

The role of N-body dynamics in producing
Gravitational Waves
– A review of progenitor theories

Dorottya Szécsi

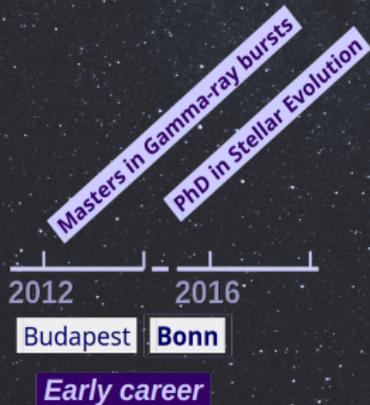
Associate Professor & OPUS group leader
Nicolaus Copernicus University
Toruń, Poland

Budapest, 2nd June 2025



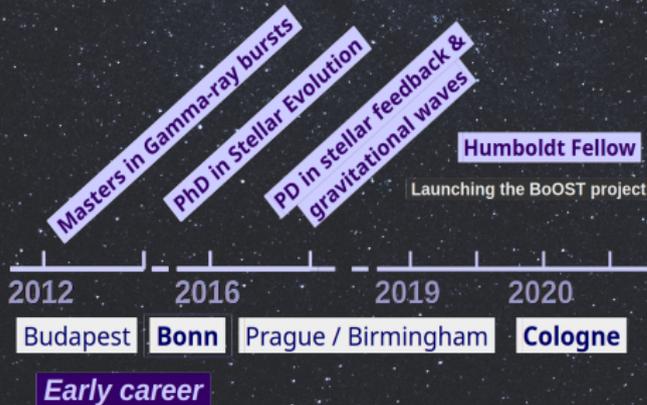
Dr. habil. Dorottya Szécsi, prof. UMK

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OPUS group leader



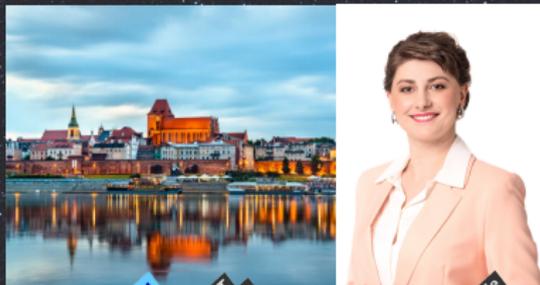
Dr. habil. Dorottya Szécsi, prof. UMK

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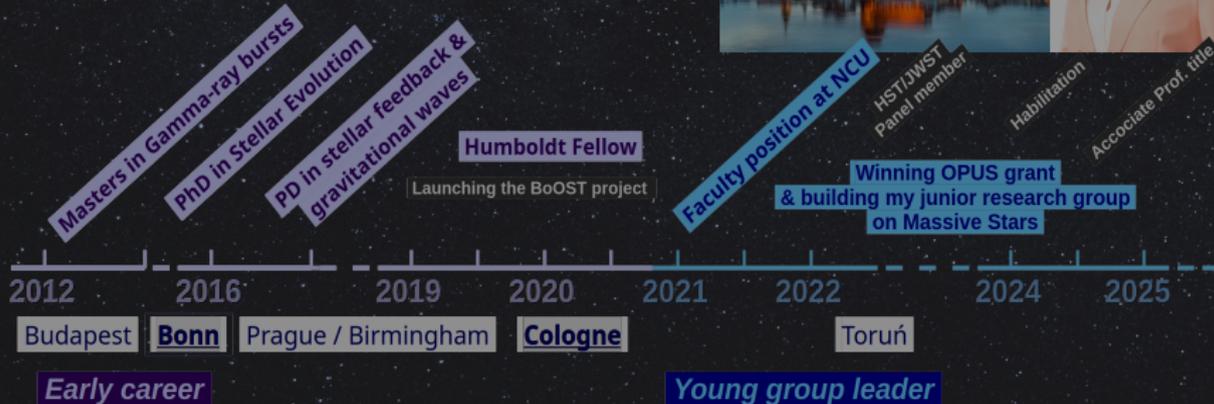
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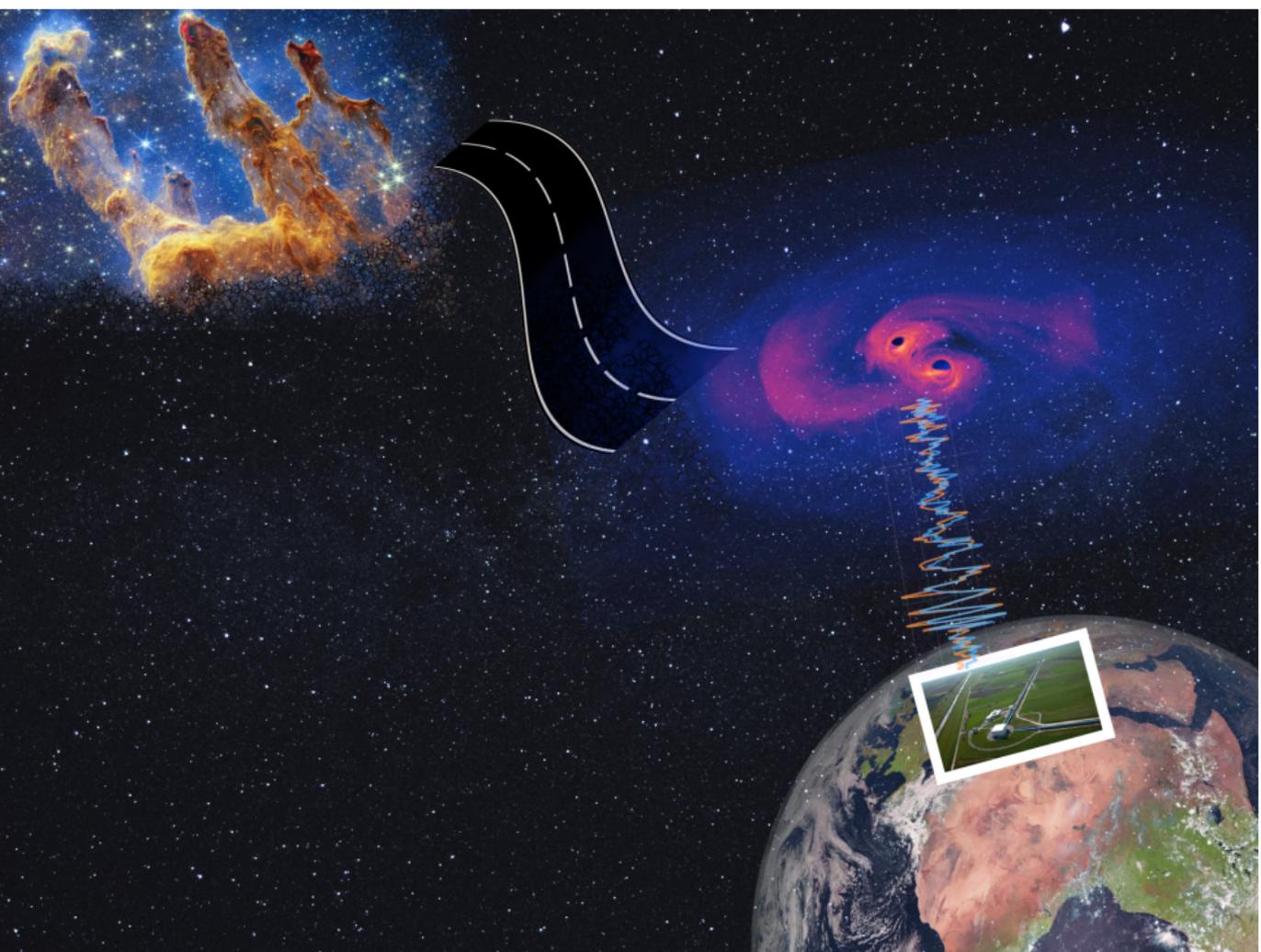
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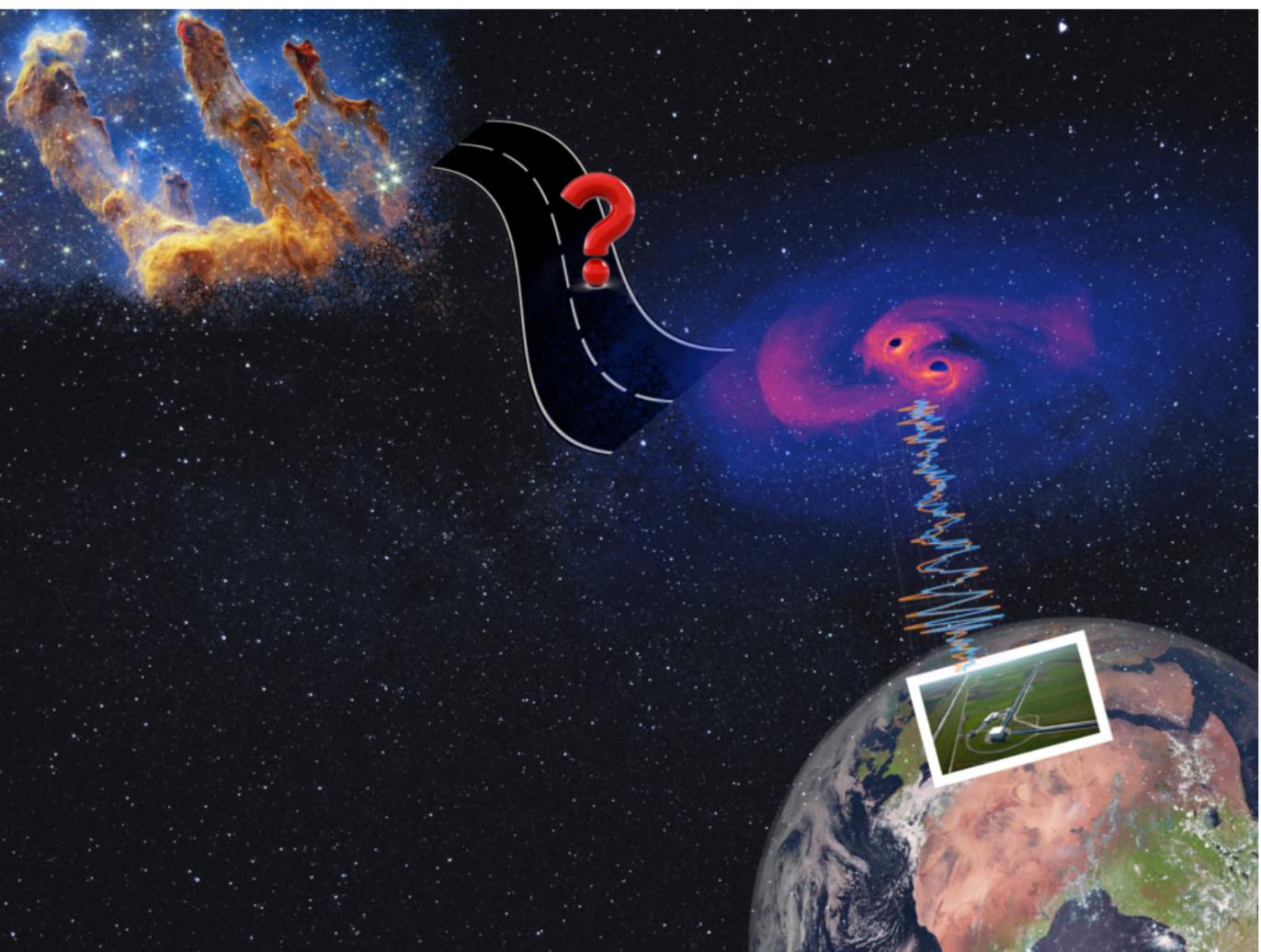


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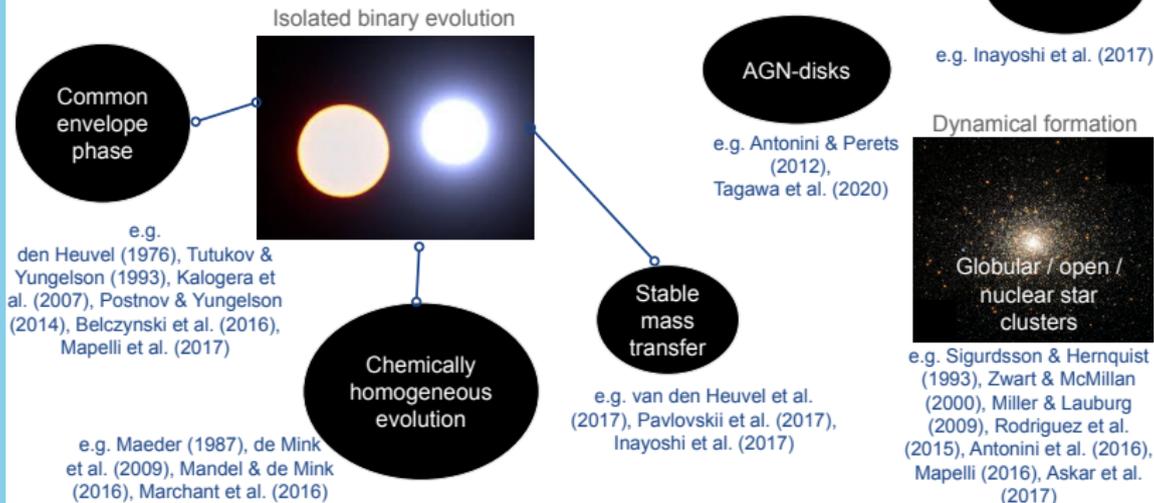


Gravitational Waves



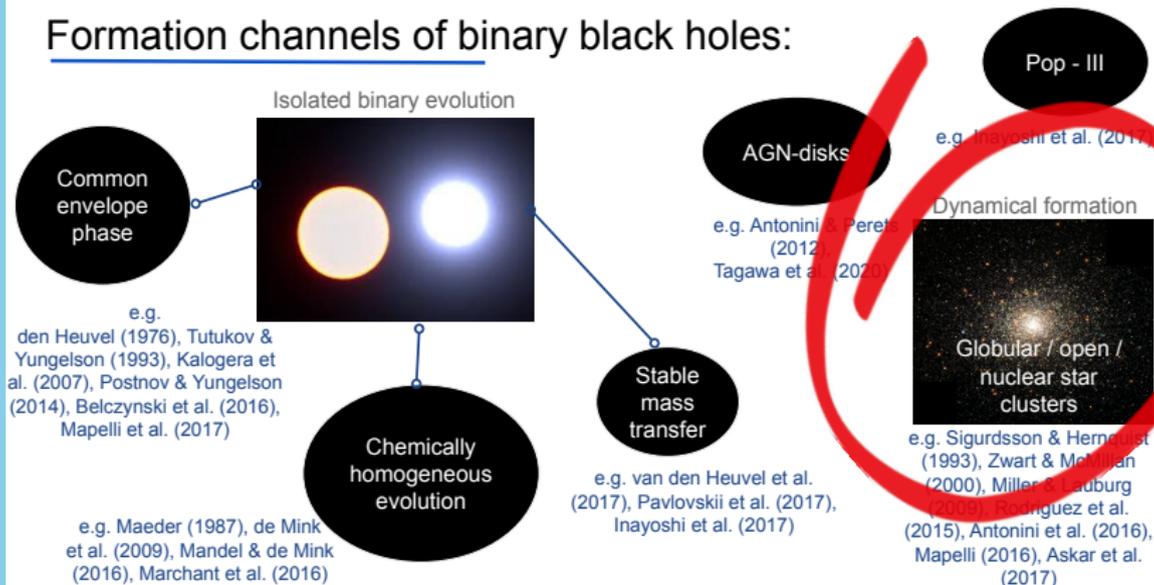


Formation channels of binary black holes:



Credit for slide: R. Sarwar

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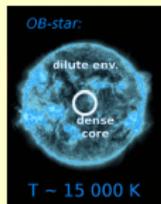
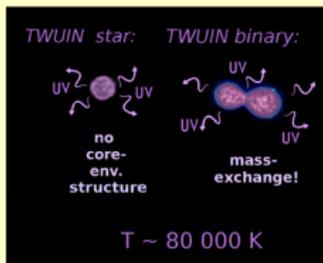
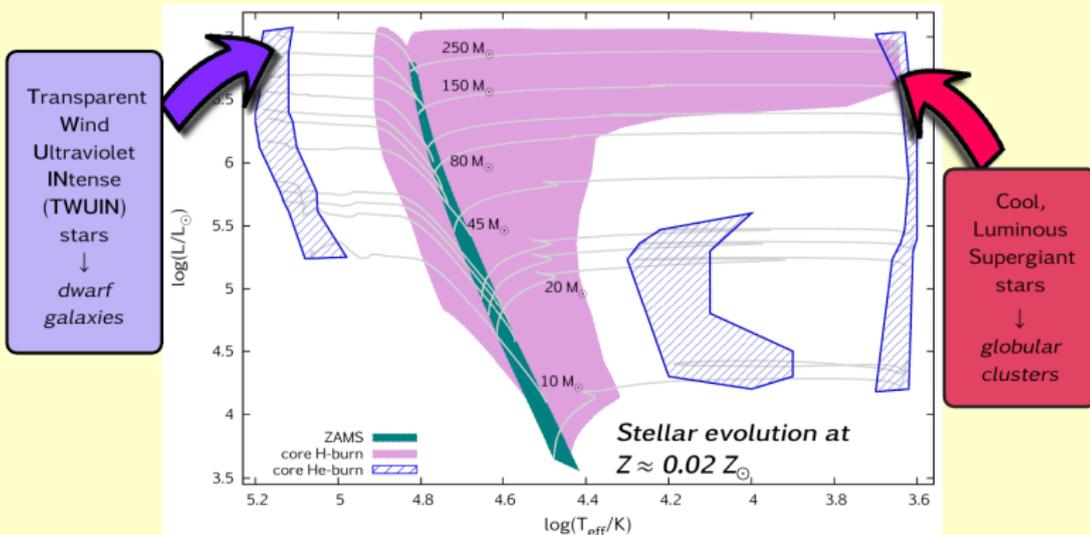
Credit for slide: R. Sarwar

“Isolated binary evolution” channel

“Isolated binary evolution” channel

because 50-100% of all massive stars are born in pairs

Szécsi et al. 2015:

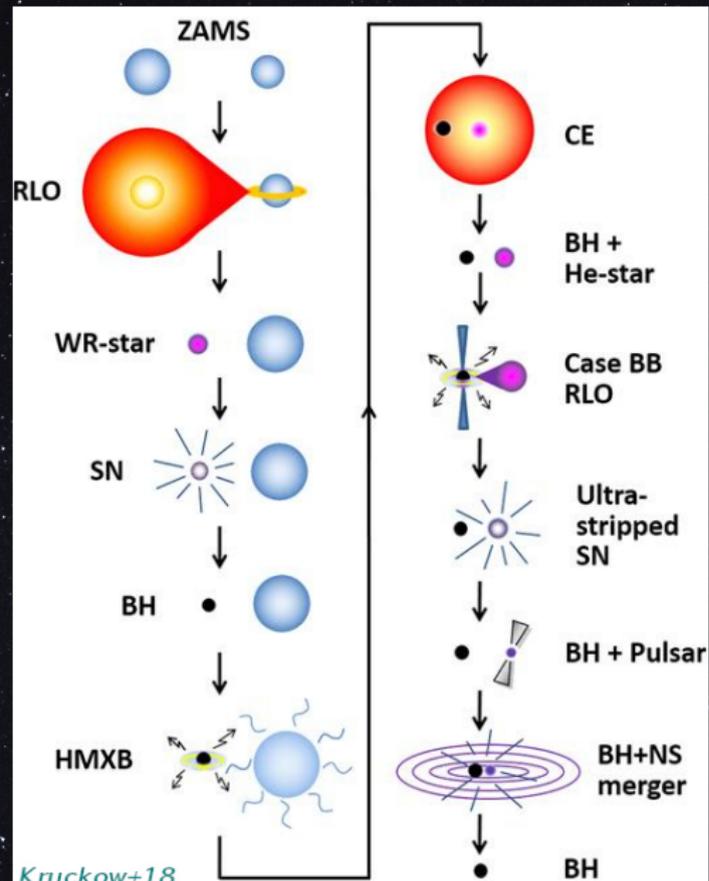


[Szécsi+22](#), [Garcia, ...](#), [Szécsi+21](#)



[Szécsi & Wünsch'19](#), [Szécsi+18](#)

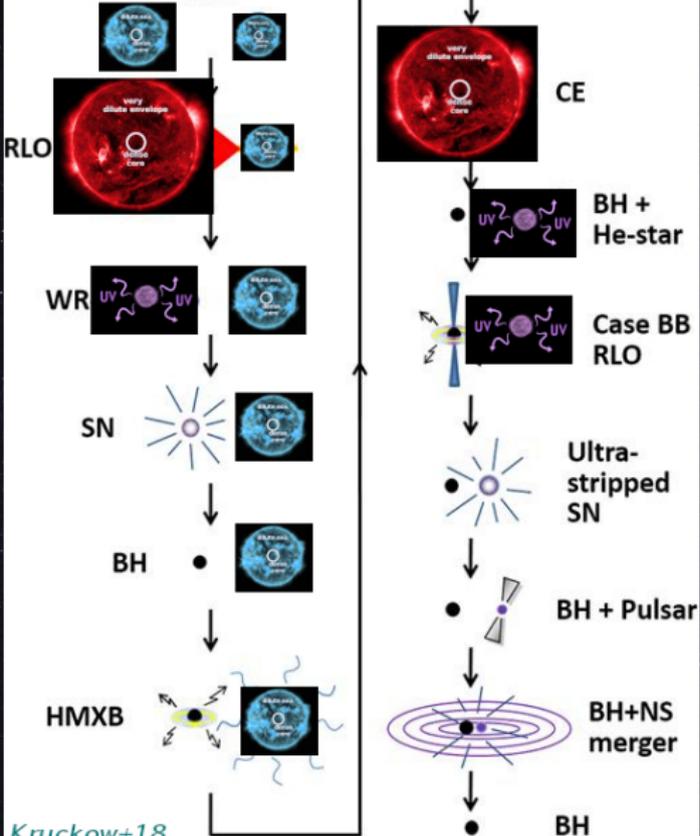
Kubátová & [Szécsi+19](#), [Szécsi'17a](#), '17b



Kruckow+18

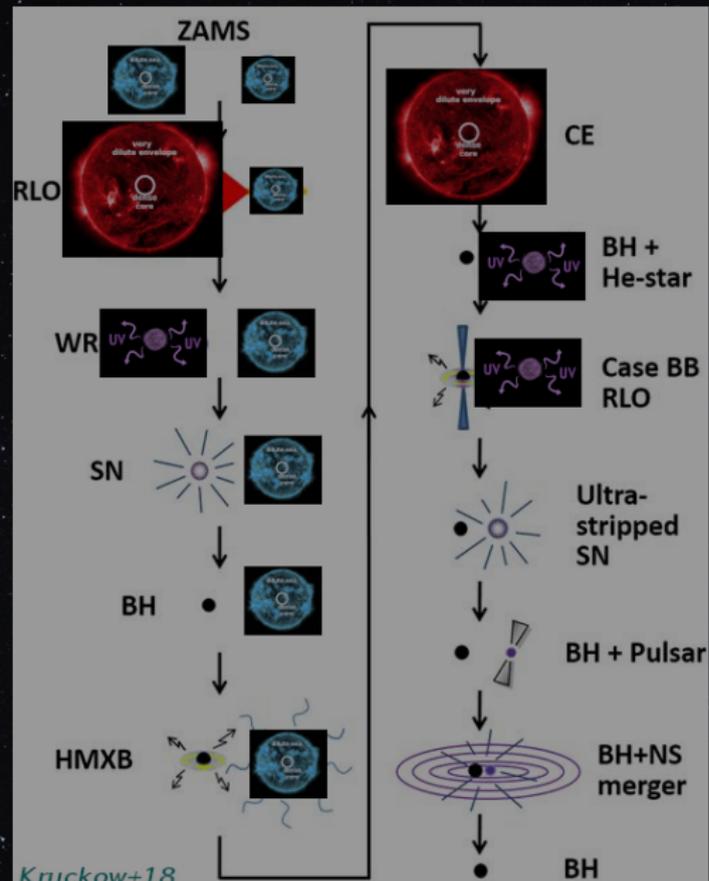
based on the models of [Szécsi+15](#)

ZAMS

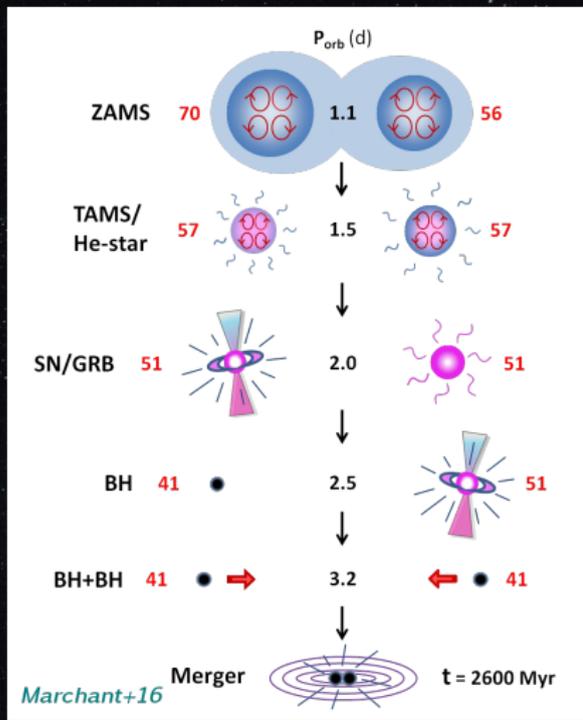


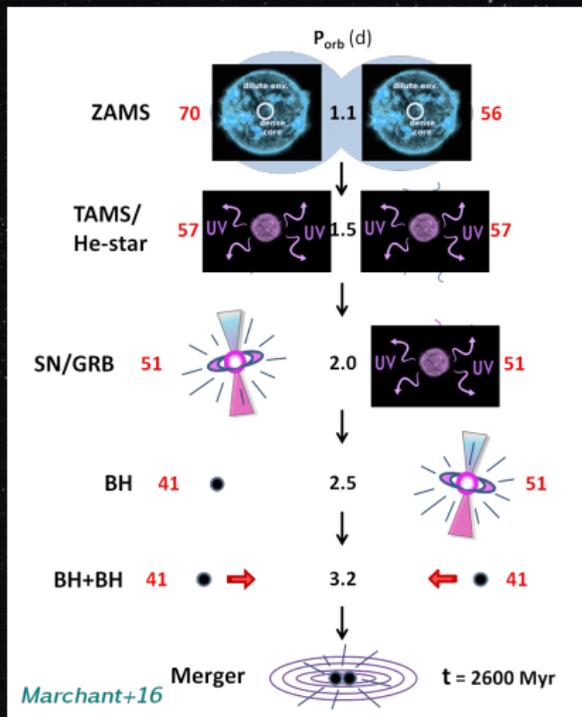
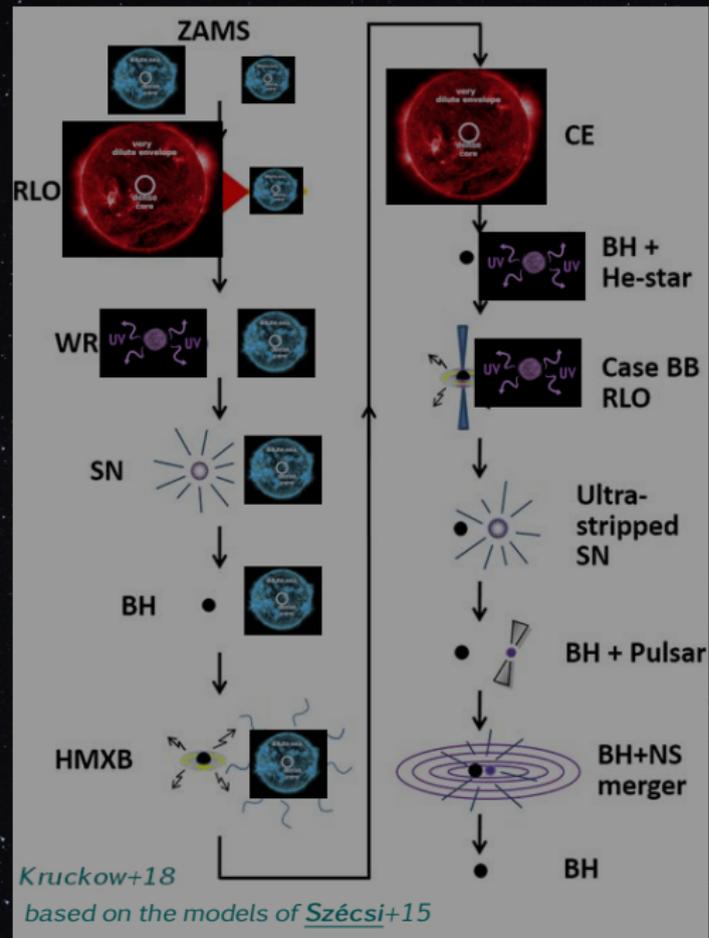
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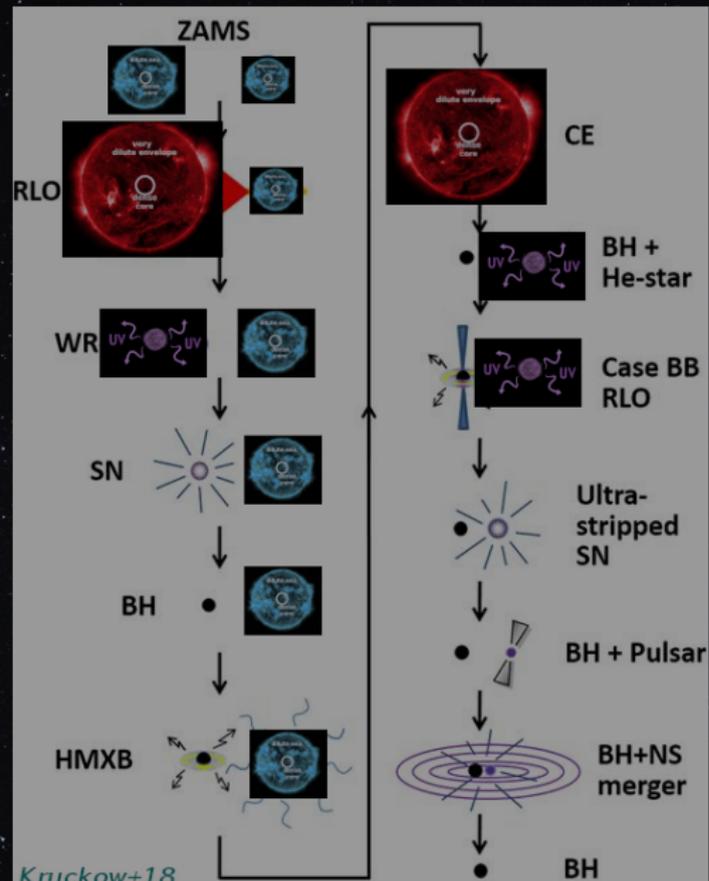
based on the models of Szécsi+15



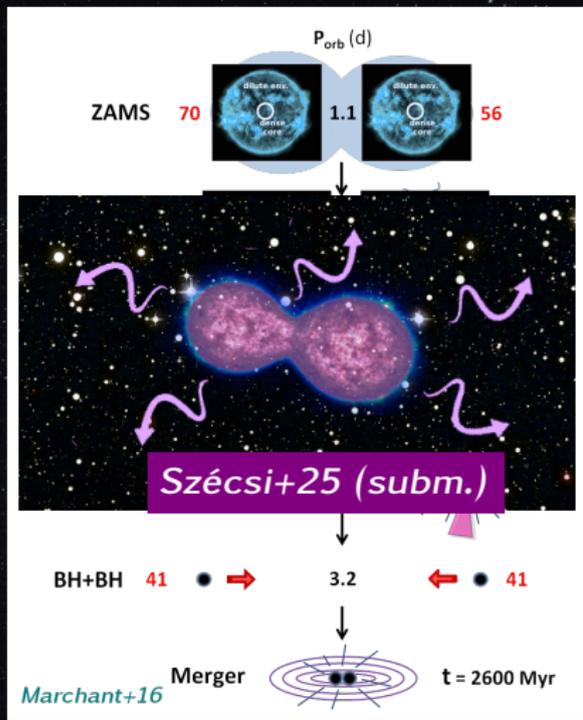
Kruckow+18
 based on the models of *Szécsi+15*

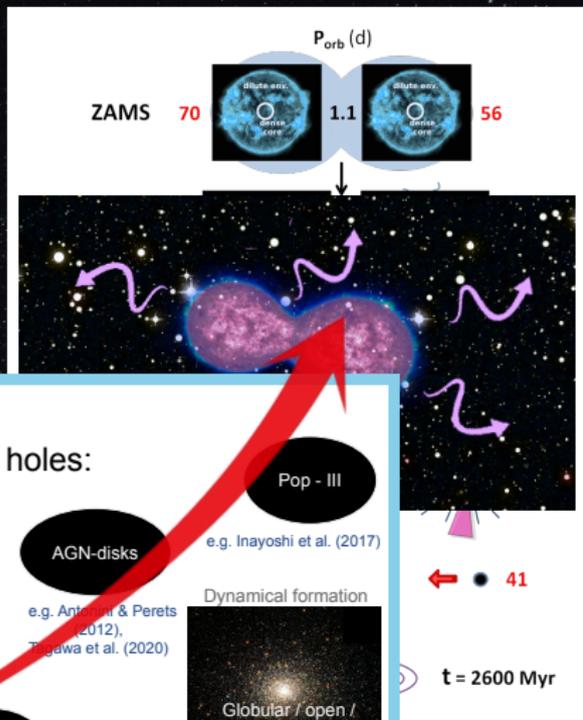
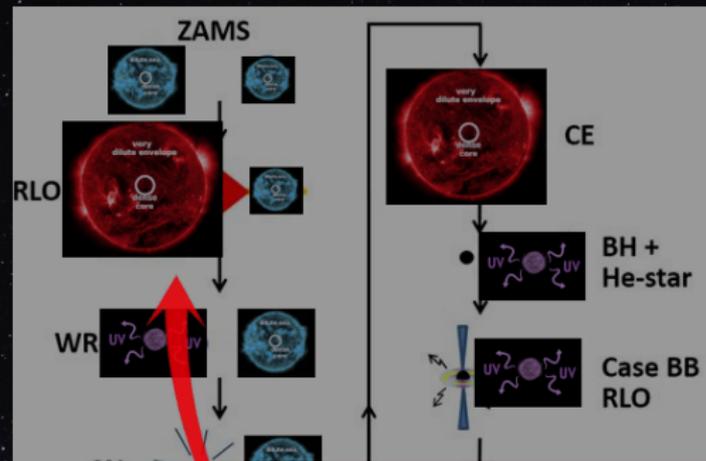




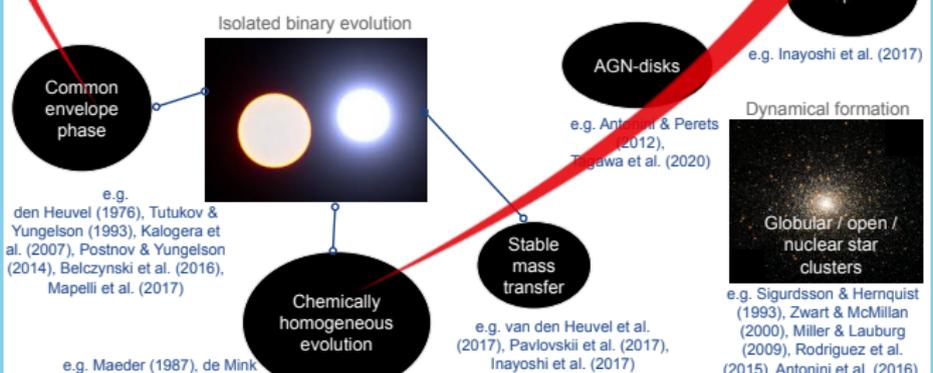


Kruckow+18
 based on the models of *Szécsi+15*





Formation channels of binary black holes:



Why called 'isolated' though?

Why called 'isolated' though?

because environment doesn't matter (cluster/field)

Uncertainties

Uncertainties

oh dear... so many

Common Envelope phase?? Stable Mass Transfer:
efficiency?? Chem.hom.evolution: does it exist??

Single-star physics: 1D codes dealing with multi-D
phenomena (convection, turbulences, rotation ...) – wind
mass loss ??

Uncertainties

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Stars → Population ???

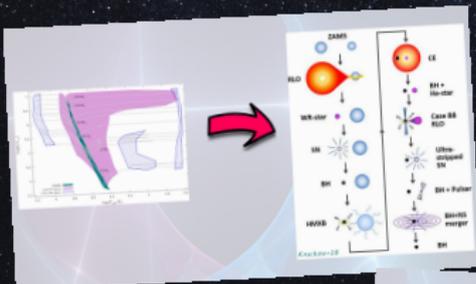
Method: (rapid) binary population synthesis



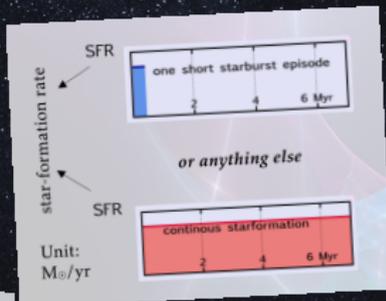
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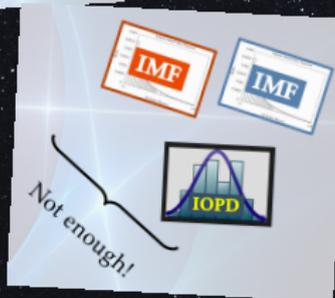
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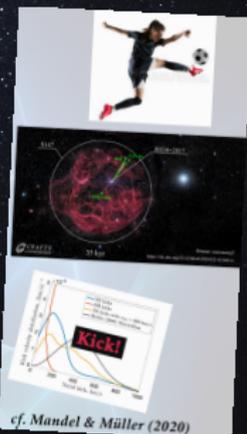
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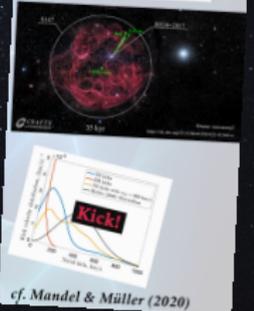
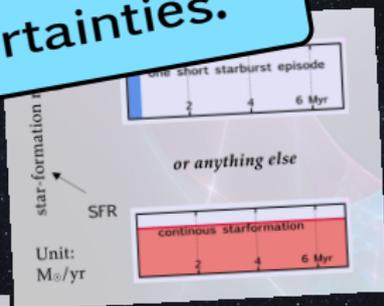
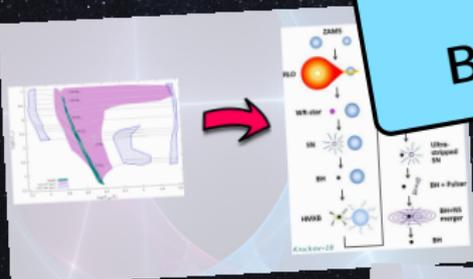
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cf. Mandel & Müller (2020)

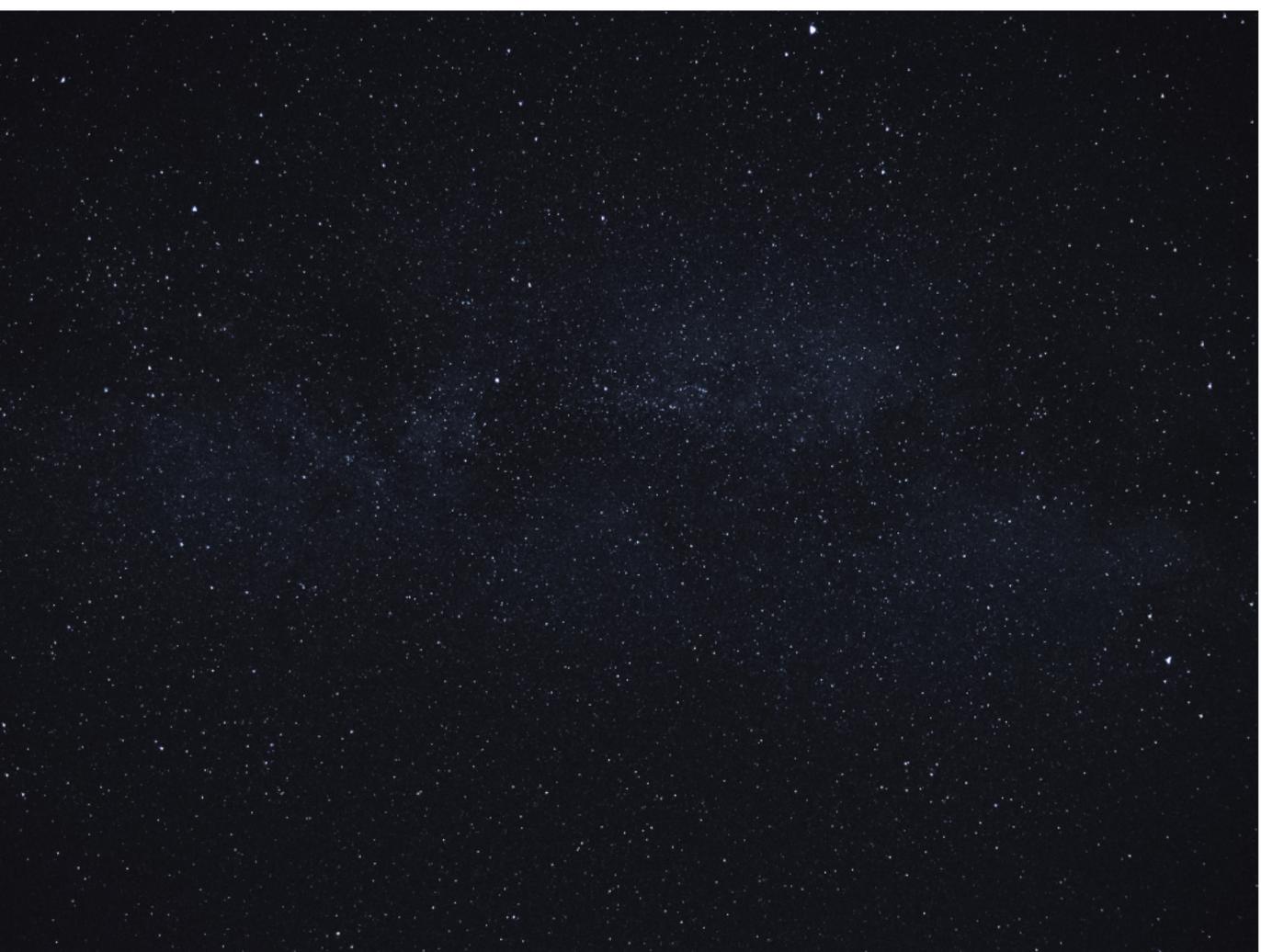
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Statistical approach
– Robust.
But: uncertainties.



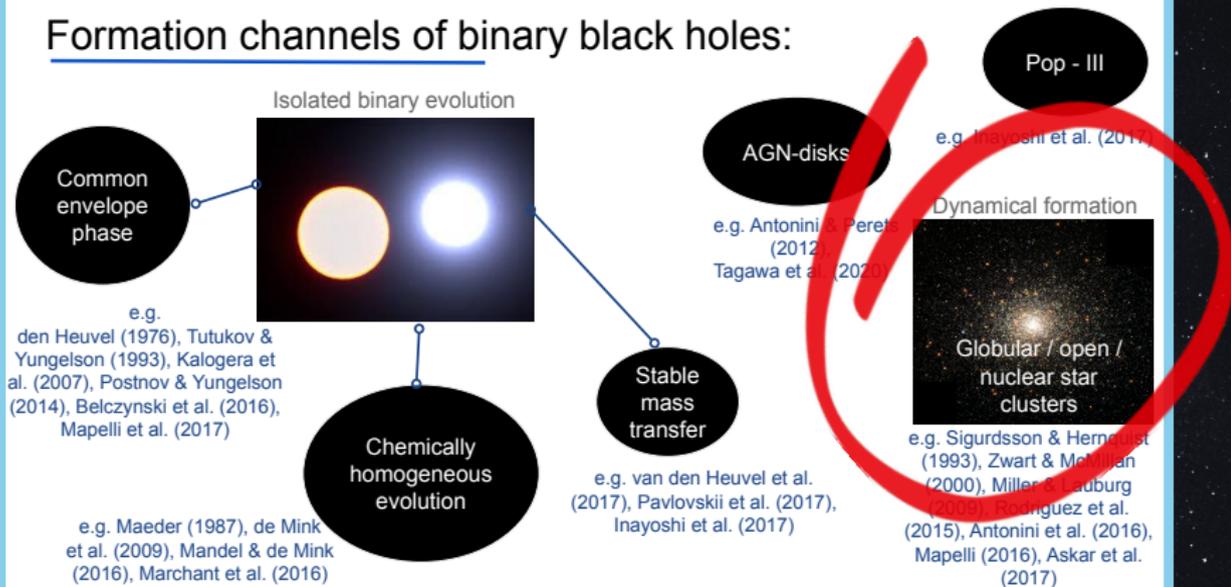
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“Dynamical formation” channel

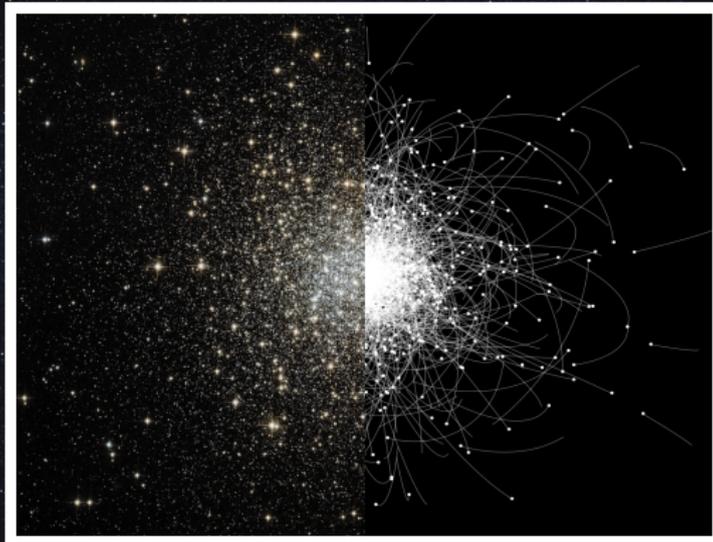
Formation channels of binary black holes:



Credit for slide: R. Sarwar

N-body simulations of cluster dynamics

needs cluster, density of stars matters, 3D codes...
+ stellar & population physics...

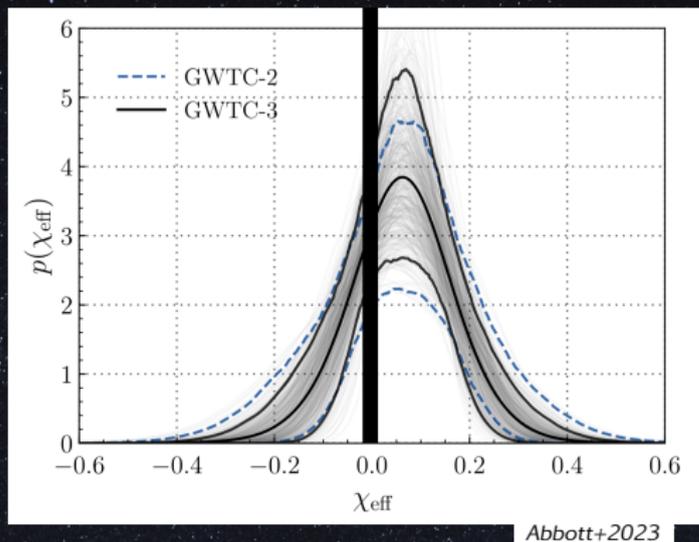
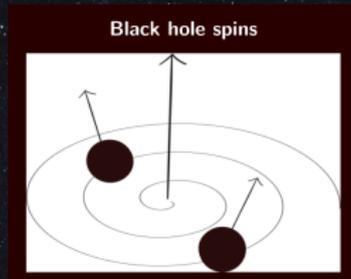


Dorval & Boily et al. 2016



Question:

Which theoretical scenario is ... *true*?



Spin distribution (χ_{eff}) observed to be slightly asymmetric



Symmetry Breaking in Merging Binary Black Holes from Young Massive Clusters and Isolated Binaries

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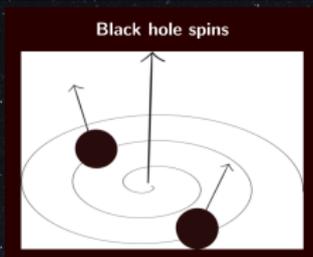
Abstract

Properties of the to-date observed binary black hole (BBH) merger events suggest a preference toward spin-orbit aligned mergers. Naturally, this has caused widespread interest and speculations regarding implications on various merger formation channels. Here we show that (i) not only the BBH merger population from isolated binaries but also (ii) BBH population formed in young massive clusters (YMCs) would possess an asymmetry in favor of aligned mergers, in the distribution of the events' effective spin parameter (χ_{eff}). In our analysis, we utilize BBH merger outcomes from state-of-the-art N -body evolutionary models of YMCs and isolated binary population synthesis. We incorporate, for the first time in such an analysis, misalignments due to both natal kicks and dynamical encounters. The YMC χ_{eff} distribution has a mean (an antialigned merger fraction) of $\langle \chi_{\text{eff}} \rangle \leq 0.04$ ($f_X \approx 40\%$), which is smaller (larger) than but consistent with the observed asymmetry of $\langle \chi_{\text{eff}} \rangle \approx 0.06$ ($f_X \approx 28\%$) as obtained from the population analysis by the LIGO–Virgo–KAGRA collaboration. In contrast, isolated binaries alone tend to produce a much stronger asymmetry; for the tested physical models, $\langle \chi_{\text{eff}} \rangle \approx 0.25$ and $f_X \lesssim 7\%$. Although the YMC χ_{eff} distribution is more similar to the observed counterpart, none of the channels correctly reproduce the observed distribution. Our results suggest that further extensive model explorations for both isolated binary and dynamical channels as well as better observational constraints are necessary to understand the physics of “the symmetry breaking” of the BBH merger population.

Unified Astronomy Thesaurus concepts: Stellar mass black holes (1611); Massive stars (732); N -body simulations (1083); Gravitational wave sources (677); Close binary stars (254); Young massive clusters (2049)

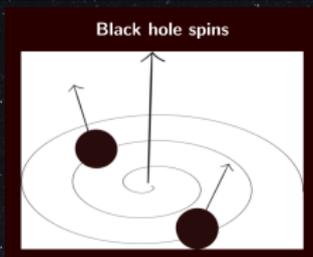
Effective spins χ_{eff} , individual spin components $\chi_{1,2}$?

$$\chi_{\text{eff}} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$



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$$\chi_{\text{eff}} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$



What do the scenarios predict?

Dynamical formation channel:

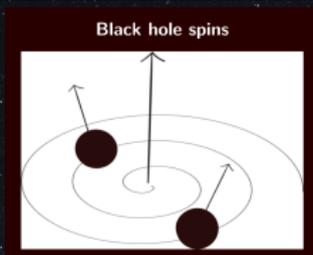


Isolated binary channel:



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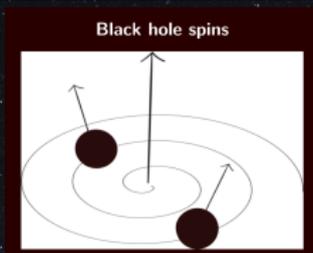
random pairing \rightarrow symmetric distr.

Isolated binary channel:

most often aligned \rightarrow asymmetric distr.

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What do the scenarios predict?

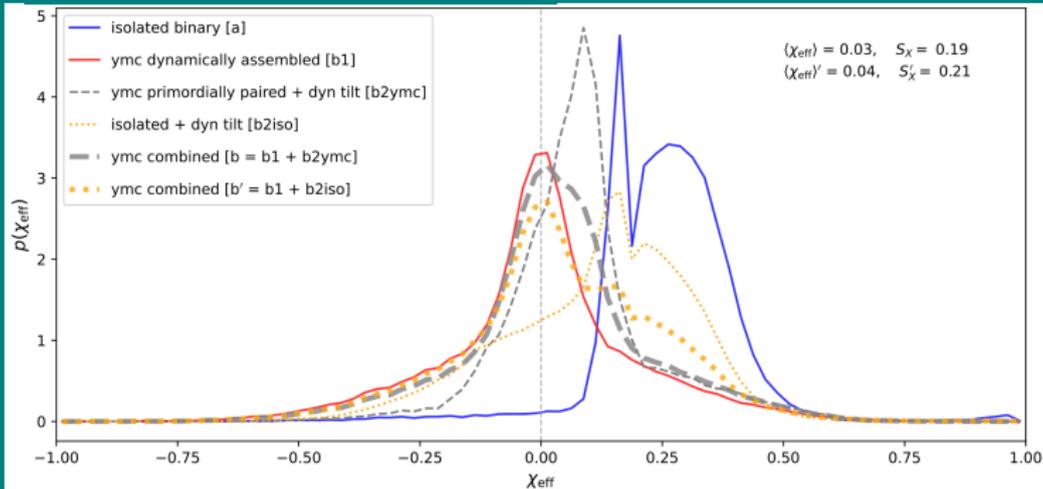
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Banerjee, Olejak & Belczynski '23



Conclusions

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Which theoretical scenario is true?

Probably both.

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But there's more work needed.

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But there's more work needed.

'Cause it's hard.

Conclusions

Which theoretical scenario is true?

Probably both.

But there's more work needed.

'Cause it's hard.

But we're working on it ;)

Thanks for Alexandra Olejak for tips on this talk



Krisztina Gabányi in Toruń



Me in Toruń



Krisztina Gabányi in Toruń



Me in Toruń