# End Stages from Massive Binary Evolution

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Swiss National Science Foundation

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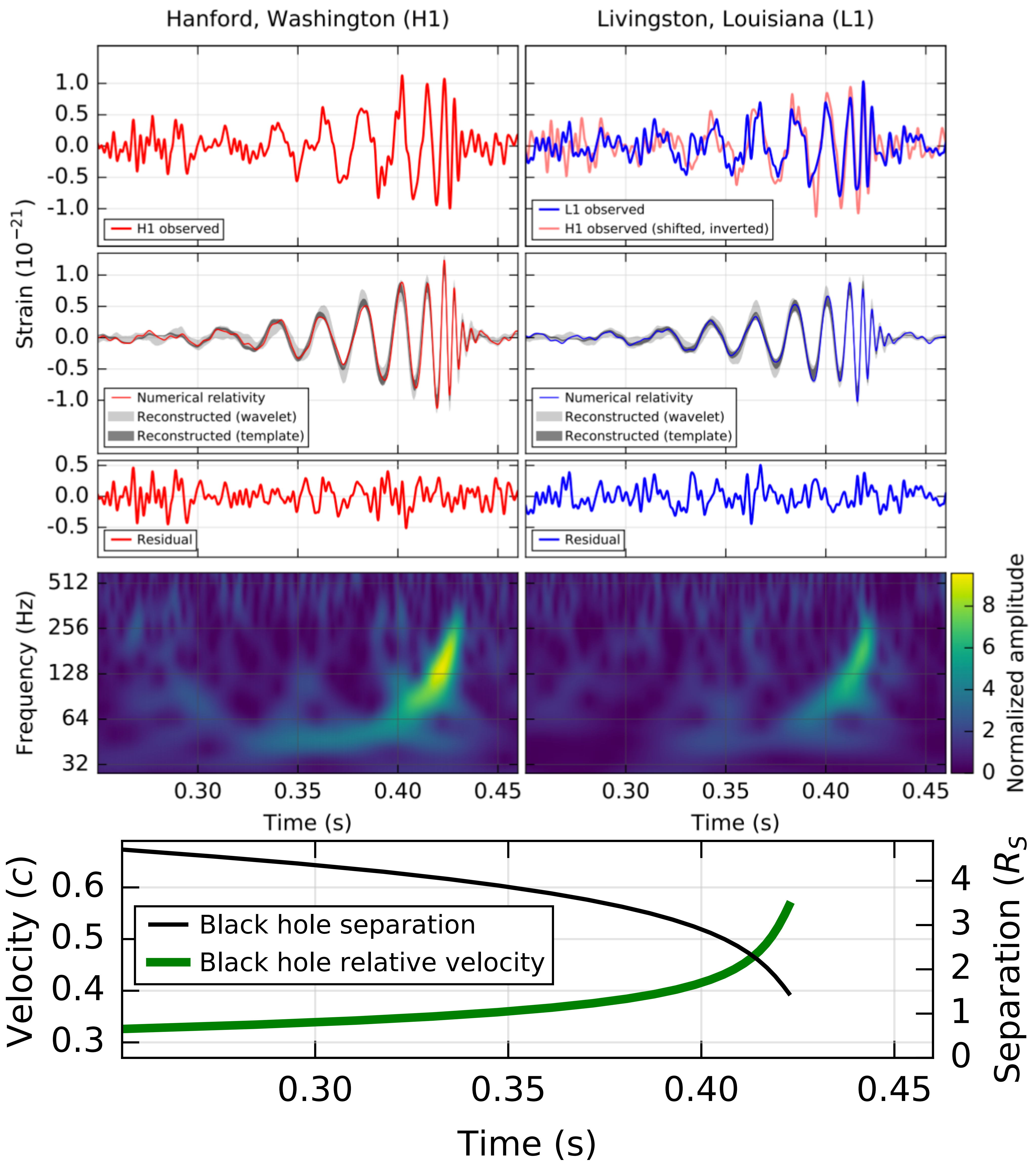
Quy Nhon, 09/08/2023

# The detection of the first gravitational-wave event

LIGO+VIRGO collaboration (2016) - arXiv:1602.03837




Detection with 5-sigma confidence.
This means that the rate at which a signal analogous to GW150914 is created by noise is less than 1 in every 203,000 years.

3 solar masses of energy is what was released in gravitational waves.
**10 times more luminous than all the stars of the Universe!!!**

# The detection of the first gravitational-wave event

LIGO+VIRGO collaboration (2016) - arXiv:1602.03840

| | EOBNR | IMRPhenom | Overall |
|---|---|---|---|
| Detector-frame total mass $M/\mathrm{M}_\odot$ | $70.3^{+5.3}_{-4.8}$ | $70.7^{+3.8}_{-4.0}$ | $70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$ |
| Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$ | $30.2^{+2.5}_{-1.9}$ | $30.5^{+1.7}_{-1.8}$ | $30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$ |
| Detector-frame primary mass $m_1/\mathrm{M}_\odot$ | $39.4^{+5.5}_{-4.9}$ | $38.3^{+5.5}_{-3.5}$ | $38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$ |
| Detector-frame secondary mass $m_2/\mathrm{M}_\odot$ | $30.9^{+4.8}_{-4.4}$ | $32.2^{+3.6}_{-5.0}$ | $31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$ |
| Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$ | $67.1^{+4.6}_{-4.4}$ | $67.4^{+3.4}_{-3.6}$ | $67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$ |
| Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$ | $65.0^{+5.0}_{-4.4}$ | $64.6^{+4.1}_{-3.5}$ | $64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$ |
| Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$ | $27.9^{+2.3}_{-1.8}$ | $27.9^{+1.8}_{-1.6}$ | $27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$ |
| Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$ | $36.3^{+5.3}_{-4.5}$ | $35.1^{+5.2}_{-3.3}$ | $35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$ |
| Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$ | $28.6^{+4.4}_{-4.2}$ | $29.5^{+3.3}_{-4.5}$ | $29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$ |
| Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$ | $62.0^{+4.4}_{-4.0}$ | $61.6^{+3.7}_{-3.1}$ | $61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$ |
| Mass ratio $q$ | $0.79^{+0.18}_{-0.19}$ | $0.84^{+0.14}_{-0.21}$ | $0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$ |
| Effective inspiral spin parameter $\chi_\mathrm{eff}$ | $-0.09^{+0.19}_{-0.17}$ | $-0.03^{+0.14}_{-0.15}$ | $-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$ |
| Dimensionless primary spin magnitude $a_1$ | $0.32^{+0.45}_{-0.28}$ | $0.31^{+0.51}_{-0.27}$ | $0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$ |
| Dimensionless secondary spin magnitude $a_2$ | $0.57^{+0.40}_{-0.51}$ | $0.39^{+0.50}_{-0.34}$ | $0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$ |
| Final spin $a_\mathrm{f}$ | $0.67^{+0.06}_{-0.08}$ | $0.67^{+0.05}_{-0.05}$ | $0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$ |
| Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$ | $390^{+170}_{-180}$ | $440^{+140}_{-180}$ | $410^{+160\pm20}_{-180\pm40}$ |
| Source redshift $z$ | $0.083^{+0.033}_{-0.036}$ | $0.093^{+0.028}_{-0.036}$ | $0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$ |
| Upper bound on primary spin magnitude $a_1$ | 0.65 | 0.71 | $0.69 \pm 0.05$ |
| Upper bound on secondary spin magnitude $a_2$ | 0.93 | 0.81 | $0.88 \pm 0.10$ |
| Lower bound on mass ratio $q$ | 0.64 | 0.67 | $0.65 \pm 0.03$ |
| Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$ | $288.7 \pm 0.2$ | $290.1 \pm 0.2$ | — |

Chirp mass: $\mathrm{M}_{\mathrm{chirp}} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

Effective spin parameter: $\chi_{eff} = \dfrac{m_1\mathbf{a}_1 + m_2\mathbf{a}_2}{m_1+m_2}\hat{\mathbf{L}}$

Mass ratio: $q = \dfrac{m_2}{m_1}$

Luminosity Distance: $D_L$
or
redshift of merger: $z_{\mathrm{merger}}$

LIGO+VIRGO collaboration (2016) - arXiv:1602.03846

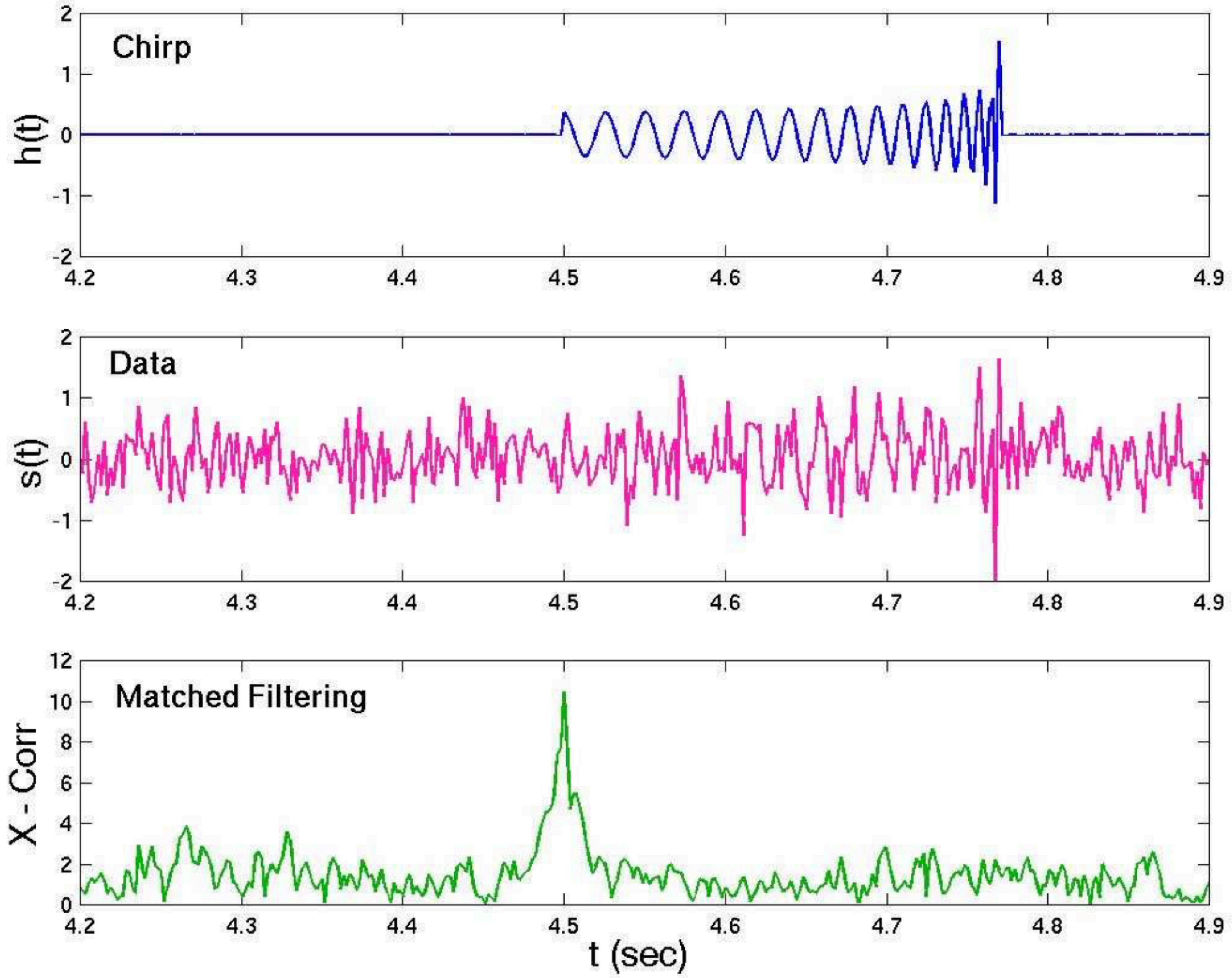
**The detection confirms that:**

1) "heavy" black holes (BHs) exist
2) binary BHs form in nature
3) Binary BHs merge within a Hubble time (at a detectable rate)

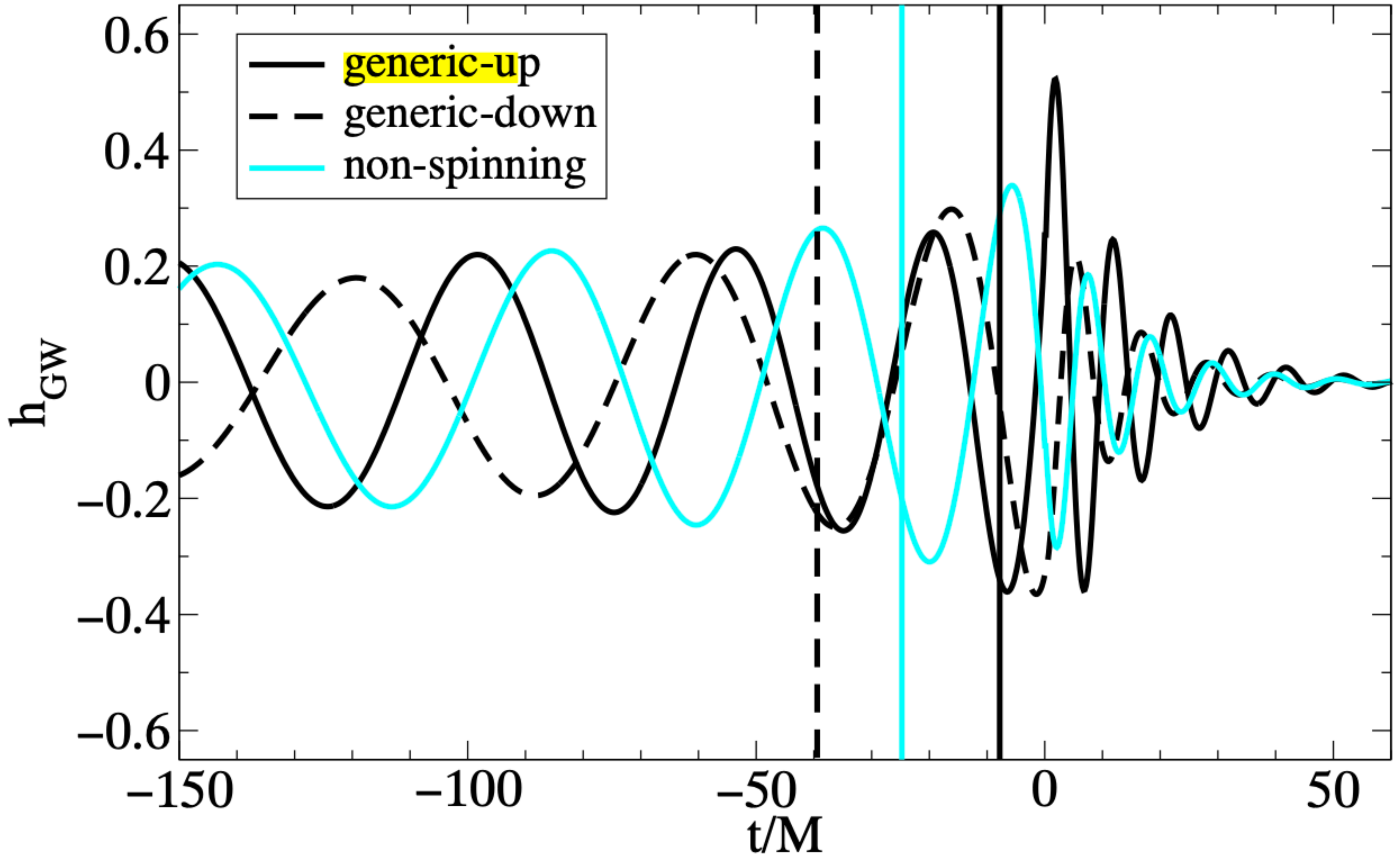
# The matched filtering technique

16-dimensional (9 intrinsic + 7 extrinsic) waveform template banks

Dhurandhar et al (2004)




Buonanno et al. (2005)



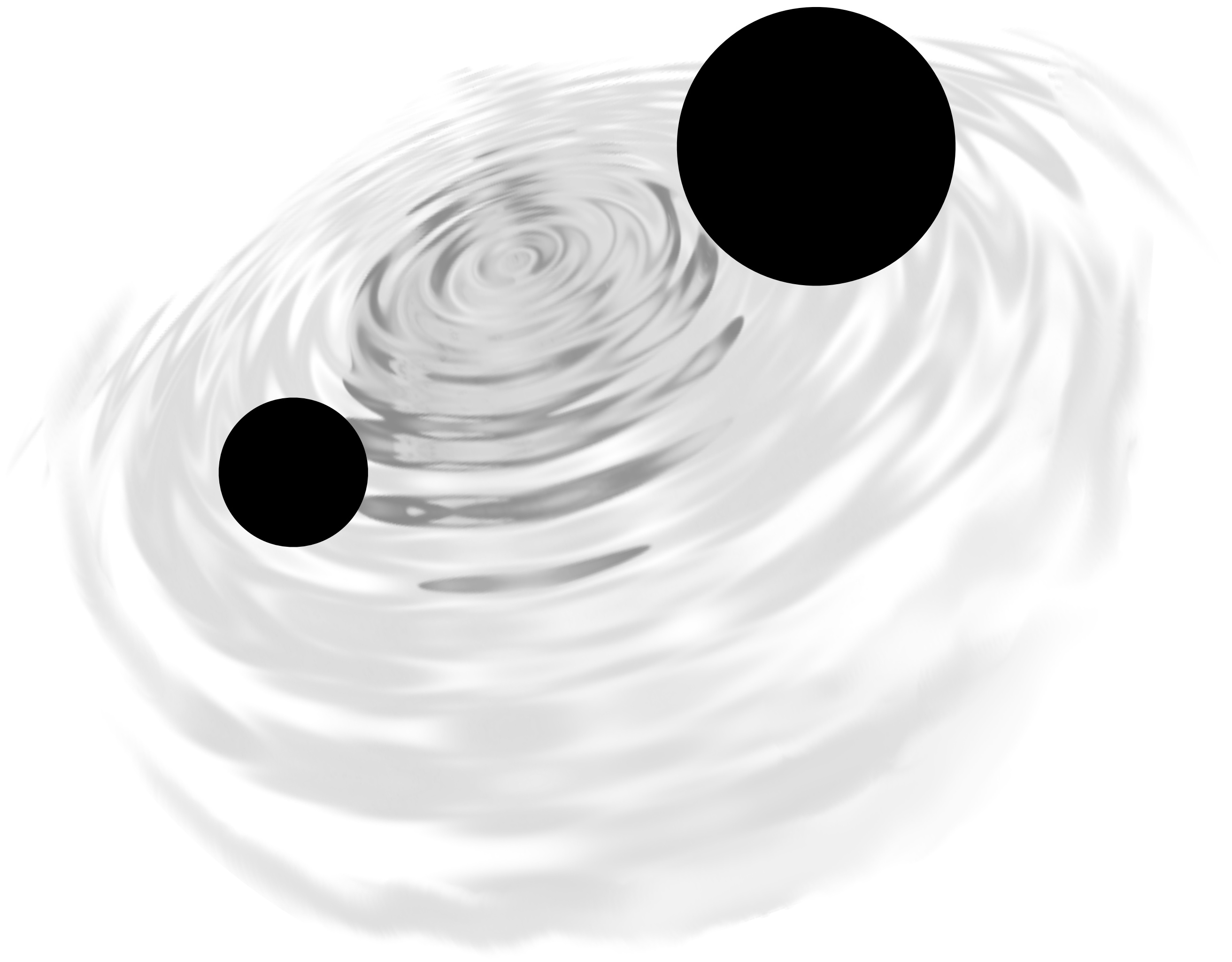

Scaling of characteristic strain: $$h \sim 2.5 \times 10^{-23} \left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right)^{5/3} \left(\frac{r}{100\ \mathrm{Mpc}}\right)^{-1} \left(\frac{f}{100\ \mathrm{Hz}}\right)^{2/3}$$

A 30$M_\odot$ BH is ~32 more likely to be observed than a 15$M_\odot$ one,

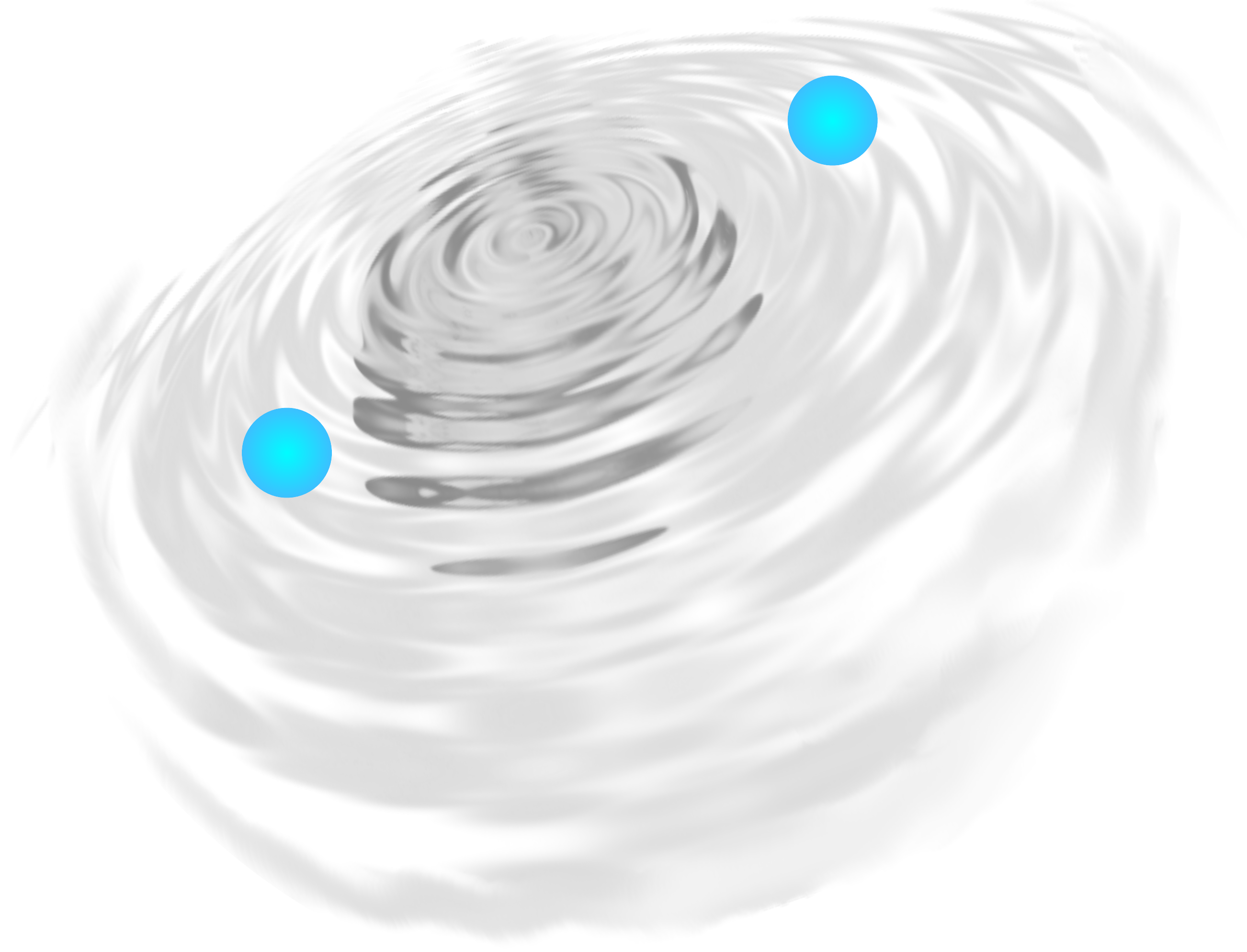
while a 60$M_\odot$ is ~1024 more likely to be observed than a 15$M_\odot$ one!!!

# The Gravitational-Wave Transient Catalogue 3 (GWTC-3)

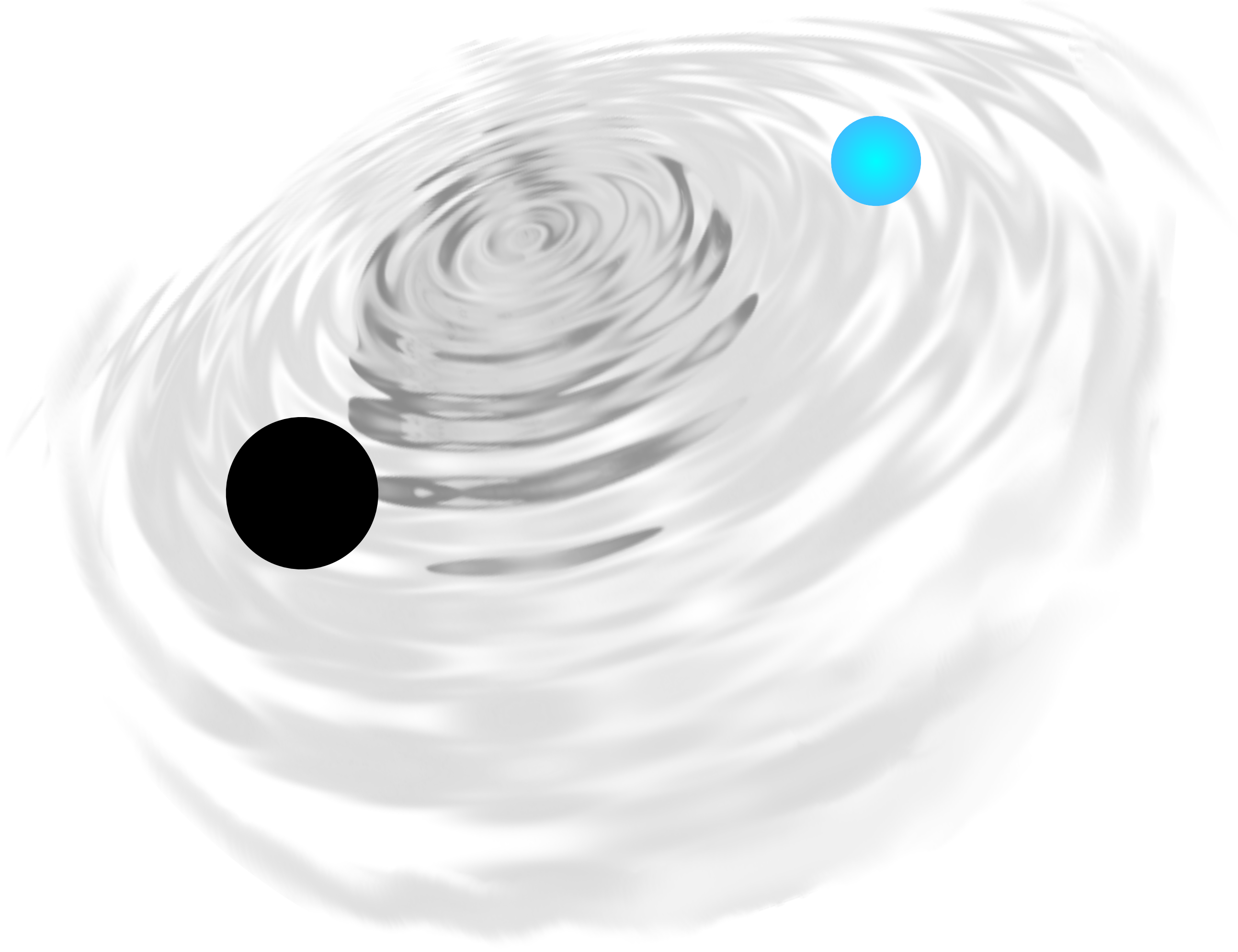
Abbot et al. arXiv:2111.03606 (2021)



**83-85**
binary black holes (BBH)



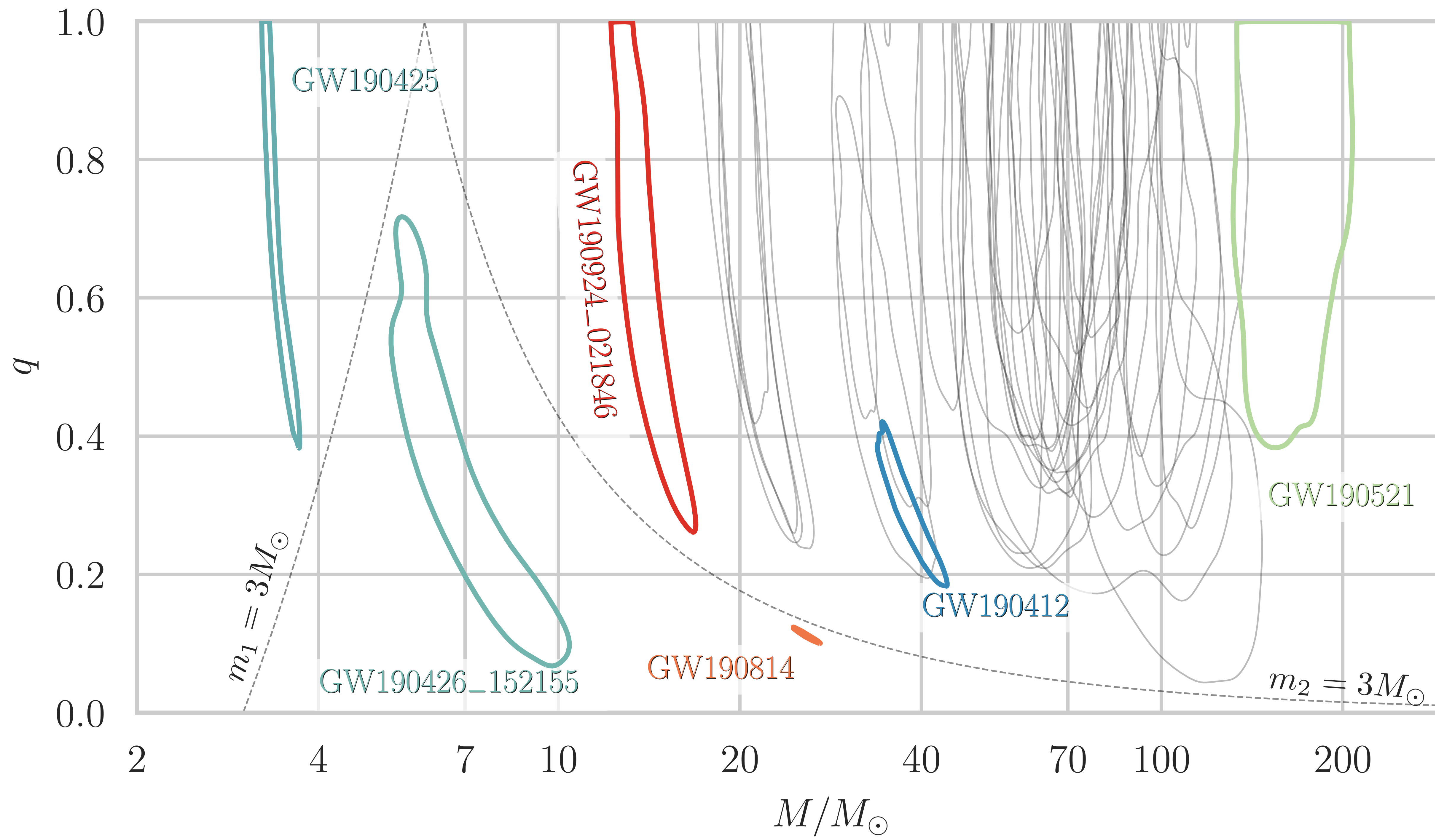
**2**
binary neutron star (BNS)

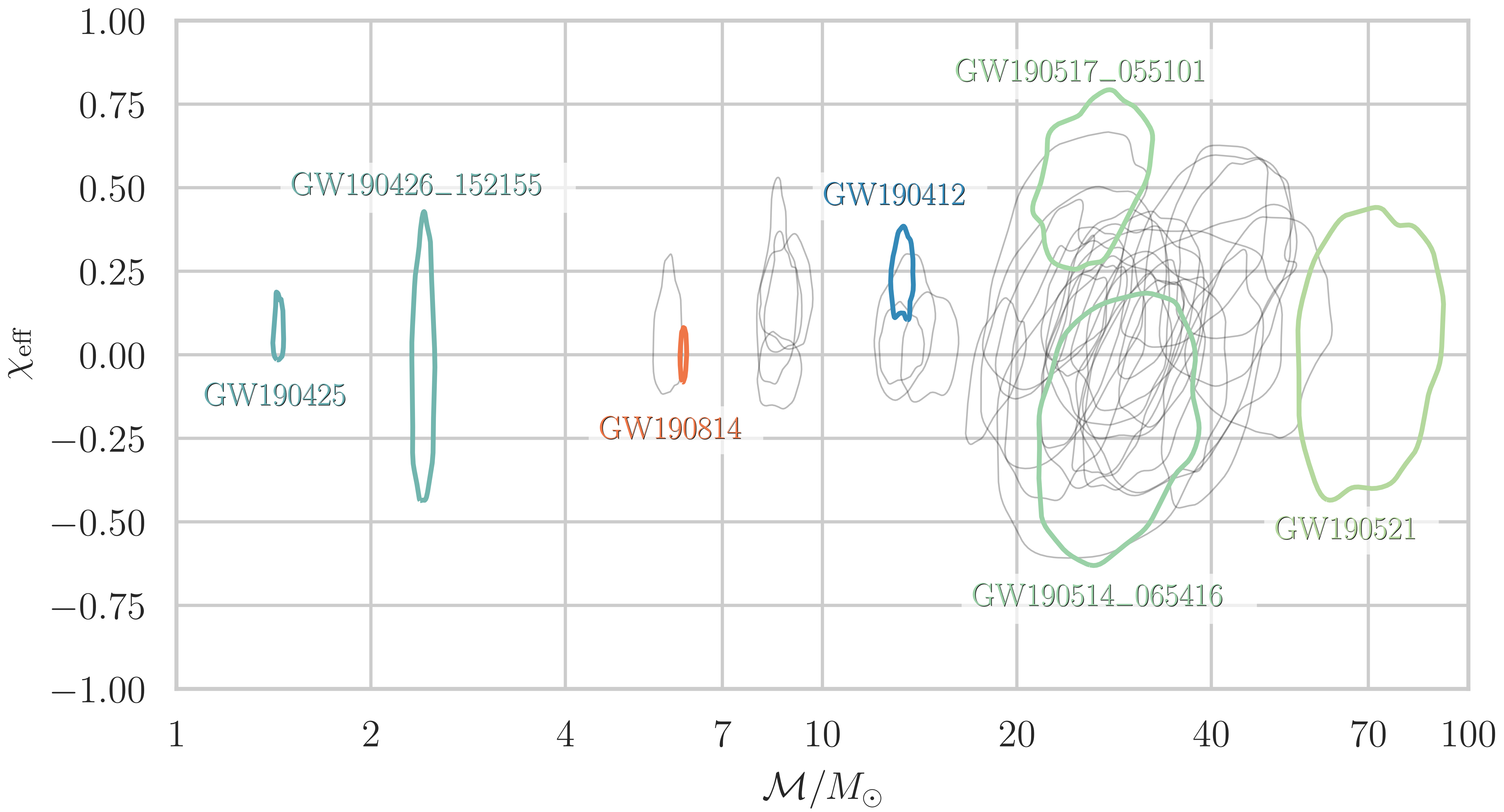


**3-5**
black hole - neutron star (BHNS)

# The Gravitational-Wave Transient Catalogue (GWTC-2/3)

Abbot et al. arXiv:2010.14527 (2021)

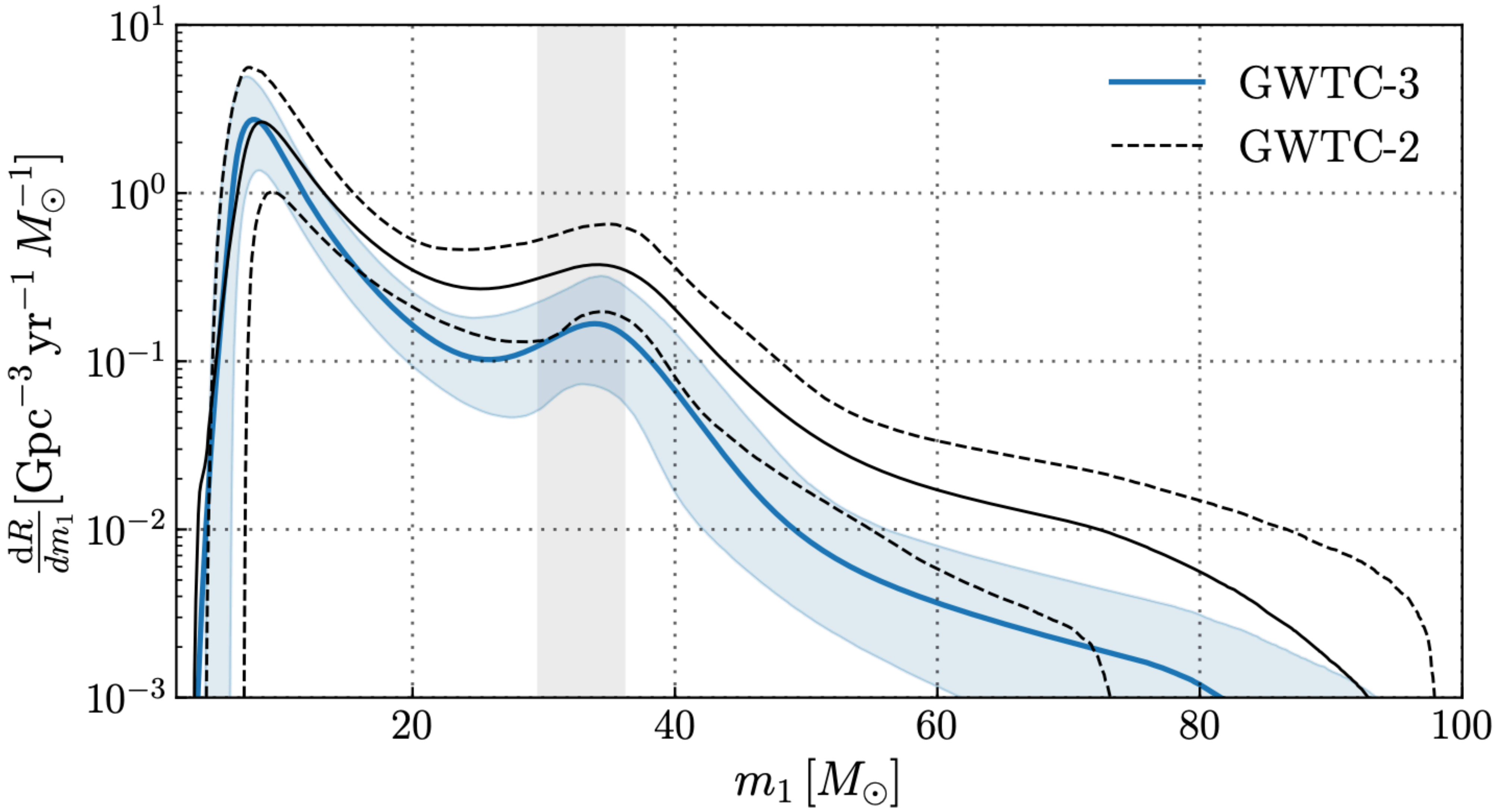


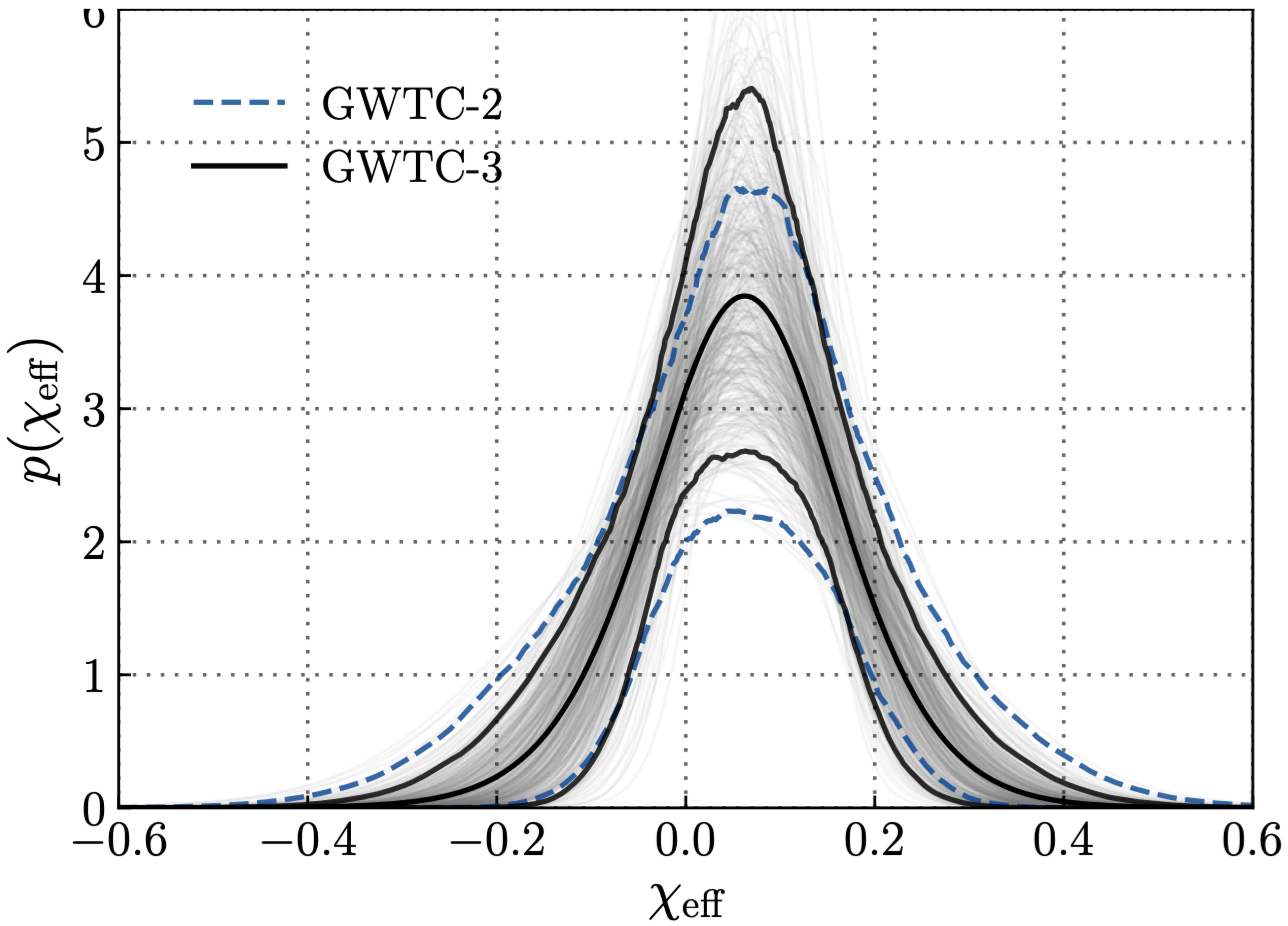

- **Heavy BHs,**
  well into the "PISN mass-gap"
- **Light BHs,**
  consistent with Galactic BH X-ray binaries
- **Unequal mass BBHs**
- **Heavy NSs,**
  inconsistent with Galactic binary pulsars

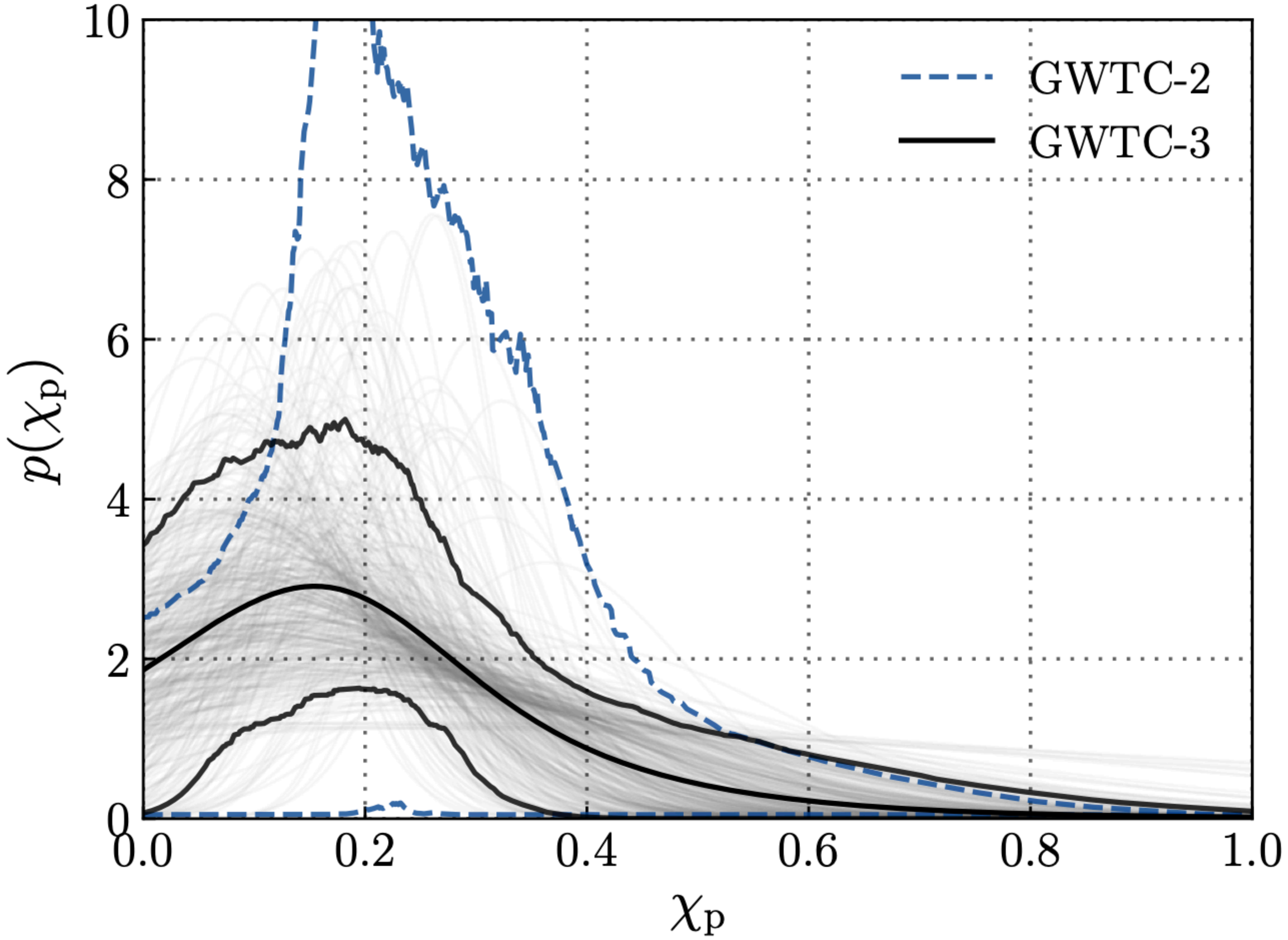
- **Several BBHs with positive $\chi_{\rm eff}$**
  (inconsistent with $\chi_{\rm eff} = 0$)
- **No individual BBHs with negative $\chi_{\rm eff}$**
- **No individual BBHs inconsistent with $\chi_p = 0$**

# Looking at coalescing BBH population properties




- **Several features emerge in the BH mass function**
- **Support for $\chi_{eff} \lesssim 0$ in the underlying BBH population**
- **Support for $\chi_p > 0$ in the underlying BBH population**
- **Caution: conclusions are model-dependent!**




Abbot et al. arXiv:2111.03634 (2021)

# Correlation of gravitational-wave observables

**Chirp mass:** $M_{\rm chirp} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

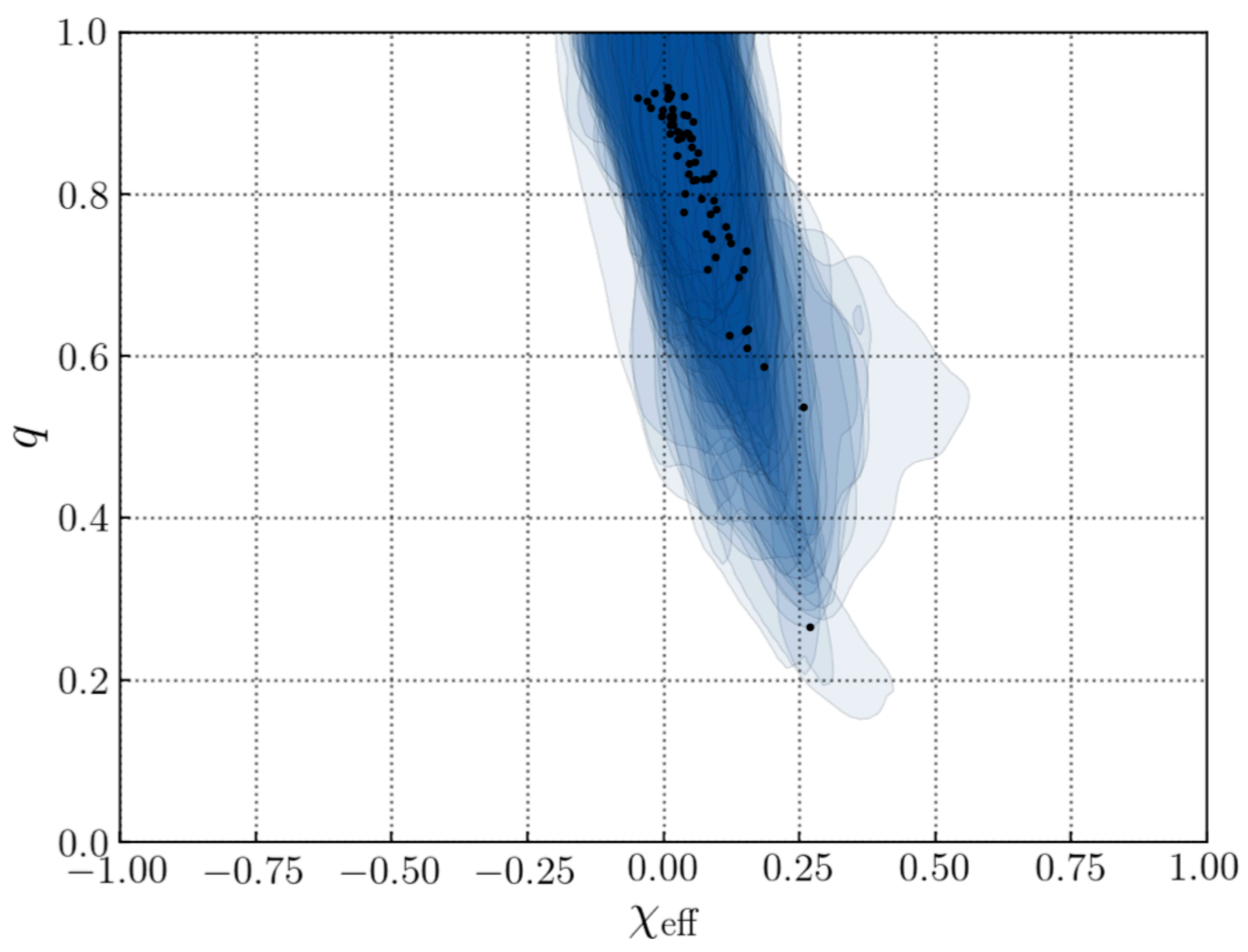
**Effective spin parameter:** $\chi_{\rm eff} = \dfrac{m_1\vec{\chi}_1 + m_2\vec{\chi}_2}{m_1+m_2}\hat{\vec{L}}$

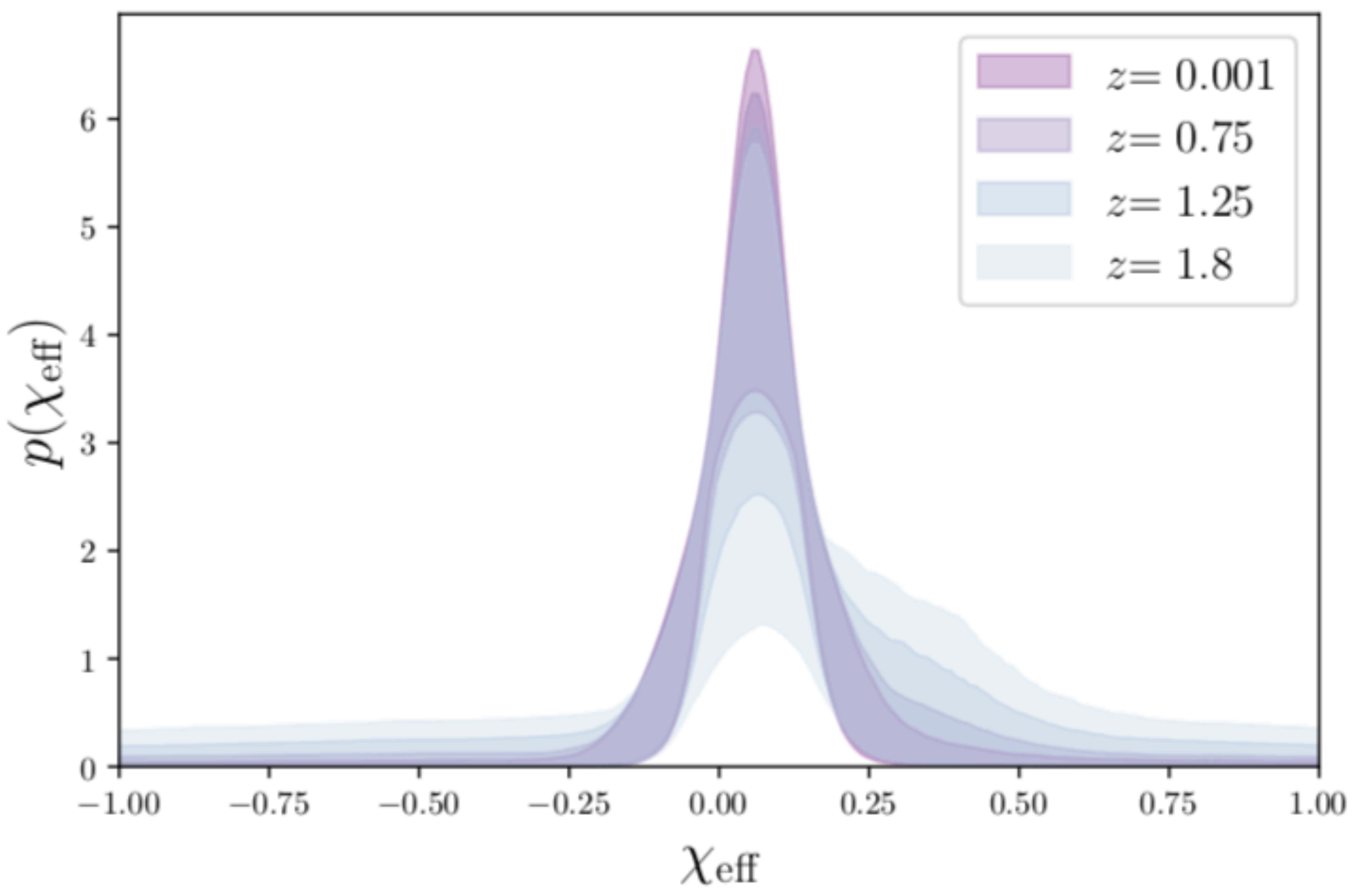
**Merger redshift:** $z_{merger}$

**Mass ratio:** $q$

Indications appear already in the O3 LVC data, e.g.,

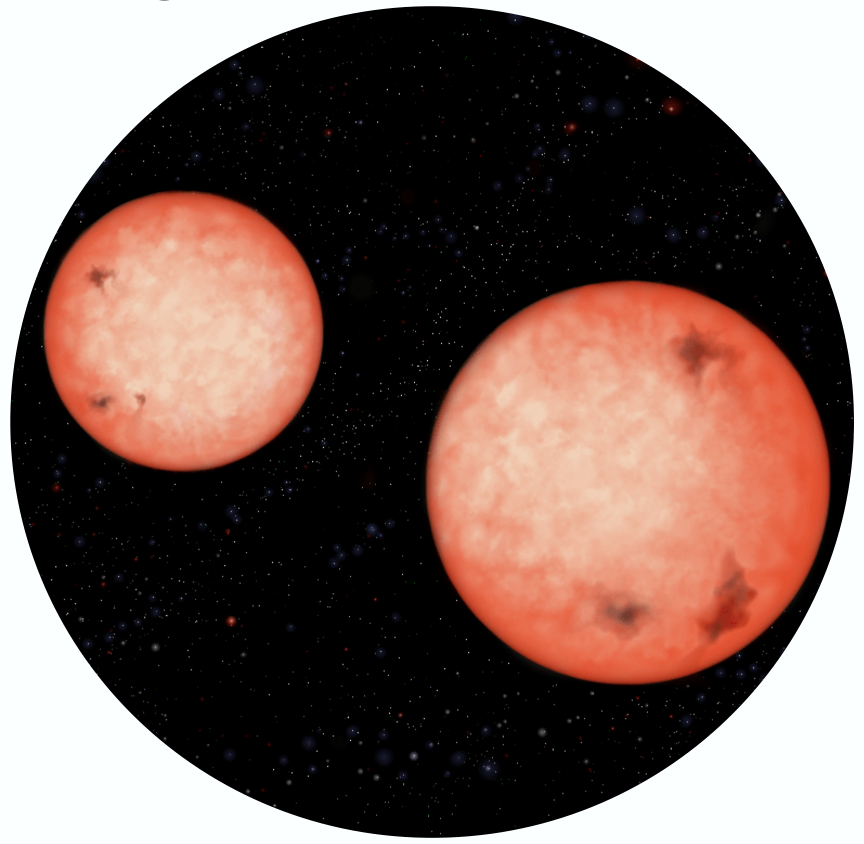
- Correlation between $M_{chirp}$ and $\chi_{\rm eff}$
  e.g. Franciolini & Pain (2022), Safarzadeh et al. (2020)
- Anti-correlation between $\chi_{\rm eff}$ and mass ratio $q$
  e.g., Callister et al. (2021), Abbott et al. (2021)
- Correlation between $\chi_{\rm eff}$ and merger redshift $z$
  e.g., Biscoveanu et al. (2022), Bavera, …, TF et al. (2022)



# Astrophysical binary black-hole formation models

## Isolated binary evolution in galactic fields



**Common Envelope**:
e.g. vd Heuvel (1976), Tutukov & Yungelson (1993), Kalogera et al. (2007), Postnov & Yungelson (2014), Belczynski et al. (2016), Mapelli et al. (2017)
**Stable Mass Transfer**:
e.g. van den Heuvel et al. (2017), Pavlovskii et al. (2017), Inayoshi et al. (2017)
**Chemically homogeneous evolution**:
e.g. Maeder (1987), de Mink et al. (2009), Mandel & de Mink (2016), Marchant et al. (2016)

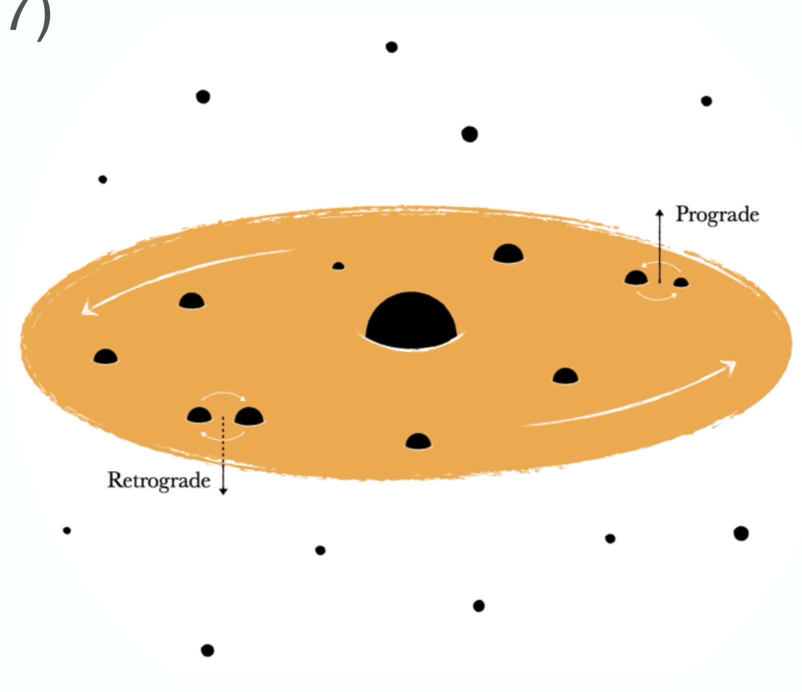
e.g. Sigurdsson & Hernquist (1993), Zwart & McMillan (2000), Miller & Lauburg (2009), Rodriguez et al. (2015), Antonini et al. (2016), Mapelli (2016), Askar et al. (2017)

## Dynamical formation in dense stellar environments

## Population III stars

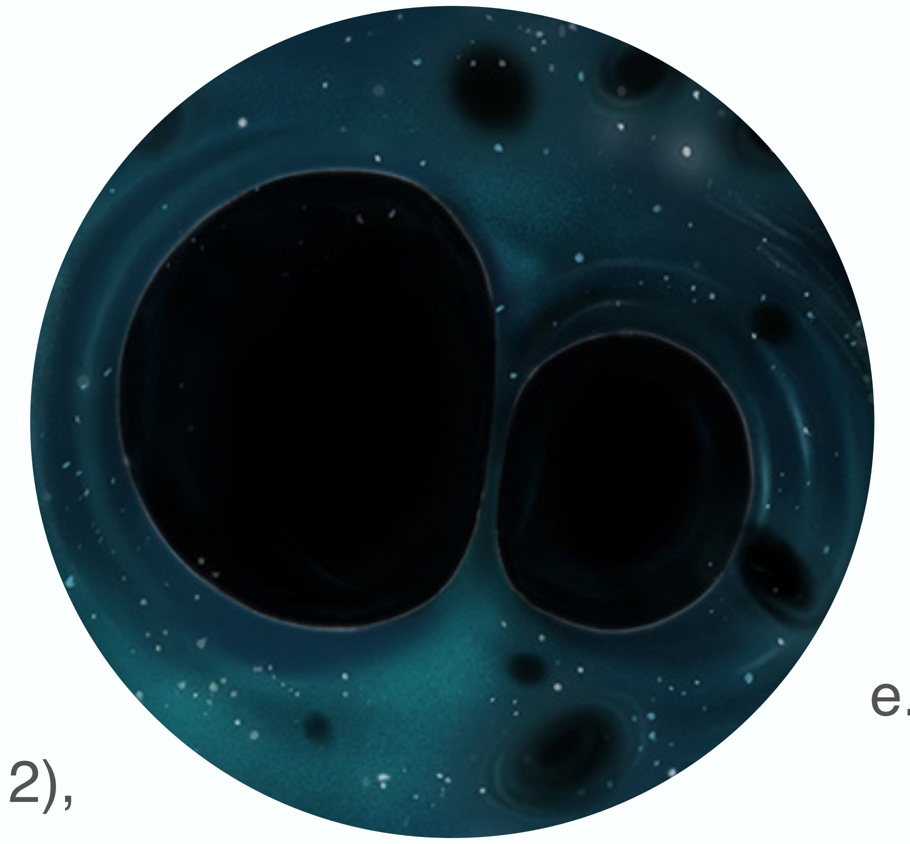
e.g. Inayoshi et al. (2017)

e.g. Antonini & Perets (2012), Tagawa et al. (2020)




## Active galactic nuclei disks

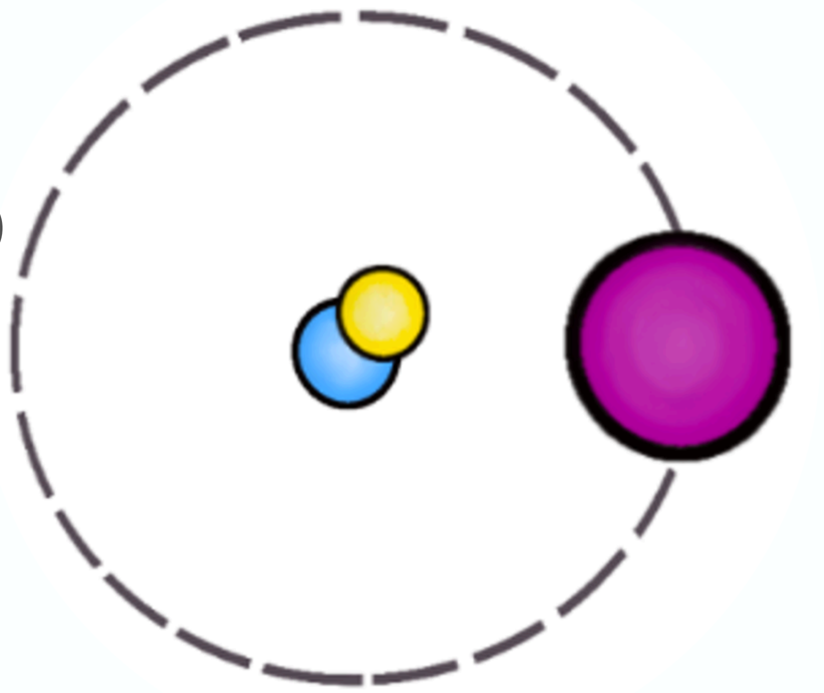
## Primordial black holes



e.g., Bird et al. (2016); Sasaki et al. (2018); Clesse & Garcia-Bellido (2020); Da Luca et al. (2020,2021) Wong et al. (2021)

## & MORE …

e.g. Silsbee & Tremaine (2017), Moe & Di Stefano (2017); Toonen et al. (2022)



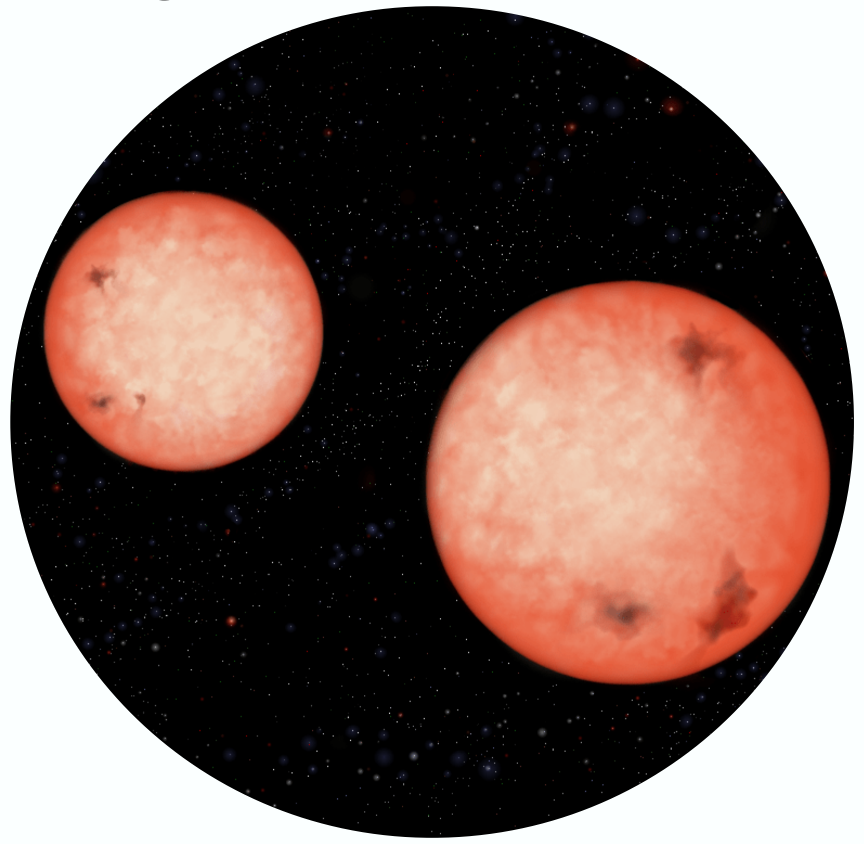
## Triple and multiples

# Binary black-hole formation channels

**Rates cannot distinguish among the channels**

e.g. see Mandel & Broekgaarden (2022)

Isolated binary evolution in galactic fields



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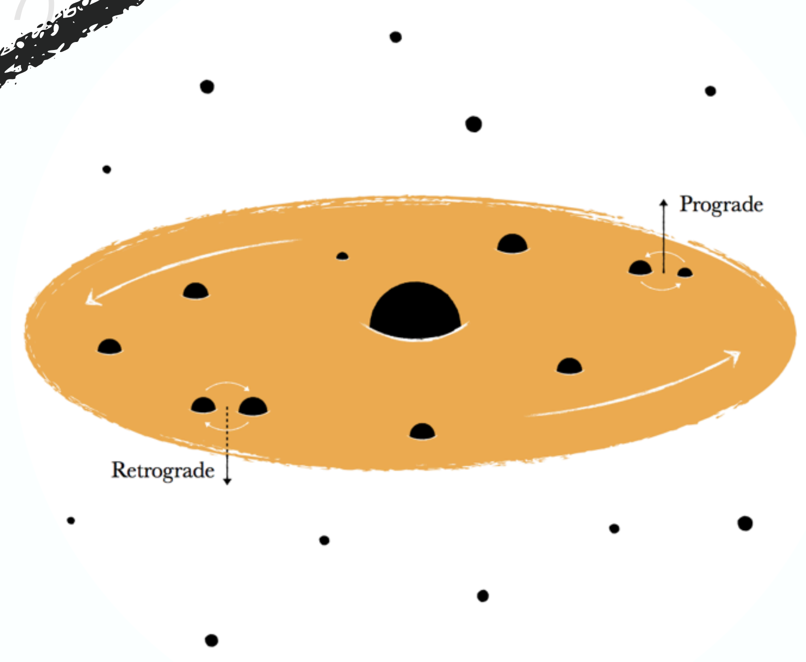
e.g. Sigurdsson & Hernquist (1993), Zwart & McMillan (2000), Miller & Lauburg (2009), Rodriguez et al. (2015), Antonini et al. (2016), Mapelli (2016), Askar et al. (2017)

Dynamical formation in dense stellar environments

Population III stars

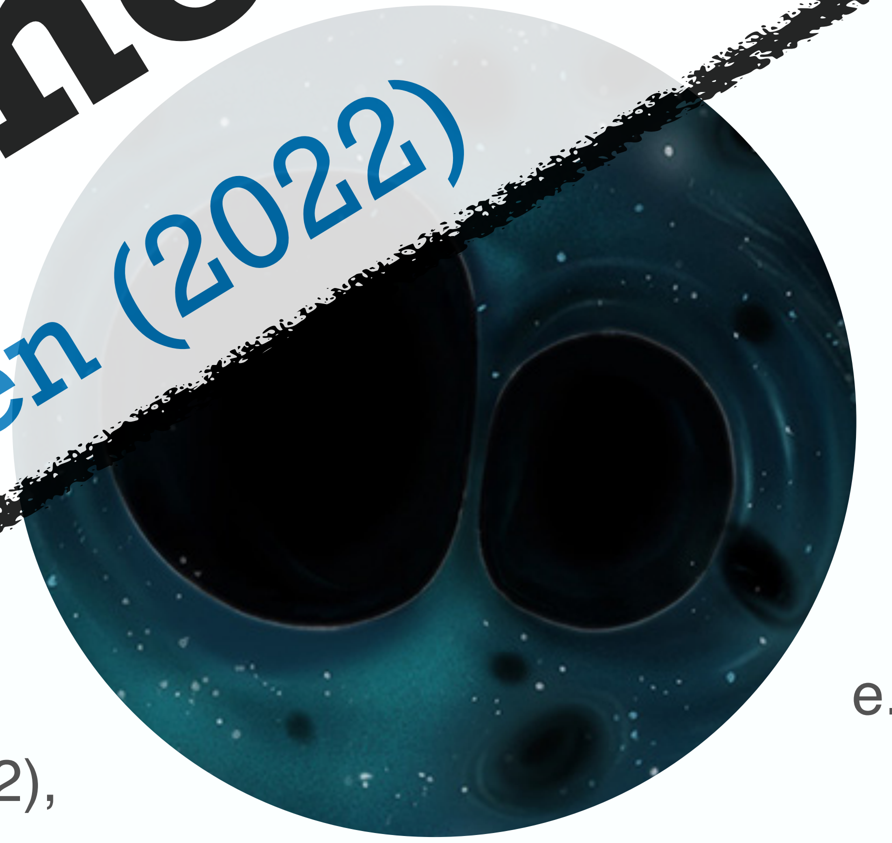
e.g. Inayoshi et al. (2017)

e.g. Antonini & Perets (2012), Tagawa et al. (2020)




Active galactic nuclei disks

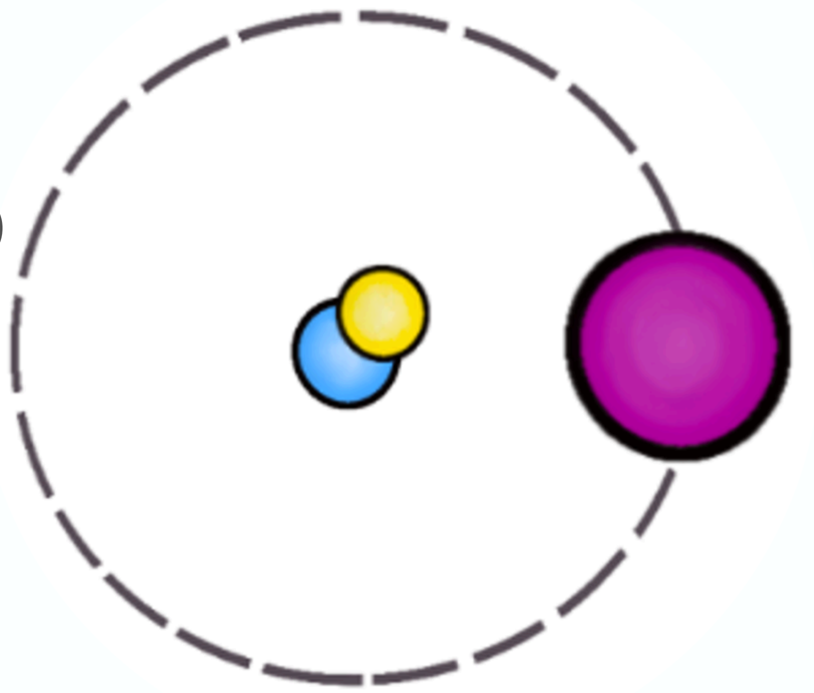
Primordial black holes



e.g., Bird et al. (2016); Sasaki et al. (2018); Clesse & Garcia-Bellido (2020); Da Luca et al. (2020,2021) Wong et al. (2021)

& MORE …

e.g. Silsbee & Tremaine (2017), Moe & Di Stefano (2017); Toonen et al. (2022)



Triple and multiples

# What can cause a black-hole to spin?

Angular momentum of the progenitor star

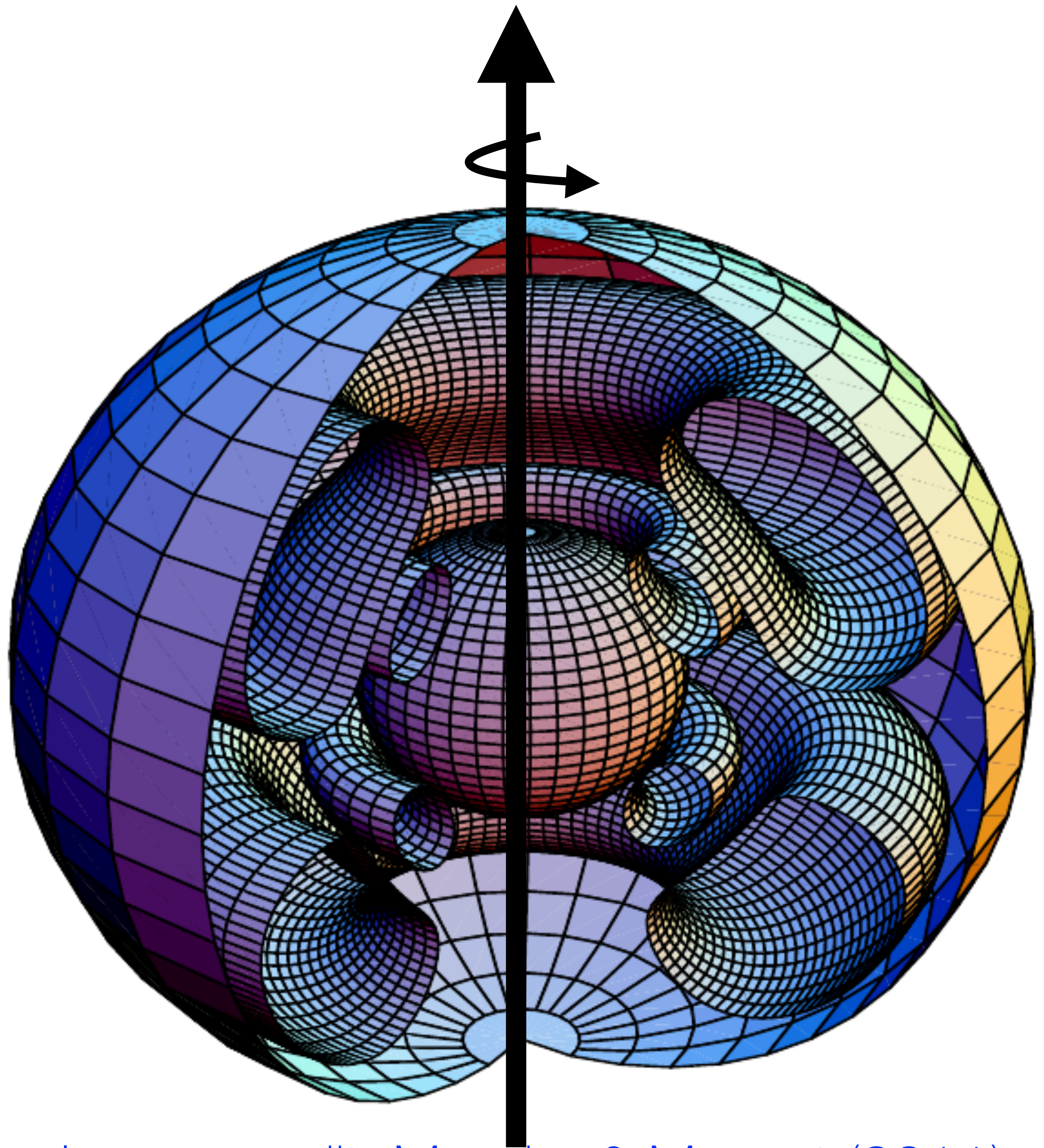


Image credit: Maeder & Meynet (2011)

Unknown process during core-collapse

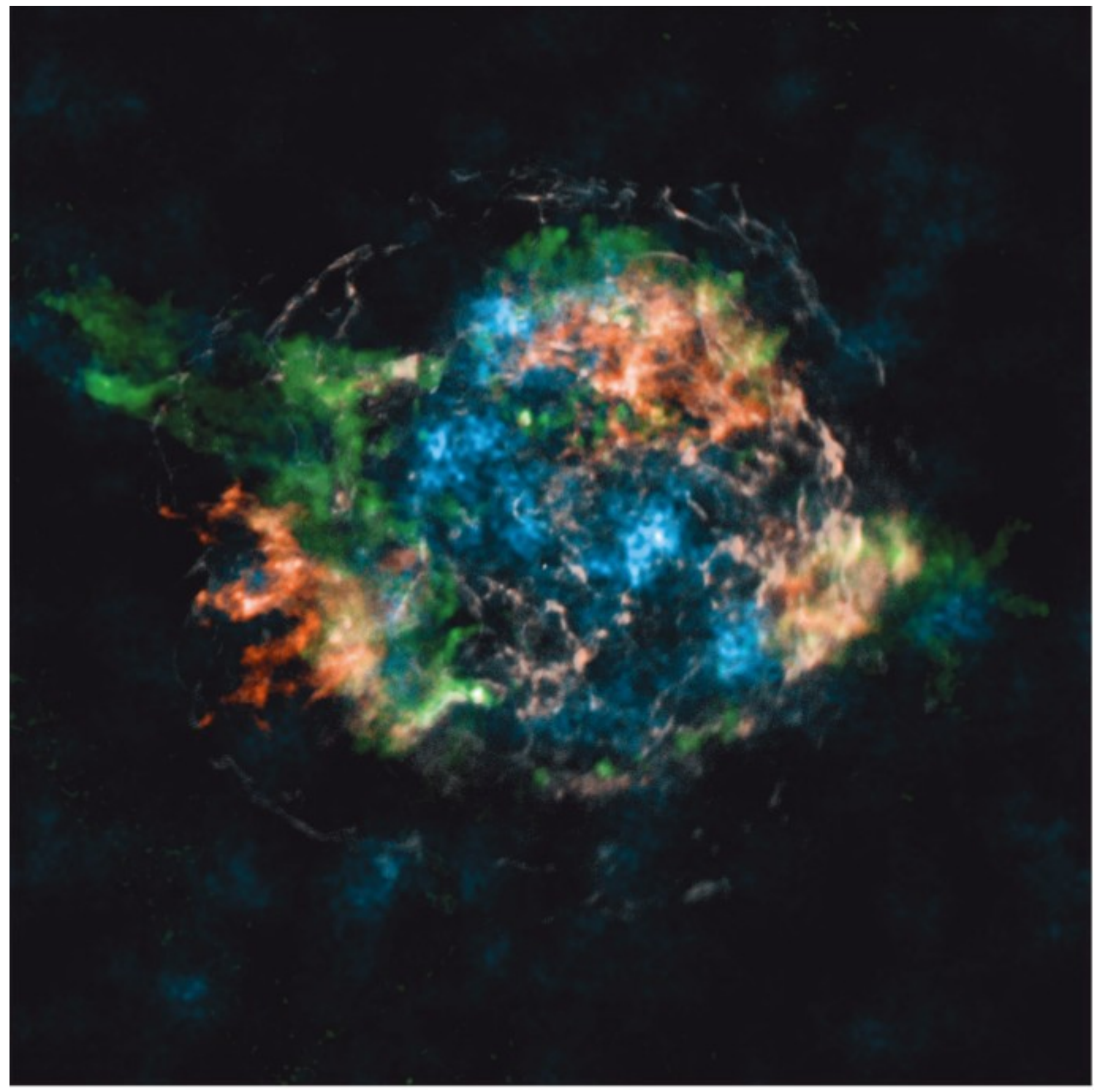


Image credit: Grefenstette et al. (2014)

Accretion onto a black hole

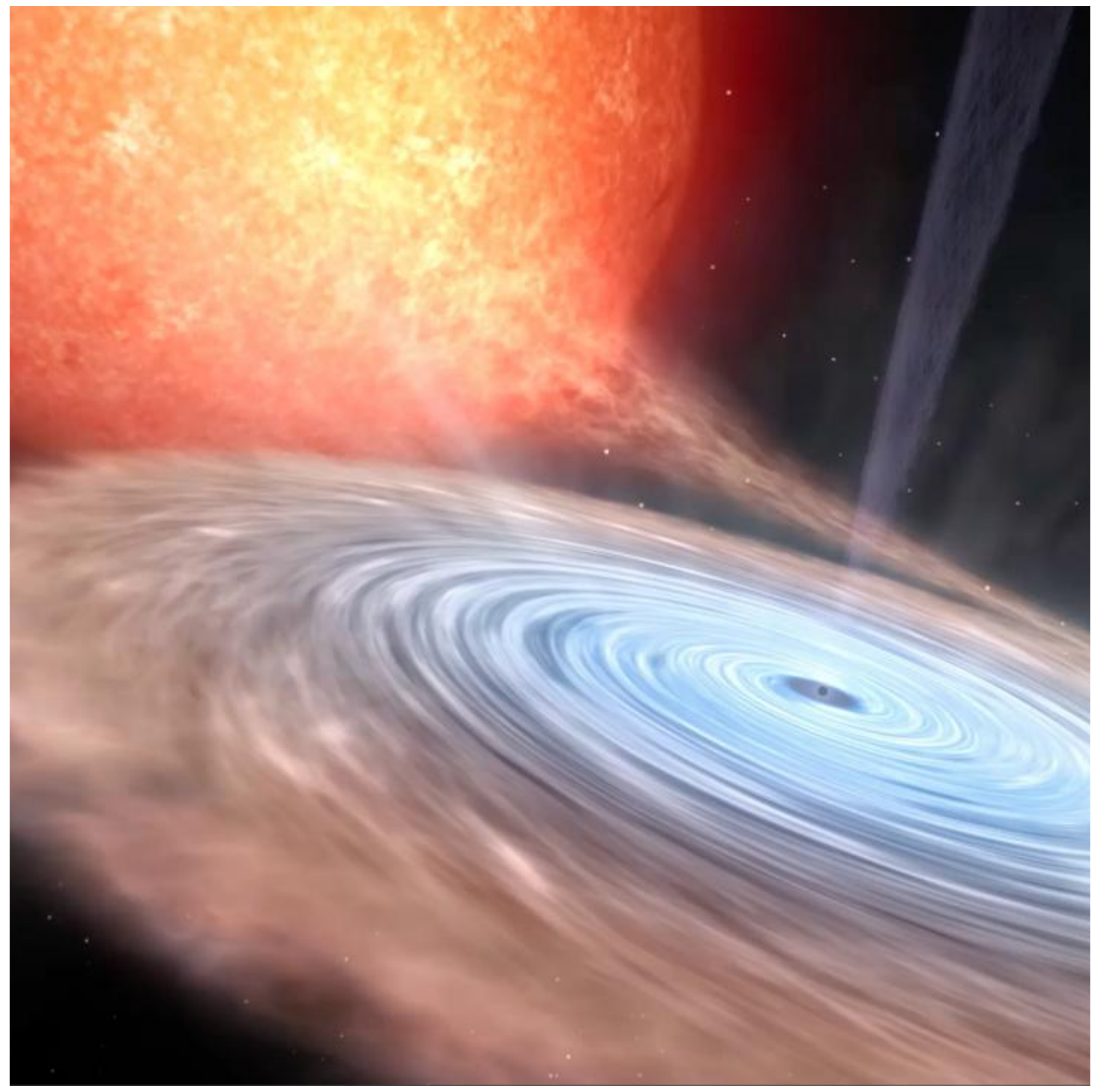


Image credit:Gabriel Pérez

Hierarchical mergers

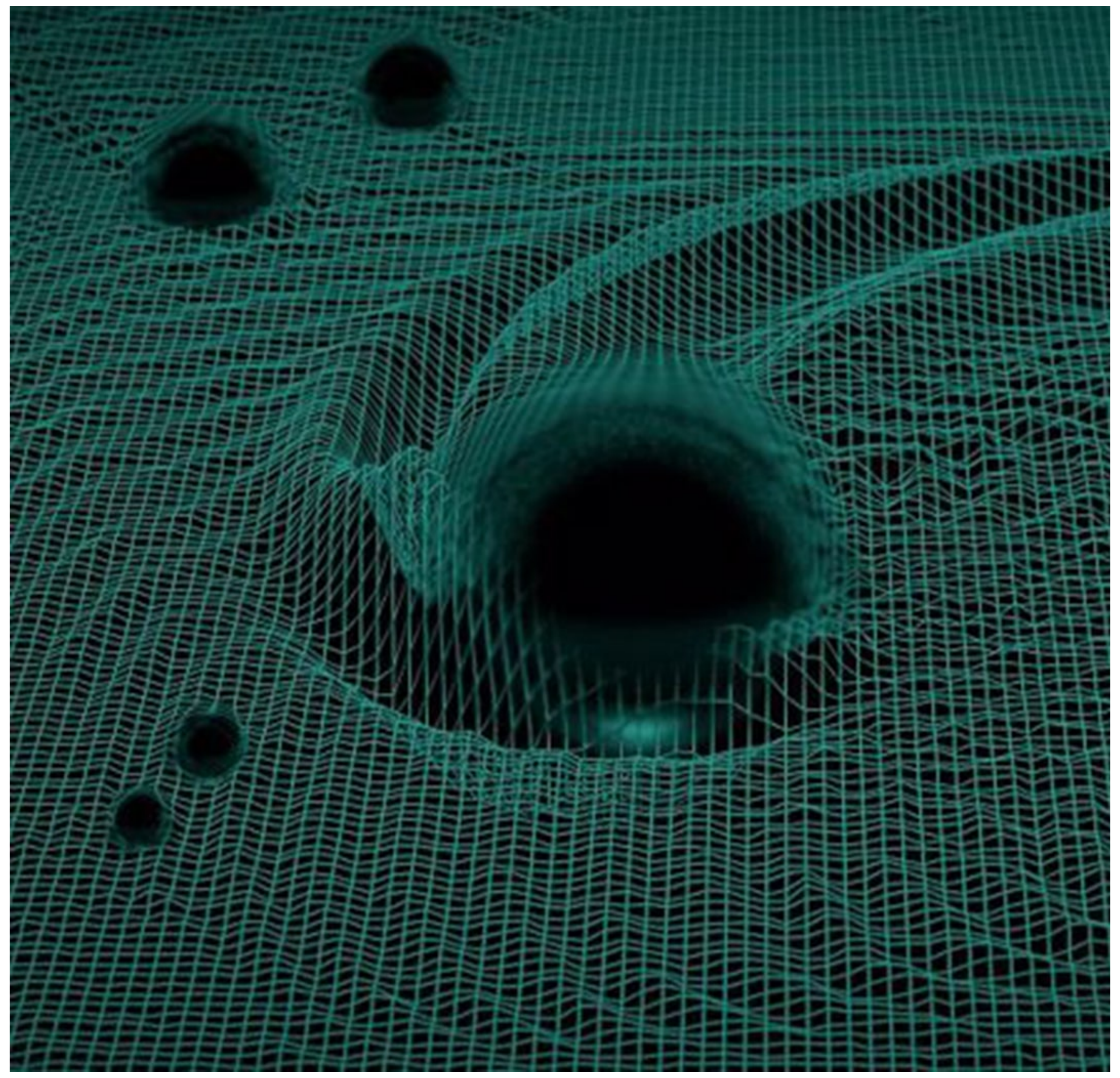


Image credit: Riccardo Buscichio

# What can cause a  black-hole to spin?

See e.g.,
Moreno-Mendez & Cantiello 2016
Fuller et al. 2015

Angular momentum of the progenitor star

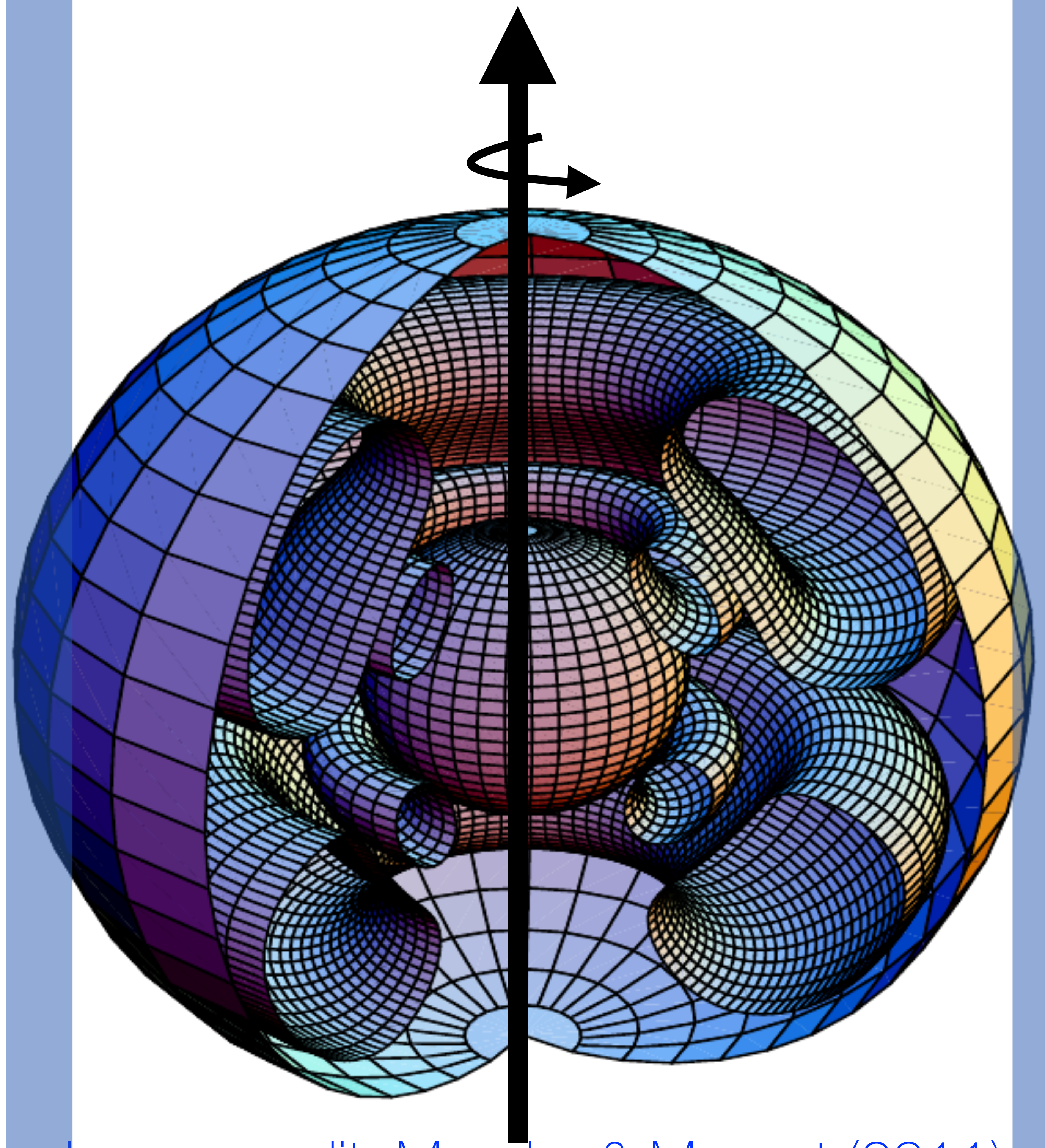


Image credit: Maeder & Meynet (2011)

~~Unknown process during core-collapse~~

Image credit: Grefenstette et al. (2014)

Accretion onto a black hole

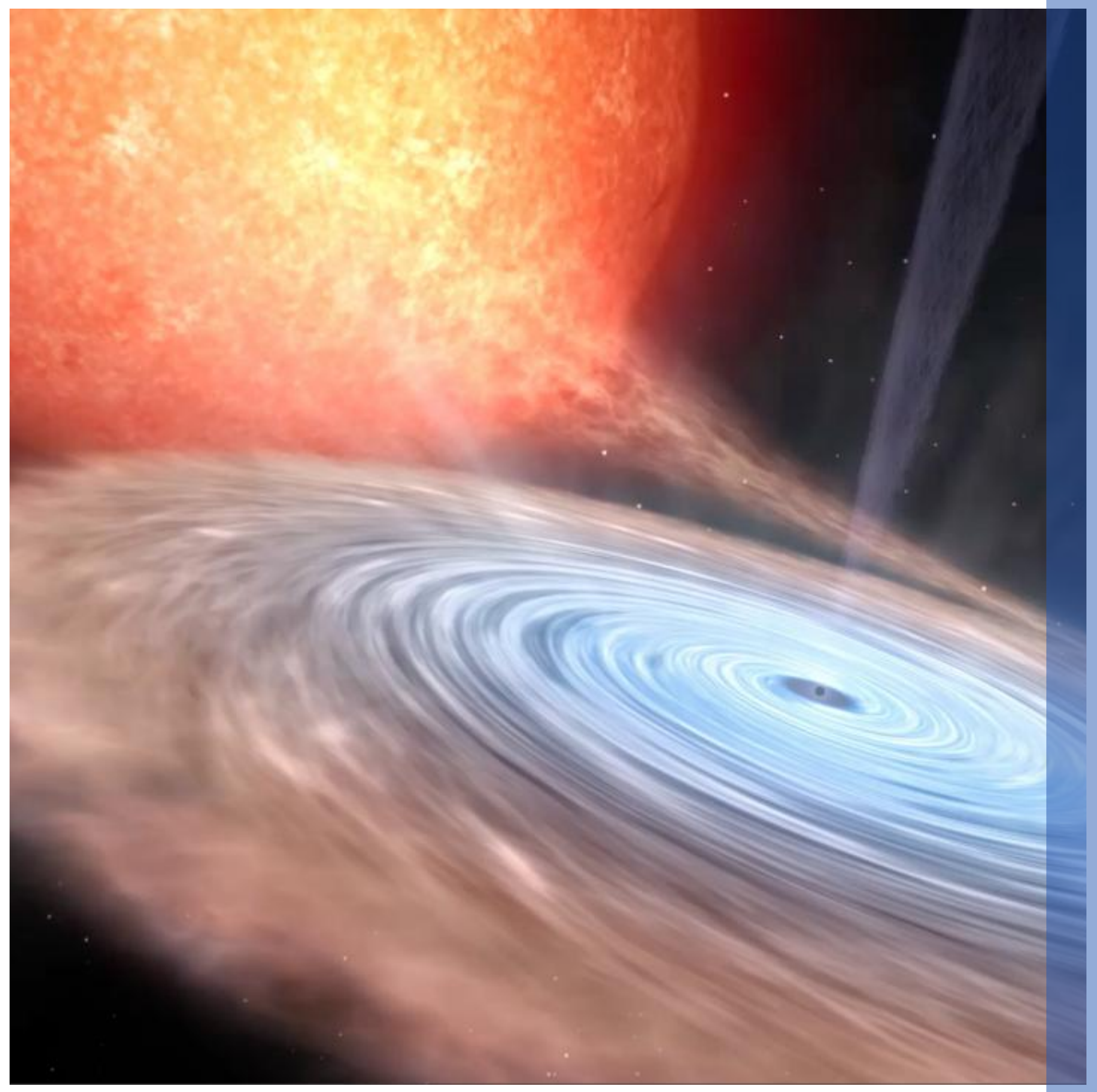


Image credit:Gabriel Pérez

Hierarchical mergers

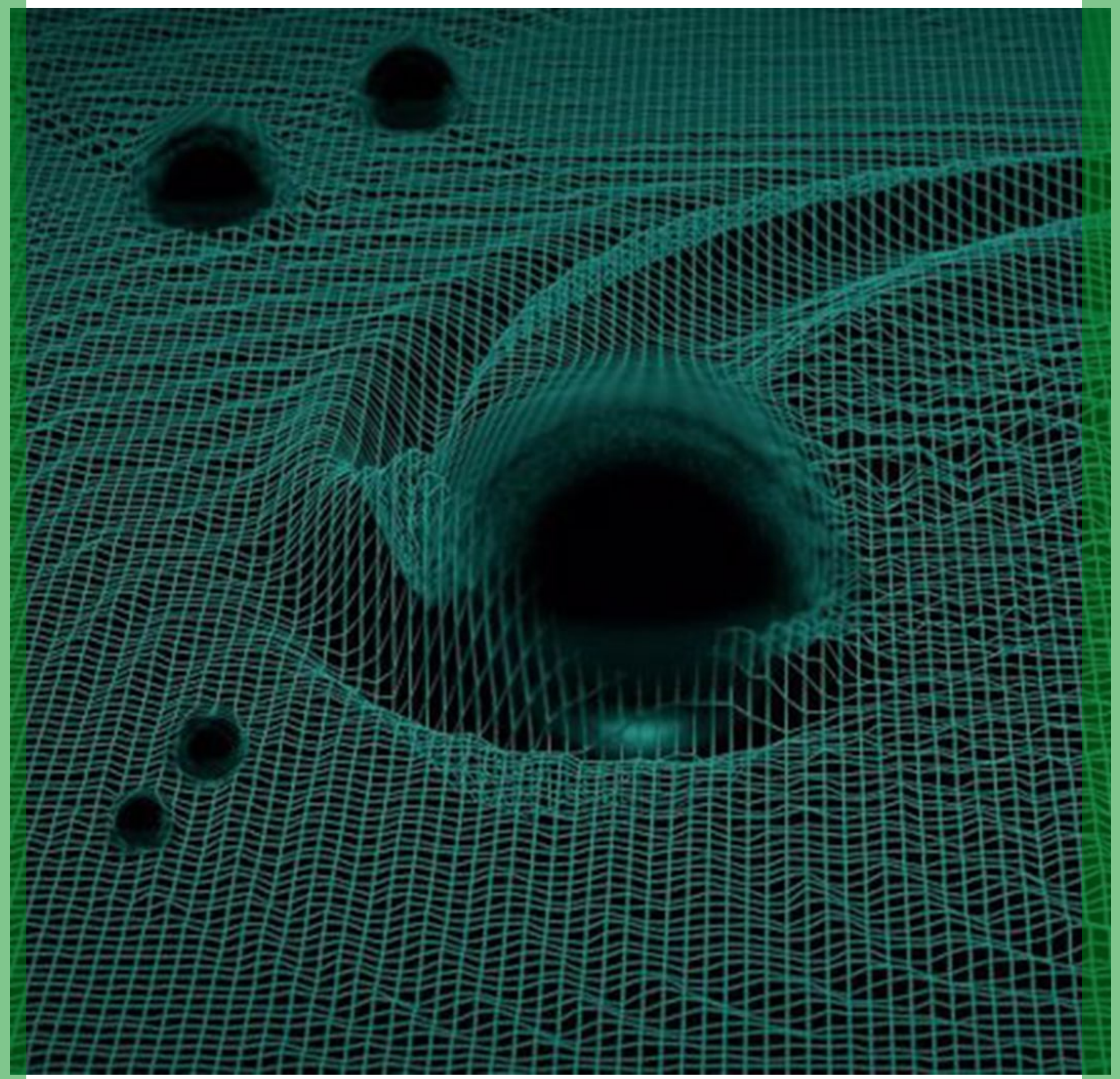
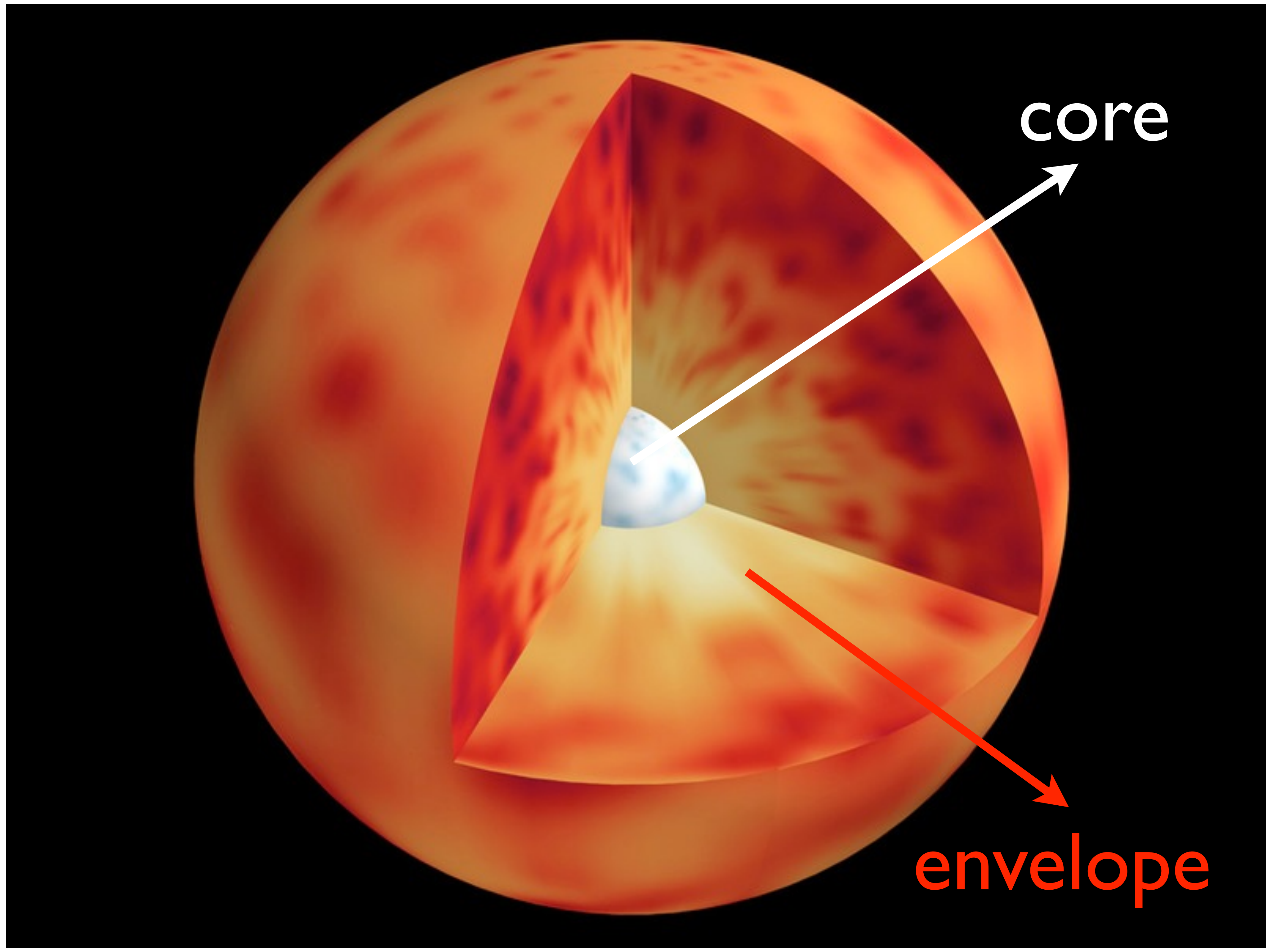
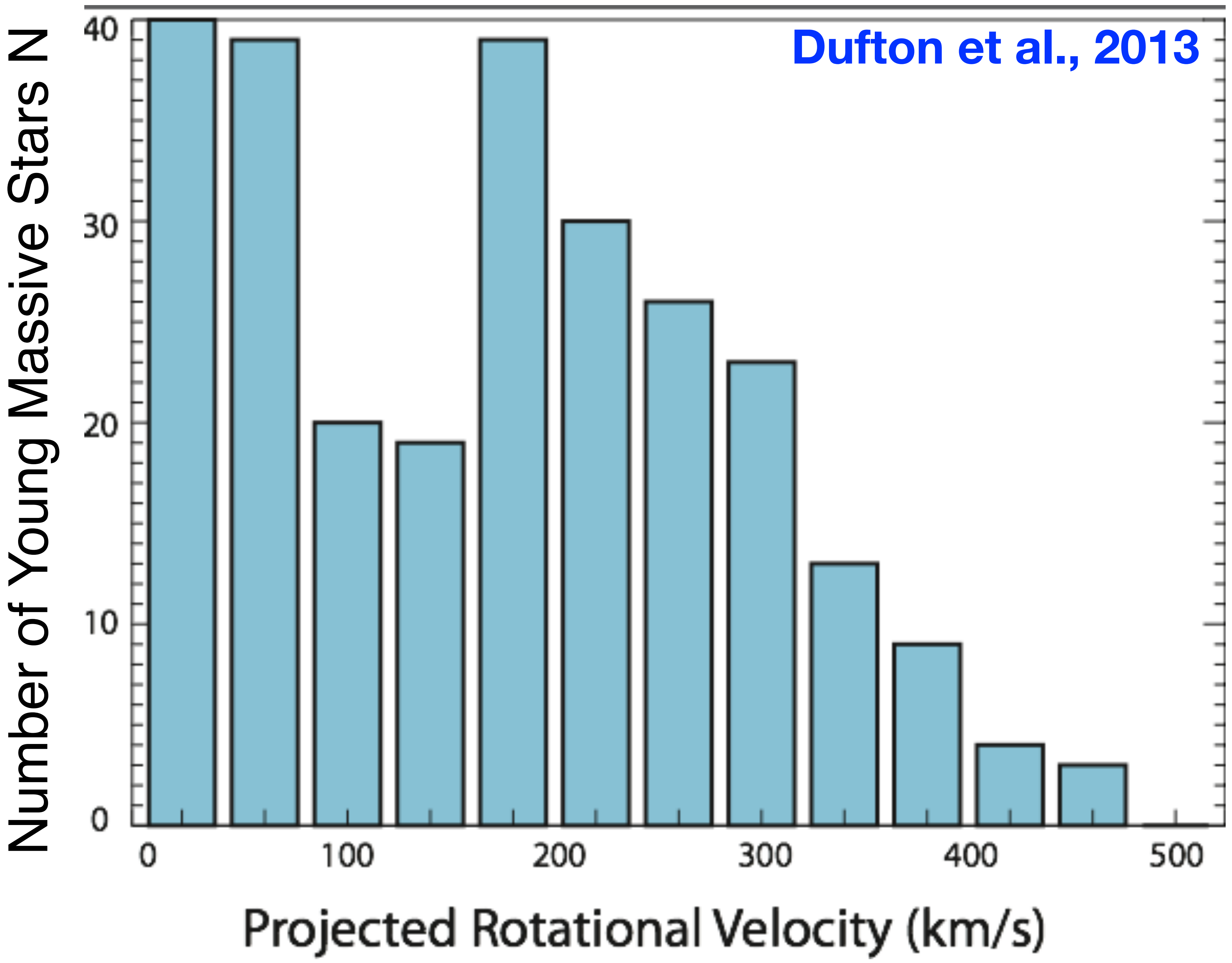


Image credit: Riccardo Buscichio

# Stellar rotation

The question of the origin of black hole spin is inherently related to the rotation of massive stars.



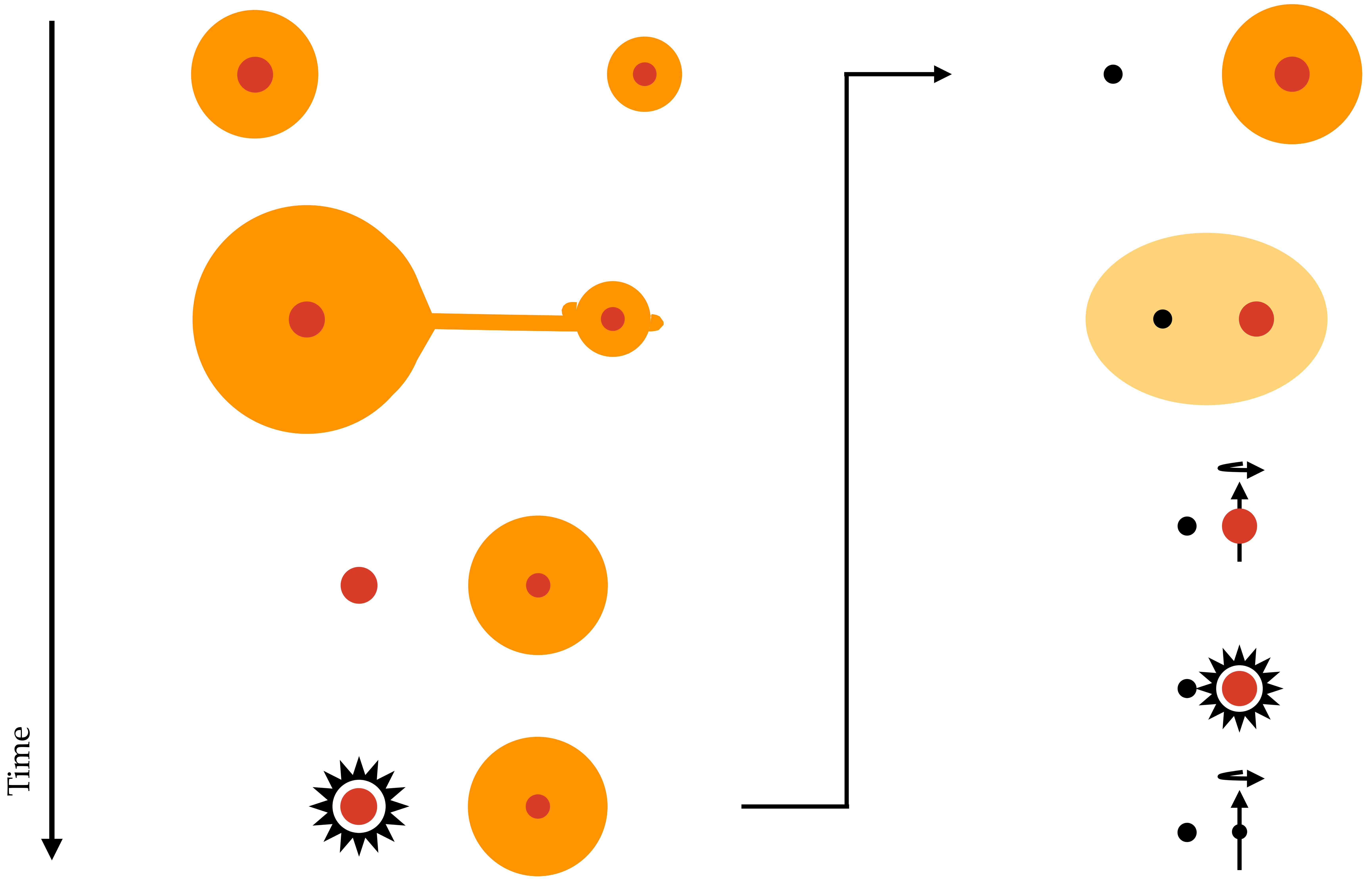




Constraints from asteroseismic observations of low mass (sub-)giants and rotation rates of young neutron stars and white dwarves point towards efficient angular momentum transport.

e.g. Kurtz et al. 2014; Deheuvels et al. 2015; Gehan et al. 2018, Langer et al. 2012, Fuller et al. 2019

# The common envelope formation scenario

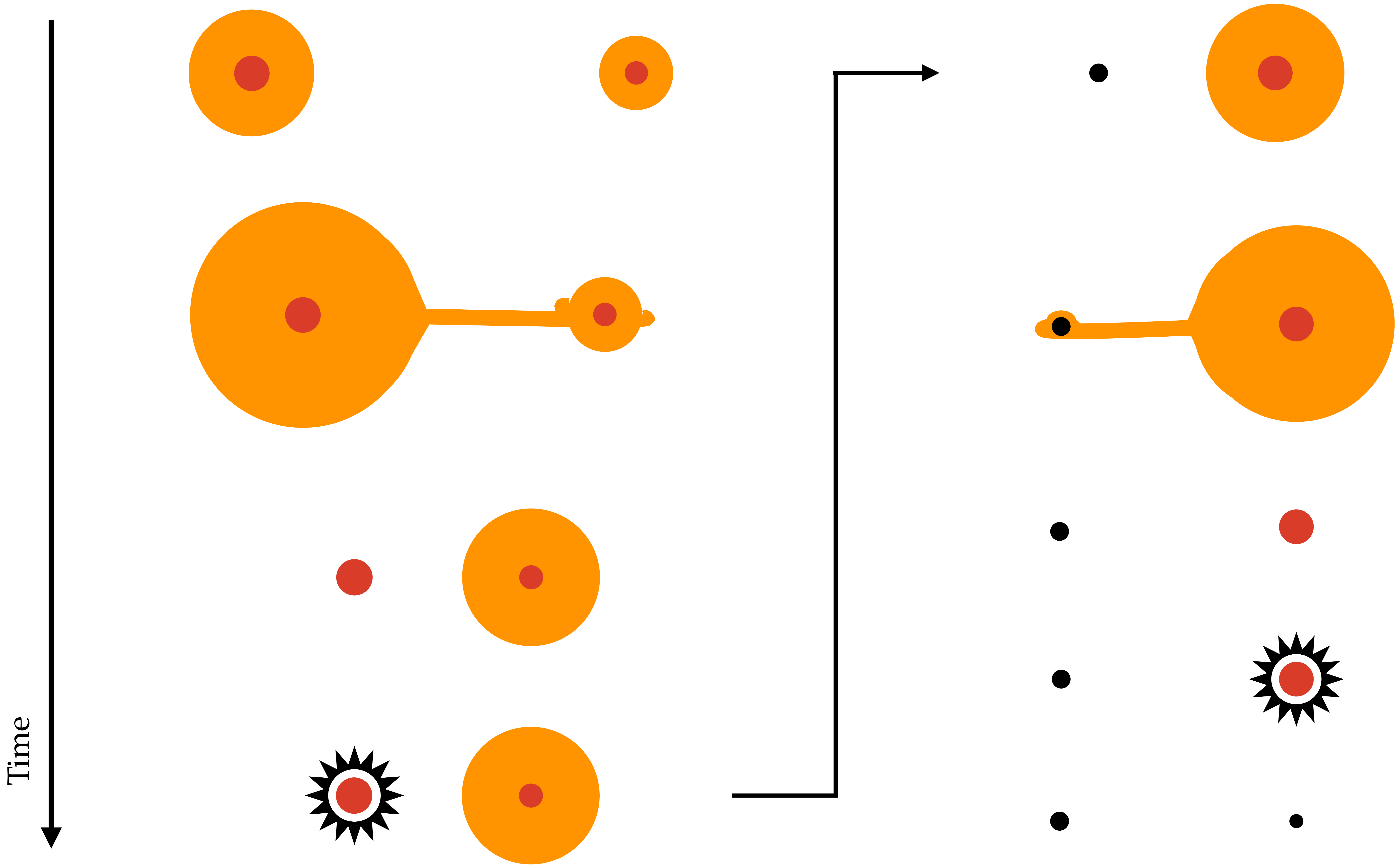
$p_{\mathrm{ZAMS}} \sim 100$ days




e.g., van den Heuvel (1976), Kalogera et al. (2007), Dominik et al. (2012, 2013, 2015), Belczynski et al. (2016, 2020), Bavera et al. (2020, 2021a, 2022a,c)

# The stable mass transfer formation scenario

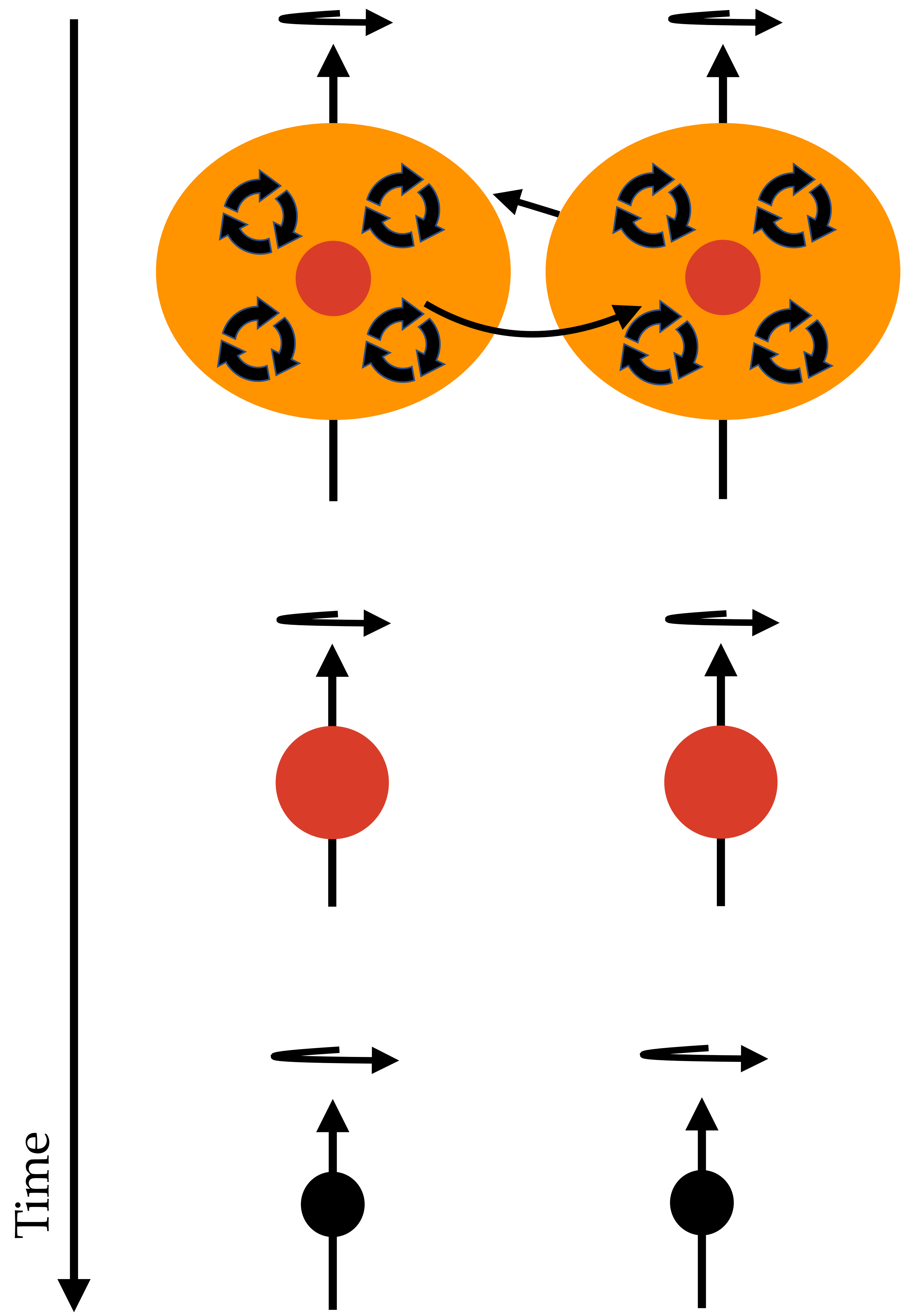
$p_{\rm ZAMS} \sim 10$ days




e.g., Pavlovskii et al. (2017), van den Heuvel et al. (2017), Neijssel et al. (2019), van Son et al. (2021), Bavera et al. (2021a, 2022a,c)

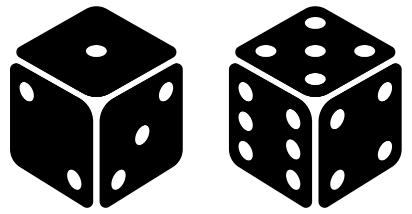
# The chemically homogeneous evolution scenario

$p_{\mathrm{ZAMS}} \lesssim 1$ day




e.g., Marchant et al. (2016), de Mink & Mandel (2016), du Buisson et al. (2021), Riley et al. (2021), Bavera et al. (2022a,c)

# Binary population synthesis



Initial binary population (ZAMS)

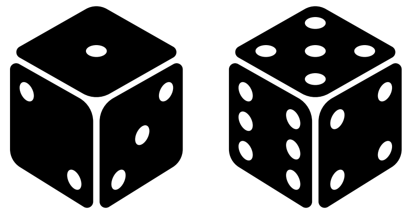
~10M binaries

Binary evolution →

Synthetic binary black hole population

~100k binaries

# Binary population synthesis



Initial binary population (ZAMS)

~10M binaries

Binary evolution

Synthetic binary black hole population

~100k binaries

×

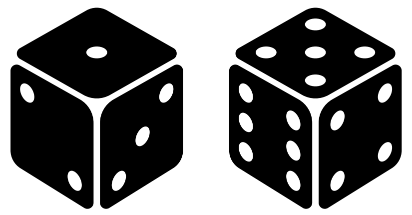
Star-formation history of the Universe

Gravitational-wave detector selection effects

→

Detectable/ intrinsic binary black hole population

# Binary population synthesis



Initial binary population (ZAMS)

~10M binaries

→ Binary evolution →

Synthetic binary black hole population

~100k binaries

×

Star-formation history of the Universe

Gravitational-wave detector selection effects

→

Detectable/intrinsic binary black hole population

## Binary evolution simulation tools:

- Rapid (parametric) binary evolution:

PRO: fast ~1 CPU second.

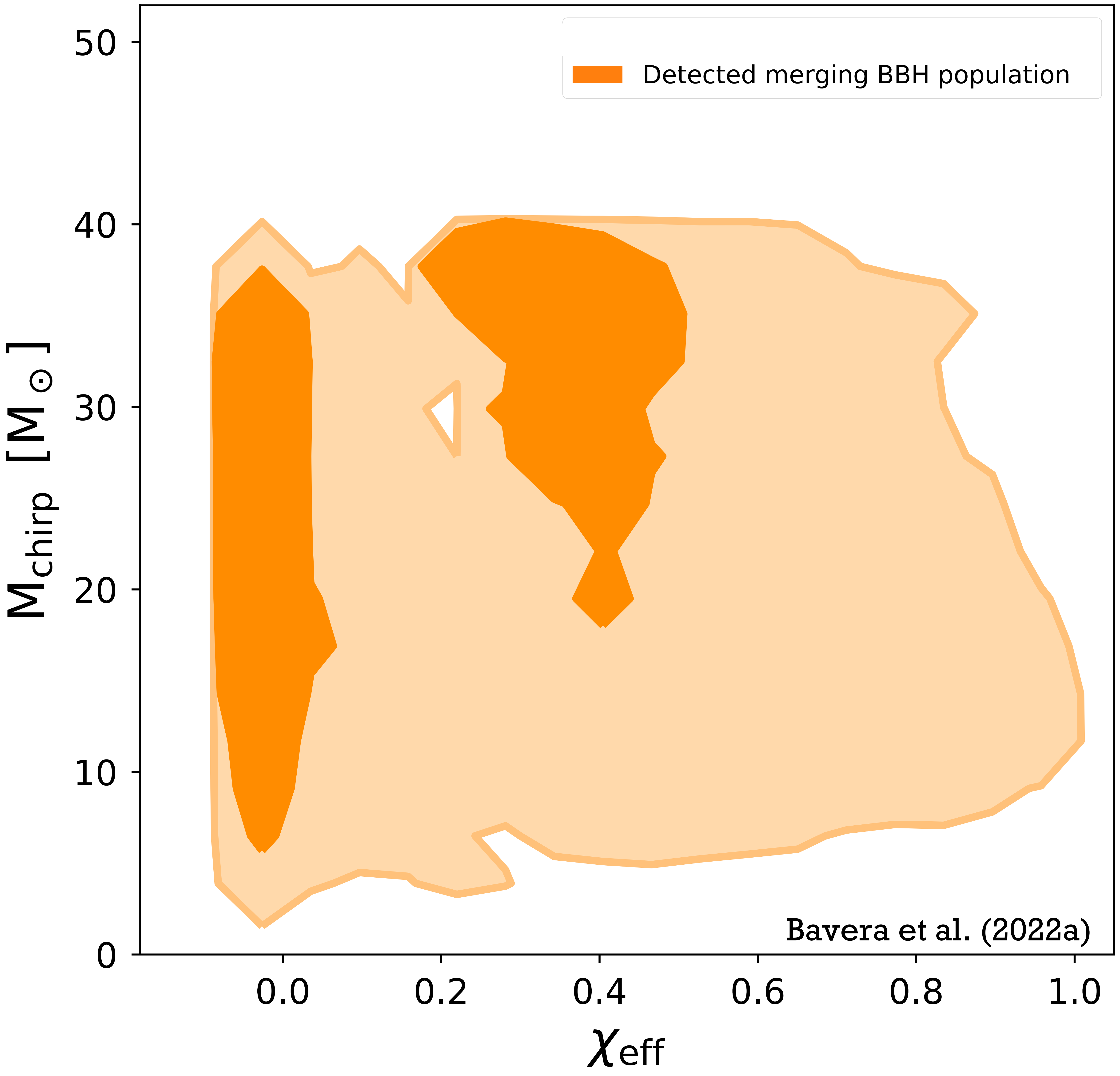
CON: approximate star's evolution and binary interactions with fitting formulae.

- Detailed binary evolution:

PRO: accurate modelling of binary interactions and feedbacks on stellar evolution.

CON: slow ~ 10-100 CPU hours.

# Binary black hole mass-spin distribution




**Chirp mass:** $M_{\rm chirp} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

**Effective spin parameter:** $\chi_{\rm eff} = \dfrac{m_1\vec{\chi}_1 + m_2\vec{\chi}_2}{m_1+m_2}\hat{\vec{L}}$

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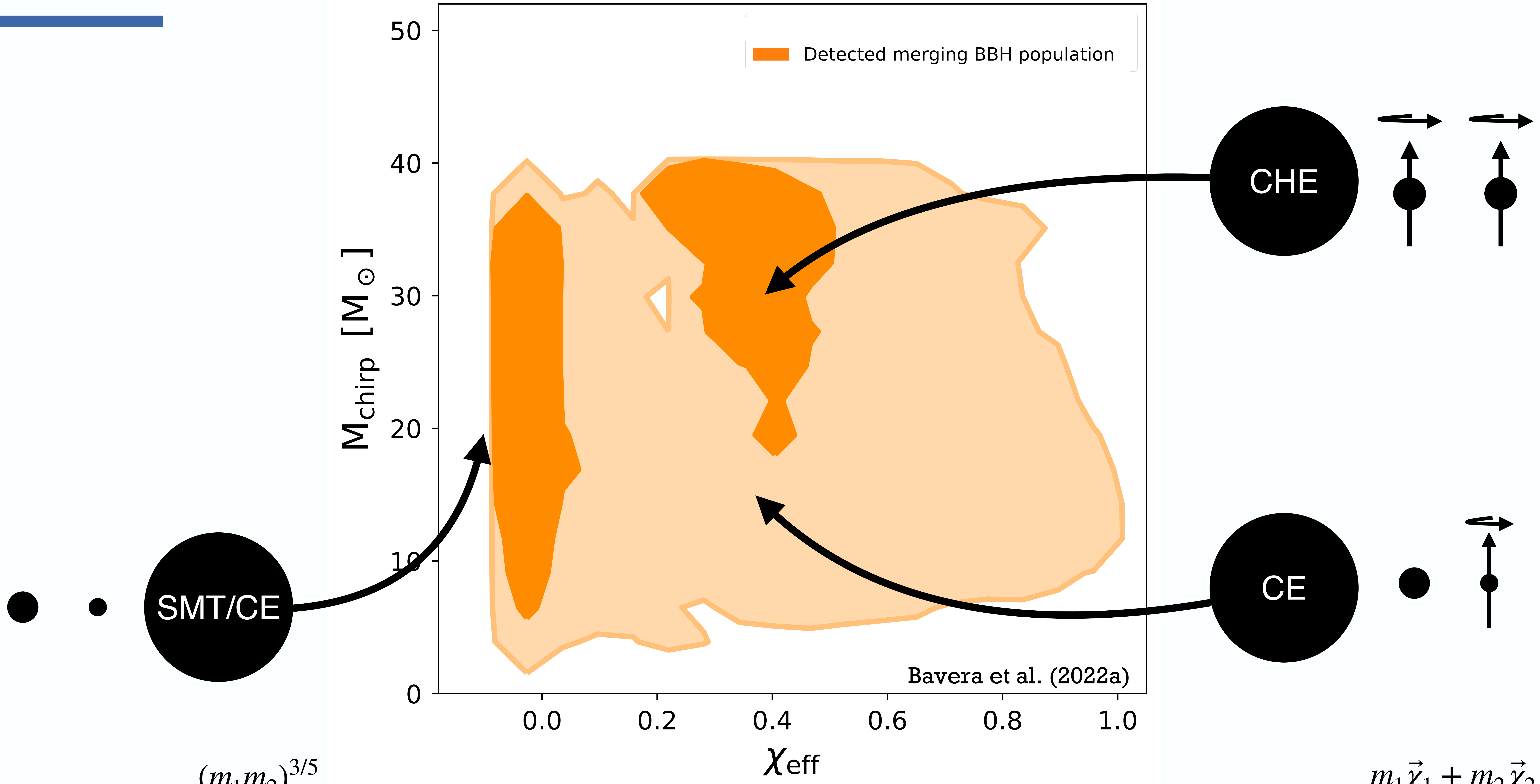


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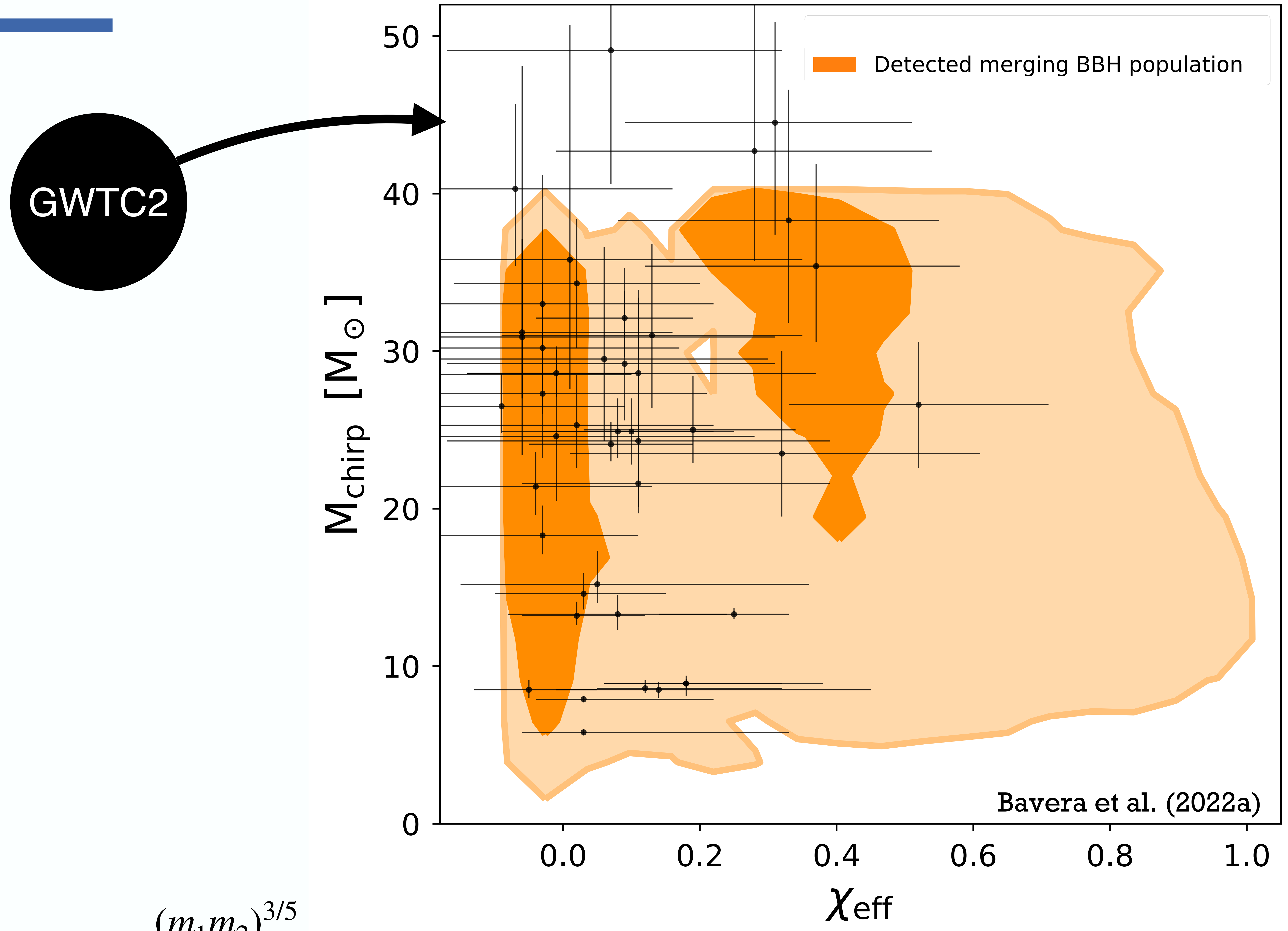


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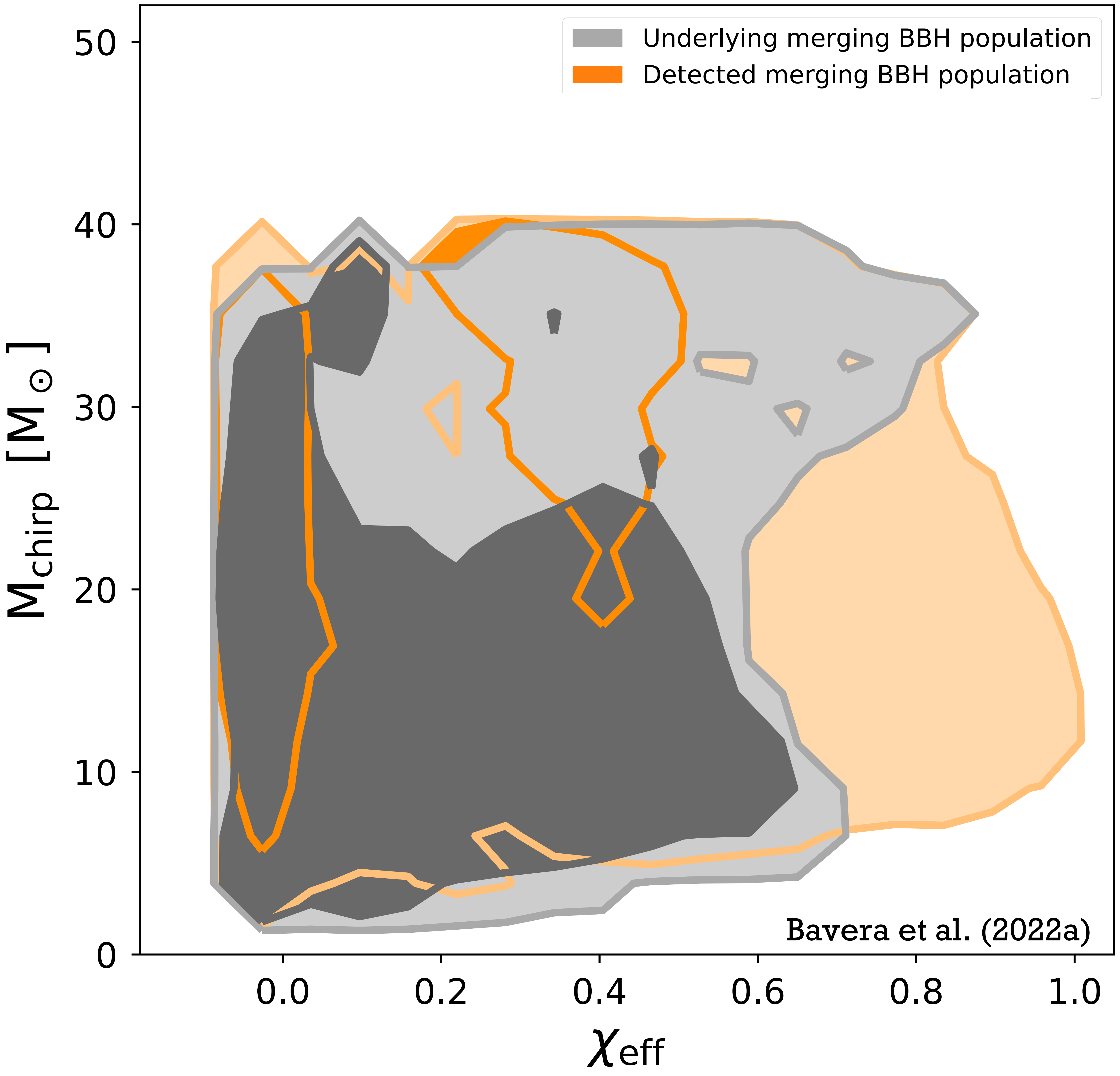


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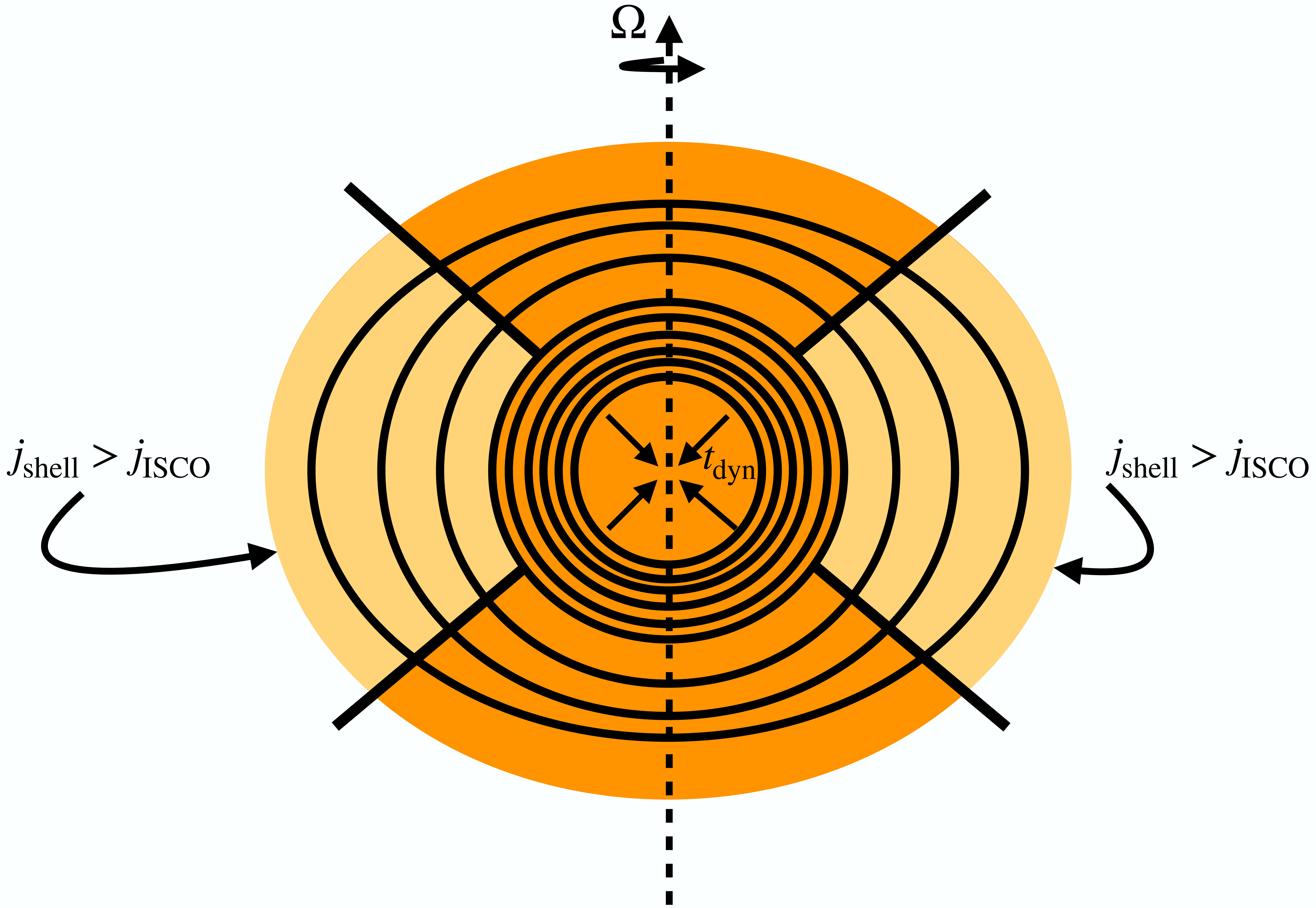
# The collapsar model

e.g., Woosley (1993), Paczynski (1998)



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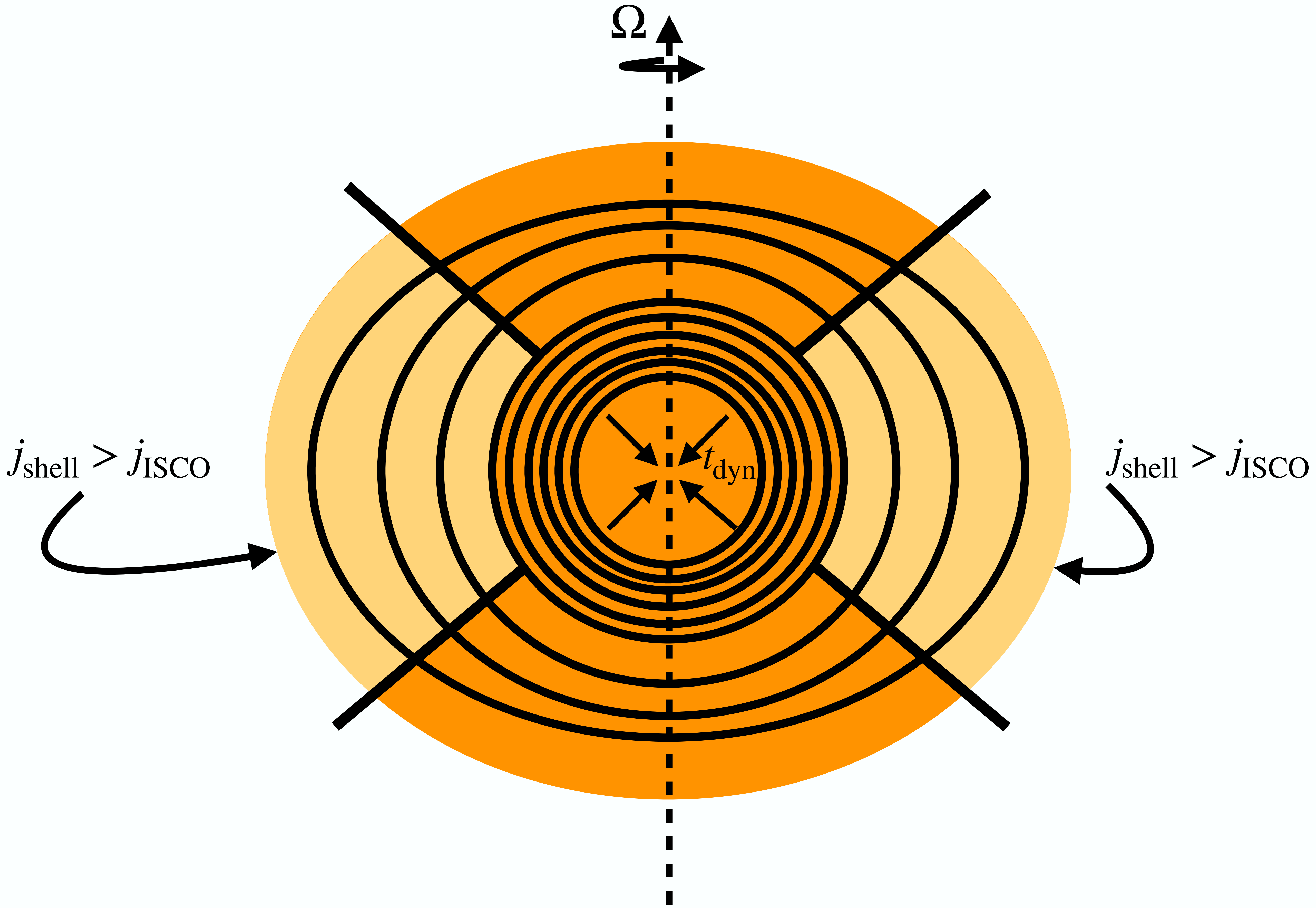
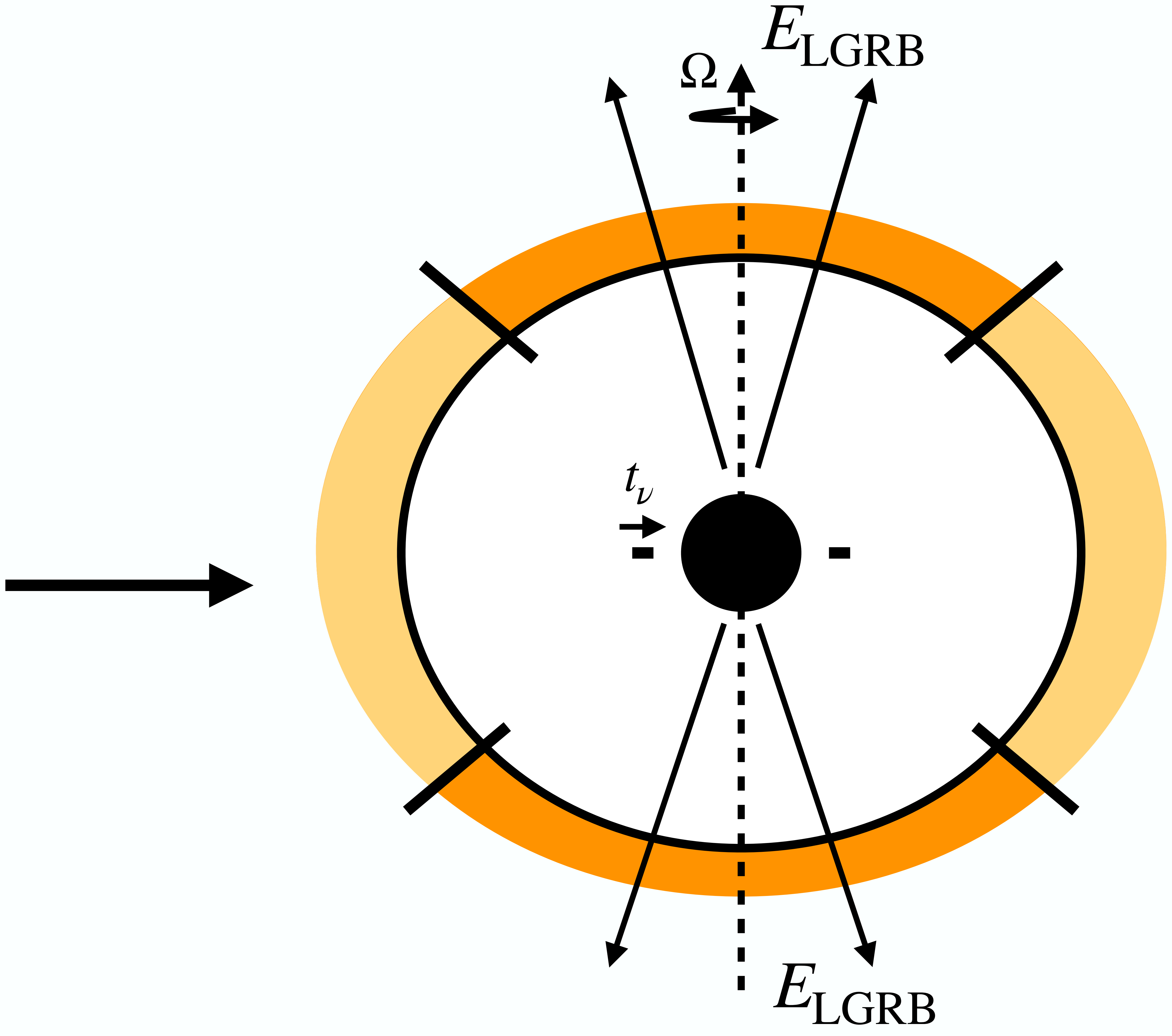
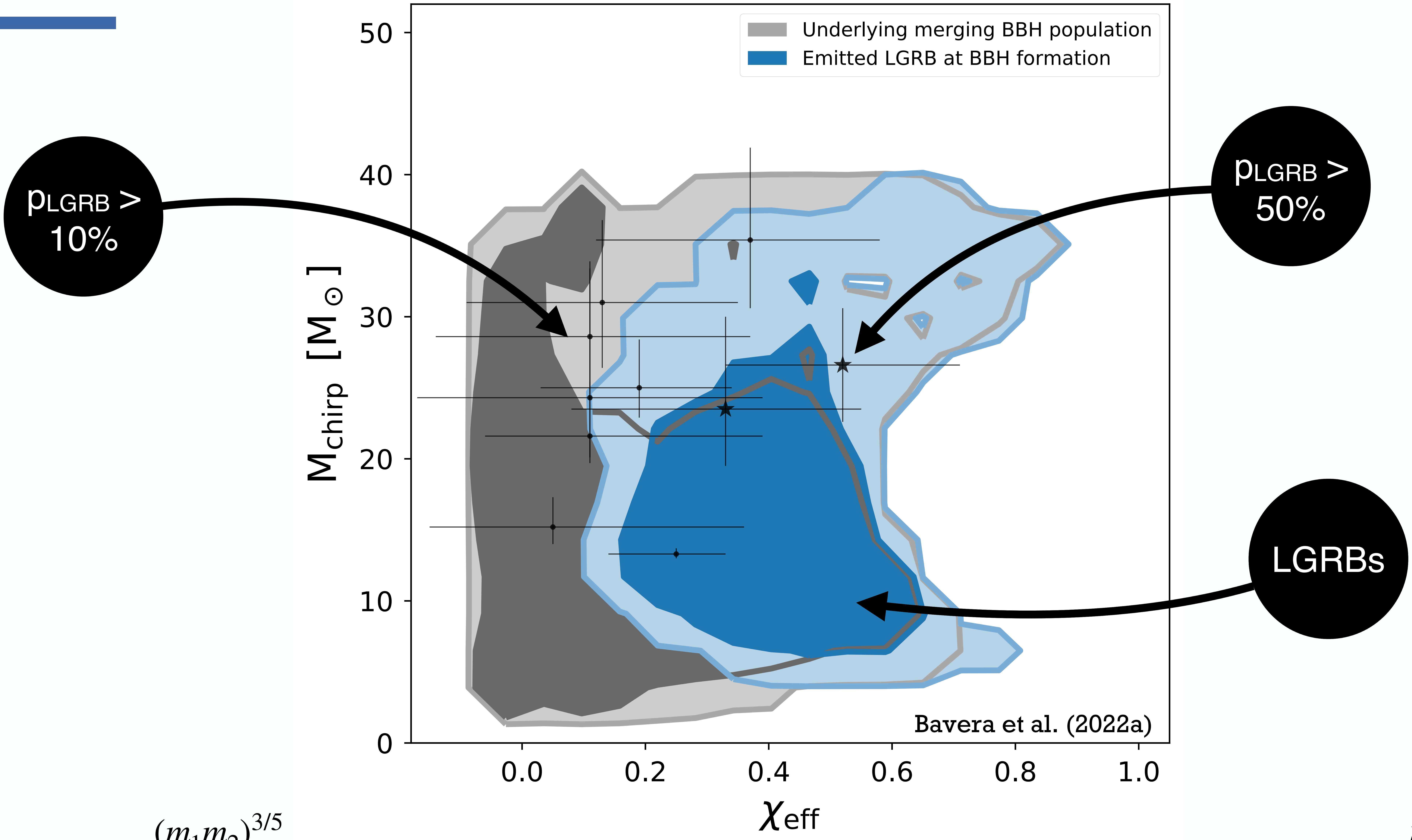


# Probing binary black hole formation with LGRBs

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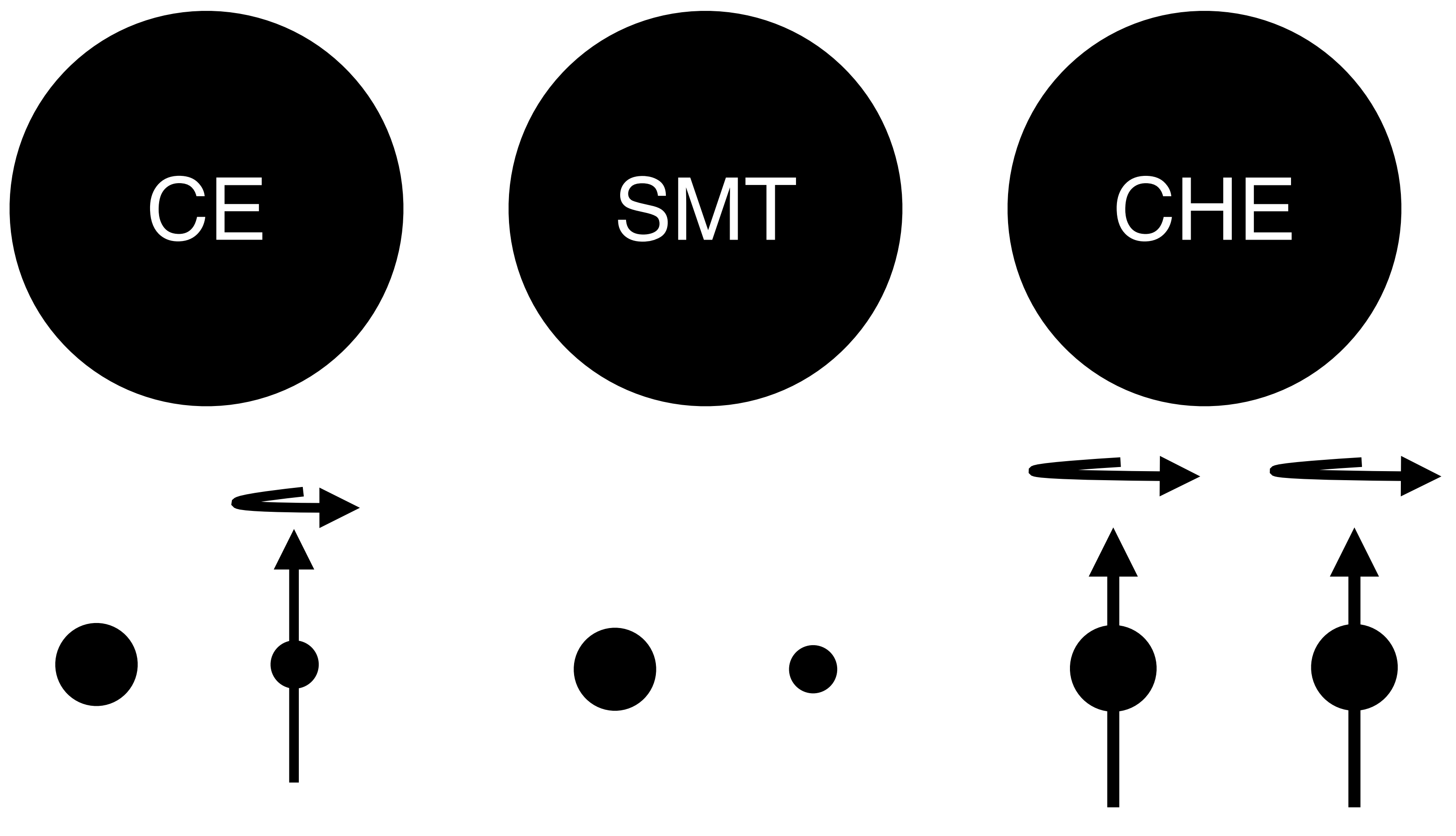
# Hierarchical bayesian model selection

e.g. Zevin, Bavera, …, TF et al. (2021), Wong et al. (2021), Franciolini et al. (2022), Mapelli et al. (2022), Arca Sedda et al. (2023)

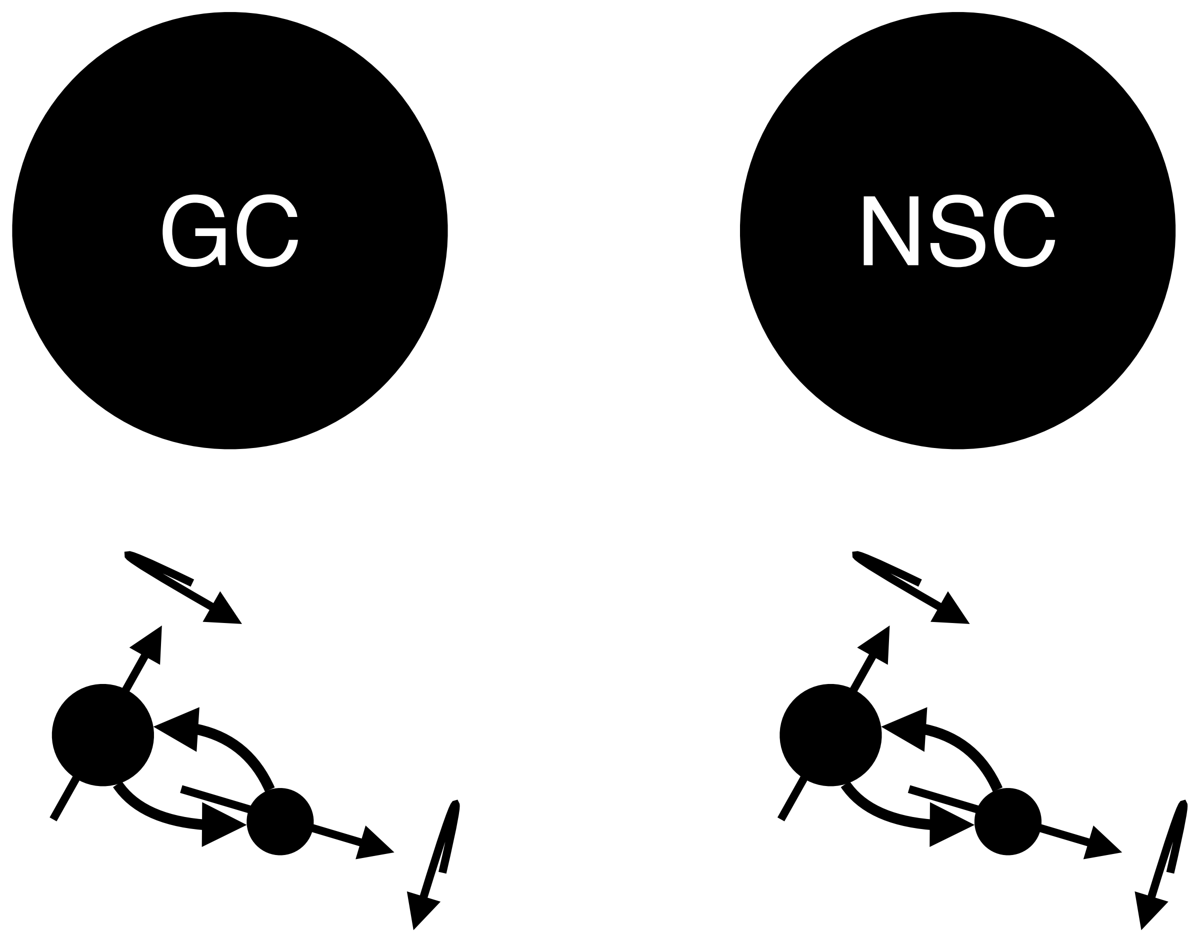
## Isolated binary evolution

Bavera, TF et al. (2021) Du Buisson et al. (2020)




## Dynamical formation

Rodriguez et al. (2019) Antonini et al. (2018)

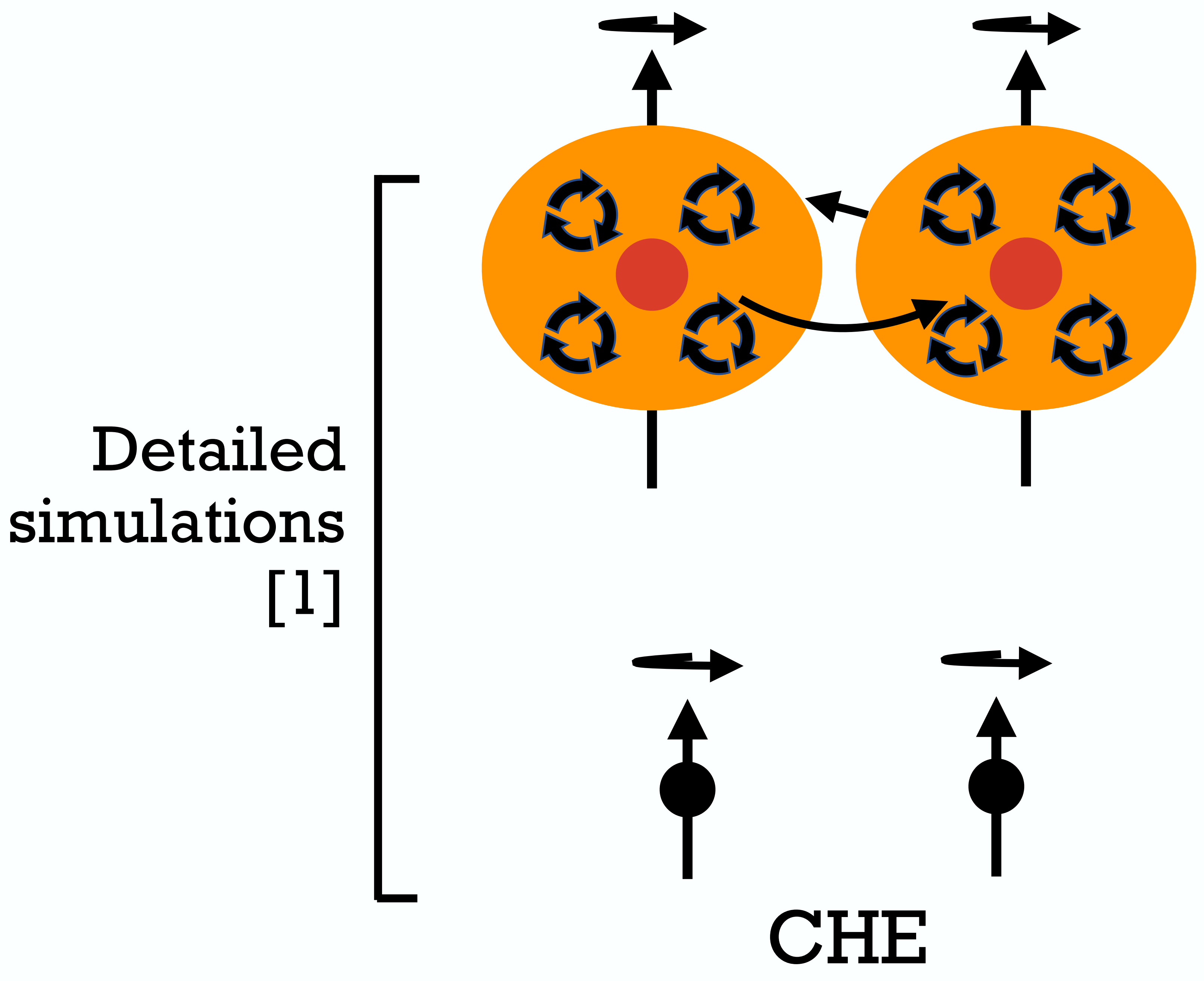



- Constrain uncertain physical processes: e.g., black hole birth spin $|\vec{\chi}|$
- Determine the branching fraction $\beta$ of each channel

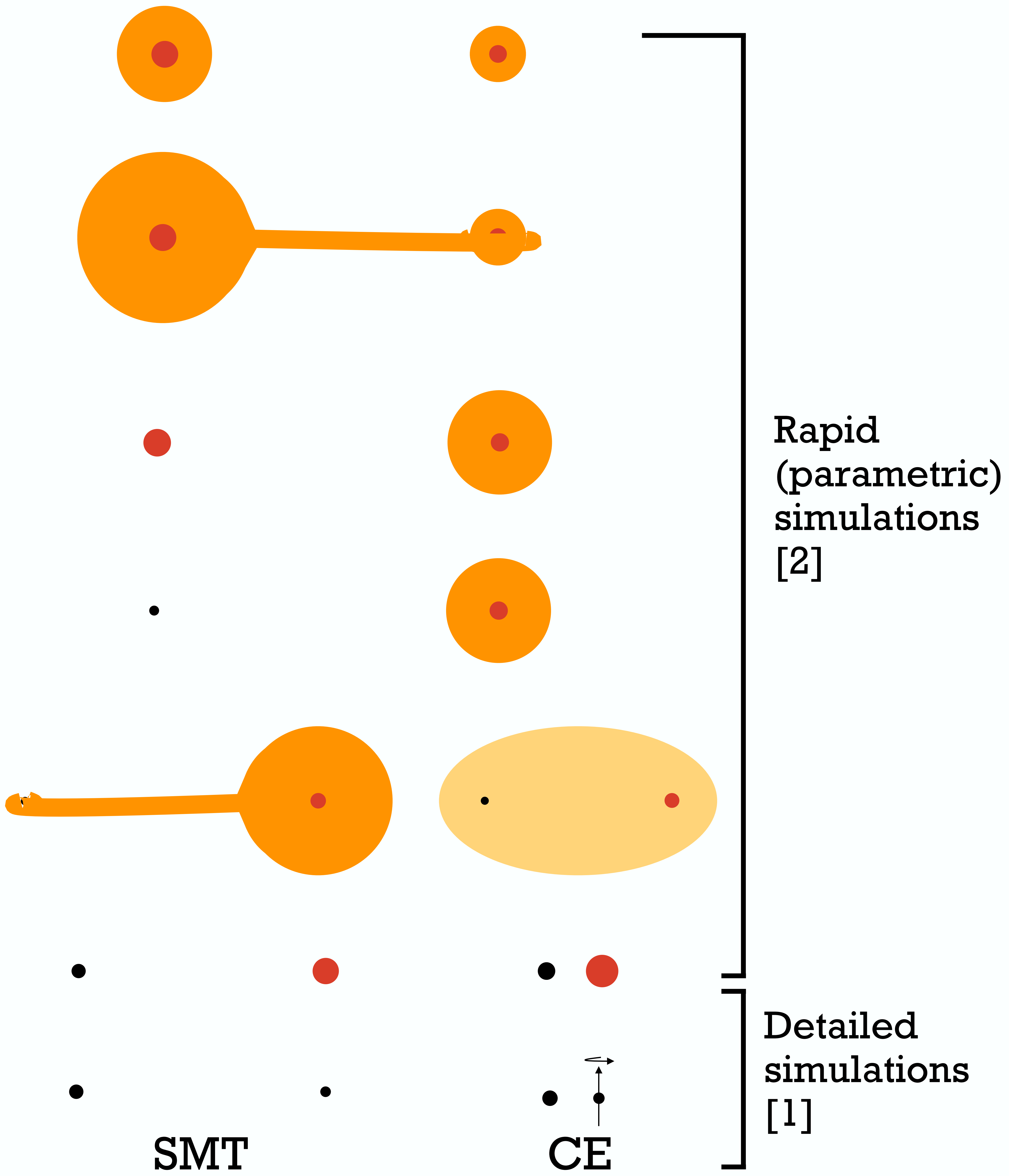
**A significant increase in the observed sample**
**and advances in theoretical models* are required for robust results.**

*See **https://posydon.org** for one of the efforts to improve the physical accuracy of population synthesis simulations

# Binary population synthesis




du Buisson et al. (2021)




Bavera et al. (2020, 2021a, 2022b,c)

[1] Paxton et al. (2009, 2013, 2015, 2017, 2019)

[2] Breivik et al. (2019)

**POSYDON** is a new framework for binary population synthesis studies that uses detailed stellar structure and binary evolution simulations (Fragos et al. 2023).

https://posydon.org

# The core developer team

The **POSYDON collaboration**: Jeff Andrews, Simone Bavera, Christopher Berry, Scott Coughlin, Aaron Dotter, Tassos Fragos, Prabin Giri, Vicky Kalogera, Aggelos Katsaggelos, Konstantinos Kovlakas, Shamal Lalvani, Devina Misra, Philipp Shrivastava, Ying Qin, Jaime Román-Garza, Kyle Rocha, Juan Gabriel Serra Pérez, Petter Alexander Stahle, Meng Sung, Xu Teng, Goce Trajcevski, Zepei Xing, Manos Zapartas

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GORDON AND BETTY MOORE FOUNDATION

NORTHWESTERN UNIVERSITY

CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

# Key points of this talk

Black hole spins contain the most information regarding the astrophysical origin of BBHs

Correlations of GW observables contain signatures of the astrophysical processes taking place in the formation of BBHs

Approximate progenitor models are reaching the limit of their applicability to GW data interpretation

Moving forward requires constraining astrophysical models with diverse, multi messenger datasets