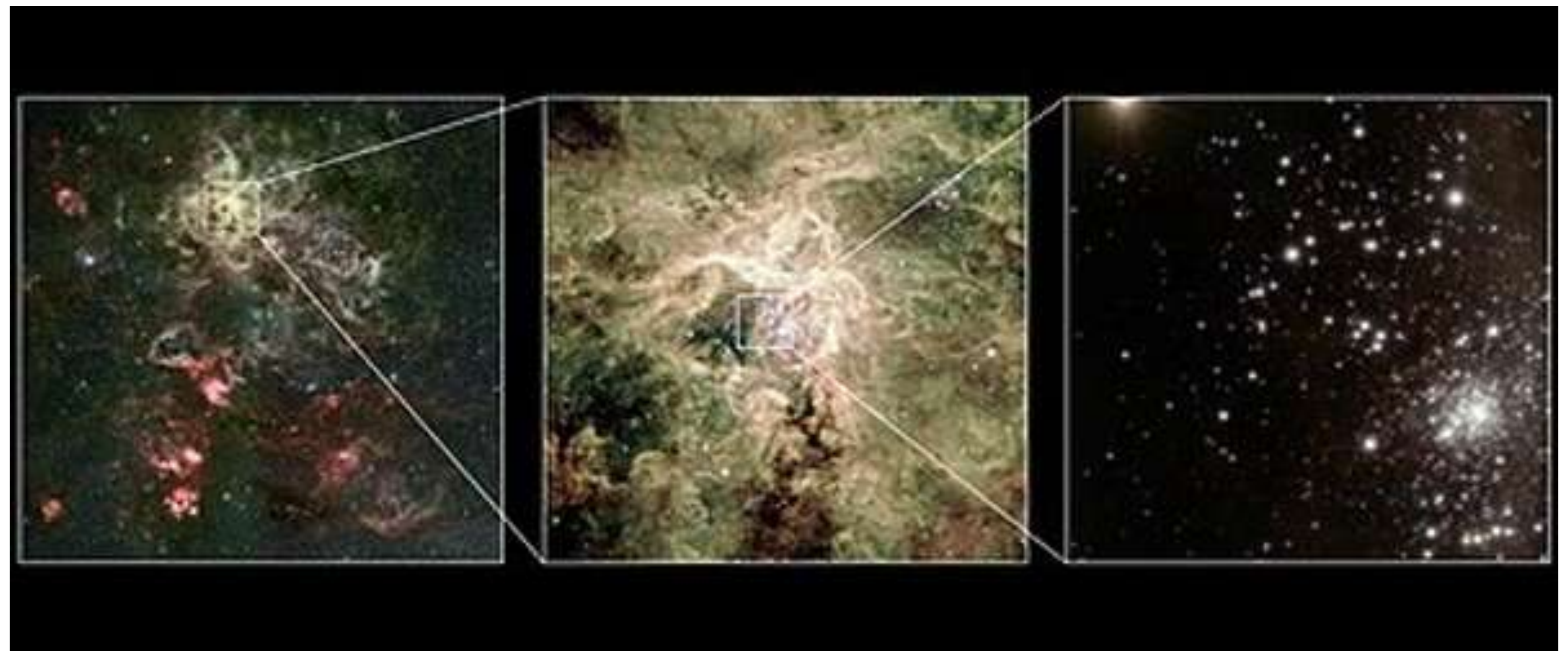
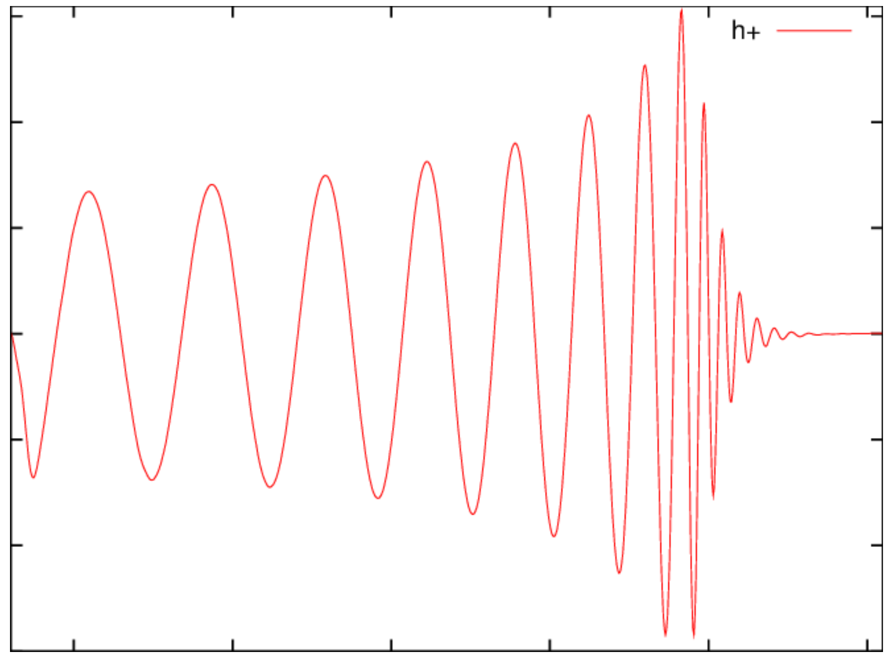
BINARY BLACK-HOLE ASTROPHYSICS

Jean-Pierre Lasota

Institut d'Astrophysique de Paris & Nicolaus Copernicus Astronomical Center, Warsaw





Based on research by Krzysztof Belczyński and his team and collaboration with Chris Done

Carter Fest: Black Holes and other Cosmic Systems

4–6 juil. 2022
IAP, Paris & Observatoire de Paris, Meudon

1988GReGr..20.1173A 1988/11 cited 147

Optical reference geometry for stationary and static dynamics.

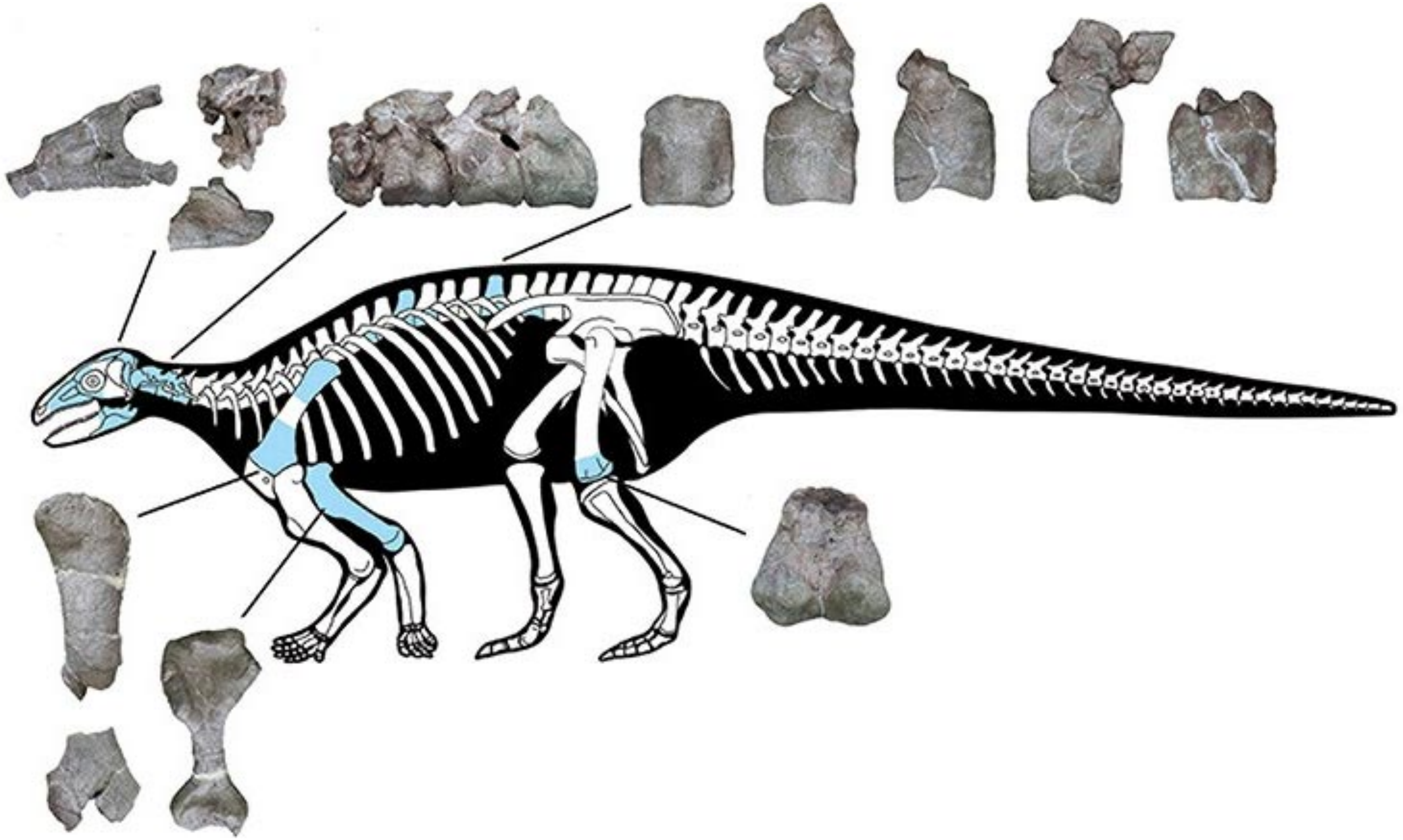
- Abramowicz, M. A.;
- Carter, B.;
- Lasota, J. P.

1984Natur.308..163B 1984/03 cited: 5

Resonant reception in the Solar System of gravitational waves from external sources

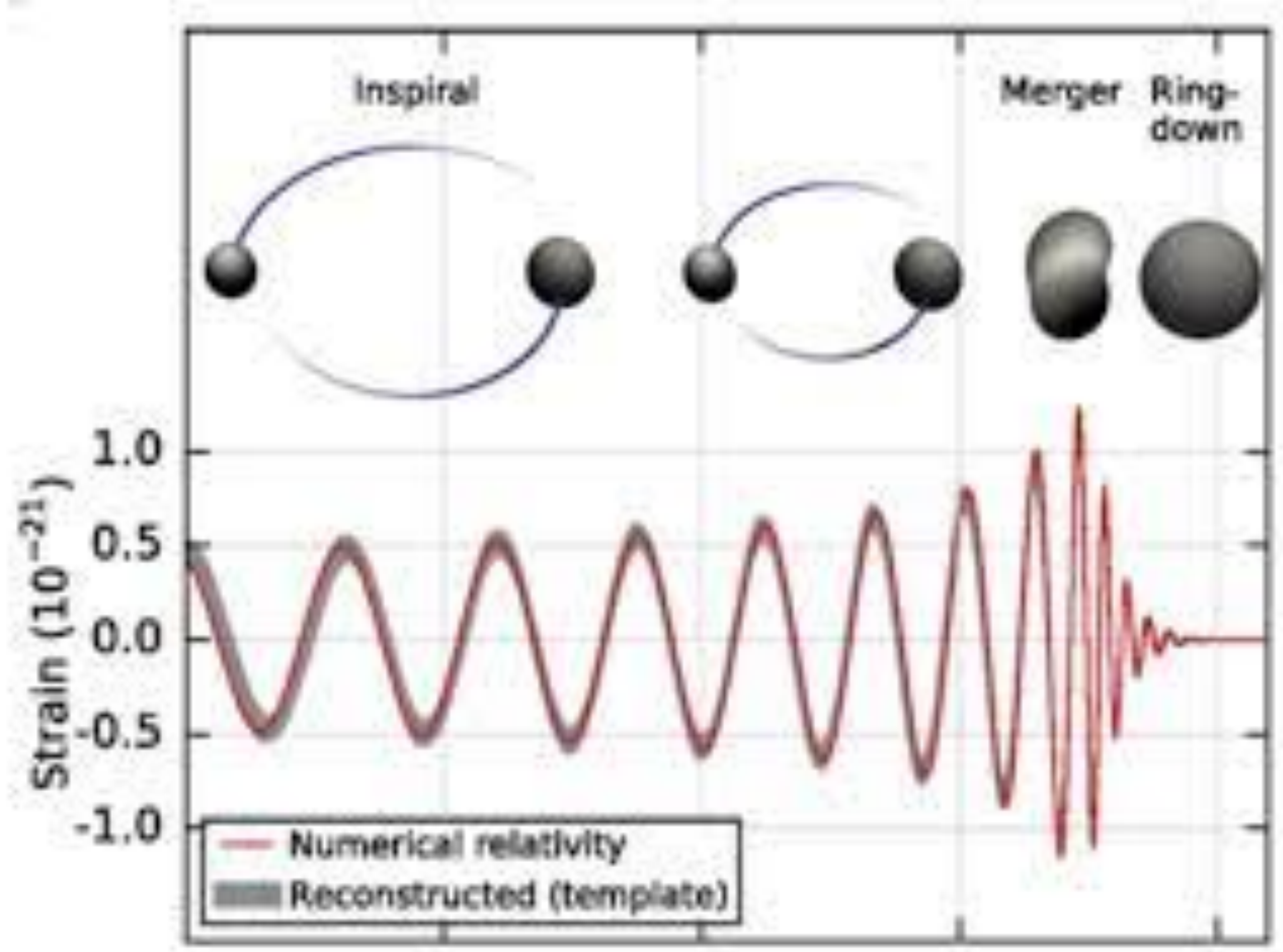
- Bonazzola, S.;
- Carter, B.;
- Heyvaerts, J.;
- Lasota, J. P.

Paleontology



Paleontology

Gravitational wave paleontology



Masses: M_1, M_2

Effective spin: $$\chi_{\rm eff} = \frac{M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2}{M_1 + M_2}$$

- from which one can reconstruct a_1, a_2 and the angles

... and that's all. Thank you Brandon!

Gravitational wave paleontology

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... and that's all. Thank you Brandon!

There are many possible ways leading to BH-BH mergers:

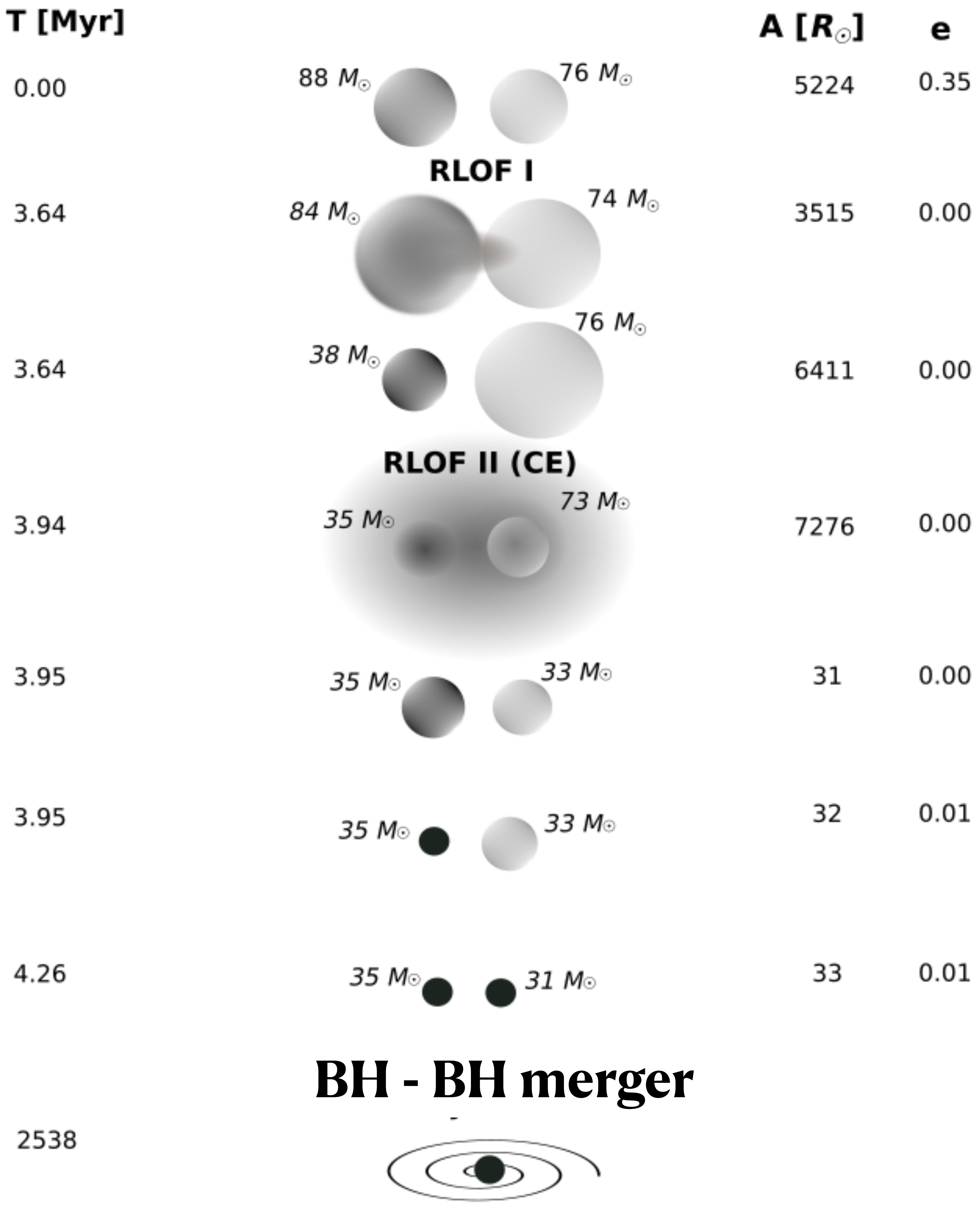
- isolated (massive) binary evolution
- globular clusters
- nuclear stellar clusters
- AGN discs
- primordial BH

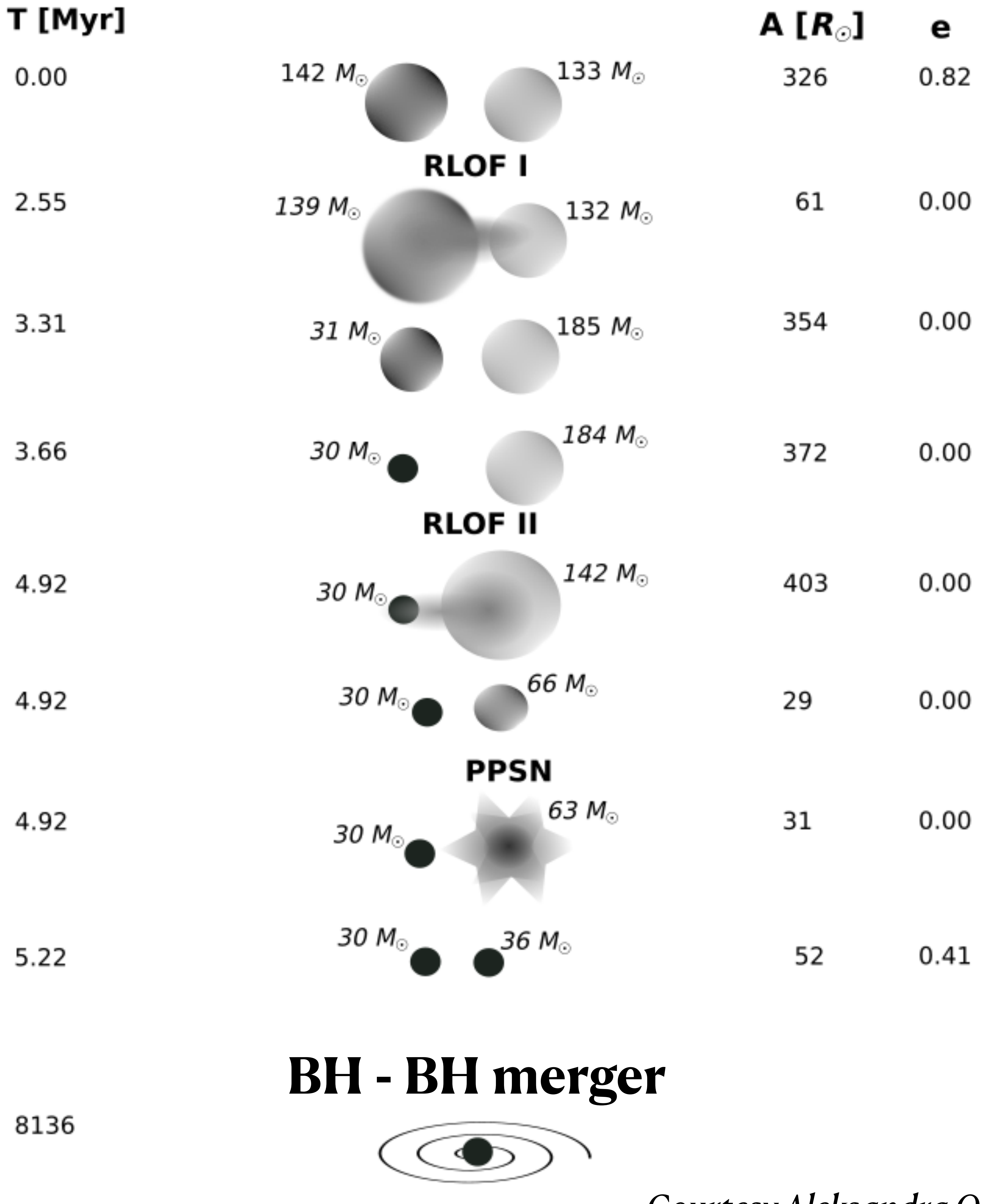
There are claims in the literature that LVC O3 results suggest several BHBH formation channels and some articles even give the fraction of systems formed in each ...

O sancta simplicitas!

GW150914

Stellar population synthesis





StarTrack (Belczyński et al. 2002, 2008)

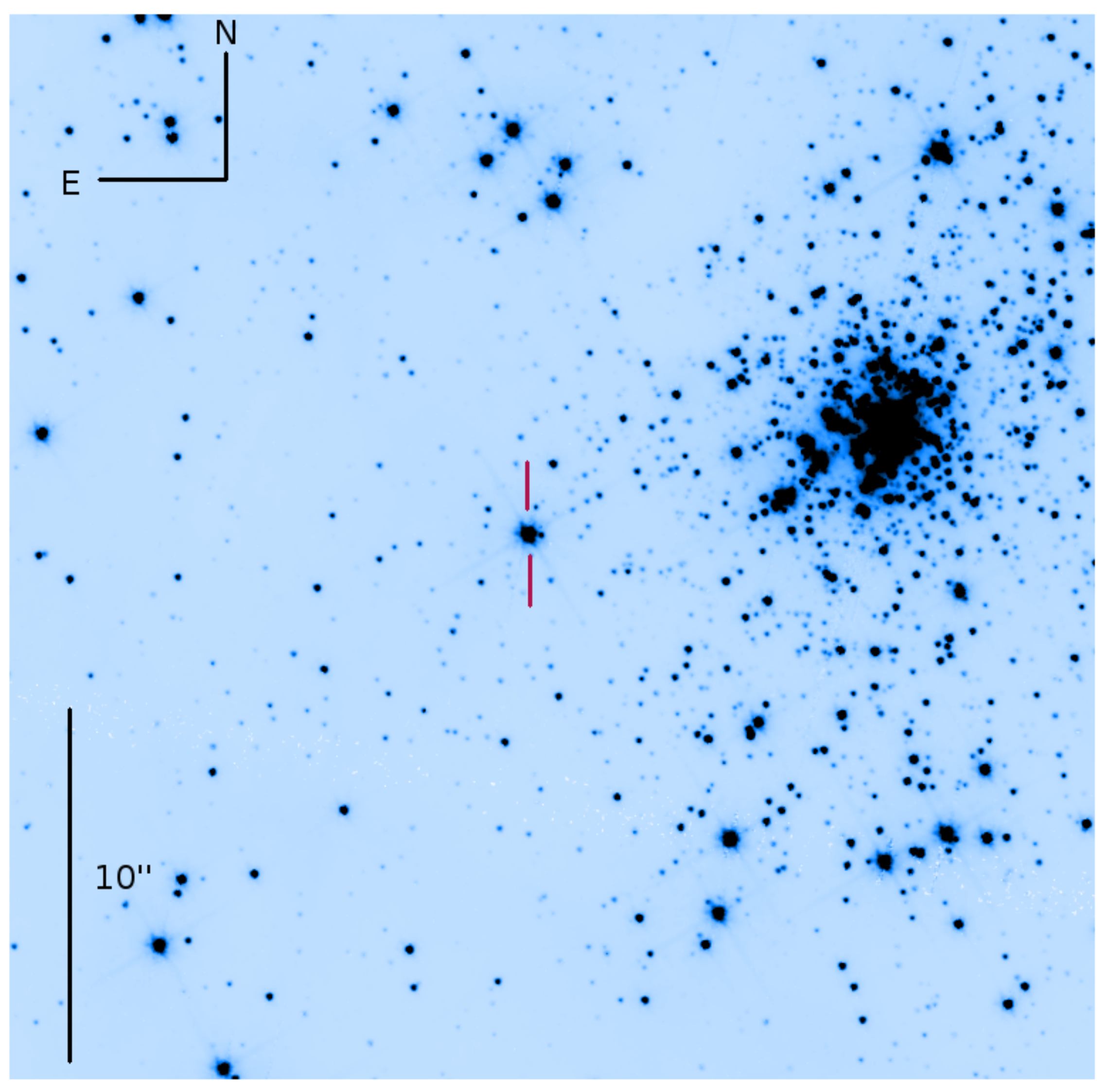
Courtesy Aleksandra Olejak

The Uncertain Future of Massive Binaries: the case of Melnick 34

Belczyński et al. 2022

Testing the isolated-binary origin of BH-BH mergers

Melnick 34 in the LMC

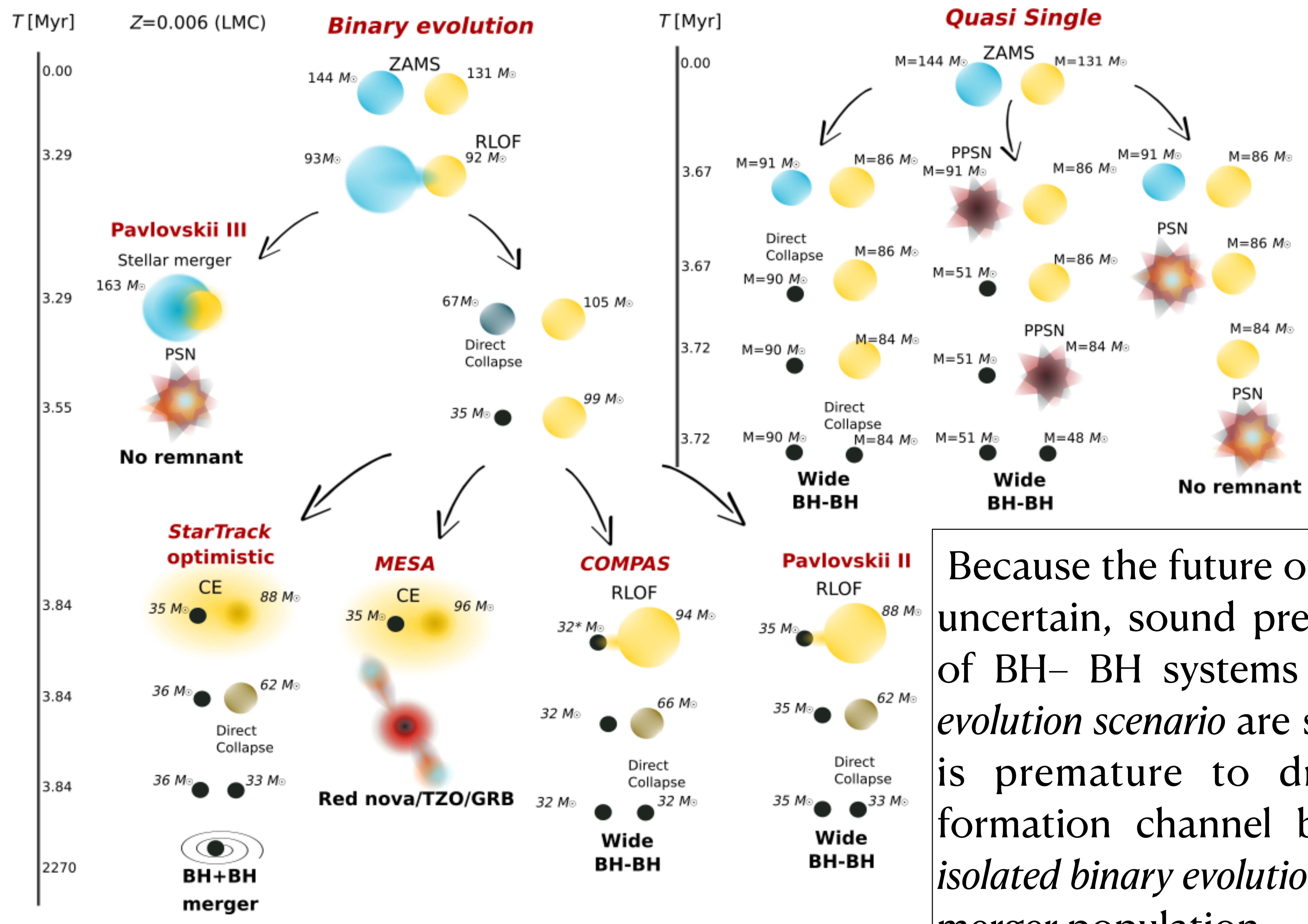


Tehrani et al. 2019

The most massive binary known: $M_a = 139\,\mathrm{M}_\odot$, $M_b = 127\,\mathrm{M}_\odot$, $e = 0.68$, age ~ 0.6 Myr

Calculations starts with a $M_a = 144\,\mathrm{M}_\odot$ and $M_a = 131\,\mathrm{M}_\odot$ stars, so that after 0.6 Myr one gets the Mk34 parameters with $a = 760\,\mathrm{R}_\odot$. LMC metallicity $Z = 0.006$.

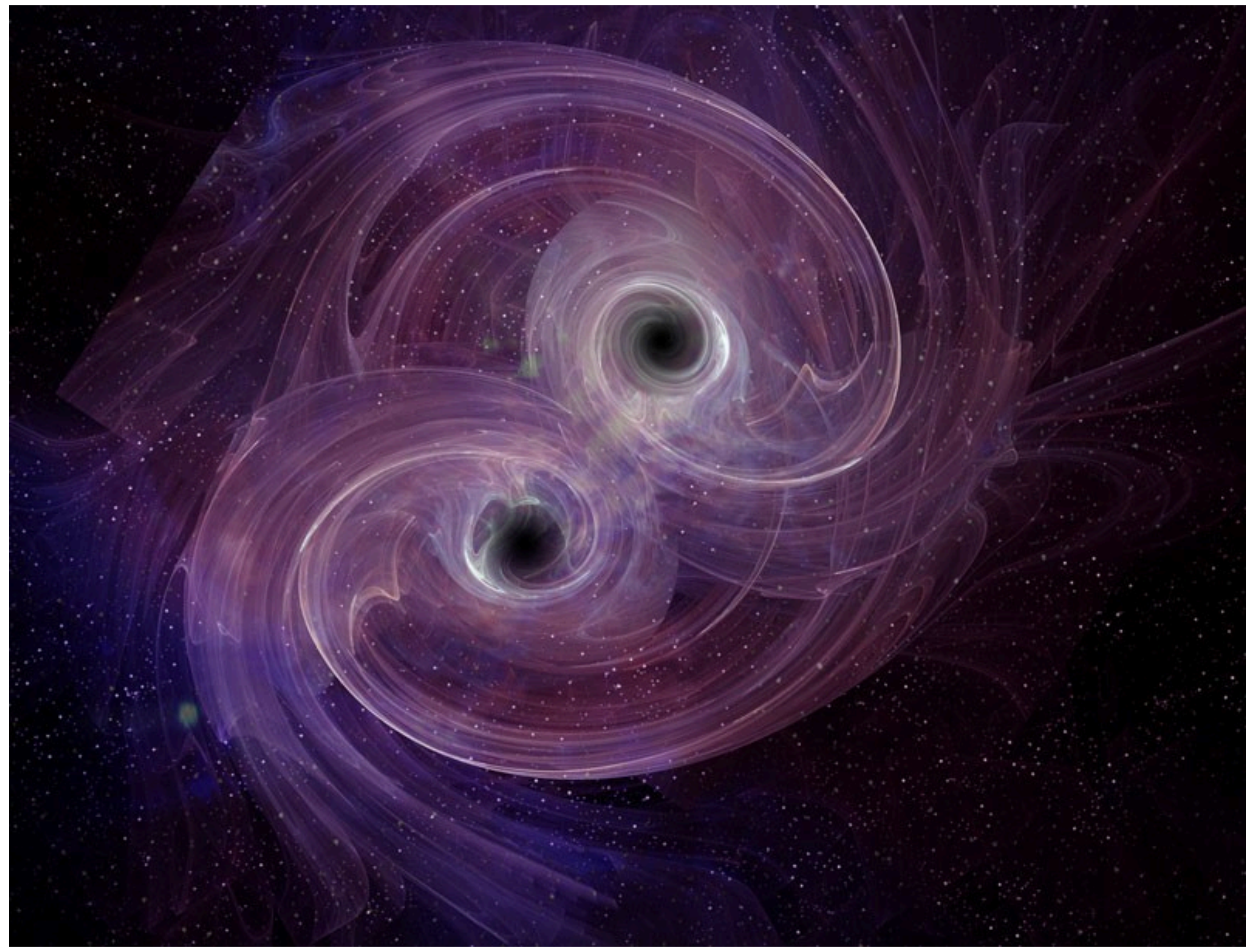
Multiple futures of Mk34: from BHBH merger, through Thorne-Żytkow object to wide BHBH or no remnant (all these with "cutting edge" physics and the best numerical codes



Because the future of massive binaries is inherently uncertain, sound predictions about the properties of BH– BH systems formed in the *isolated binary evolution scenario* are still highly challenging. Thus it is premature to draw conclusions about the formation channel branching ratios that involve *isolated binary evolution* for the LIGO/ Virgo BH– BH merger population.

Belczyński et al. 2022

Merging BH-BH



Masses: $\sim 3 - 100\,\mathrm{M}_\odot$

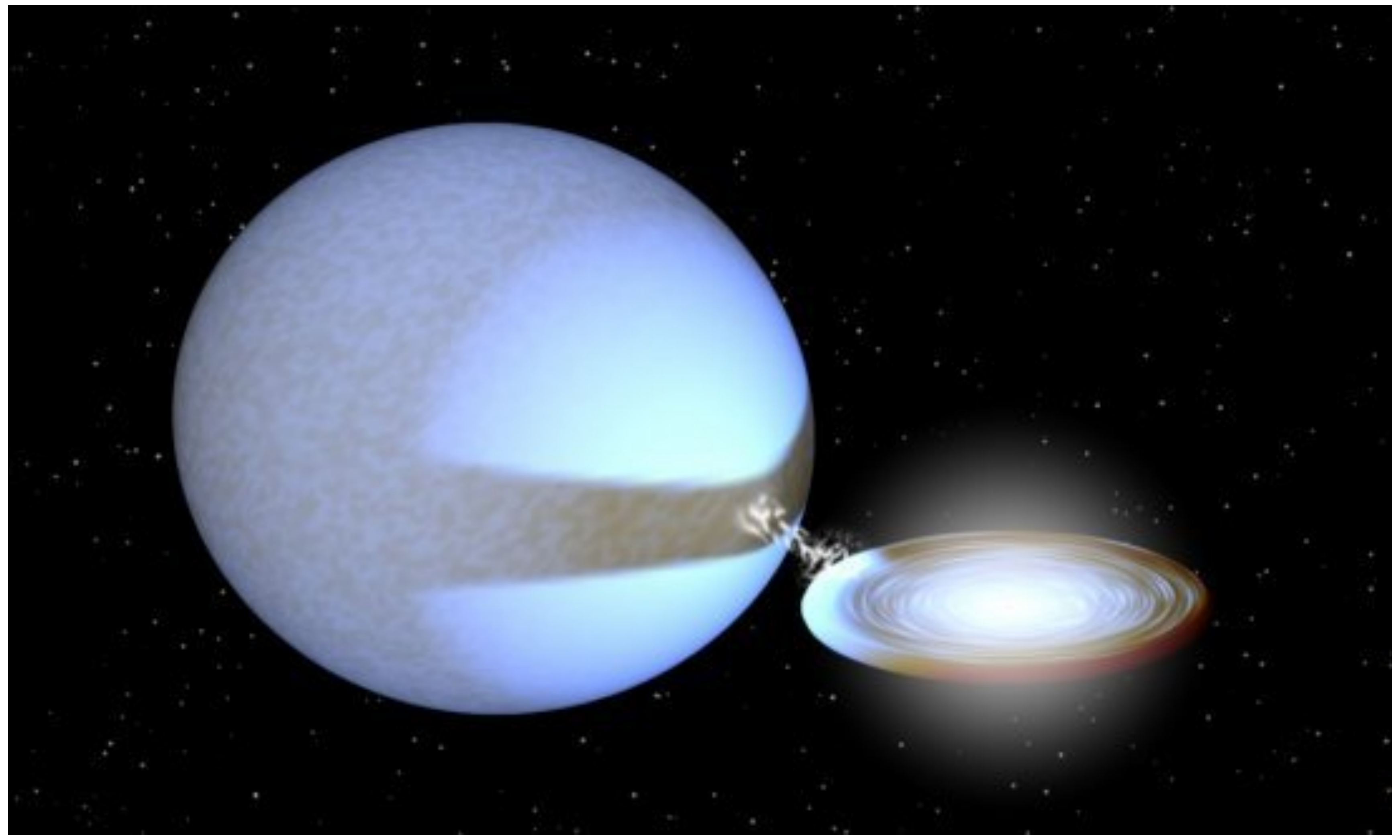
Many primary (more massive) BH with $\sim 10\,\mathrm{M}_\odot$ and $\sim 30\,\mathrm{M}_\odot$, the most massive pair: $\sim 95\,\mathrm{M}_\odot$ and $\sim 69\,\mathrm{M}_\odot$

Low effective positive spins peaking at $\chi_{\rm eff} \approx 0.05$

BH individual spin magnitudes in BH-BH mergers peak at *a*=0.2 (long tail)

High-Mass X-ray binaries

(potential BH-BH mergers)



3 BHHMXBs with companion masses: $\gtrsim 20\,\mathrm{M}_\odot$:

Cyg X-1 $\sim 40\,\mathrm{M}_\odot$; LMC X-1 $\sim 30\,\mathrm{M}_\odot$; M33 X-7 $\sim 70\,\mathrm{M}_\odot$

BH masses - Cyg X-1: $21.2\,\mathrm{M}_\odot$; LMC X-1:$10.9\,\mathrm{M}_\odot$; M33 X-7:$15.7\,\mathrm{M}_\odot$

BH spins - Cyg X-1: *a*>0.93 ; LMC X-1: *a*=0.92; M33 X-7: a=0.84

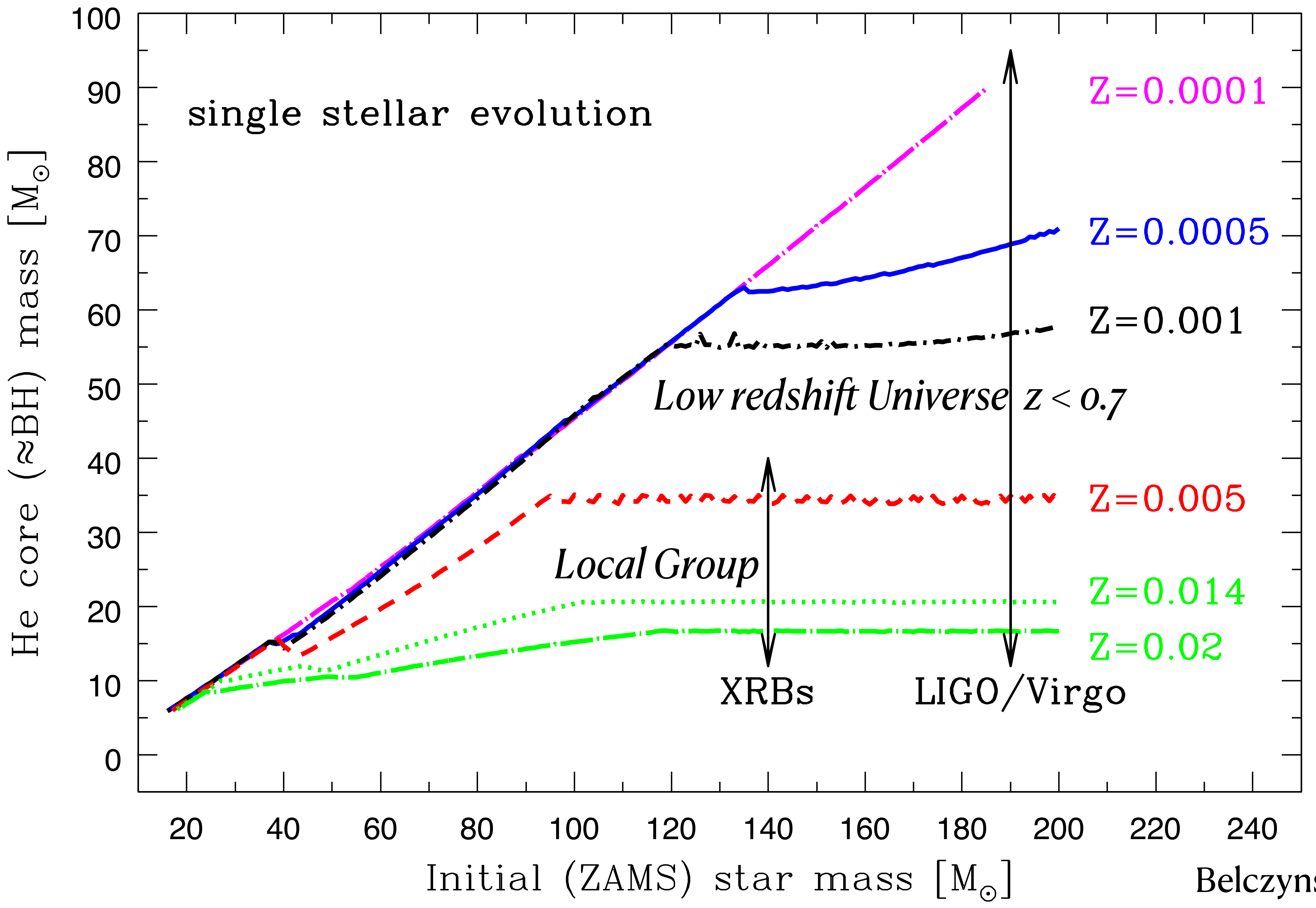
BHHMXB: lower masses, much higher spins then BHBH mergers: different populations ?

Fishbach & Kalogera 2022

- BHHMXB have been observed only in the Local Group: high metallicities ➔ strong stellar winds, "low-mass" He cores that form BHs

- LVC O3 BH-BH have been observed up to z=0.7: large metallicity range, includes very low Z, hence allows high-mass He cores

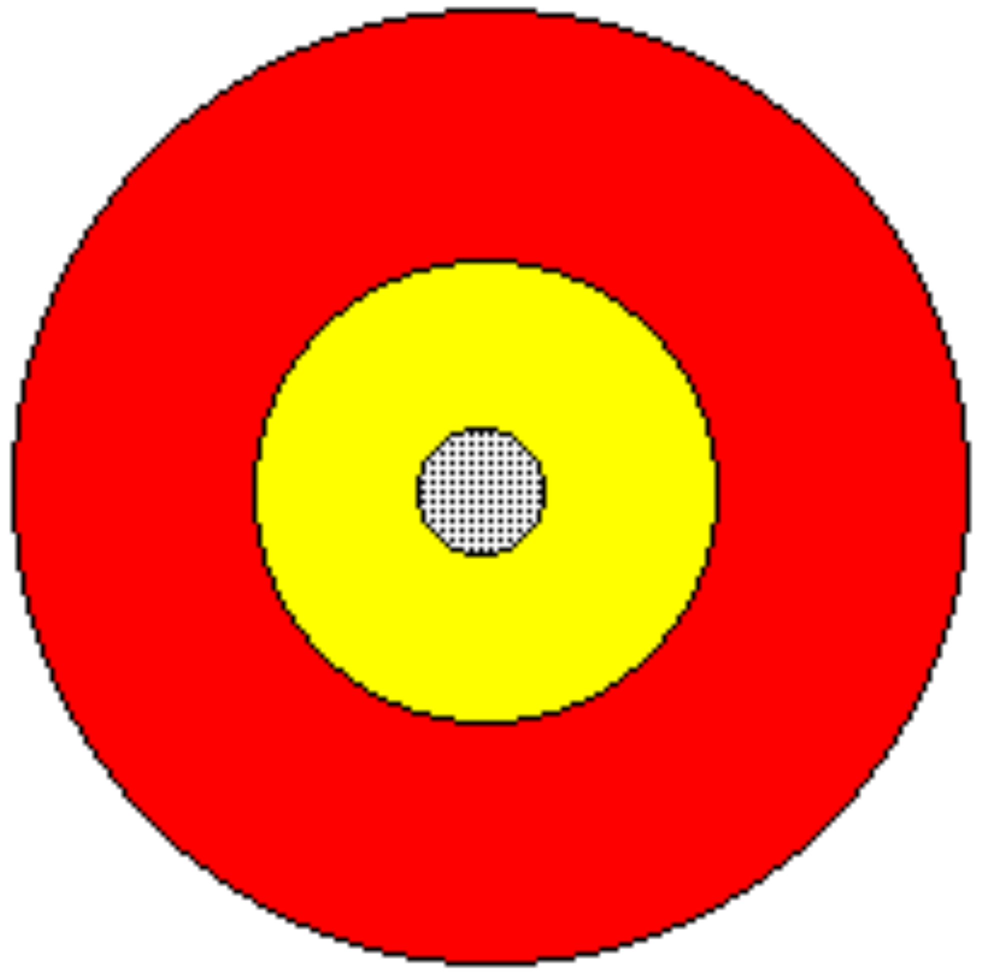
He cores (~ BH masses) calculated with standard **StarTrack**

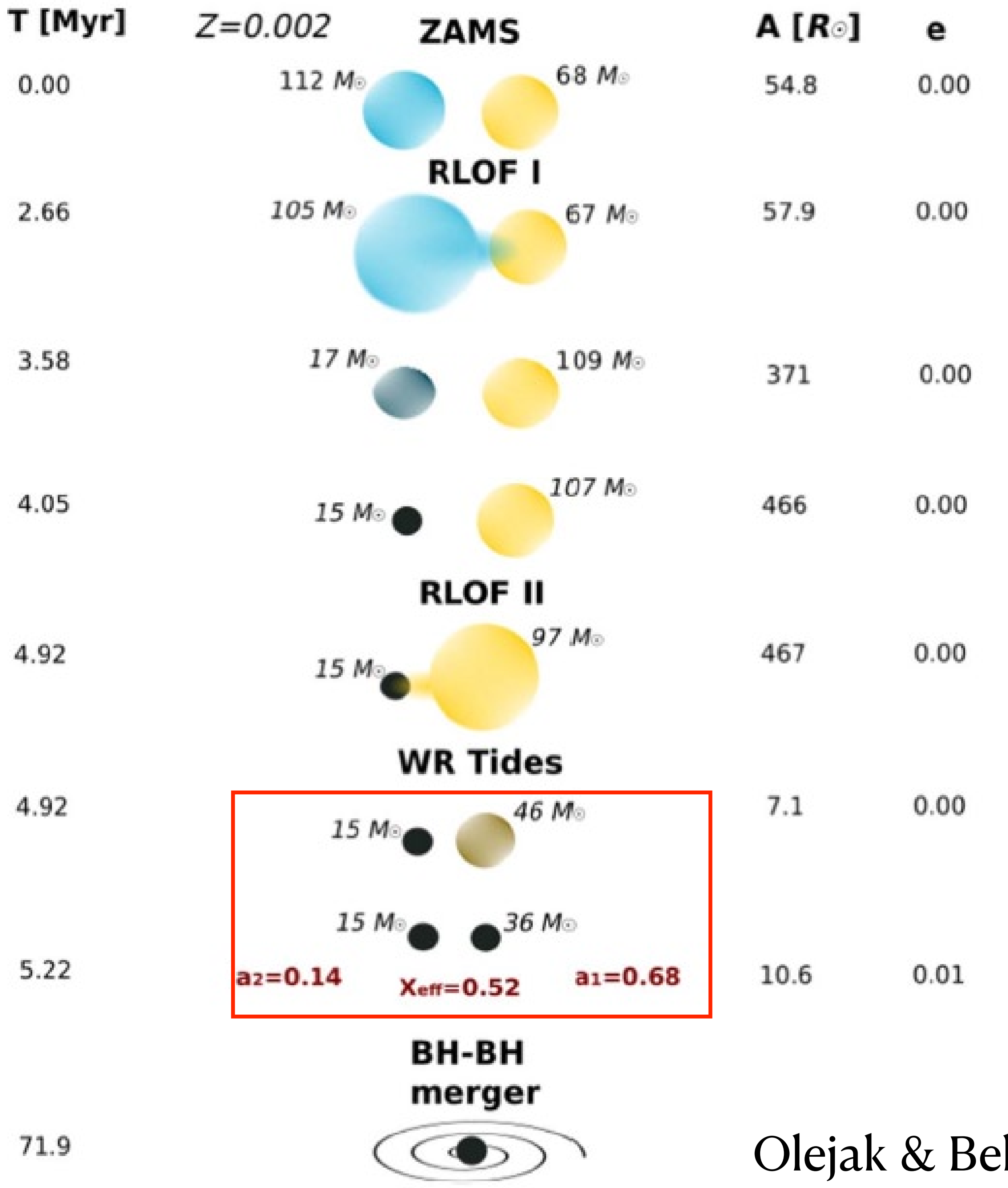


Belczynski, Done, Lasota 2021

Spins

Observations suggest the existence of an efficient mechanism of removing angular momentum from the core (to the envelope), hence low spins of BH formed through core collapse





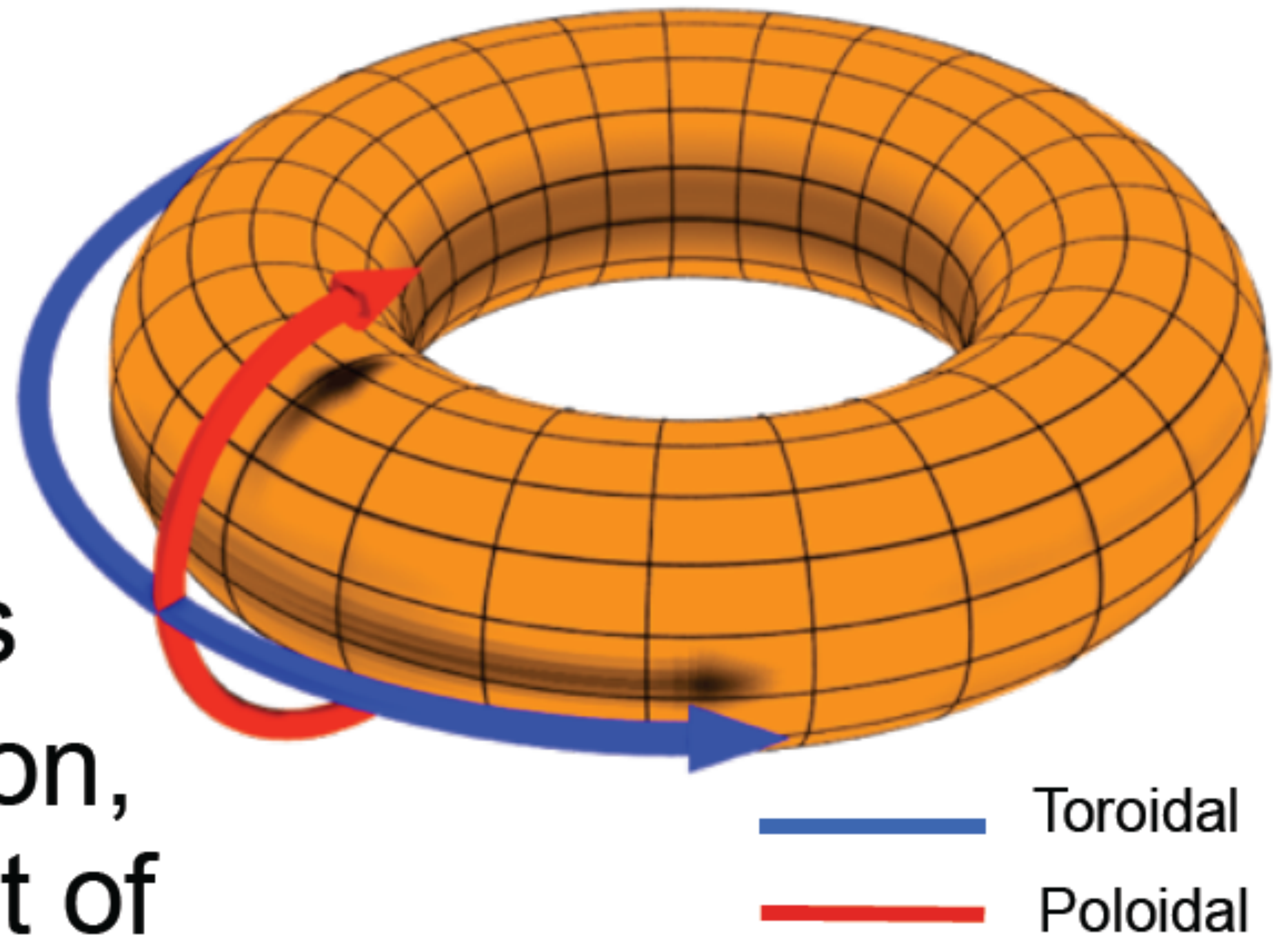
Olejak & Belczyński 2021

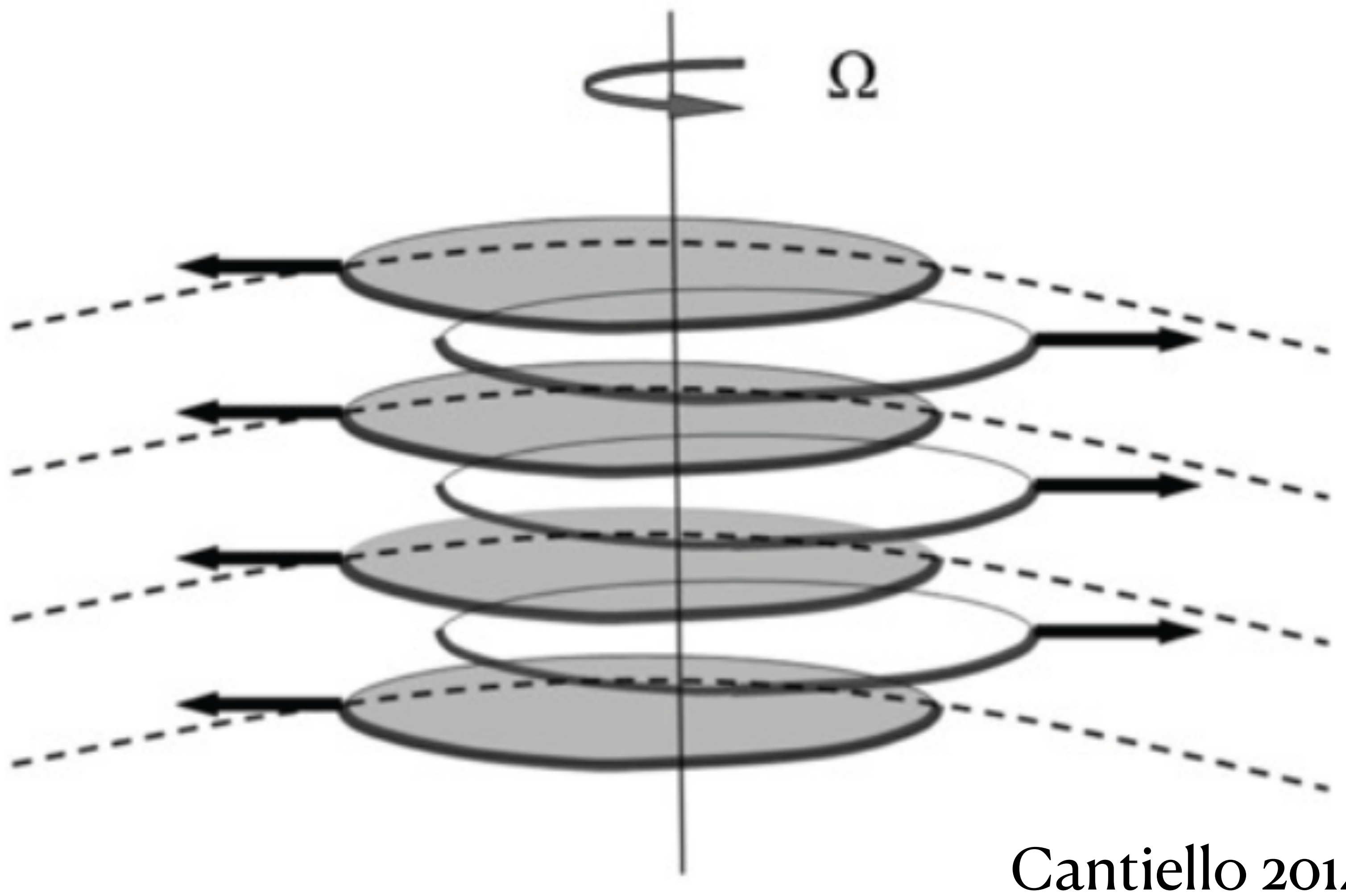
Possibility of spinup of the WR BH-progenitor through tides

The Tayler-Spruit dynamo

- Dynamo in a radiative layer
- Magnetic energy is generated from differential rotation
- Initially a seed magnetic field is stretched by the differential rotation, amplifying the toroidal component of the field
- An instability in the toroidal component of the field (Tayler instability) is used to close the dynamo loop

Spruit 2002

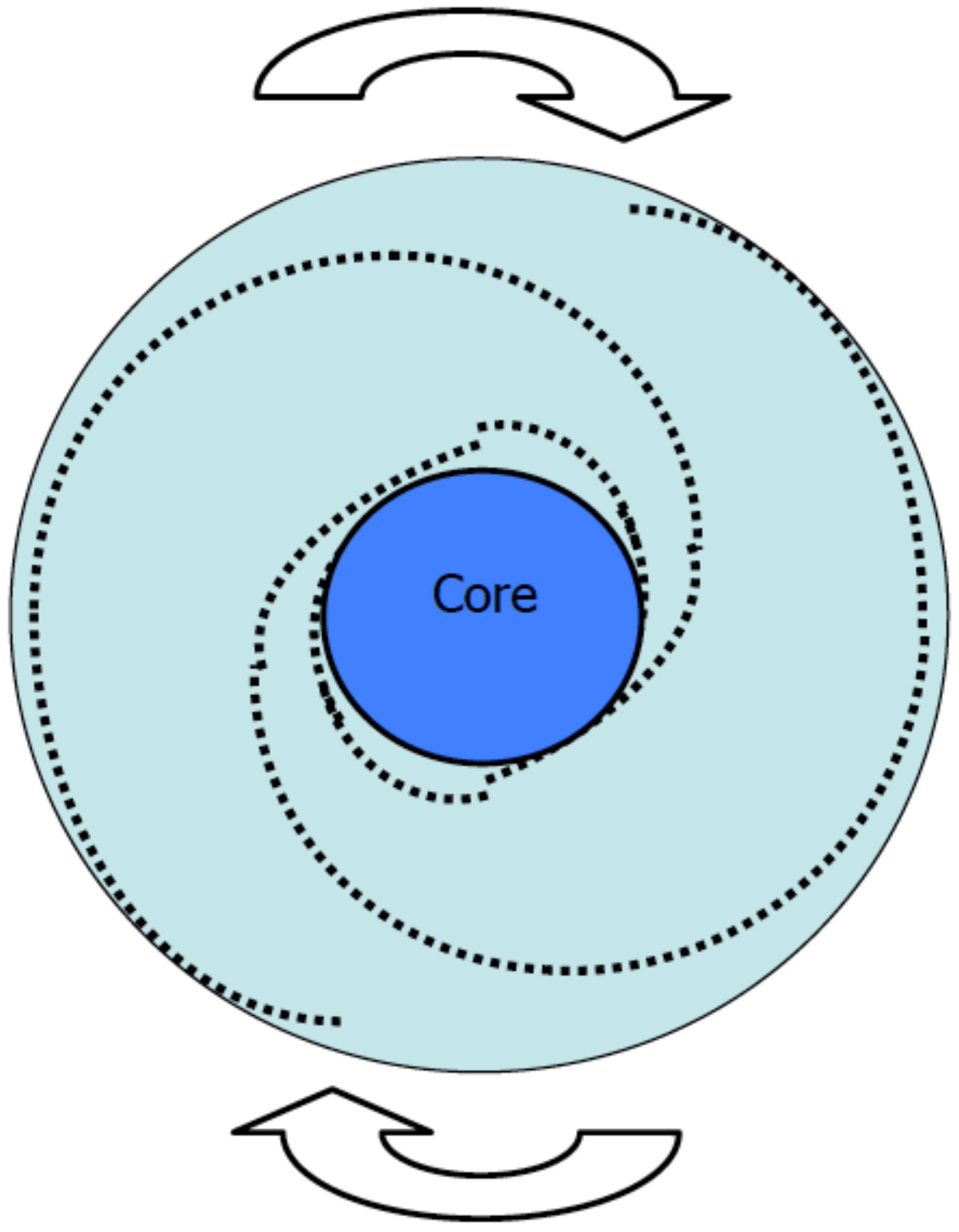




Cantiello 2014

Removing angular momentum from the core (BH progenitor)

- Tayler-Spruit Dynamo (Spruit 2002)
- Core - Envelope coupling



1. Differential rotation winds up toroidal component of B
2. Magnetic torques tend to restore rigid rotation

If the envelope slows down angular momentum is also removed from the core

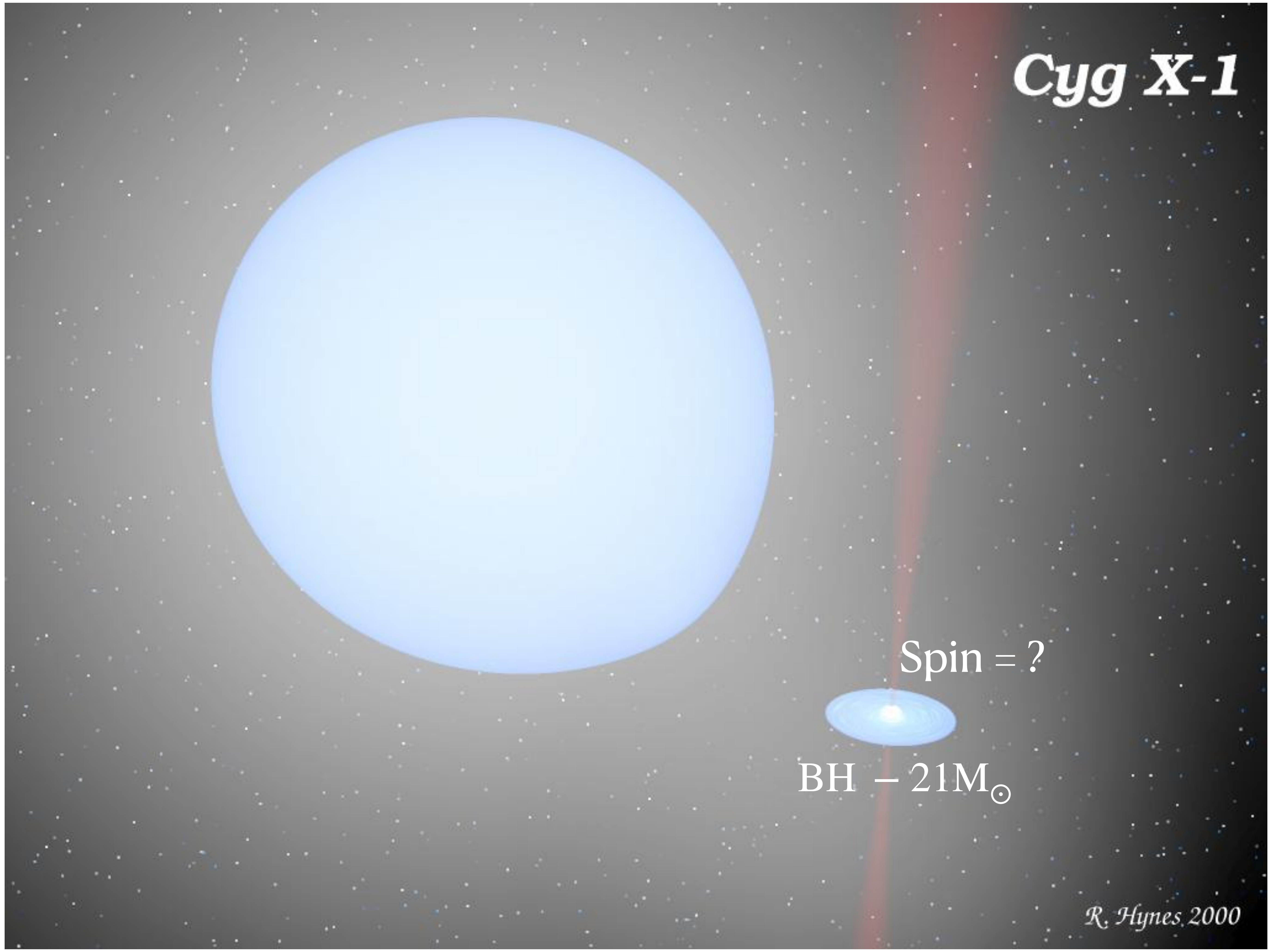
hence BH inherit low spin

Cantiello 2014

<u>Caveat</u>: is TS dynamo universal? Does it really work?

Is used in population syntheses as angular-momentum removal mechanism avatar.

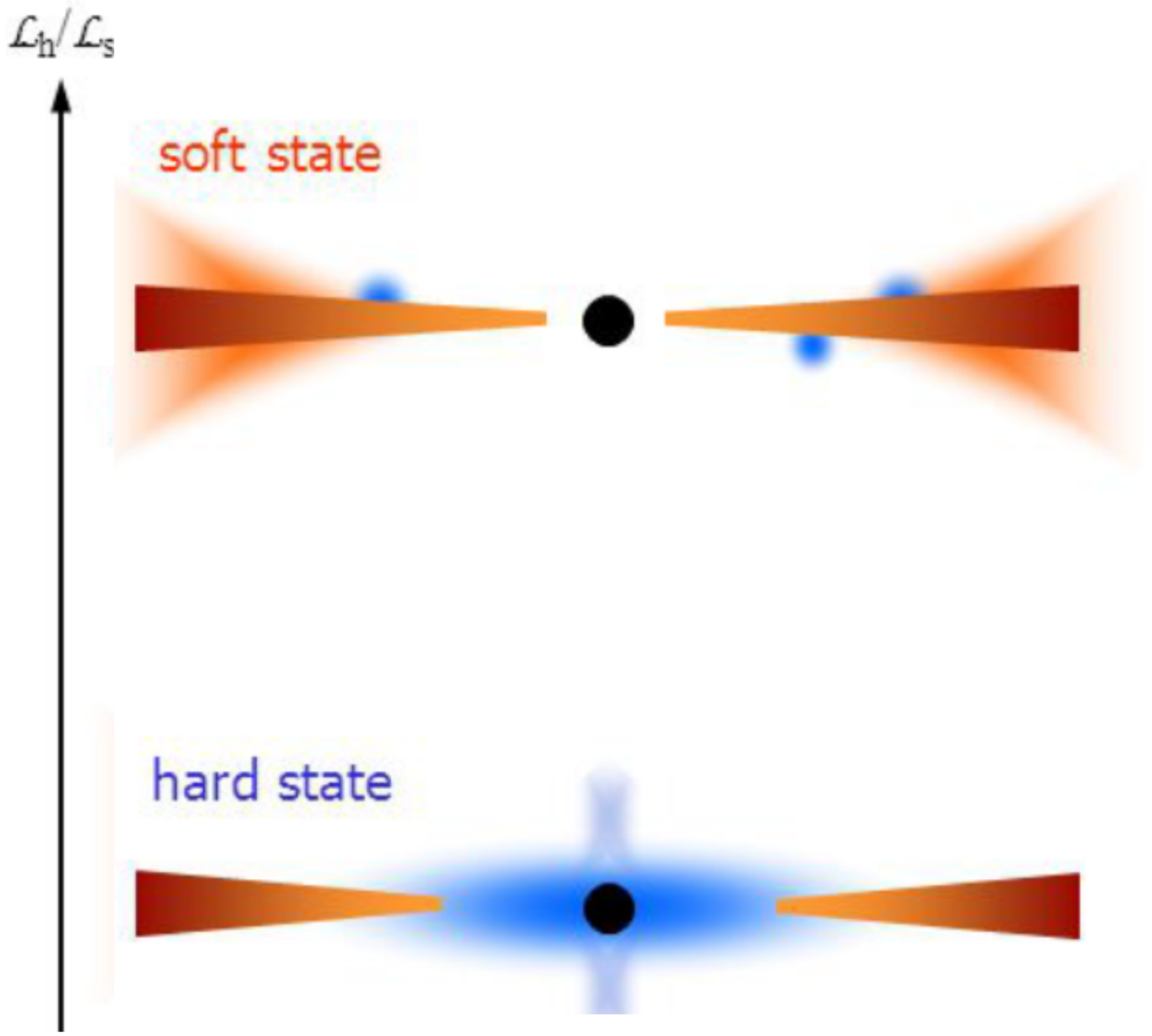
The spin of the Cyg X-1 black hole: is it really high?

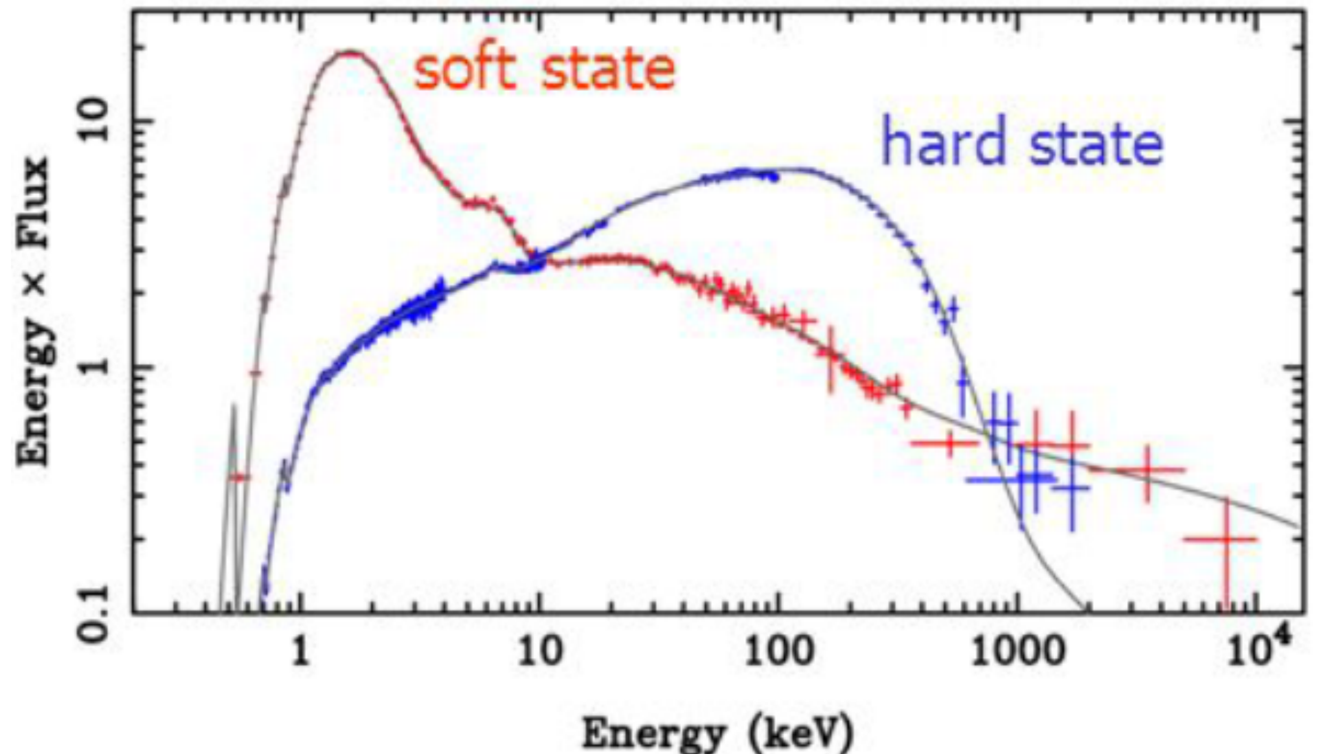


Paczyński (1974): mass of Cyg-1 $> 9.5\ M_\odot$

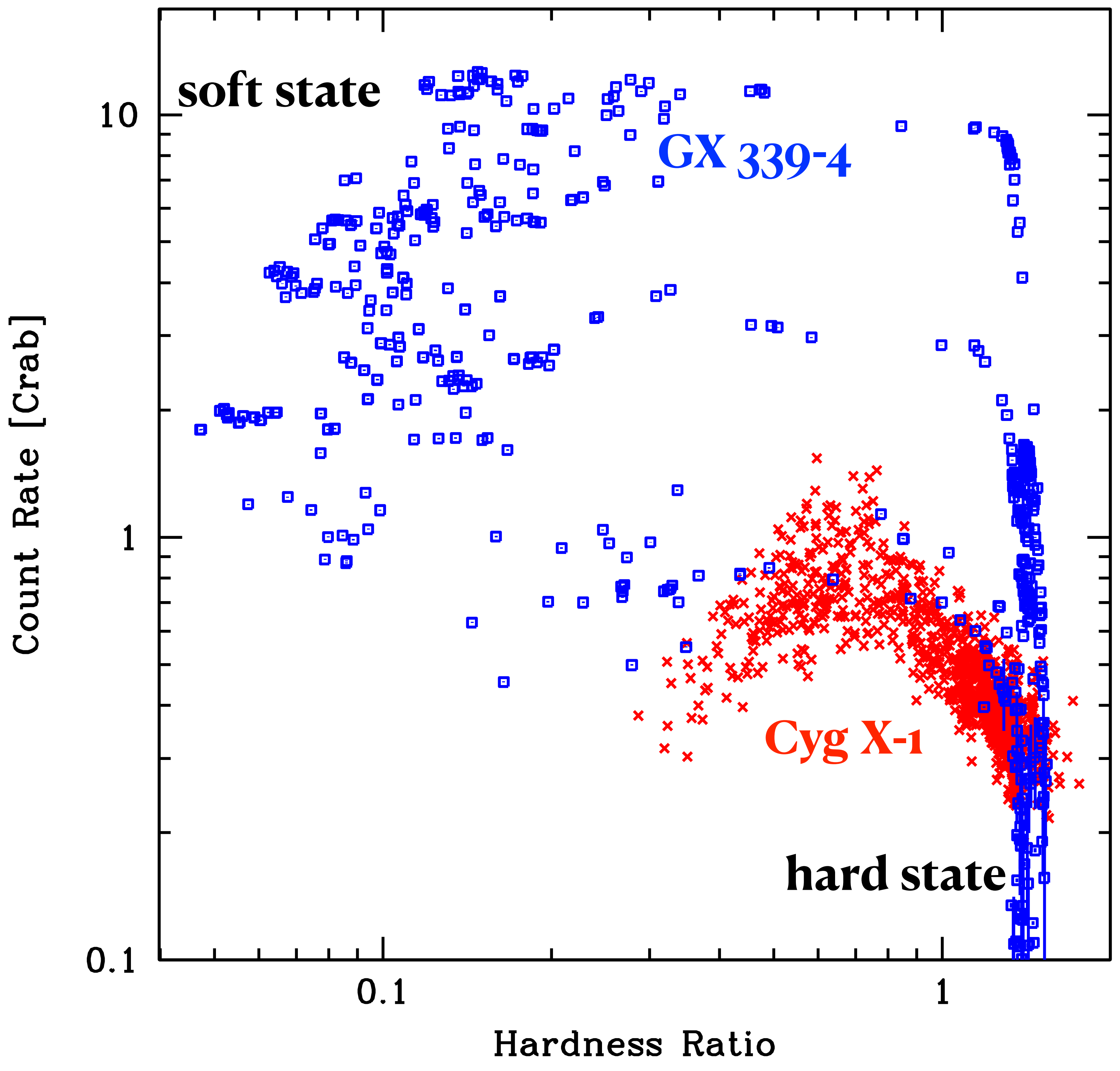
The method used to get *a > 0.98* requires the existence of <u>fully formed accretion disc</u>

Then most of the observed light is emitted by the disc. This is supposed to be happening in the *soft spectral state*





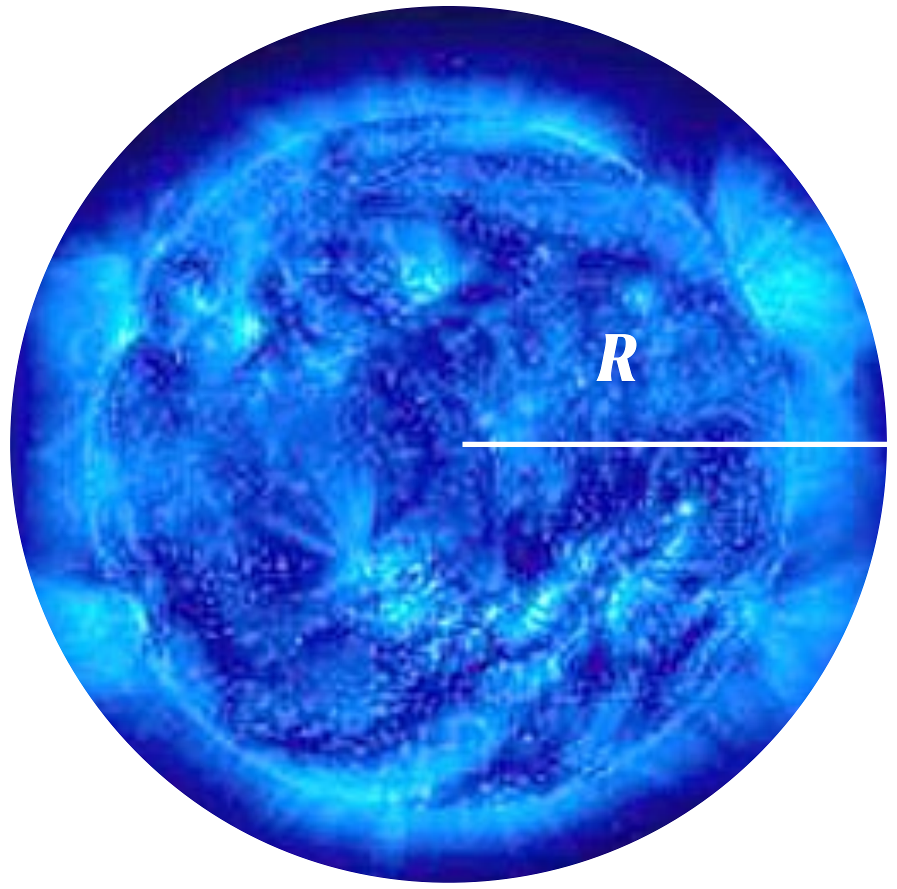
Spectral states of XRBs



Cyg X-1 is never in a *soft state*

From the measured flux *F* and temperature (spectra) on can get the radius

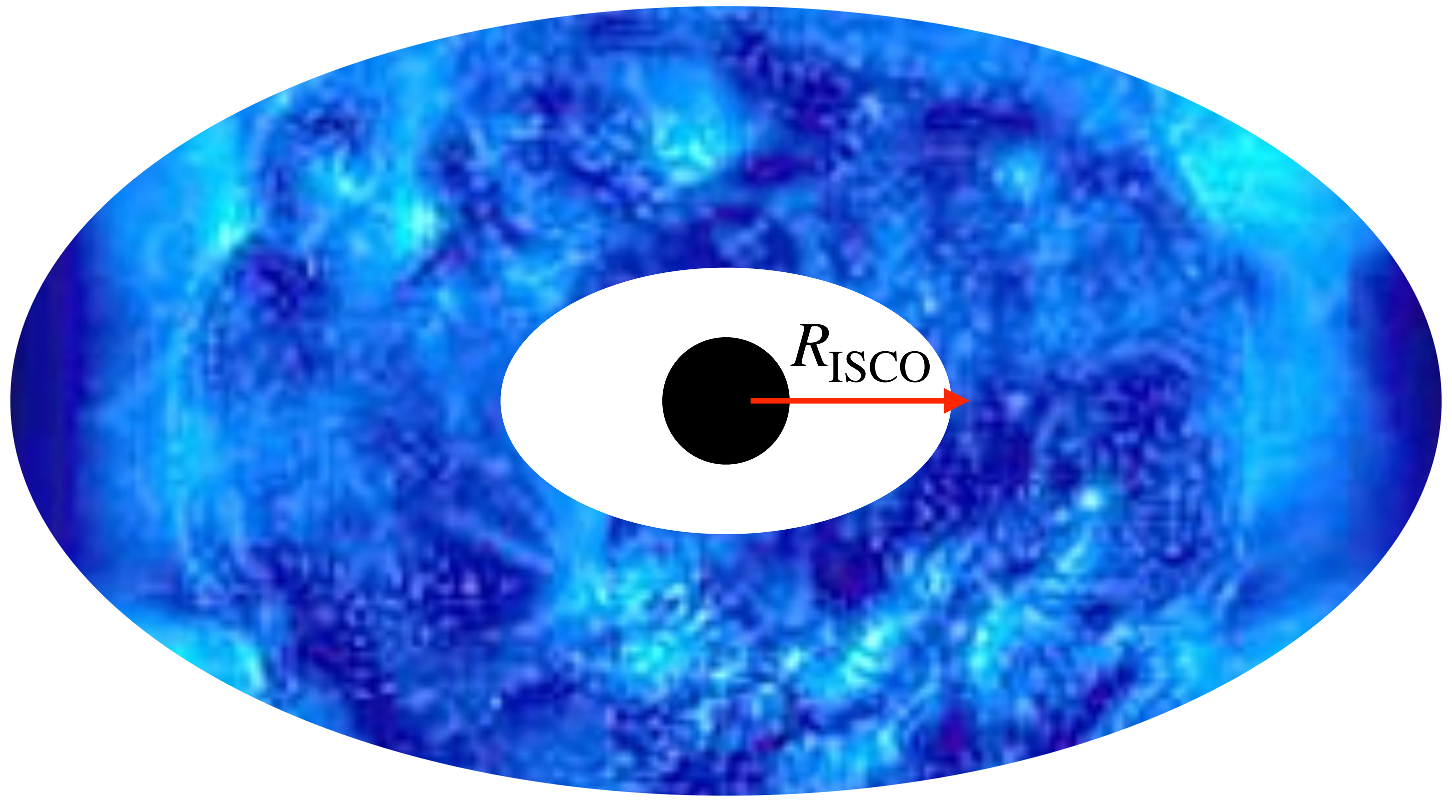
of a star



$$L = 4\pi D^2 F = 4\pi R^2 \sigma T^4$$

$$R^2 = \frac{F}{4\pi\sigma T^4} D^2$$

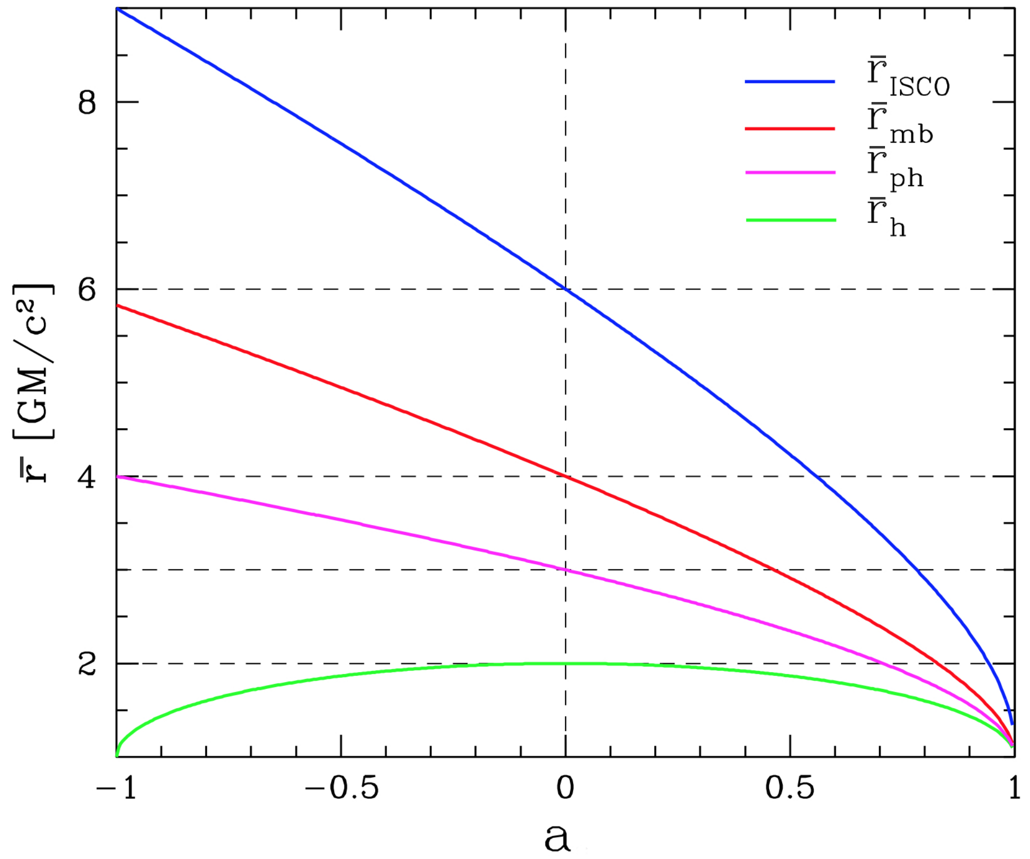
of the inner disc edge



$$L = 2\pi D^2 \gamma(i,a)^{-1} F \approx 4\pi R_p^2 T_p^4$$

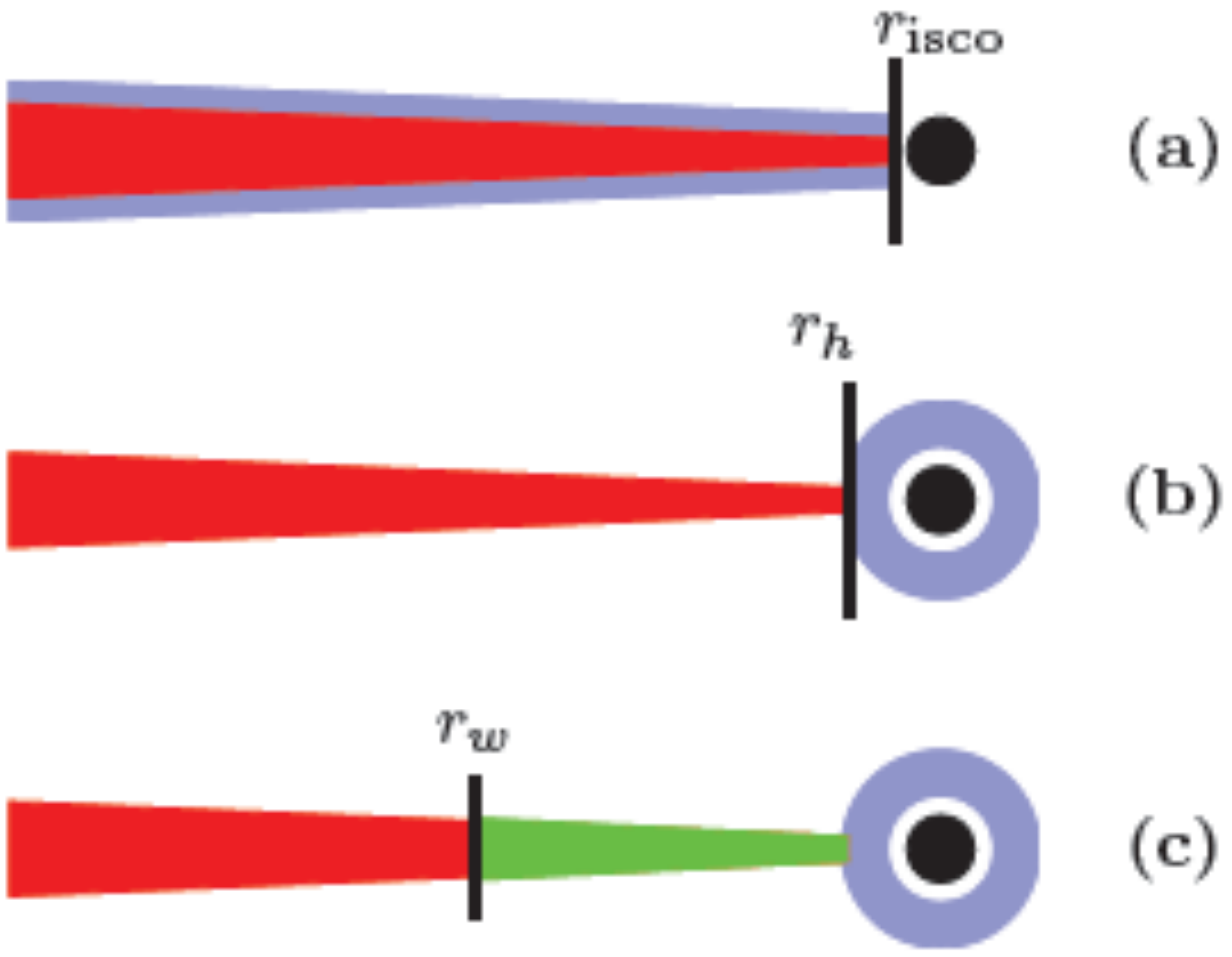
$$R_{\rm ISCO}^2(M,a) = \epsilon(a)^2 D^2 \left[\frac{F}{2\sigma\gamma(i,a)}\right] \left[\frac{f_{\rm col} f_{\rm GR}(i,a)}{T_c}\right]^4$$

From $R_{\rm ISCO}$, knowing the BH mass, one obtains the value of *a:*

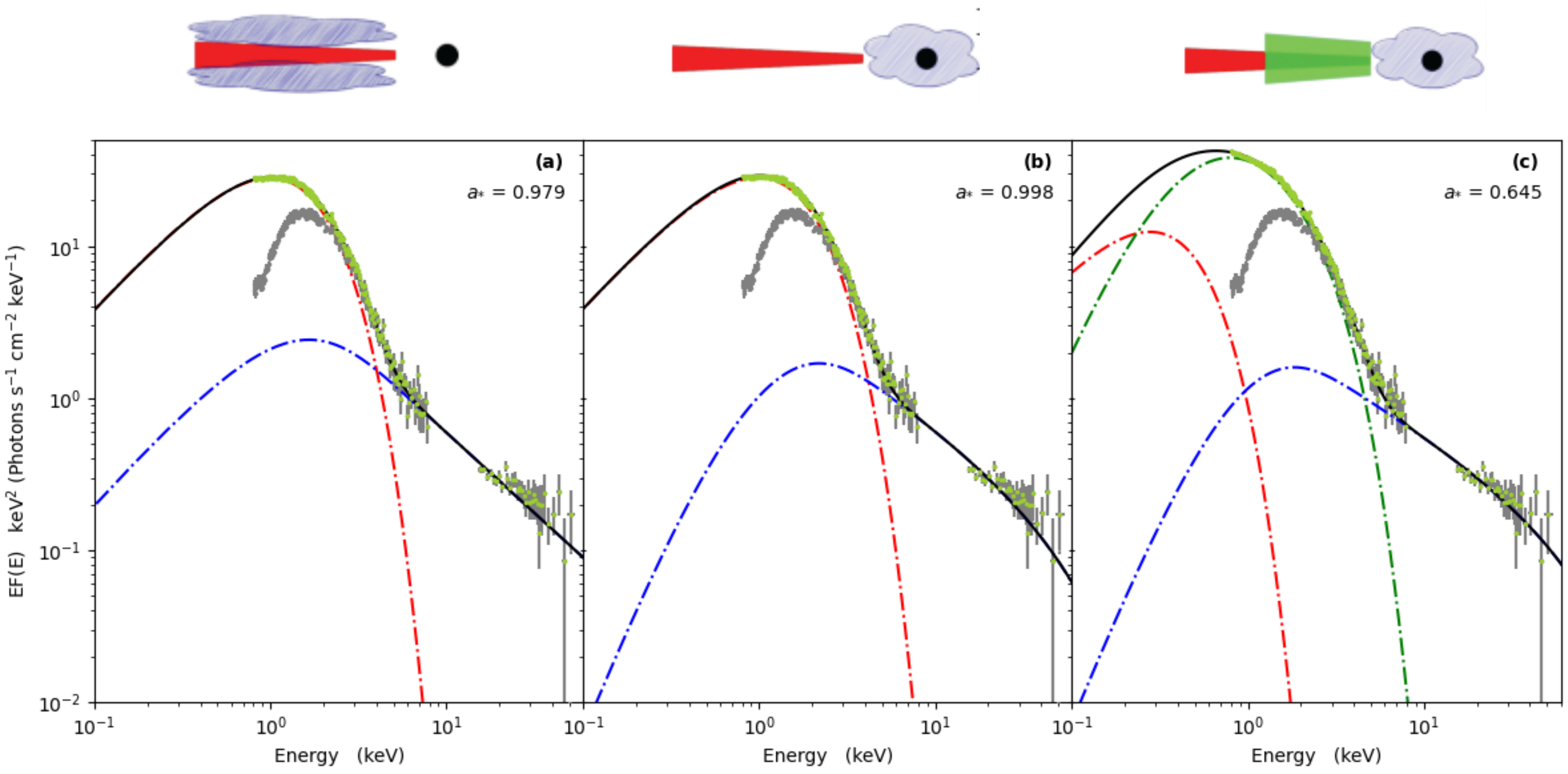


Courtesy Aleksander Sądowski

Three possible disc structures for Cyg X-1 in an intermediate state



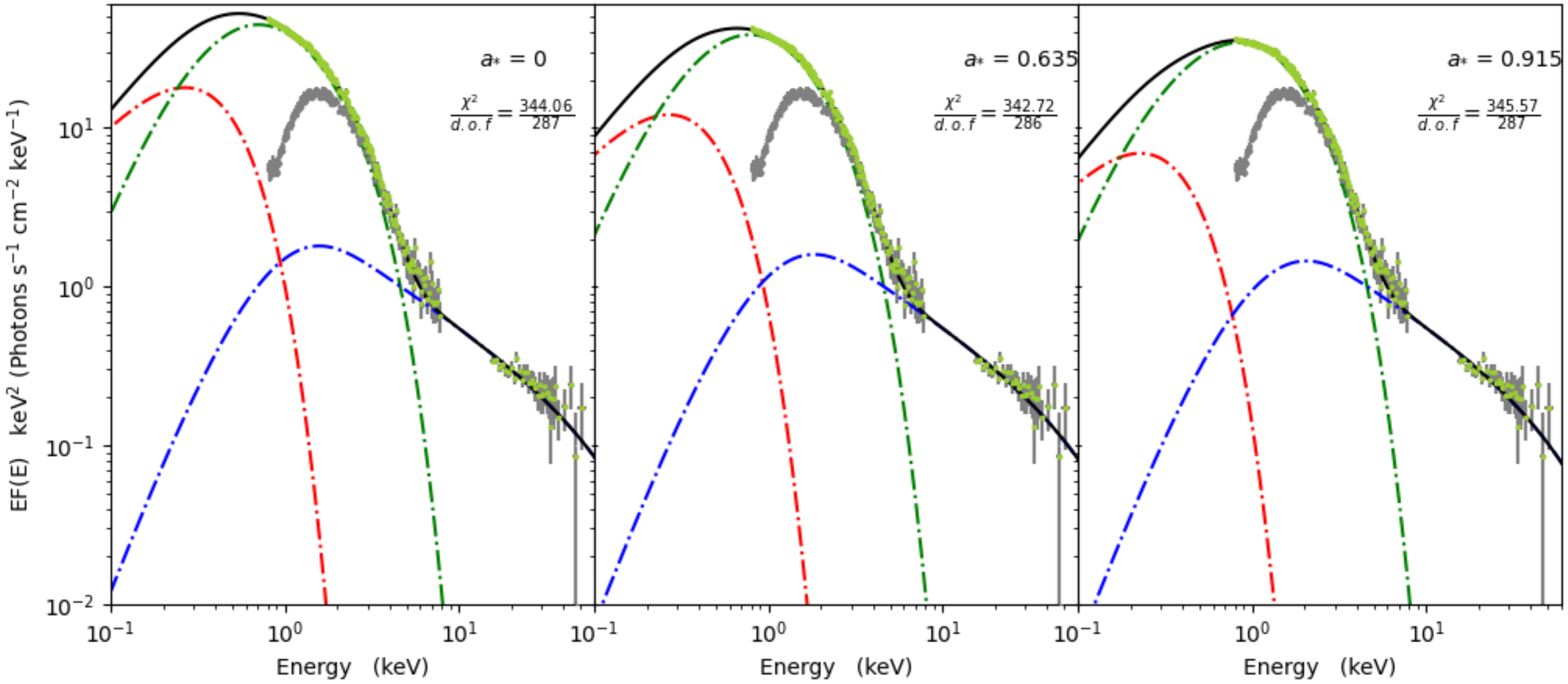
Determining the Cyg X-1 BH spin:



$a_* = 0.979$ $a_* = 0.998$ $a_* = 0.645$

Belczyński et al. 2022 - in preparation

For model (c) one gets comparable fits giving *a* from 0.0 to 0.9



Belczyński et al. 2022 - in preparation

Conclusions

- The available information (or lack thereof) is consistent with LIGO/Virgo BHs and HMXB BHs being the same population.
- However, if the BH spins in HMXBs were really high, this would not imply the existence of two populations, but would indicate a fundamental lack of understanding of the formation of BHs in massive binaries, since there is no known way of spinning up the progenitor of the first-formed BH.
- On the other hand one should stress that, although we know for certain that field XRBs result from isolated binary evolution, no evolutionary scheme has been able to reproduce their observed properties (e.g. mass distribution, see Wiktorowicz et al. 2014). Therefore drawing conclusions about the nature of XRBs and LIGO/Virgo BH-BH merger populations based on their masses and spin values is premature.

Binary black-hole astrophysics is still in infancy but it would never have been born if it were not for the theorem of Brandon and his colleaugues