Binary Population Synthesis

Robert Izzard
Institute of Astronomy
and
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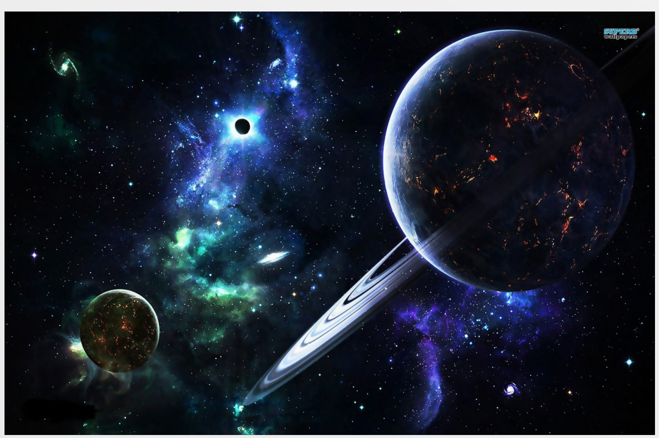
University of Cambridge

How do they function?
How did they get here?
What are they going to do?

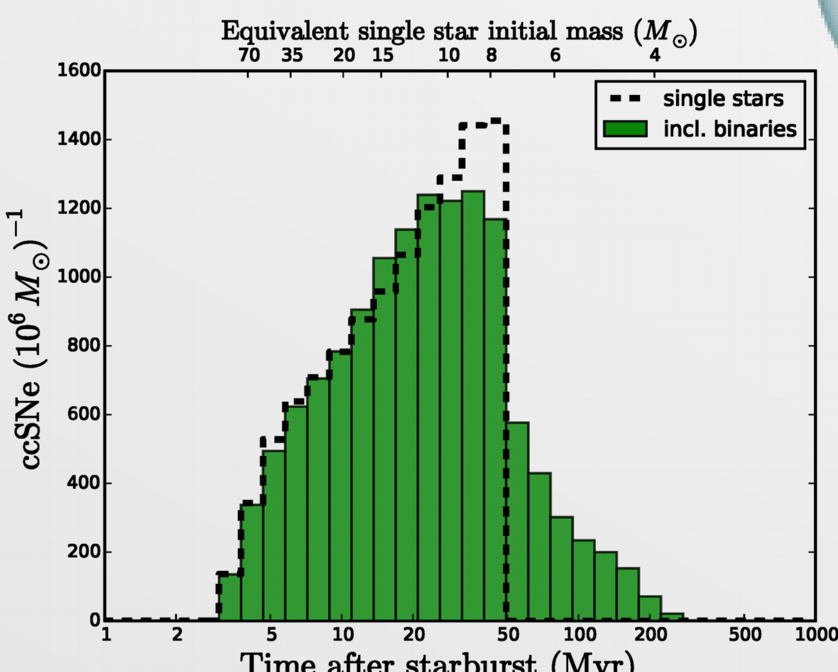
How do they function?
How did they get here?
What are they going to do?

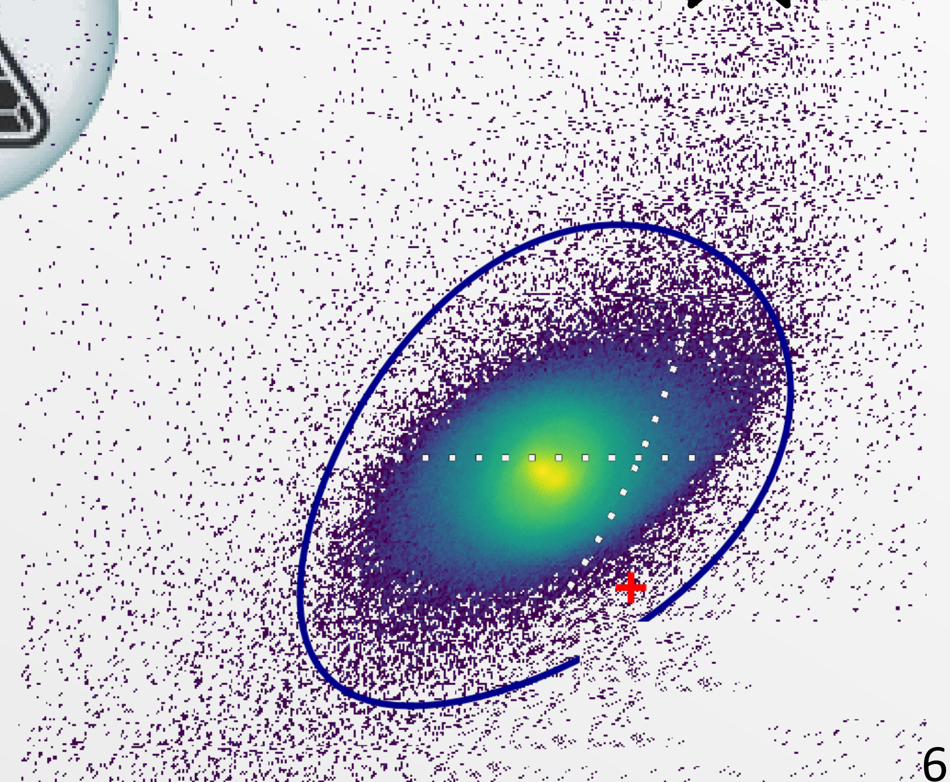
- Robert Izzard

What is Population Synthesis



What is Population Synthesis

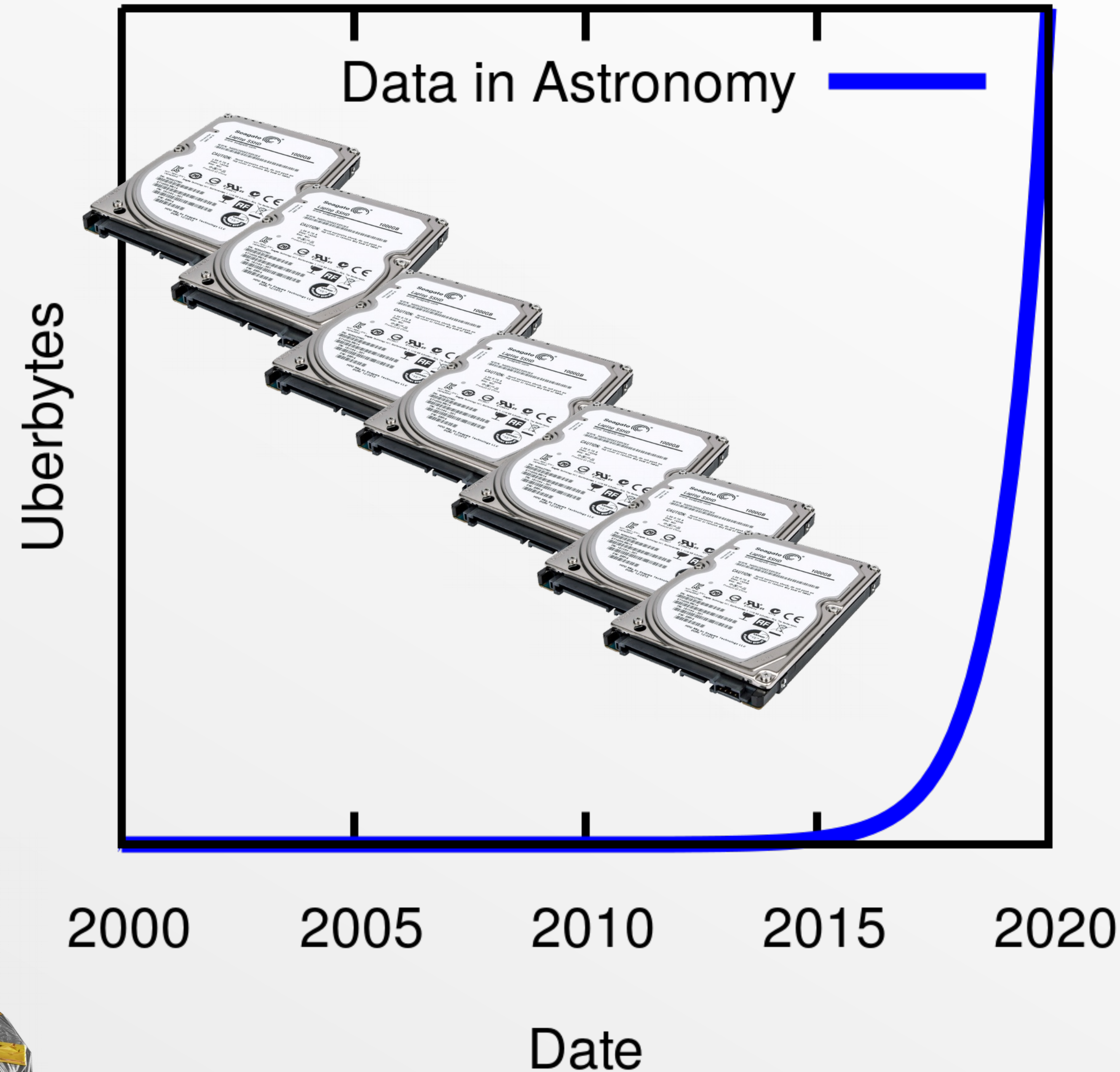


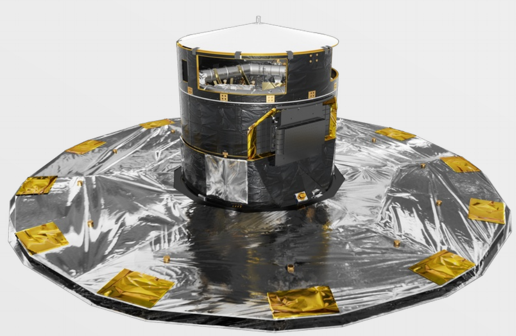


Justification: Data and Big Data

- Now: Gaia/ESO, Kepler,

  SDSS (APOGEE etc)
- Now/soon:
  - Gaia
  - BHBH mergers etc.
- Soon:
  - LSST, TESS, SKA, LISA ...





(Graph is not necessarily to scale)

Stellar Accountancy

Let's count stars!

$$N = \sum_{t=0}^{t_{\mathrm{max}}} S(t) \sum_{i} \psi_i \sum_{\tau=0}^{t_{\mathrm{max}}-\tau} \delta_i(t-\tau)\Delta\tau$$

Stellar Accountancy

$$N = \sum_{t=0}^{t_{\mathrm{max}}} S(t) \sum_{i} \psi_i \sum_{\tau=0}^{t_{\mathrm{max}}-\tau} \delta_i(t-\tau)\Delta\tau$$

N **is the number of stars you are counting**

Stellar Accountancy

$$N = \sum_{t=0}^{t_{\max}} S(t) \sum_{i} \psi_i \sum_{\tau=0}^{t_{\max}-\tau} \delta_i(t-\tau)\Delta\tau$$

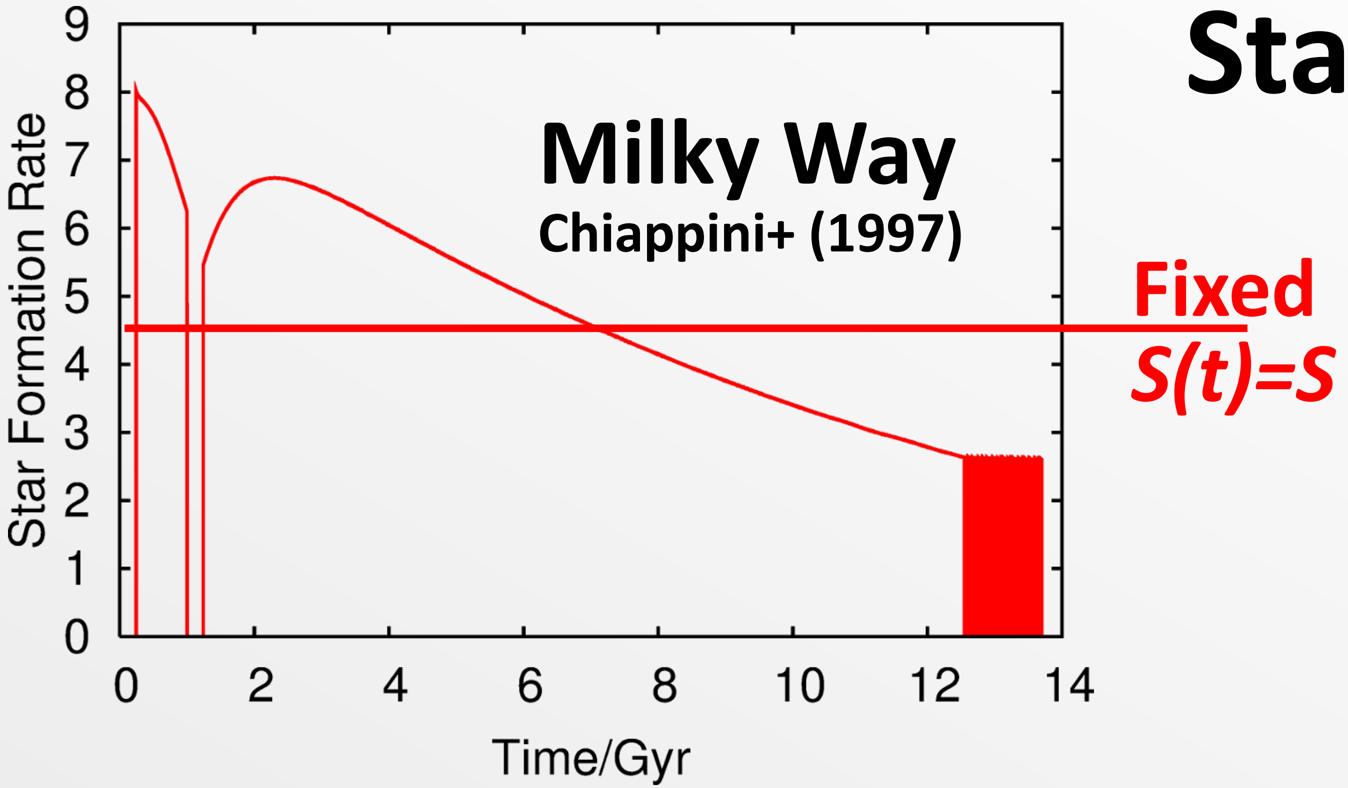
Evolve stars from t=0 to t_{max}

Star formation rate is *S*(*t*)

Often choose *S*=1 then calculate ratios: *S* cancels!

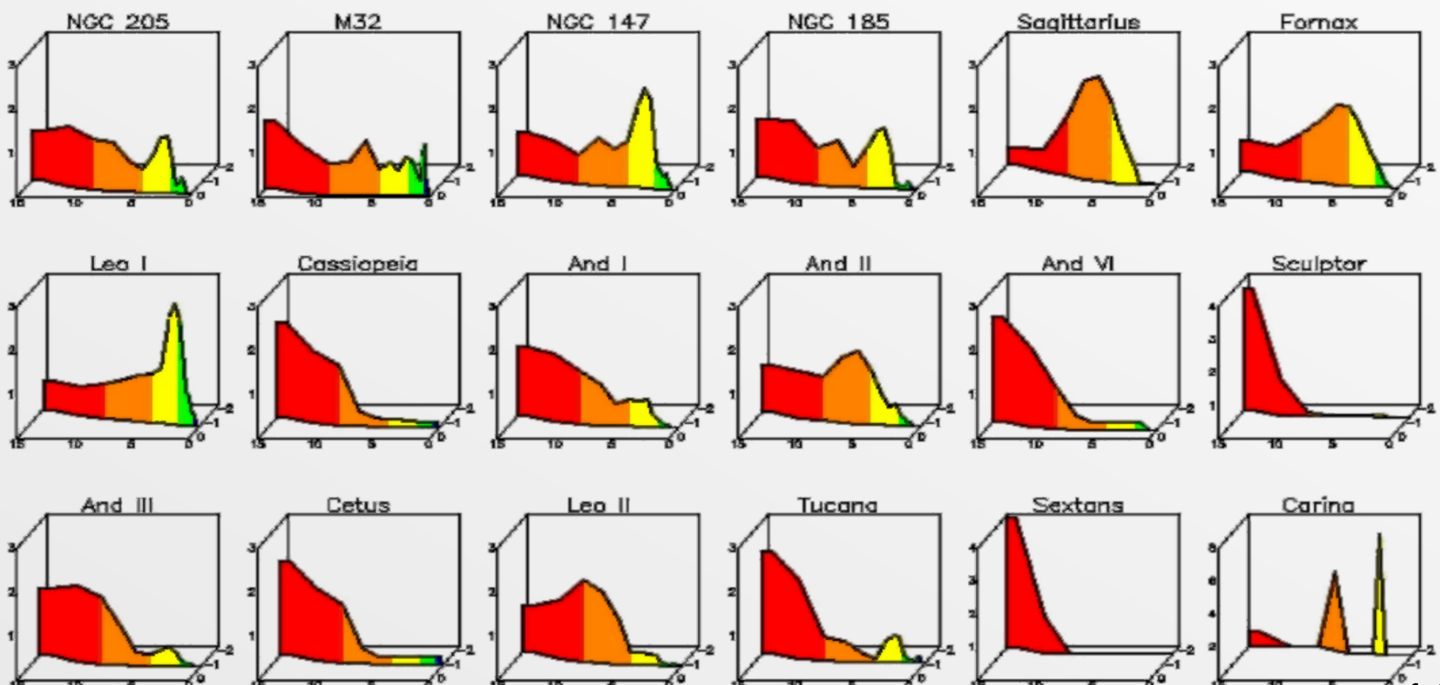
(~ removes one important source of systematic error)

Star formation rate $S(t)$



Other galaxies

(Dolphin+2005)



Stellar Accountancy

$$N = \sum_{t=0}^{t_{\max}} S(t) \color{red}{\sum_{i} \psi_i} \sum_{\tau=0}^{t_{\max}-\tau} \delta_i(t-\tau)\Delta\tau$$

At time *t* evolve a grid of *n* systems with 0<*i*<*n*

Each is weighted by function ψ

Initial mass function, or *q*, *P*, *e* distributions

Could be $\Sigma\ \Sigma\ \Sigma\ \Sigma\ \Sigma\ \Sigma$ ...

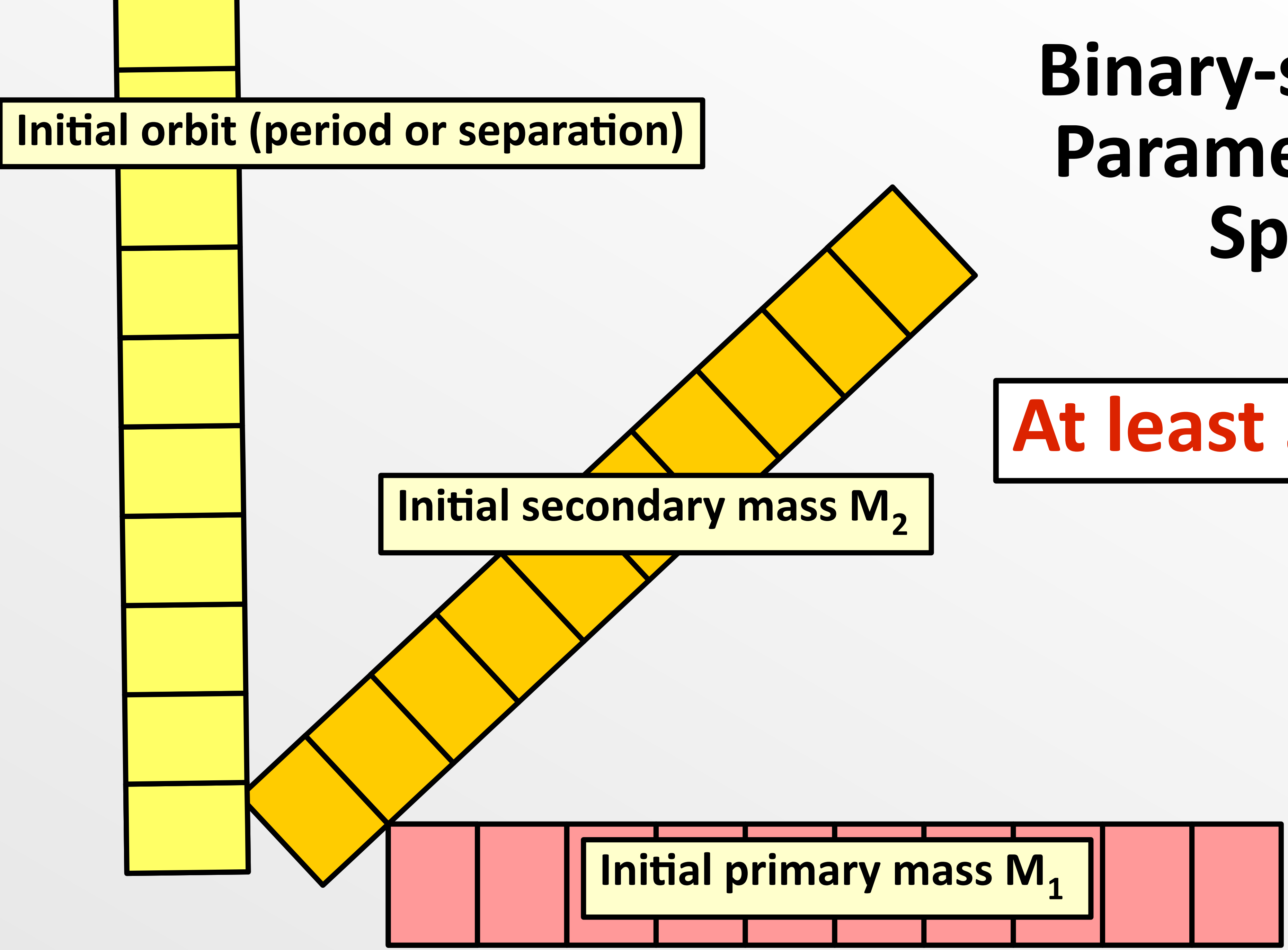
Single stars : vary *M*

5	15	25	35	45	55	65	75	85	95

Initial mass / $M_\odot$

Uncertainties: talks of Salaris, Langer, many others

Binary-star Parameter Space



At least 3D!

+ tides,mass loss,accretion,pollution,comenv,discs,jets, novae,supernovae,kicks,grav.radiation,mergers, etc.

Stellar Accountancy

$$N = \sum_{t=0}^{t_{\mathrm{max}}} S(t) \sum_{i} \psi_i \sum_{\tau=0}^{t_{\mathrm{max}}-\tau} \delta_i(t-\tau)\Delta\tau$$

Star evolves for as long as it must: t_{max} - τ
Stellar codes work in timesteps Δτ
we sum over those required

Stellar Accountancy

$$N = \sum_{t=0}^{t_{\max}} S(t) \sum_{i} \psi_i \sum_{\tau=0}^{t_{\max}-\tau} \delta_i(t-\tau)\Delta\tau$$

δ is a function which is

1 if in the evolutionary phase of interest

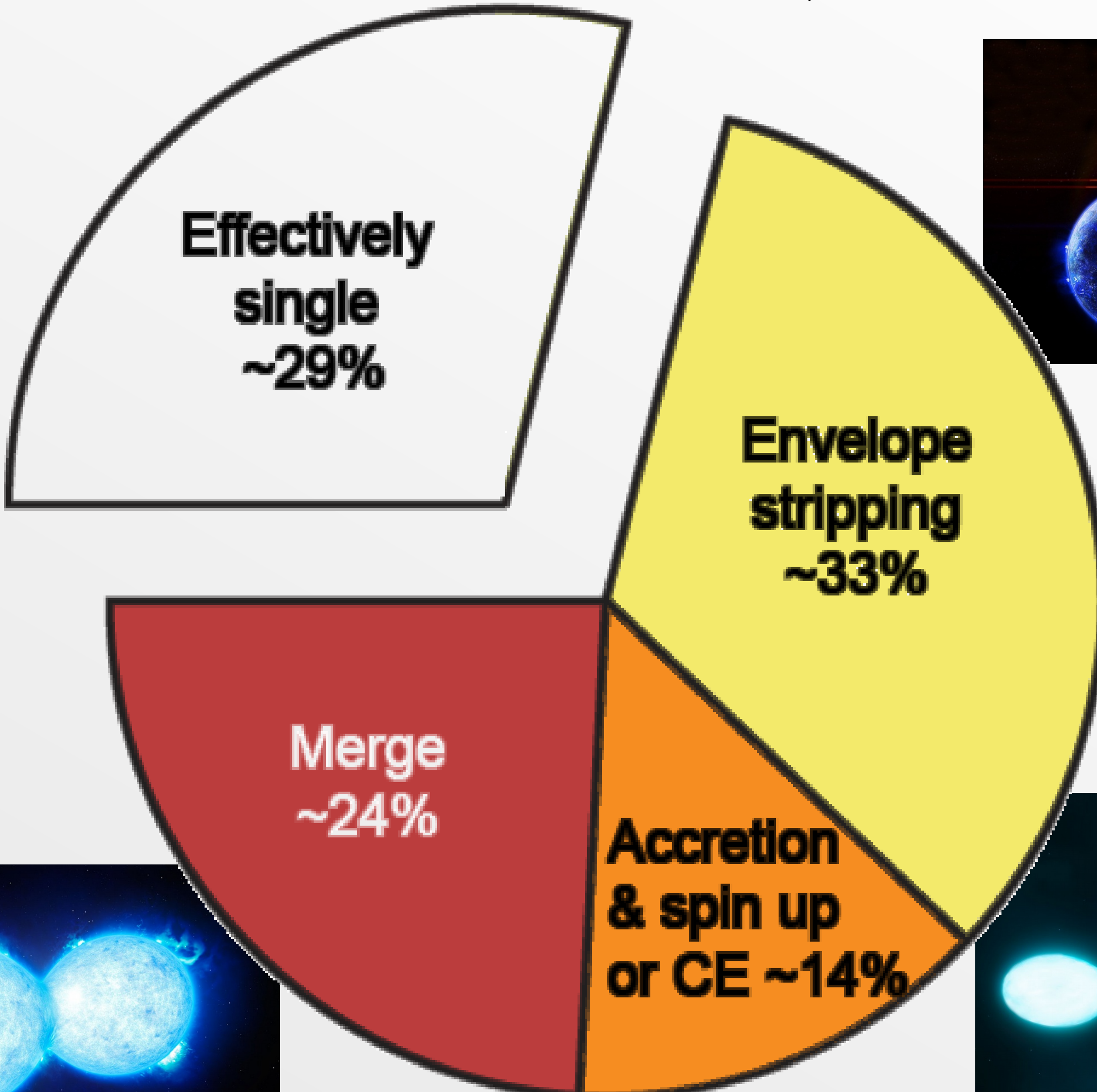
0 otherwise

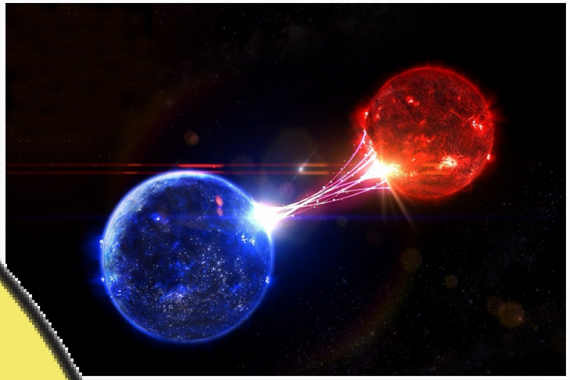
Must be evaluated at each timestep Δτ

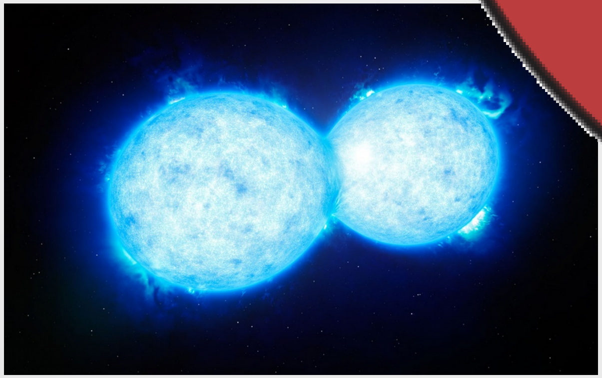
***binary_c* has >200 such functions**

→ REQURIES SINGLE / BINARY STELLAR EV. CODE ←

$N \rightarrow$ Number/event counts

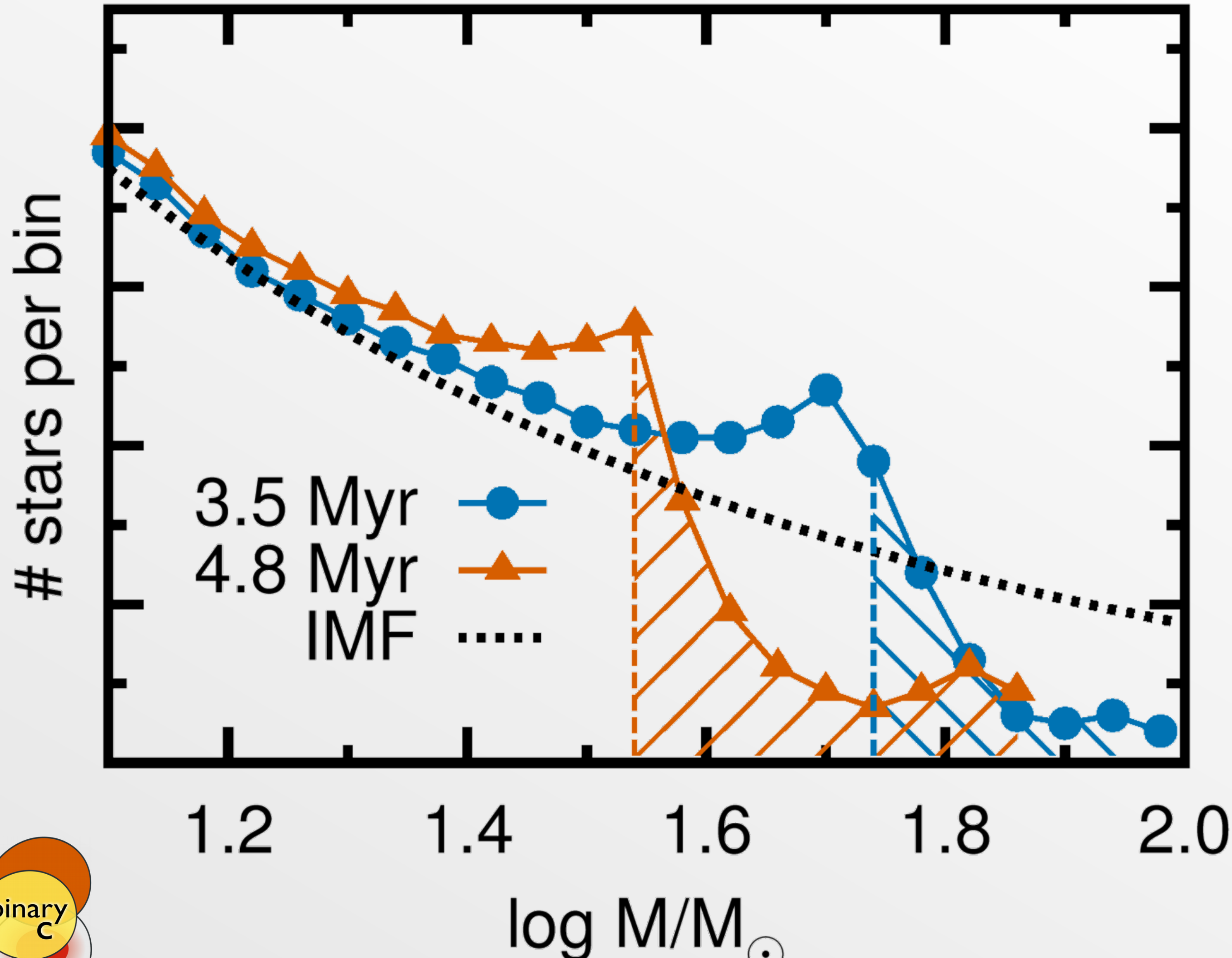






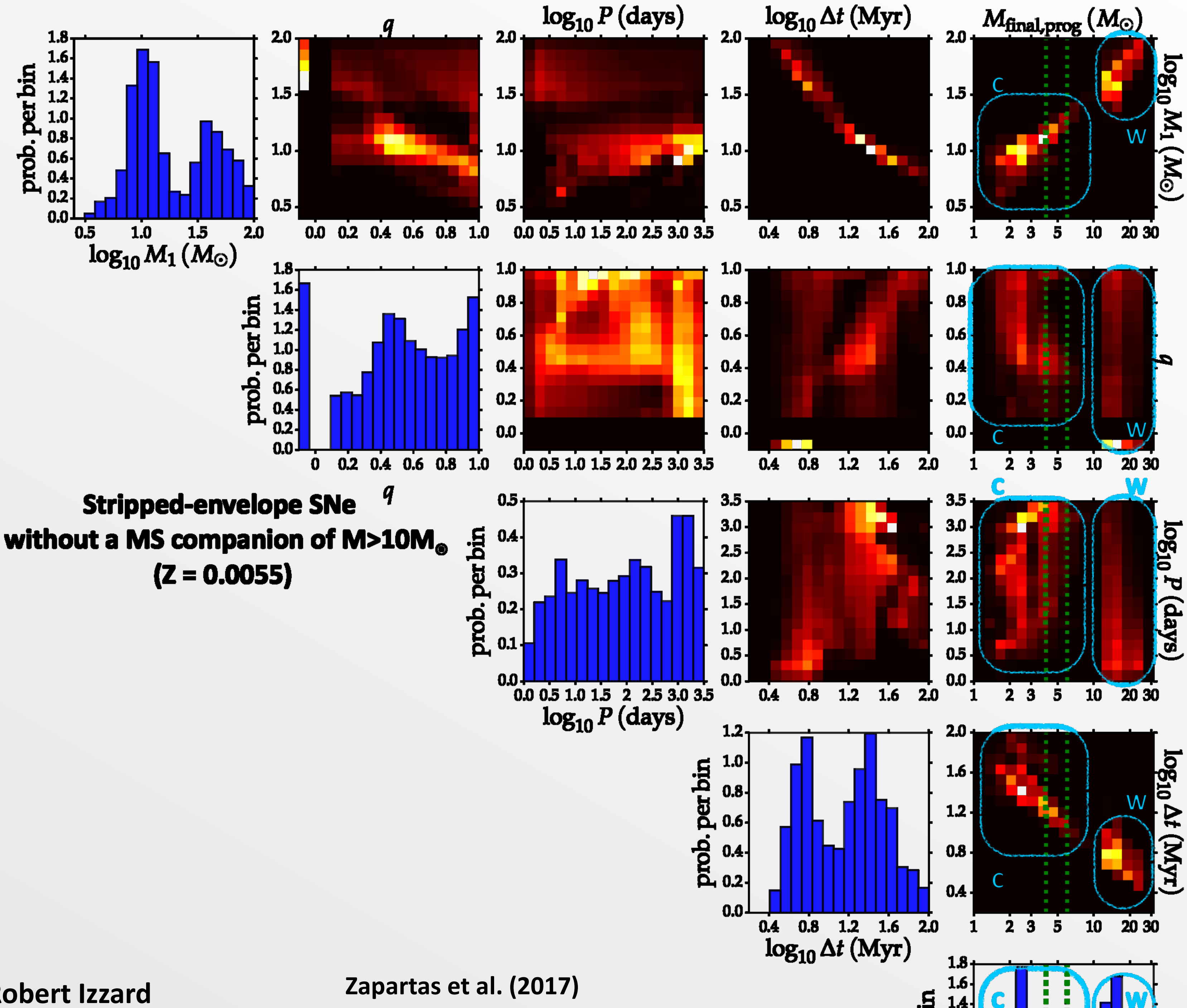
Sana et al. 2012 (Science 337,444)

$N \rightarrow$ Distributions of objects



Schneider, Izzard, Langer et al. (ApJ, 2014)

$N \rightarrow$ 2+D distributions: parameter study



Stripped-envelope SNe
without a MS companion of M>10M$_\odot$
(Z = 0.0055)

Zapartas et al. (2017)

Computation time

- **Single** stars: $\psi(\boldsymbol{M})$

  N x 1 hour = N hours = **10 hours** with N=10

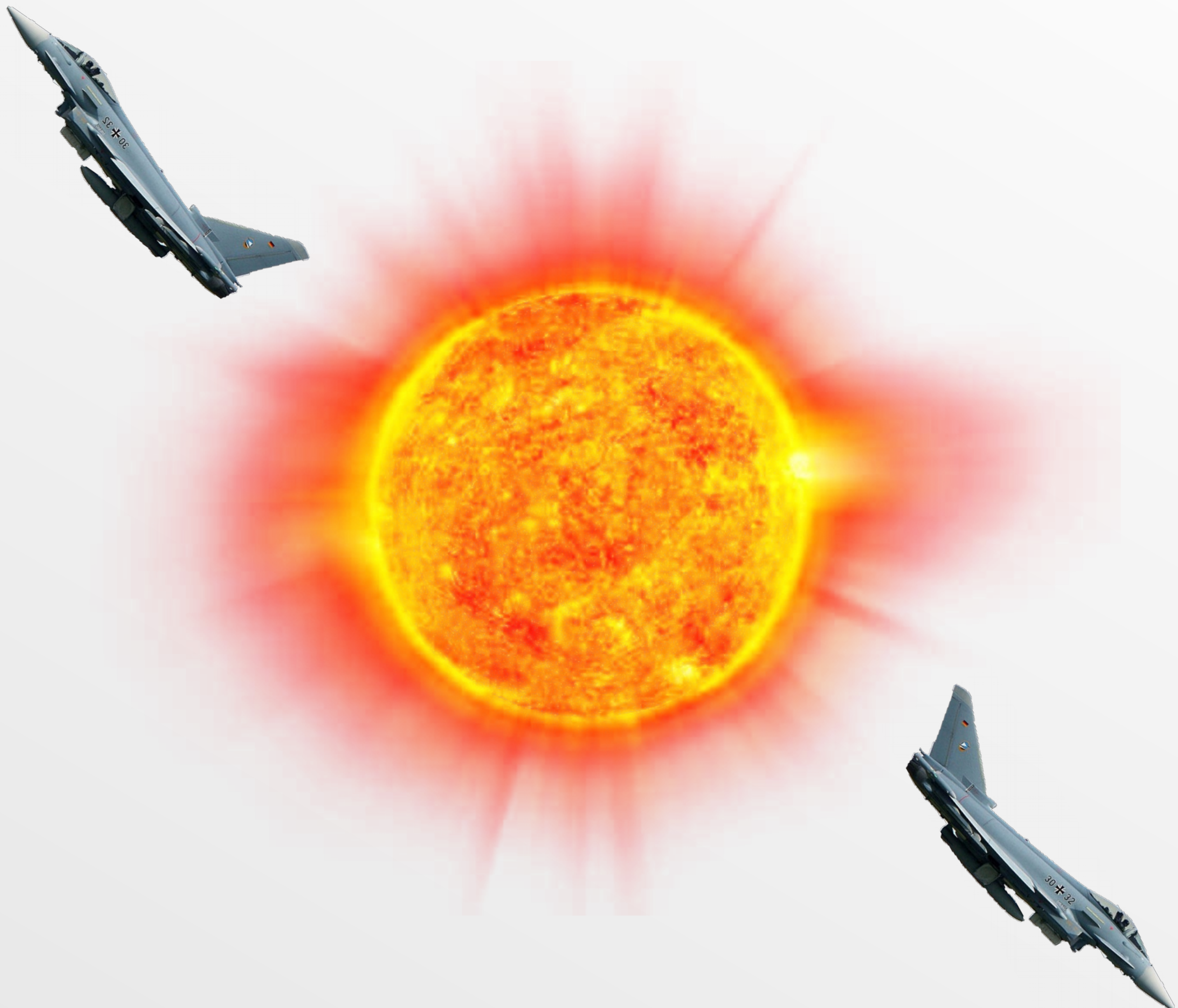
- **Binary** stars: $\psi(\boldsymbol{M_1} \text{ x } \boldsymbol{M_2} \text{ x } \boldsymbol{P})$

  N x N x N x 2 hours = $2N^3$ hours = **2000 hours**

An expensive problem!

- Especially for rare channels which need large N (>100)
- Or difficult channels e.g. TPAGB stars, explosions
- Need to be smart about this!

What about (binary) stellar evolution codes?



- Use **traditional (Henyey) code**
  - STARS (+family), BEC, BINSTAR, Brussels, MESA, Geneva(?), Benvenuto's code etc.
  - Beware: likely to require human intervention, **will crash**
  - Cannot model some phases, e.g.,

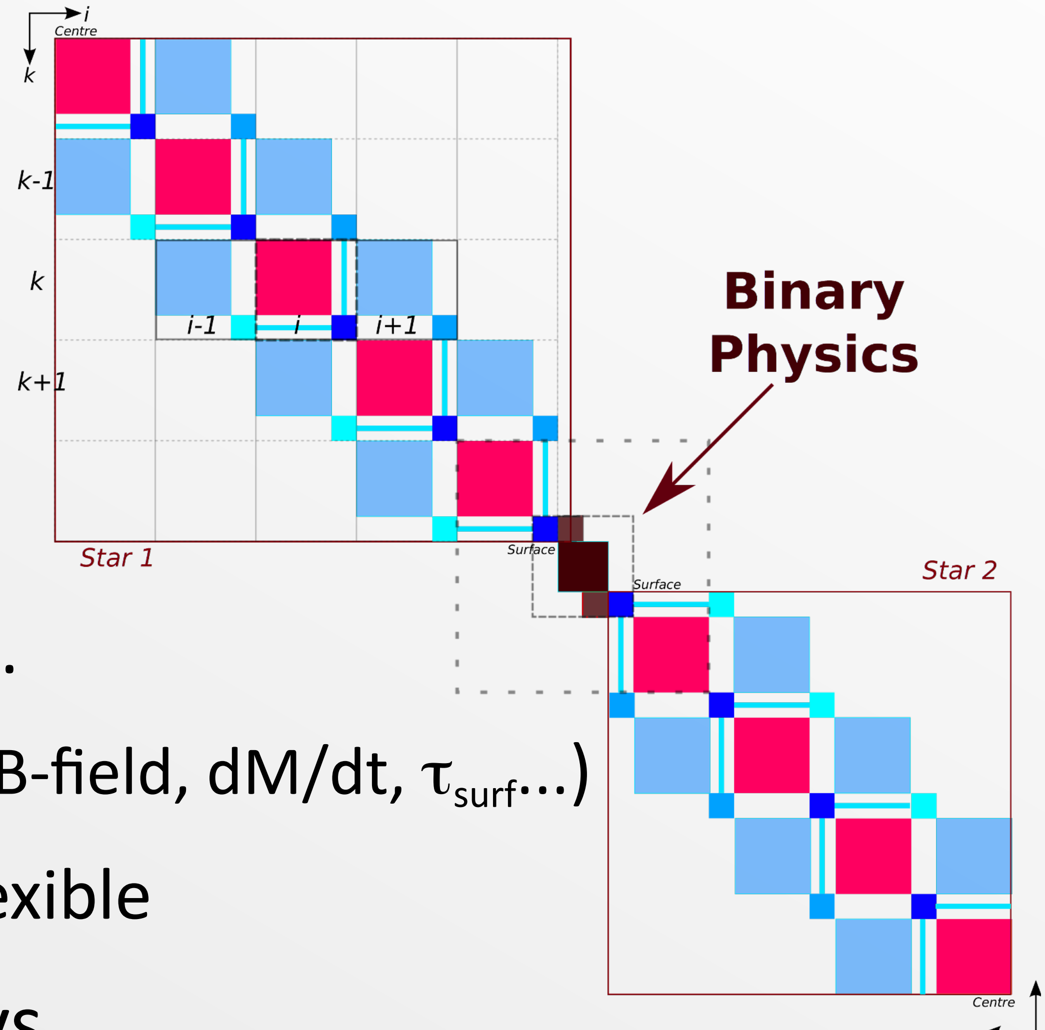
    Common envelope

    (super)novae

    jets

STARS code
backup server

- ***STARS*** family, **Brussels**, **BEC**, ***BINSTAR***, ***MESA***, ...
- Usually **1D** + **1D** + binary interaction terms



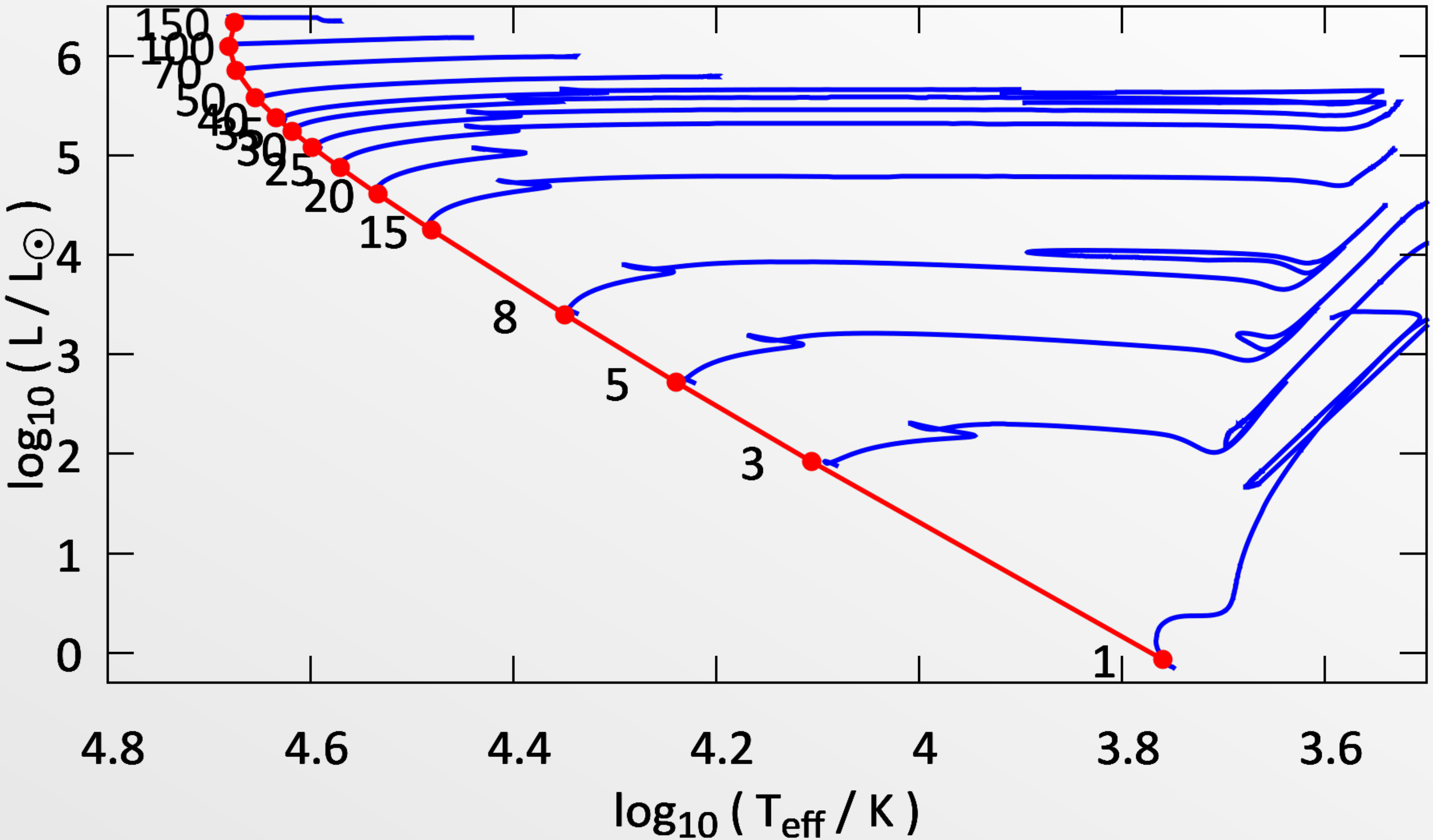
- "Accurate", well-tested
  - Few approximations required.
  - (Except 1D, MLT+, $d\Omega/dm$, [no]B-field, dM/dt, τ_{surf}...)
  - Physics (very) detailed and flexible
- "Slow": typically hours – days

- Use traditional (Henyey) code
  - STARS (+family), BEC, BINSTAR, PNS(bxl), MESA, Geneva...
- Offload ~detached ("well-understood") stellar evolution

"Synthetic" stellar evolution codes

Code summary: De Marco & Izzard (2017) Table 2

Example: Zero-age main sequence



Example: Zero-age main sequence

- **SSE/BSE** library → Eggleton, Fitchett, Tout 1989, Pols+ 1998, Hurley et al. 2000, 2002

$$
\mathrm{L}_0 = \begin{cases} \frac{1.107M^3+240.7M^9}{1+281.9M^4} & M \leqslant 1.093 \\ \frac{13990M^5}{M^4+2151M^2+3908M+9536} & M \geqslant 1.093 \end{cases}
$$

$$
\mathrm{R}_0 = \begin{cases} \frac{0.1148M^{1.25}+0.8604M^{3.25}}{0.04651+M^2} & M \leqslant 1.334 \\ \frac{1.968M^{2.887}-0.7388M^{1.679}}{1.821M^{2.337}-1} & M \geqslant 1.334 \end{cases}
$$

"Simple" formulae : **fast** to calculate.

Can also use table lookup (faster?).

$>10^6$ times faster than a detailed code.

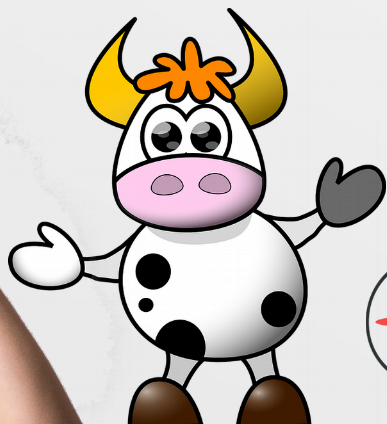
Stable (at least compared to a real stellar code) but **inflexible**.

- Traditional (Henyey) code
  - STARS (+family), BEC, BINSTAR, PNS(bxl), MESA, Geneva, etc.
- Offload ~ detached ("well-understood") stellar evolution

"Synthetic" stellar evolution codes

  - SSE/BSE based: binary_c (Izzard), startrack (Belczynski), biseps (Kolb), Seba (Nelemans,Toonen) (SSE++), COMPAS, etc.
  - Others: Ibis (Tutukov), Scenario machine (Lipunov)

Code summary: De Marco & Izzard (2017, arXiv 1611.03542) Table 2



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"Synthetic" stellar evolution codes

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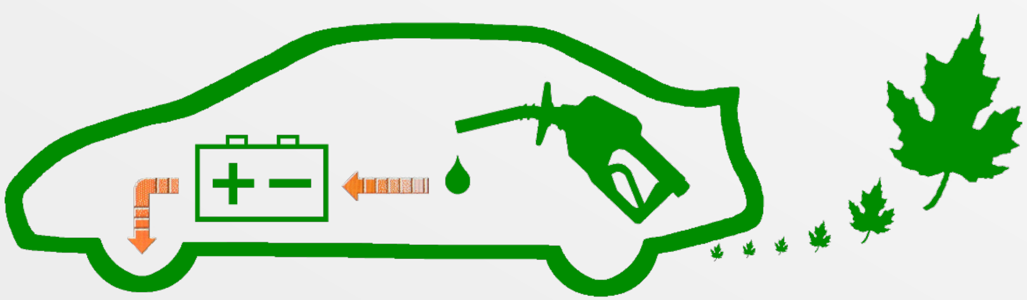
  - Others: Ibis (Tutukov), Scenario machine (Lipunov)
- **Hybrid codes**
  - BSE + NBODY6 (Aarseth, Hurley) also MOCCA (Giersz)
  - BSE + STARS (Church)
  - BSE + MESA (Chen+ 2014)



Code summary: De Marco & Izzard (2017) Table 2

Pros … and cons

+ Parameter space tractable: error bars
+ Stable, fast, easily fixed
+ Resolution: 1,000,000 stars easily.

– Systematics: Only as good as your input model set (fixed!) your binary algorithm and input distributions:

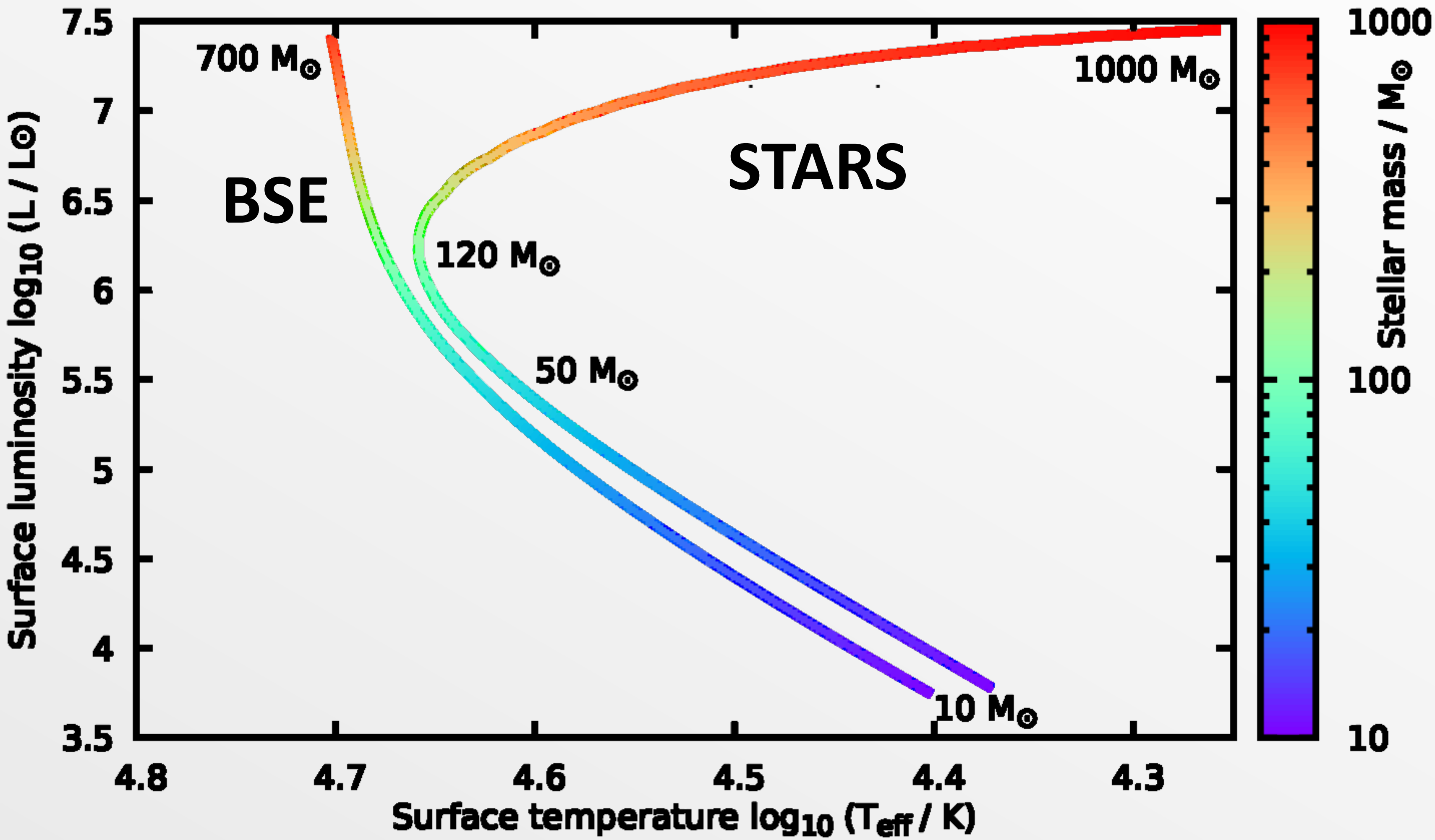
– Requires "non-canonical" treatment

Off grid models e.g. helium stars, mergers, non-thermal-eq.

– Hard to deal with thermal-timescale mass transfer

– Lose (most) internal structure information

Only as good as your input models



Usually: No rotation(al mixing), extra mixing, magnetic fields, etc.

Z=0.02 ZAMS

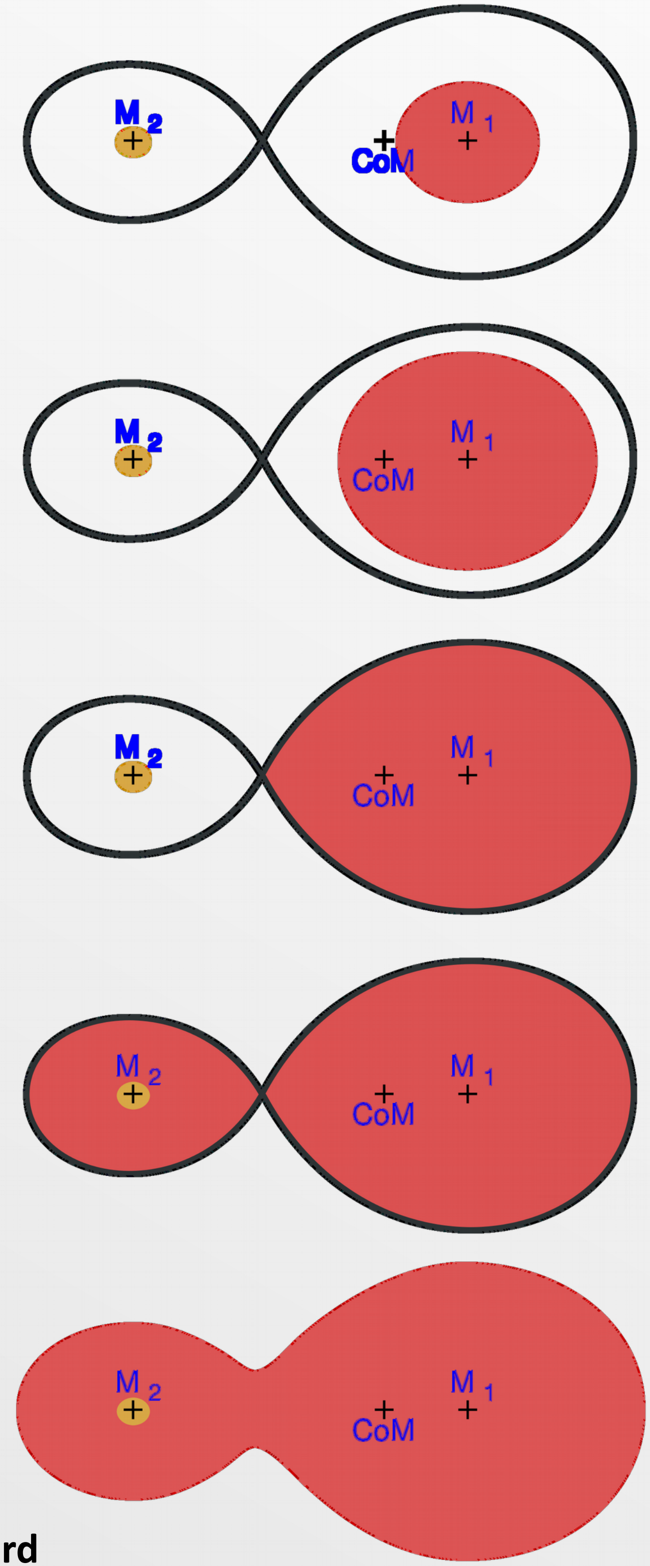
Binary Interaction

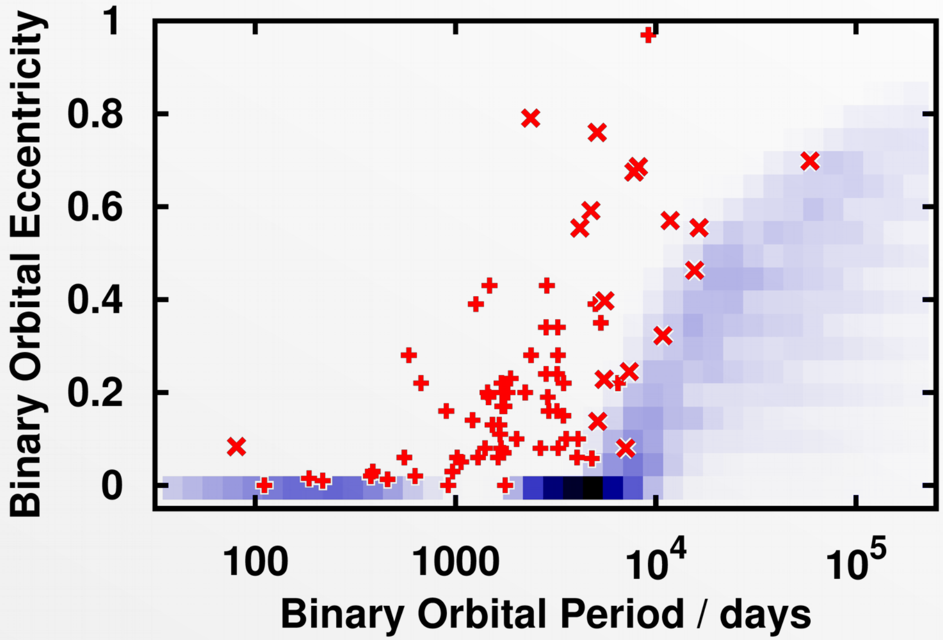
especially

Common Envelope Evolution

Is often

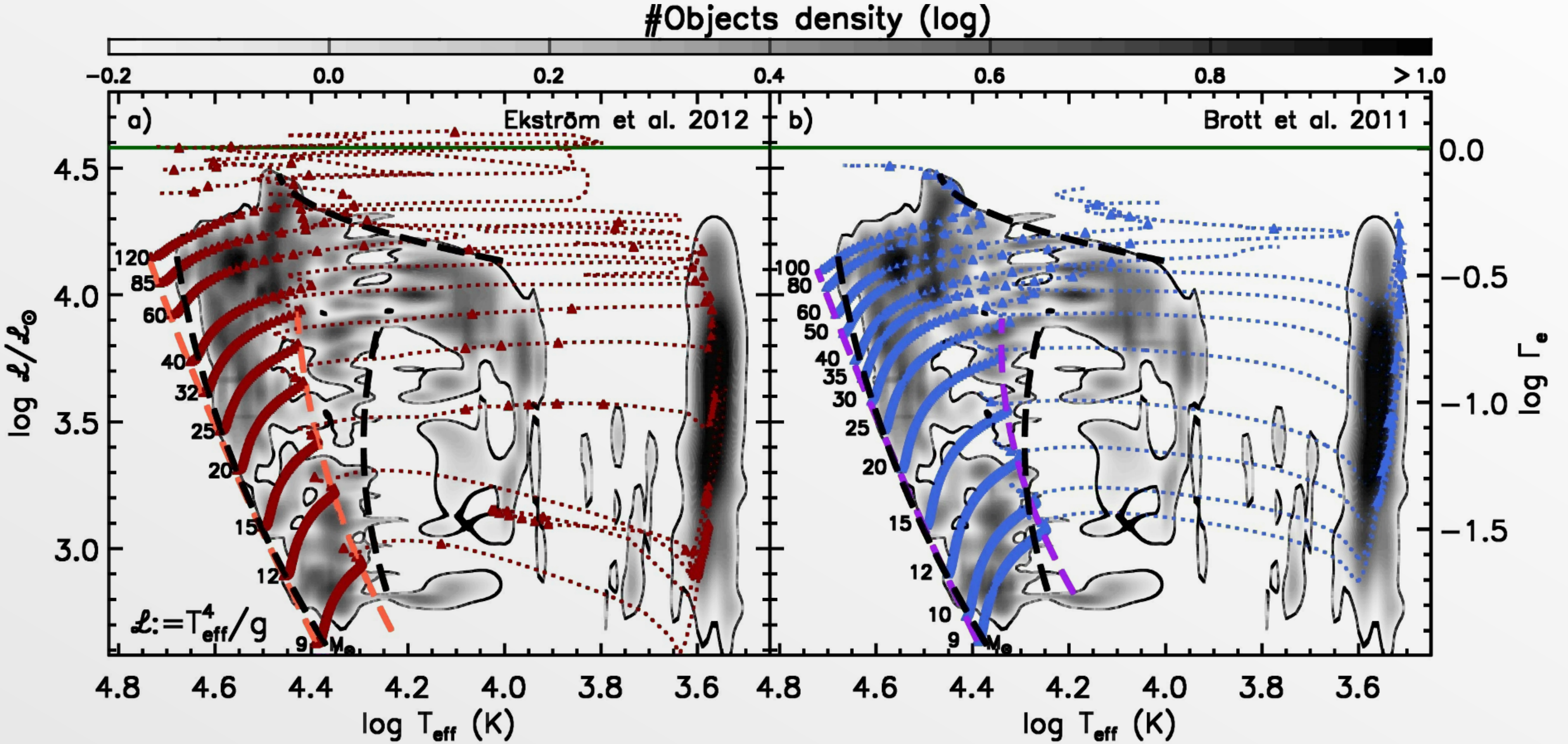
not well modelled in → ALL ← codes





Models vs observations

- … which is the best ?

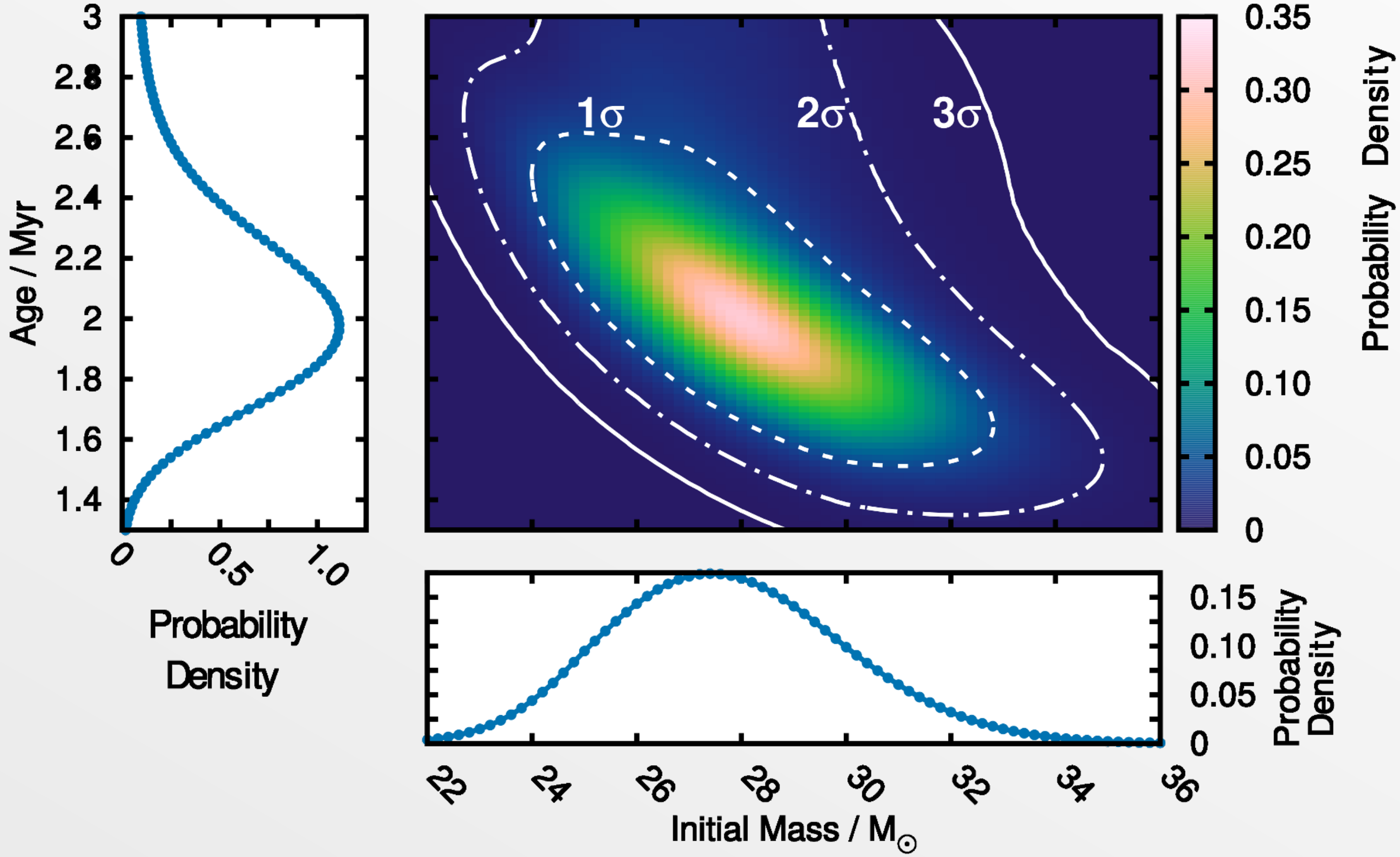


Castro-Rodriguez et al. (2014)

Bayesian methods

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

Given L, T_{eff} and g, what is M?



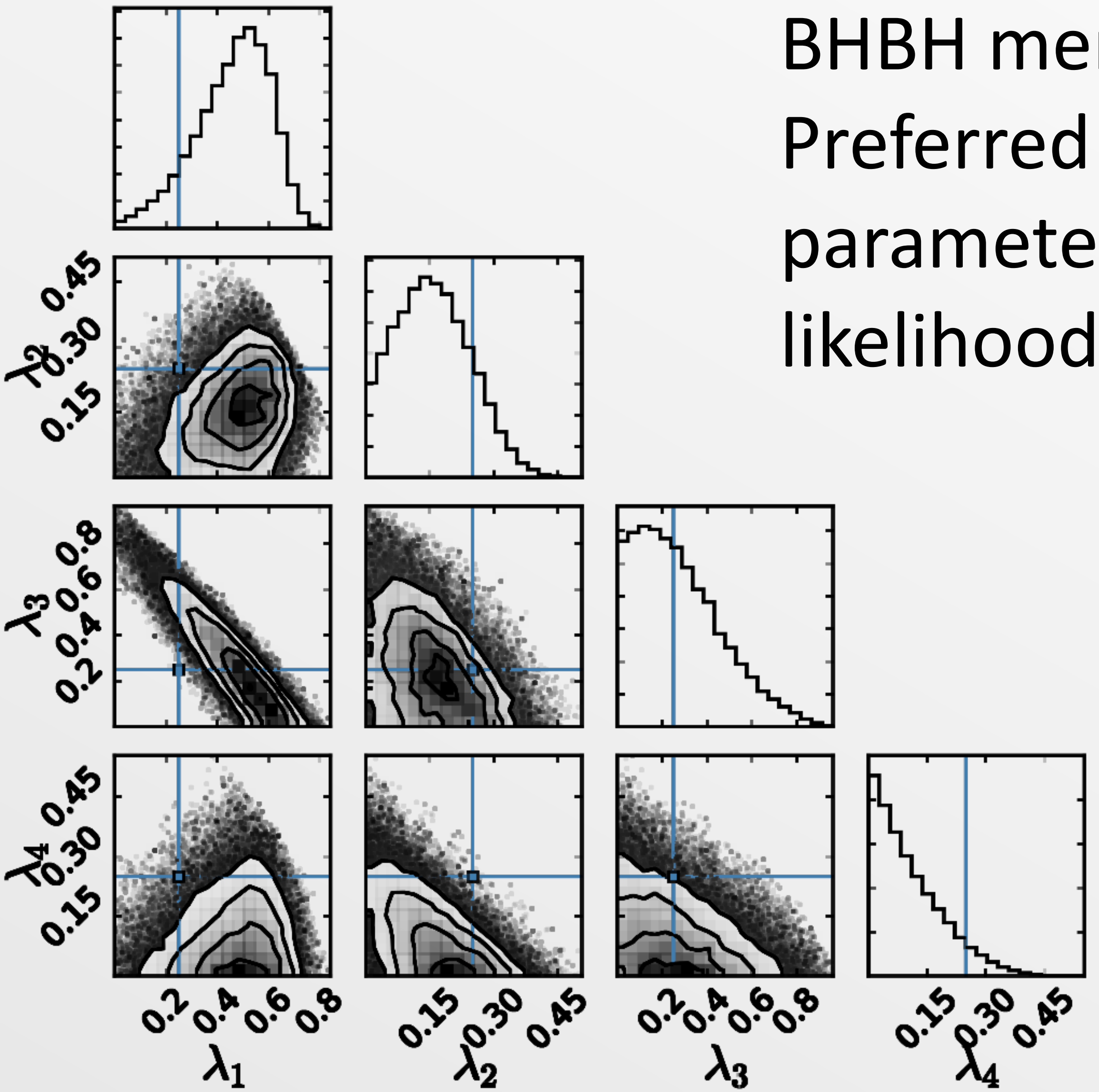
Torres et al. (2010) V3903 Sgr A: $M = 27.27 \pm 0.55\,M_\odot$

Best model fit: $M = 26.8^{+2.5}_{-2.0}\,M_\odot$ age $= 2.0^{+0.5}_{-0.4}$

http://www.astro.uni-bonn.de/stars/bonnsai/

Schneider et al. (2014)

Bayes for populations



BHBH mergers →
Preferred population parameters based on Bayseian likelihoods / posteriors.

The way forward!

Stevenson+ (2017)

Systematics: POPCORN tests

binary_c

vs

SeBa

vs

StarTrack

vs

Brussels

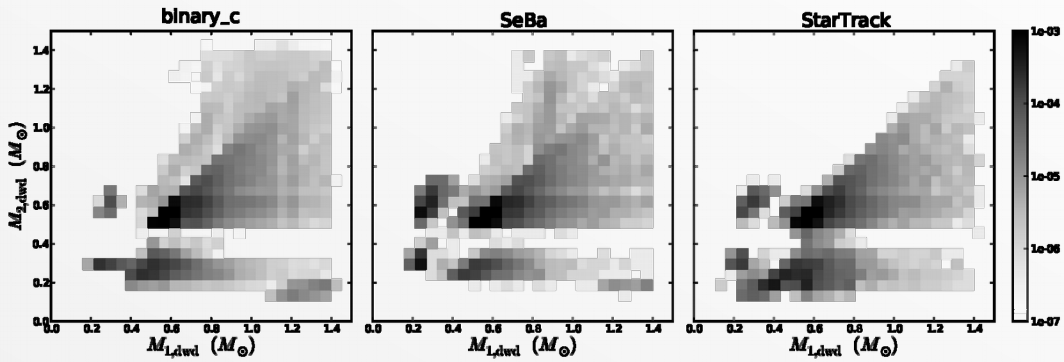


Fig. 10. Secondary WD mass versus primary WD mass for all DWDs in the full mass range at the time of DWD formation.

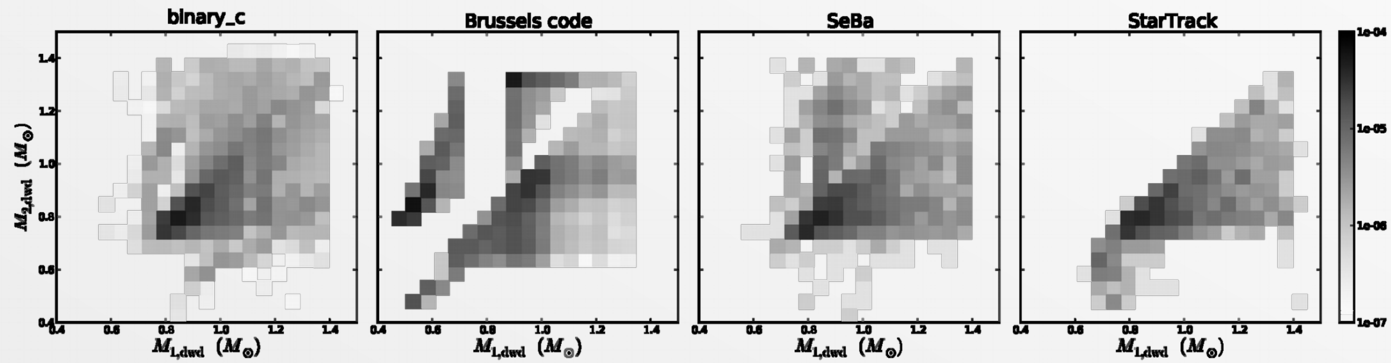
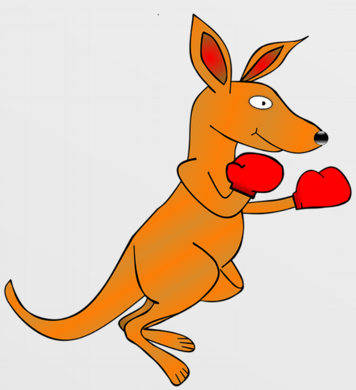


Fig. 11. Secondary WD mass versus primary WD mass for all DWDs in the intermediate mass range at the time of DWD formation.



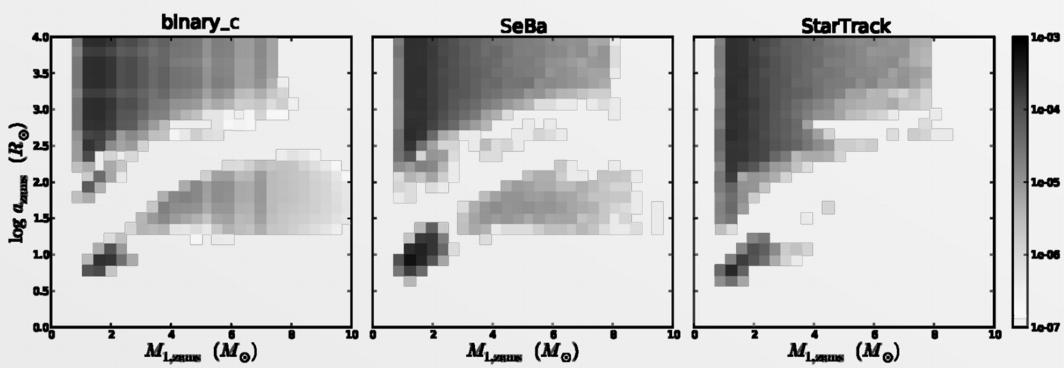
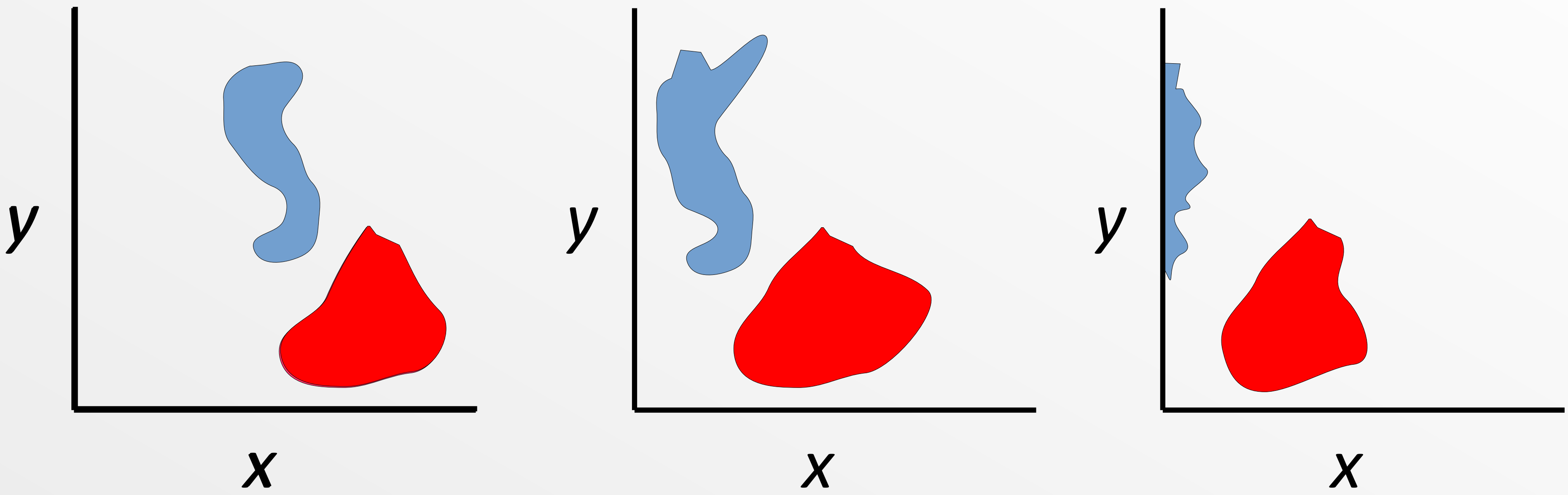


Fig. 12. Initial orbital separation versus initial primary mass for all DWDs in the full mass range.

Toonen+ (2014)

Parameter space blobs

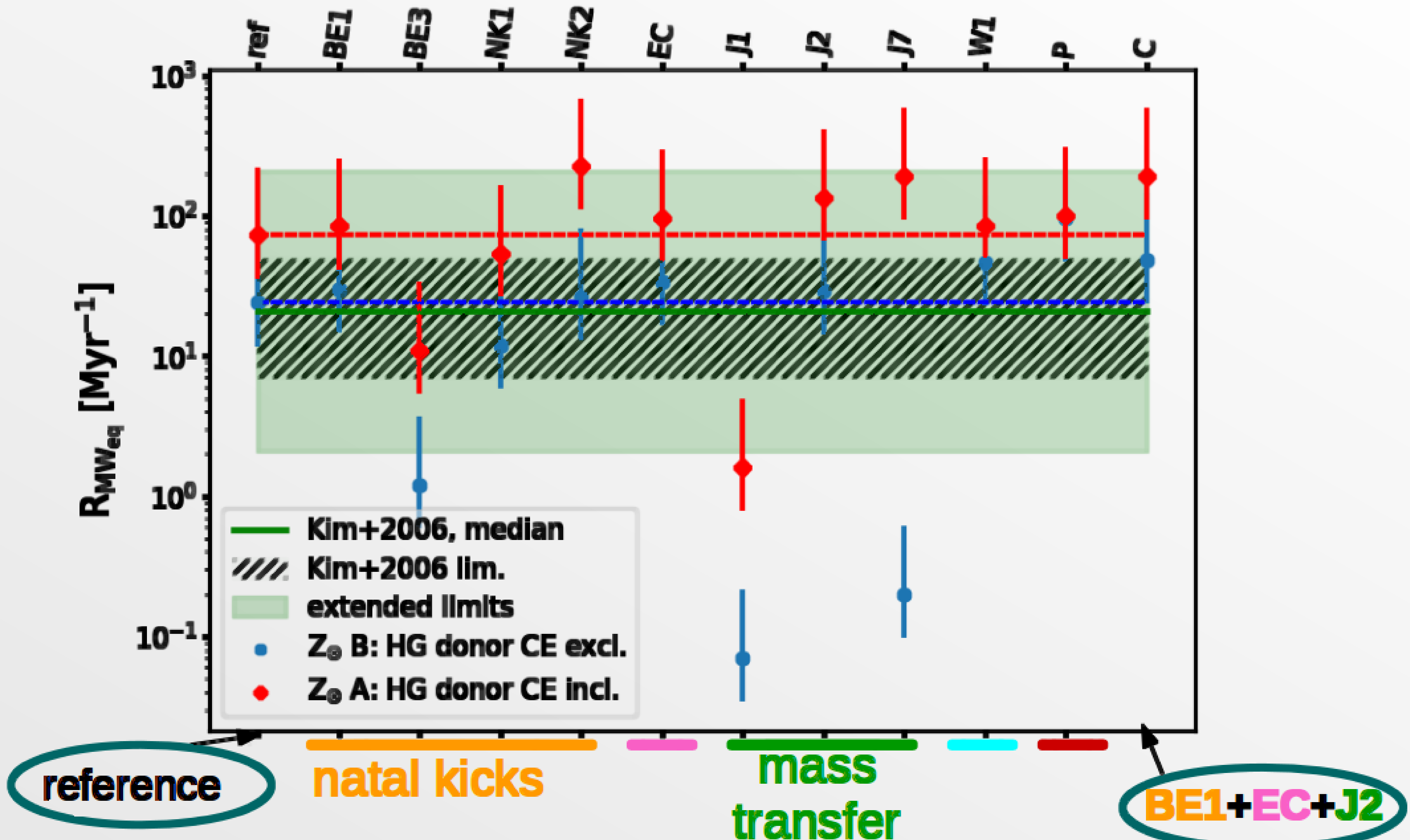


Z=0.001 Z=0.005 Z=0.01

Many blobs are **red**: they change little with the parameter

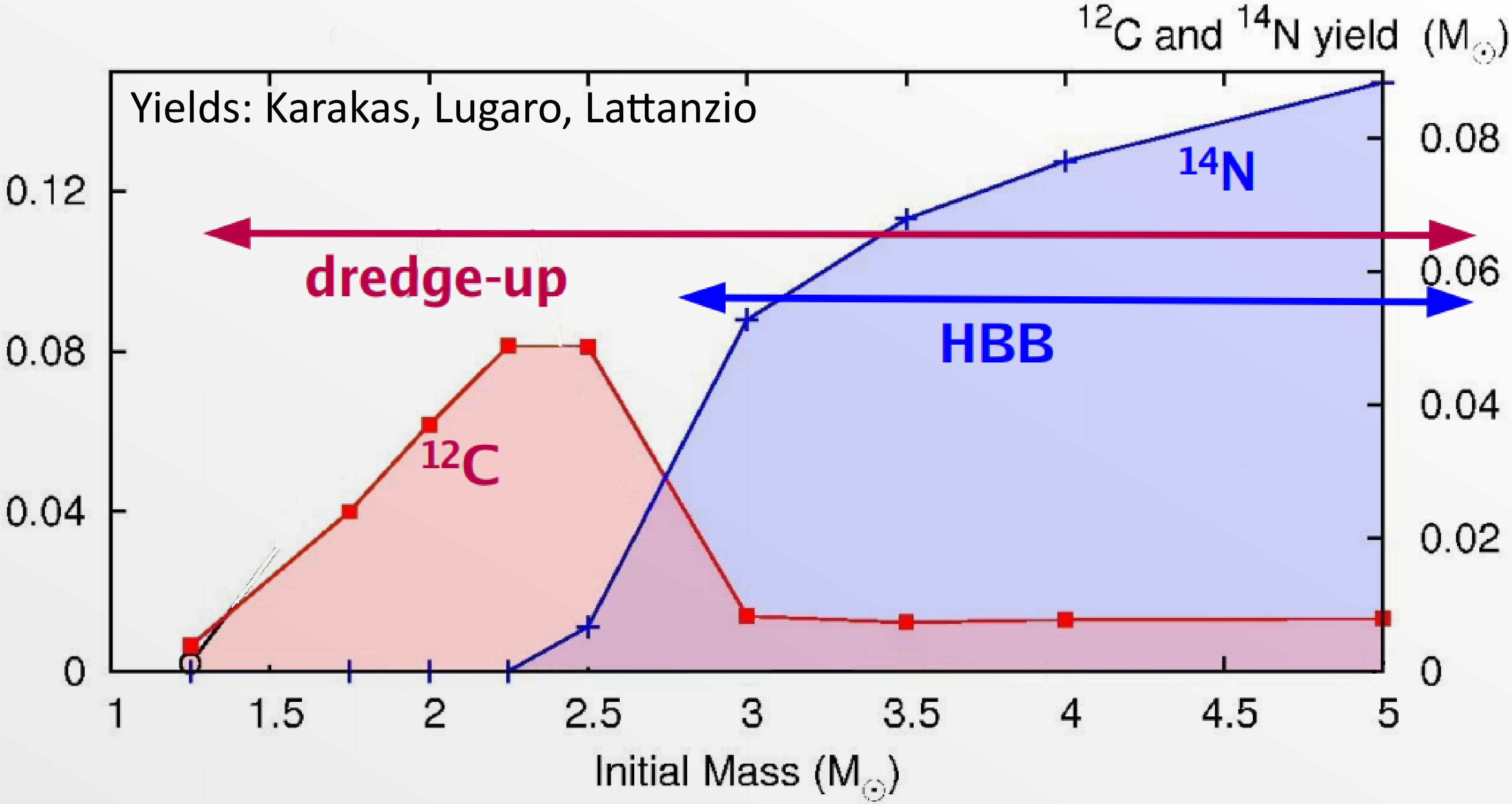
Blue could be: **CH stars** – lots at Z=0.001; none at Z=0.02

Example: parameter space of NS-NS merger rates



Martyna Chruślińska's poster

Example: CEMP stars, observed CEMP/EMP=10-20%



Models: Lucatello+ 2005 20% if **top-heavy IMF**

Izzard+ 2009 2.3% → **fails**

Pols+ 2012 but this makes NEMP stars! (very rare)

Izzard+2009,Abate+201x: low *M* DUP+WRLOF → **15% ?**

Binary Popsyn in **The News!**

05/07/2017 Rare stars in the Milky Way actually come from other galaxies, say Cambridge students - Cambridge News

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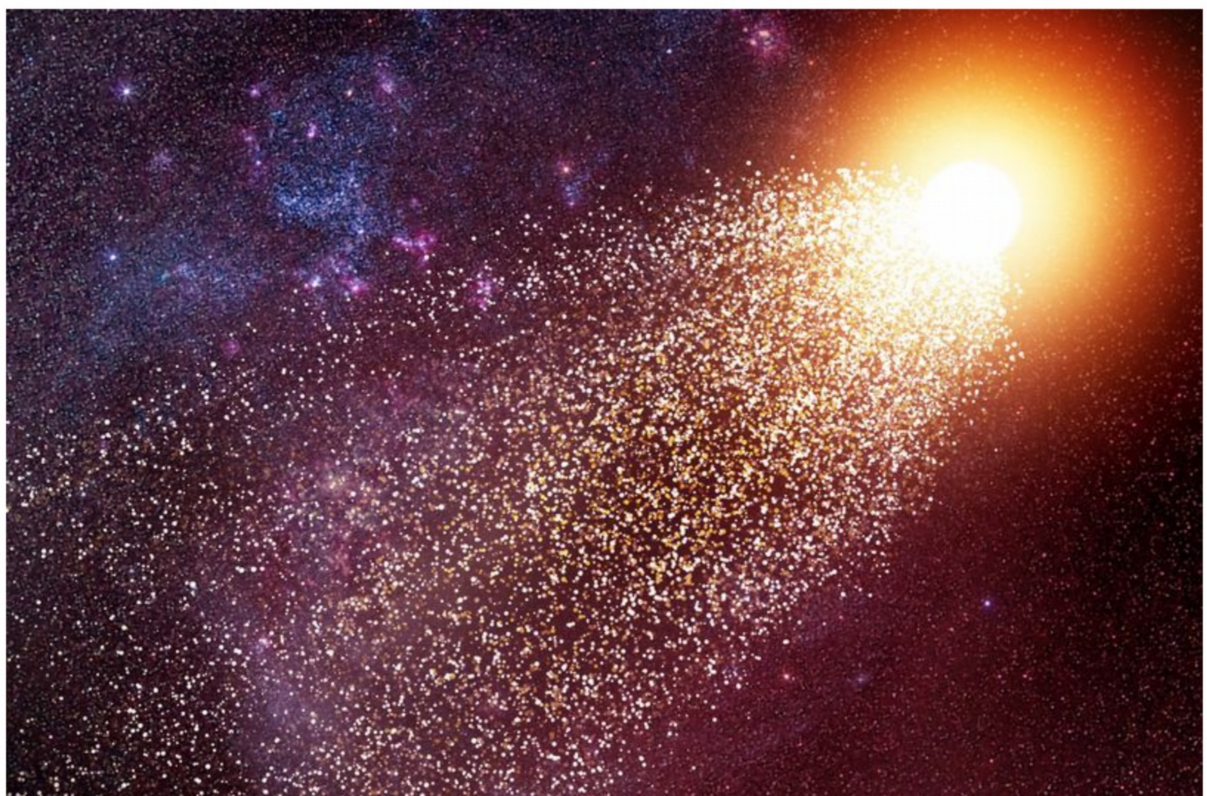
CAMBRIDGE news

Rare stars in the Milky Way actually come from other galaxies, say Cambridge students

The group of scientists believe these rare 'blue' stars come from a dwarf galaxy called the Large Magellanic Cloud, which is thought to orbit the Milky Way

3 COMMENTS

BY BERNY TORRE
05:00, 5 JUL 2017



SCIENCE

The Milky Way is hosting 'runaway stars' from a galaxy far, far away

Research claims rare, fast-moving stars in the Milky Way have actually travelled in from other galaxies

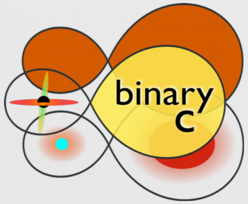
BY JEFF PARSONS
17:11, 5 JUL 2017

Inside the Milky Way are extremely rare, fast-moving stars called hypervelocity stars.

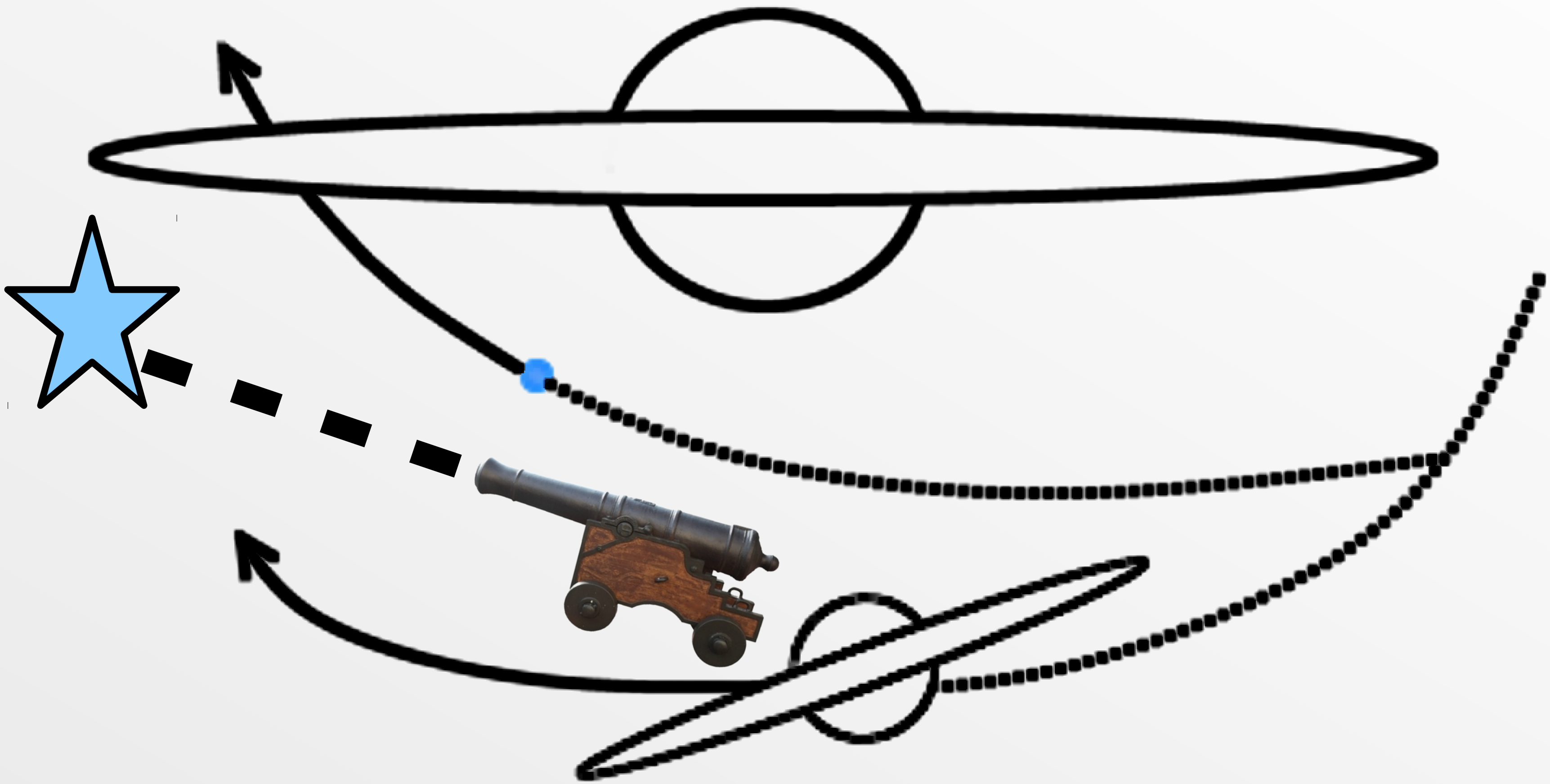
So far, only 20 have been identified and scientists have puzzled over where they came from. It was previously suggested they were expelled from the centre of our galaxy by a supermassive black hole.

But new research seems to suggest that might not be the case.

A team of star hunters from Cambridge University have published new research claiming they have journeyed across the cosmos from another galaxy to join our own.



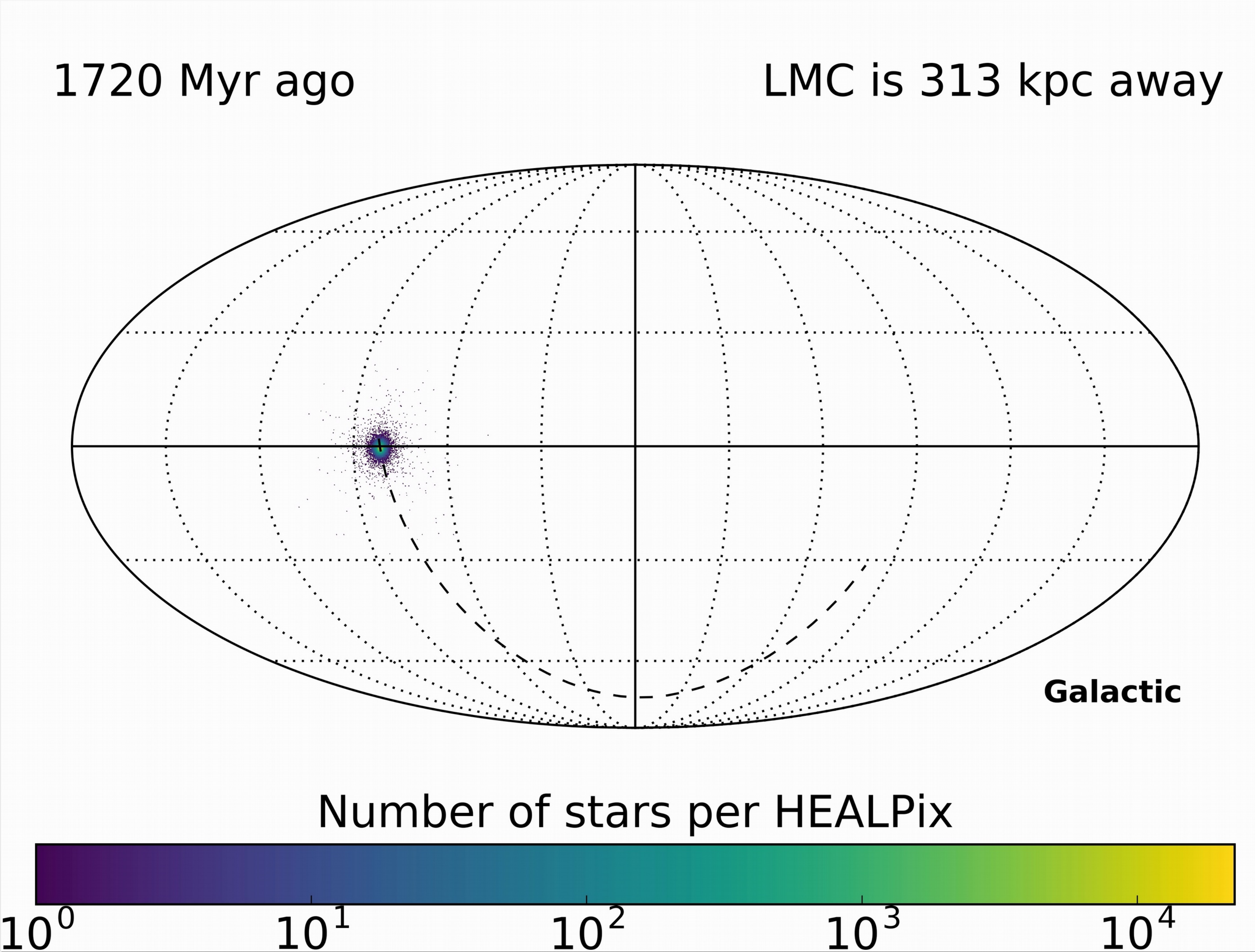
Runaways from the LMC ?



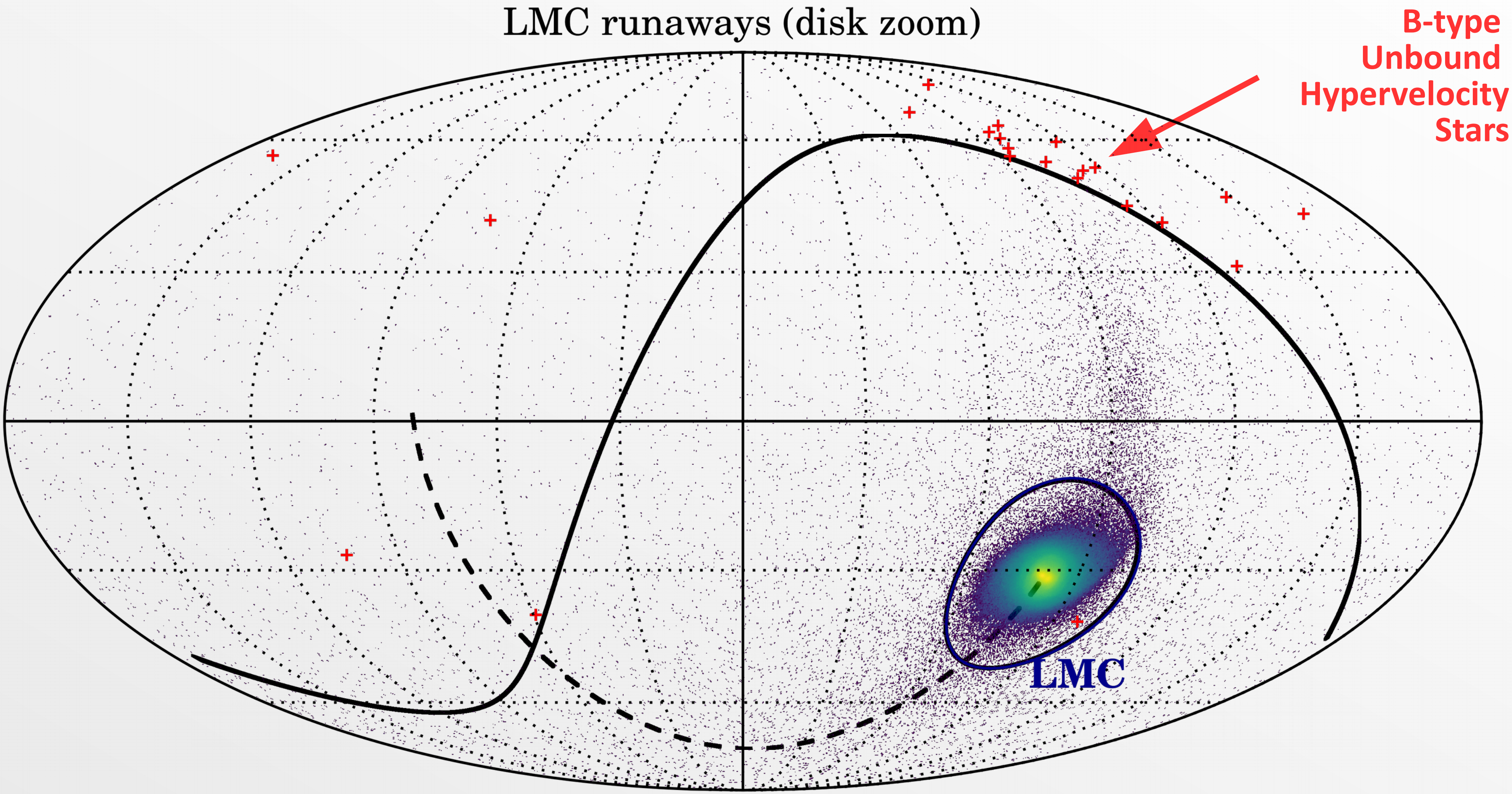
binary_c + *GADGET3* → MW + LMC model

v_{LMC} = **378km/s**

Boubert et al. (2017) MNRAS/arXiv 1704.01373



Boubert et al. (2017) arXiv 1704.01373



"These stars have just jumped from an express train - no wonder they're fast," said co-author *Rob Izzard*, a Rutherford fellow at the Institute of Astronomy. "This also explains their position in the sky, because the fastest runaways are ejected along the orbit of the LMC towards the constellations of Leo and Sextans." (various news sources)

Boubert et al. (2017) arXiv 1704.01373

It must be true if it's in the Daily Mail…

Feedback Like 11.6M

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Fastest stars in the Milky Way that travel at speeds of up to 630 miles per second may be 'runaways' from other galaxies

- **Only two dozen 'hypervelocity stars' have been observed in the Milky Way**
- **Until now, scientists believed that the speedy stars originated in our galaxy**
- **But researchers suggest that the stars may be runaways from a dwarf galaxy**
- **The predictions could pave the way for scientists to measure the mass of neighbouring galaxies within the next 20 years**

By SHIVALI BEST FOR MAILONLINE
PUBLISHED: 19:00 EDT, 4 July 2017 | **UPDATED:** 12:36 EDT, 5 July 2017

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Scientists have discovered that the fastest stars in the Milky Way may come from

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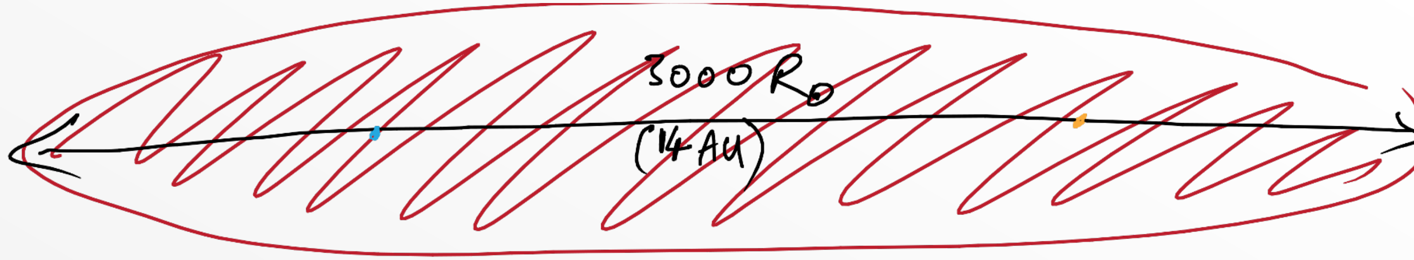
A *Nice* Preview

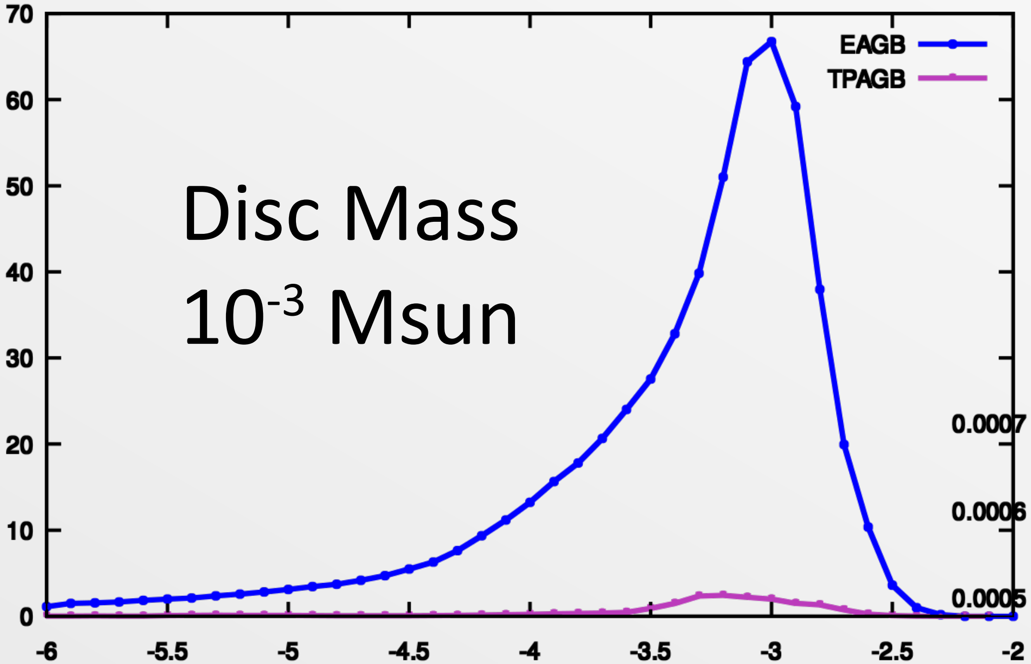


200 R☉ (1AU)

Post-AGB discs

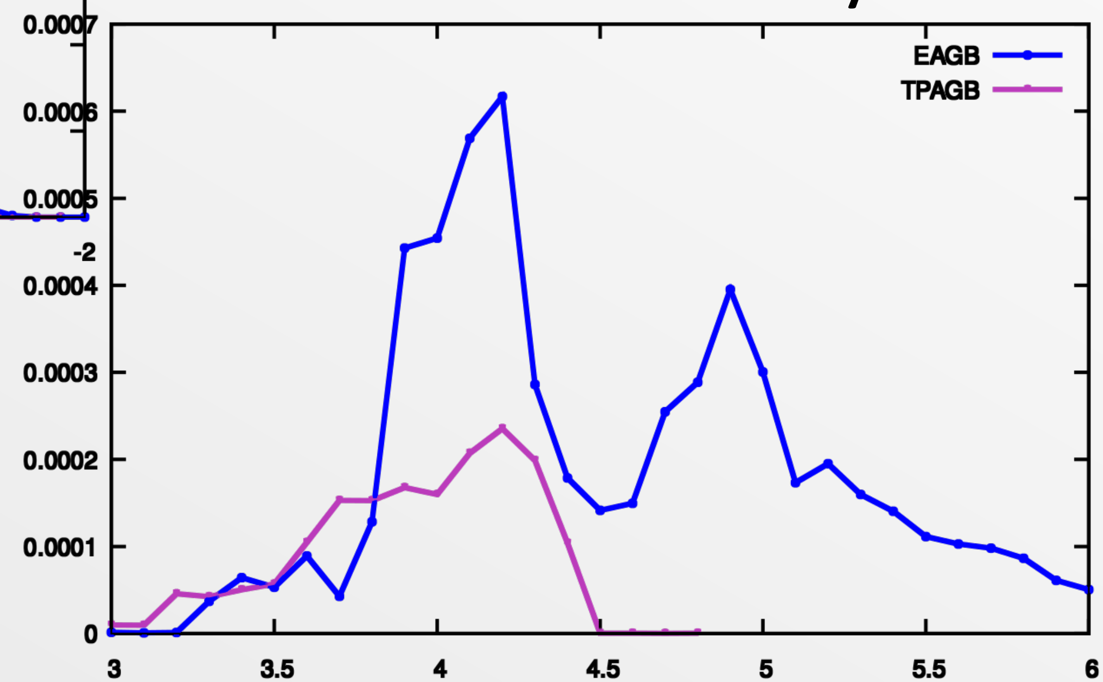
Disc Mass

10^{-3} Msun



Disc lifetime

10^{4-5} years



Yet, we are lucky.
The evolution of humans is **far more difficult** to model.
Predictions are very difficult!

Example: *Toutus cambridgensus*

Time

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Example: *Toutus cambridgensus???*

Time

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Example: *Toutus cambridgensus ???*

Time

Conclusions

Binary population synthesis Is a valuable tool.

Can solve many problems!

Yet many remain.

(common envelope, etc.)

It can contribute greatly to solving them!