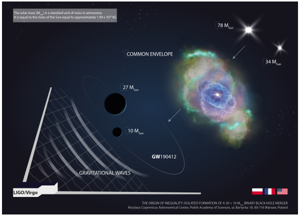
Formation of BH-BH mergers as informed by LIGO/Virgo/KAGRA detections of GWs



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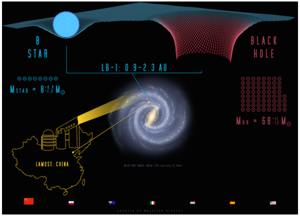
J.Klencki, C.Miller
C.Fryer, T.Bulik
D.Holz, R.Hirschi
A.Matamala, J.-P.Lasota, et al.



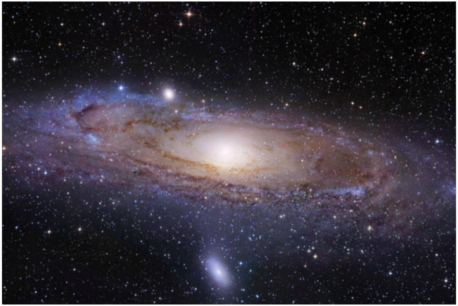
– O1/O2/O3 mergers (rates): 69 BH-BH, 4 BH-NS, 2 NS-NS, 1 ?

– BH masses ($2 - 100\ \mathrm{M}_\odot$): decline with M and peaks at $8\ \mathrm{M}_\odot$ and $35\ \mathrm{M}_\odot$

– BH spins ($50\% : a < 0.25$): mostly small and aligned (with exceptions)

major formation scenarios: stars

isolated binaries:



– spirals, ellipticals, dwarf galaxies
– stellar/binary evolution
– 99% of stars
– formation efficiency: $X_{\rm BHBH} \approx 10^{-6}$

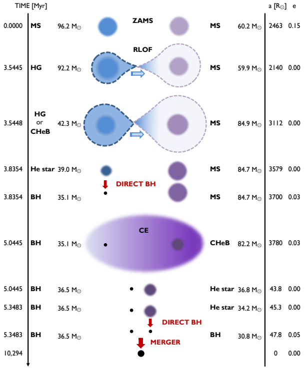
dynamical interactions:

– globular, nuclear, open clusters
– dynamics + stellar/binary evolution
– 0.1% of stars
– formation efficiency: $X_{\rm BHBH} \approx 10^{-4}$

+ some exotica: triple stars, single stars, binaries in AGN disks, primordial BHs

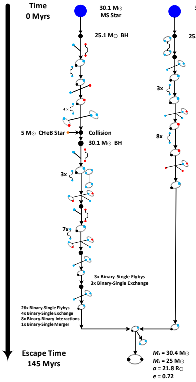
GW150914: $30 + 30\ M_\odot$ massive BH-BH merger

binary evolution



credit: W.Gladysz – StarTrack simulation

dynamics/globular clusters

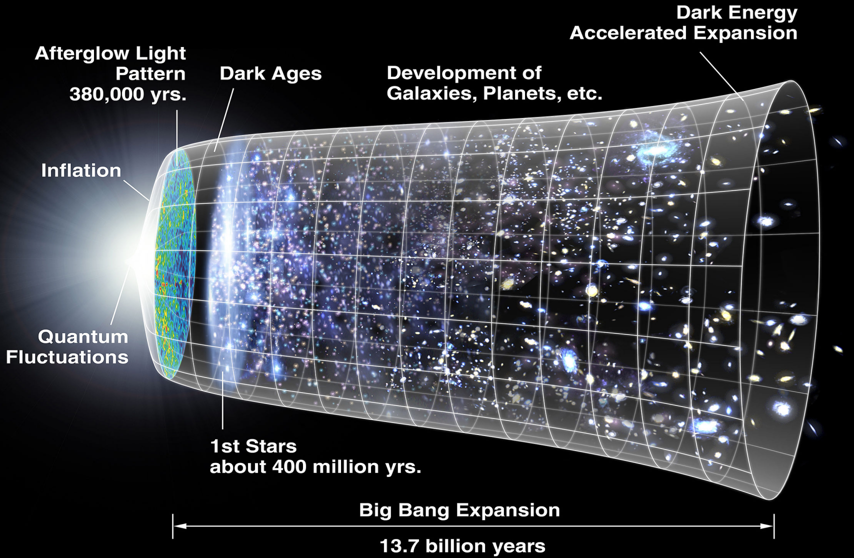


credit: A.Askar – MOCCA simulation

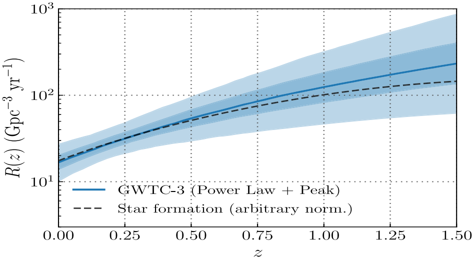
1) binary evolution and dynamics: can produce massive BH-BH mergers

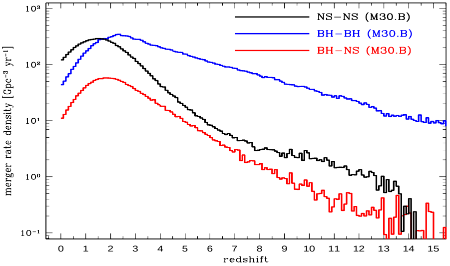
2) because of (1): the origin of BH-BH mergers unknown...

modeling: synthetic universe



Merger rates: LIGO vs models





LIGO merger rates:

NS-NS: $10 - 1700\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-NS: $8 - 140\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-BH: $18 - 44\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ $(z = 0.2)$
(increase with redshift)

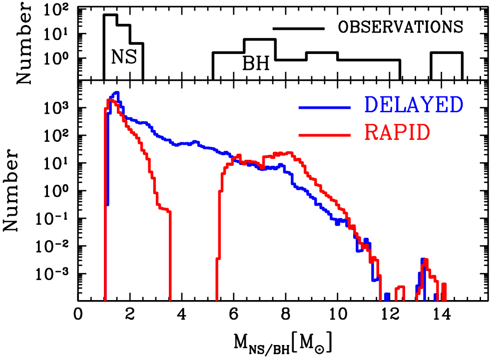
Stellar-origin mergers: binary evolution

NS-NS: $50 - 120\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-NS: $0.5 - 97\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-BH: $1.1 - 469\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Stellar-origin mergers: dynamical origin

NS-NS: $\sim 0\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-NS: $\sim 0\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH-BH: $\lesssim$ *few* – *tens* $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Stellar-origin BH masses: $\sim 2 - 100 M_{\odot}$



NS/BH mass spectrum (pre-LIGO):

neutron stars:	$1 - 2$ M$_\odot$
lower mass gap:	$2 - 5$ M$_\odot$
black holes:	$5 - 50$ M$_\odot$
upper mass gap:	$50 - 130$ M$_\odot$
black holes:	$130 - ???$ M$_\odot$

lower mass gap: core-collapse SN

– rapid explosions: $\sim$ 0.1s (yes)

– delayed explosions: $\sim$ 1s (no)

+ claims of very massive BHs:

– NGC300 X-1: 20 M$_\odot$

– IC10 X-1: 30 M$_\odot$

– LB-1: 70 M$_\odot$

that were questioned and forgotten

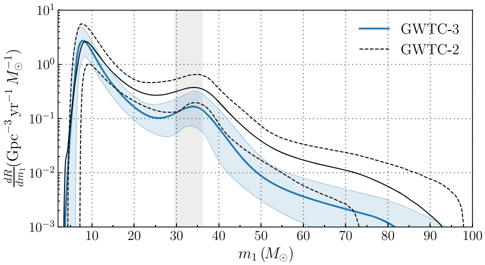
upper mass gap: pair-instability SN

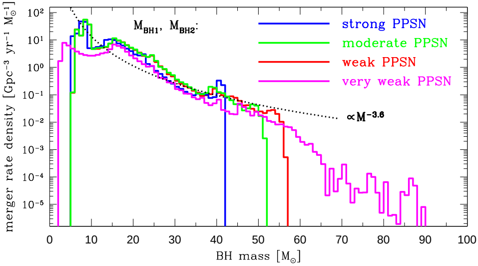
– explosive oxygen burning

– envelope removal or disruption

(convection, mixing, reaction rates)

BH masses: LIGO vs models





LIGO BH mass spectrum:

neutron stars: $1 - 2$ M$_\odot$
lower mass gap: no evidence
black holes: $2.6 - 95$ M$_\odot$
upper mass gap: no evidence

– rapid decrease with $M_{\rm BH}$

– two peaks: 8 M$_\odot$, 35 M$_\odot$ (real?)

Stellar-origin BHs: binary evolution

– rapid decrease with $M_{\rm BH}$

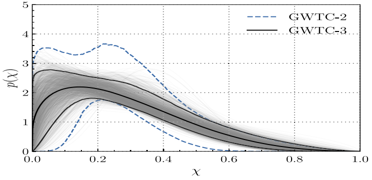
– no obvious peaks

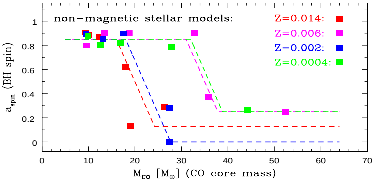
– range: adjustable up and down

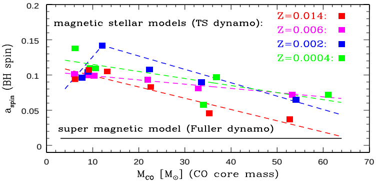
comparison/matching data:

potential of learning lots of physics

BH spins: LIGO vs stars







LIGO BH individual spins ($a = (c\,J)/(G\,M^2)$) :

peak: $a = 0.13^{+0.12}_{-0.11}$ (!)
median: $a = 0.25$
tail: a -> 0.9
highly uncertain estimates: small spins

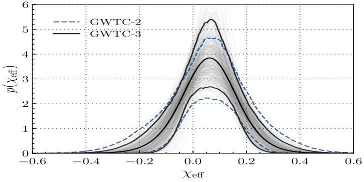
Stellar-origin (single) BH spins:

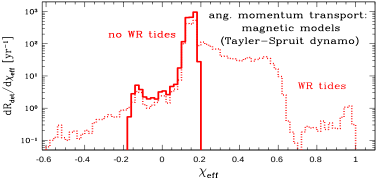
– begin with (single) rotating star
– apply angular momentum transport
– remove ang. momentum with winds
– collapse core/star to a BH

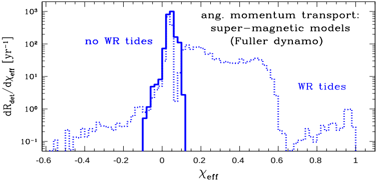
Results:

1) non-magnetic model: $a \sim 0 - 0.9$
2) magnetic model: $a \sim 0.05 - 0.15$
3) super magnetic model: $a \sim 0.01$

BH-BH effective spin parameter: $\chi_{\rm eff}$







LIGO BH-BH effective spins:

$$\chi_{\rm eff} = (M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2)/(M_1 + M_2)$$

peak, mean: $\chi_{\rm eff} = 0.05$, $\chi_{\rm eff} = 0.06^{+0.04}_{-0.05}$

positive/negative: 71% / 29% ($\pm$15%)

asymmetric distr.: mostly small positive $\chi_{\rm eff}$

Stellar-origin BH-BH effective spins:

– accretion onto BHs ($\sim$ no effect)

– natal kicks (negative $\chi_{\rm eff}$)

– tidal spin-up (high positive $\chi_{\rm eff}$)

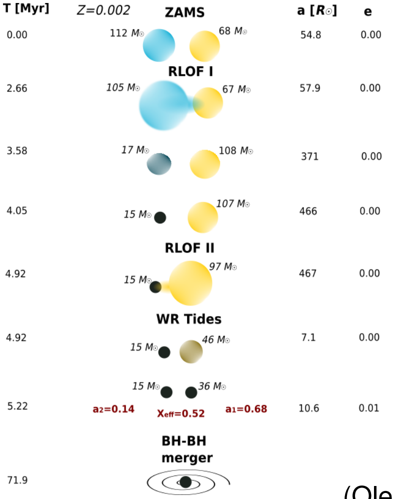
Results:

1) both: asymmetric with small positive $\chi_{\rm eff}$

2) super magnetic model: peak at $a \sim 0.05$

3) magnetic model: better overall statistics

Making rapidly spinning Black Holes



LIGO/Virgo: 76 BH-BH mergers

(1) 68: low effective spins $0 < \chi_{\rm eff} < 0.3$

(2) 7: high effective spins $\chi_{\rm eff} > 0.3$

(3) 1: negative effective spin $\chi_{\rm eff} < 0$

(4) 1: high primary BH spin $a \approx 0.9$

Non-Classical Isolated Binary Evolution
(magnetic model: Tayler-Spruit dynamo)

(1) low effective spins: $\sim 70 - 90\%$

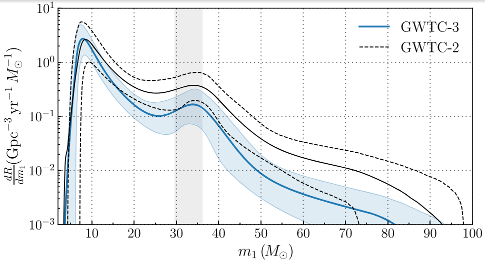
(2) high effective spins: $\sim 10 - 30\%$

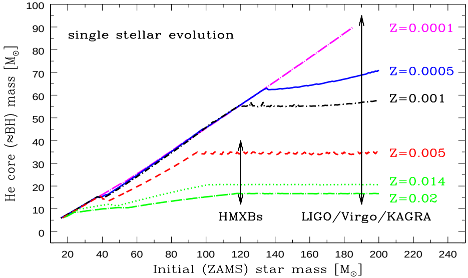
(3) negative effective spins: $\sim 3 - 7\%$

(4) high primary BH spin: $\sim 1\%$

(Olejak & Belczynski 2021: ApJ Lett. 921, L2)

LIGO – High-mass X-ray Binary (HMXB) tension





LIGO BHs:

BH masses: $\sim 2 - 100\ \mathrm{M}_\odot$

BH spins: $a \lesssim 0.25$

HMXBs: LMC X-1, M33 X-7, Cyg X-1

BH masses: $11,\ 16,\ 21\ \mathrm{M}_\odot$

BH spins: $a = 0.92,\ 0.84,\ 0.99$

companion mass: $30,\ 70,\ 40\ \mathrm{M}_\odot$

(LMC X-3 BH: $7\ \mathrm{M}_\odot$, $a \sim 0.2 - 0.3$, but $M_{\mathrm{comp}} \sim 4\ \mathrm{M}_\odot$)

is there LIGO-HMXB data tension?

possibly not...

1) BH masses:

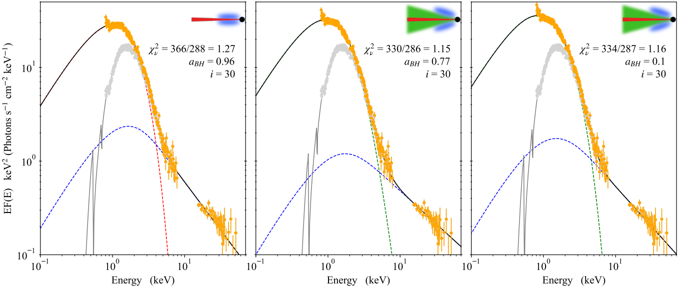
– HMXB: local galaxies high Z ($\sim$ *Mpc*)

– LIGO: broad Z range ($\sim$ *Gpc*)

LIGO – High-mass X-ray Binary (HMXB) tension

2) BH spins: overestimated in HMXBs?

BH spin from spectral fitting depends sensitively on modeling (Cyg X-1):



–for Cyg X-1: spins in broad range found, low spin allowed $a \sim 0.1$

–for LMC X-1: similar analysis also allows for low spin $a \sim 0.2$

–for M33 X-7: poor data, and no alternative analysis was yet performed

tension: not really apparent if we allow for low BH spins in HMXBs

Summary

(1) BH-BH/BH-NS/NS-NS merger rates can be explained by: isolated binaries

(BH-BH merger rates alone: by many models)

(2) BH masses explained easier by: dynamical evolution

(yet, high mass BHs can not be excluded in binary evolution)

(3) BH spins explained: by some mixture of isolated binaries and dynamics

(majority of spins small and positive, but some negative...)

(4) the origin of LIGO/Virgo BH-BH mergers: remains an open issue

– do we even have a full list of formation channels?

– is there one dominant channel or several channels?

– do BH-BH and NS-NS have the same dominant channel?

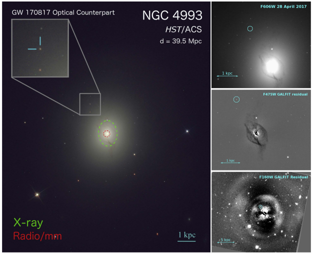
NGC 4993: GW170817 host galaxy star formation

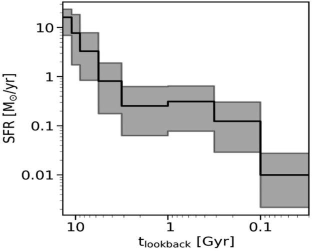
NS-NS merger with kilonova: $\sim 1.5\,M_\odot + 1.3\,M_\odot$

NGC 4993:

- medium size elliptical galaxy: at 40 Mpc
- stars at near-solar metallicity: $Z \approx 0.01$
- total star forming mass: $7.9 \times 10^{10}\,M_\odot$
- peak of star formation rate: 11 Gyr ago
- extra (?) episode of SFR: 0.5-1 Gyr ago (but only $< 1\%$ of total SFR)

almost no current/recent star formation...
(Blanchard, Berger et al. 2017, ApJ 848, L22)

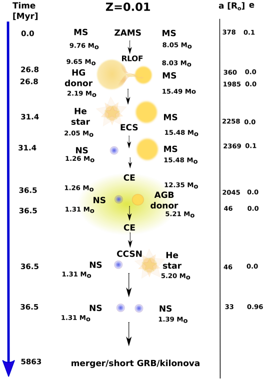




estimate NS-NS merger rate in 100 Mpc cube
only in elliptical galaxies (old: $\sim$ 5 Gyr) –>

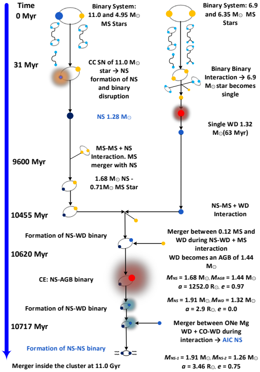
NS-NS merger: in old host galaxies (NGC4993-like)

binary stars:



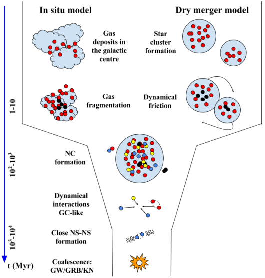
rate: 1×10^{-2} yr^{-1}

globular clusters:



rate: 5×10^{-5} yr^{-1}

nuclear clusters:

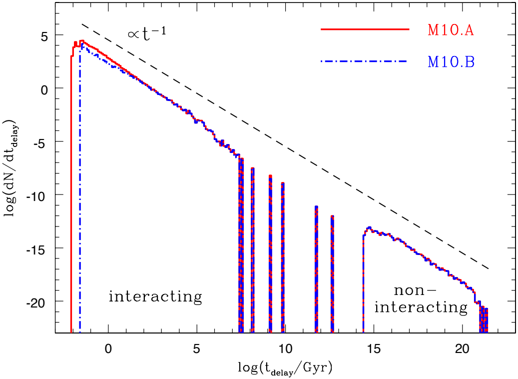


rate: 1×10^{-5} yr^{-1}

LIGO rate: ~ 1 yr^{-1} – so why first NS-NS in old host galaxy?

(Belczynski, Askar, Arca-Sedda, Chruslinska, Donnari, Giersz, Benacquista, Spurzem, Jin, Wiktorowicz, Belloni 2018, A&A, 615, 91)

NS-NS mergers: delay time distribution



1) binary evolution: typically short delays (mergers in star forming regions)
(this is a generic result and very hard to change... $t_{\rm delay} \propto a^4 \propto t^{-1}$)

2) cluster evolution: typically very long delays... ($t_{\rm delay} > t_{\rm hubble}$)