With credit to the following external collaborators: Chris Belczynski, Ilya Mandel, Matteo Cantiello, Andrew King, Norbert Langer, Pablo Marchant, Philip Podsiadlovski, Hugues Sana, Simon Stevenson, Ed van den Heuvel, Alejandro Vigna-Gómez, Nathan Smith, Maria Drout, Thomas Kupfer, Sung-Chul Yoon, Wolfgang Kerzendorf, Jose Groh, Carles Badenes, Simon Portegies-Zwart, Rob Izzard, Coen van Neijssel, Abel Schootemeijer, Onno Pols, Tom Maccarone, Chris Evans, Ori Fox, Schuyler van Dyk, Claus Leitherer, Leonardo Almeida, Alex de Koter, Tony Piro, Paul Crowther, Danny Lennon, Imants Platais, VLT-FLAMES Massive Star Consortium
Intuition for the timescales

1. Detection of signal
   - 1.4 Gyrs

2. Merger
   - “a few” Gyrs

3. Formation binary black holes
   - “a few” Myrs

4. Birth of progenitors stars
   - “a few” Myrs

GW detections still probe relatively local events for now, but the already probed stellar endpoints at very substantial redshifts.
Probing how stars die across cosmic time

(A) Stellar Origin

(B) Primordial

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

“Cosmic time” (not to scale)
This is not exotic

Initial distributions of
- Masses
- Mass ratios
- Separations/Periods
- 
- Cosmic Starfomation history $f(Z, z)$

cf. Abt+78, Kobulnicky+Fryer07, Mason+09, Chini+12, Sana,SdM+12, Sana,deKoter,SdM+13, Kobulnicky+14, Dunstall+w/SdM15, Moe+16, Almeida+w/SdM17, ...
This is not Exotic ...

... but this is.

Other exciting objects
Formation Channels
Why is it so hard to make close double compact objects

Birth ➔ Formation BHs ➔ Coalescence

1. “Separation Challenge”

2. “Mass Challenge” (for BHs)
Why is it so hard to make close double compact objects

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
Traditional Division

“Evolutionary Channels” (Field)

i) Classical (Common Envelope)

“Dynamical Channels”

ii) Dynamical formation in massive star clusters

Cf. talks by Mandel, Rasio, Naoz, Shoemaker, Holz, ...
Formation Channels

“Evolutionary Channels” (Field)

i) Classical (Common Envelope)

ii) Dynamical formation in massive star clusters

iii) Chemically Homogeneous Channel

iv) Kozaii resonance with SMBH

v) In gas disk of Active Galactic Nuclei

vi) Triples

...?...

vii) Stable non-conservative mass transfer

See talks by Mandel, Rasio, Naoz, Shoemaker, Holz, ...
Chemically Homogeneous Channel

“Case M Evolution”,
“The Rotational Channel”,
“Tidally Induced Mixing Channel”

de Mink et al. (2008, 2009), Mandel & de Mink (2016), Song et al. 2016;
Marchant et al. (2016), de Mink & Mandel (2016), Marchant et al. (2017)
Marchant et al. (to be subm.)

Primary Collaborators:
Ilya Mandel (2016), Matteo Cantiello (2009)
Single stars with Rotation

Effective Temperature (kK)

Log \[ \text{Luminosity (L}_{\text{sun}}) \]

Zero-age main sequence

Z = 0.004
Single stars with Rotation

Effective Temperature (kK) vs Log [ Luminosity (L\textsubscript{sun}) ]

Brott & de Mink et al. (2011)

Z = 0.004
Single stars with Rotation

Single stars with Rotation

Maeder89, Yoon+05/06
Maeder & Meyet 2000,

Effective Temperature (kK)

60 M\(_{\odot}\)
40 M\(_{\odot}\)
30 M\(_{\odot}\)
20 M\(_{\odot}\)
16 M\(_{\odot}\)

\(L_{\odot}\)

Z = 0.004
What if you could do this in a close binary?

| Standard Evolution | Chemically Homogeneous |

De Mink+08,'09
Full Evolutionary Calculations

2b) Homogenous

De Mink + 2009

1. Zero-Age

2a) Normal Evolution

Log Effective Temperature (kK)

Log Luminosity

H rich

Roche lobe overflow

Constant radius
Do such tight binaries exist?

**VFTS 352** - Orbit: 1.1 Day
A case for (partial)Chemically Homogeneous Evolution?

28 $M_\odot$  
28 $M_\odot$

Almeida, Sana, de Mink et al. (2015)  
Image Credit: ESO/L. Calçada
Predictions for the Chemically Homogeneous Channel

(Take these with a grain of salt)

**Delay Time**  
Mandel & de Mink (2016)

**Masses**  
de Mink & Mandel (2016)

**Rates**  
DCC: LIGO-G1800370

**Open Questions:**
- **What about Spins?** - Open question, hard to predict
- **Lower mass events?** – Probably only massive
- **What about side products?** - ....

Cf. Marchant et al. (2016)
How to Proceed from here
How to Proceed from here?

- Runaway stars
- Overcontact binaries
- Stellar mergers
- (Ultra Luminous) X-ray Sources
- (Pair Instability) Supernovae
- ....
Challenge of Simulating Rare Events
(such as BH-NS systems)

Birth distribution Monte Carlo

BH-NS systems
1 Million Binaries ~ 90 CPU hours, w/ Compas
w/ Gair, Justham, Barett, Justham, Mandel, Stevenson, Vigna-Gomes
Challenge of Simulating Rare Events

Broekgaarden et al. in prep.

- ~10x Smaller Uncertainty
- ~100x Speed Up

Floor Broekgaarden
How not to make a binary black hole
Runaway and Walkaway Stars

Renzo et al. w/SdM 2018

“Small BH kicks”

BH momentum kick ($\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$, fiducial)

“Big BH kicks”

BH: $\sigma_{\text{kick}} = 100 \text{ km s}^{-1}$
NS: $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$
(no fallback for BH)
Side Products (2)

Marchant et al. w/SdM (2017)
Marchant et al. w/SdM (2017)

- Massive Contact binaries
- Ultra Luminous X-ray sources
- Binary Black Holes
- Pair Instability Supernova
- Inverse RLOF
Gap? (2-5 $M_{\text{sun}}$)

Second Gap? (Predicted $\sim$40-140 $M_{\text{sun}}$)
Wrap up
This is not Exotic ...

... but this is.
How did we get here?

Massive Star Generations

(I) Cosmic Engines

(II) Cosmic Probes

How did we get here?