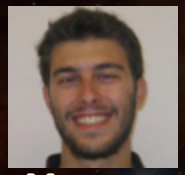
Progenitors of LIGO's Black Holes

The era of GW Astronomy, Paris, June 26-20, 2017

Credit background NASA Paresce., Design E. Buunk

Bin Cosmos Amsterdam



Manos Zapartas PhD

Ylva Götberg PhD

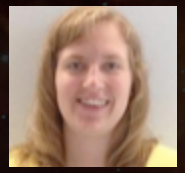
Mathieu Renzo PhD

Silvia Toonen VENI fellow

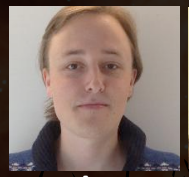
?

Interested?

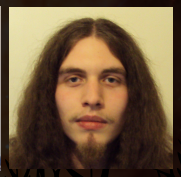
6 new PhD/PD



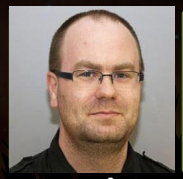
Louise Edstam MSc



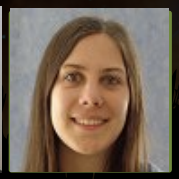
Walter v Rossem MSc



Thomas Dodds BSc



Rob Farmer Postdoc



Eva Laplace PhD

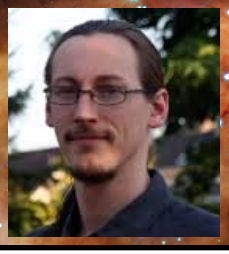
Selma E. de Mink

Anton Pannekoek Inst., University of Amsterdam

Progenitors of LIGO's Black Holes

The era of GW Astronomy, Paris, June 26-20, 2017






Ilya Mandel, Rob Izzard, Hugues Sana, Pablo Marchant, Chris Belczynski, Andrew King, Philip Podsiadlowski, Simon Stevenson, Alejandro Vigna-Gómez, Norbert Langer, Fabian Schneider, Stephen Justham, Sung-Chul Yoon, Ori Fox, Schuyler van Dyk, Jose Groh, Nathan Smith, **,** Carles Badenes, Alex de Koter, Tom Maccarone, Leo Almeida, Tony Piro, Maria Drout, Coen van Neijssel, Abel Schootemeijer, Colin Norman, ….

VLT-FLAMES Massive Star Consortium (PI: Evans)

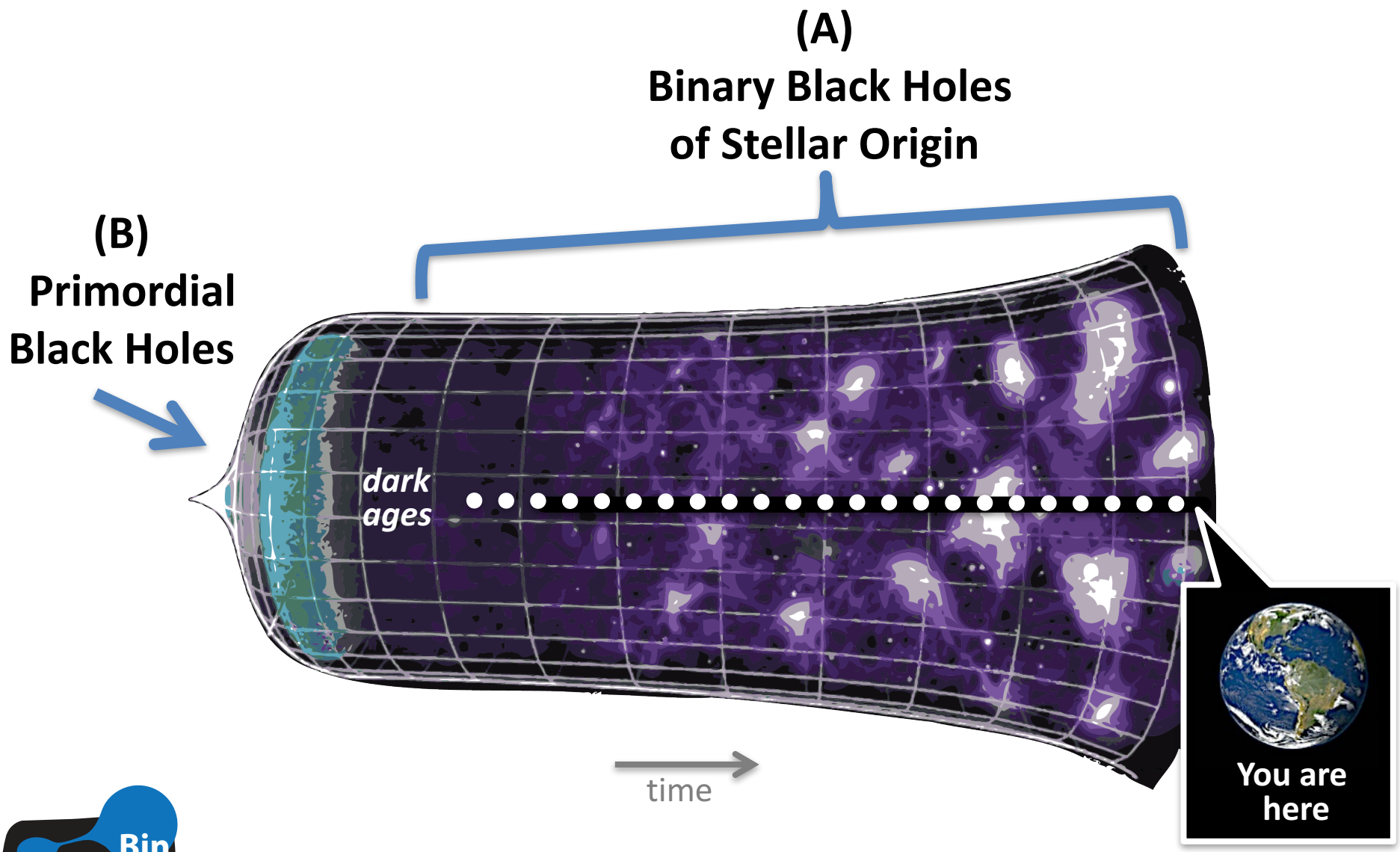
Selma E. de Mink

Anton Pannekoek Inst., University of Amsterdam

How did they form?

*Unofficial Merchandise: Baby black hole, comes with adoption certificate www.etsy.com

How did they form?



Scope

(A) Stellar Origin Black Holes

This Talk

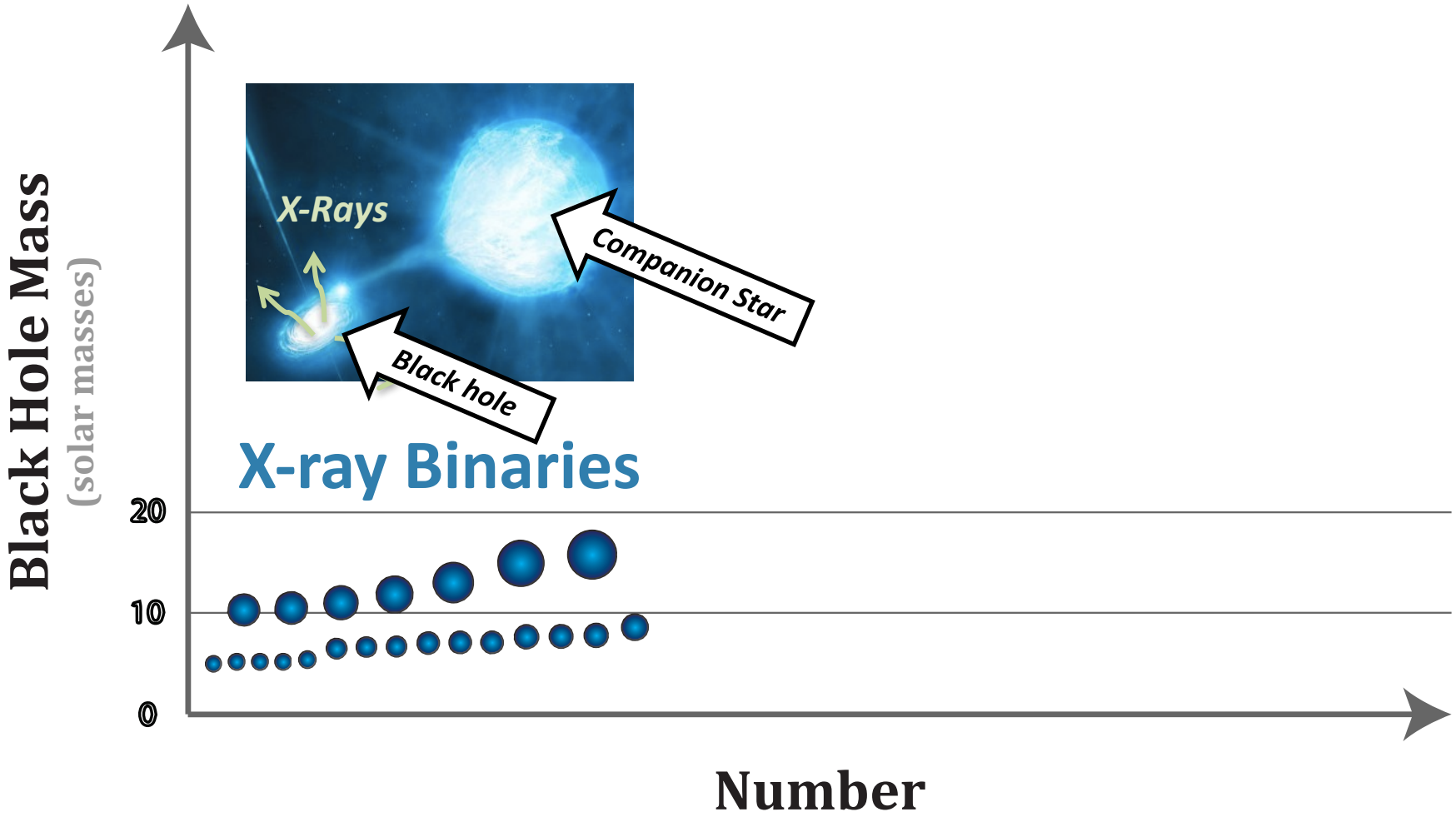
- ✓ Gravitational Collapse of (the core of) a massive star
- ✓ Observed (albeit at somewhat lower mass)

(B) Primordial Black Holes

Carr & Hawking (1974), Carr (1975, 1976), Garcia-Bellido et al. (1996), Khlopov (2010), Frampton et al. (2010), Blais et al. (2002), …

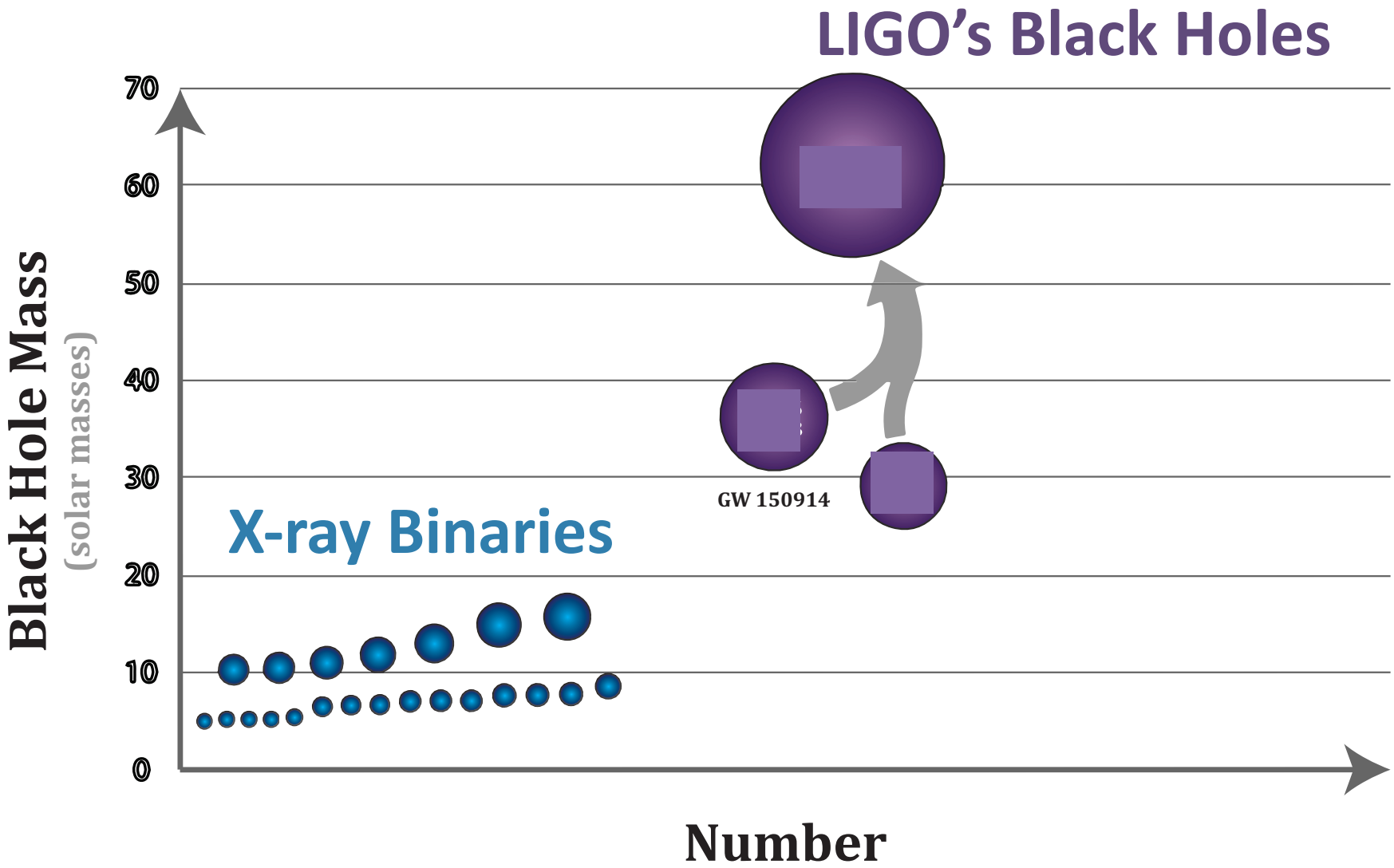
- ✓ Gravitational Collapse of extreme densities at high redshift
- ✓ Still hypothetical … (so far)
- ✓ Somehow evaded strong constraints by
  - Micro lensing events
  - CMB spectral distortions
- ✓ Constituent of Dark Matter (instead / in addition to more popular but still elusive WIMPs)

Known black holes that have a stellar origin (presumably)



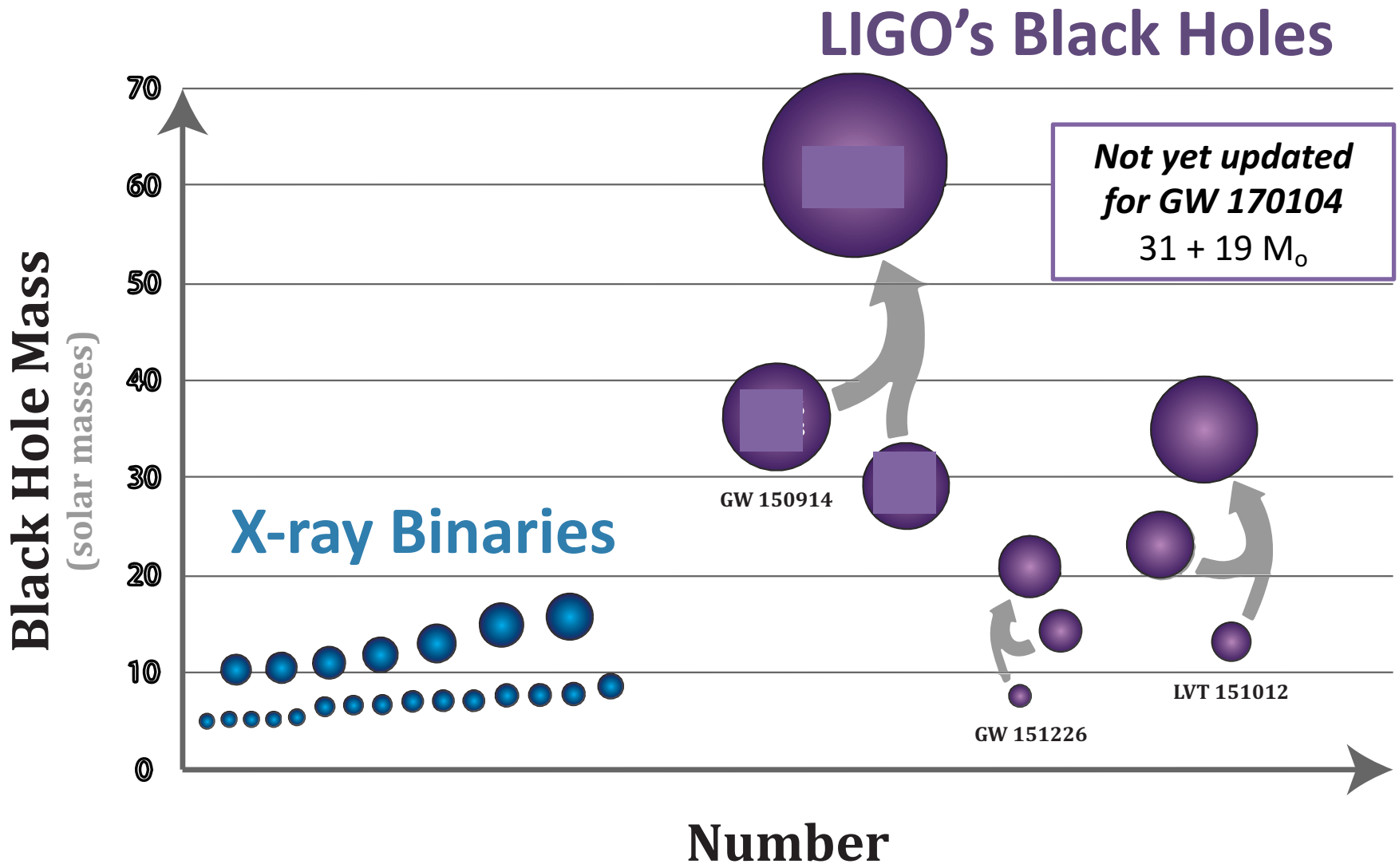
Credit: ESO/L. Calçada/M.Kornmesser, & Caltech/MIT/LIGO

Are LIGO's black holes of stellar origin?



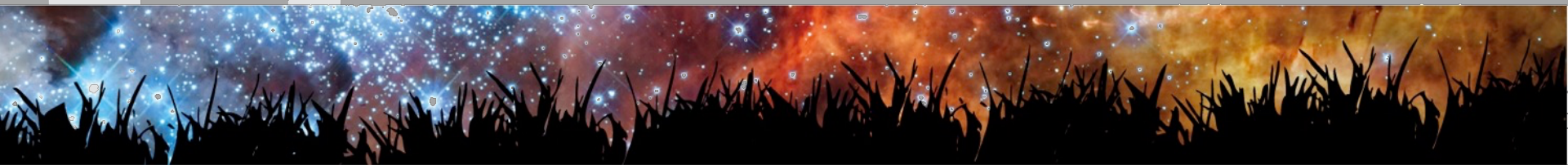
Credit: ESO/L. Calçada/M.Kornmesser, & Caltech/MIT/LIGO

Are LIGO's black holes of stellar origin?



Credit: ESO/L. Calçada/M.Kornmesser, & Caltech/MIT/LIGO

When did LIGO's black holes form?



When did the progenitors of LIGO's black holes form?

1. **Such that they merge within LIGO's reach.**
   (optimum between: detection horizon & delay time)

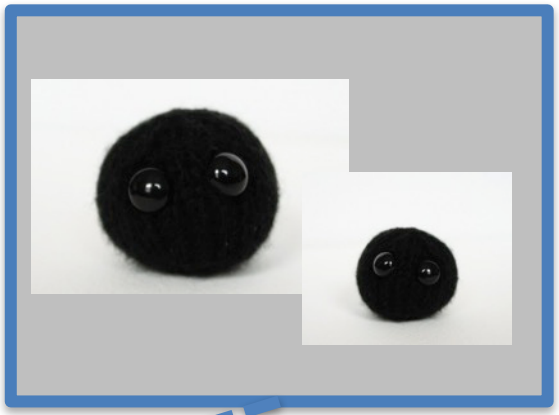
2. **When the Universe was forming stars at high rate**

3. **When "conditions" where "right"**
   (to form binary black holes, e.g. metallicity)

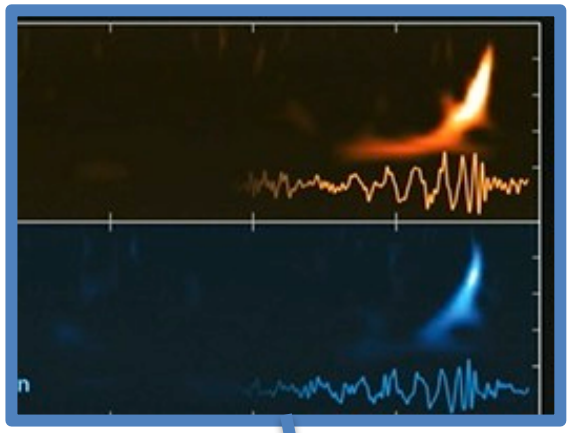
1.

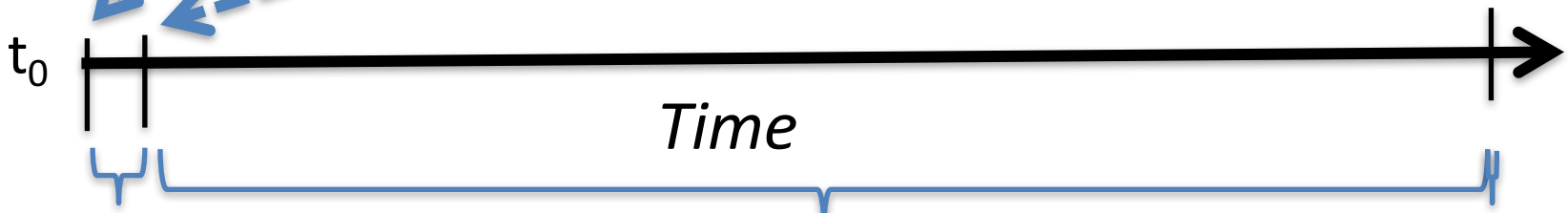
Birth of progenitors stars

Formation black holes



Coalescence

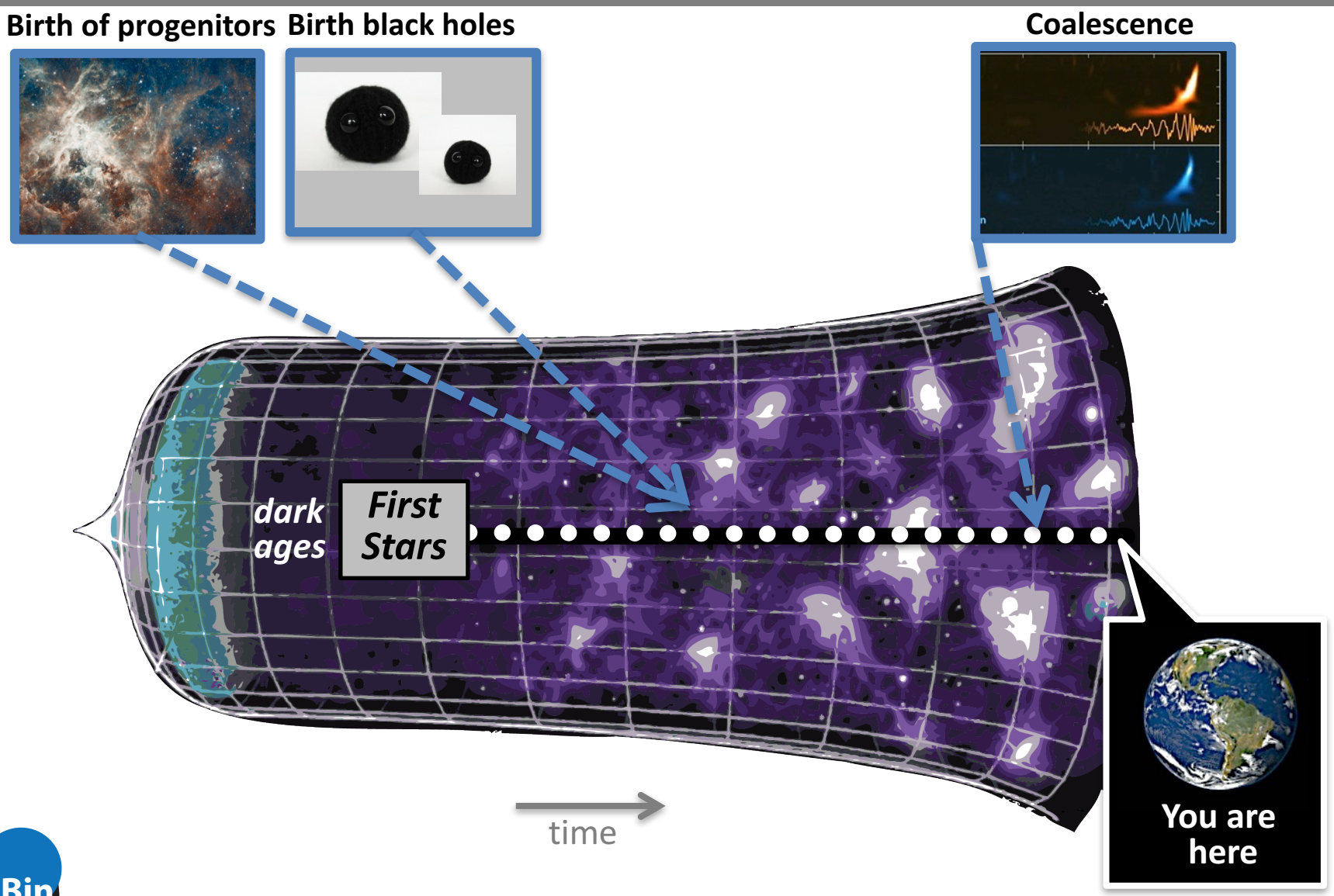




Lifetime stellar progenitors
~ 10 Myrs

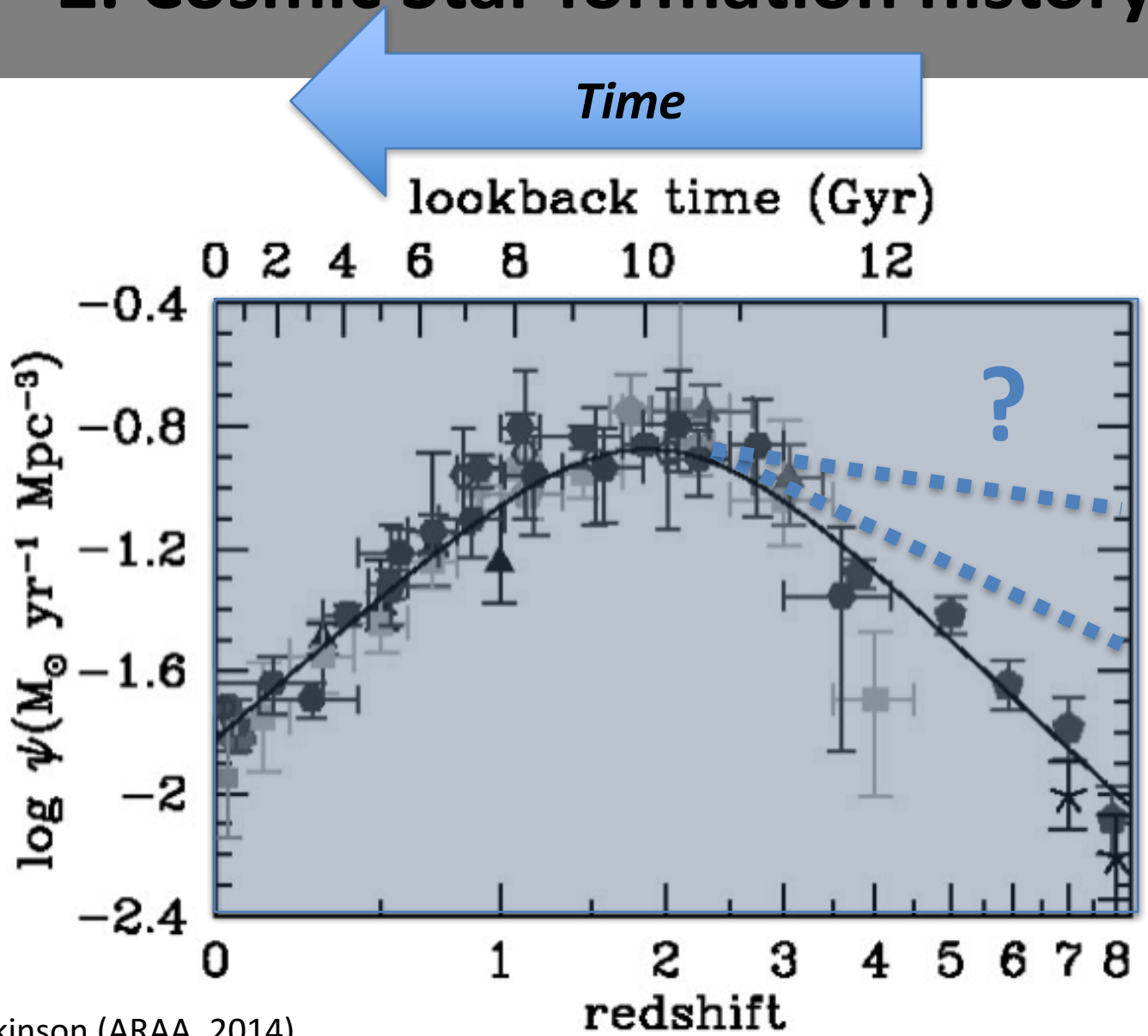
In-spiral due to Gravitational Waves
Model dependent: Typically: ~ Gyrs

Detectable Signal
~ 0.1 second


Birth of progenitors
Birth black holes
Coalescence
dark ages
First Stars
time
You are here

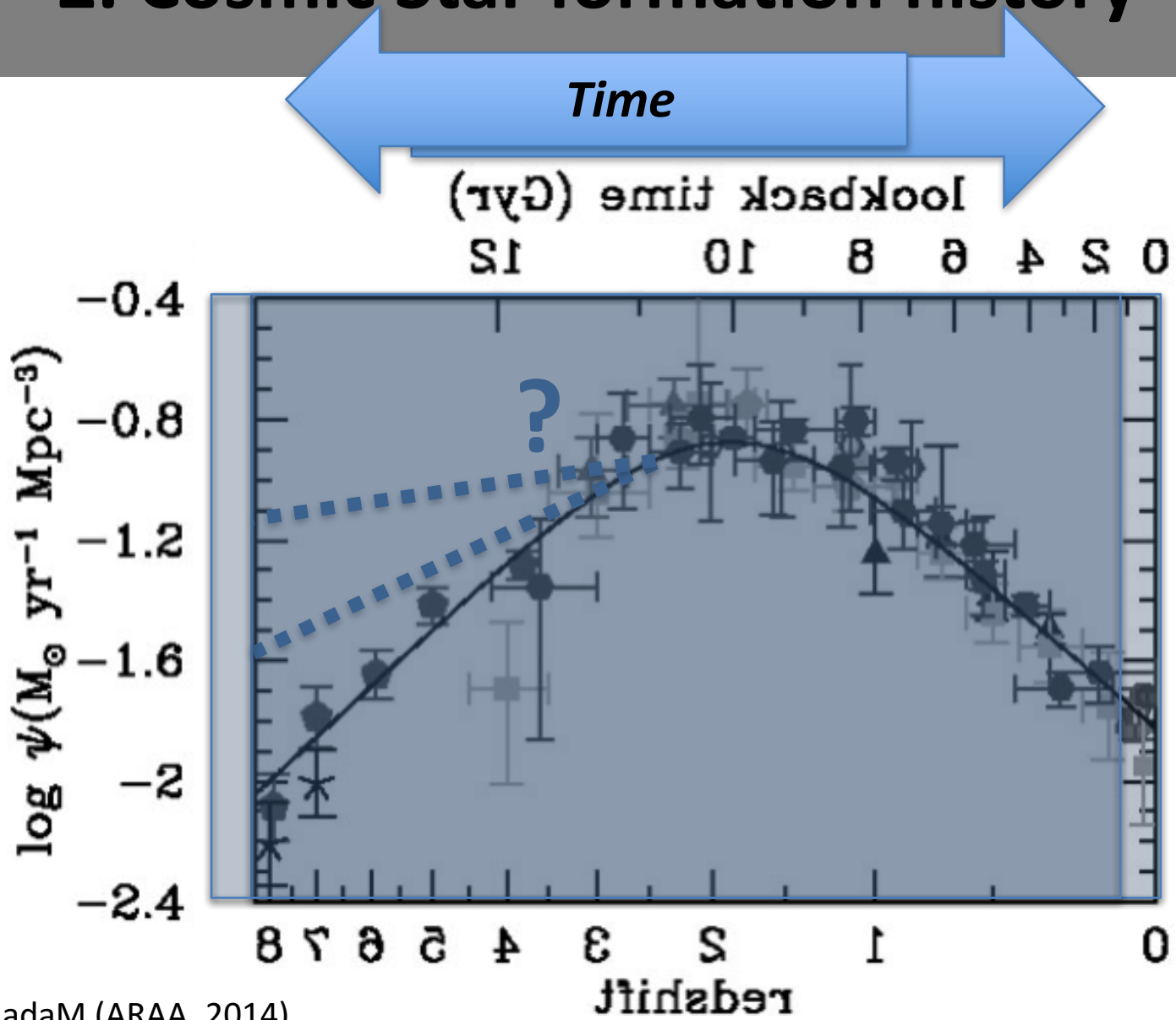
BinCosmos

2. Cosmic Star formation history

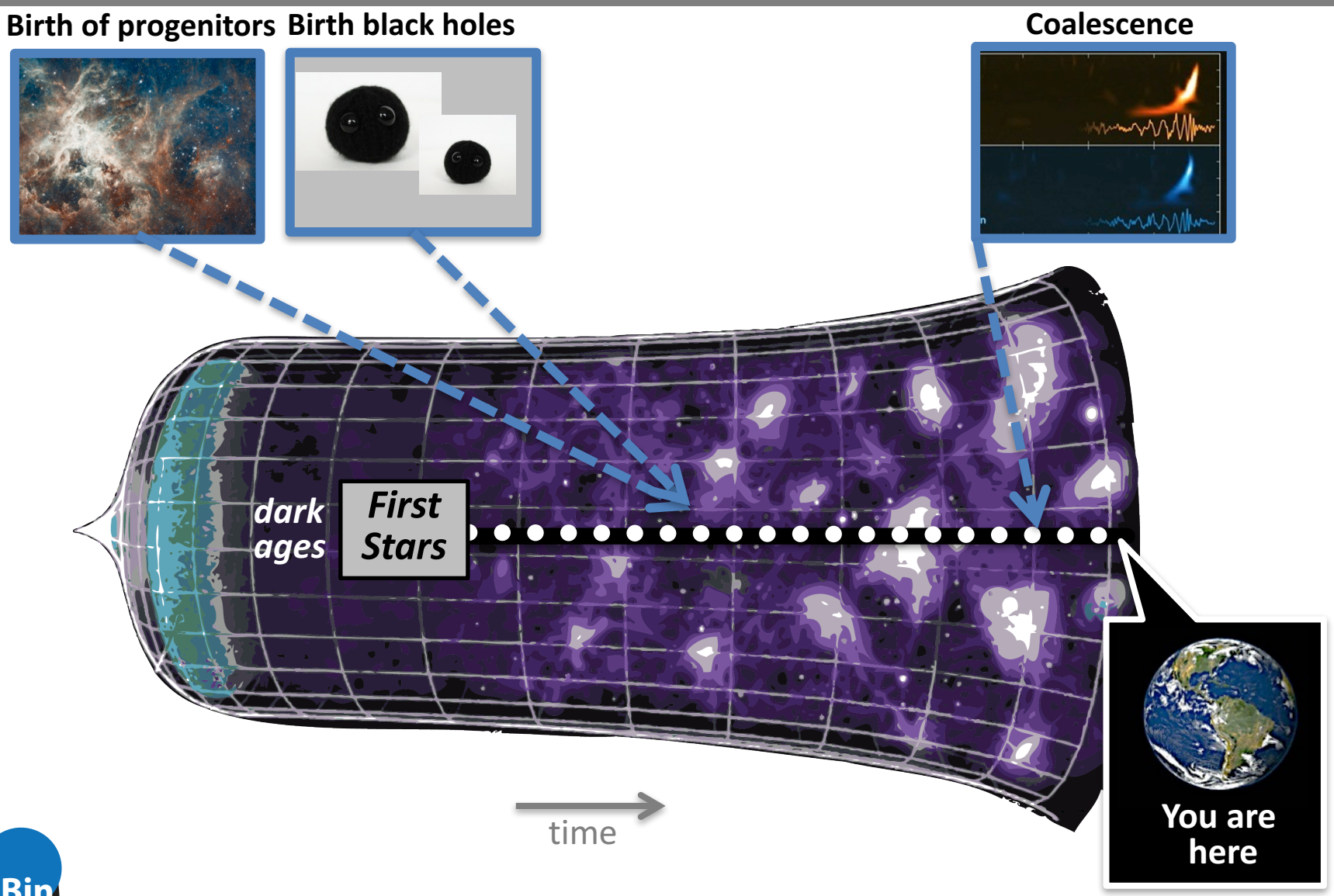


Madau & Dickinson (ARAA, 2014)

2. Cosmic Star formation history



nosnikciD & uadaM (ARAA, 2014)

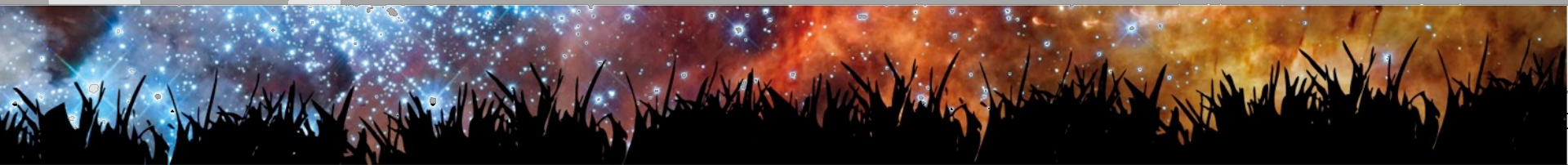

Birth of progenitors
Birth black holes
Coalescence
dark ages
First Stars
time
You are here

BinCosmos

Which stars make black holes?

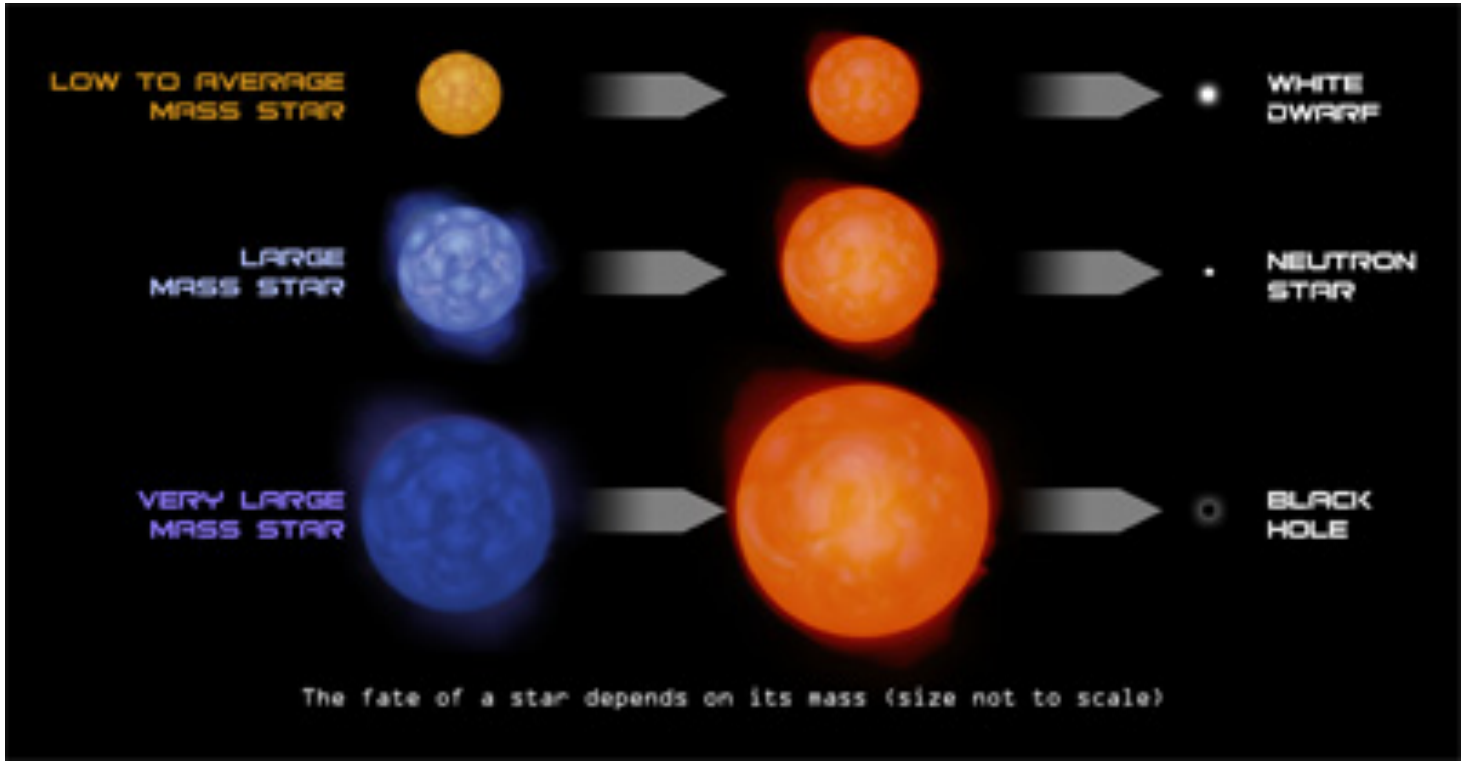
Small print

Disclaimer: we don't know.
Any assumptions you make are at your own risk



Final fate of stars

How hard can it be …? We all know this …



NASA outreach material.

Stellar Evolution
How hard can it be … ?

Four coupled differential equations

I. Conservation of Mass

$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho}$$

"Heroic Struggle against gravity"

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

III. Conservation of Energy

$$\frac{dL_r}{dM_r} = \epsilon$$

IV. How is energy transported

$$\frac{dT}{dM_r} = -\frac{1}{16\pi^2 r^4 \lambda \rho} L_r$$

Independent variable

$$M_r.$$

Four primary variables

$$r,\ P,\ L_r \text{ and } T,$$

Boundary conditions:

$$r = 0, \quad L_r = 0, \quad \text{for} \quad M_r = 0$$

$$P = 0, \quad T = 0, \quad \text{for} \quad M_r = M,$$

Auxiliary equations

ρ: equation of state, $P = P(\rho, T, X_i)$

λ: coefficient of conductivity, $\lambda(\rho, T, X_i)$

ϵ: nuclear fusion rate, $\epsilon(\rho, T, X_i)$

Nuclear reaction network

Bin Cosmos

2 types of simulations

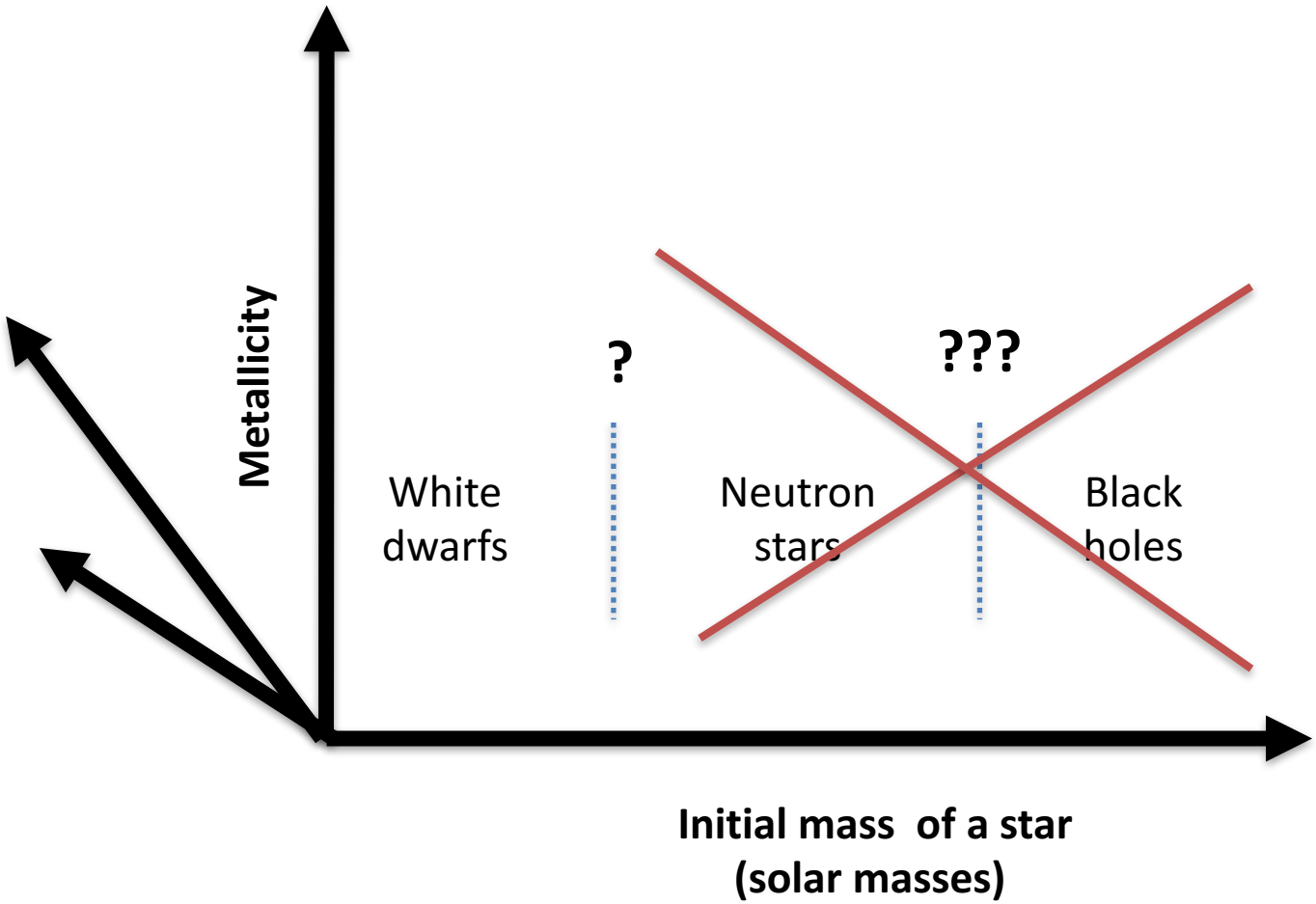
Rapid evolutionary 'prescriptions'

- Computationally cheap ➔ used to make predictions for populations / rates
- StarTrack, binary_c, BSE, …

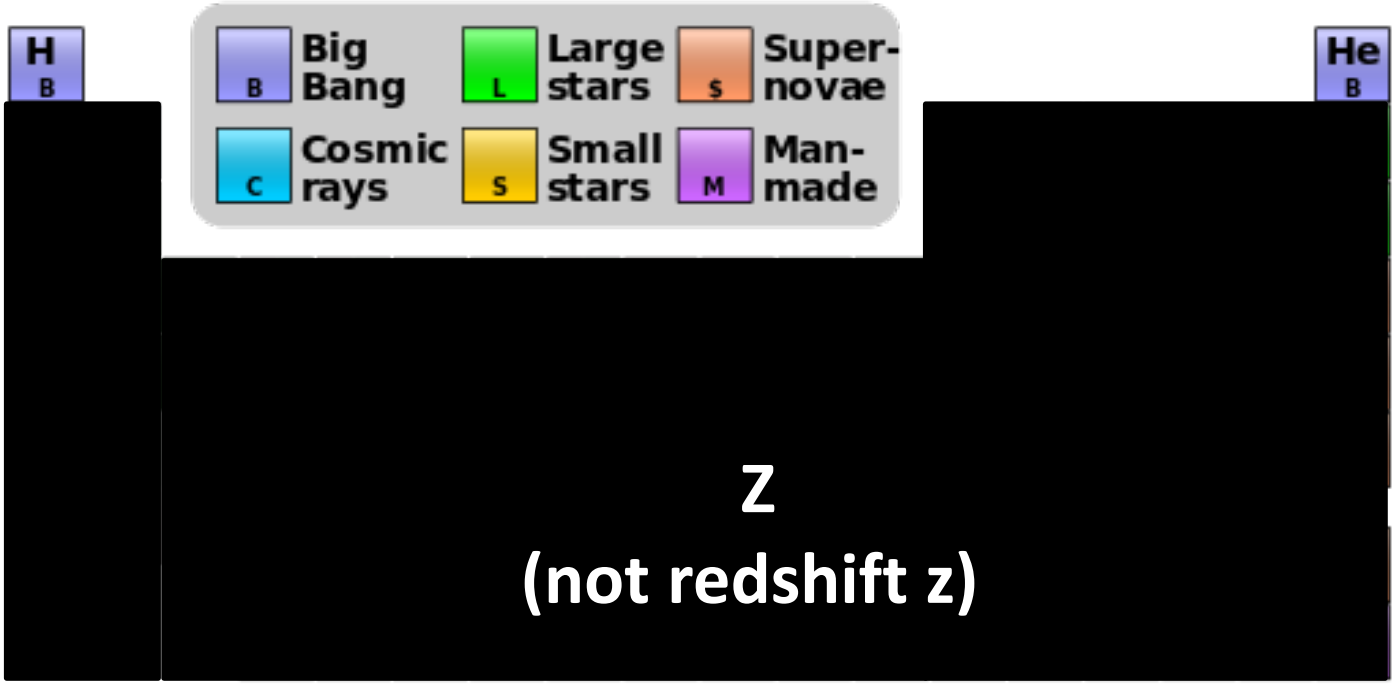
Full solutions to stellar evolution equations

- More expensive computationally, (in part due to convergence issues)
- Kippenhahn codes, MESA

Mass loss


Metallicity
?
???
White dwarfs
Neutron stars
Black holes
Initial mass of a star (solar masses)

Metallicity

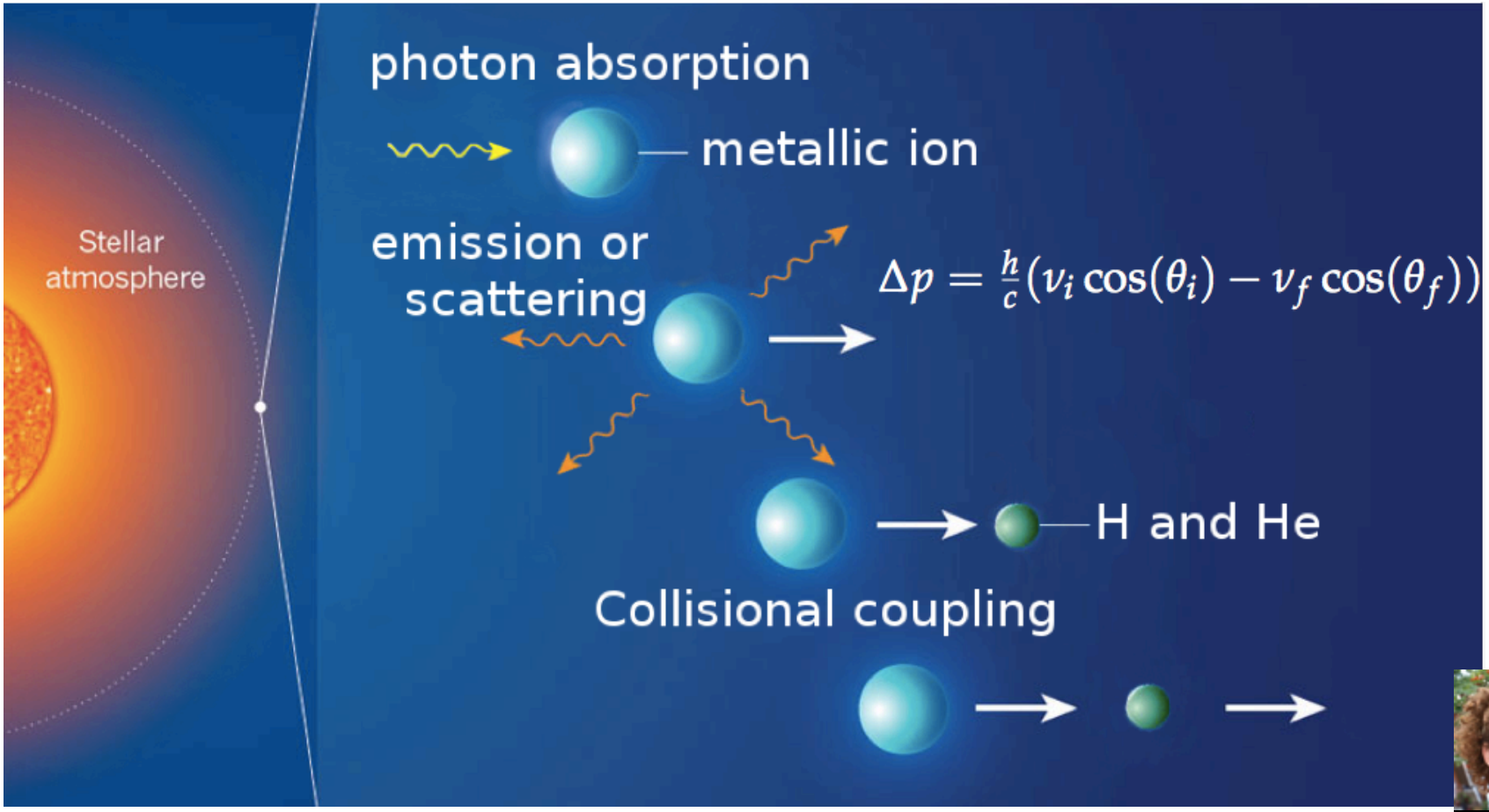


Z : Mass fraction of all elements more massive than H & He

[Fe/H], [O/H]: Log_{10} of ratio compared to the sun

Why do stars care about Metallicity

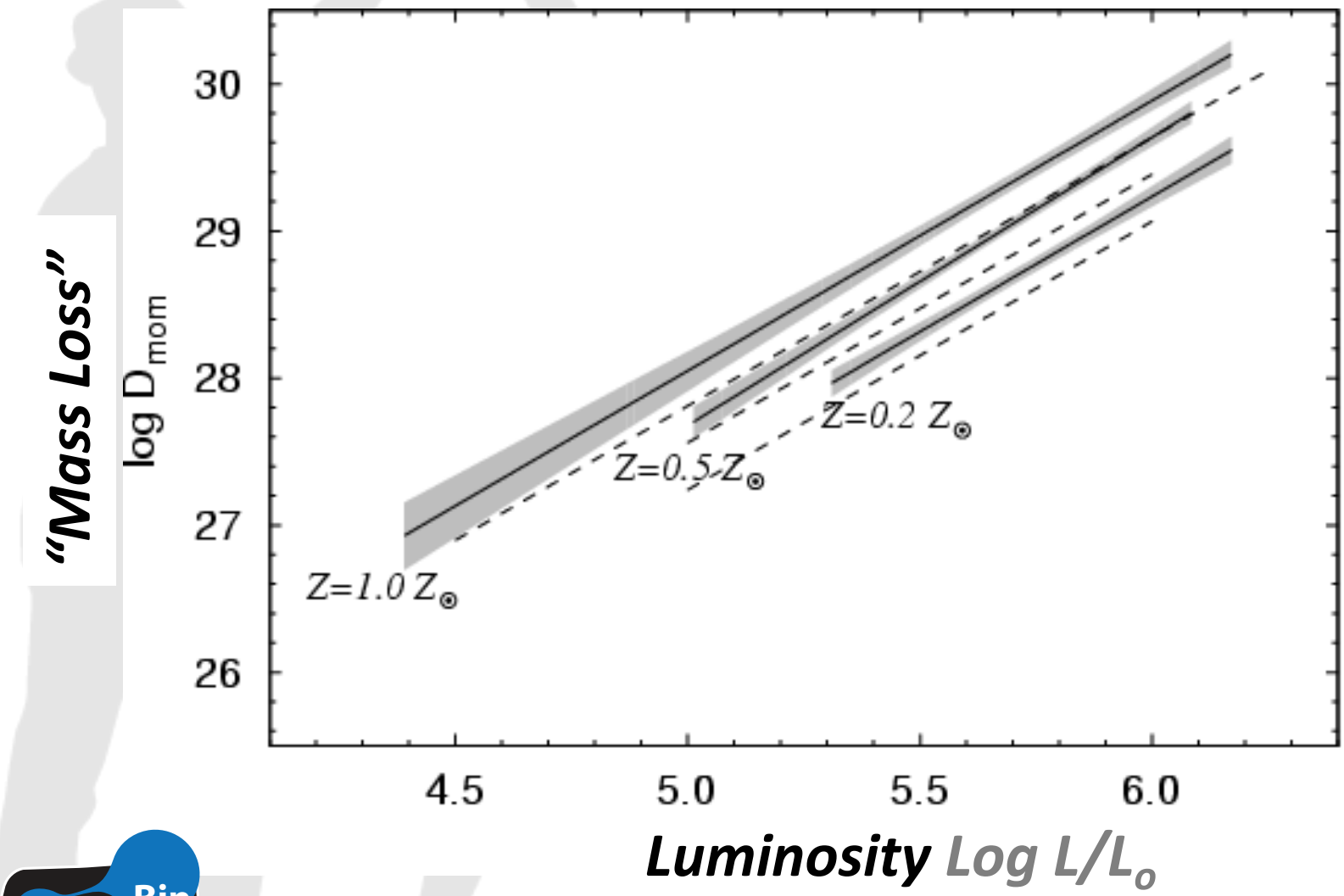
Mass loss by (radiatively driven) stellar winds cares about metals



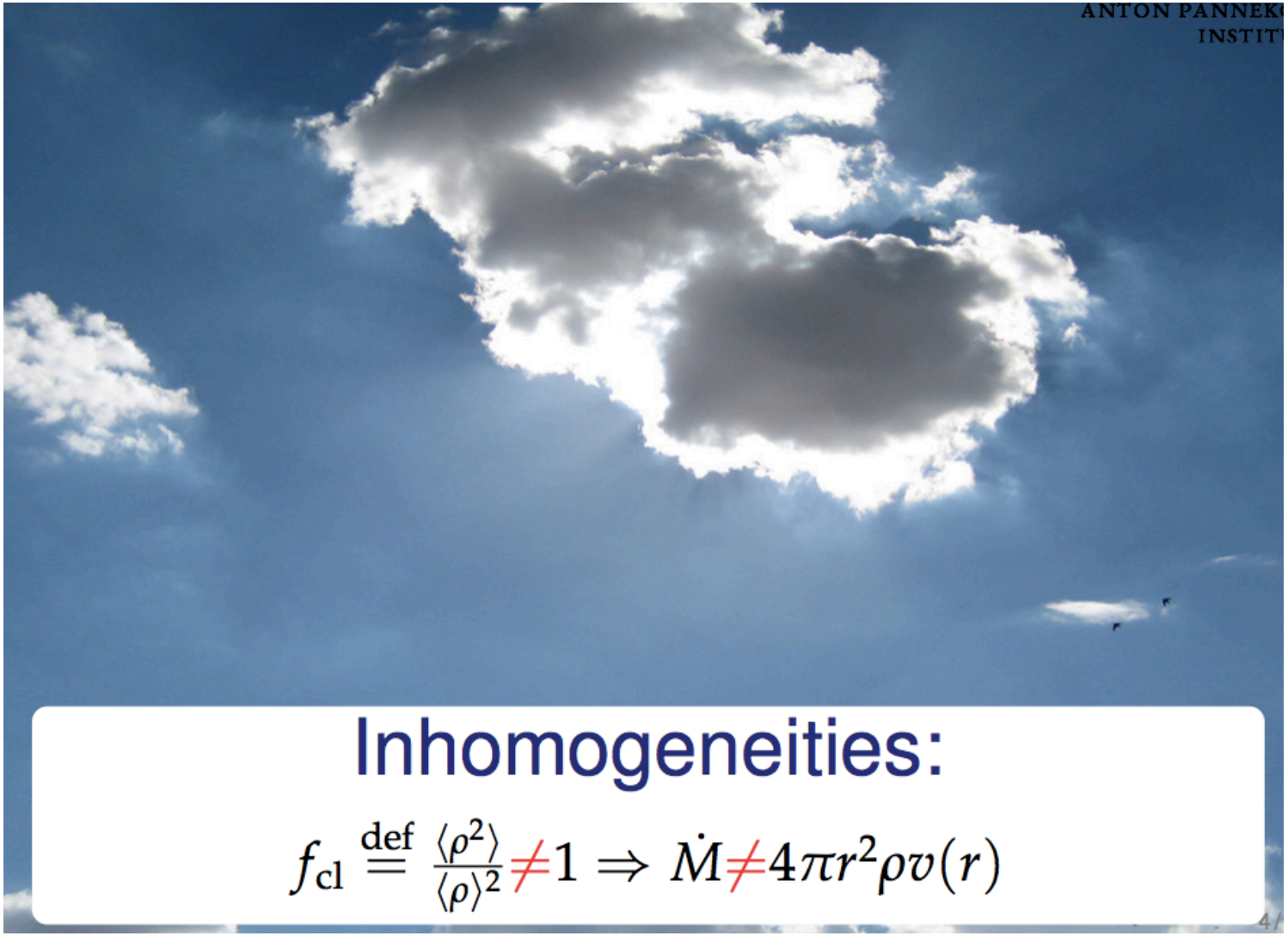
Mathieu Renzo

Reduced (line driven) winds at lower metallicity

Vink et al. 2000, Mokiem et al. 2005



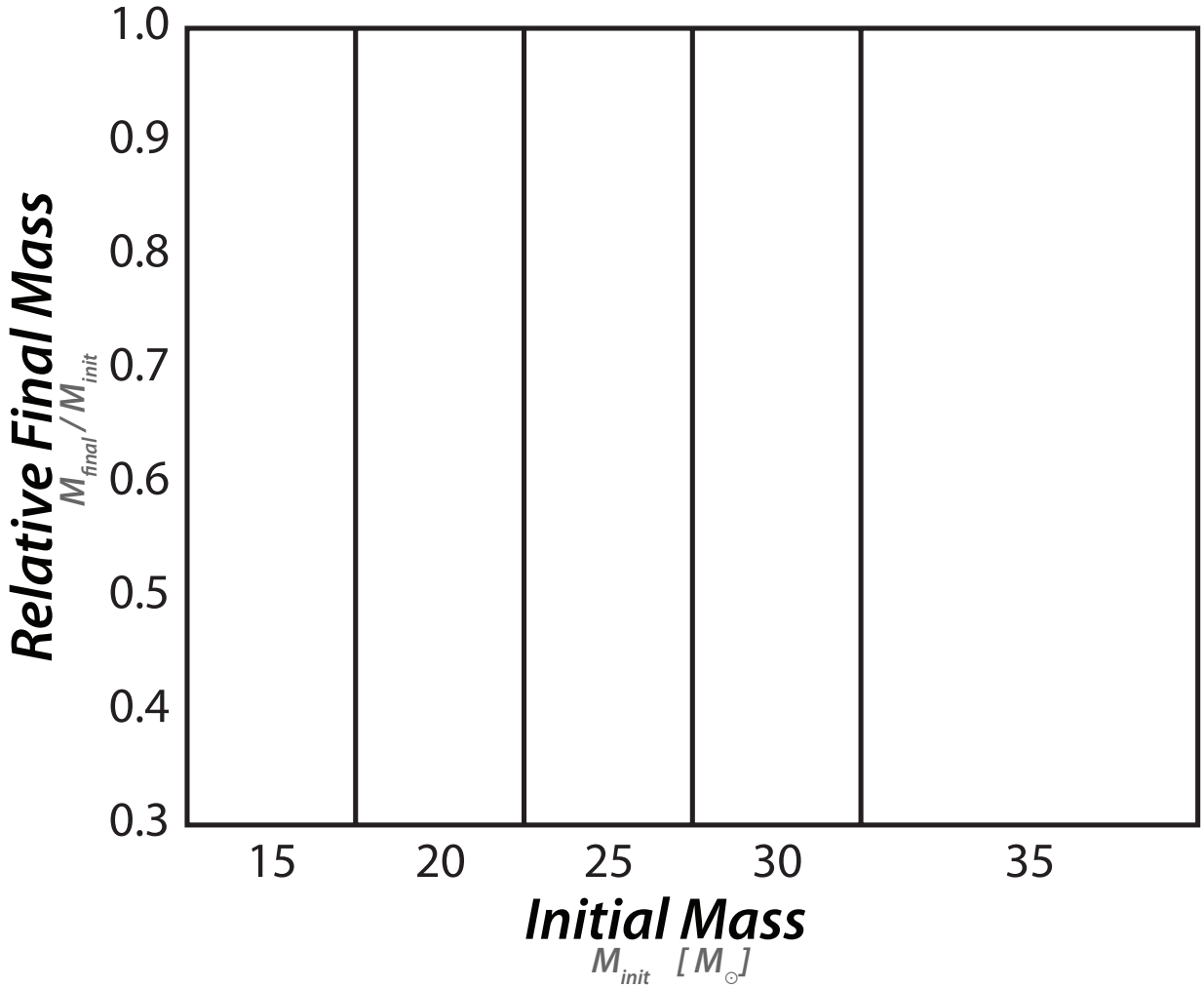
Challenge 1
wind clumping?



Mathieu Renzo

Mass loss uncertainties

Renzo et al. (2017)

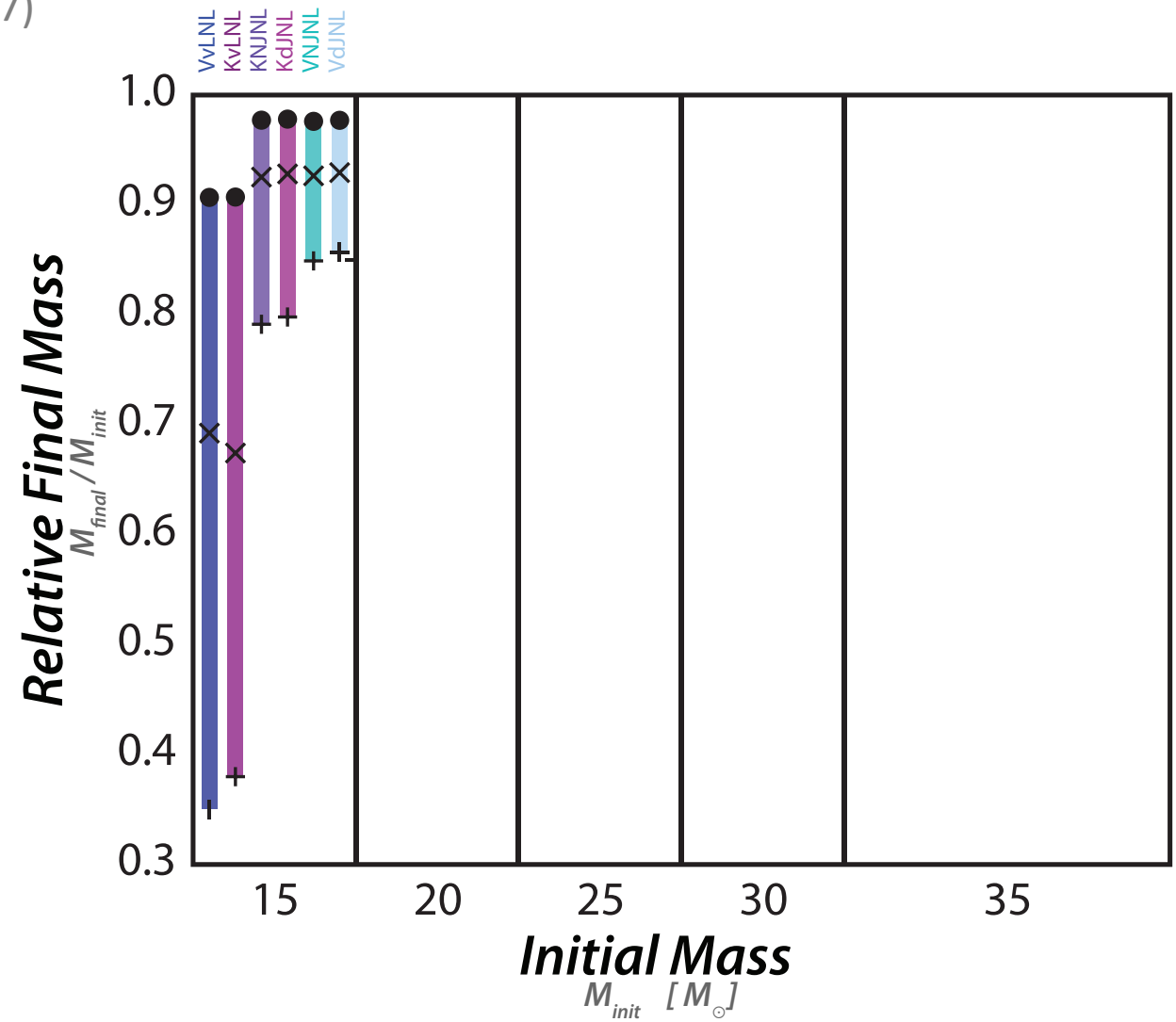


Mathieu Renzo

Bin Cosmos

Mass loss uncertainties

Renzo et al. (2017)

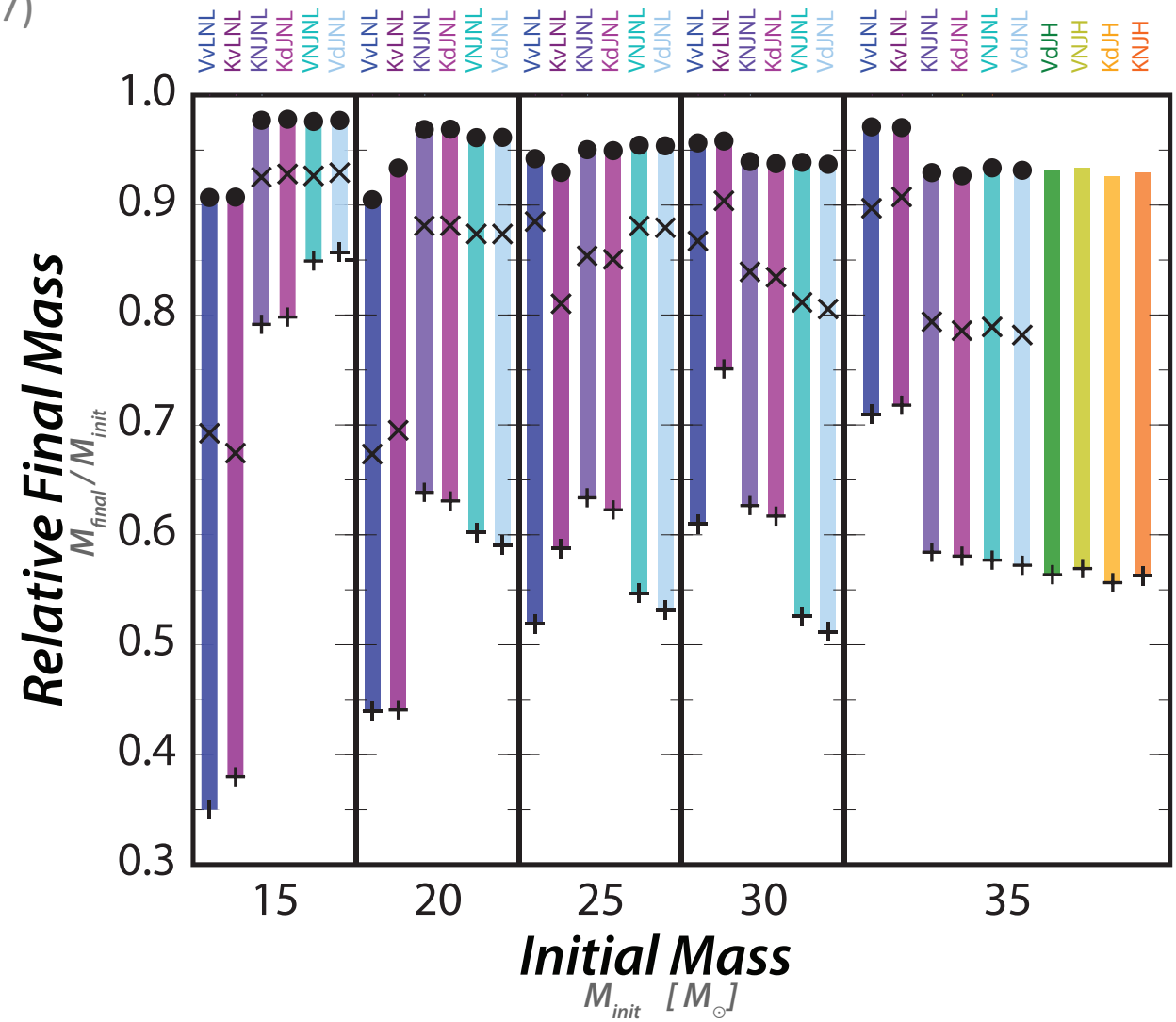


Mathieu Renzo

Bin Cosmos

Mass loss uncertainties

Renzo et al. (2017)

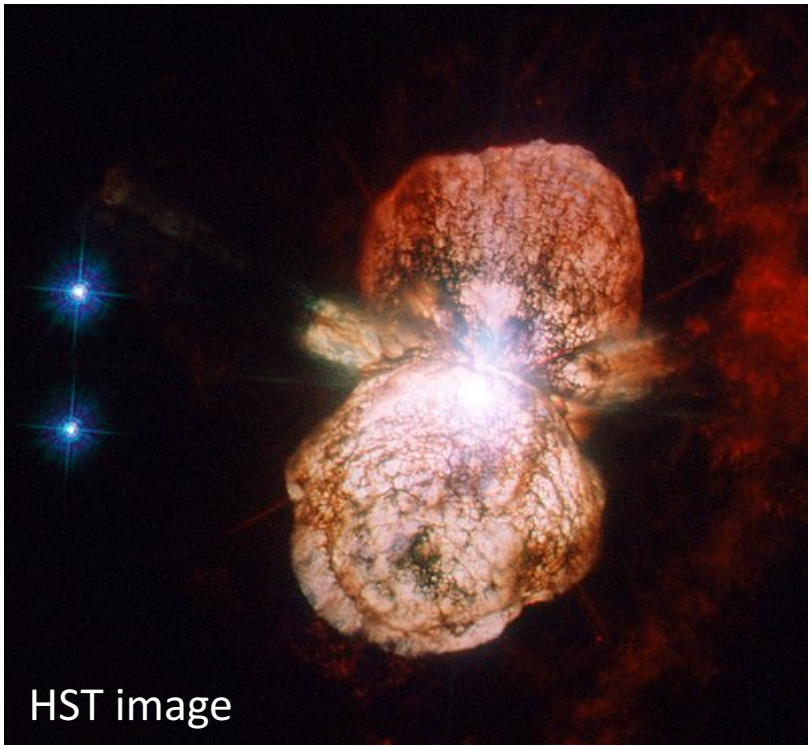


Mathieu Renzo

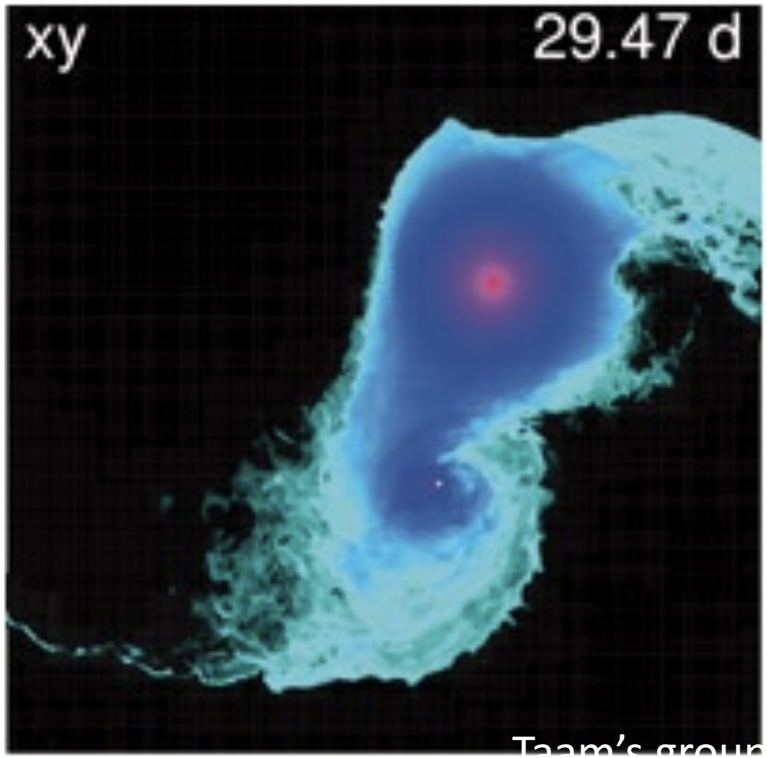
Bin Cosmos

Challenge 2: Other poorly understood modes of mass loss

Eruptive Mass loss



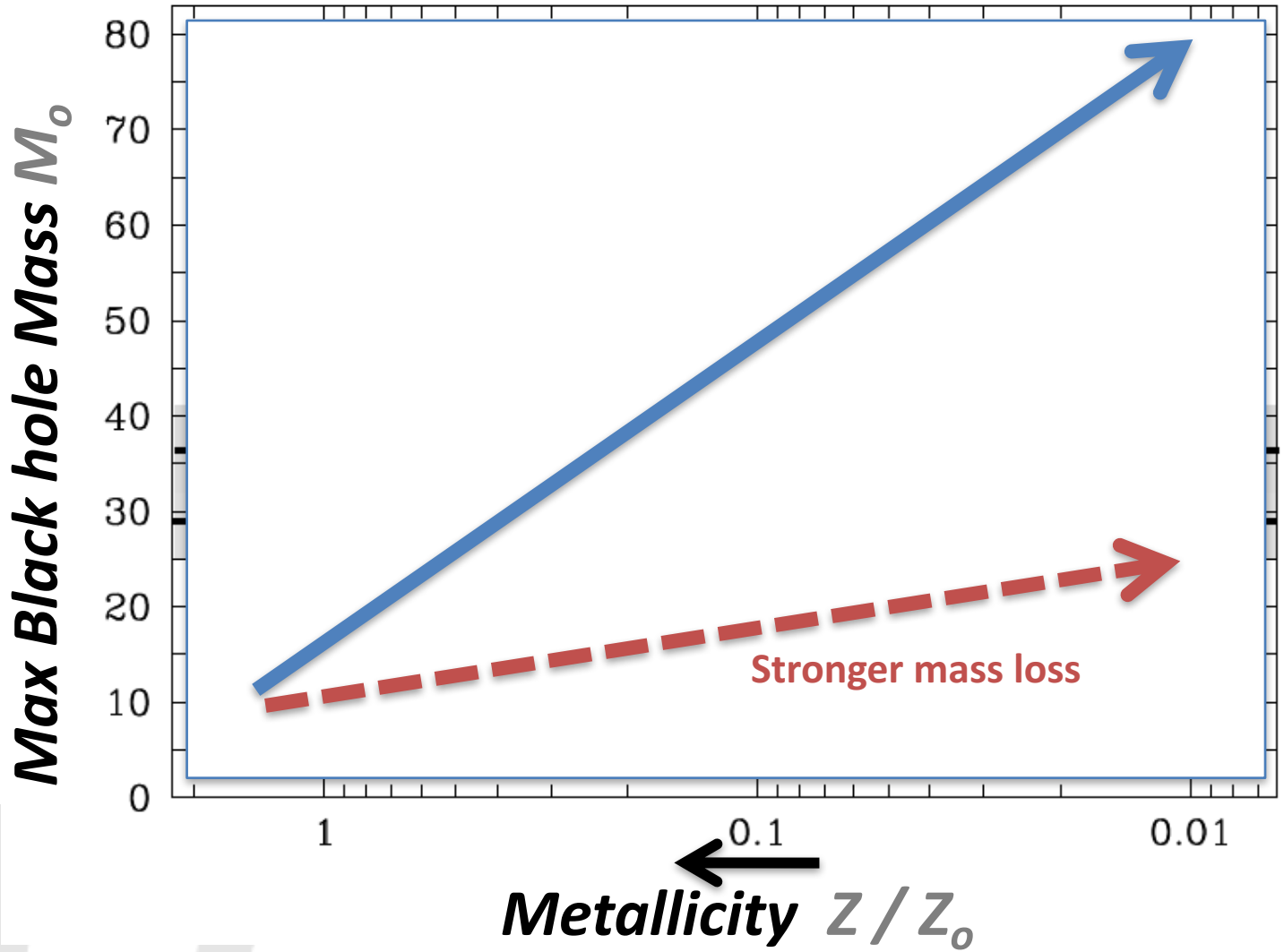
Stripping by Companion



Need for reduced winds

Belczynski et al. 2010

Astrophysical implications paper

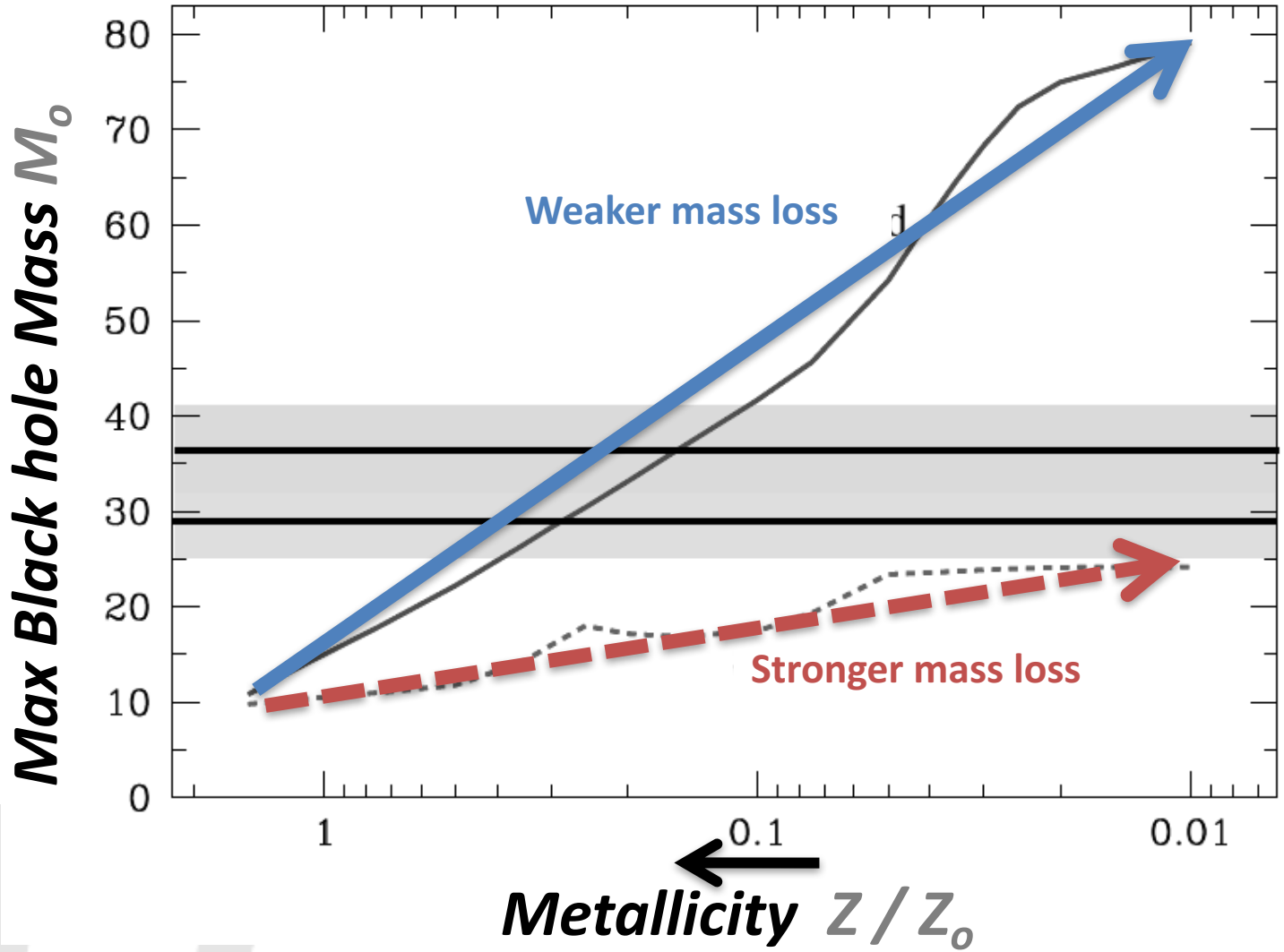


Bin Cosmos

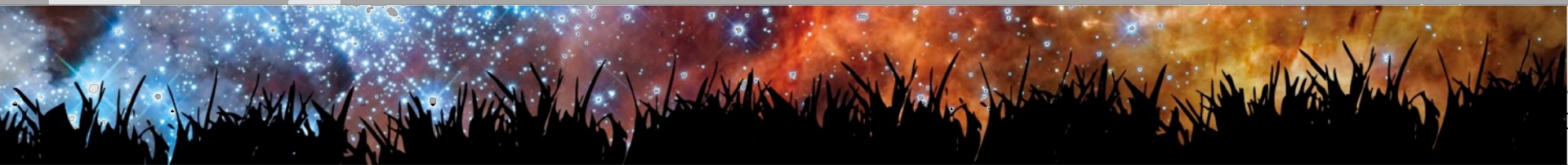
Need for reduced winds

Belczynski et al. 2010

Astrophysical implications paper

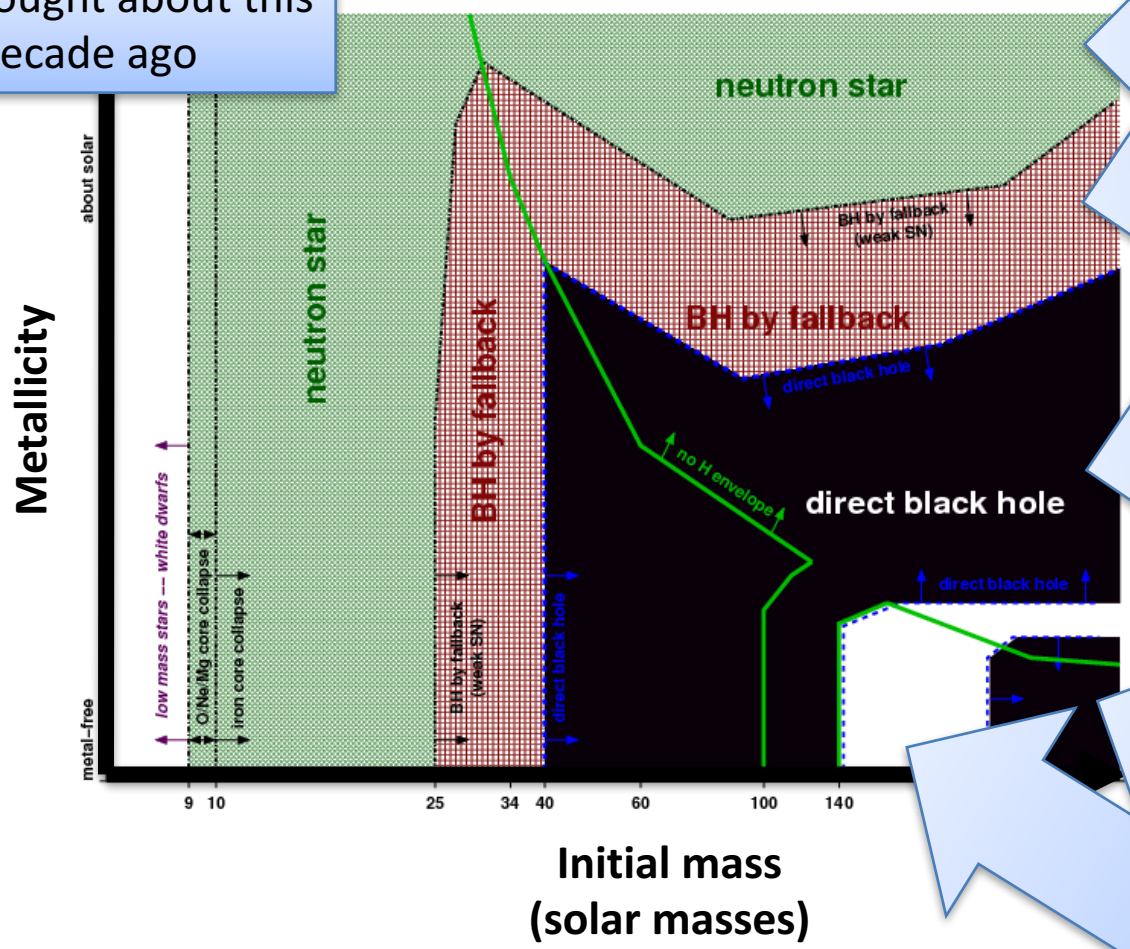


Which (single) stars make black holes



How massive single stars end their lives? - 1

As we thought about this a decade ago

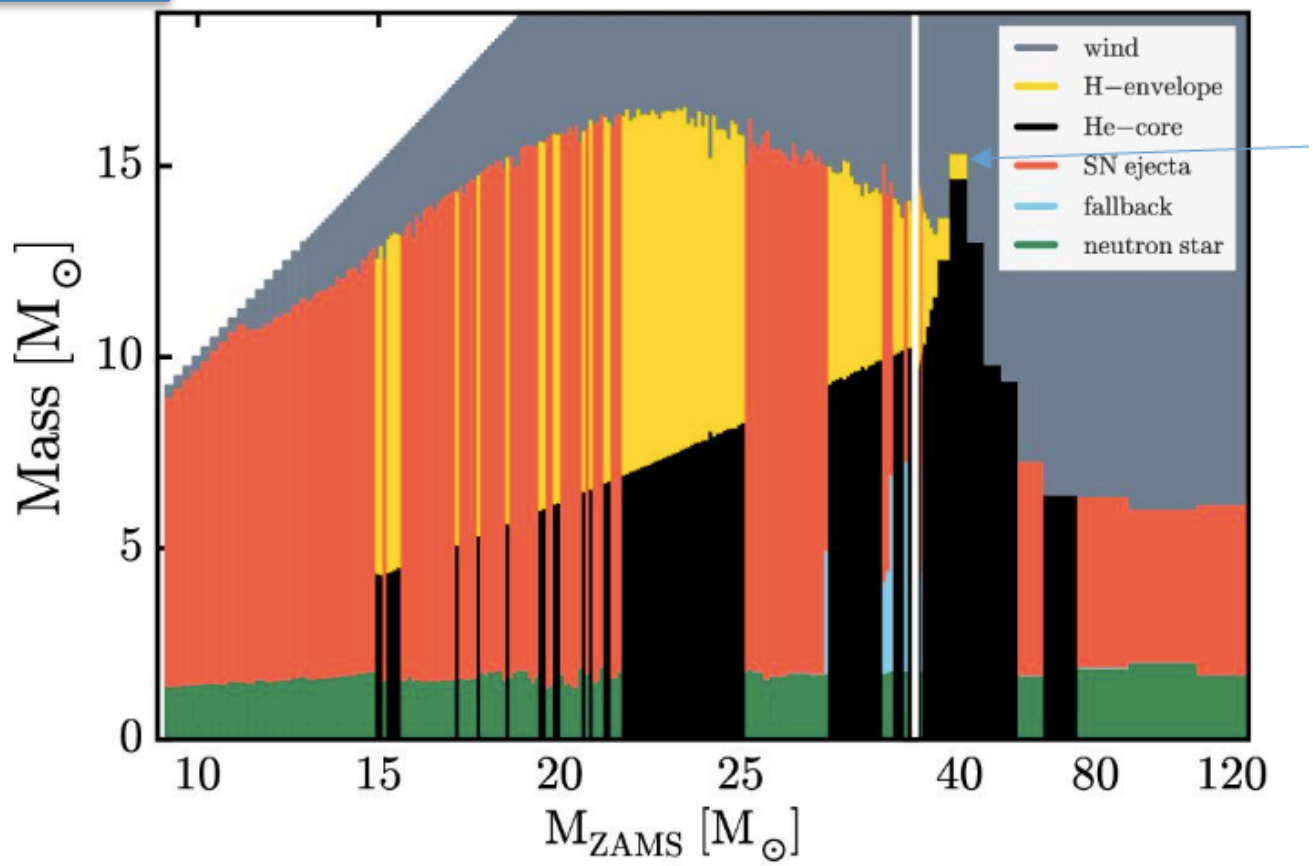


eger+00

Maybe not that simple:

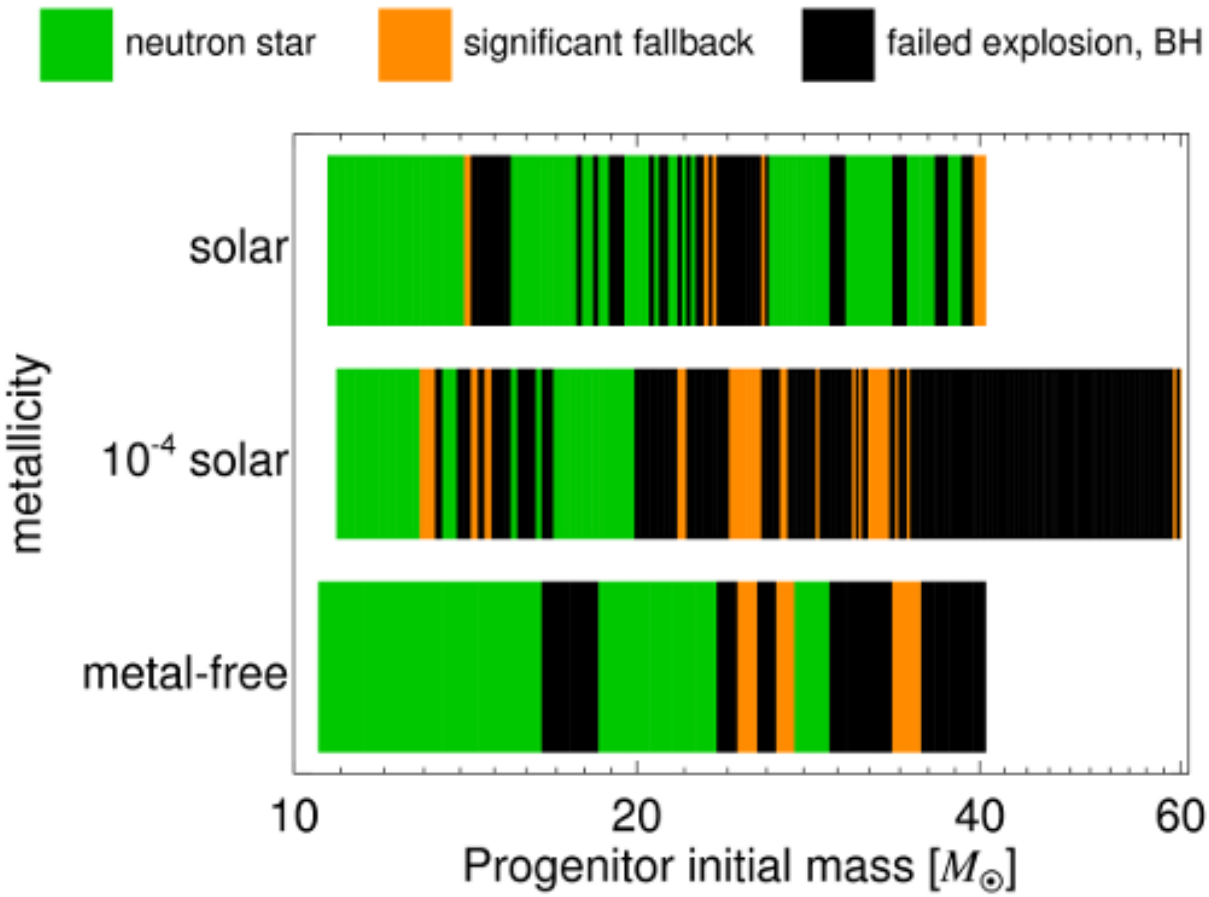
“Islands” of black hole formation.

Current discussion

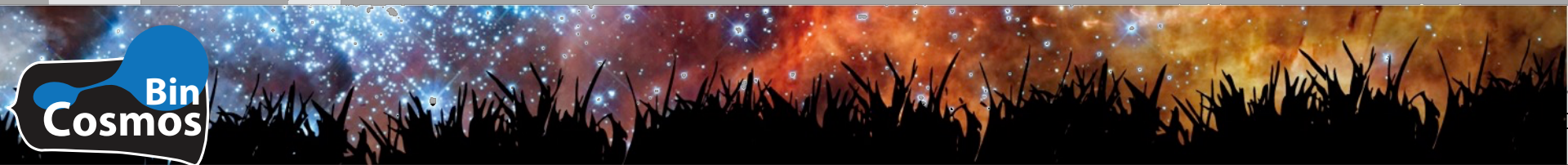


Maybe not that simple

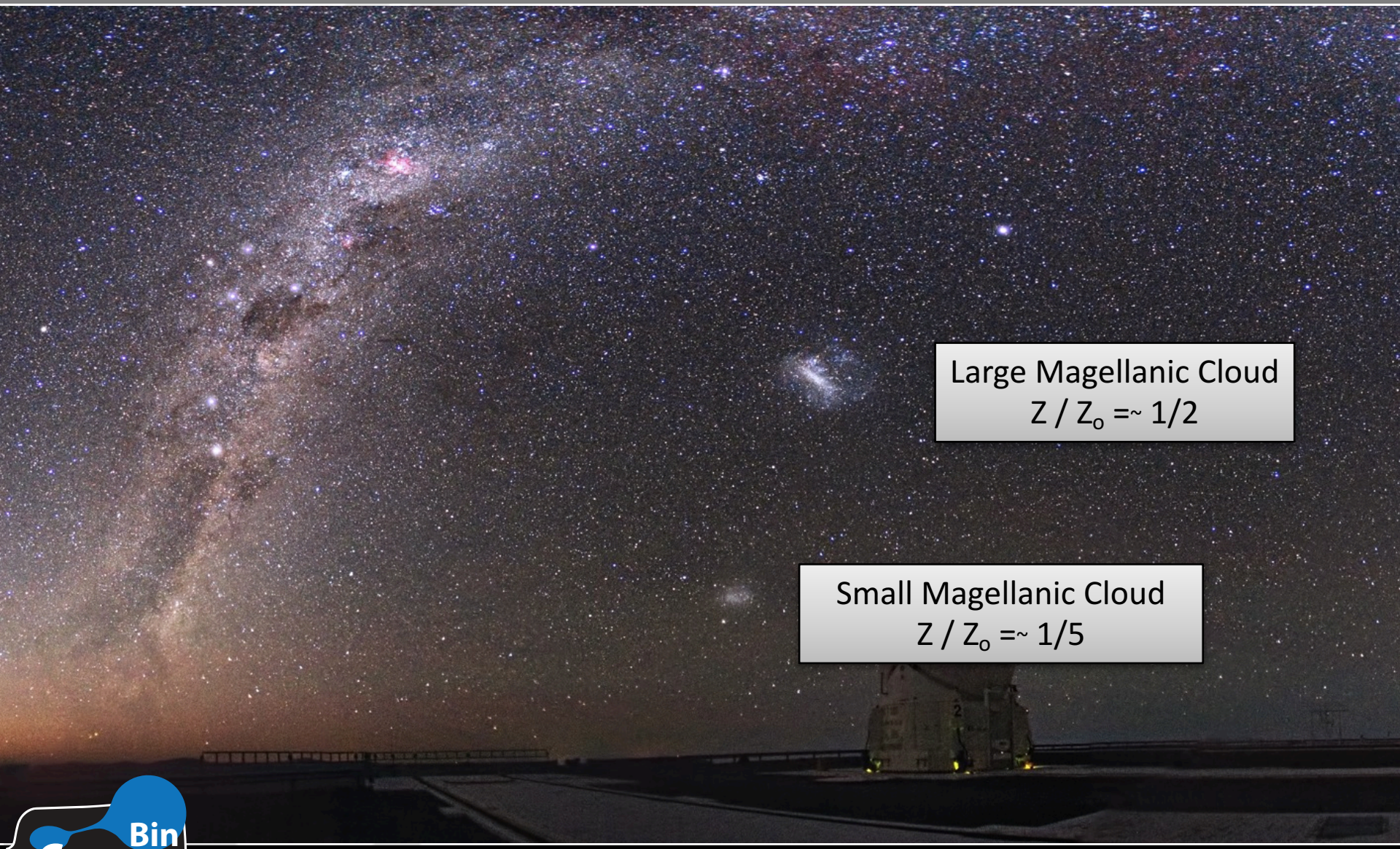
O. Pejcha[1] and T. A. Thompson[2]



What do we know about the progenitors



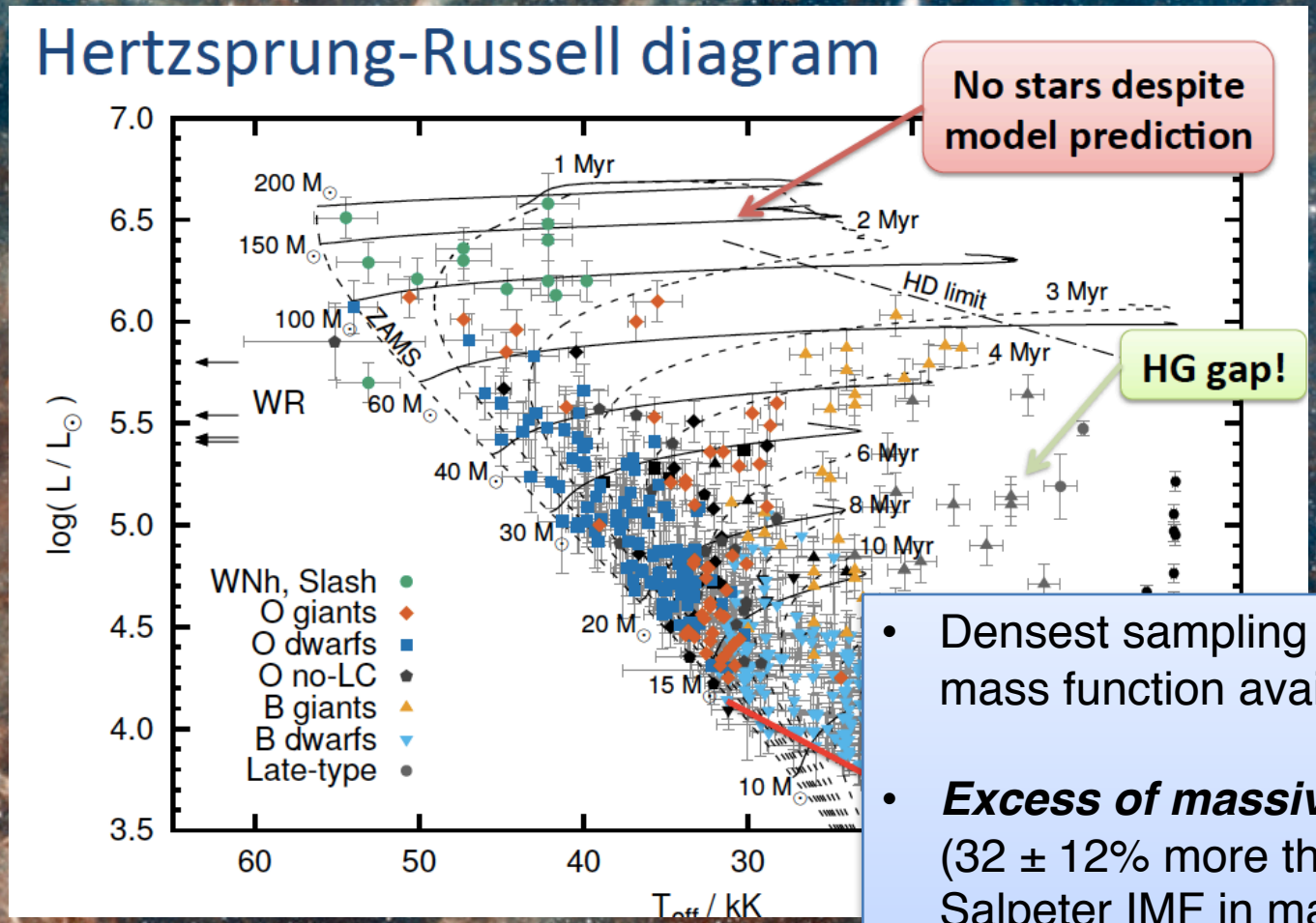
Closest Peak at their Progenitors



Black Holes in the making: Tarantula Nebula

VLT-FLAMES (Evans, Sana), HST (Sabbi, Lennon, Crowther), Chandra (Townsley)

Black Holes in the making: Tarantula Nebula



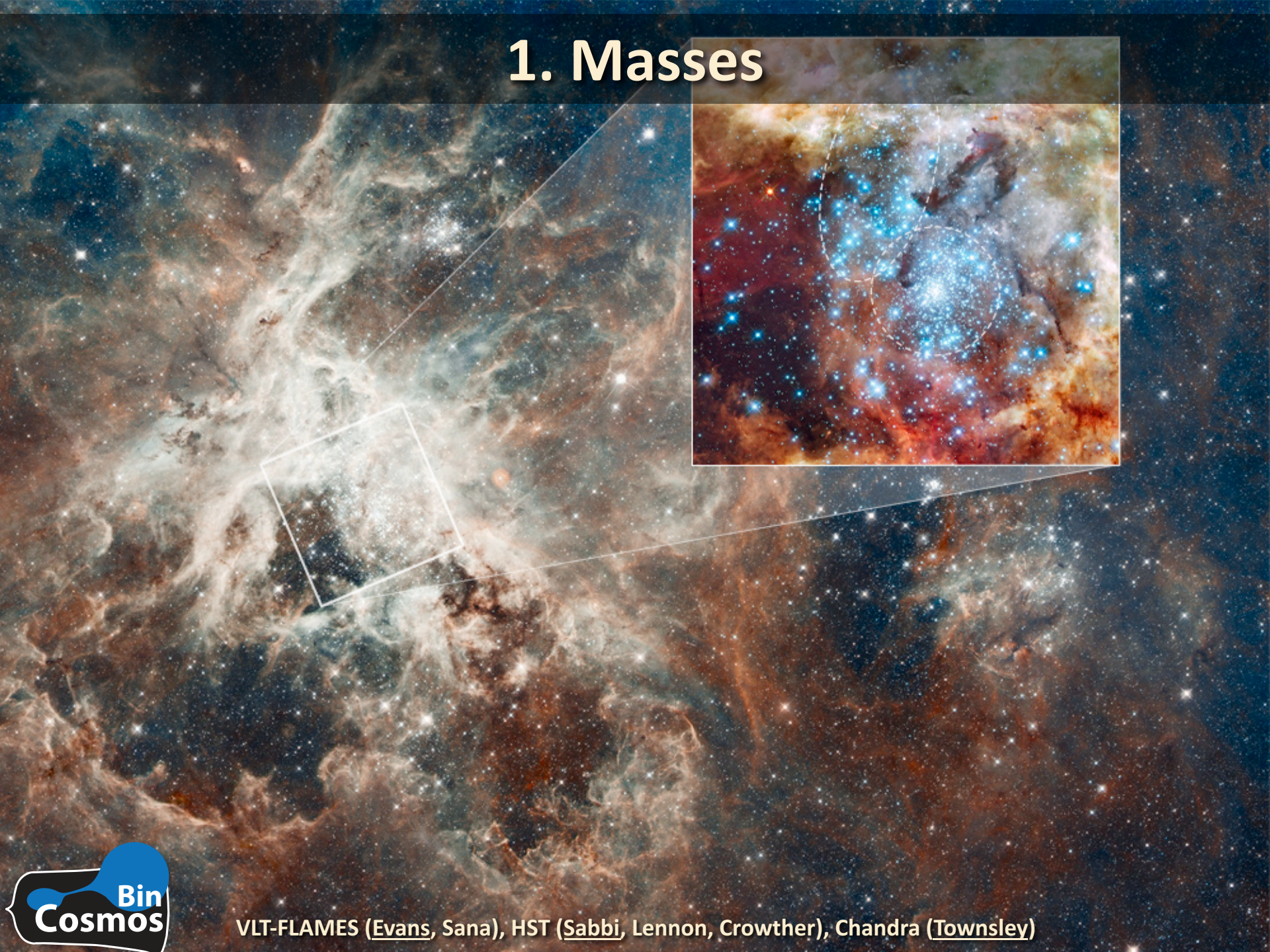
- Densest sampling of the upper stellar mass function available (up to 200M_o)
- ***Excess of massive stars*** above 30M_o (32 ± 12% more than predicted by Salpeter IMF in mass range 15–200M_o)
- ***Flatter IMF slope:*** $1.90^{+0.37}_{-0.26}$ (cf. Salpeter = 2.35)

Scheider et al. (under review)

VLT-FLAMES (Evans, Sana), HST (Sabbi

Bin Cosmos

1. Masses



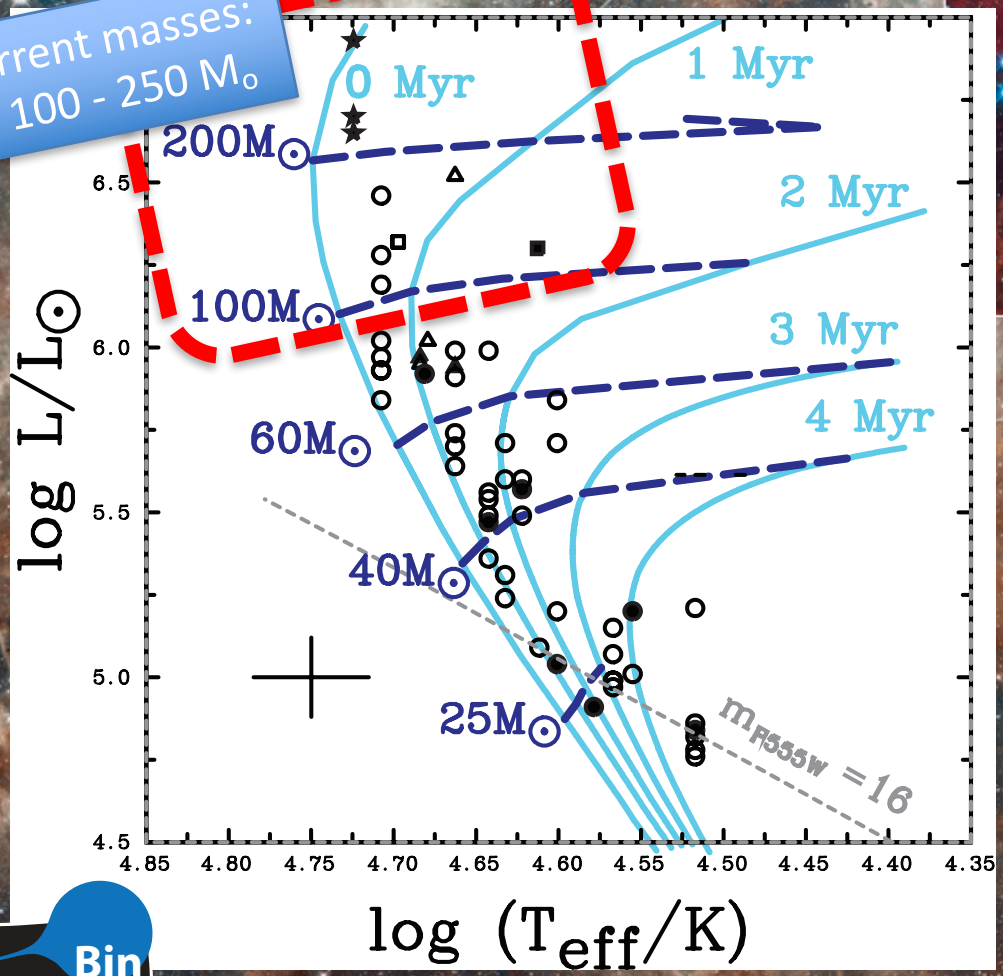
VLT-FLAMES (Evans, Sana), HST (Sabbi, Lennon, Crowther), Chandra (Townsley)

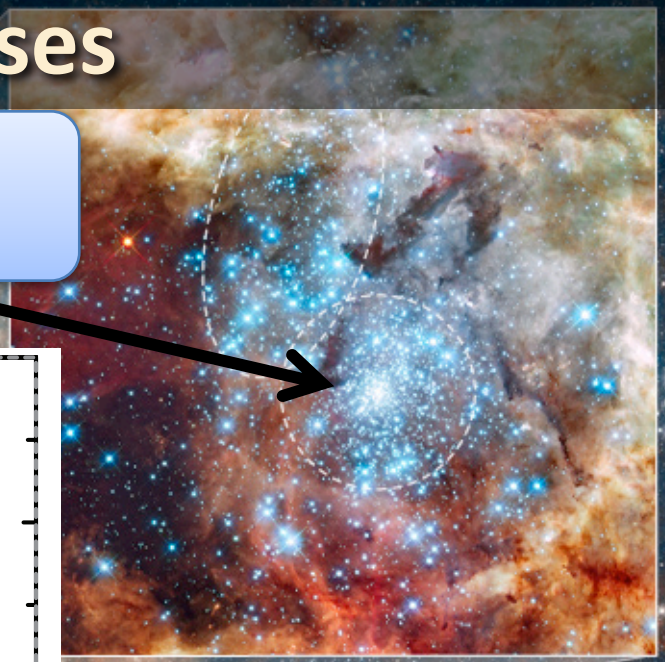
1. Masses

Nine "Monster" stars

Crowther+10,+15

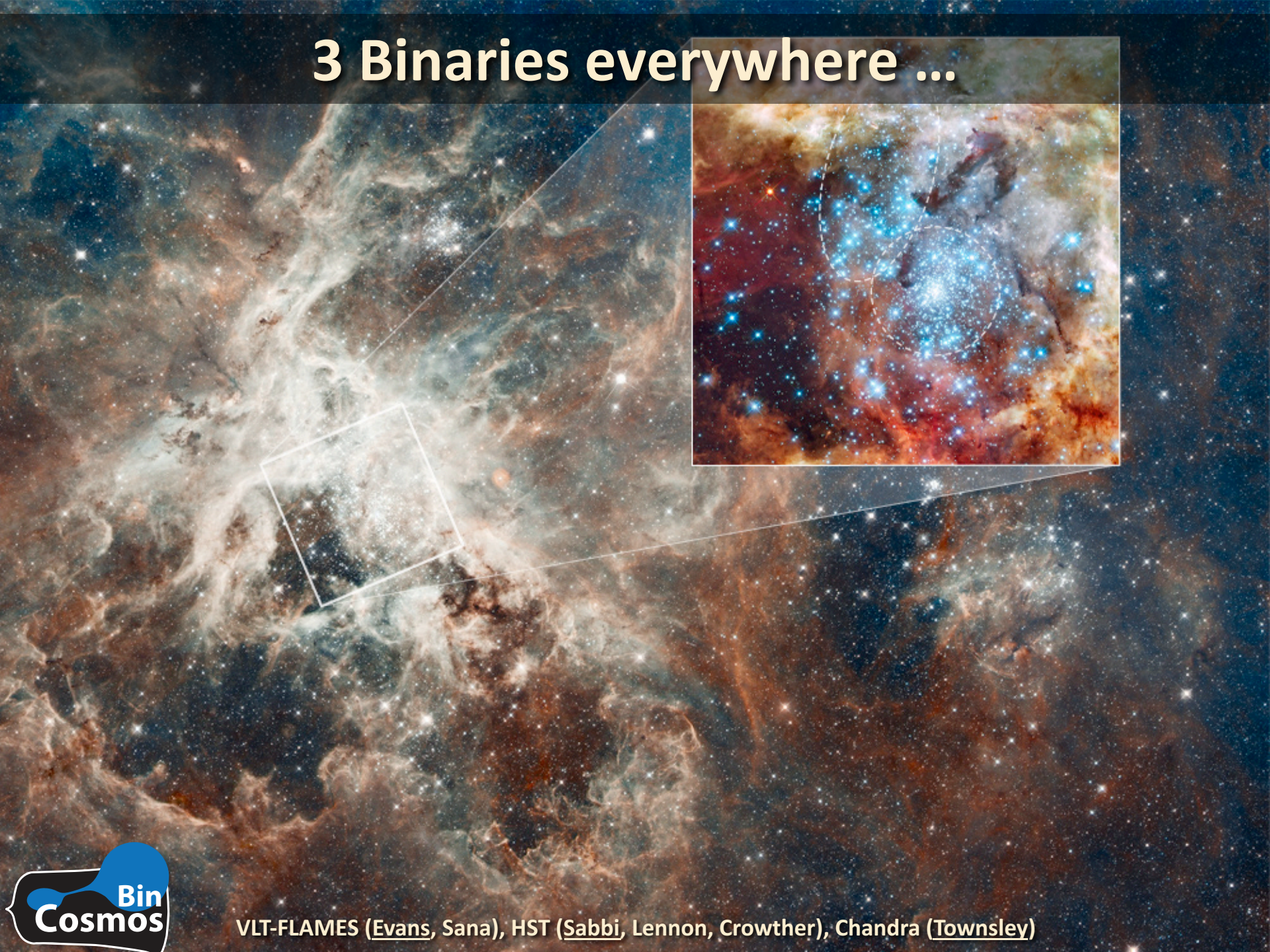
Current masses:
~ 100 - 250 $M_\odot$





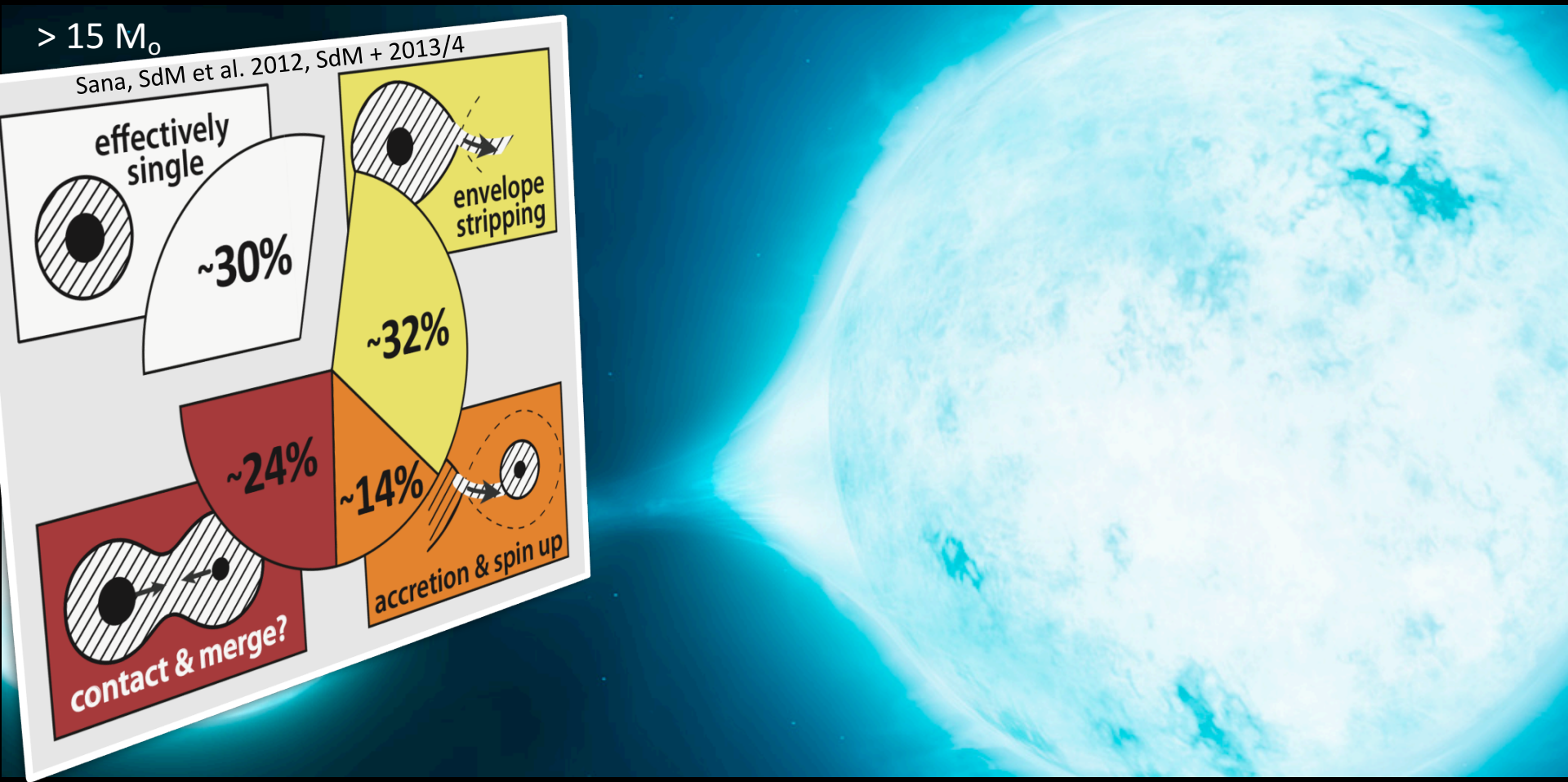
Bin Cosmos

3 Binaries everywhere …



VLT-FLAMES (Evans, Sana), HST (Sabbi, Lennon, Crowther), Chandra (Townsley)

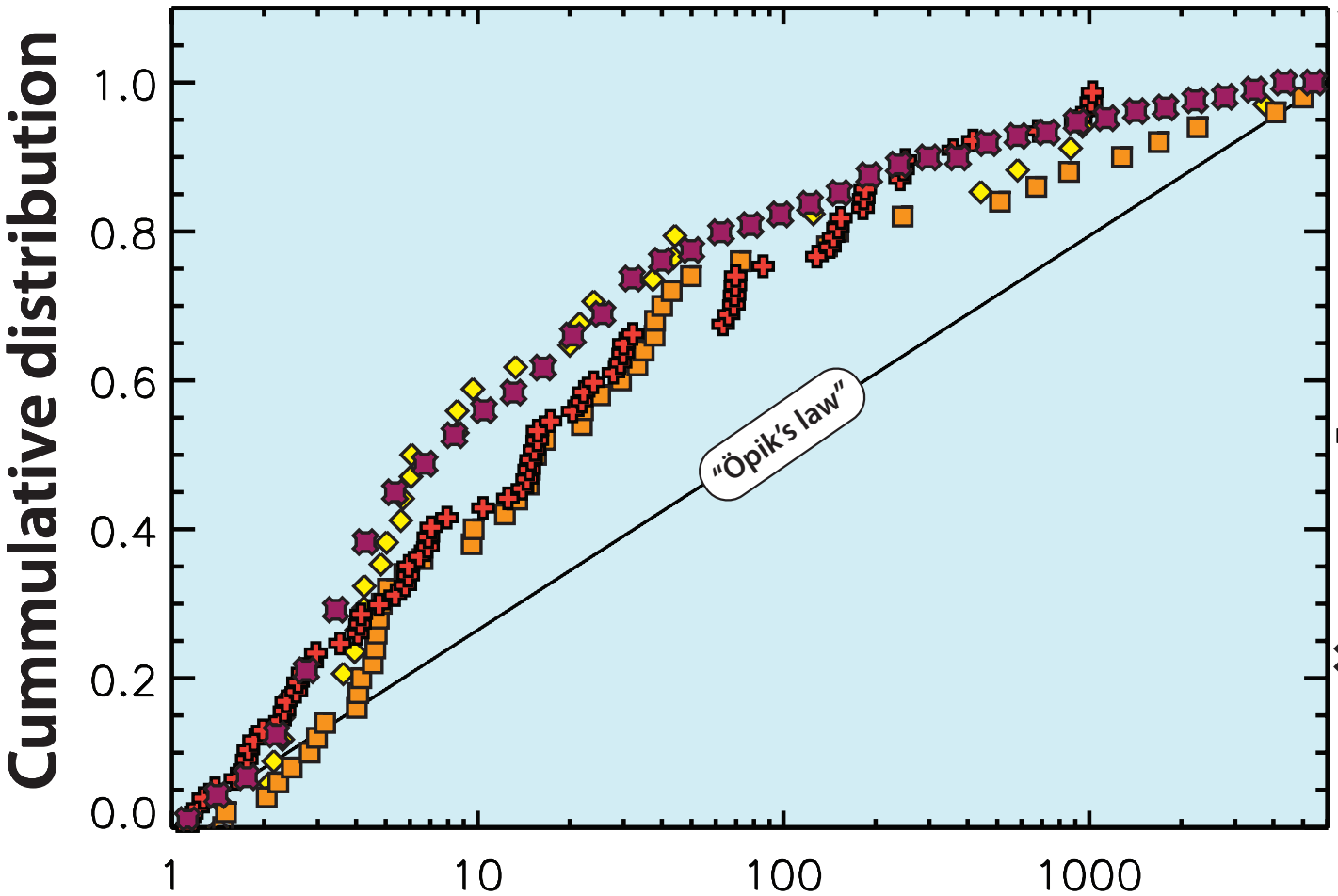
This is not exotic



cf. Abt+78, Kobulnicky+Fryer07, Mason+09, Chini+12, Kobulnicky+14, Sana+12, Sana+13, Dunstall+15, Moe+16, Almeida+17, ...

Bin Cosmos

How do we know?



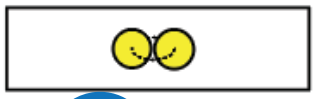
Sana, de Mink et al. (2012)
Young clusters (MW)
$f_{bin,O}$ = 0.56 ± 0.06
N_O = 71

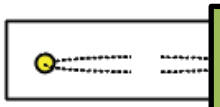
Kobulnicky et al. (2014)
association Cyg OB2 (MW)
$f_{bin,O}$ = 0.51 ± 0.07
N_O = 45

Almeida et al. w/SdM (2017)
30 Doradus (LMC)
$f_{bin,O}$ = 0.35 ± 0.03
N_O = 360

Barba et al. *
OWN Southern sky (MW)
$f_{bin,O}$ = 0.50 ± 0.03
N_O = aa205

*Adapted from Sana (2017)

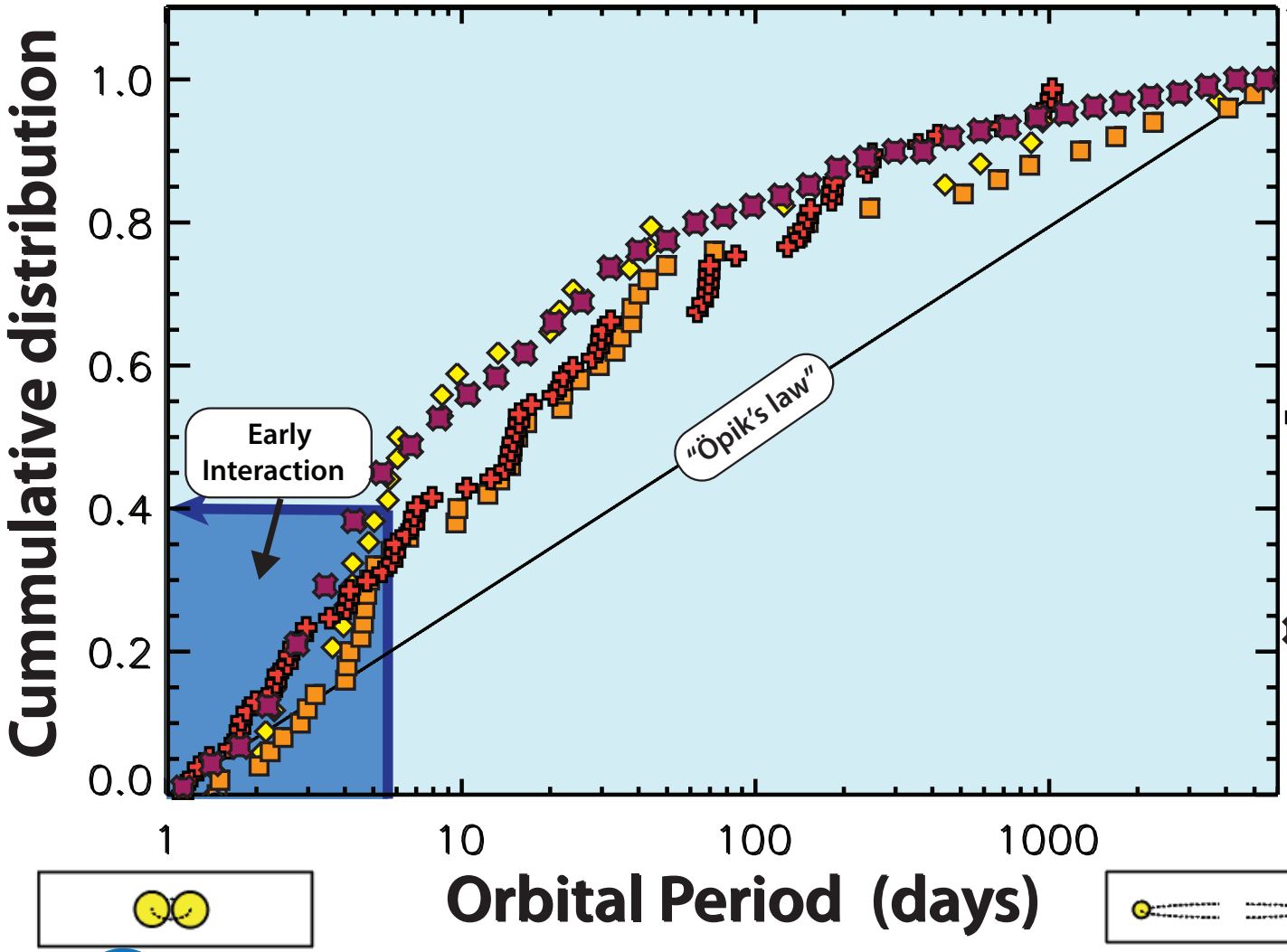




Soon:
early B Star Surveys
(PIs: Taylor / Sana)

Bin Cosmos

How do we know?



Sana, de Mink et al. (2012)
Young clusters (MW)
$f_{bin,O}$ = 0.56 ± 0.06
N_O = 71

Kobulnicky et al. (2014)
association Cyg OB2 (MW)
$f_{bin,O}$ = 0.51 ± 0.07
N_O = 45

Almeida et al. w/SdM (2017)
30 Doradus (LMC)
$f_{bin,O}$ = 0.35 ± 0.03
N_O = 360

Barba et al. *
OWN Southern sky (MW)
$f_{bin,O}$ = 0.50 ± 0.03
N_O = aa205

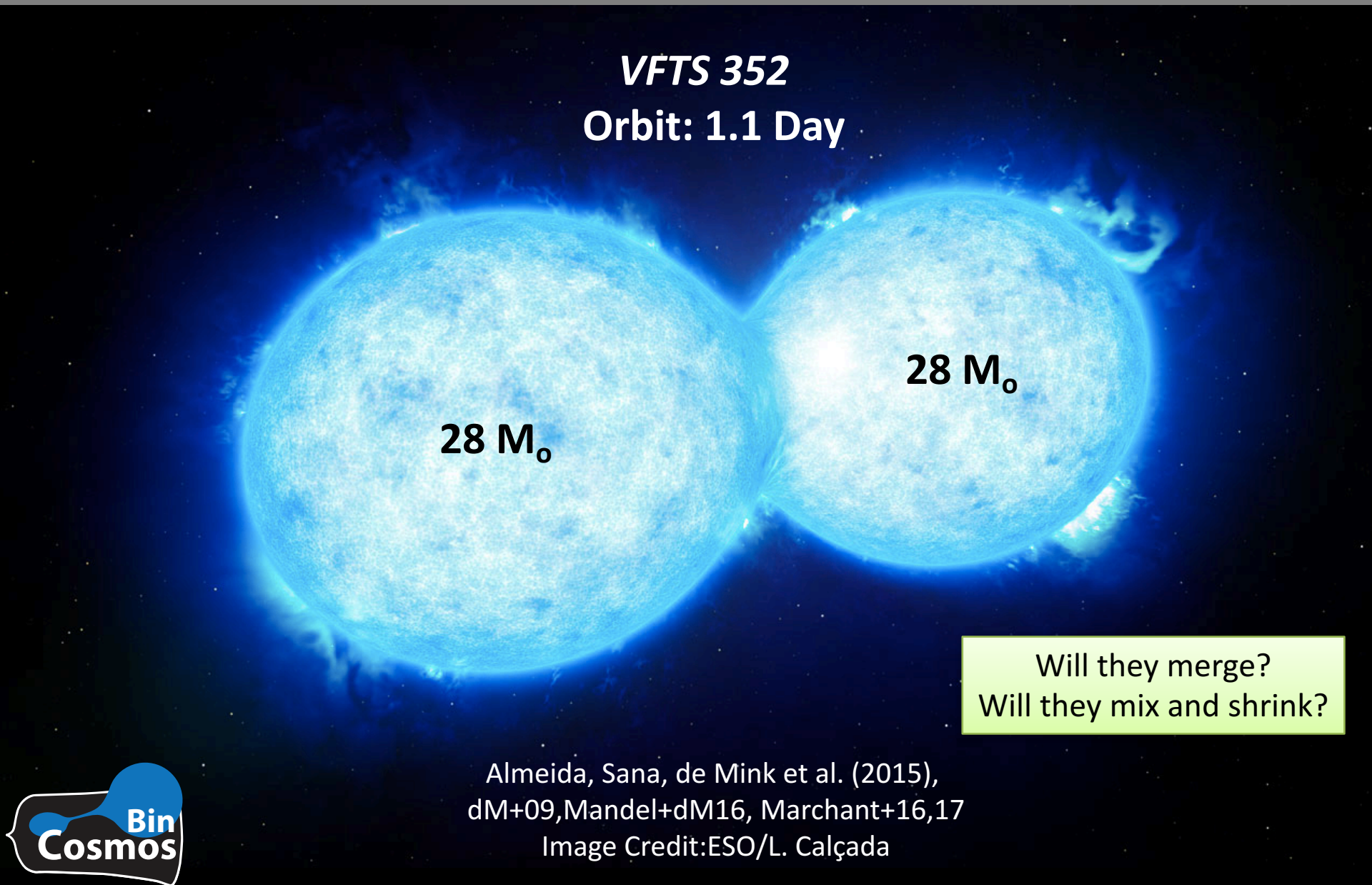
*Adapted from Sana (2017)

Soon:
early B Star Surveys
(PIs: Taylor / Sana)

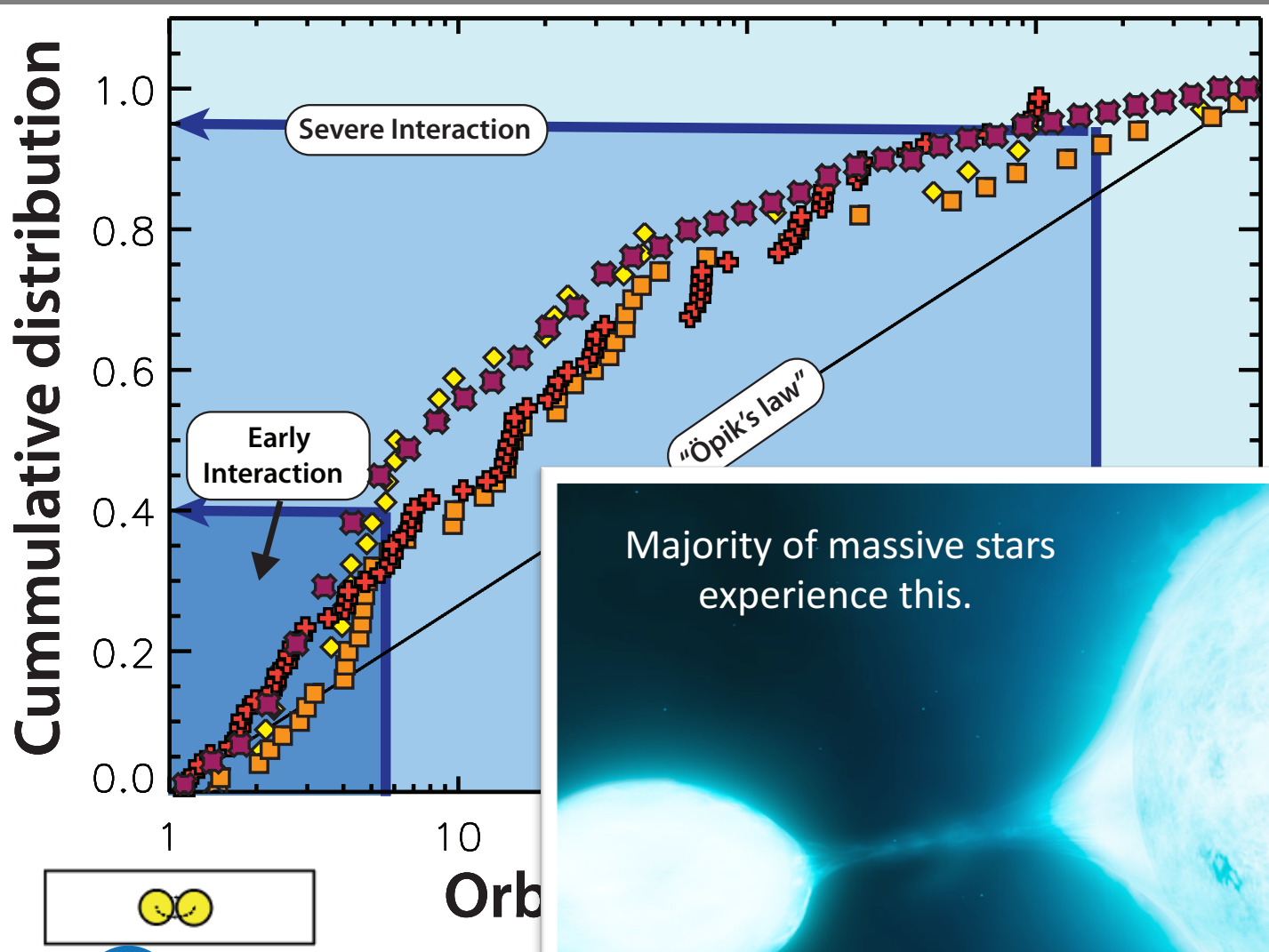
Bin Cosmos

www.eso.org

Animation credit: ESO: L. Calcada


VFTS 352
Orbit: 1.1 Day
28 M_o
28 M_o
Will they merge?
Will they mix and shrink?
Almeida, Sana, de Mink et al. (2015),
dM+09,Mandel+dM16, Marchant+16,17
Image Credit:ESO/L. Calçada
Bin Cosmos

How do we know?



Sana, de Mink et al. (2012)
Young clusters (MW)
$f_{bin,O}$ = 0.56 ± 0.06
N_O = 71

Kobulnicky et al. (2014)
association Cyg OB2 (MW)
$f_{bin,O}$ = 0.51 ± 0.07
N_O = 45

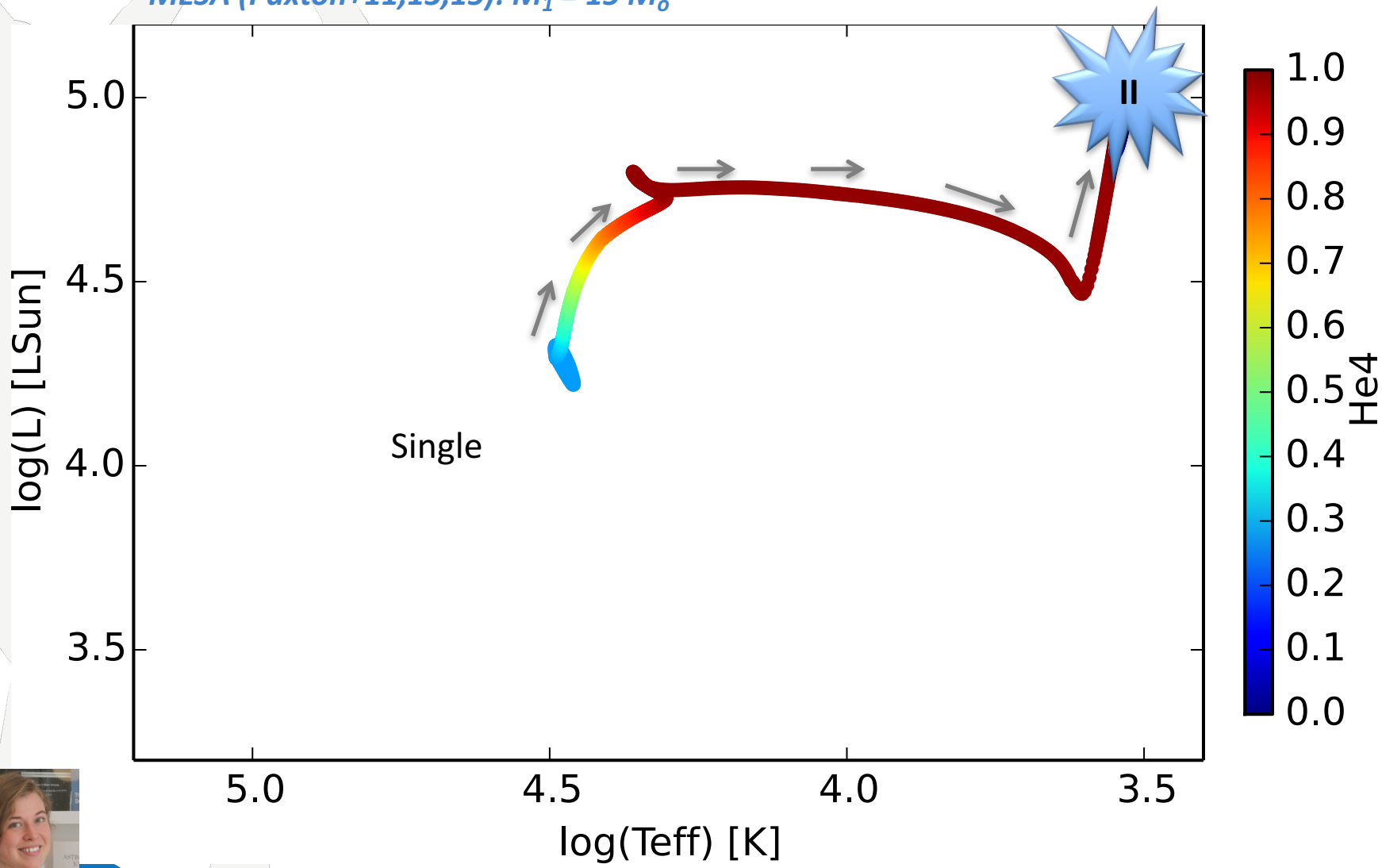
Almeida et al. w/SdM (2017)

Bin Cosmos

Evolution of a single star

Götberg et al. (2017a)

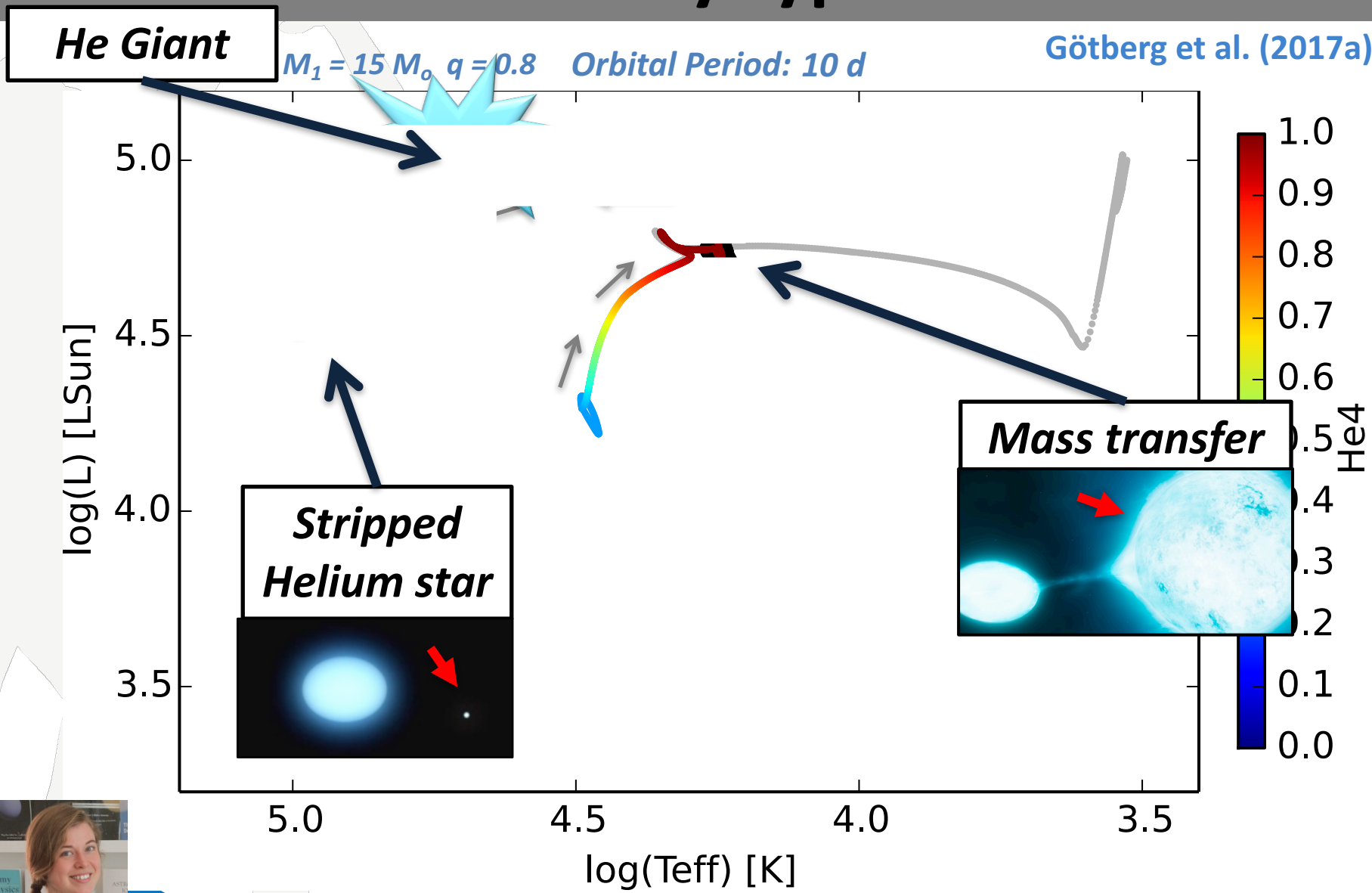
MESA (Paxton+11,13,15): M_1 = 15 M_o



Ylva Götberg

S.E. de Mink

Evolution of a very typical donor star

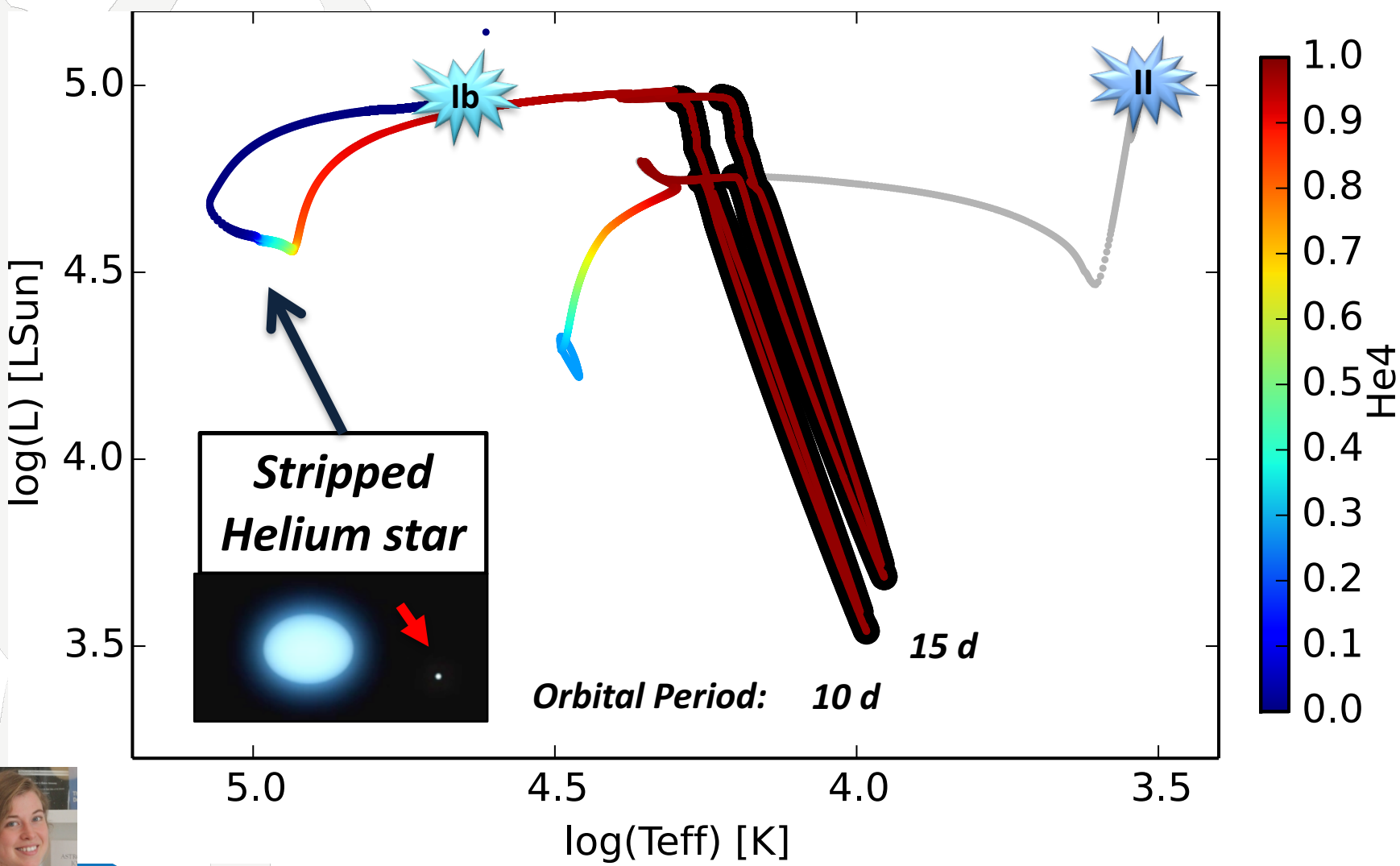


Ylva Götberg

cf. Kippenhahn, Podsiadlowski, Langer, Wellstein, Pols, Yoon, Claeys, Eldridge, Bersten ….

Donor star

Götberg et al. (in prep)



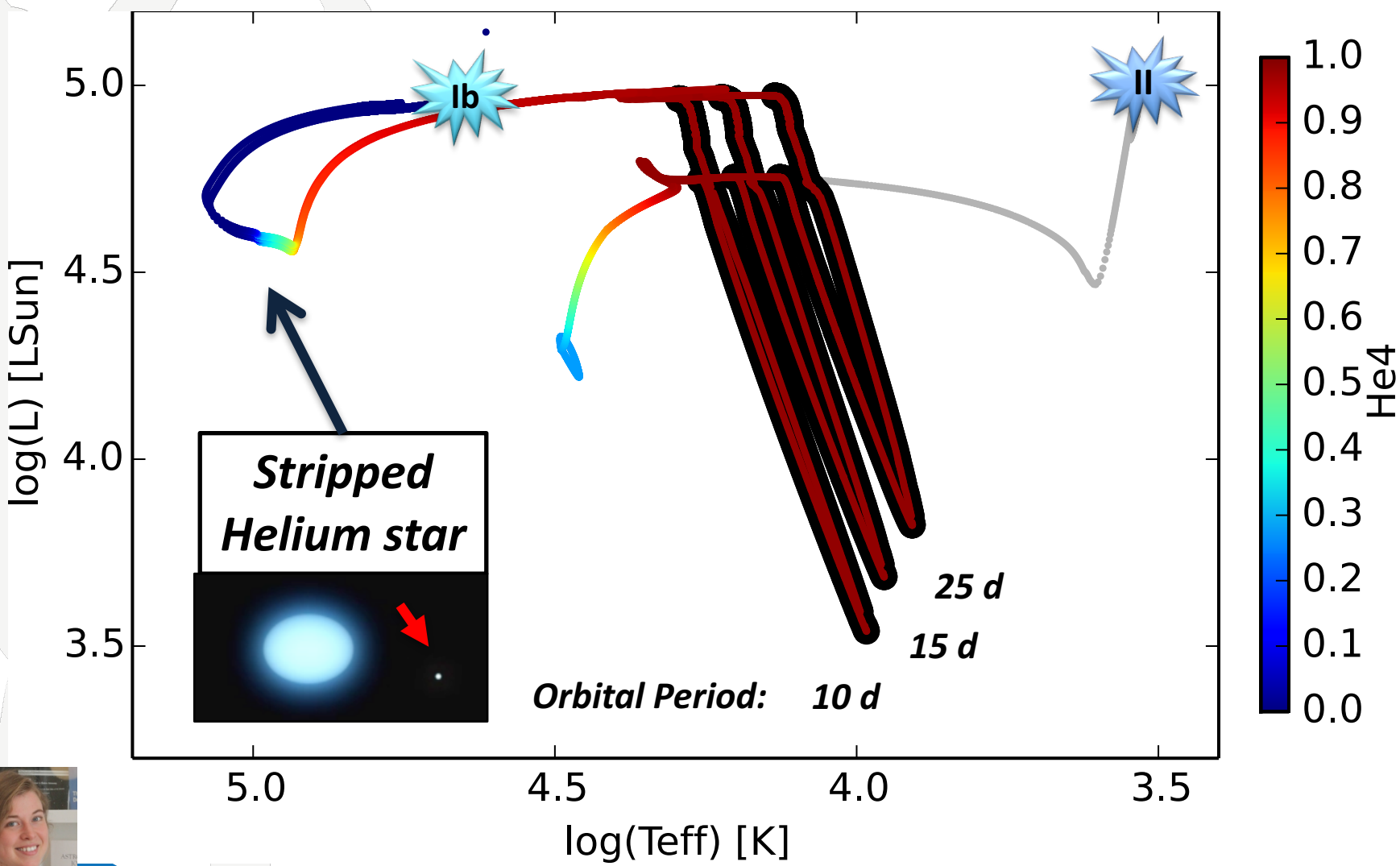
cf. Kippenhahn, Podsiadlowski, Langer, Wellstein, Pols, Yoon, Claeys, Eldridge, Bersten ….

Ylva Götberg

Donor star

Götberg et al. (in prep)

MESA: M_1 = 15 M_o q = 0.8

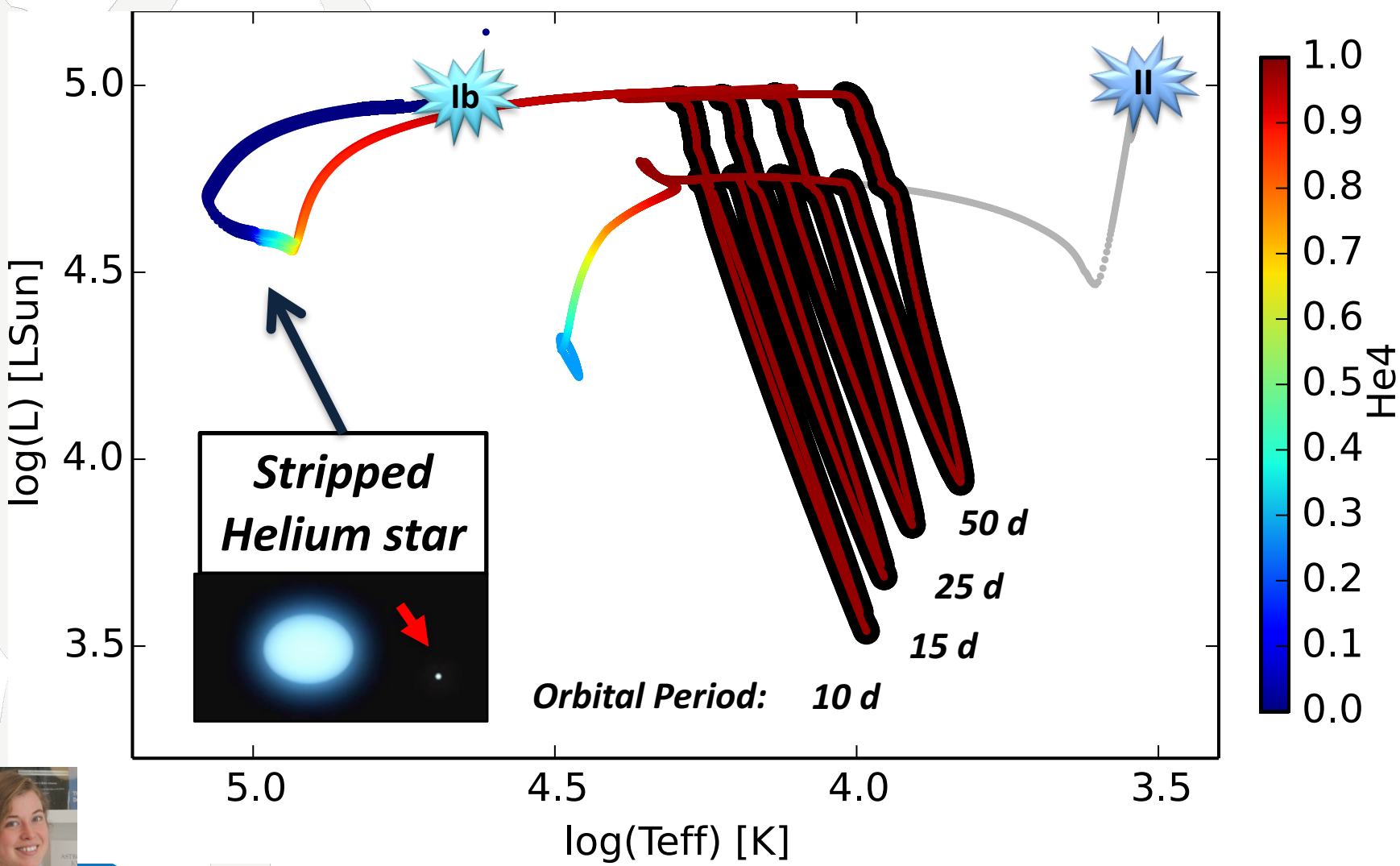


Ylva Götberg

cf. Kippenhahn, Podsiadlowski, Langer, Wellstein, Pols, Yoon, Claeys, Eldridge, Bersten ….

Donor star

Götberg et al. (in prep)



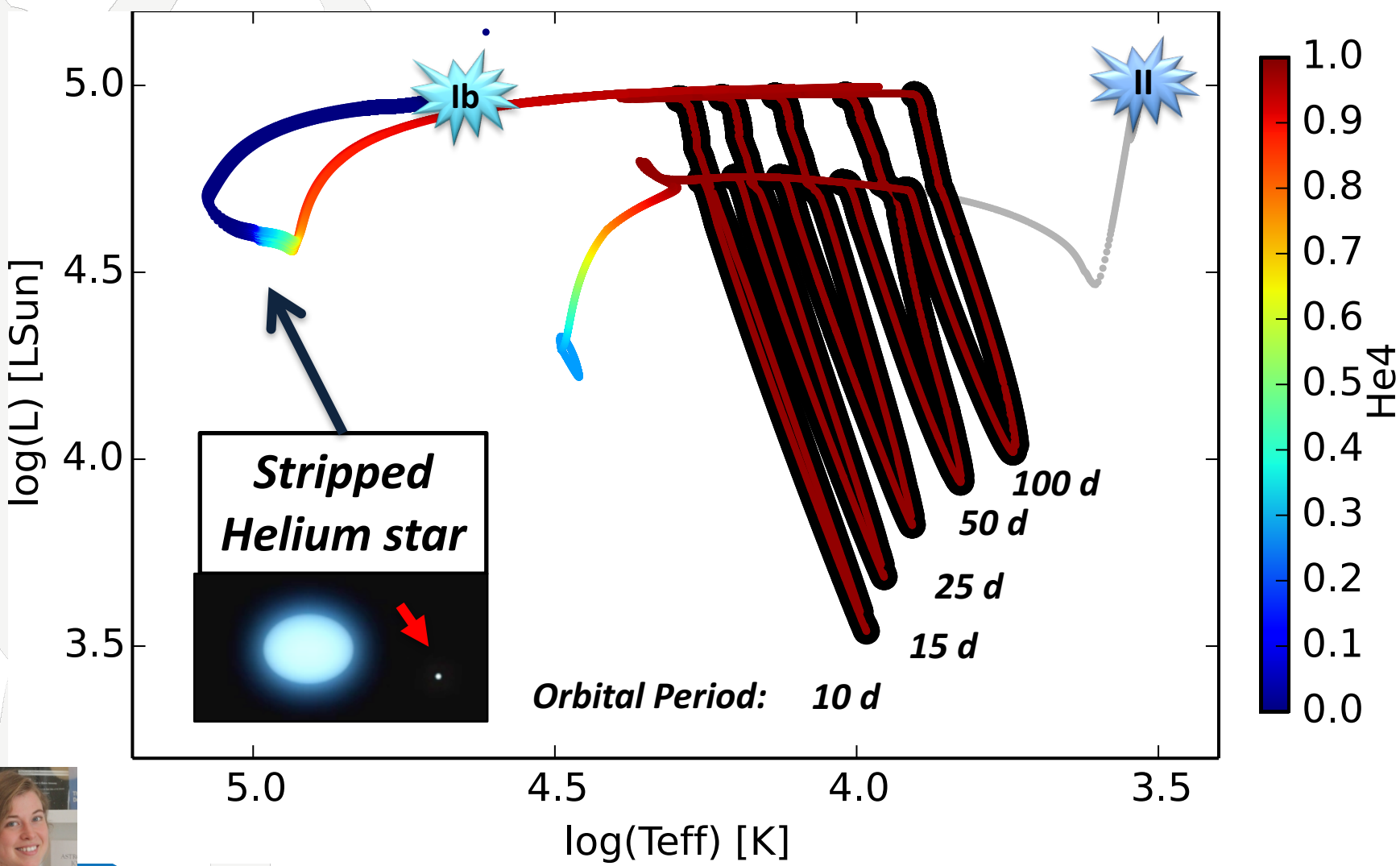
Ylva Götberg

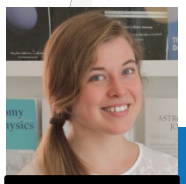
cf. Kippenhahn, Podsiadlowski, Langer, Wellstein, Pols, Yoon, Claeys, Eldridge, Bersten ….

S.E. de Mink

Donor star

Götberg et al. (in prep)





Ylva Götberg

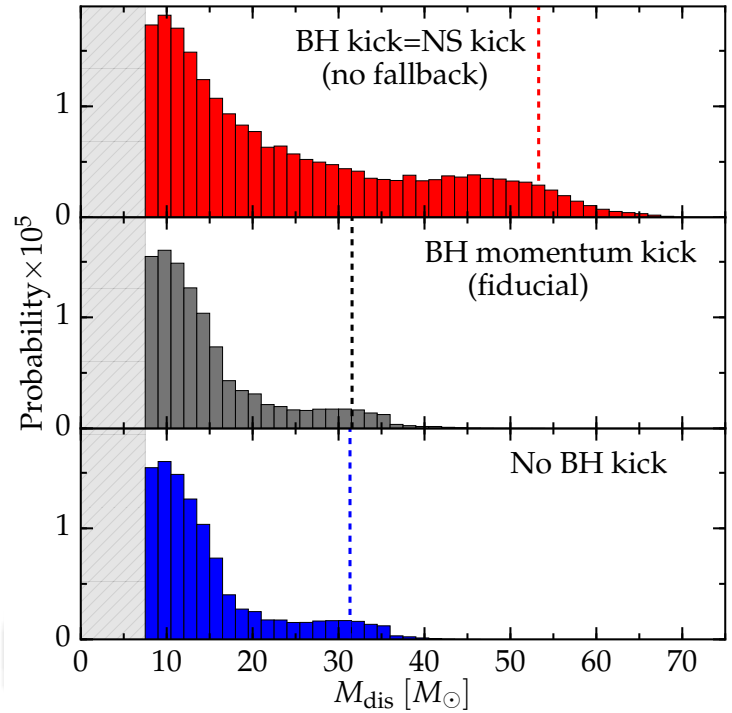
cf. Kippenhahn, Podsiadlowski, Langer, Wellstein, Pols, Yoon, Claeys, Eldridge, Bersten ….

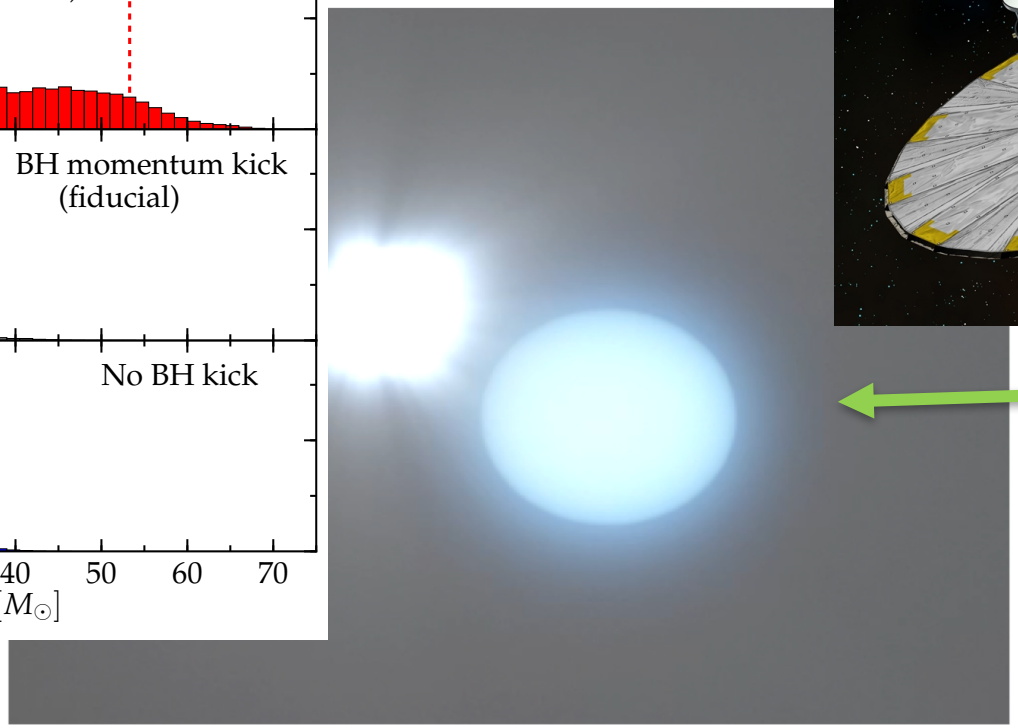
Animation of the life of a typical massive Star

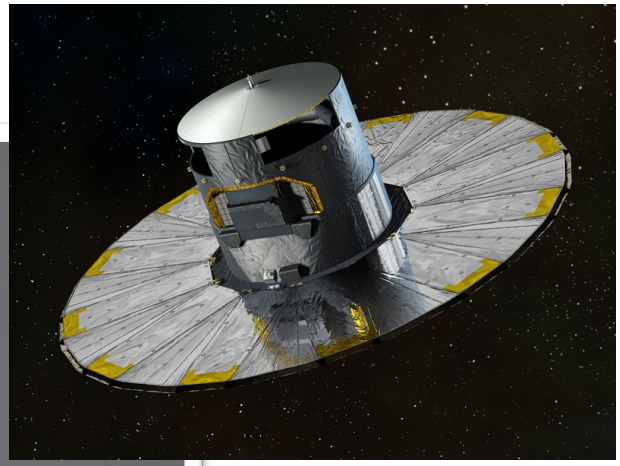
www.eso.org

Animation: ESO: Calçada/Kornmesser/de Mink

Majority (75-98%) disrupt when the first star explodes







Runaway stars
(or "walkaway stars")

Zapartas, dM +17b
Renzo & dM (in prep)

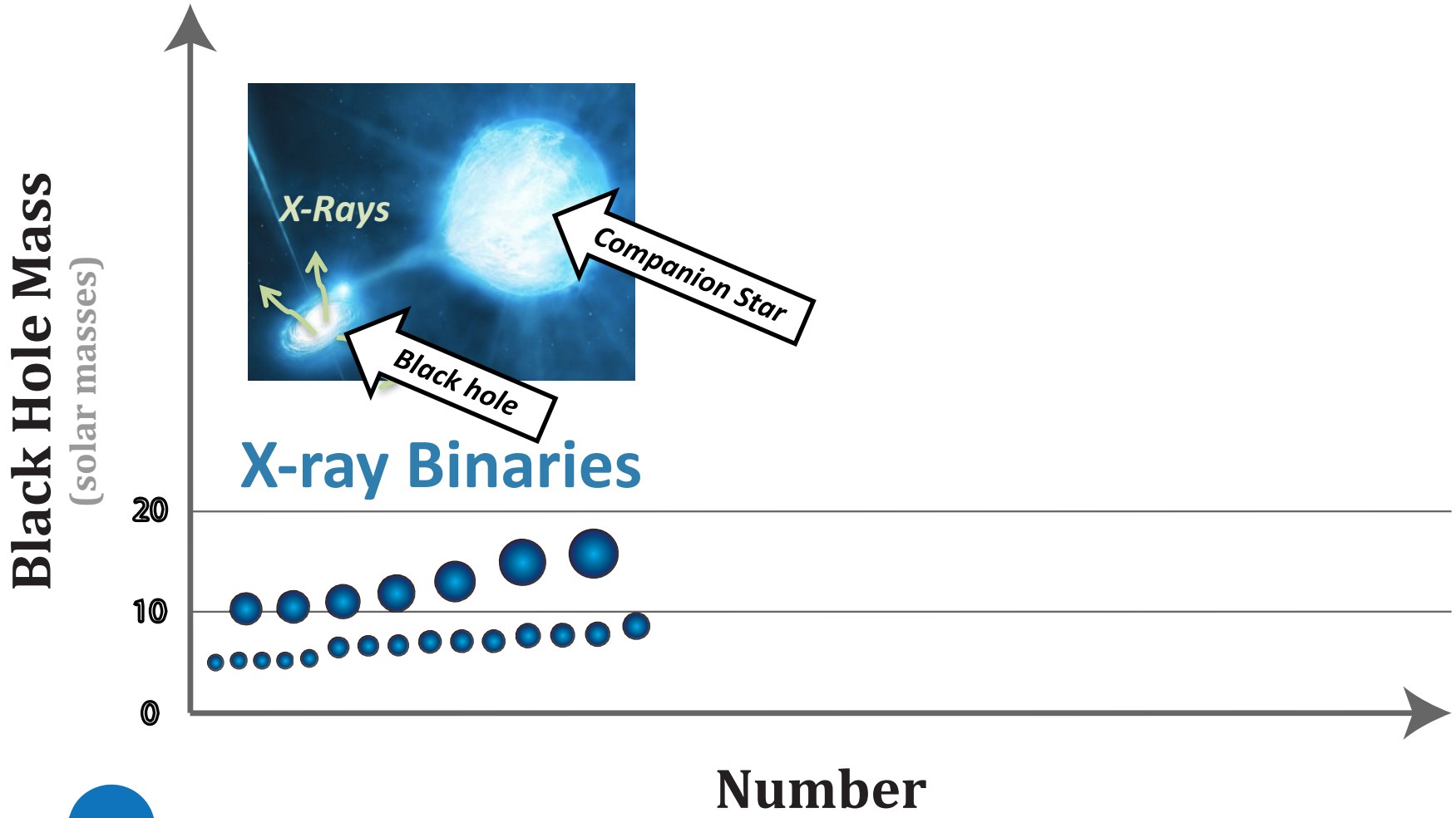
Manos Zapartas

Mathieu Renzo

Cf. Zwicky57, Blaauw61, Boersma61, Brandt+Podsiadlovski95, Kalogera96, Fryer+98, Dray+05, Eldridge+11, Sana+prep

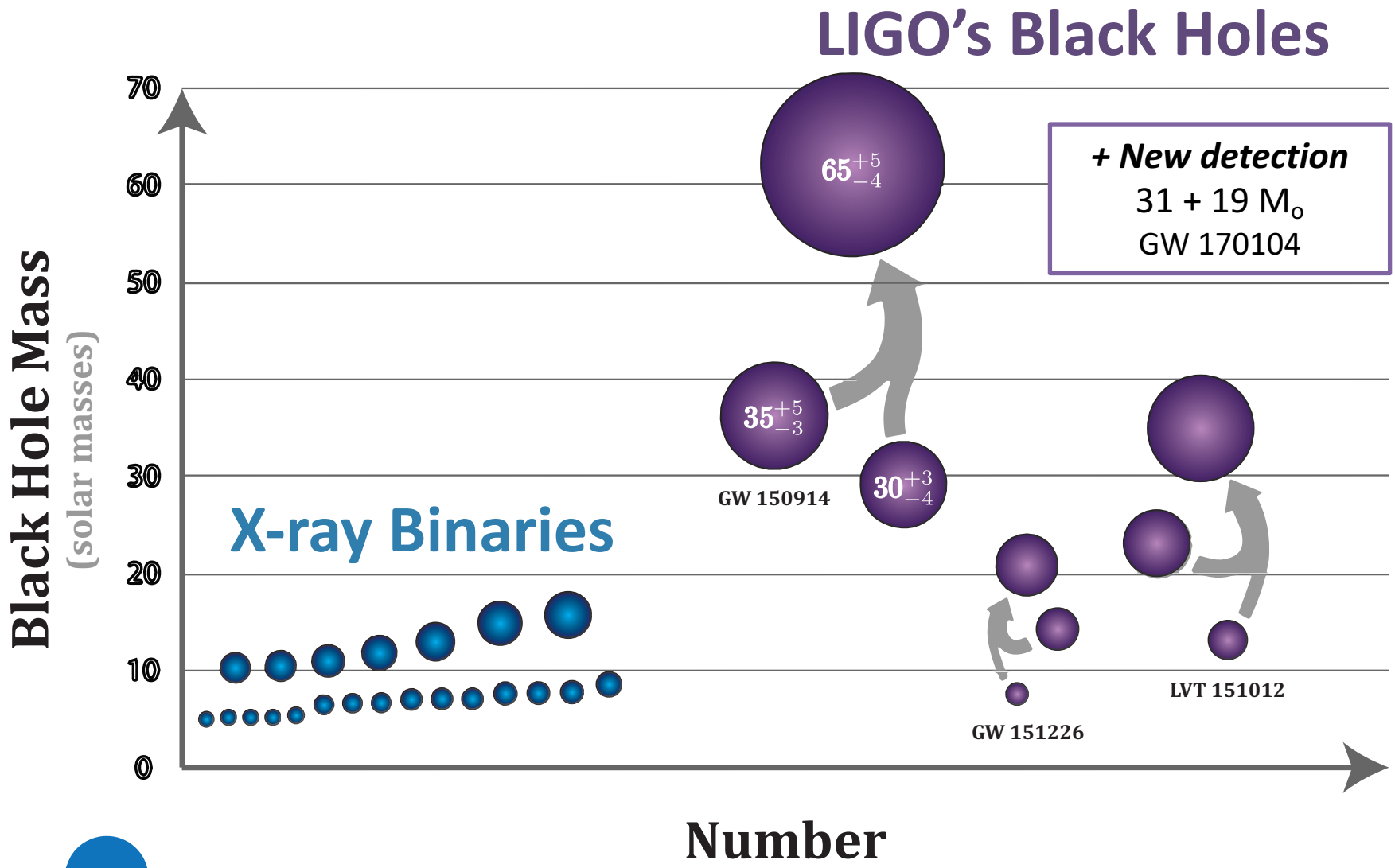
Bin Cosmos

Some binaries survive



Credit: ESO/L. Calçada/M.Kornmesser, & Caltech/MIT/LIGO

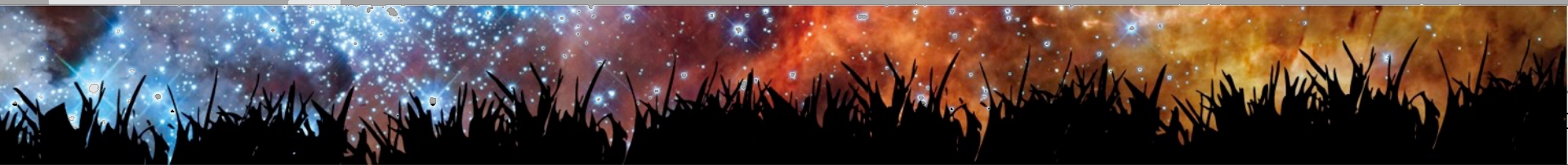
Some binary stars stay together forever



Credit: ESO/L. Calçada/M.Kornmesser, & Caltech/MIT/LIGO

BinCosmos

Why is it so hard to form binary black holes?

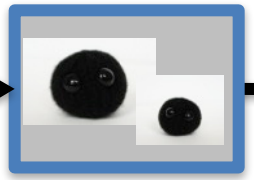


Two Main Challenges for all progenitor scenarios

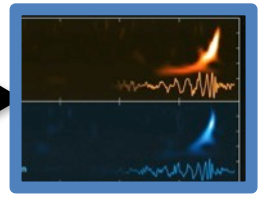
Progenitors

Birth

Formation BHs



Coalescence



0. Need to overcome their "Relationship issues"

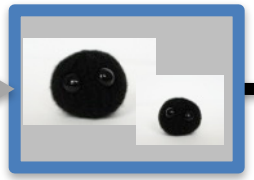
1. "Separation Challenge"

2. "Mass Challenge"

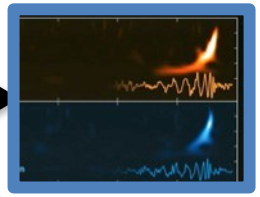
Separation

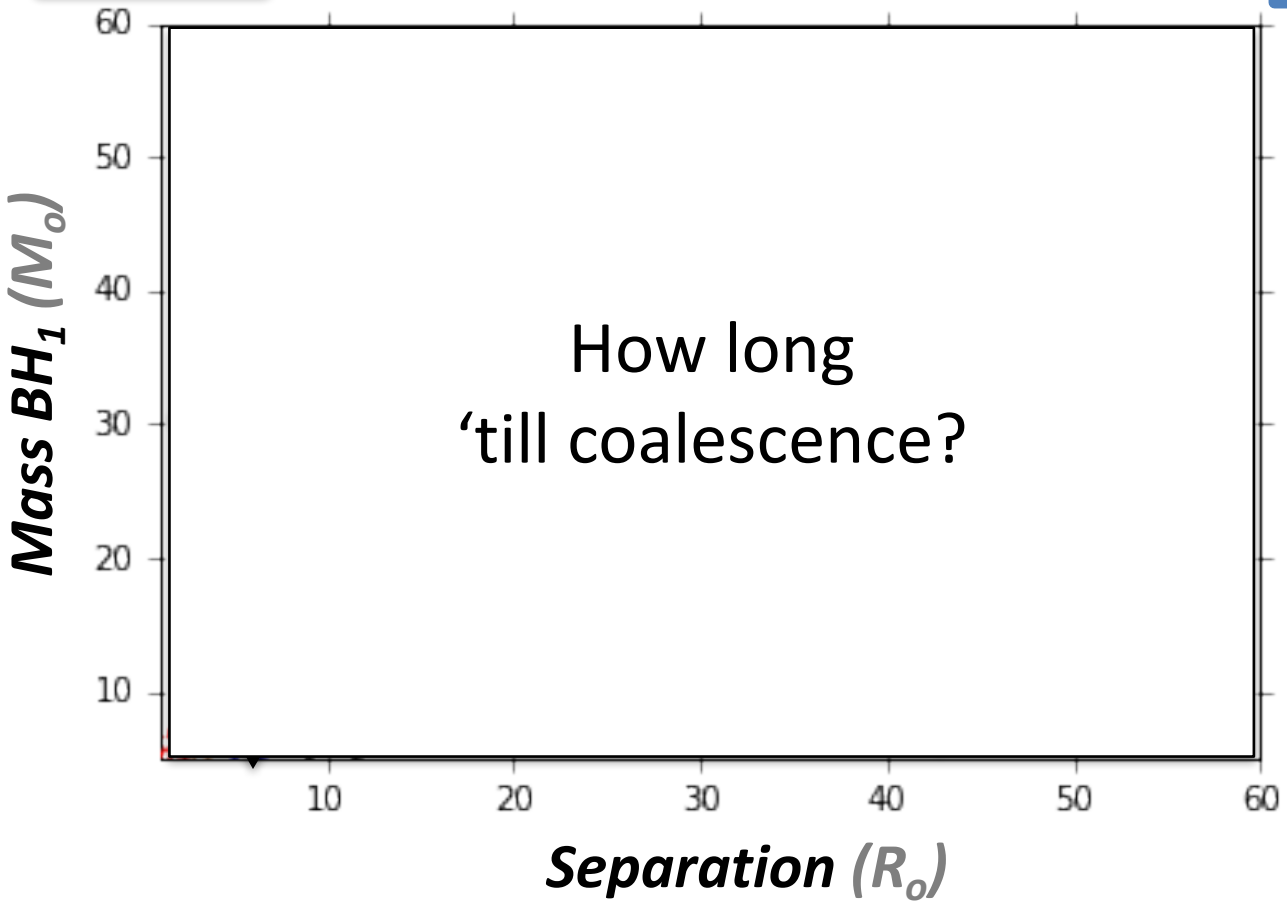
Birth

Formation BHs



Coalescence



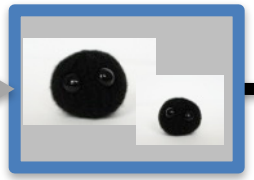


Using Peters '64

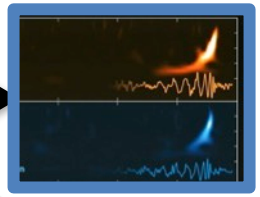
Separation

Birth

Formation BHs

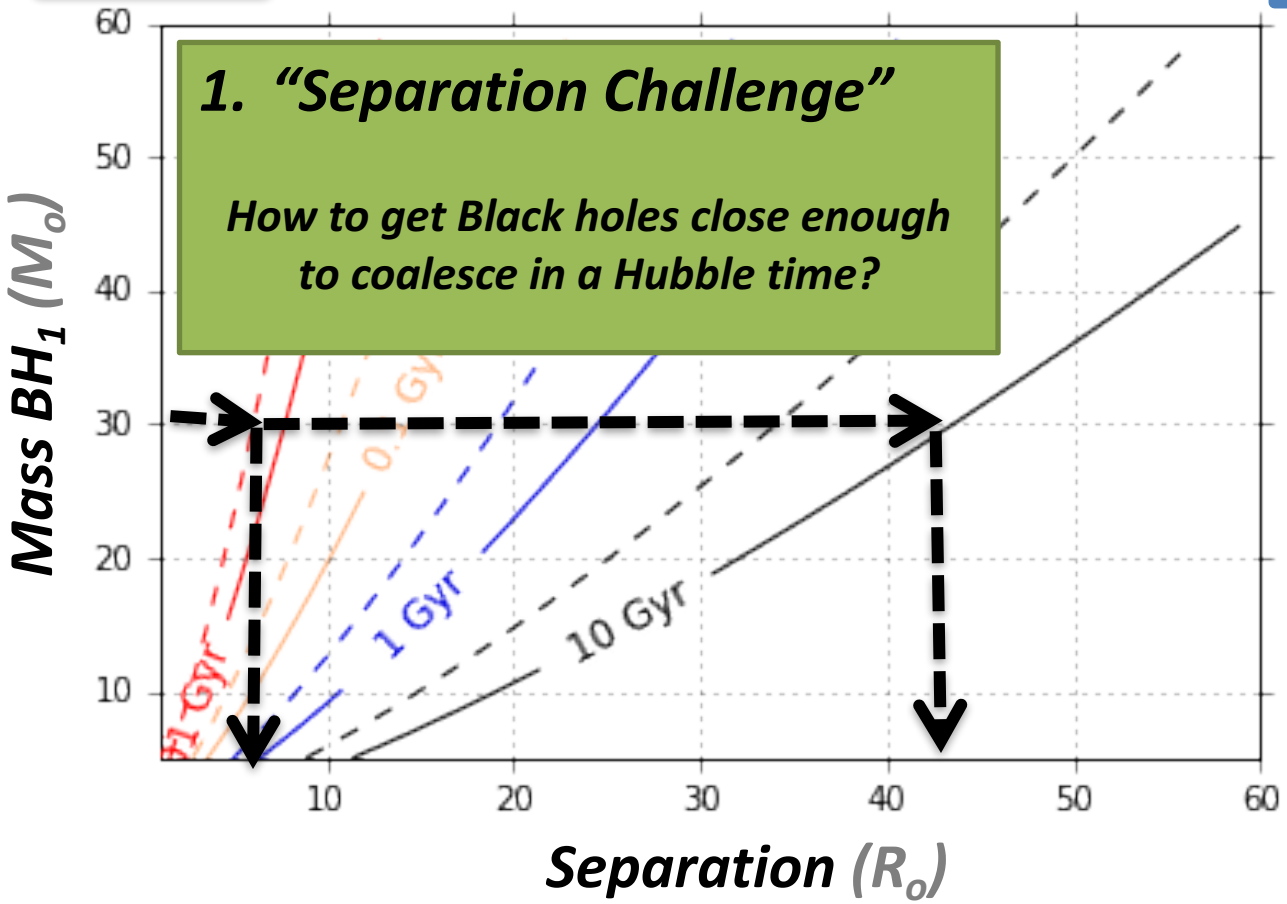


Coalescence



1. "Separation Challenge"

How to get Black holes close enough to coalesce in a Hubble time?



R_o ~ 7e10 cm

Using Peters '64

Separation

1. "Separation Challenge"

How to get Black holes close enough to coalesce in a Hubble time?

$10\ R$

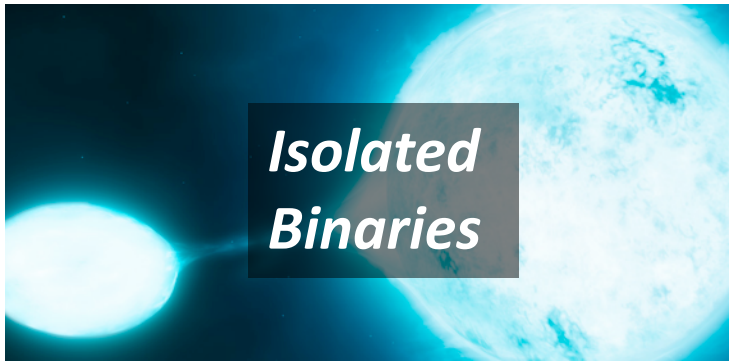
2. "Mass Challenge"

How to avoid excessive Mass loss?

Two types of Formation Channels

1. Evolutionary formation channels

2. Dynamical formation channels



Stellar Density

Two types of Formation Channels

1. Evolutionary formation channels

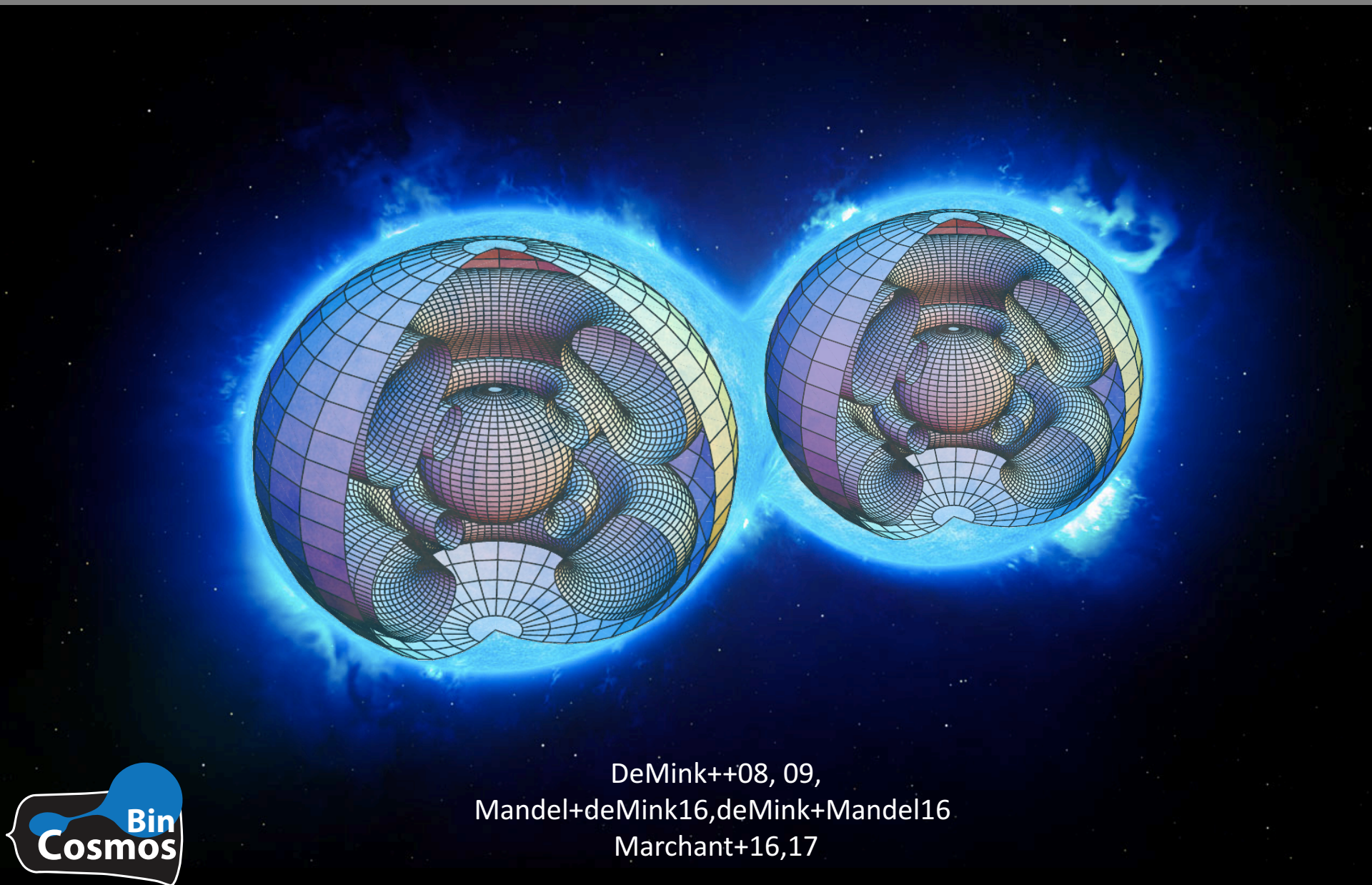
- ✓ **Classical channel** (involving common envelope or other forms of mass transfer)
- ✓ **Chemically Homogeneous Channel** (mixing processes in near contact binaries)
- ✓ Population III binaries
- ✓ Stable mass transfer …

2. Dynamical formation channels

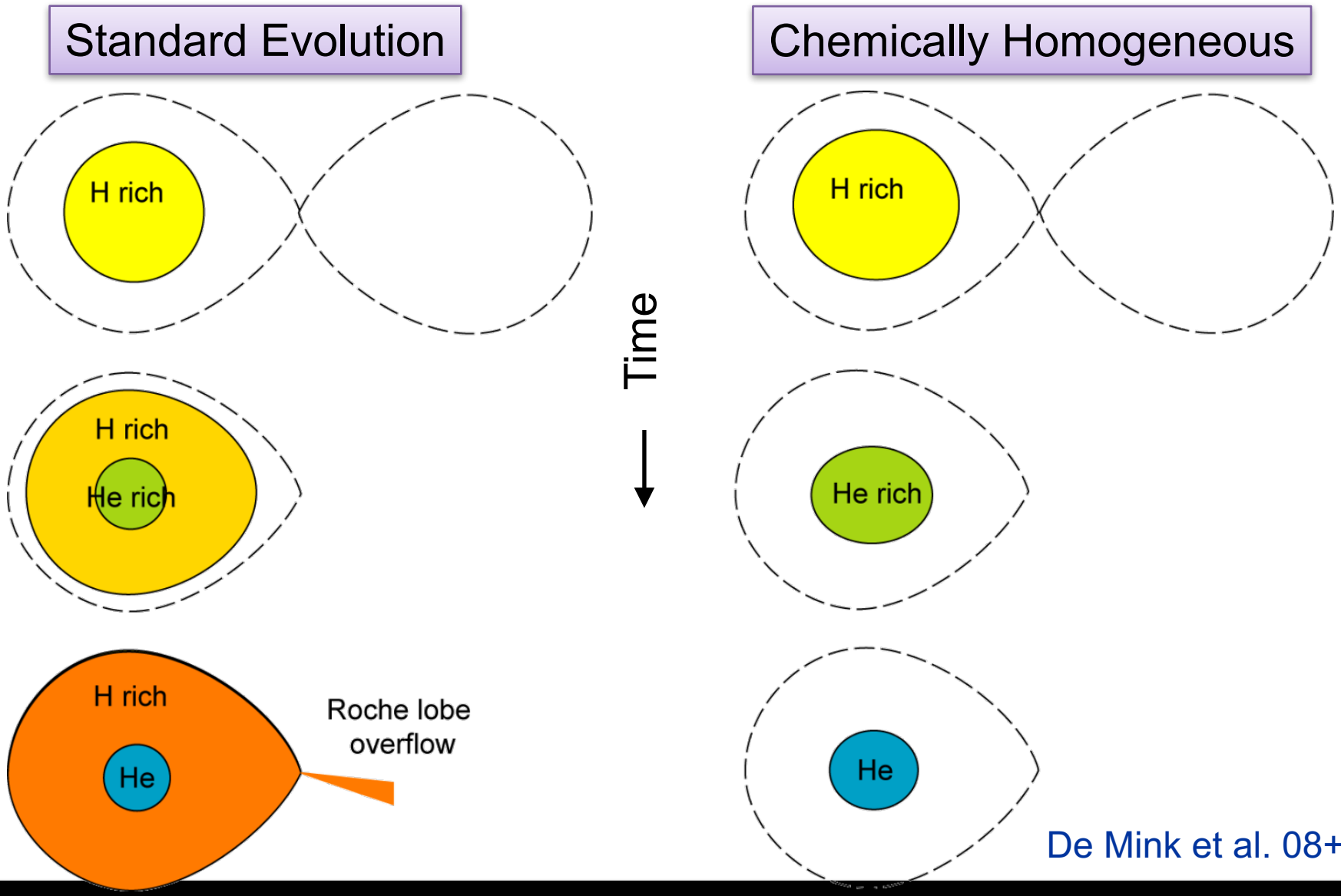
- ✓ Chaotic Dynamics in **dense Star Clusters** or Nuclear star clusters
- ✓ “” in Nuclear star clusters in center of galaxies
- ✓ “” Near a supermassive black hole, possibly with **AGN discs**
- ✓ Dynamics in lower mass clusters
- ✓ Resonances in **Triple systems**
- ✓ …

Chemically Homogeneous Channel

deMink+08, +09,
Mandel+deMink16, deMink+Mandel16
Marchant+16, 17

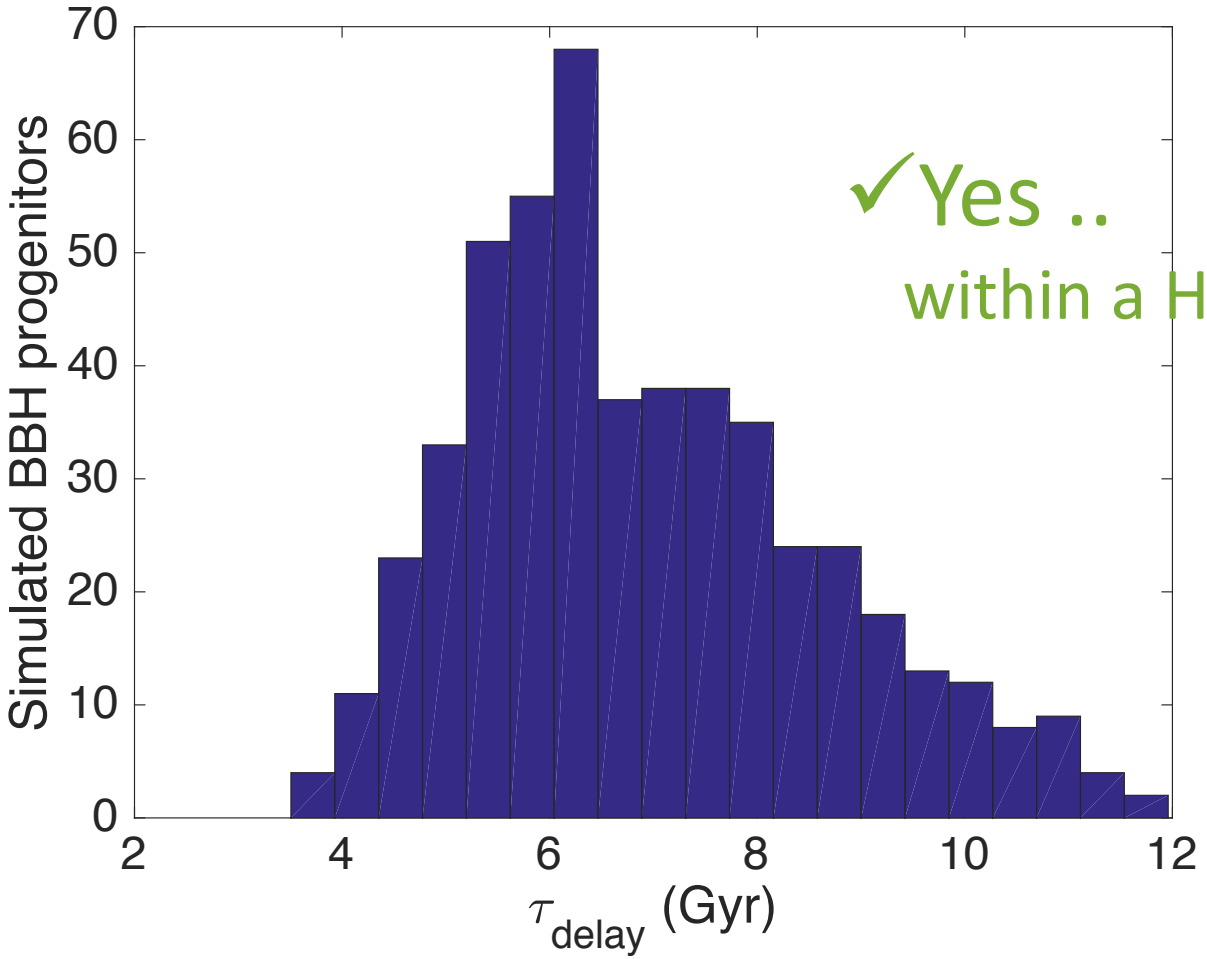


DeMink++08, 09,
Mandel+deMink16,deMink+Mandel16
Marchant+16,17



De Mink et al. 08+09

Do the Binary BHs merge?

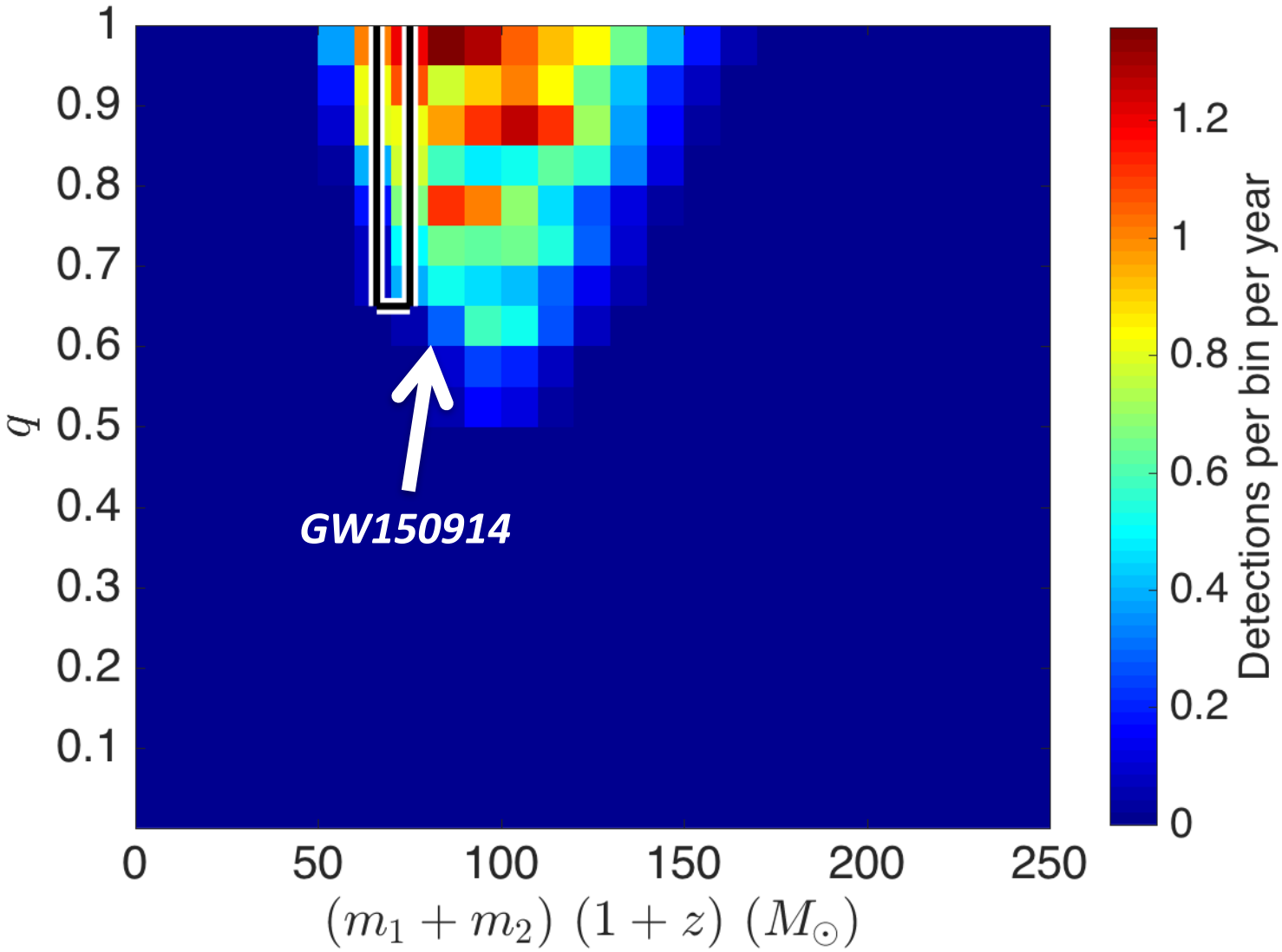


✓Yes ..

within a Hubble time

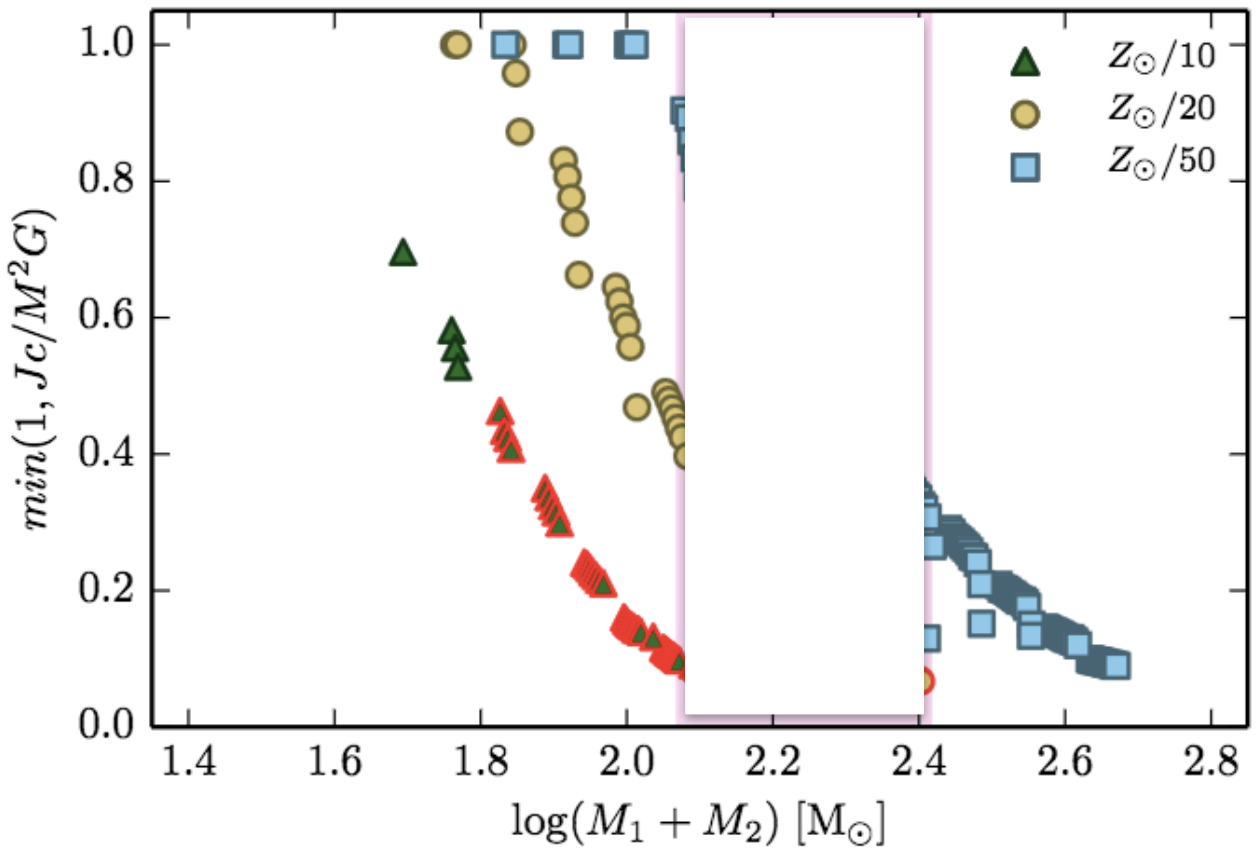
Mandel & De Mink (2016) cf. Marchant et al. (2016)

De Mink & Mandel (2016)



What about the spins?

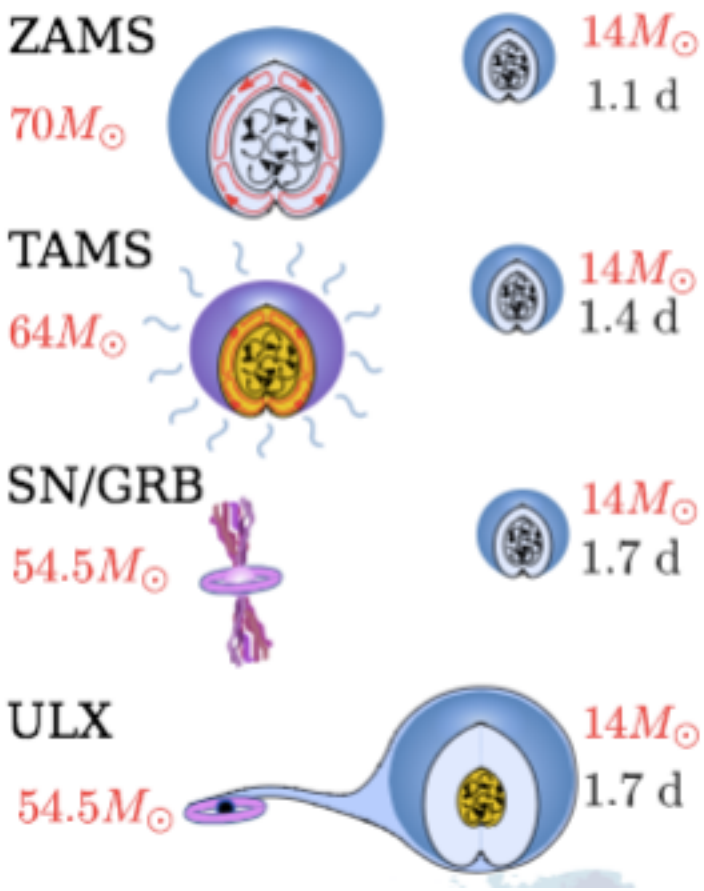
Low spins from metallicities Zsun / 10

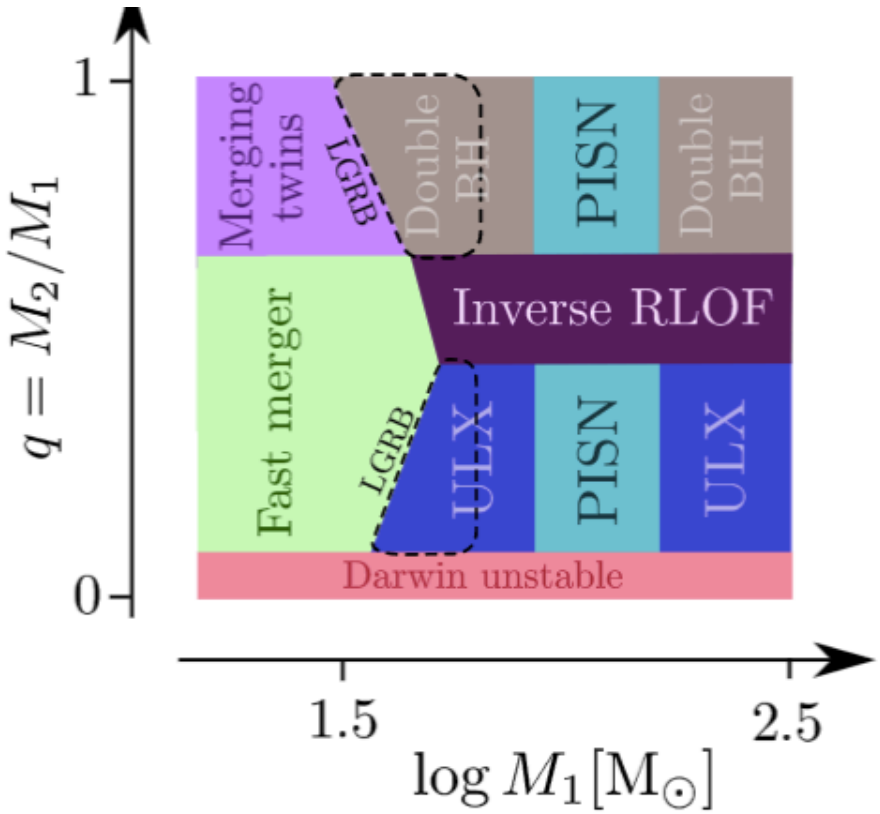


Marchant + 2016,
De Mink+ in prep, Marchant in prep.

Side products: what if only one star evolves chemically homogeneous

ULX: Marchant + 2017, Pair Instability Supernova: Du Boisson + to be submitted





Wrap up

Main challenges that (Single) Star evolution faces

- How much mass do stars lose?
- How much mixing occurs (how big are their cores)?
- What decides whether a star forms a NS or BH?
- What are the kicks?

Recent Insight from (EM) observations

- Binarity very common
- IMF extends above 150 Msun
- Possibly evidence for excess of massive stars

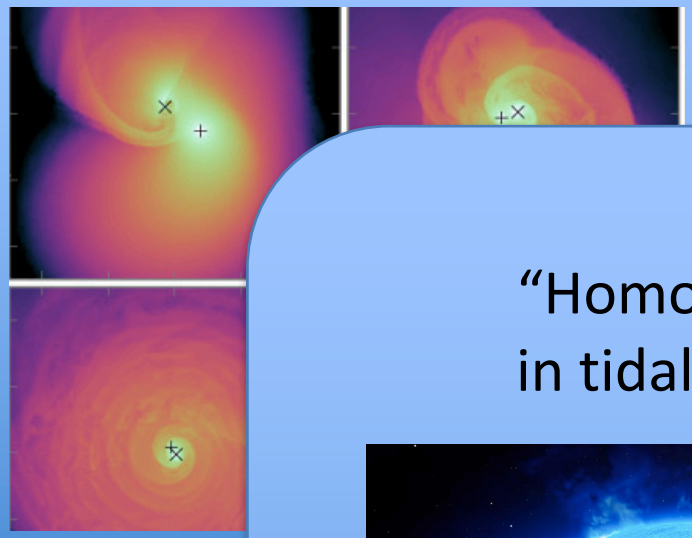
Formation scenarios:

- Explanations for the Mass and Separation Challenge

Homgeneous evolution scenario

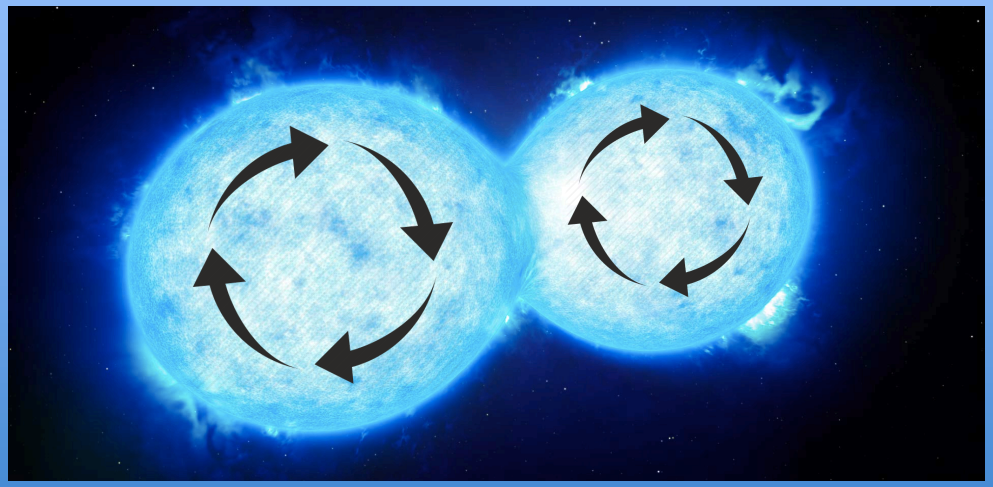
Making-of

(i)
"Classical" Channel



(ii)
Dynamical interactions

(iii)
"Homogeneous evolution"
in tidally distorted binaries




… Positions opening in Amsterdam