U}^1 & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{L}^2 & \mathbf{D}^2 & \mathbf{U}^2 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{L}^3 & \mathbf{D}^3 & \mathbf{U}^3 & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{L}^4 & \mathbf{D}^4 & \cdots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{D}^N \end{pmatrix}$$

$$\frac{\partial R_{j,i}}{\partial \rho_i}$$

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The Henyey method (Henyey 1959)

$$\vec{x} = (r_1, P_1, T_1, L_1, \ldots, r_n, P_n, T_n, L_n)$$

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And refine it! $f(\vec{x}_0 + \Delta\vec{x}) = \vec{0}$

The Henyey method (Henyey 1959)

Linearization: $f(\vec{x}_0 + \Delta\vec{x}) \simeq f(\vec{x}_0) + J(f)_{\vec{x}-\vec{x}_0}\Delta\vec{x}$

And we simply need

to solve a linear system!

$$J(f)_{\vec{x}-\vec{x}_0}\Delta\vec{x} = -f(\vec{x}_0) = -\vec{b}$$

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$$\frac{\partial R_{j,i}}{\partial \rho_i}$$

Solver complexity:

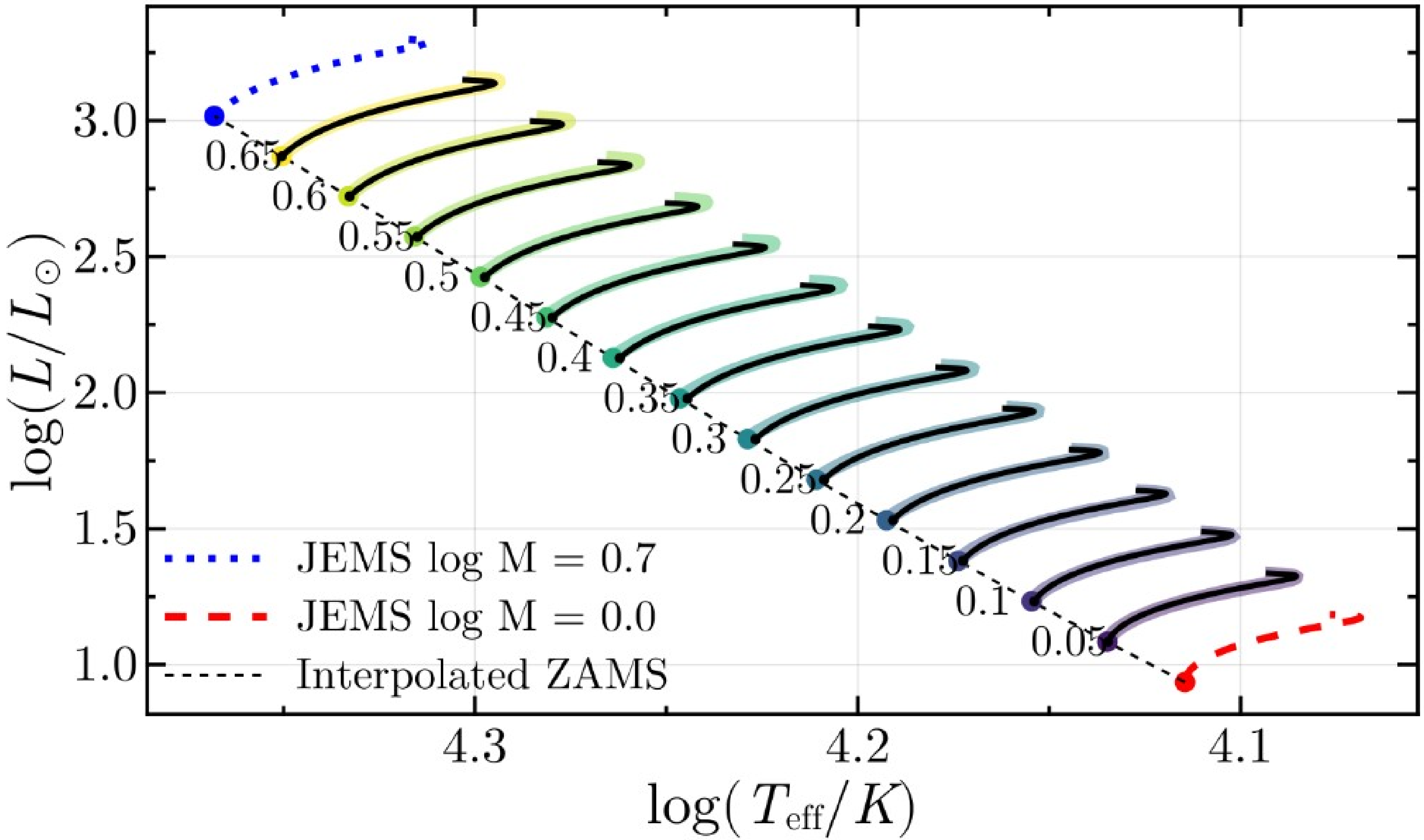
$$\mathcal{O}(n_{\text{zones}} \times n_{\text{vars}}^3)$$

Differentiable stellar evolution

Rahman et al. (2024, MsC thesis)

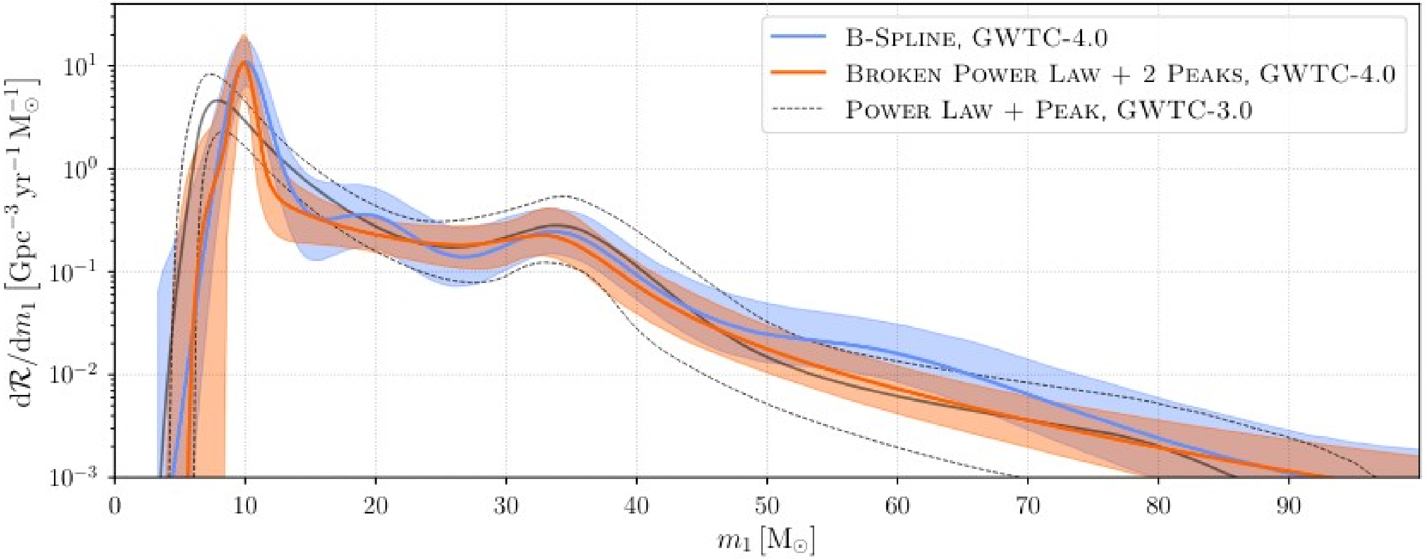
Fabry, Marchant et al. (in prep)

Example of interpolation



One use case of population synthesis

Abac et al. (2025)



Say we want to compare this to theory, what do we do? We do not know how much binary evolution contributes!

See Mandel & Farmer (2023) for a recent review

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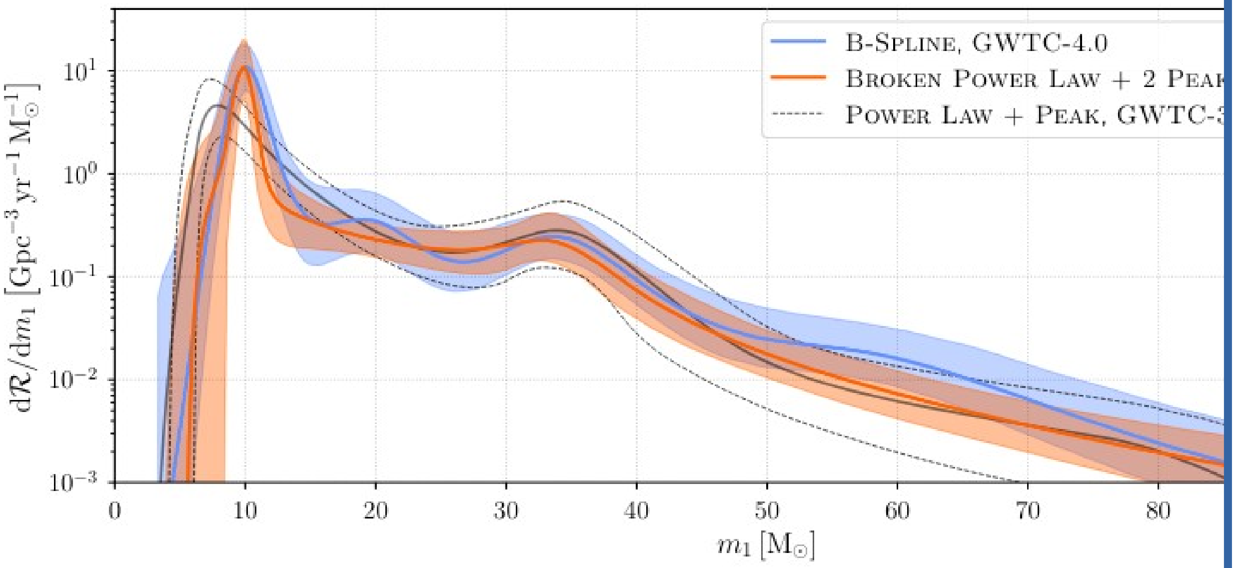


Say we want to compare this to theory, what do we do? We do not know how much binary evolution contributes!

See Mandel & Farmer (2023) for a recent review

Predictions combine multiple uncertain ingredients!

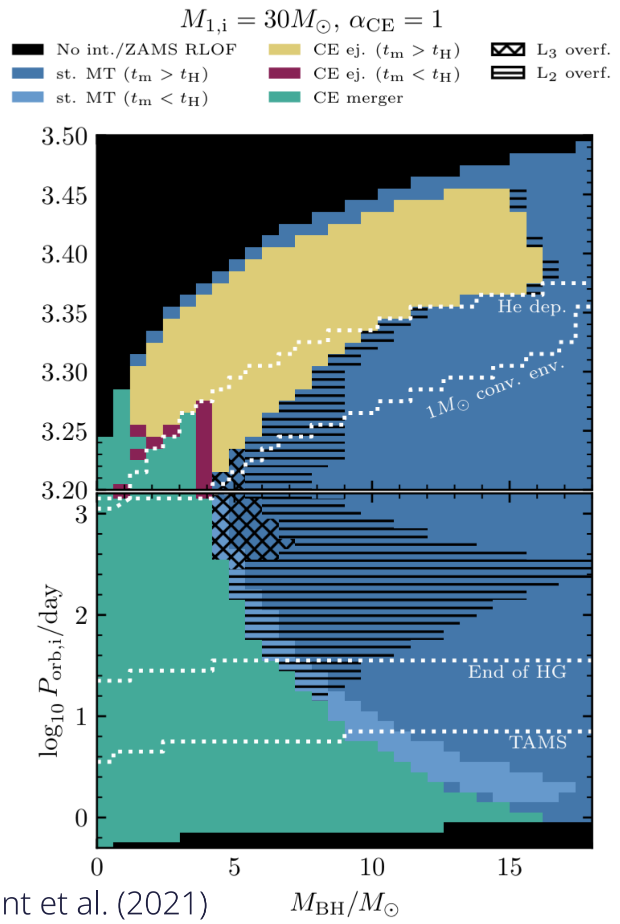
$$\mathrm{SFR}(Z, z)$$

Initial binary properties through cosmic time

All uncertainties of binary evolution

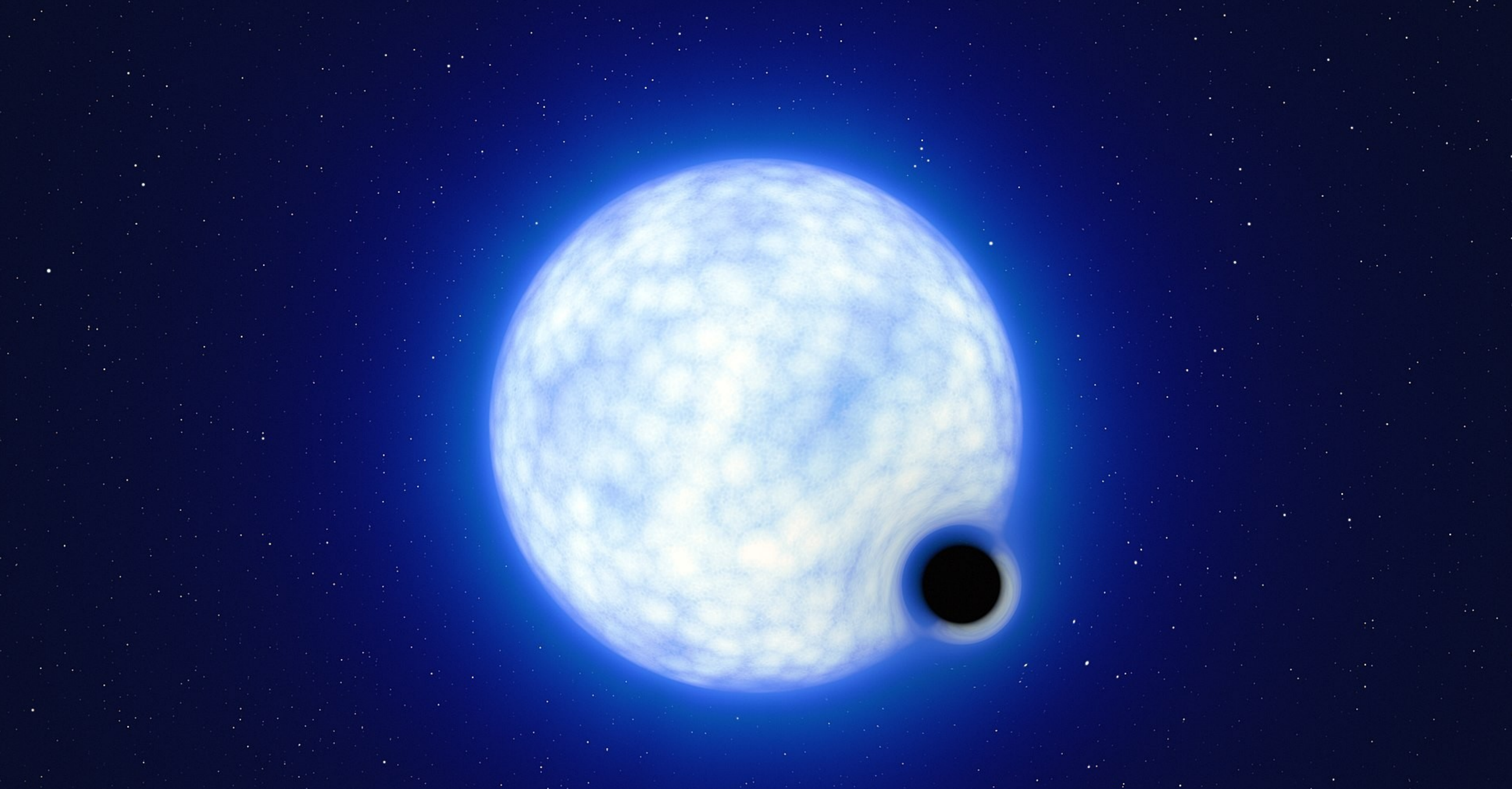
All uncertainties of single star evolution

Surveying the initial conditions of binary evolution



Marchant et al. (2021)

- Challenging the standard formation scenario of merging binary black holes (Picco et al. 2024).
- Predicting population properties of observed merging compact objects (Marchant et al. 2024).
- Unveiling new evolutionary channels (Picco, Marchant & Sana, in prep)



Artist illustration of VFTS 243
Image credit: ESO/L. Ca

Giesers et al. (2018)

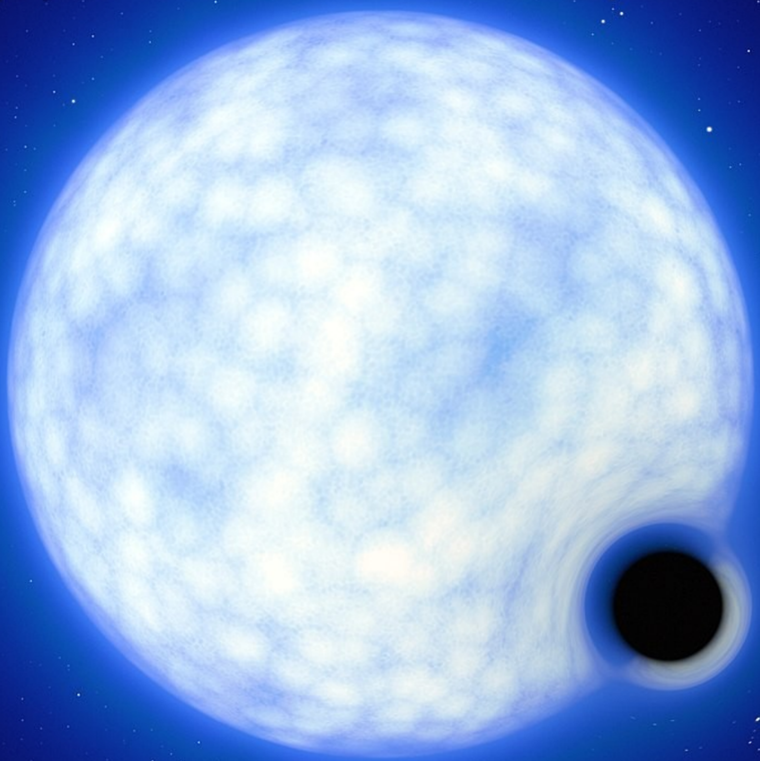
>4 $M_\odot$ BH in orbit with a ~0.8 $M_\odot$ star (P=167 days)

$e = 0.595 \pm 0.022$

Mahy et al. (2022, incl. PM)

>7 $M_\odot$ BH in orbit with a ~24 $M_\odot$ star (P=14.6 days)

$e = 0.457 \pm 0.007$



Shenar et al. (2022, incl. PM)

>8 $M_\odot$ BH in orbit with a ~25 $M_\odot$ star (P=10.4 days)

$e = 0.017 \pm 0.012$

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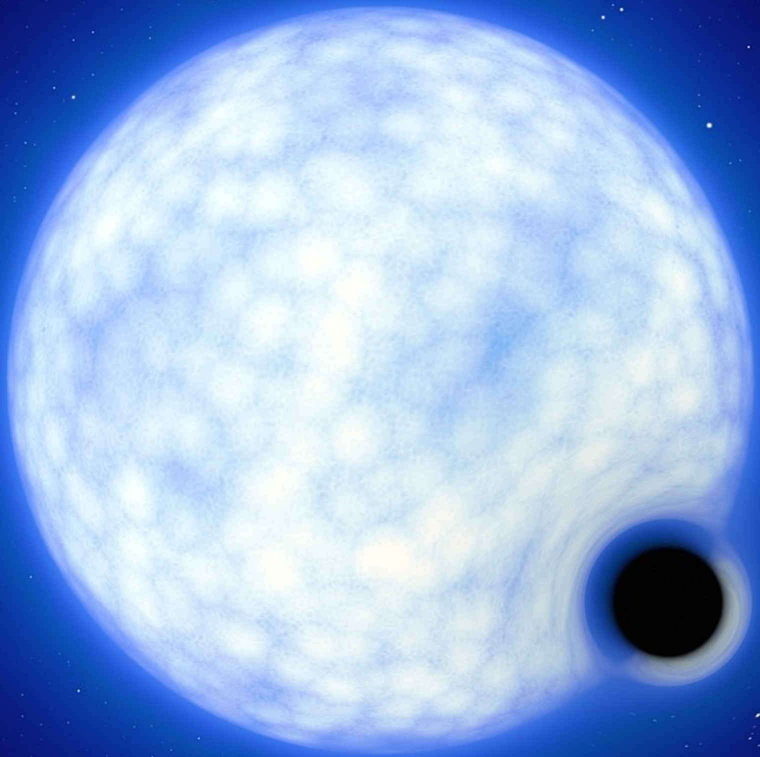

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BLOEM

SMC large program
~900 massive stars, 25 epochs
(Shenar et al. 2024,
incl. PM)

Giesers et al. (2018)

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~0.8 $M_\odot$ star (P=167 d

e = 0.595 ± 0.022

Best constraints to date on the possible absence of supernovae at BH formation!

Willcox, Marchant et al. 2025

et al. (2022, incl. PM)

$M_\odot$ BH in orbit with a
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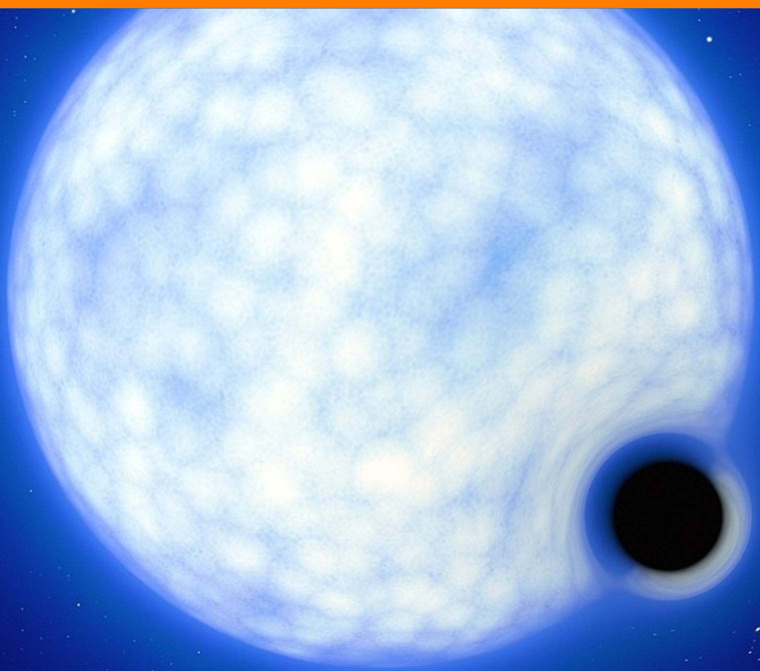
e = 0.457 ± 0.007



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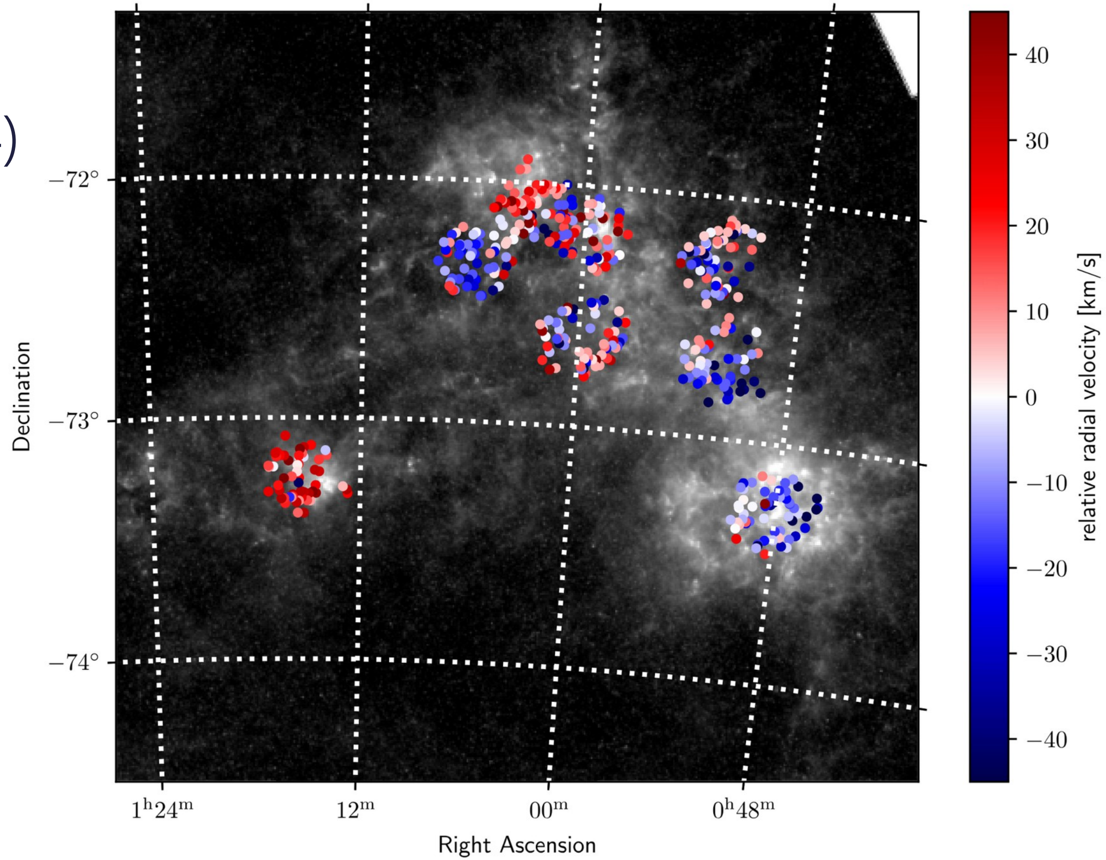
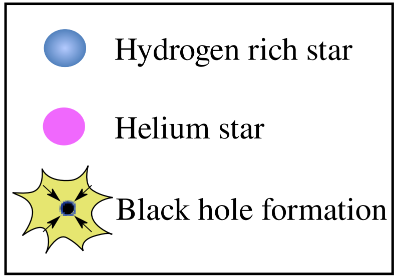
BLOeM (Binarity at LOw Metallicity survey)

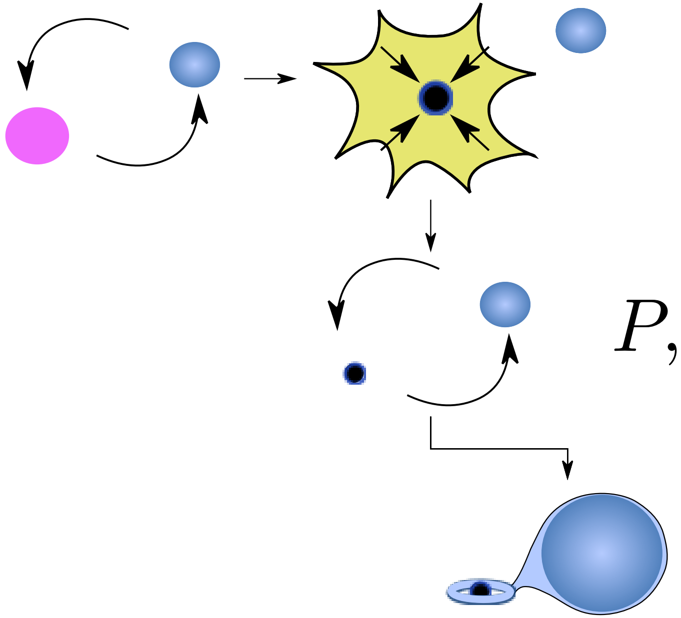
- Shenar, Bodensteiner et al. (2024) VLT-FLAMES observations of nearly 1000 massive stars in the SMC.
- 25 epochs per object, designed for characterisation of binary systems.



What do inert black hole binaries tell us



$$P, \cancel{e}, m_1, m_2 \qquad v_{\text{kick}}, \Delta M, \theta, \phi, \cancel{\nu}$$



$$P, e, m_1, m_2, v_{\text{sys}}, \alpha, \beta$$

$$P_{\text{circ}}, e = 0$$

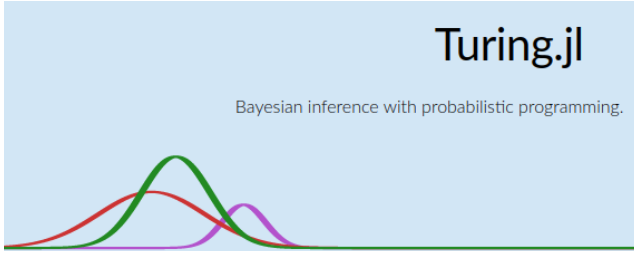
SIDEKICKS: Statistical Inference to DEtermine KICKS

$$P, e, m_1, m_2, K_1, K_2, v_r, \mu_\alpha, \mu_\delta, \Omega, \omega, \iota$$

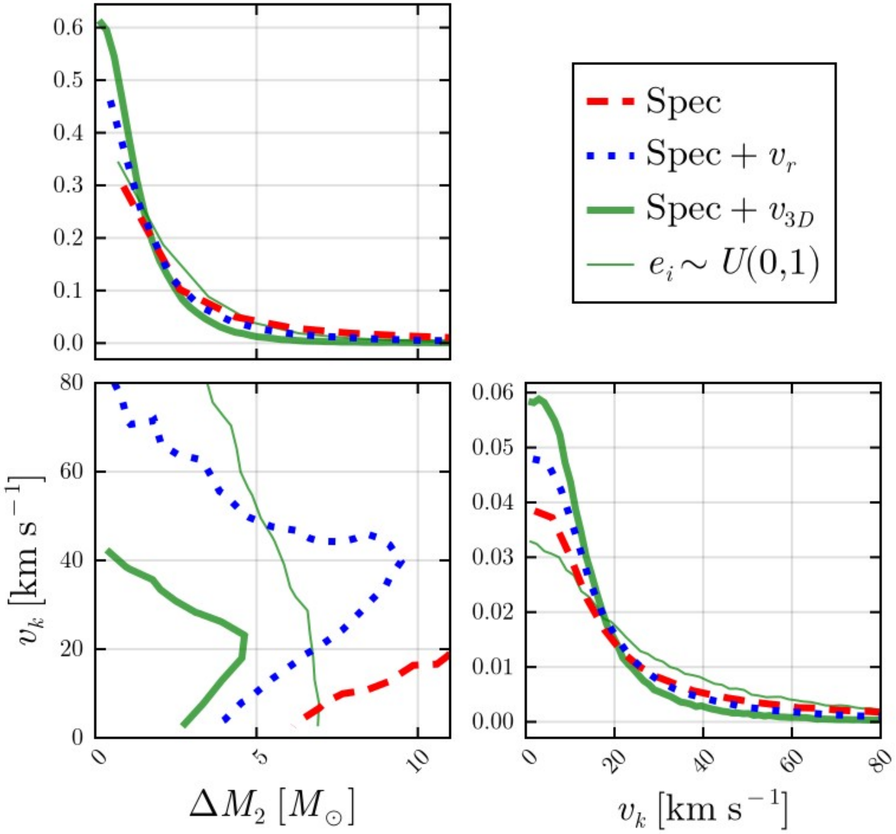
$$P(\vec{\theta}|\vec{d}) = \frac{P(\vec{d}|\vec{\theta})P(\vec{\theta})}{P(\vec{d})}$$

$$P, e, m_1, m_2, v_r, \mu_\alpha, \mu_\delta, \Omega, \omega, \iota, v_{\rm kick}, \Delta M, \theta, \phi, \nu$$

Led by PD
Reinhold Willcox



Application to VFTS 243



Shenar et al. (2022, incl. PM)

>8 M⊙ BH in orbit with a ~25 M⊙ star (P=10.4 days)

e = 0.017 ± 0.012

Kick constrained to be below ~40 km/s, and mass loss below 5 M⊙ within a 90% credible interval.