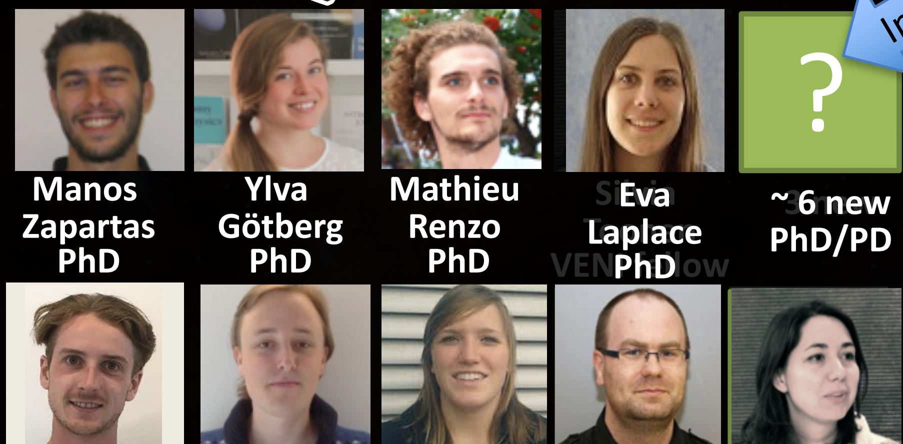
How did “they” form?

Astrophysical Origin of the Gravitational Wave Detections

BinCosmos Amsterdam



Manos Zapartas PhD | Ylva Götberg PhD | Mathieu Renzo PhD | Eva Laplace PhD | ~6 new PhD/PD

Interested?

David Hendriks MSc | Walter v Rossem MSc | Floor Broekgaarden MSc | Rob Farmer Postdoc | Silvia Toonen Prize fellow

Selma E. de Mink
University of Amsterdam

edit background NASA Paresce, Design E. Buunk

How did "they" form?

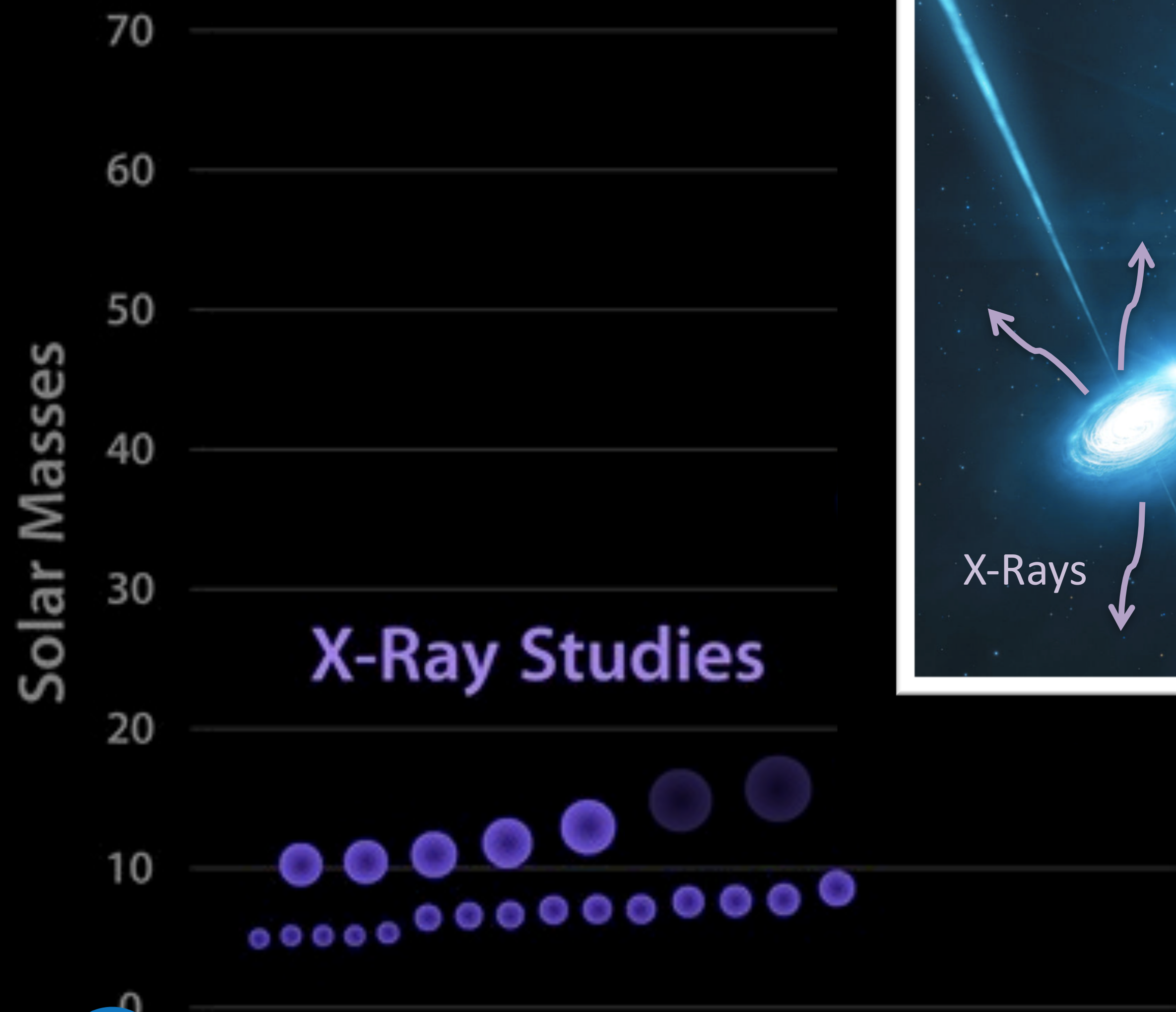
Astrophysical Origin of the Gravitational Wave Detections

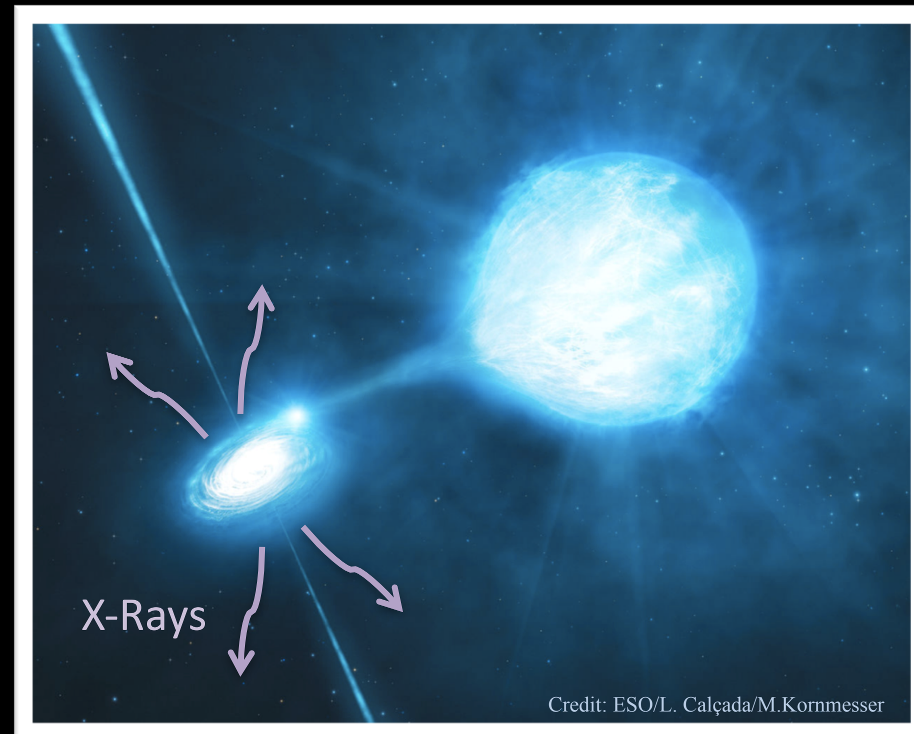
Recent / long term external collaborators include: Wolfgang Kerzendorf, Jose Groh, **Ilya Mandel, Pablo Marchant, Chris Belczynski, Andrew King, Philip Podsiadlovski, Ed van den Heuvel,** Simon Portegies-Zwart, Rob Izzard, Simon Stevenson, **Alejandro Vigna-Gómez,** Norbert Langer, Tom Maccarone, Hugues Sana, Chris Evans, Ori Fox, Schuyler van Dyk, Claus Leitherer, Leo Almeida, Alex de Koter, Paul Crowther, Former students: Coen van Neijssel, Abel Schootemeijer, VLT-FLAMES Massive Star Consortium

edit background NASA Paresce, Design E. Buunk

Selma E. de Mink
University of Amsterdam

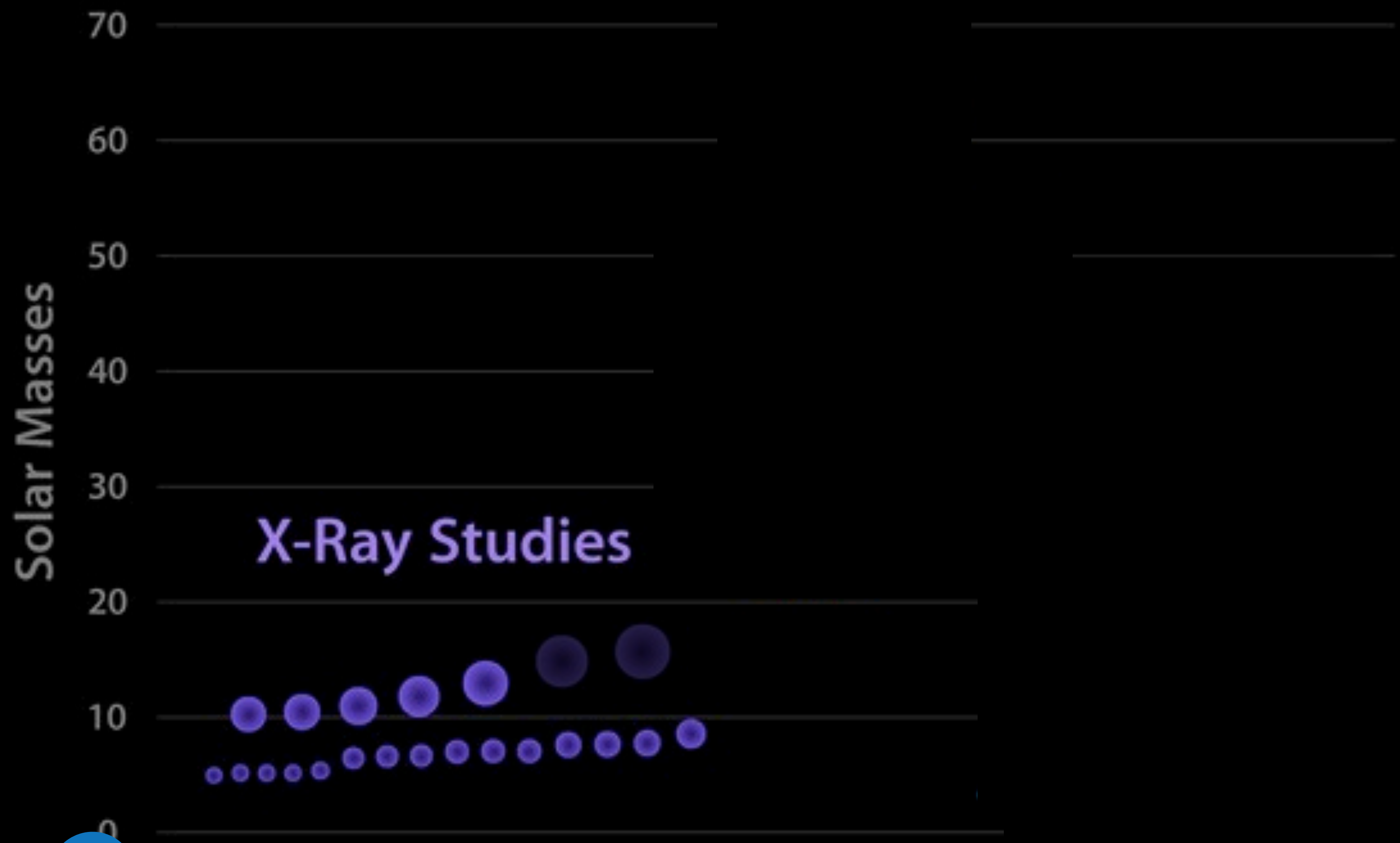
Known Black Holes*





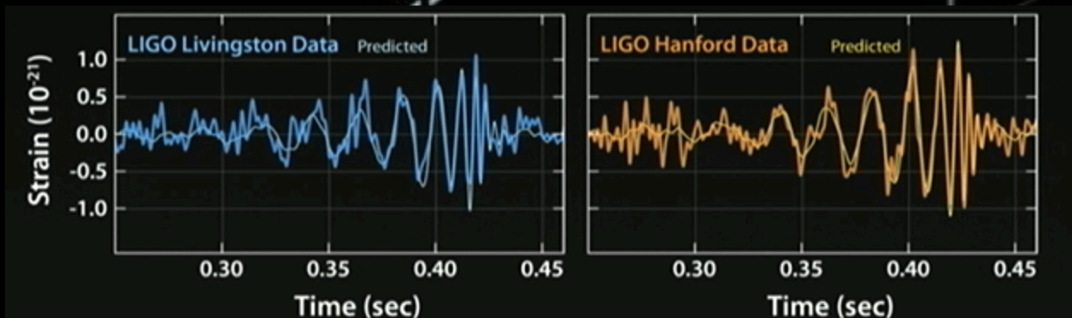
Courtesy Caltech/MIT/LIGO Laboratory

Known Black Holes*

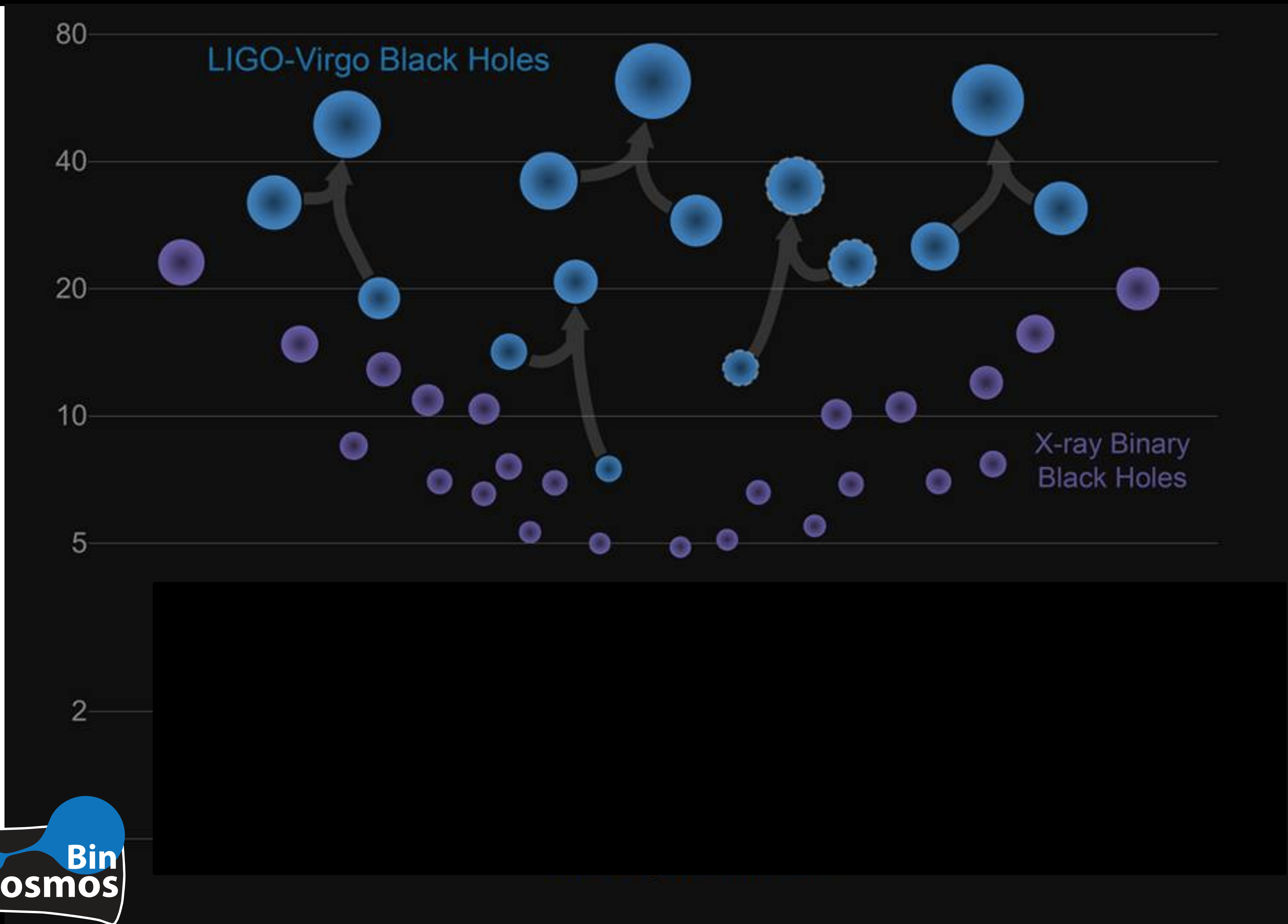


Courtesy Caltech/MIT/LIGO Laboratory

Local Responses

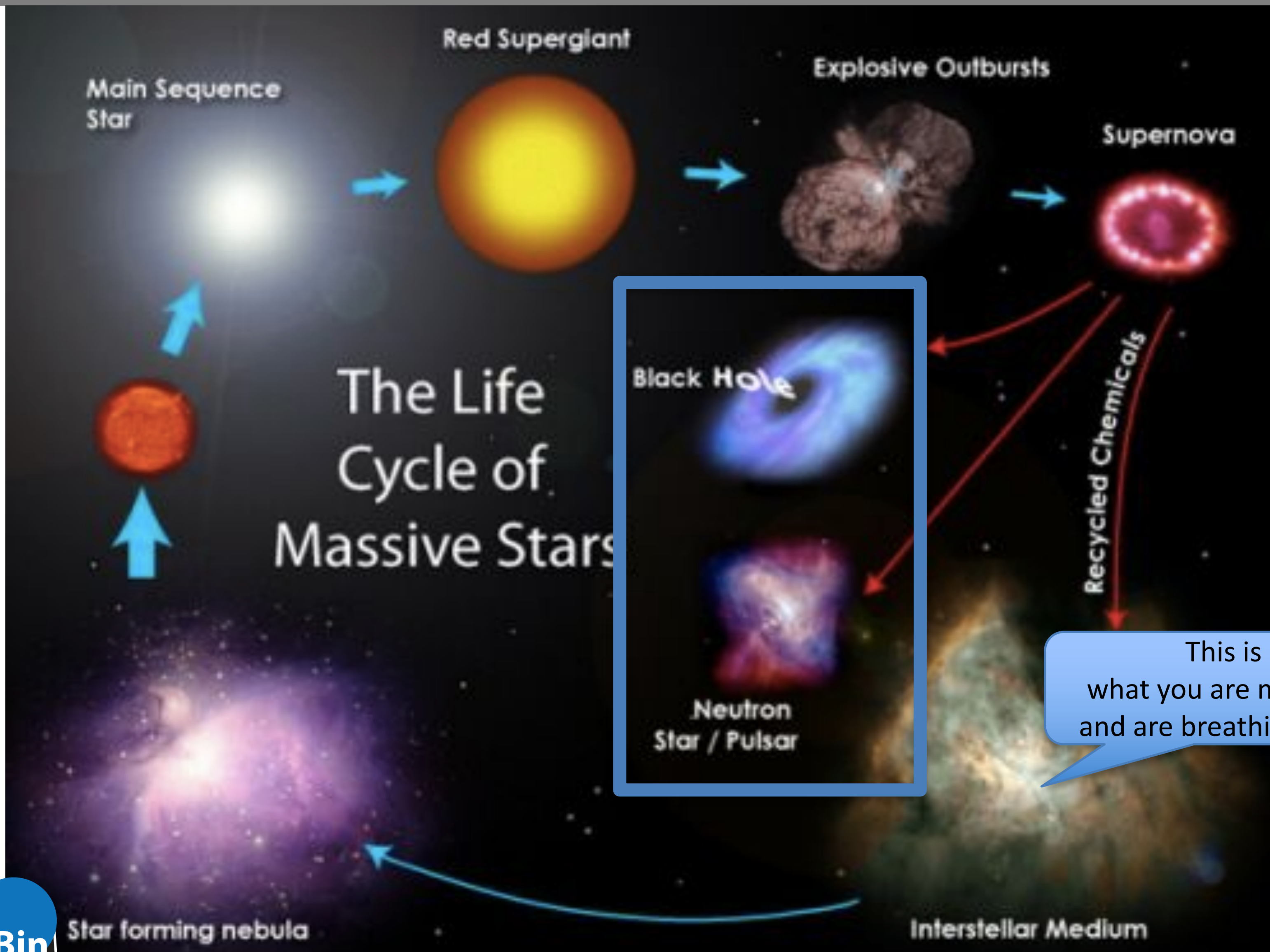


Where we are today
LIGO/Virgo's "stellar graveyard"



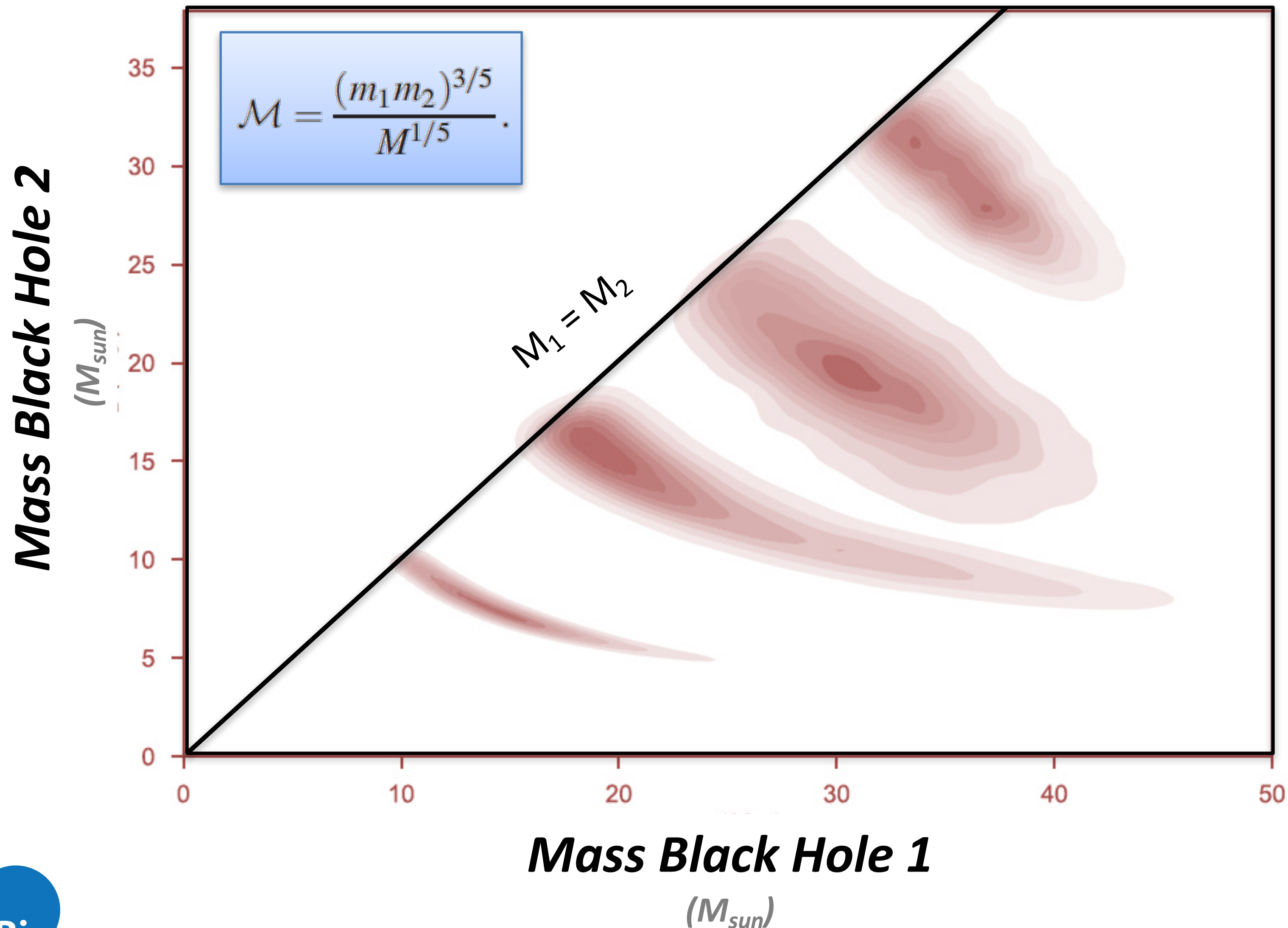
Scope of this Talk

Credit: NASA

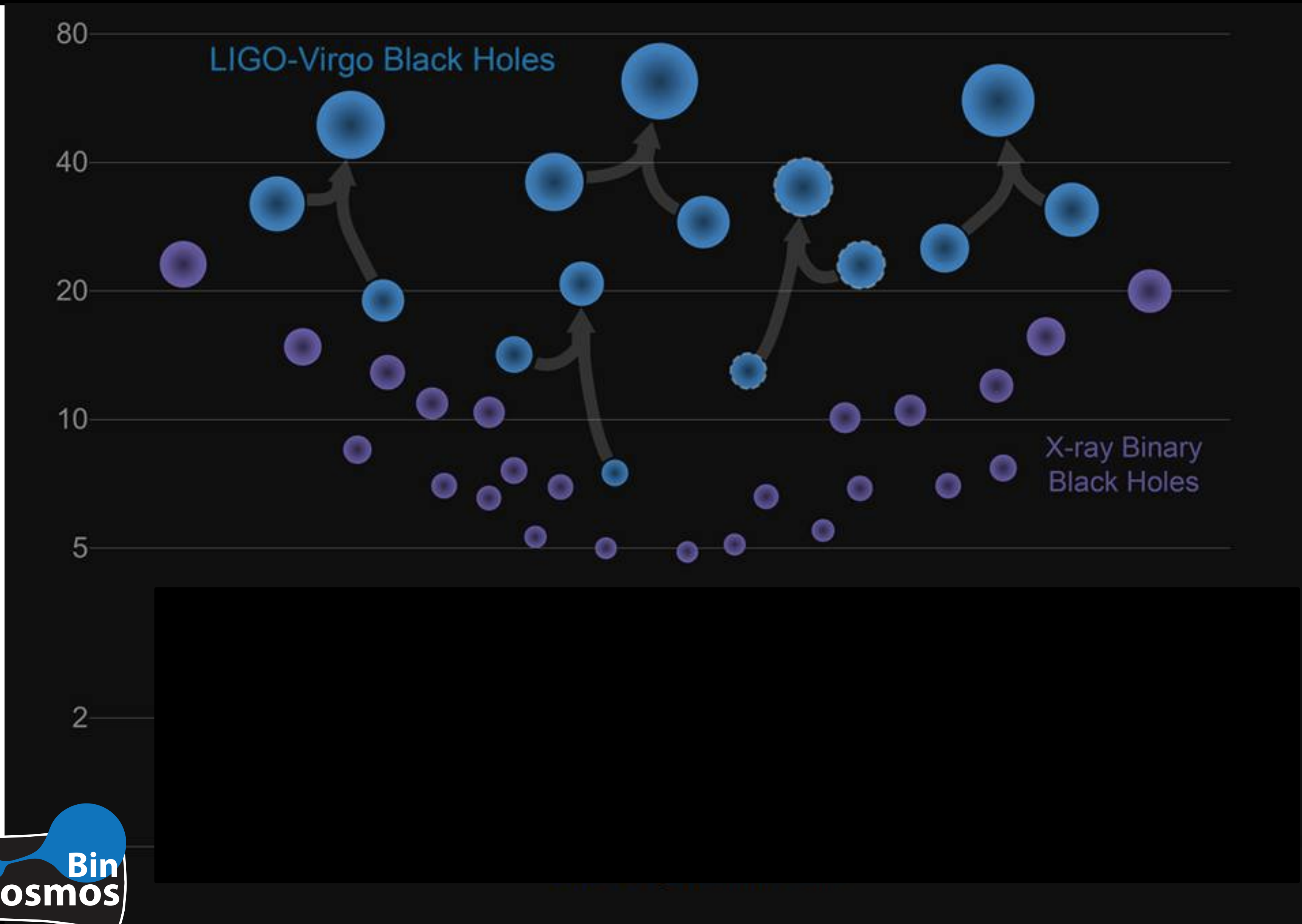


This is what you are made of and are breathing now.

Caveat: Errors on individual masses are large



Stellar Graveyard



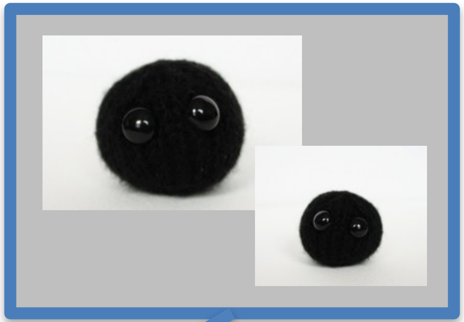
Bin
Cosmos

When and Where

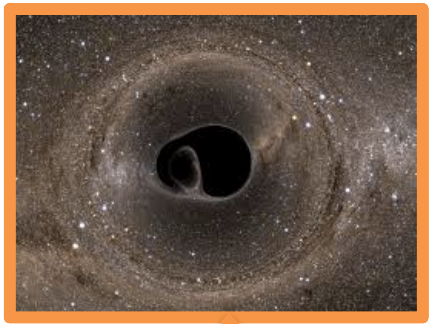
Intuition for the timescales

4. Birth of progenitors stars

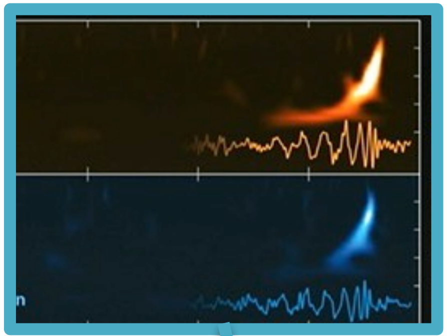
3. Formation binary black holes



2. Merger



1. Detection of signal



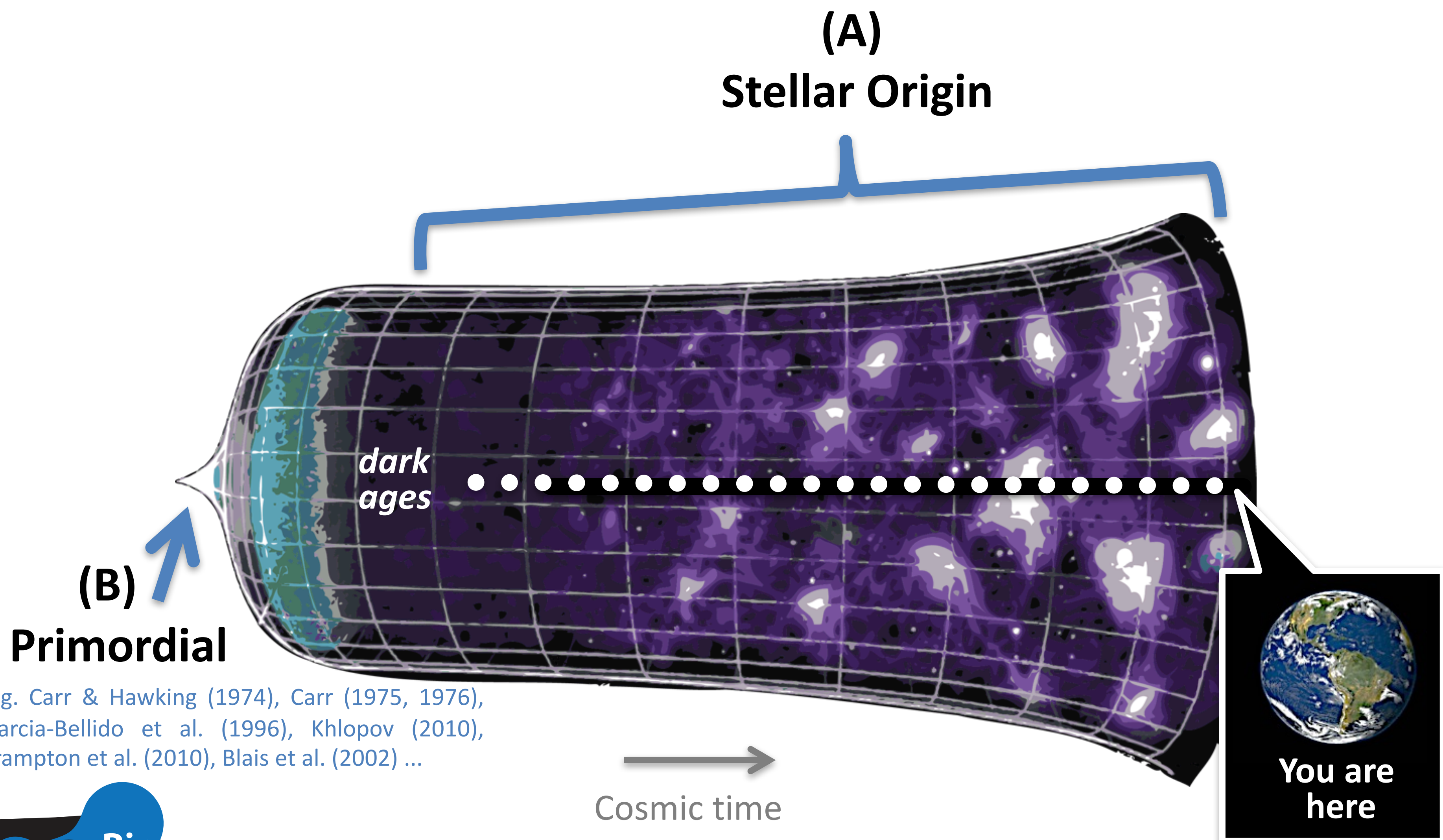
Time

Sept 14 2015

The progenitors did not live in our "back yard"

BinCosmos

A new window on how stars die across cosmic time



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

BinCosmos

Part I
New insights in the Stellar progenitors

Tarantula Nebula - a Compact Object “*Factory*”

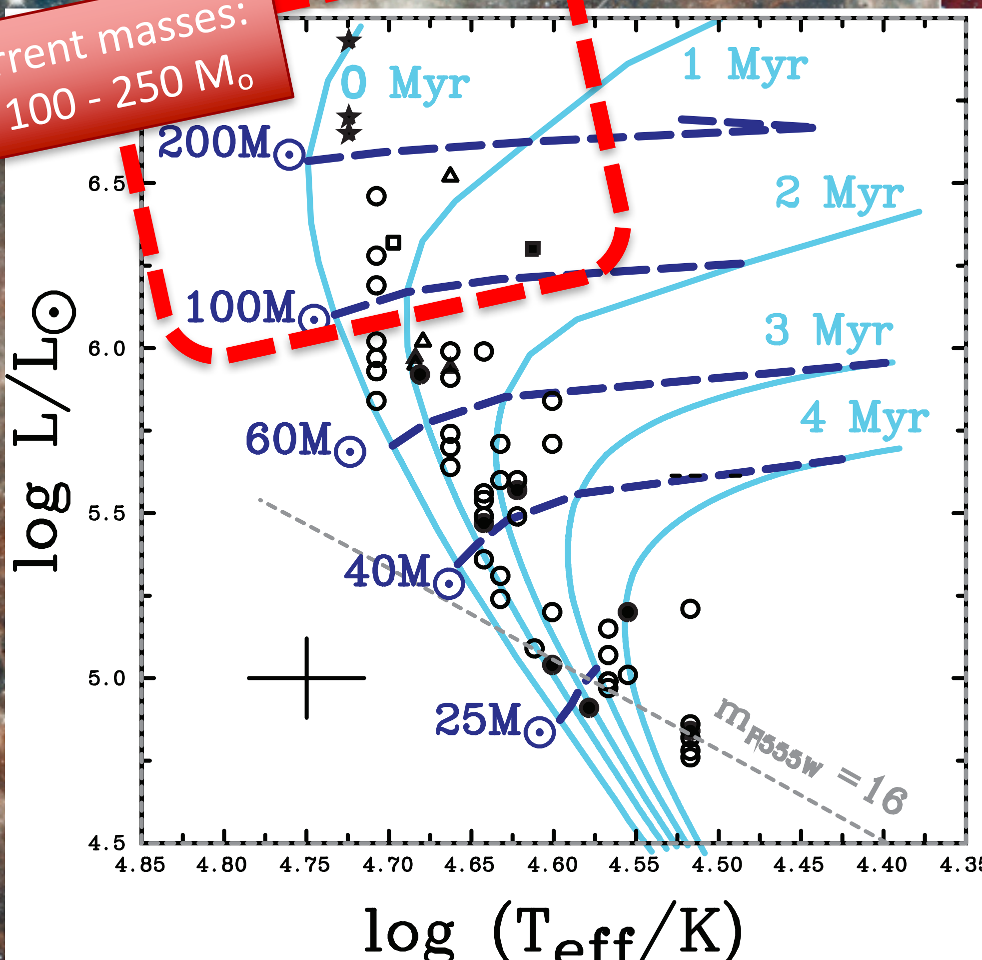
VLT-FLAMES (Evans, Sana), HST (Sabbi, Lennon, Crowther), Chandra (Townsley)

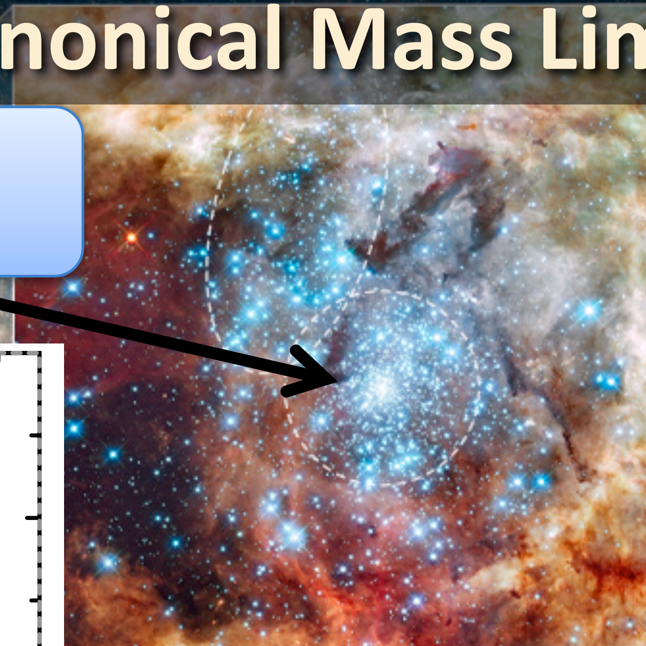
Stars Exceeding the canonical Mass Limit

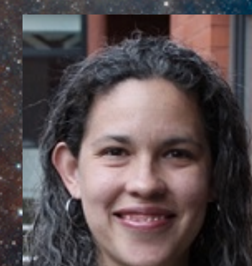
Nine "stars : > 100 $M_{\odot}$

Crowther, Caballero-Nieves + w/dM 2016

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

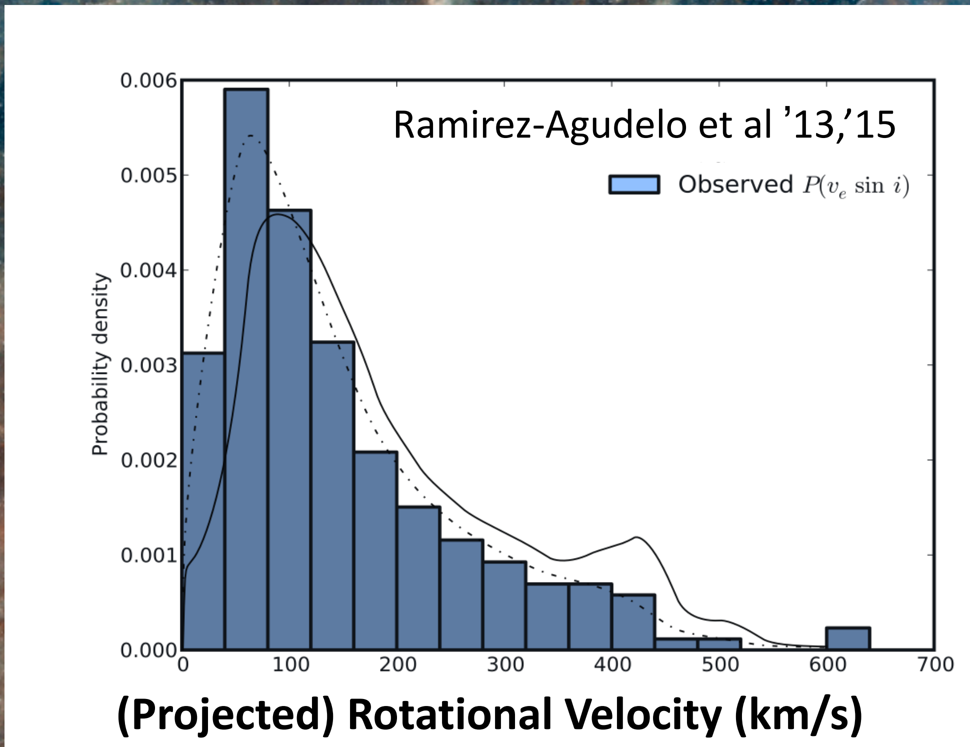


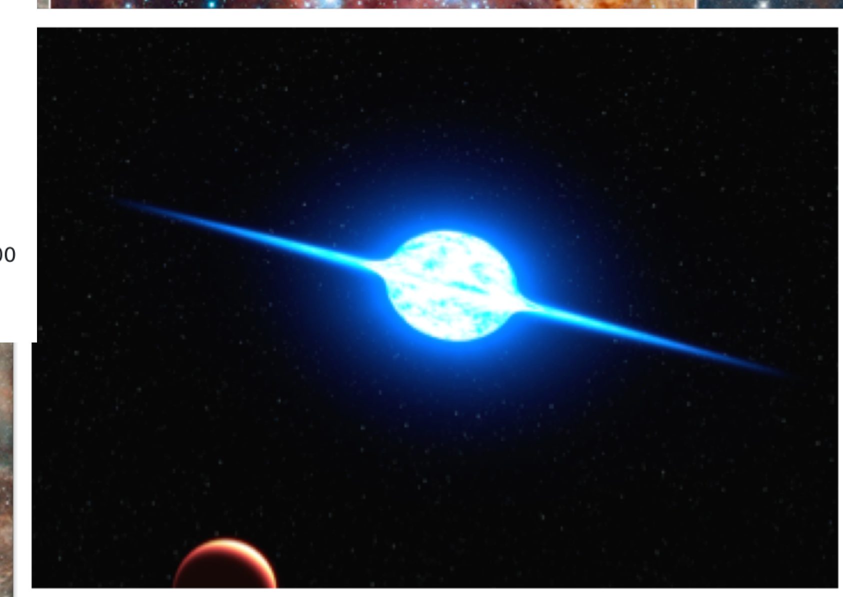


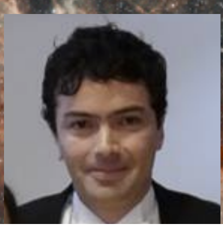


Saida Caballero-Nieves

Extremely rapid rotators







Oscar Ramírez Agudelo

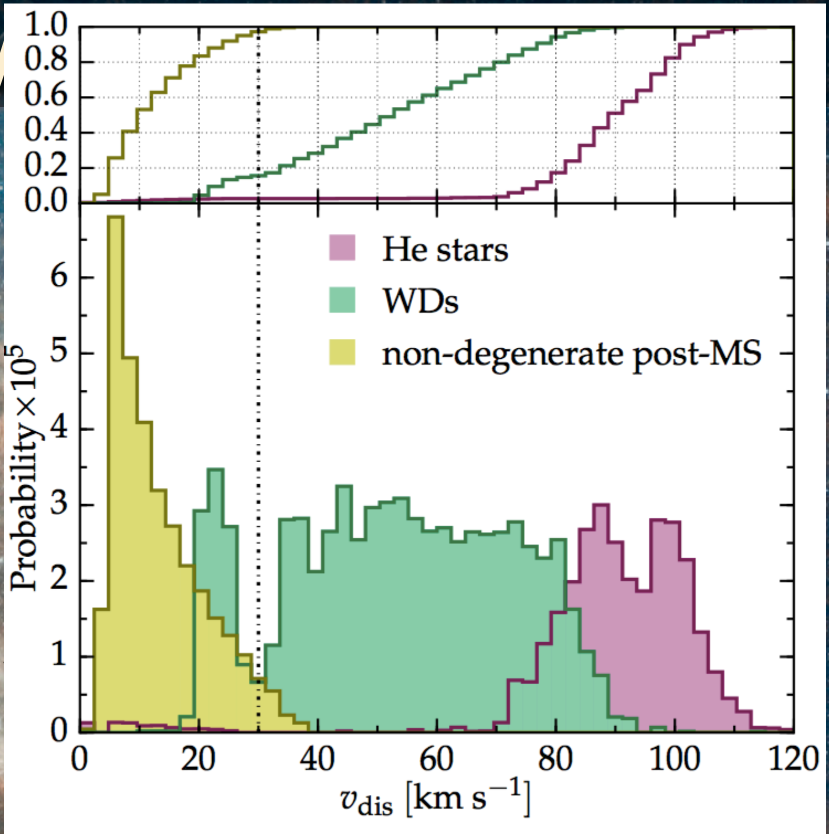
Spinning stars

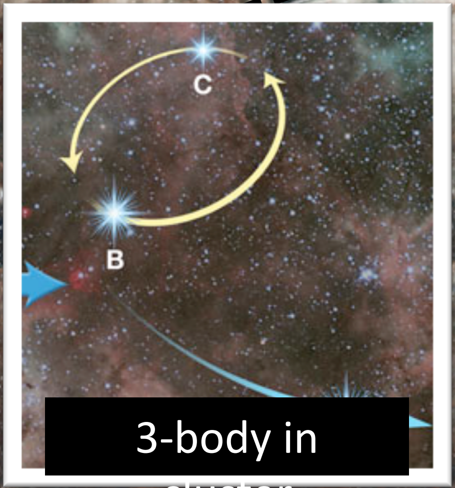
Dufton+w/dM+11,13, Ramirez-Agudelo++w/dM13,15

Runaway

20 New Runaway Stars

Evans+10, Sana + 2017 prep,
Renzo+ 2017 prep





3-body in cluster

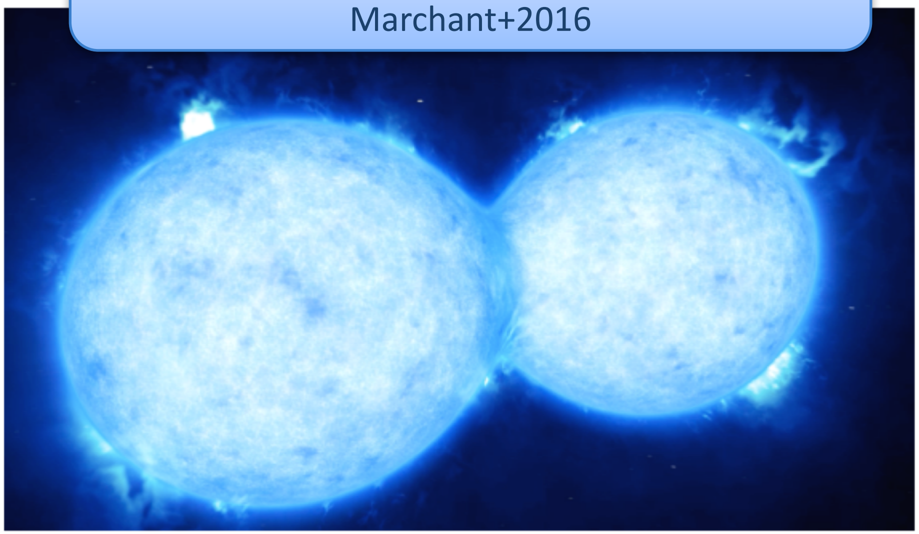
Supernova in Binary

Mathieu Renzo

Almost all of them are binaries

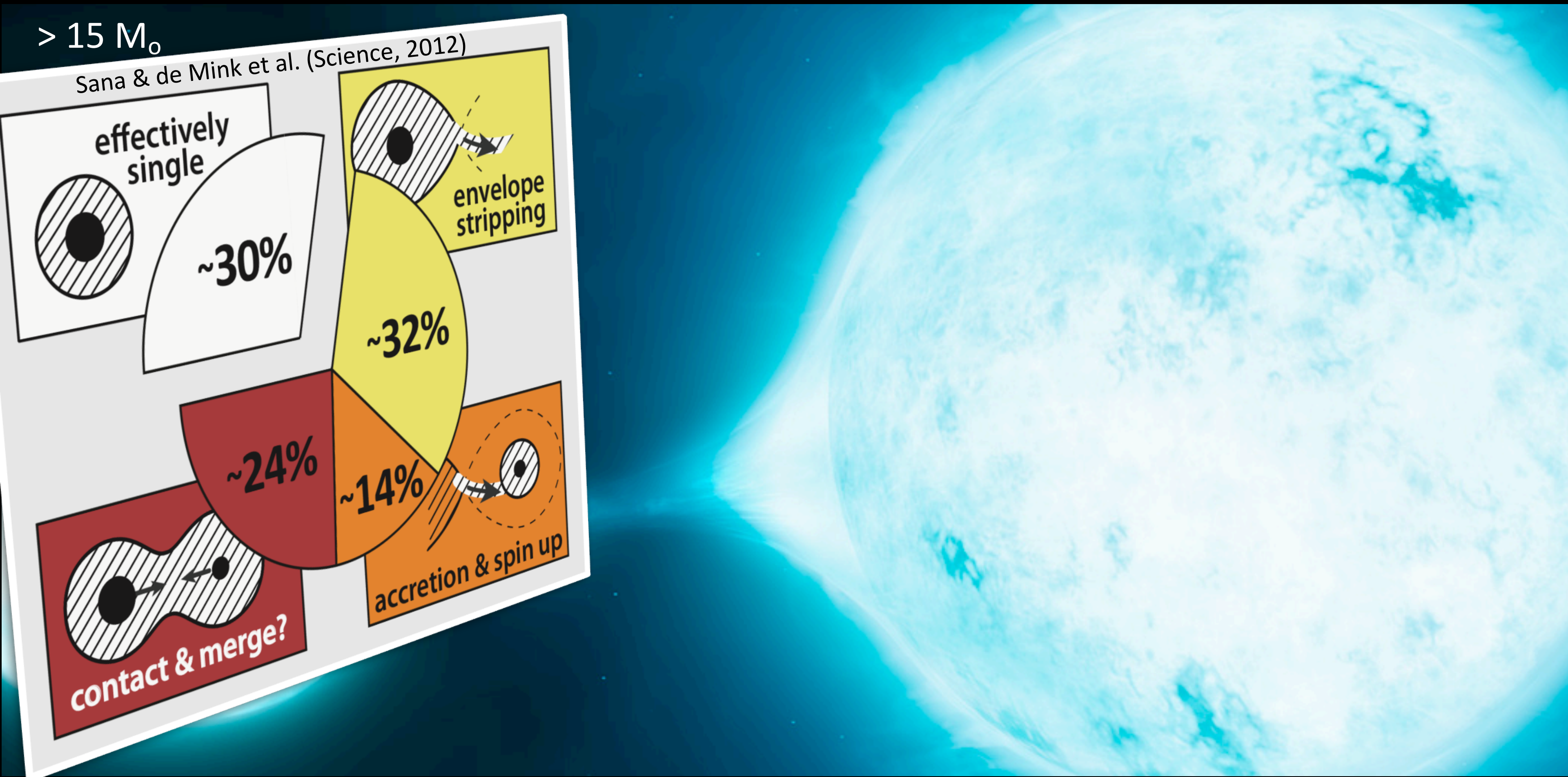
30 + 30 Msun contact binary

Alemeida, Sana, SdM + 2015,
Marchant+2016



Leonardo Almeida

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, ...

Not just "artist impressions"

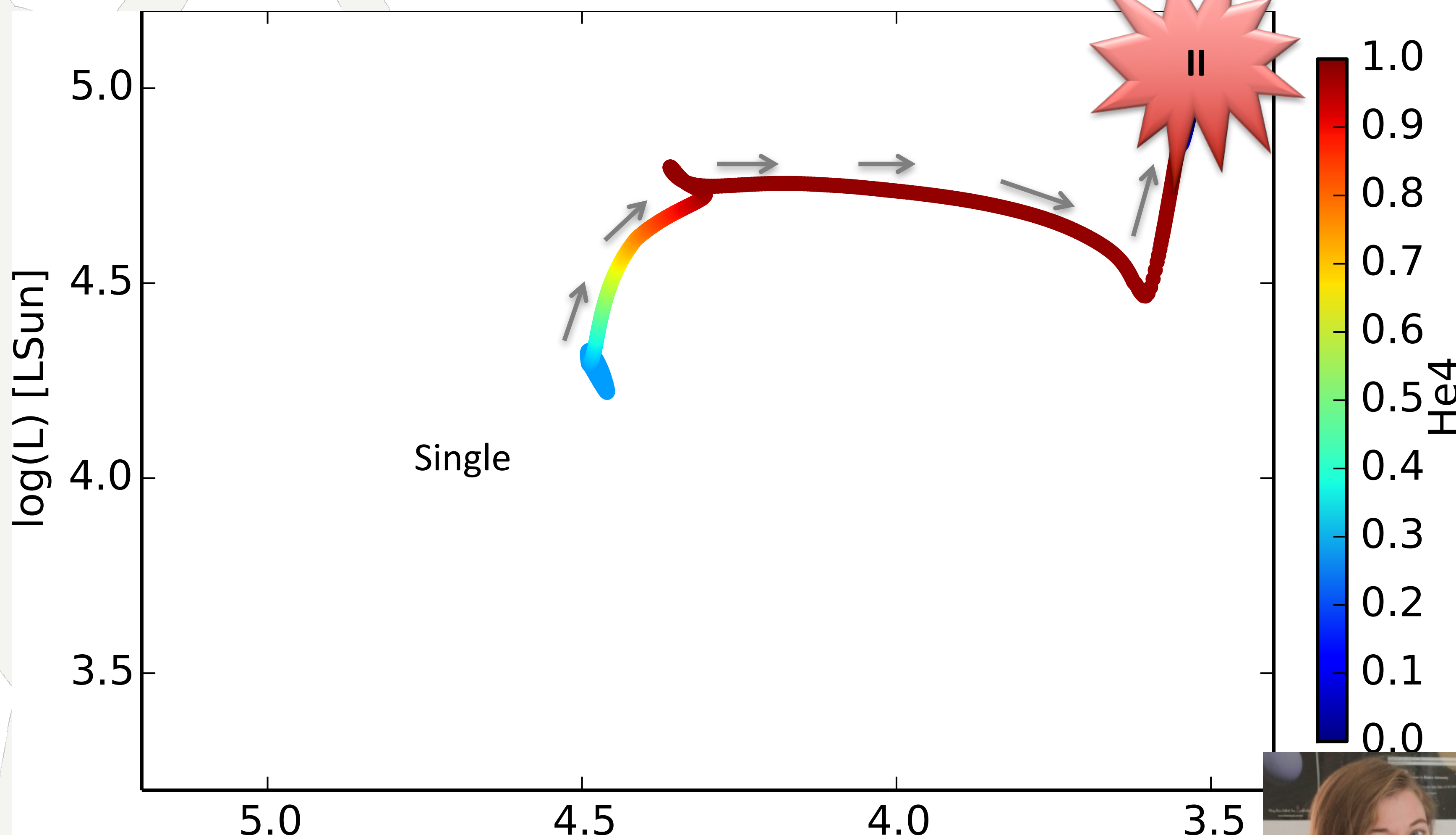
Beta Lyrae: 13 + 3 M_{sun}
(CHARA array, Zhao et al. ApJ 684, L95)

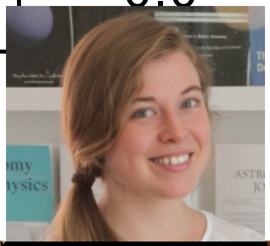
Life with a companion

Single Star

MESA: $M_1 = 15\ M_o$

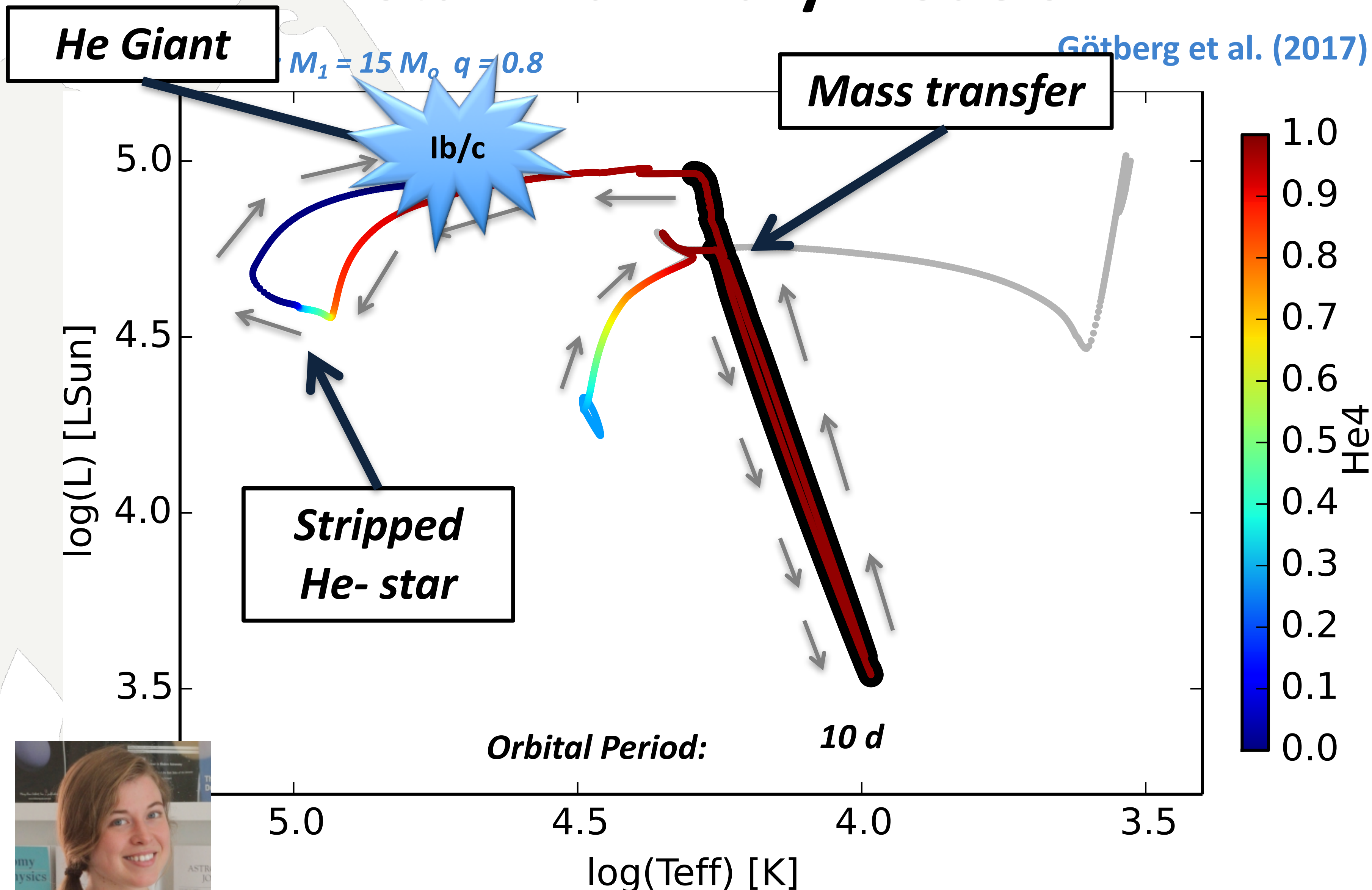
Götberg et al. (2017)





Ylva Götberg

Star in a Binary models



Ylva Götberg

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

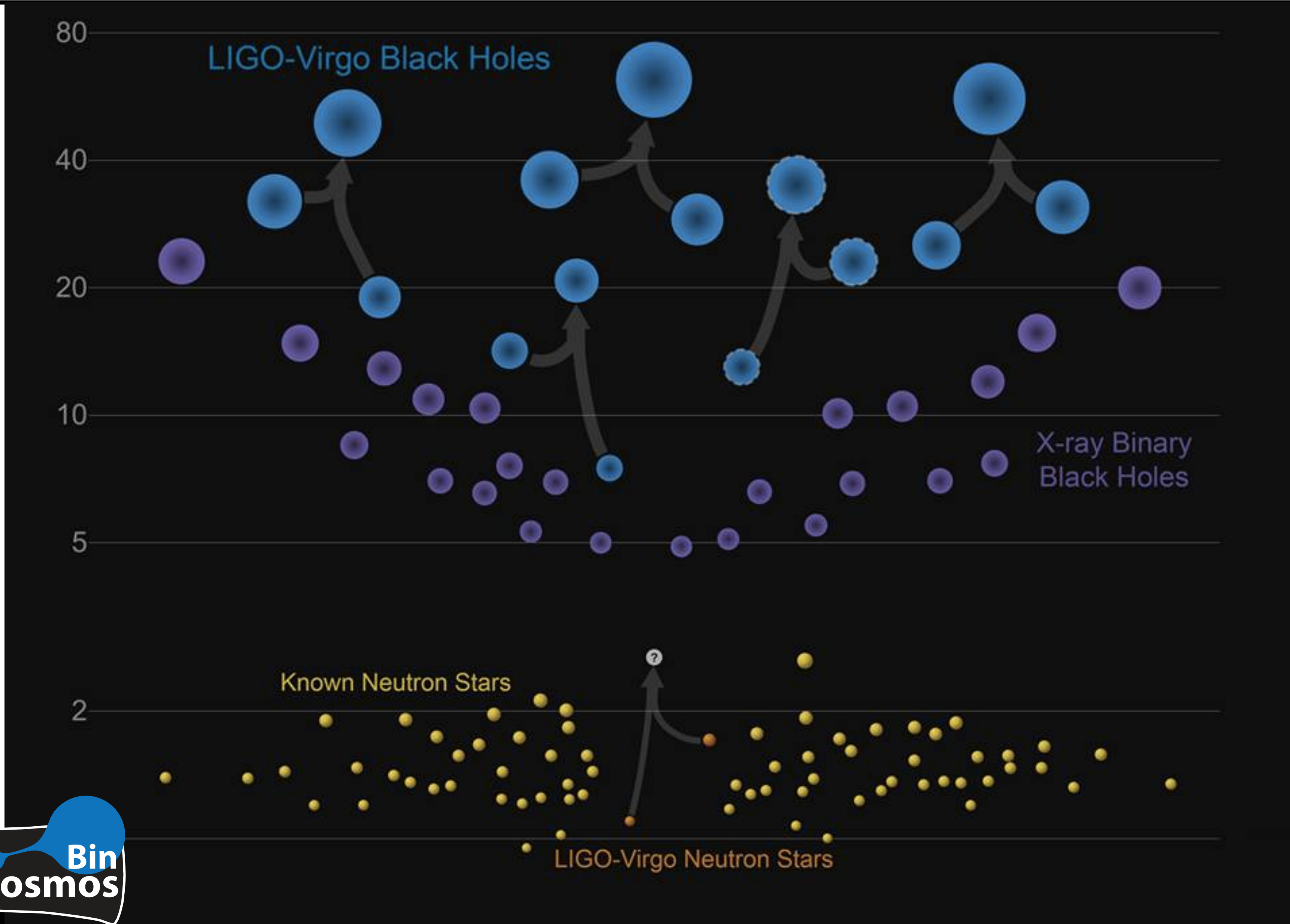
Animation of the life of a typical massive Star

www.eso.org

Animation: ESO: Calçada/Kornmesser/de Mink

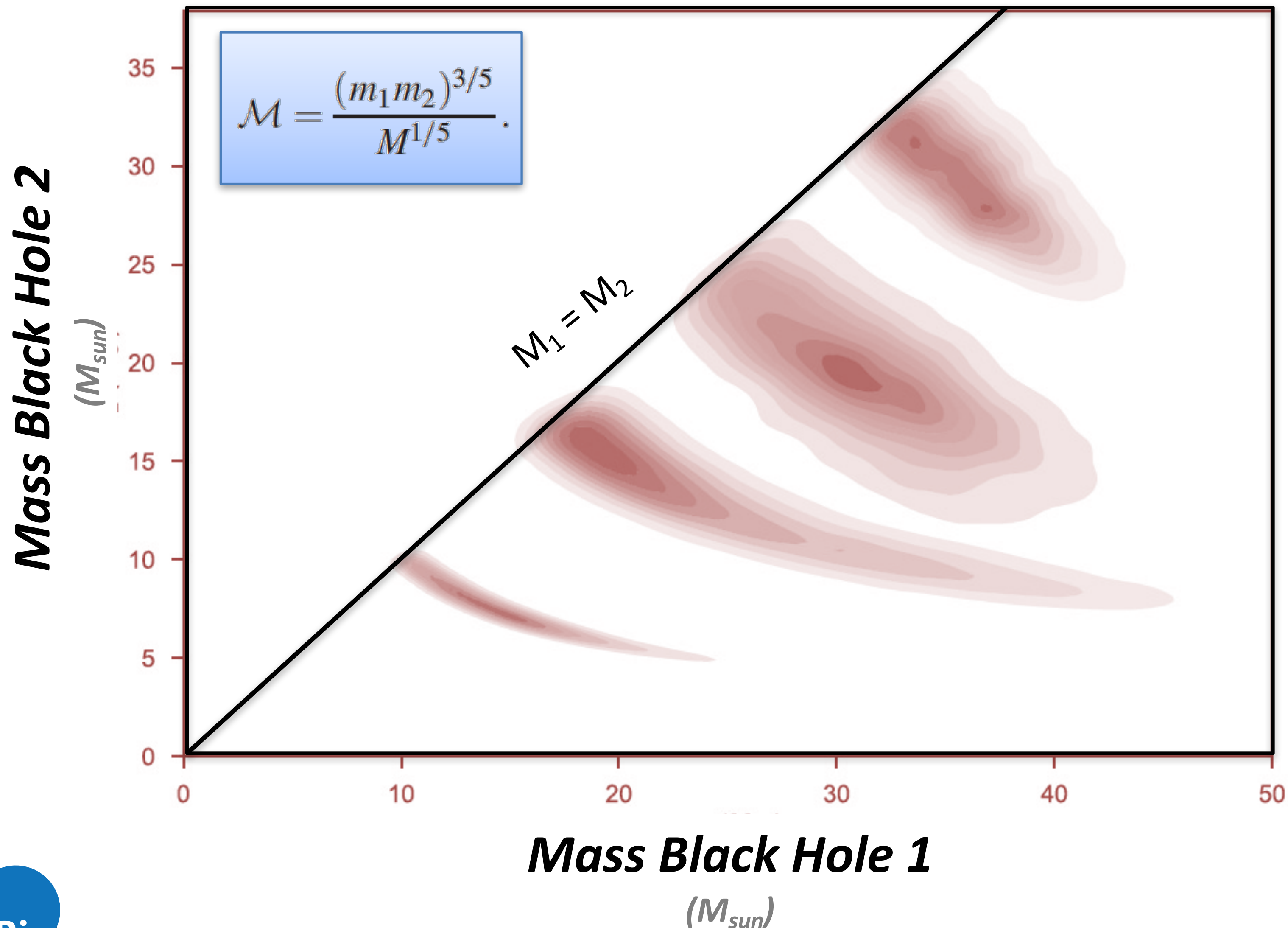
Part 2
Gravitational Wave Progenitors

Stellar Graveyard



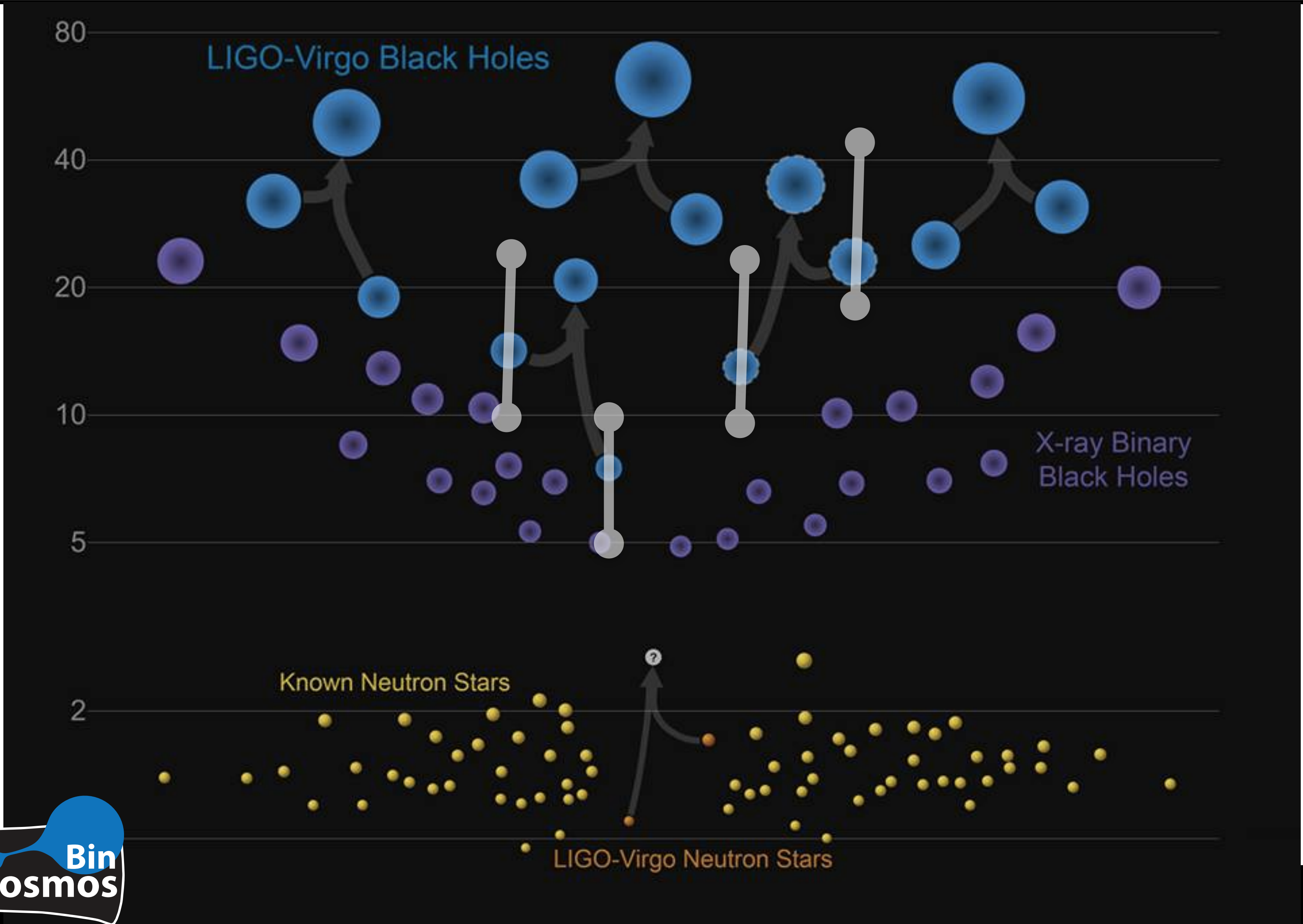
Bin Cosmos

Errors bars large and corellated



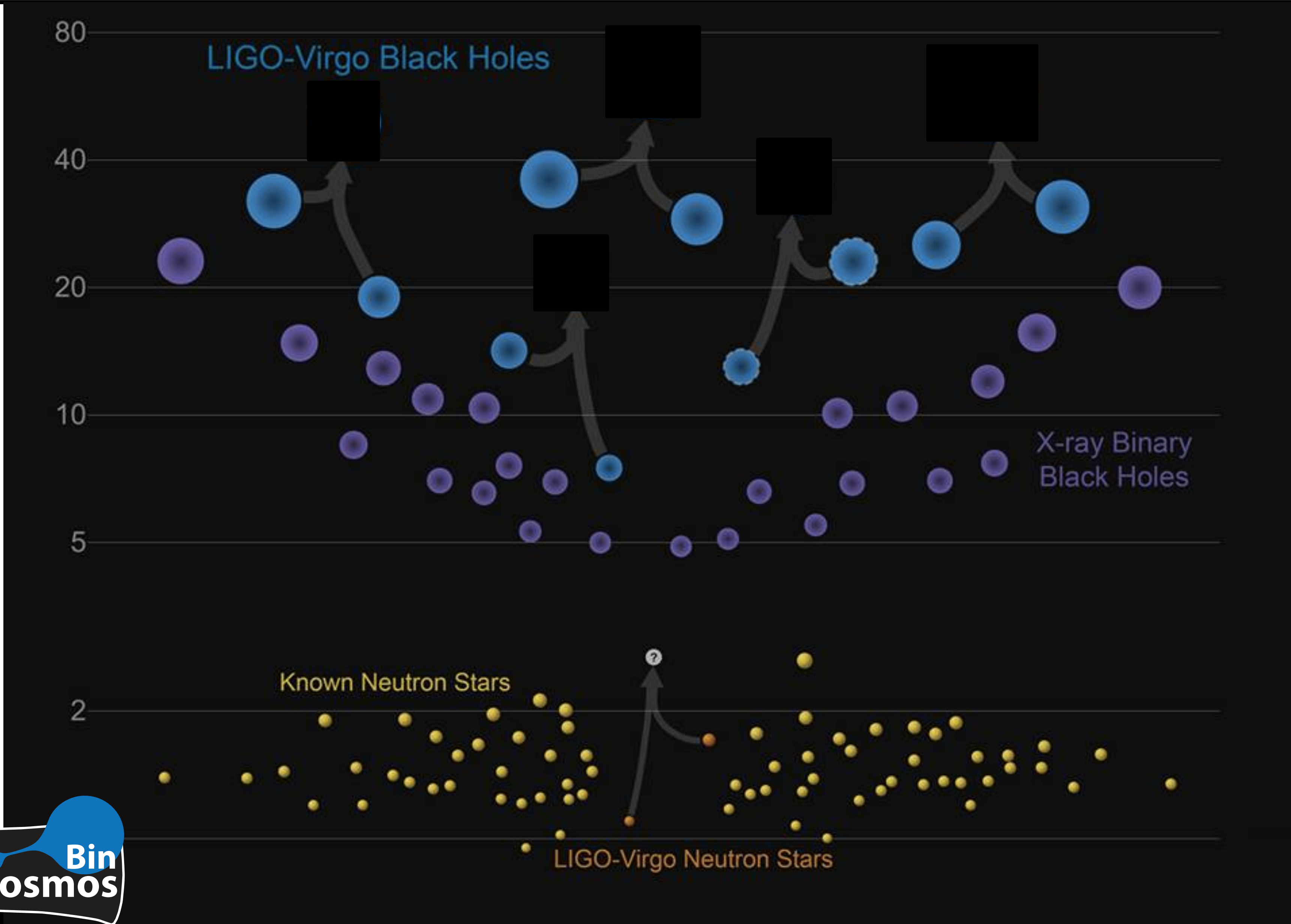
Bin Cosmos

Stellar Graveyard



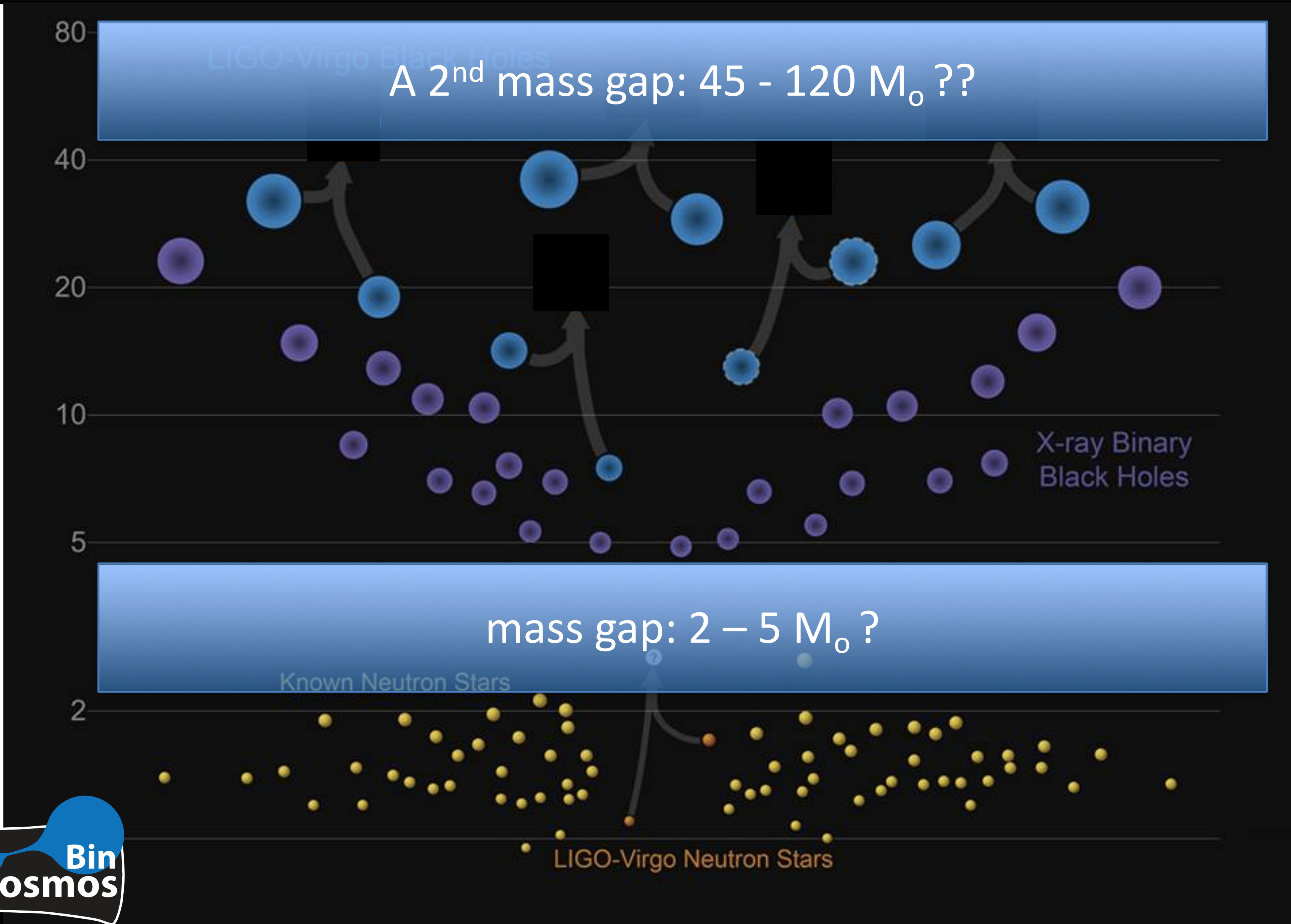
Bin Cosmos

Real Stellar Graveyard



Bin
Cosmos

Stellar Graveyard



A 2nd mass gap: 45 - 120 M_o ??

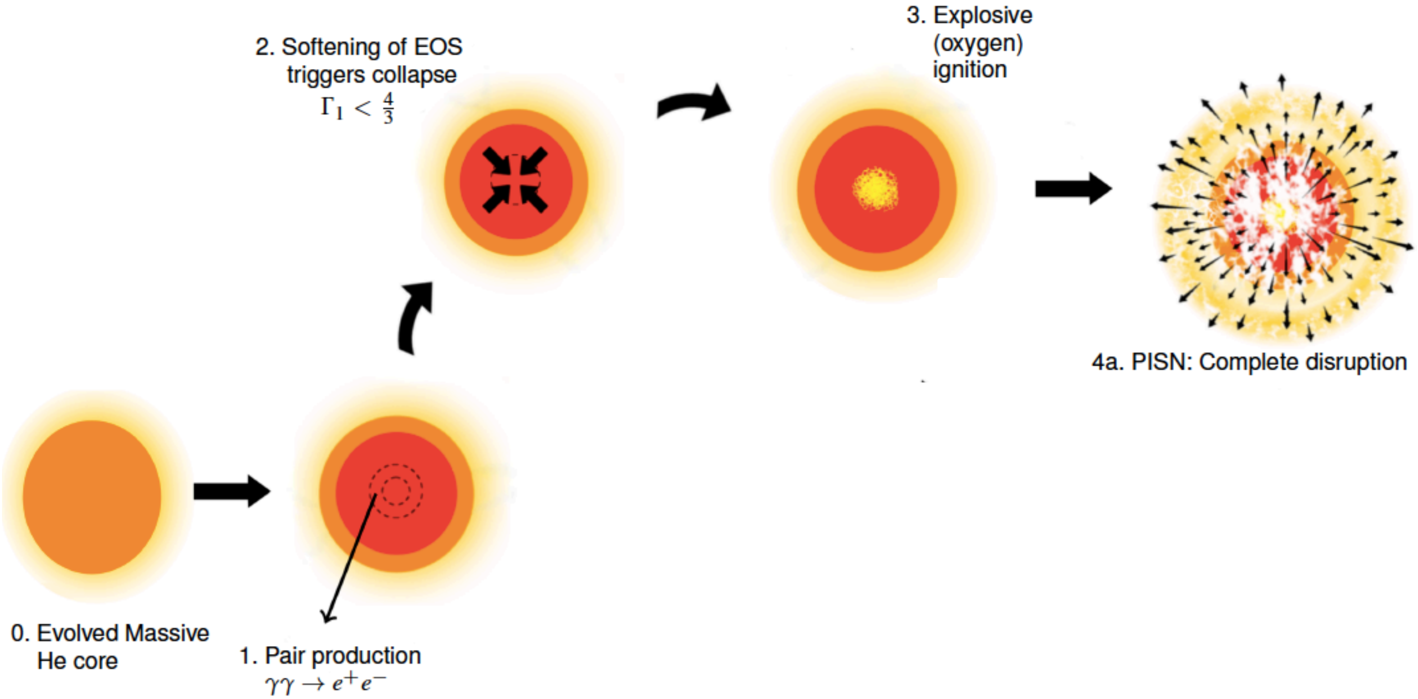
mass gap: 2 – 5 M_o ?

Second Mass Gap
45 – 120 M_o


Mathieu Renzo


Rob Farmer

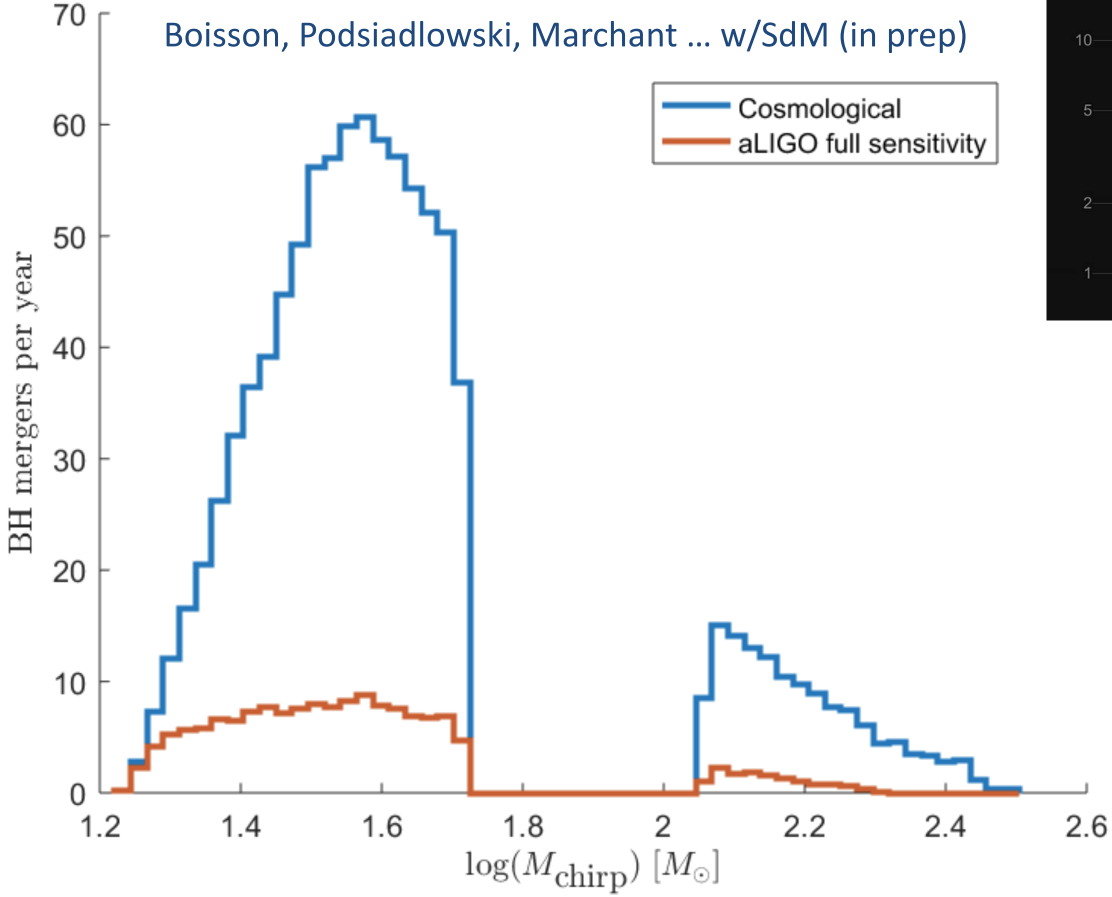
Renzo, Farmer, de Mink + in prep.

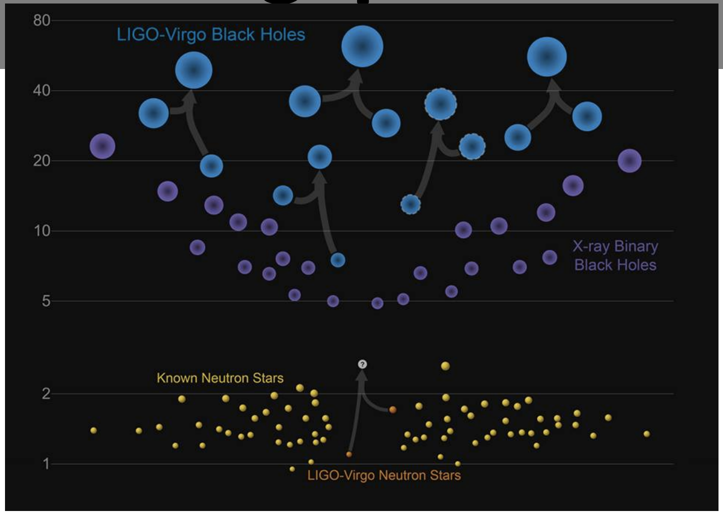


Complete disruption ➔ No BH

Mass loss ➔ BH < 45 M_o

Can we detect BHs above the gap?



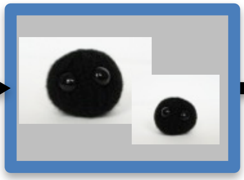


Part 3
Formation channels for compact binaries

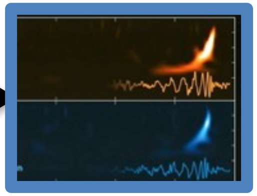
Why is it so hard to form a tight binary BH/NS

Birth

Formation BHs



Coalescence



1. "Separation Challenge"

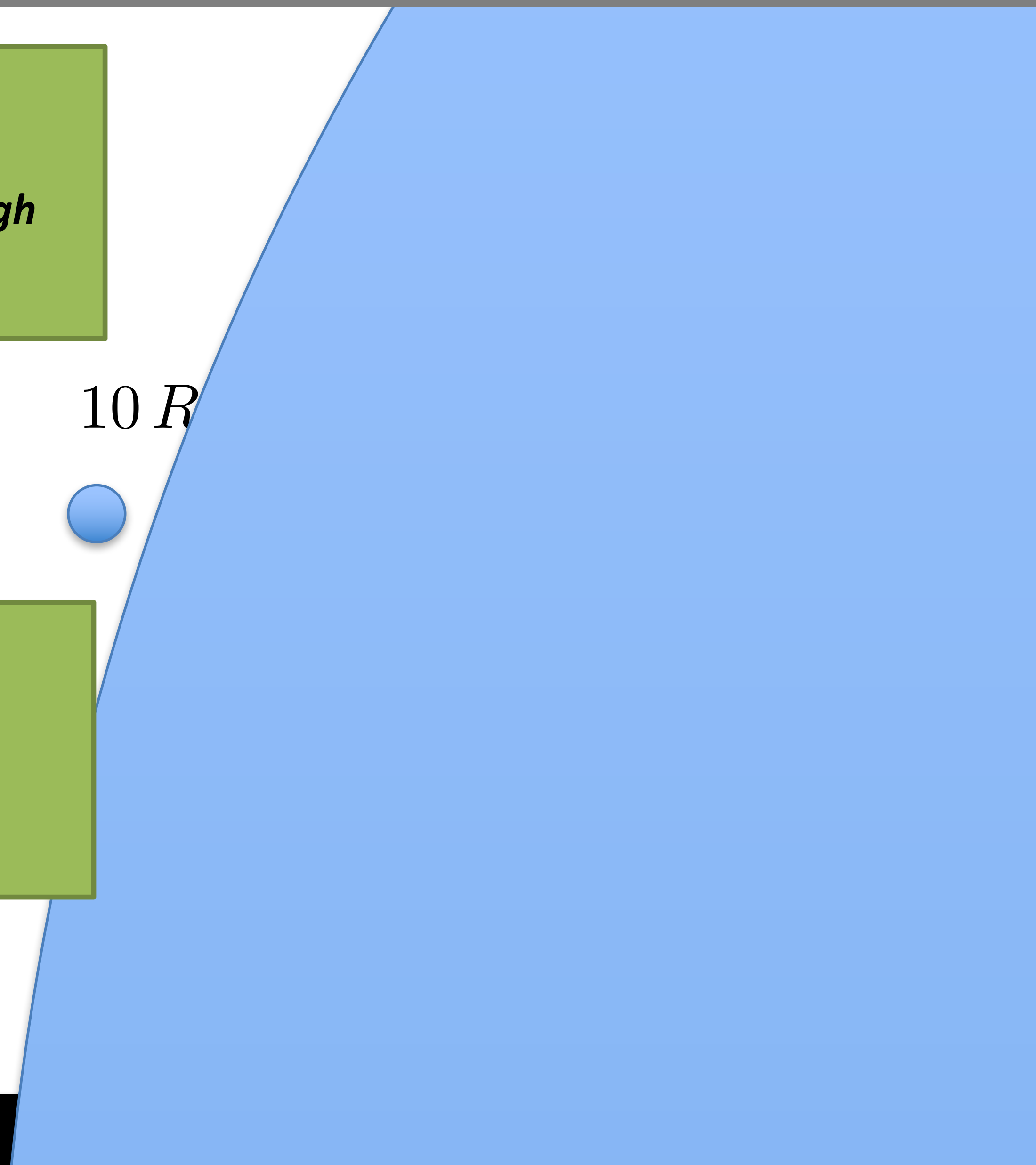
2. "Mass Challenge"

BinCosmos

Separation

1. *"Separation Challenge"*

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



2. *"Mass Challenge"*

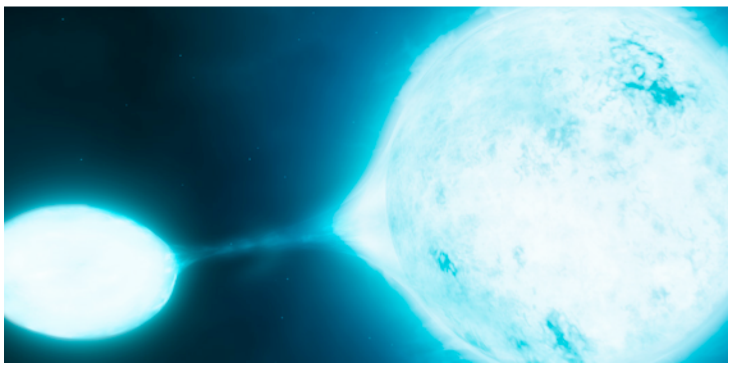
How to avoid excessive Mass loss?

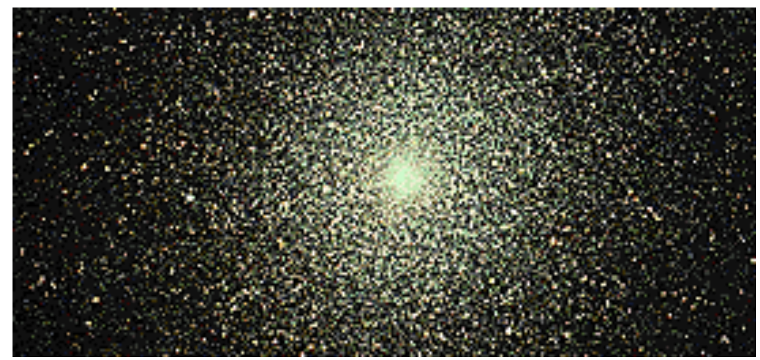
Formation Channels

Formation Channels

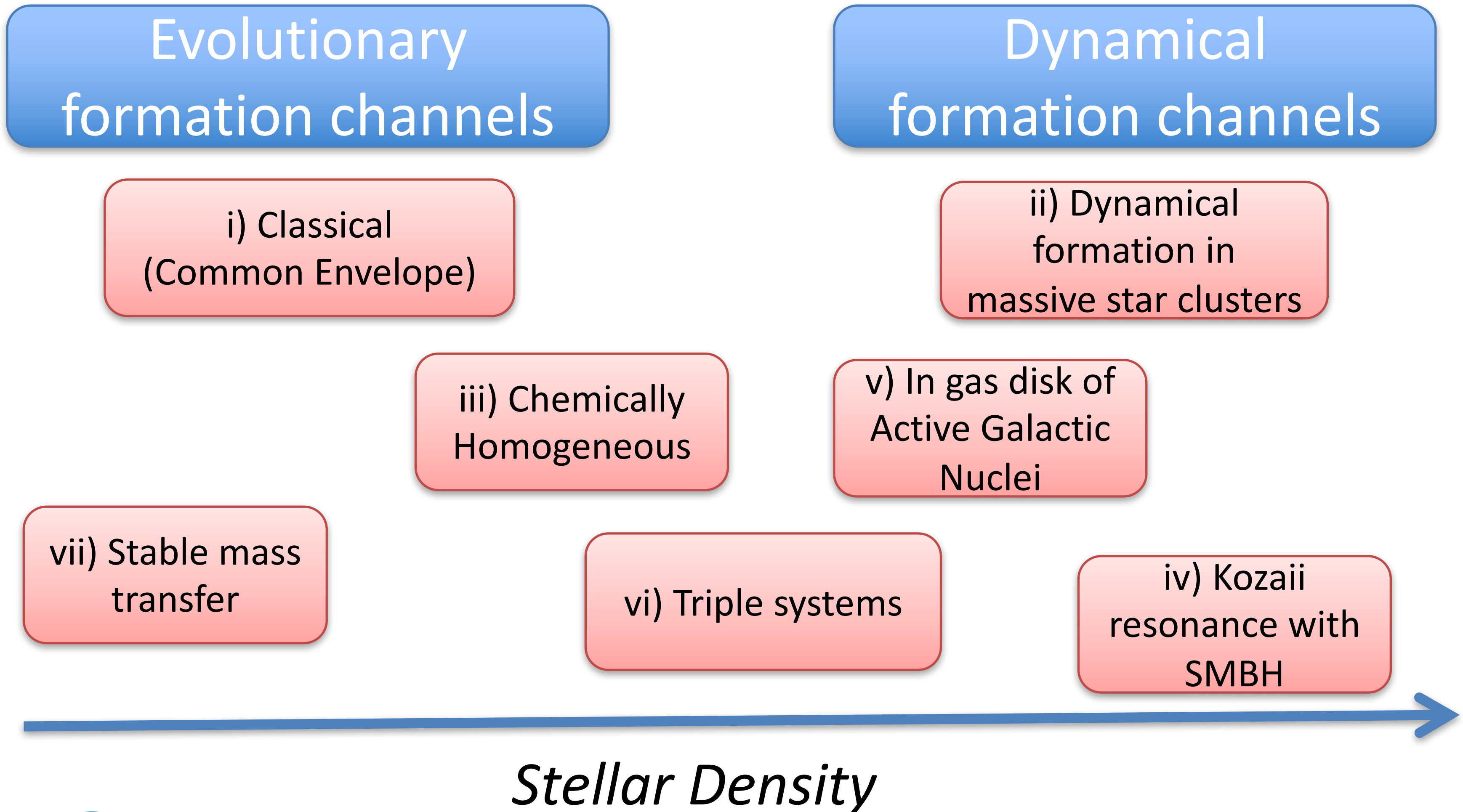
1. Evolutionary Channels

2. Dynamical Channels



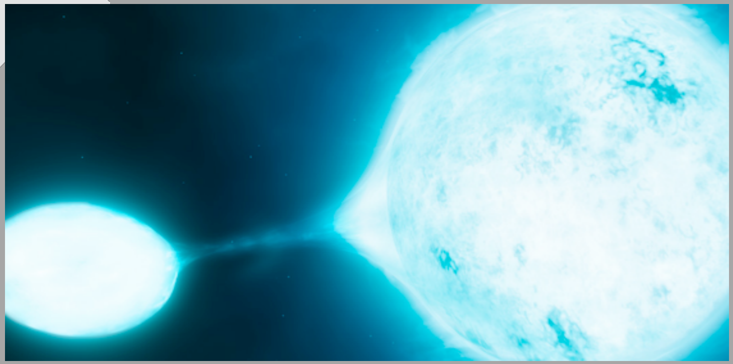


No lack of ideas

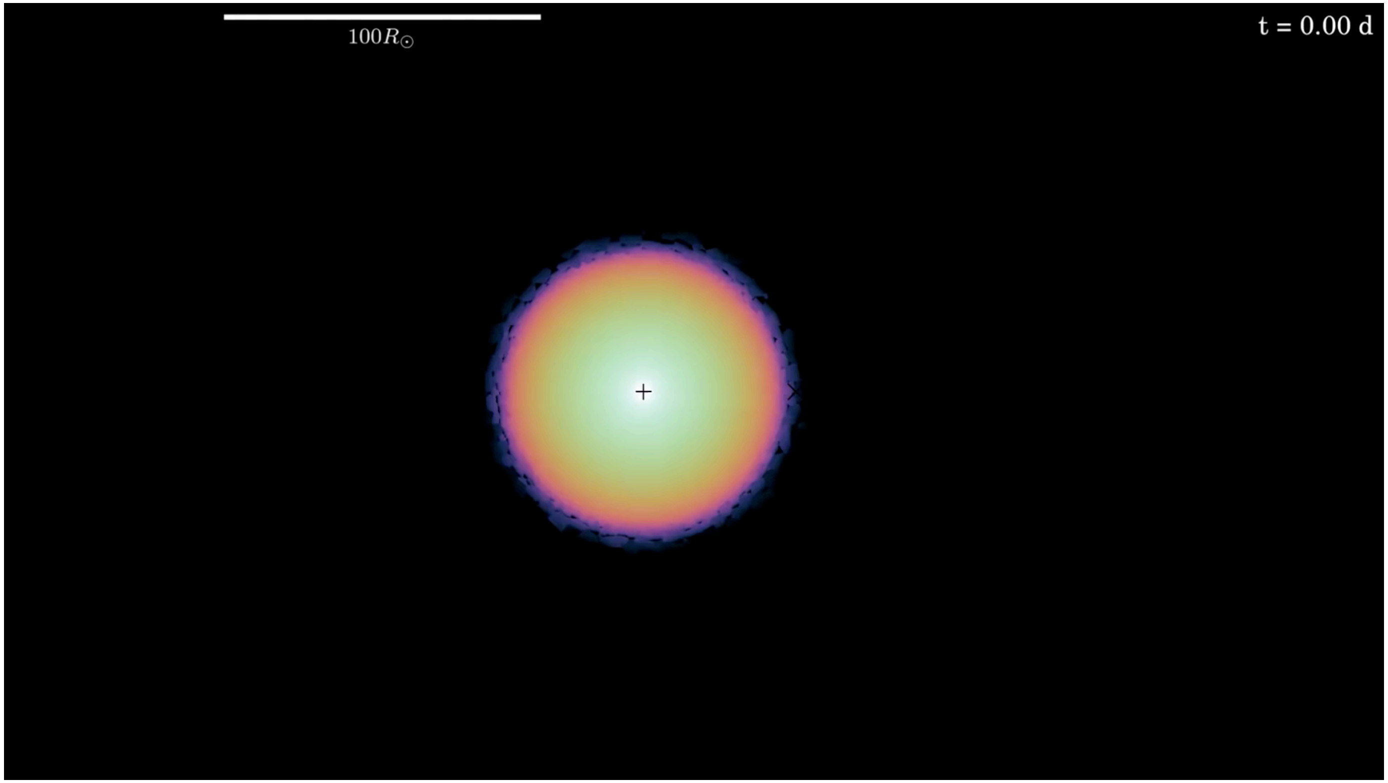


In prep. for Annual Review in Astronomy & Astrophysics (De Mink & Antonini)

Formation Channels
1) Classic Common Envelope Channel



I) Classical Evolutionary Channel: Common Envelope

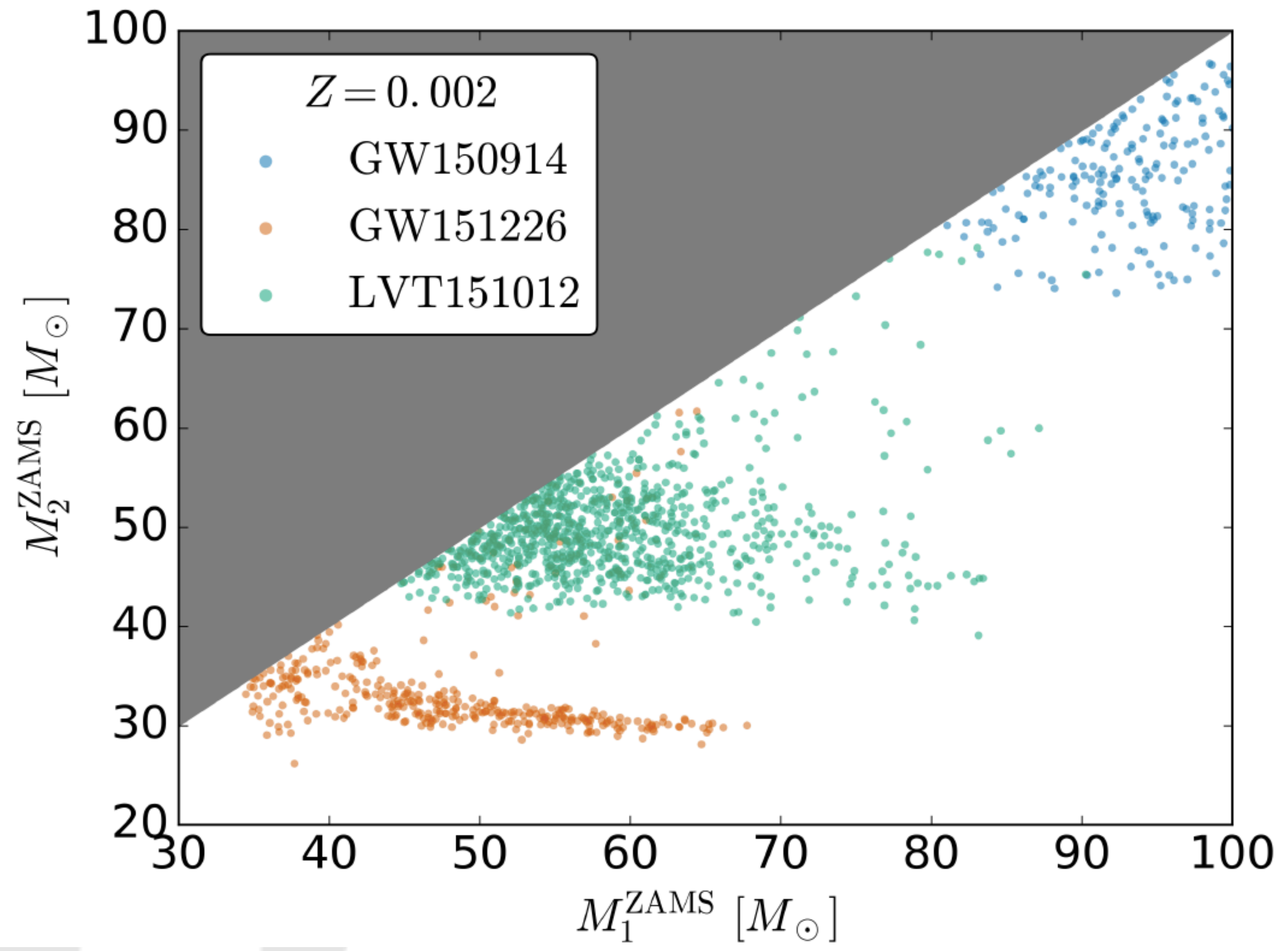


Tutukov & Yungelson 1973, 1993; Lipunov, Postnov & Prokhorov (1997), Bethe & Brown (1998), Bloom, Sigurdsson & Pols (1999), De Donder & Vanbeveren (2004), Grishchuk et al. (2001), Nelemans (2003), Voss & Tauris (2003), Pfahl, Podsiadlowski & Rappaport (2005), Dewi, Podsiadlowski & Sena (2006), Kalogera et al. 2007; O'Shaughnessy et al. (2008), Mennekens & Vanbeveren (2014), Dominik et al. (2015), de Mink & Belczynski (2015), Belczynski et al. 2016, Stevenson et al. 2017, ... More recent papers

Can the classical channel explain all events?

Yes, in principle.

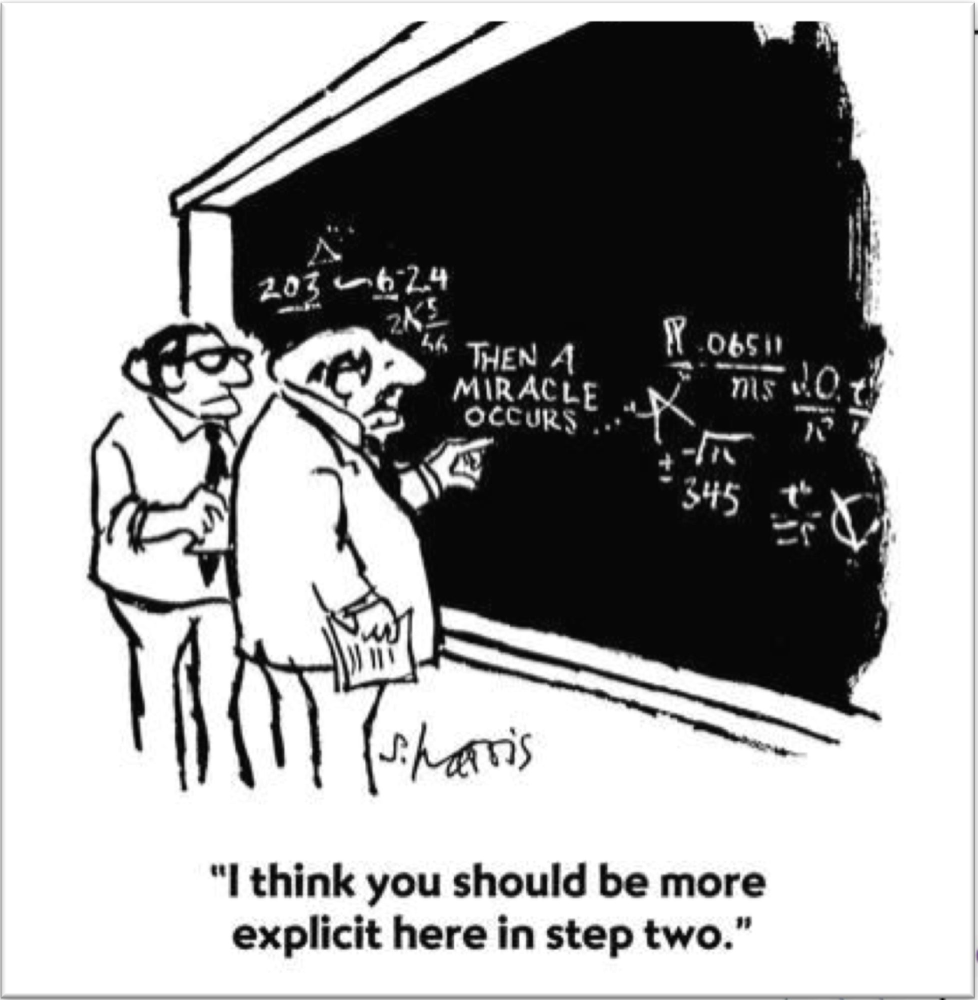
Stevenson, Vigna-Gomez, Mandel, Perkins, Barrett, de Mink (Nature Com., 2017)



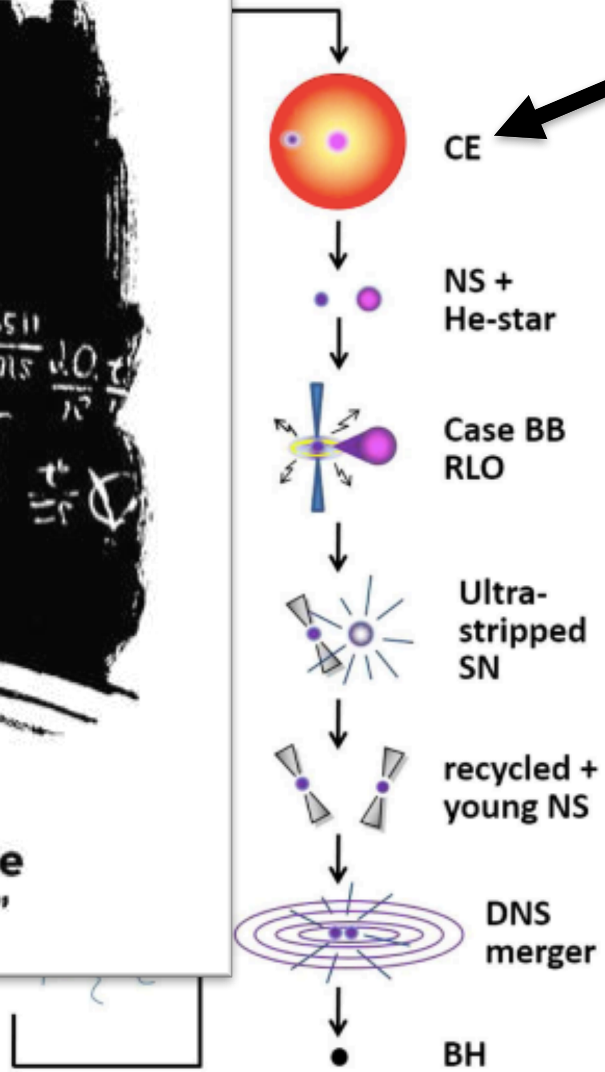
Simon Stevenson

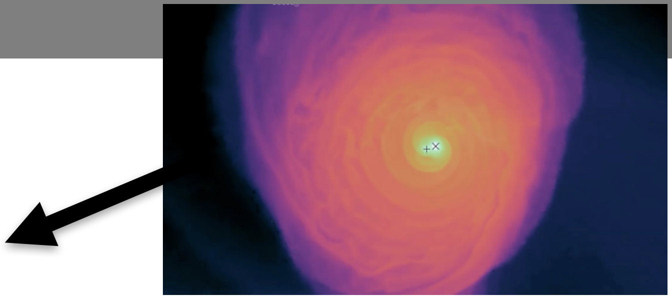
BinCosmos

It’s a little more complicated



"I think you should be more explicit here in step two."

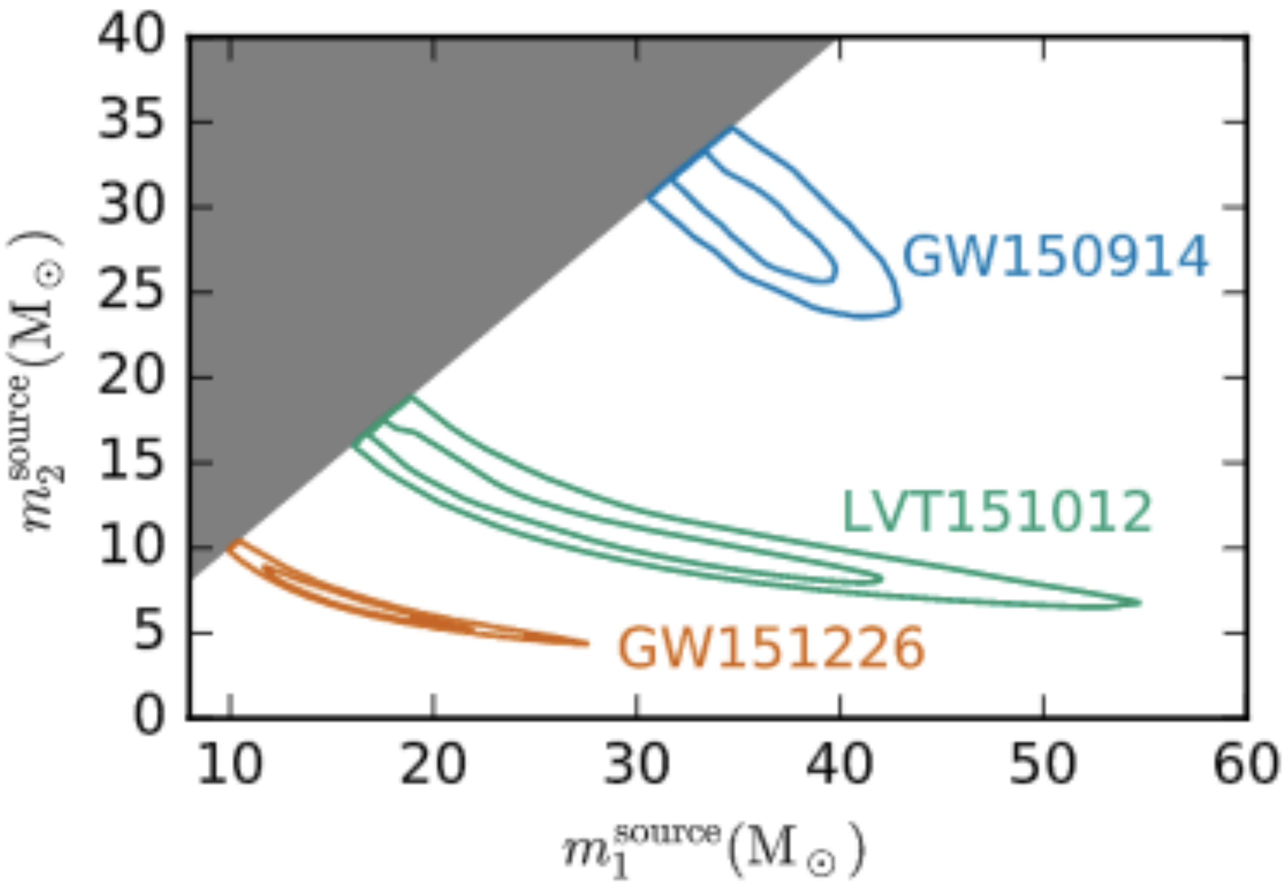




Tauris et al. 2017

Can the classical channel explain all events?

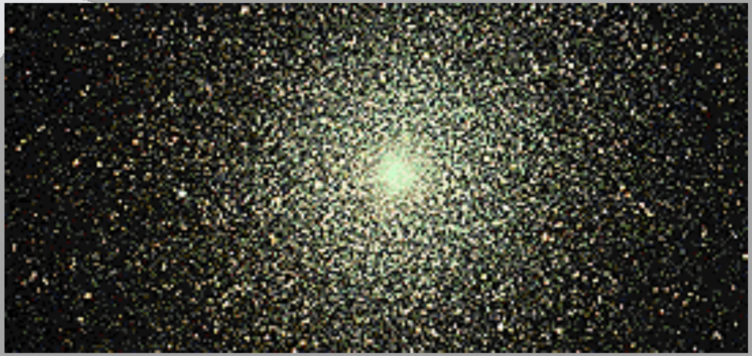
Stevenson, Vigna-Gomez, Mandel, Perkins, Barrett, de Mink (Nature Com., 2017)



Simon Stevenson

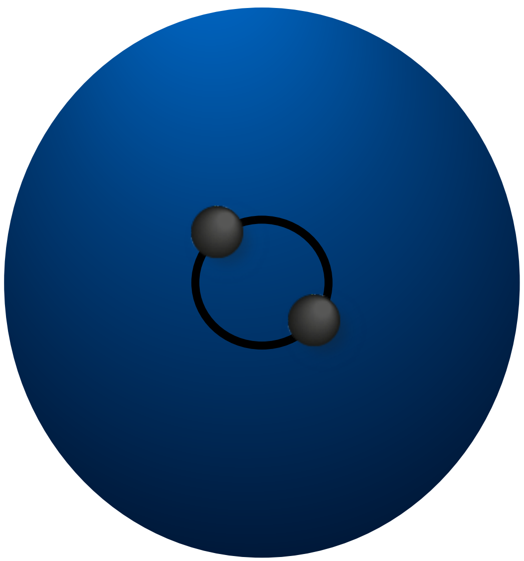
BinCosmos

Formation Channels
2) Dynamical formation



II) Classical Dynamical Channel: Hardening in star clusters

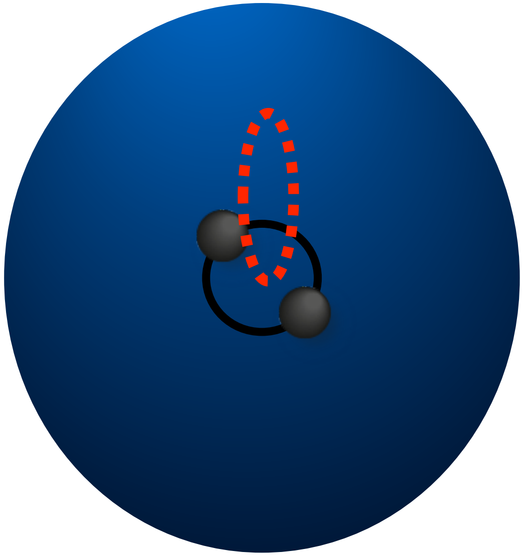
Slides by Carl Rodriguez



cf. Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000; Miller & Lauburg 2009; Rodriguez et al. 2015, 2016; Antonini et al. 2016, … (incomplete)

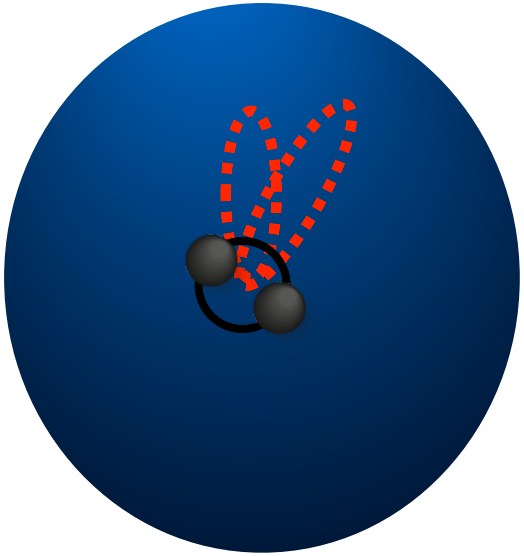
II) Classical Dynamical Channel: Hardening in star clusters

Slides by Carl Rodriguez



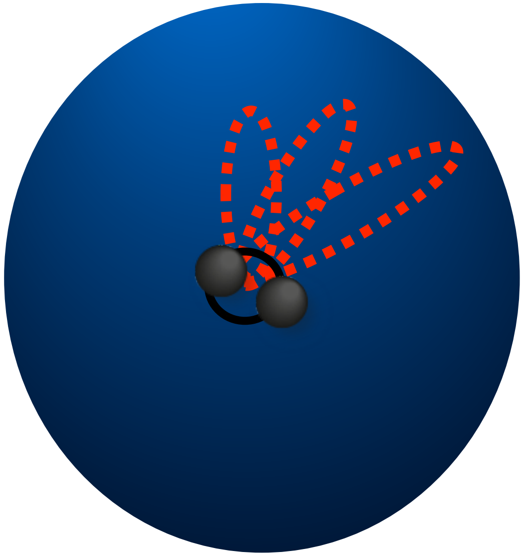
II) Classical Dynamical Channel: Hardening in star clusters

Slides by Carl Rodriguez



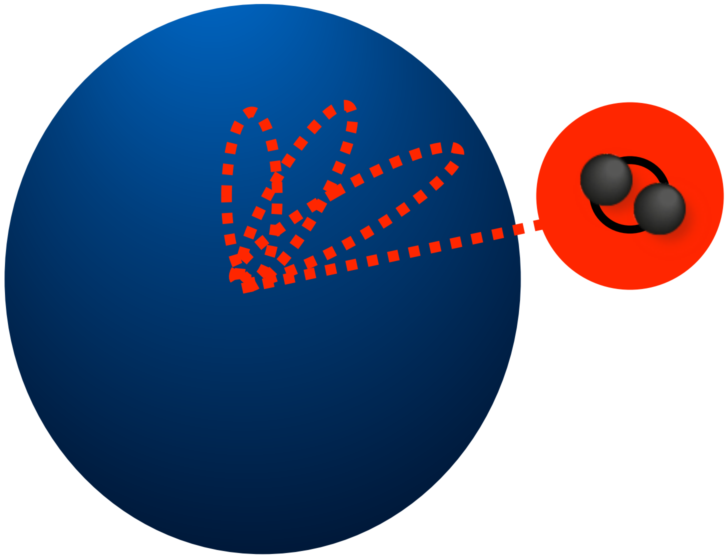
II) Classical Dynamical Channel: Hardening in star clusters

Slides by Carl Rodriguez



II) Classical Dynamical Channel: Hardening in star clusters

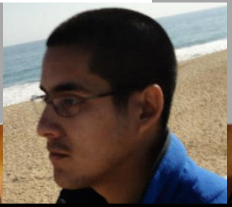
Slides by Carl Rodriguez



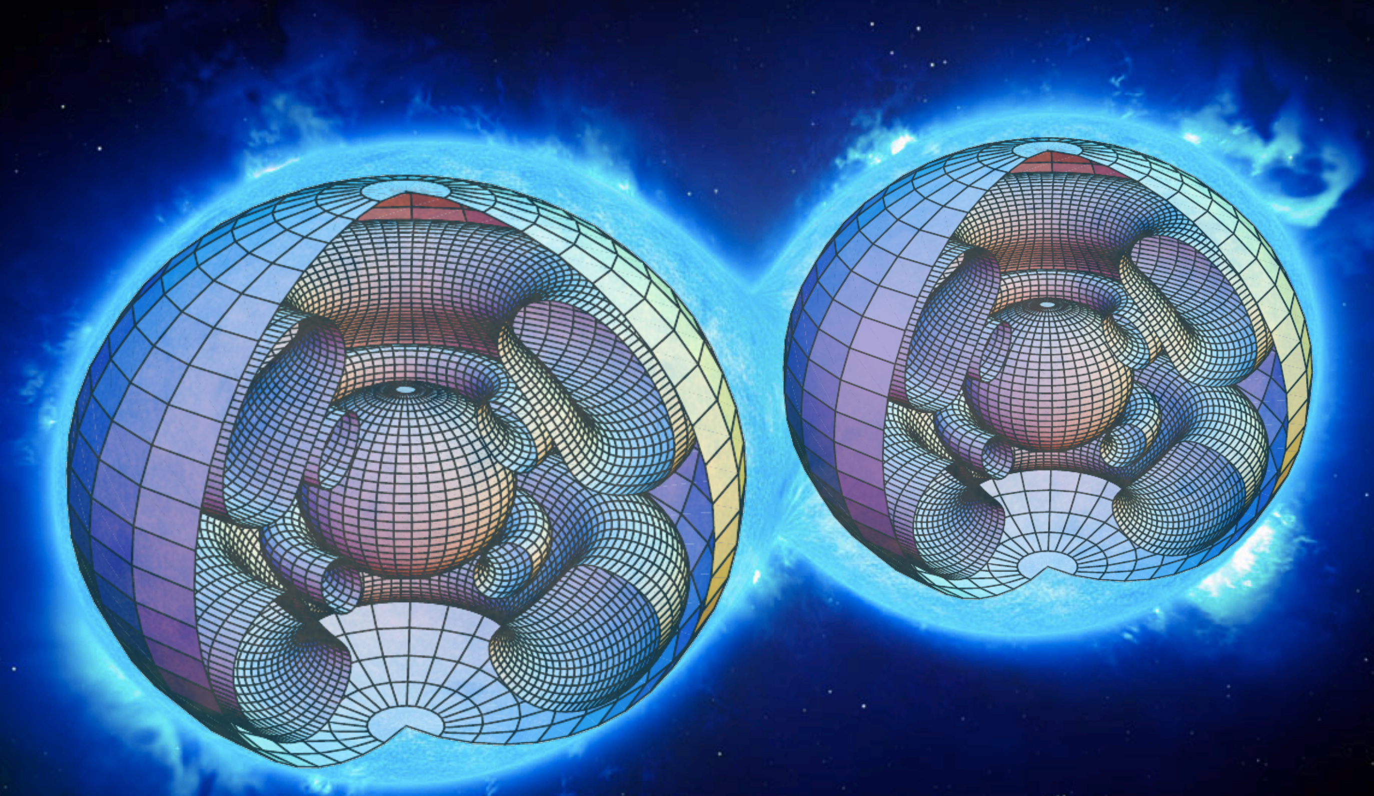
Formation Channels
2) Chemically homogeneous Channel

Other names: Case Mevolution, Tidal mixing channel,
Massive Overcontact Binary (MOB) Channel

de Mink et al. (2008, 2009), Mandel & de Mink (2016), Song et al. (2016), Almeida et al. (2017), Marchant et al. (2016), de Mink & Mandel (2016), Marchant et al. (2017)

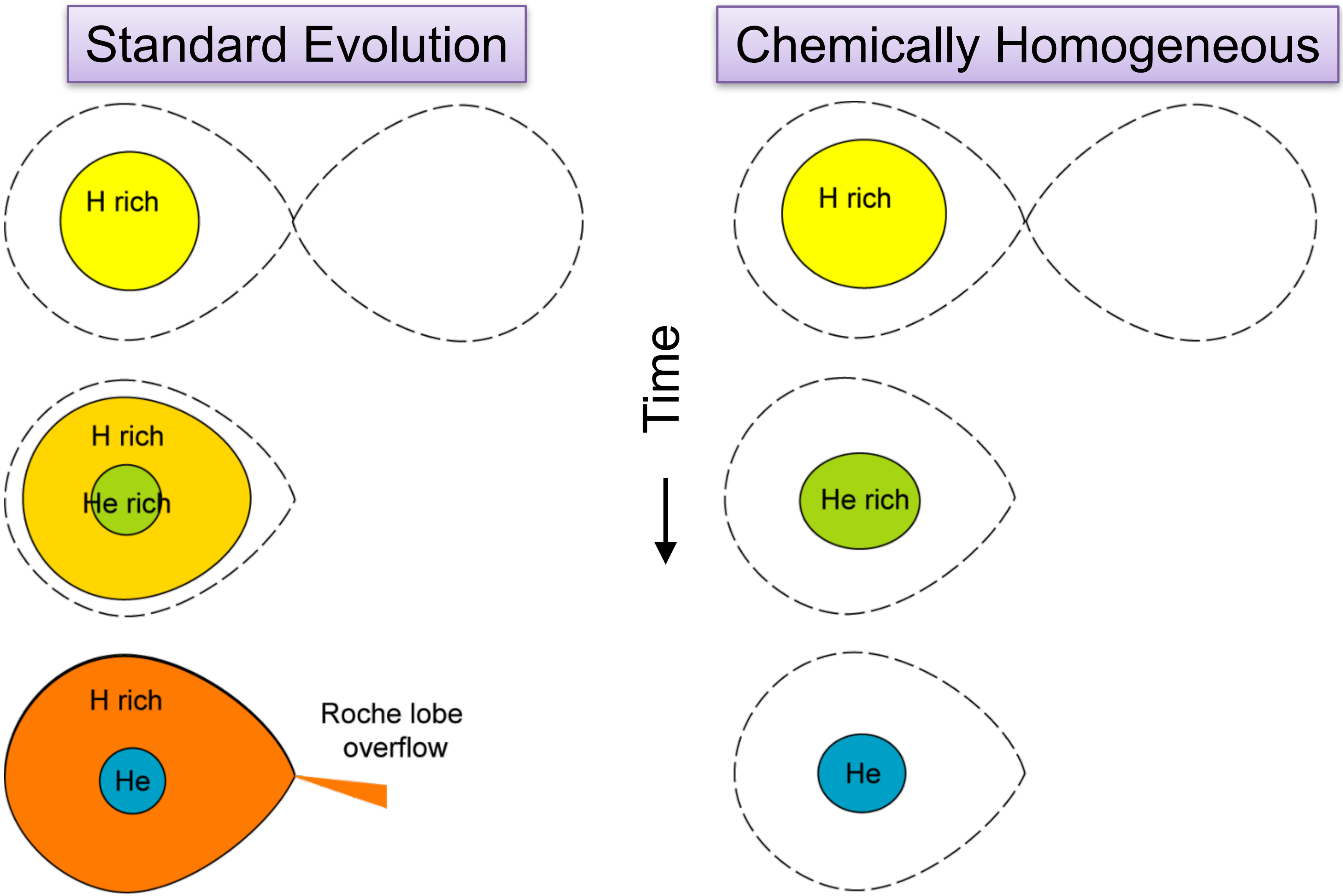


Pablo Marchant



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

Bin
Cosmos

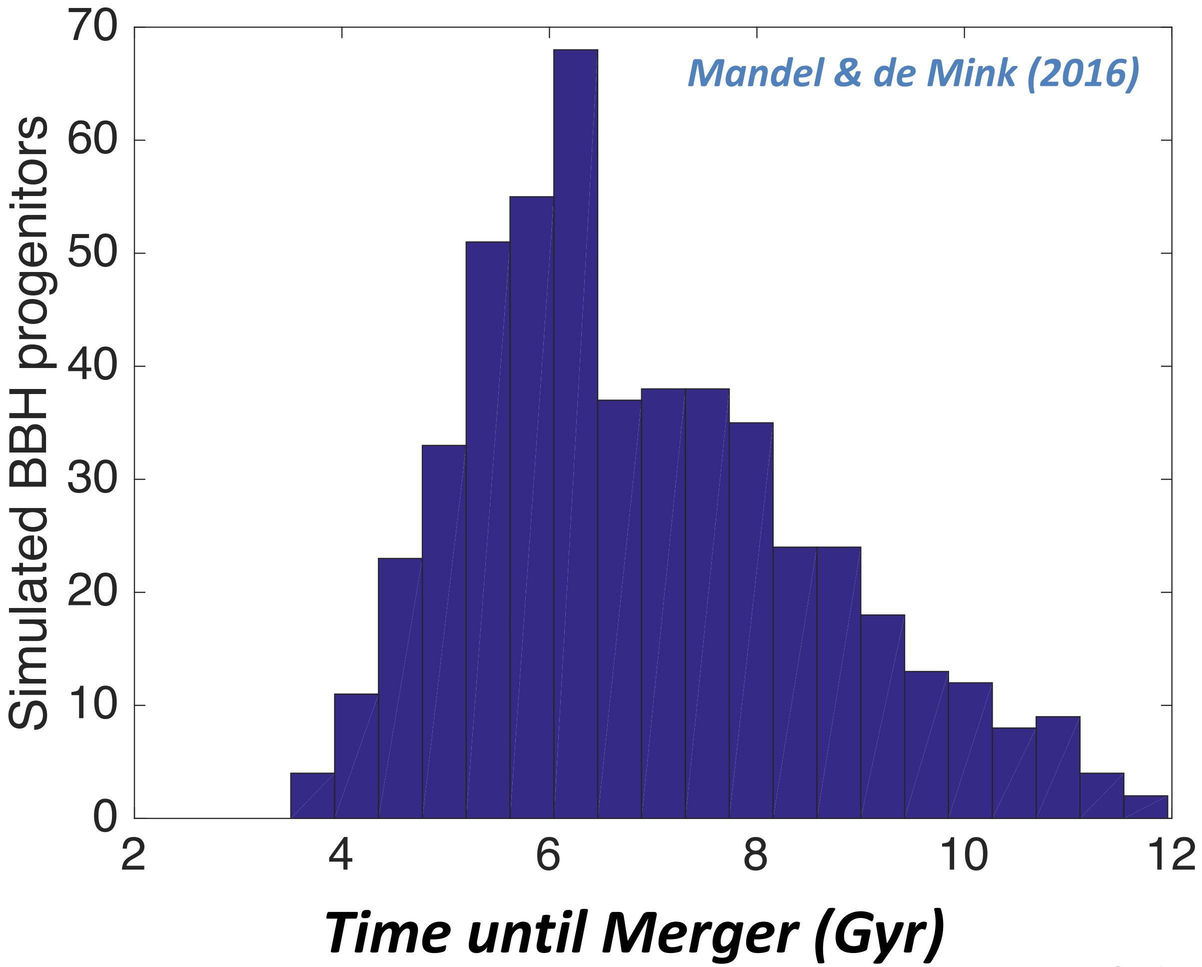


Standard Evolution
Chemically Homogeneous
H rich
H rich
Time
H rich
He rich
He rich
H rich
He
Roche lobe
overflow
He

De Mink+'08,'09

Do they merge within a Hubble time?

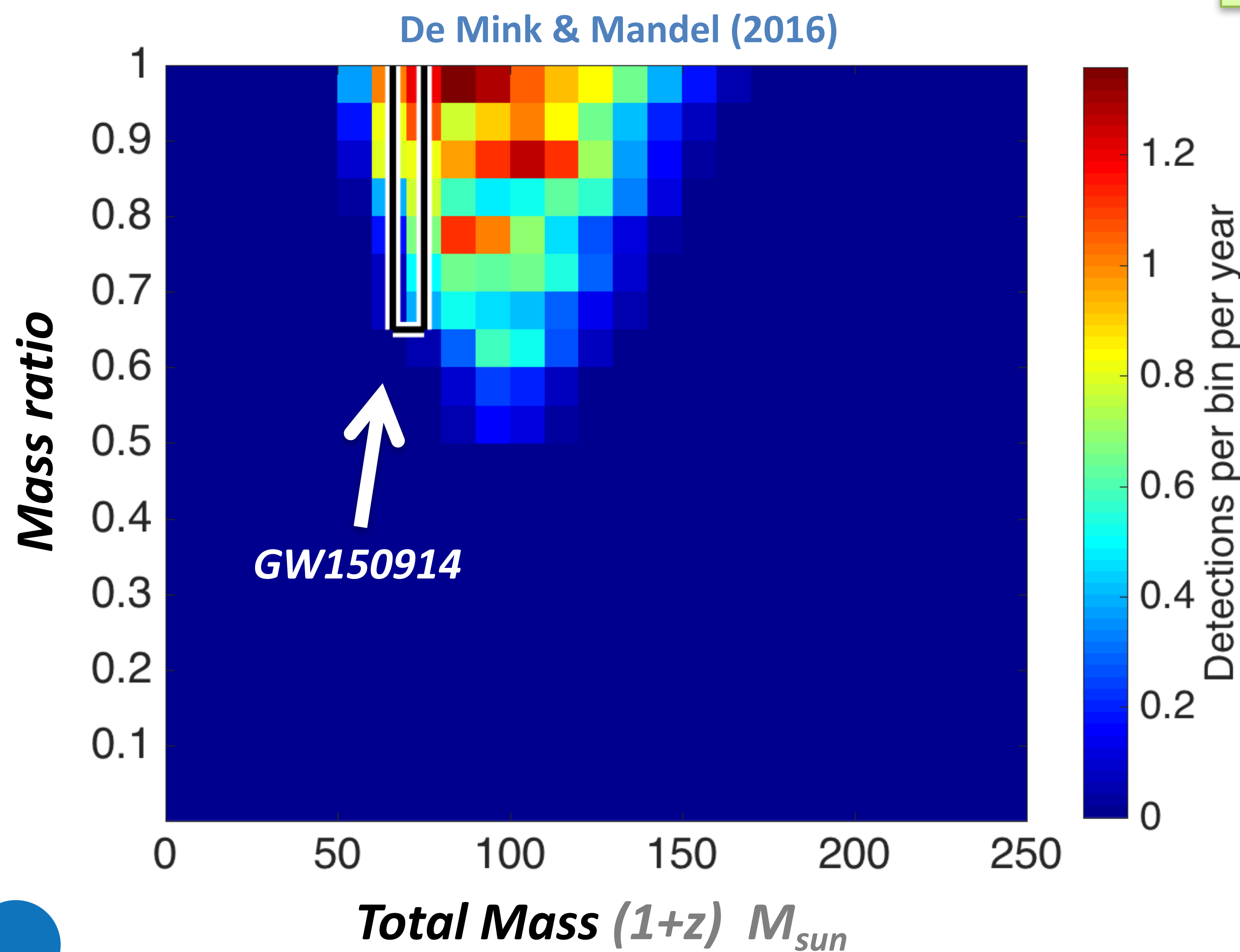
Yes.



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

Can it reproduce high masses?

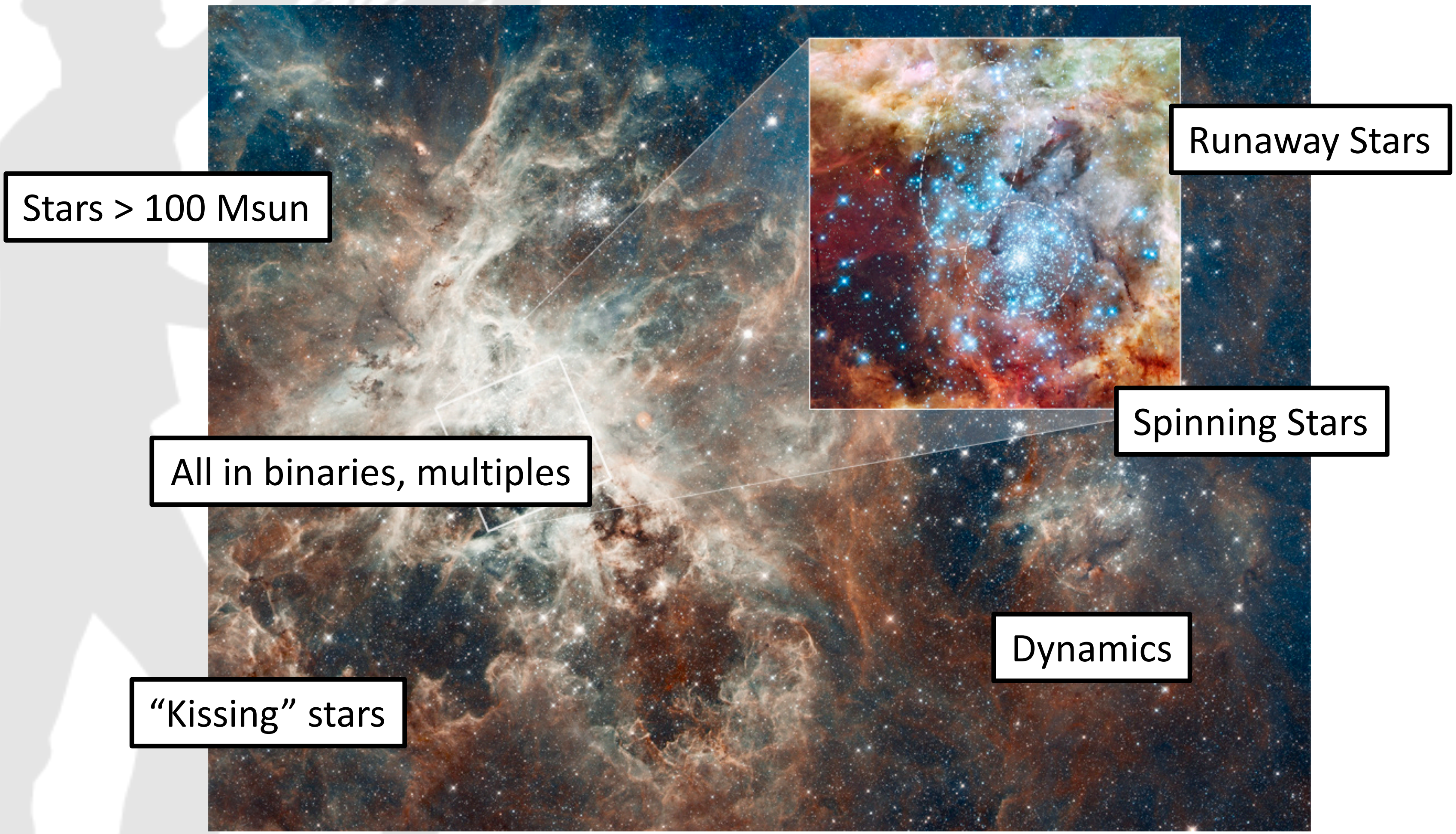
Yes*



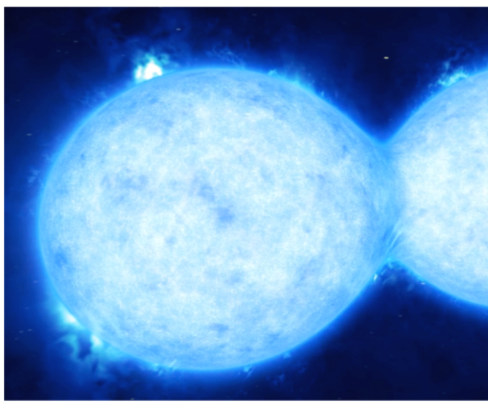
Conclusions

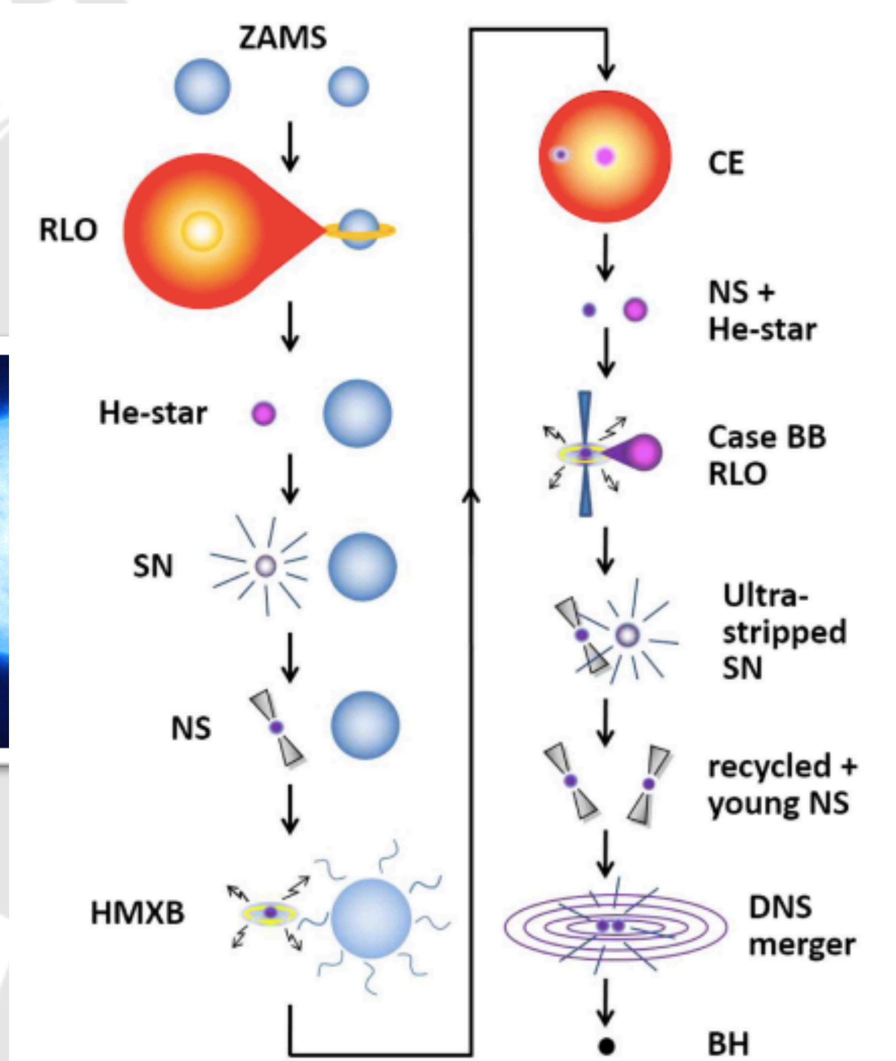
Summary Part I

Quoting V.S.: "I used to think Stellar Evolution was a solved problem"



Summary Part 2

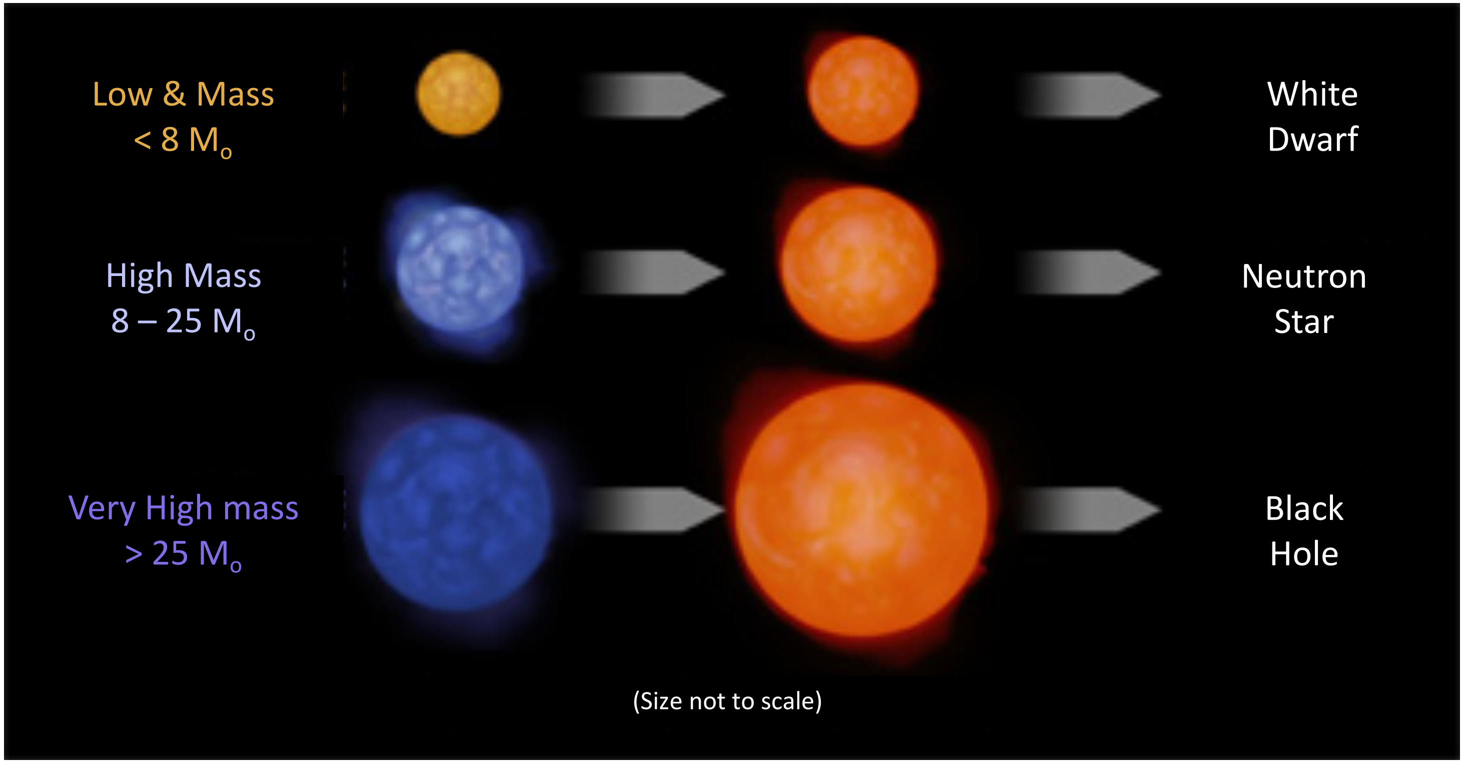




Tauris+2017

If you take away one thing from this talk ..
(NASA outreach material)

Forget about this …



… much more interesting than you learned in school

BinCosmos

BinWaves

Selma E. de Mink
MacGillavry Assistant Professor, University of Amsterdam

Acknowledgements
BinCosmos Group, University of Amsterdam

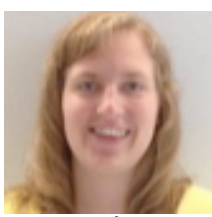
Manos Zapartas PhD

Ylva Götberg PhD

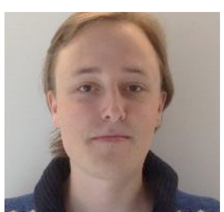
Mathieu Renzo PhD

Ehsan Moravveji MARIE CURIE

Silvia Toonen VENI fellow



Louise Edstam MSc



Walter van Rossem MSc

Floor Broekgaarden Double BSc

? ? ? ?

ANTON PANNEKOEK INSTITUUT

erc

NWO

SURF SARA

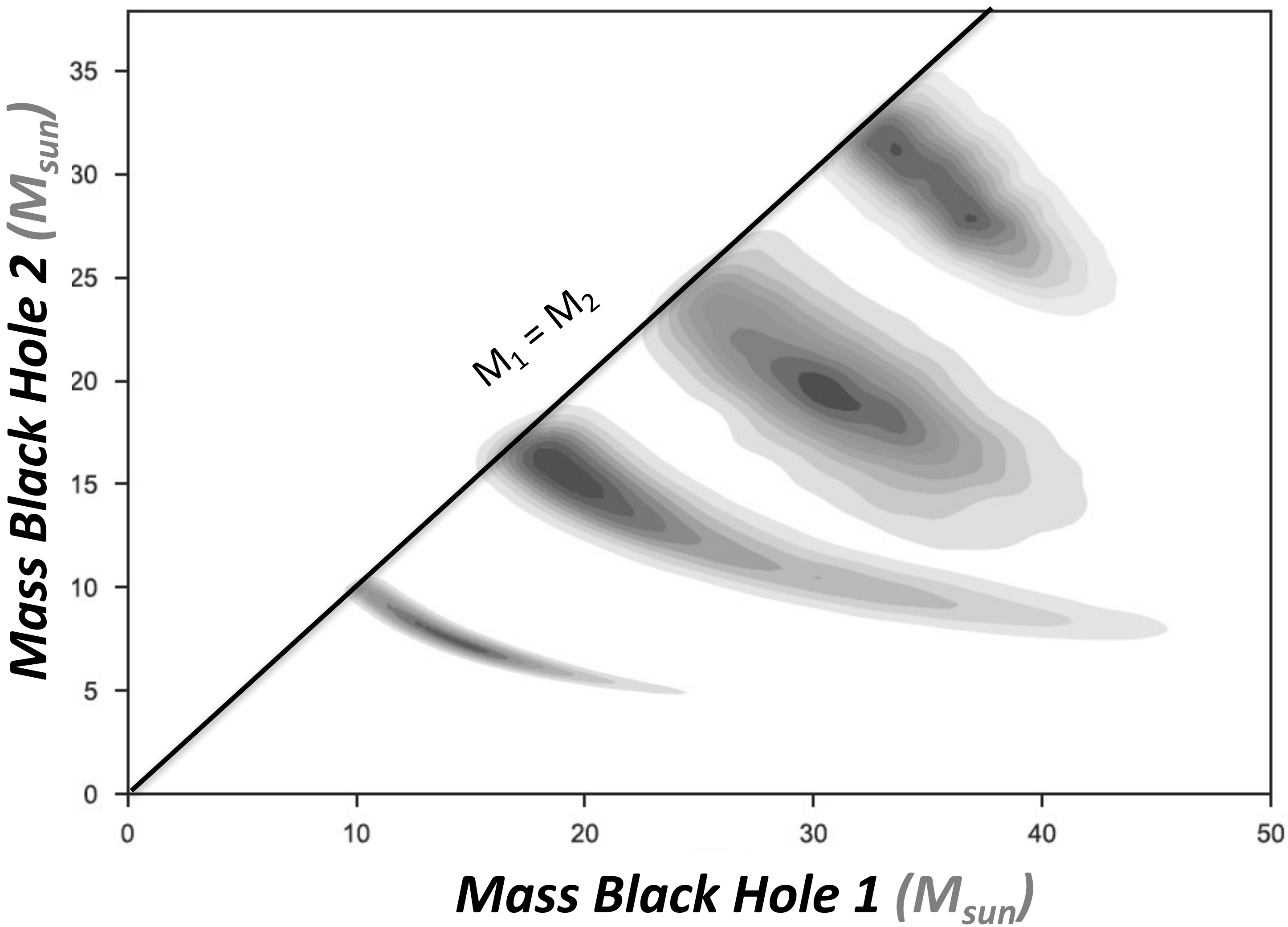
NOVA

MARIE CURIE ACTIONS

MacGillavry Fellowship

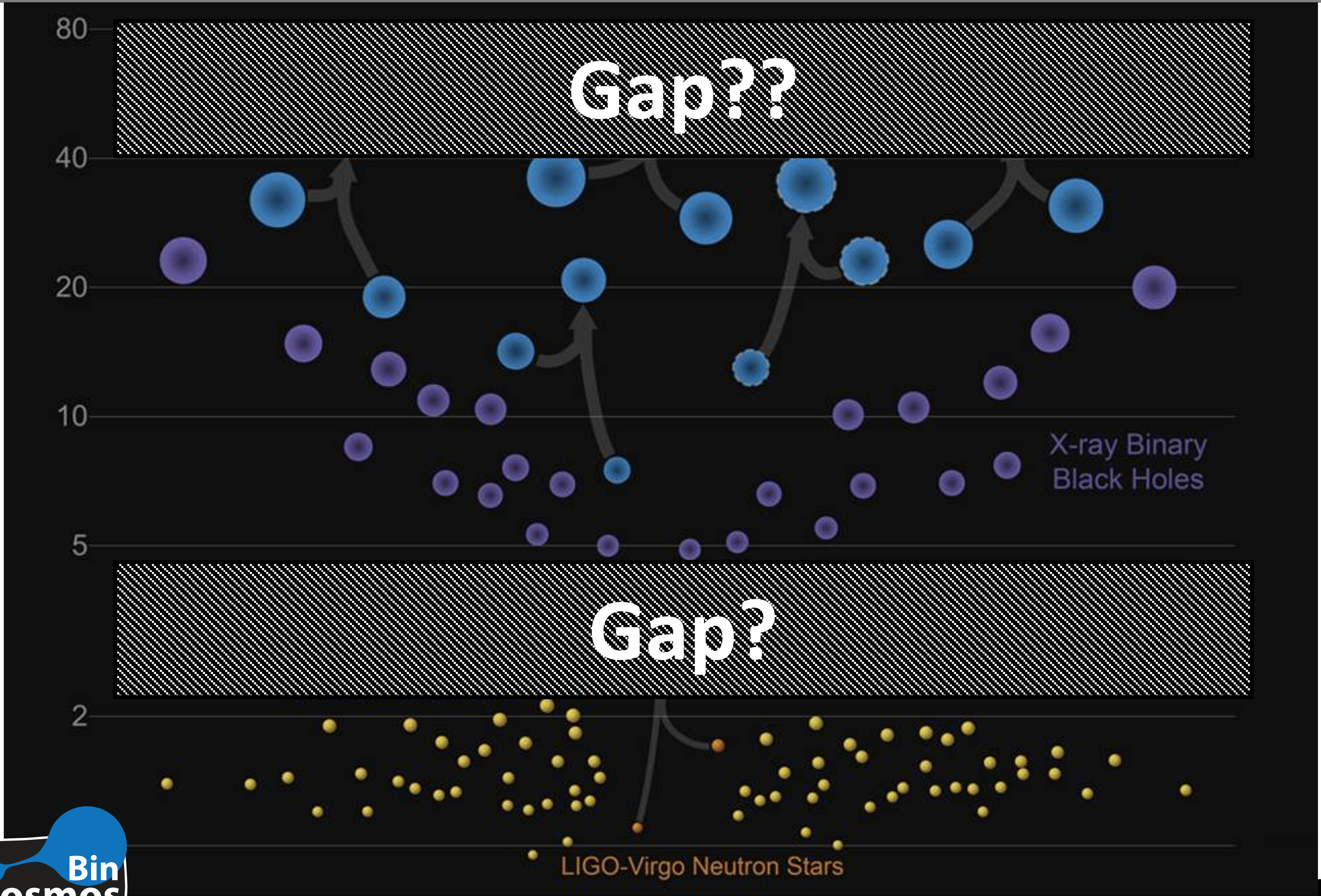
Recently graduated students: Abel Schootemeijer, Coen van Neijssel, Ruben Boots, Max Briel

Bin Cosmos



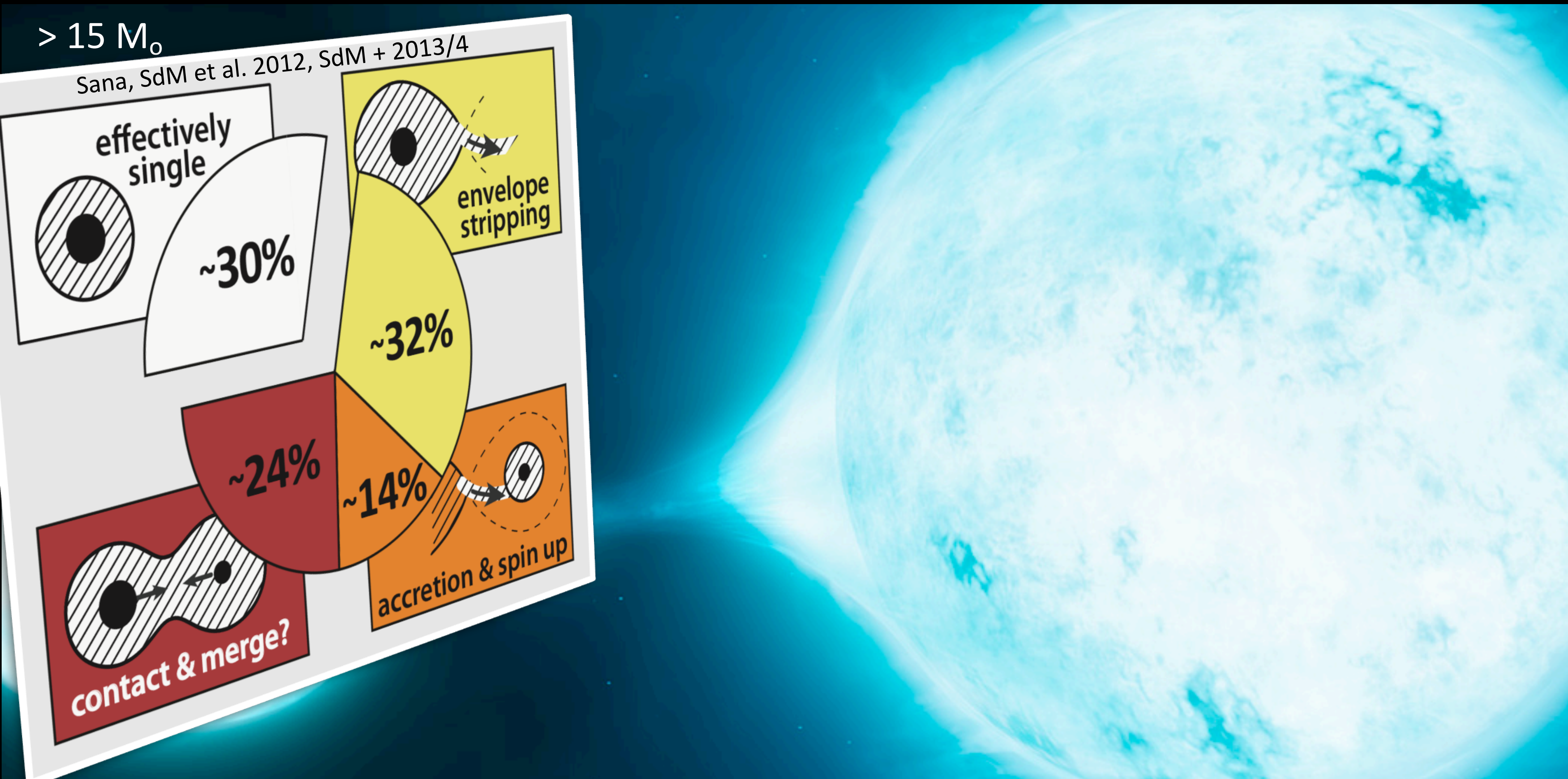
Mass Black Hole 2 (Msun)
35
30
25
20
15
10
5
0
M1 = M2
0
10
20
30
40
50
Mass Black Hole 1 (Msun)

“Stellar Graveyard” today



How do we know?

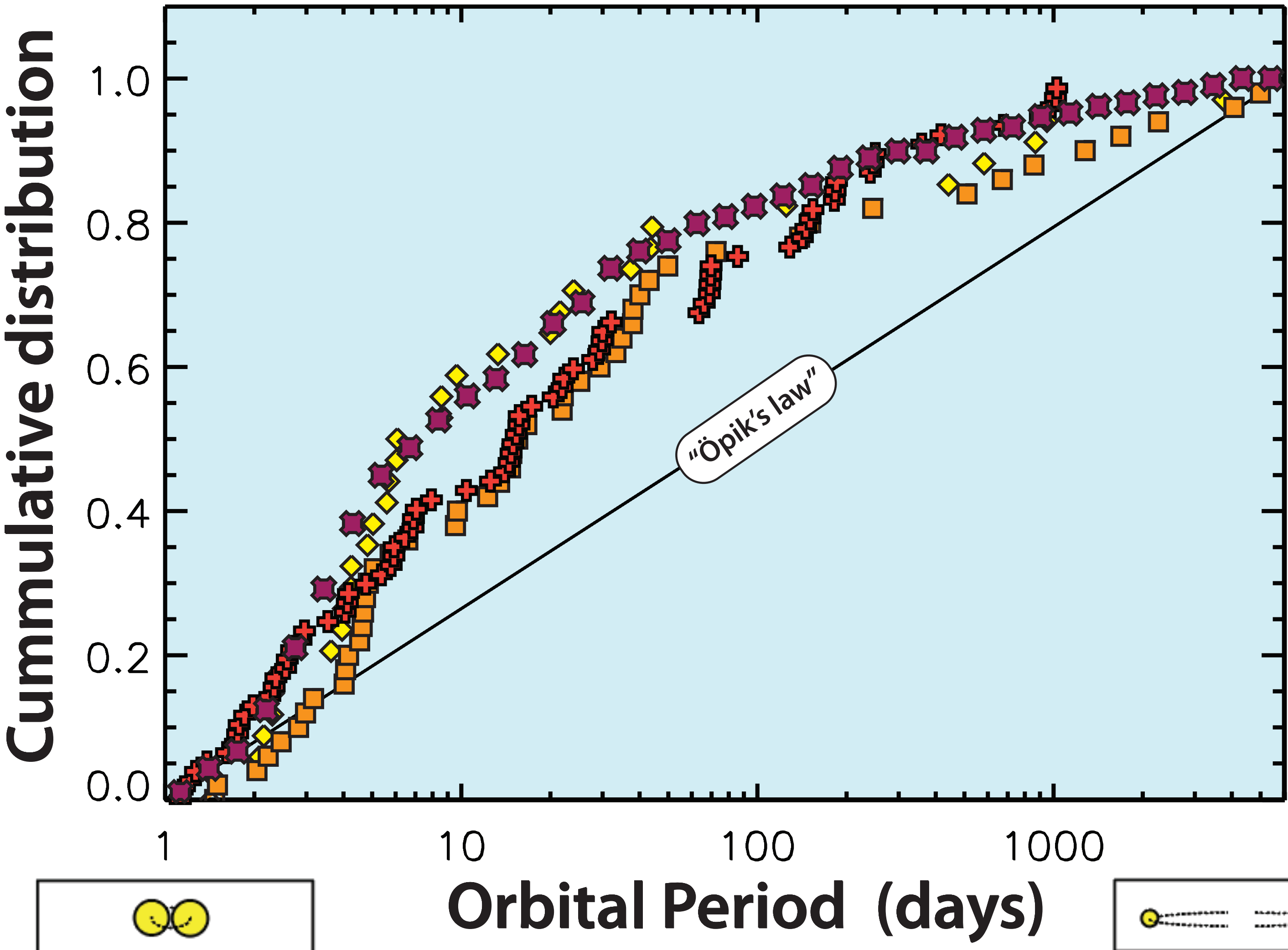
How do we know?



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

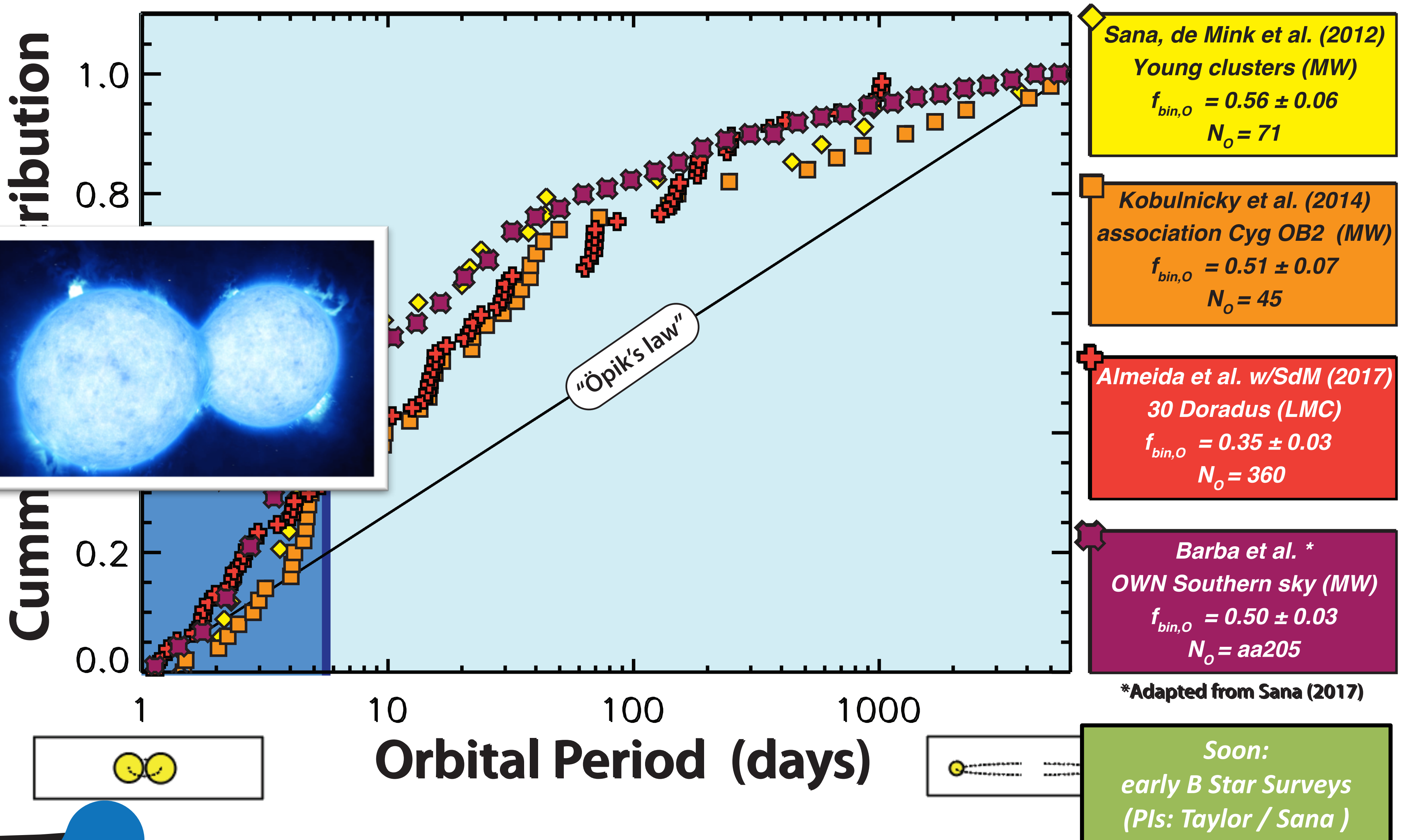
Barba et al. *
OWN Southern sky (MW)
$f_{bin,O}$ = 0.50 ± 0.03
N_O = aa205

*Adapted from Sana (2017)

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

BinCosmos

How do we know?



Bin Cosmos

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 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

BinCosmos