The origin of the coalescing compact object binaries

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with
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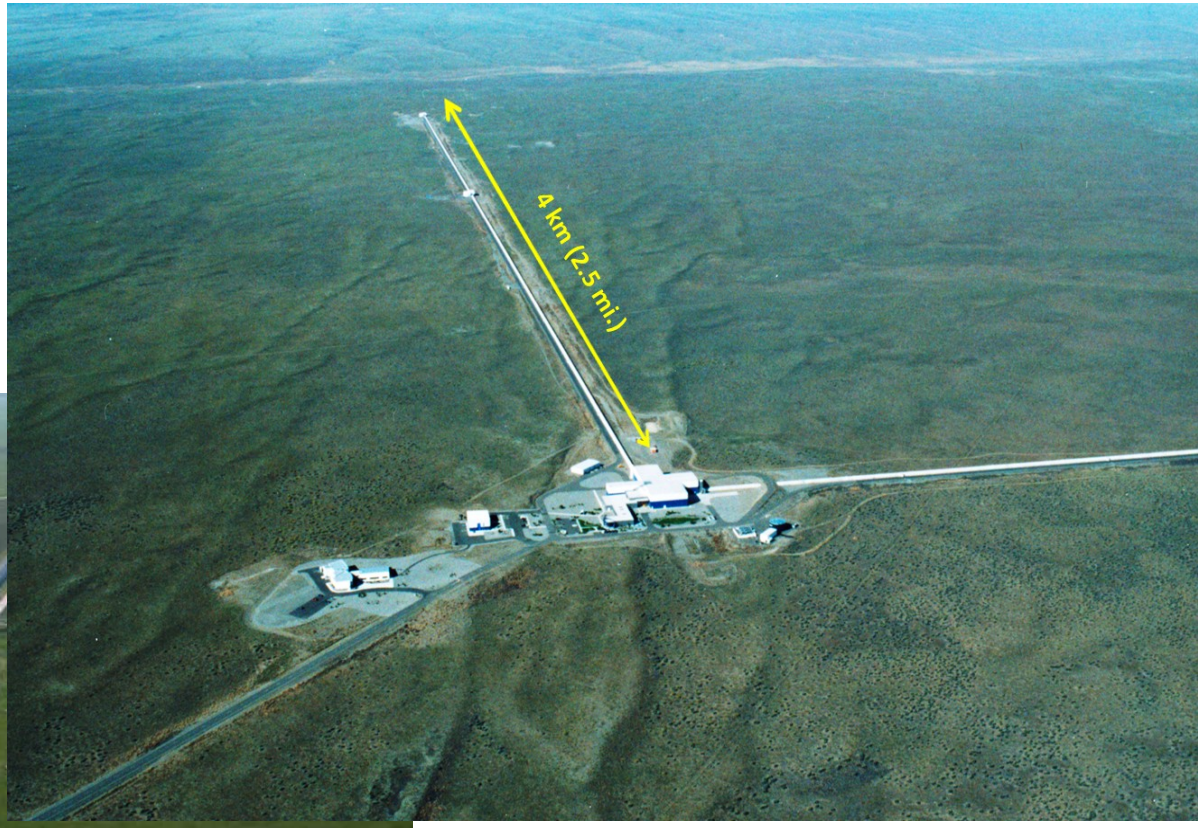
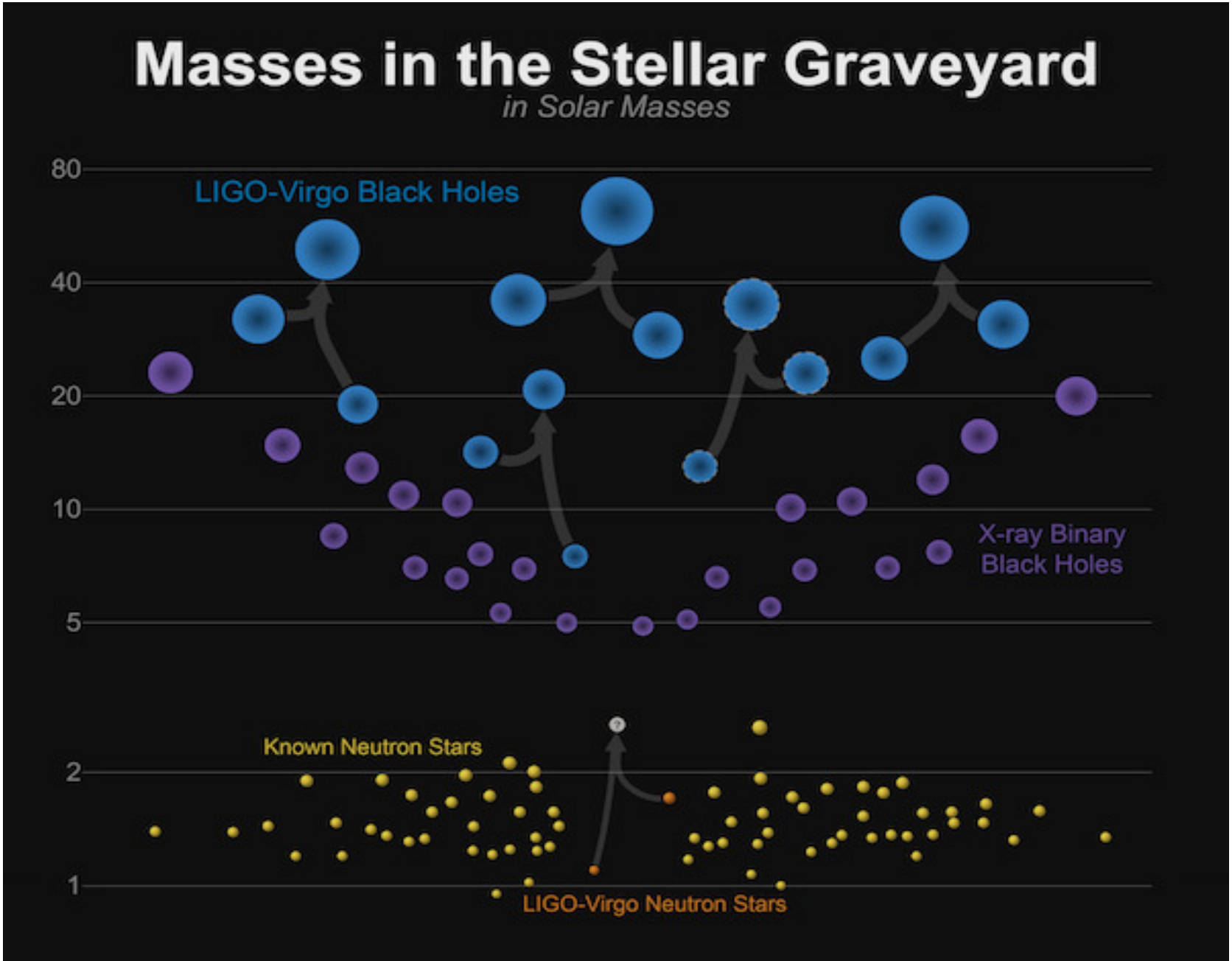
Observations

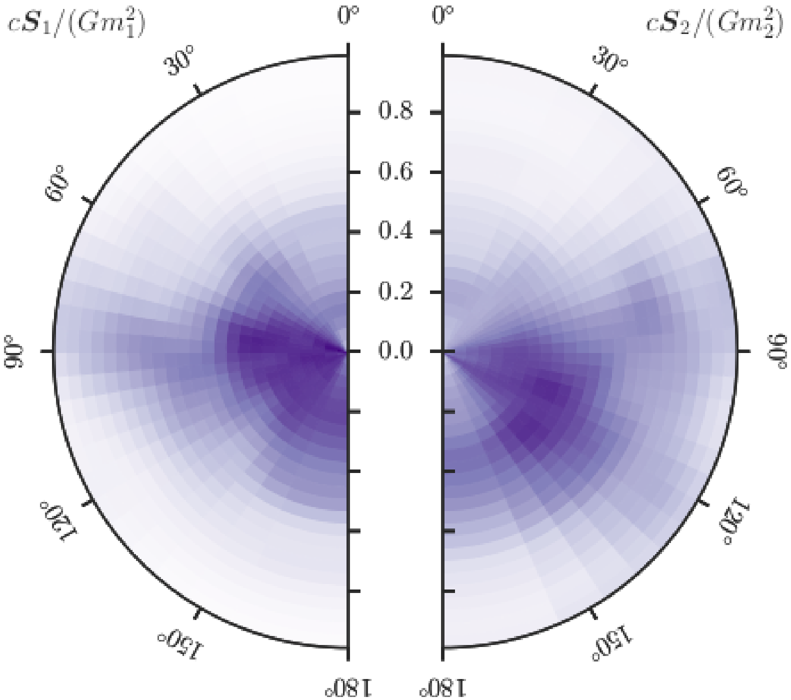
- Masses
- Spins
- Rate densities
- Locations
- Counterparts



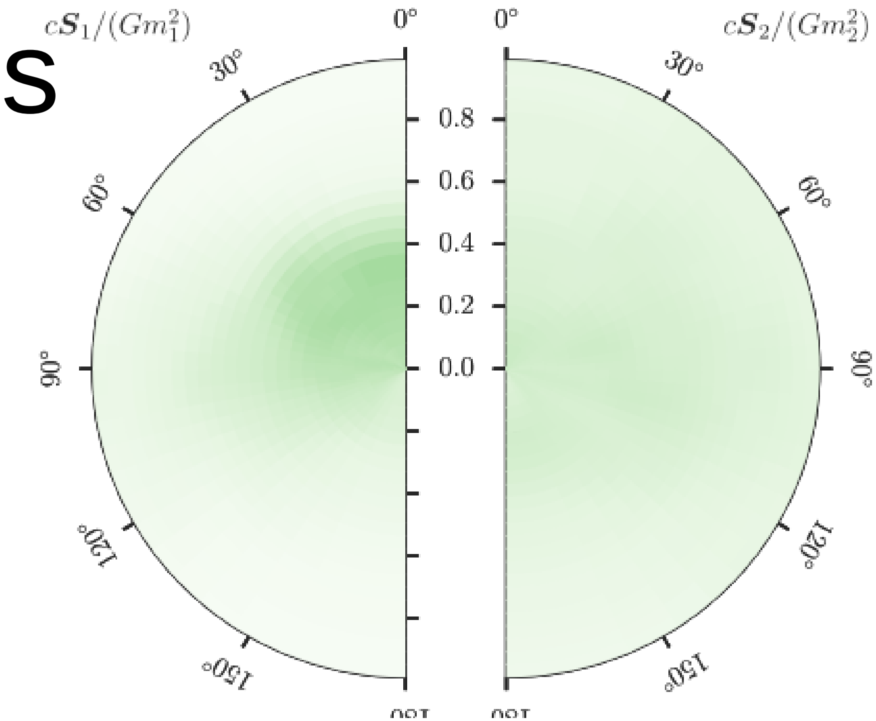
Observations -masses



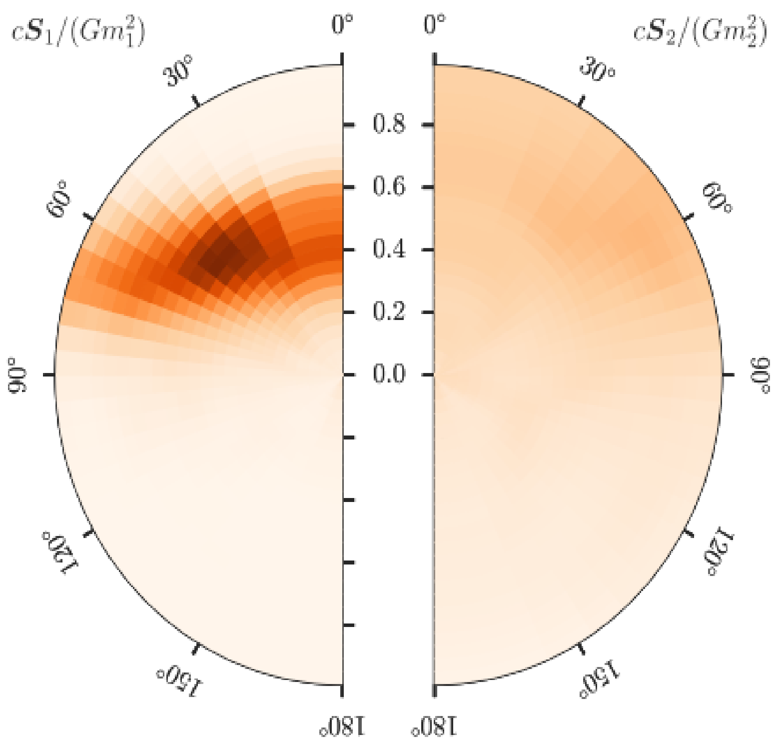
Spins



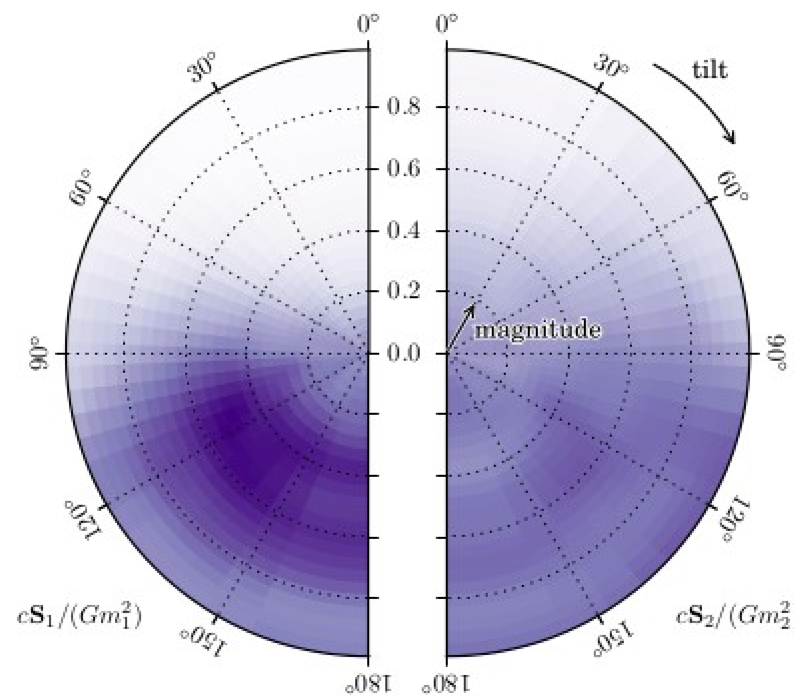
$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0



$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
0.8
0.6
0.4
0.2
0.0

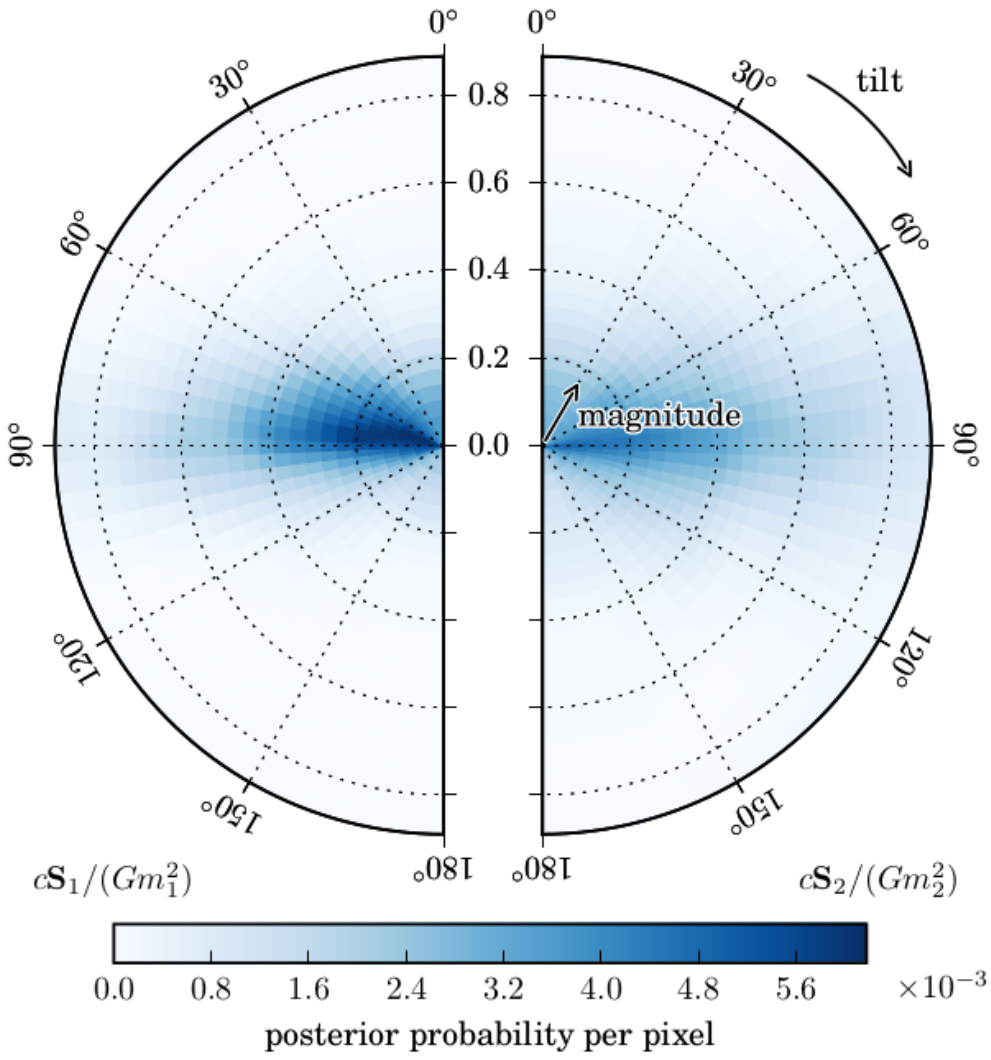


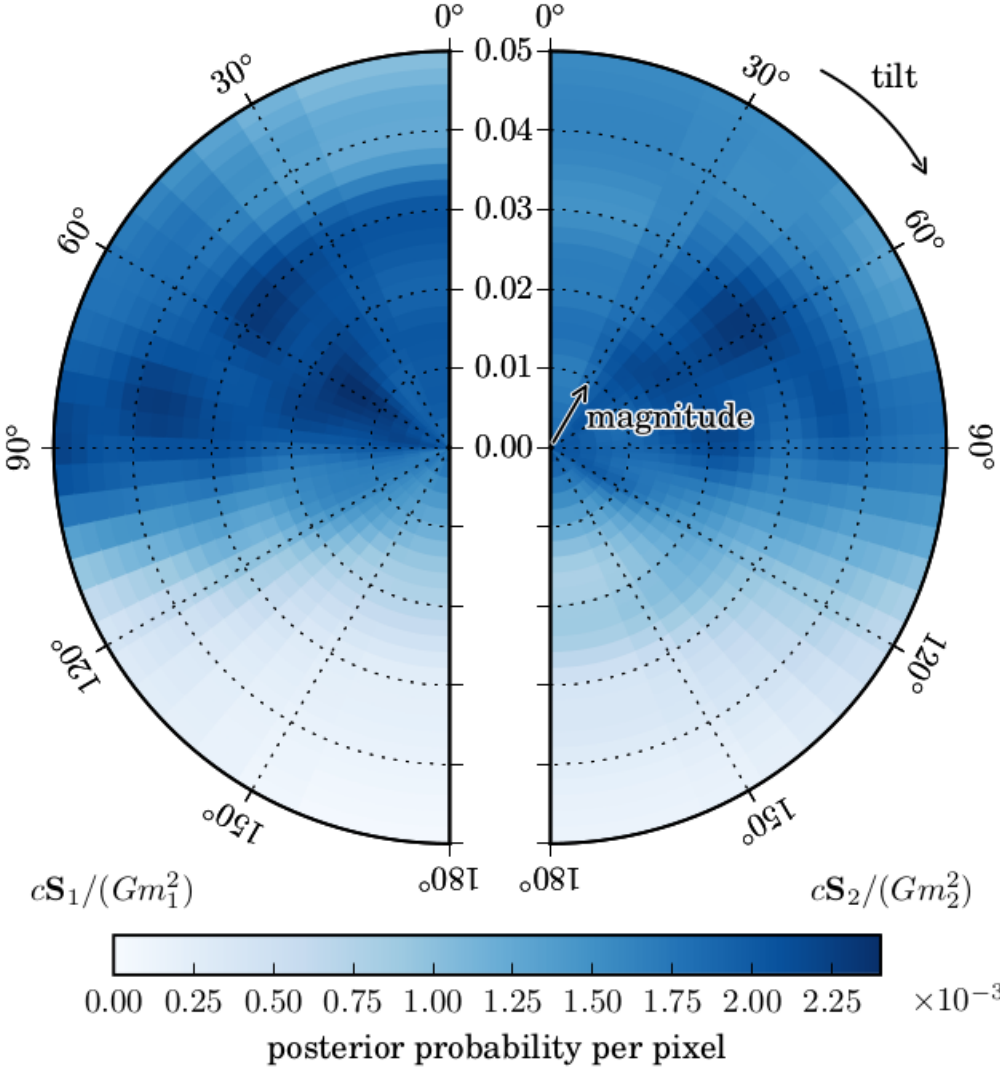
$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0



tilt
magnitude
$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0

BNS spins

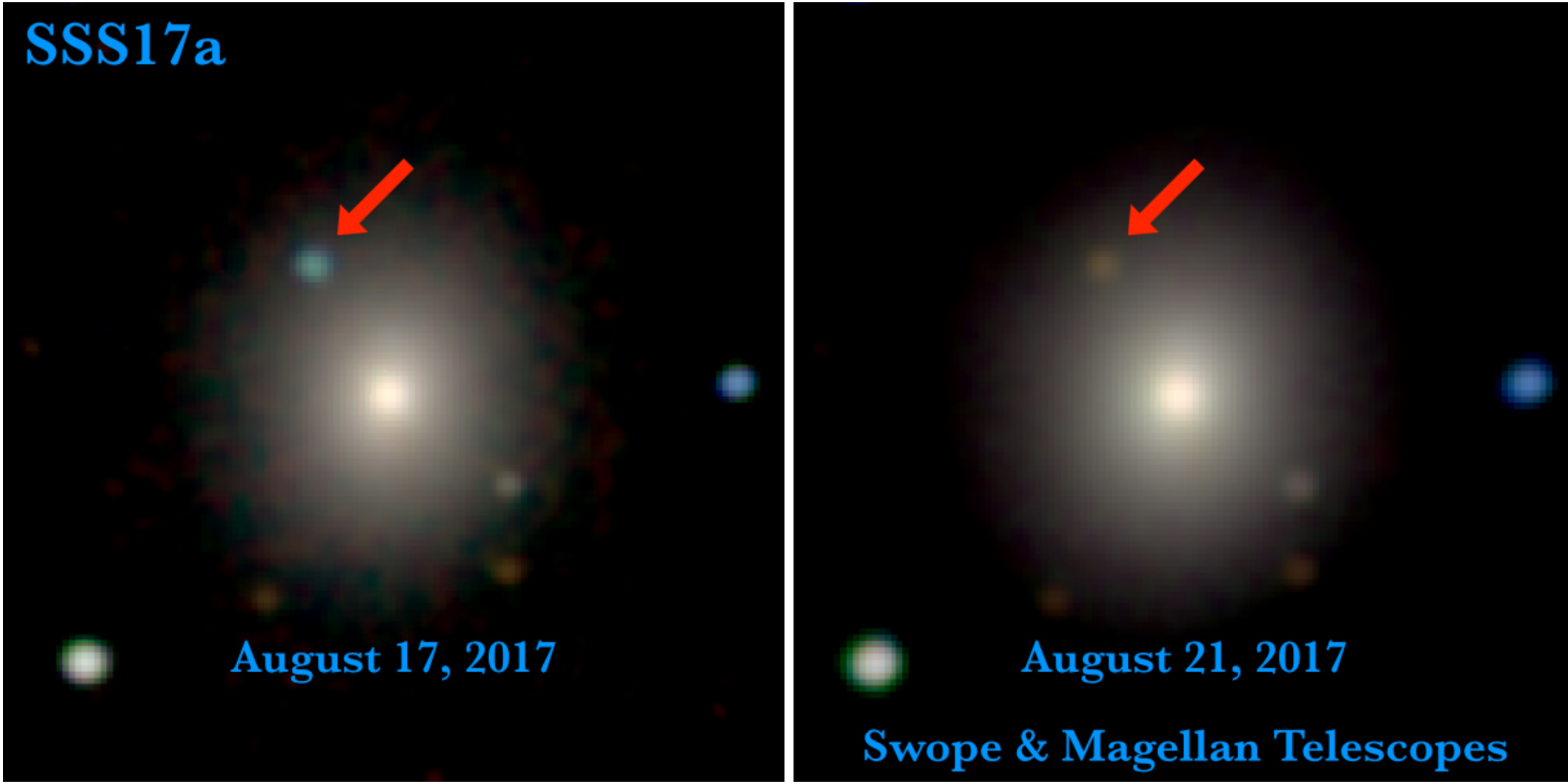

0°
30°
60°
90°
120°
150°
180°
tilt
magnitude
0.0
0.2
0.4
0.6
0.8
$c\mathbf{S}_1/(Gm_1^2)$
$c\mathbf{S}_2/(Gm_2^2)$
0.0 0.8 1.6 2.4 3.2 4.0 4.8 5.6 $\times 10^{-3}$
posterior probability per pixel


0°
30°
60°
90°
120°
150°
180°
tilt
magnitude
0.00
0.01
0.02
0.03
0.04
0.05
$c\mathbf{S}_1/(Gm_1^2)$
$c\mathbf{S}_2/(Gm_2^2)$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 $\times 10^{-3}$
posterior probability per pixel

The merger rate densities

- BBH estimate 12-213 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BNS estimate $R = 1540^{+3200}_{-1220}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The local supernova rate ~$10^5\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The BH formation rate is ~$10^4\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- About 1 black hole in a 100 ends up in a merging binary
- Similarily NS: 1 in 100 is in a merging binary!

BNS: all that + host galaxy

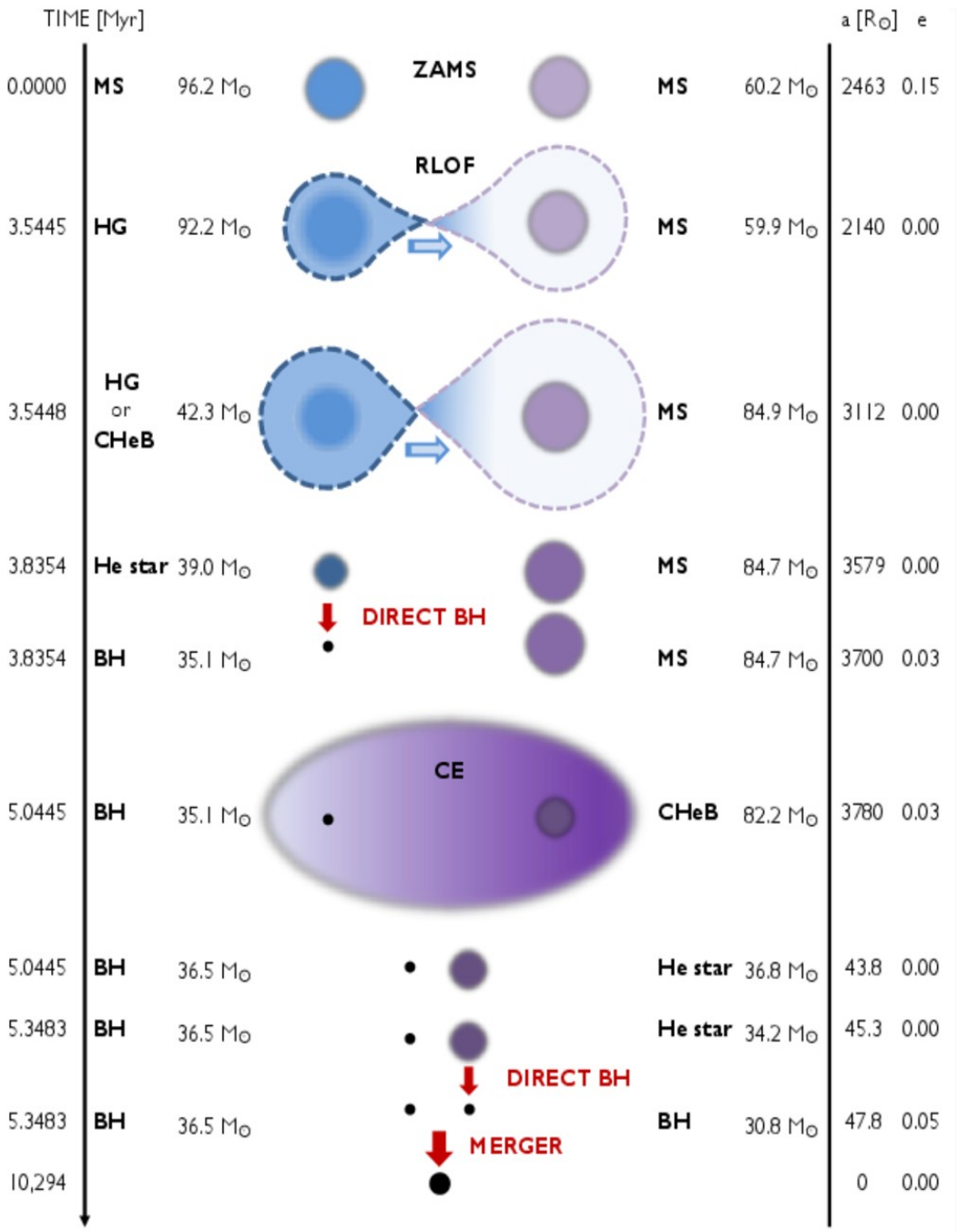


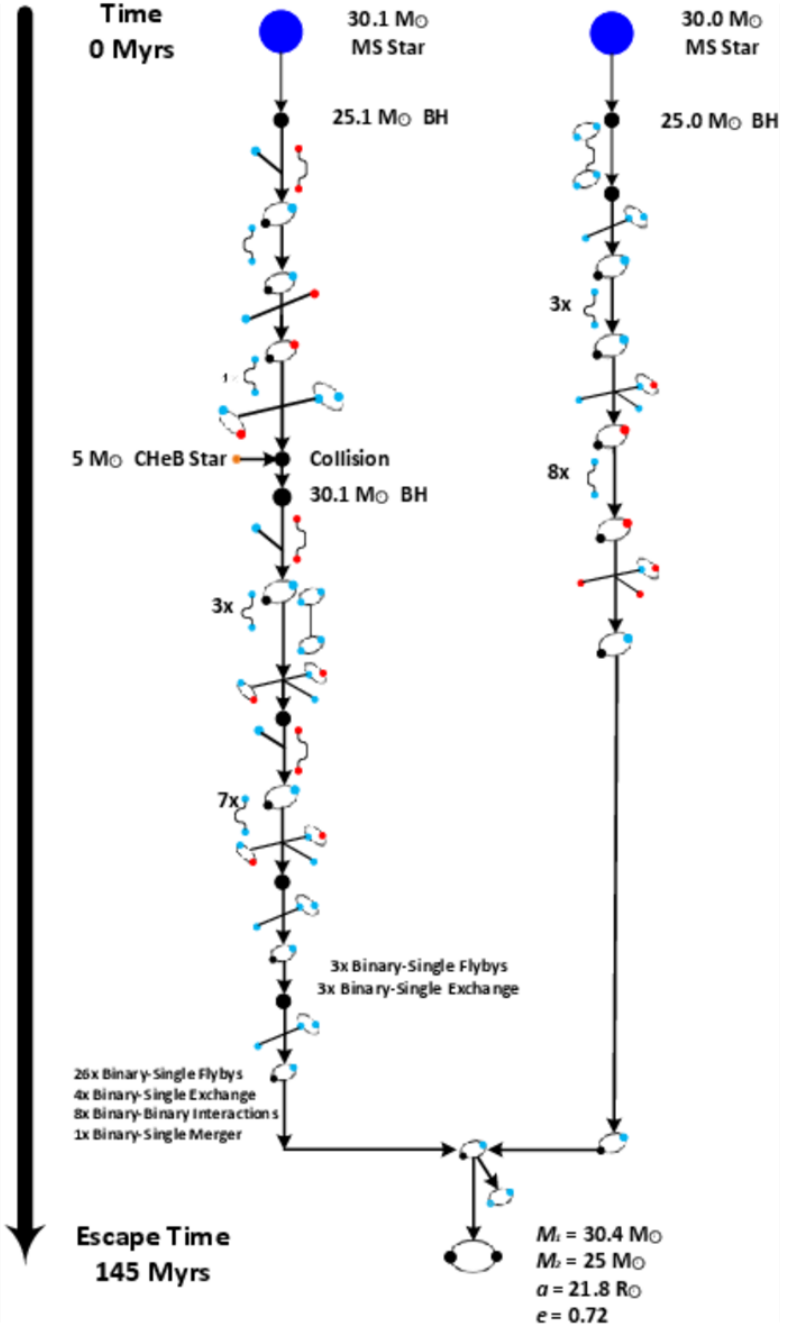
NGC 4993 – old elliptical with no traces of str formation for th last 1-2Gyrs, merger on the ourskirts of the galaxy.

What options do we have?

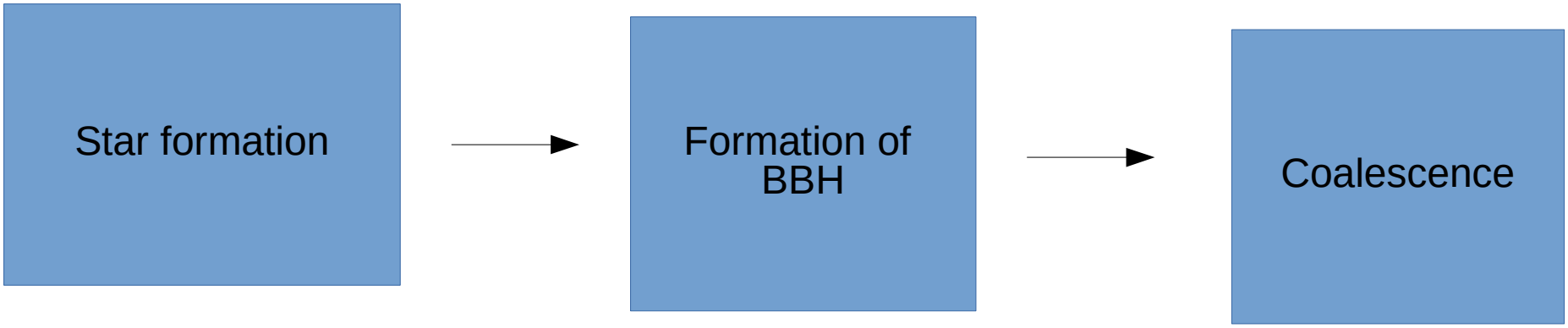
- Binary evolution
  - Standard
  - Chemically homogenous case
- Evolution in the clusters
- Exotica
  - Pop III stars
  - Exceptional environments.

Scenarios


TIME [Myr]
a [R☉] e
0.0000 MS 96.2 M☉
ZAMS
MS 60.2 M☉ 2463 0.15
3.5445 HG 92.2 M☉
RLOF
MS 59.9 M☉ 2140 0.00
3.5448 HG or CHeB 42.3 M☉
MS 84.9 M☉ 3112 0.00
3.8354 He star 39.0 M☉
DIRECT BH
MS 84.7 M☉ 3579 0.00
3.8354 BH 35.1 M☉
MS 84.7 M☉ 3700 0.03
CE
5.0445 BH 35.1 M☉
CHeB 82.2 M☉ 3780 0.03
5.0445 BH 36.5 M☉
He star 36.8 M☉ 43.8 0.00
5.3483 BH 36.5 M☉
He star 34.2 M☉ 45.3 0.00
DIRECT BH
5.3483 BH 36.5 M☉
MERGER
BH 30.8 M☉ 47.8 0.05
10,294
0 0.00


Time
0 Myrs
30.1 M☉ MS Star
25.1 M☉ BH
30.0 M☉ MS Star
25.0 M☉ BH
3x
5 M☉ CHeB Star
Collision
30.1 M☉ BH
8x
3x
7x
3x Binary-Single Flybys
3x Binary-Single Exchange
26x Binary-Single Flybys
4x Binary-Single Exchange
8x Binary-Binary Interactions
1x Binary-Single Merger
Escape Time
145 Myrs
M₁ = 30.4 M☉
M₂ = 25 M☉
a = 21.8 R☉
e = 0.72

Rates



Trace the evolution backwards to orginal SFR population to estimate the rate

Rates

- BHBH production efficiency:
  - Number of merging BBH per unit mass
- Delay times
- Mass distribution
  - Intrinsic vs observed: range and redshift effect

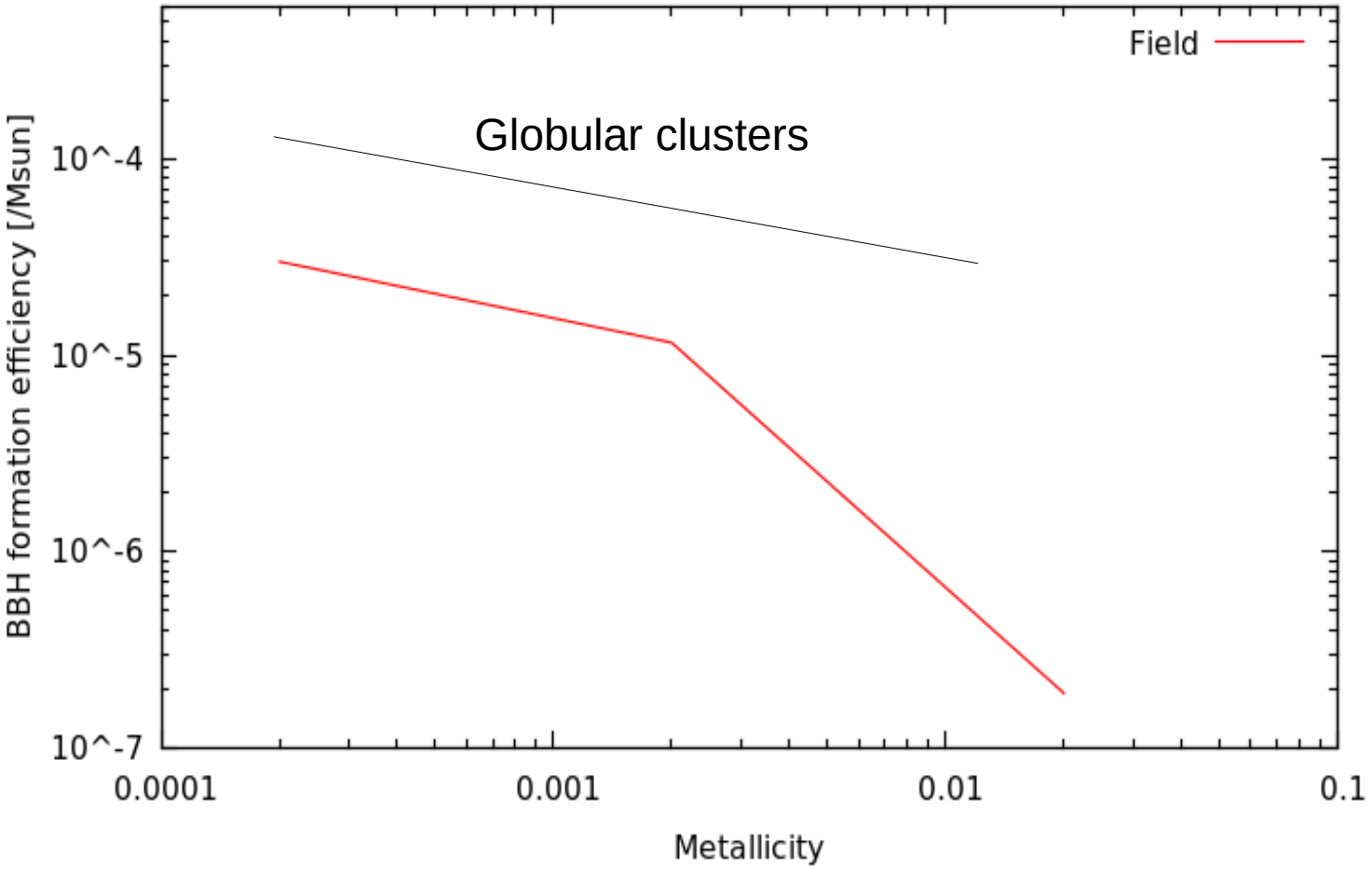
- Rate density: local and as a function of redshift

BHBH formation efficiency

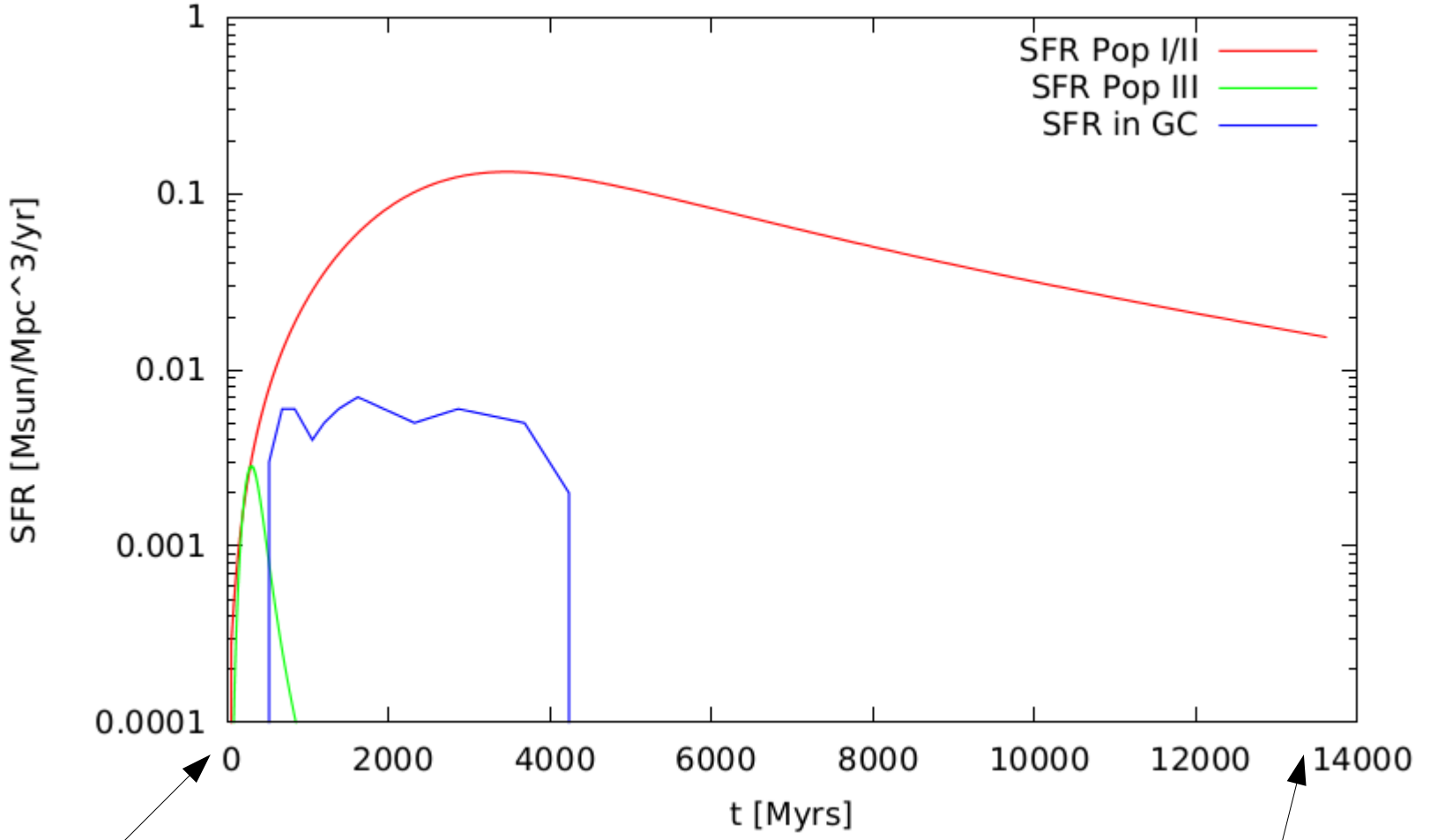
$$X_{BHBH} = \frac{N_{BHBH}}{M_*}$$

If all BHs end up in merging binaries and with Salpeter IMF

$$X_{BHBH}^{max} = 1.8 \times 10^{-3} M_{\odot}^{-1}$$



SFR



Big Bang

Today

Basic rate arguments

- Formation scenario must be generic
- Exceptional envirnments must produce BBH and BNS with extremy high efficiency
- Globular clusters are not favoured, but can contribute
- I am sceptical about exotic models

The rate implications

- Total GW luminosity density in the sky from NSNS mergers

$$\mathcal{L}_{GW} = 1560 \frac{0.025 M_\odot c^2}{3.1 \times 10^7 \mathrm{s}} \approx 2.5 \times 10^{48} \mathrm{ergs}^{-1} \mathrm{Gpc}^{-3}$$

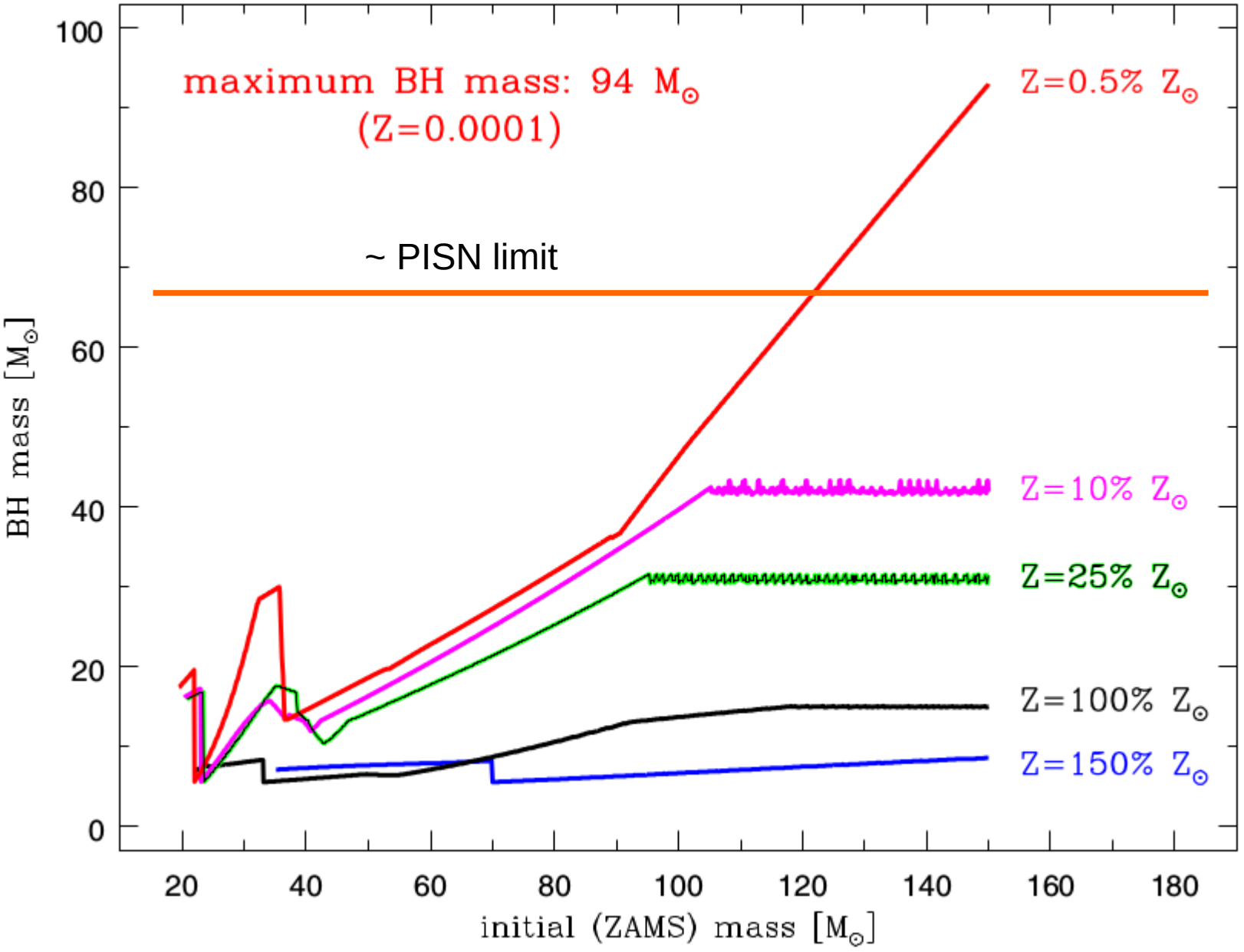
- The luminosity density of BHBH mergers is about 10 times larger

$$\mathcal{L}_{GW} = 100 \frac{2.0 M_\odot c^2}{3.1 \times 10^7 \mathrm{s}} \approx 2. \times 10^{49} \mathrm{ergs}^{-1} \mathrm{Gpc}^{-3}$$

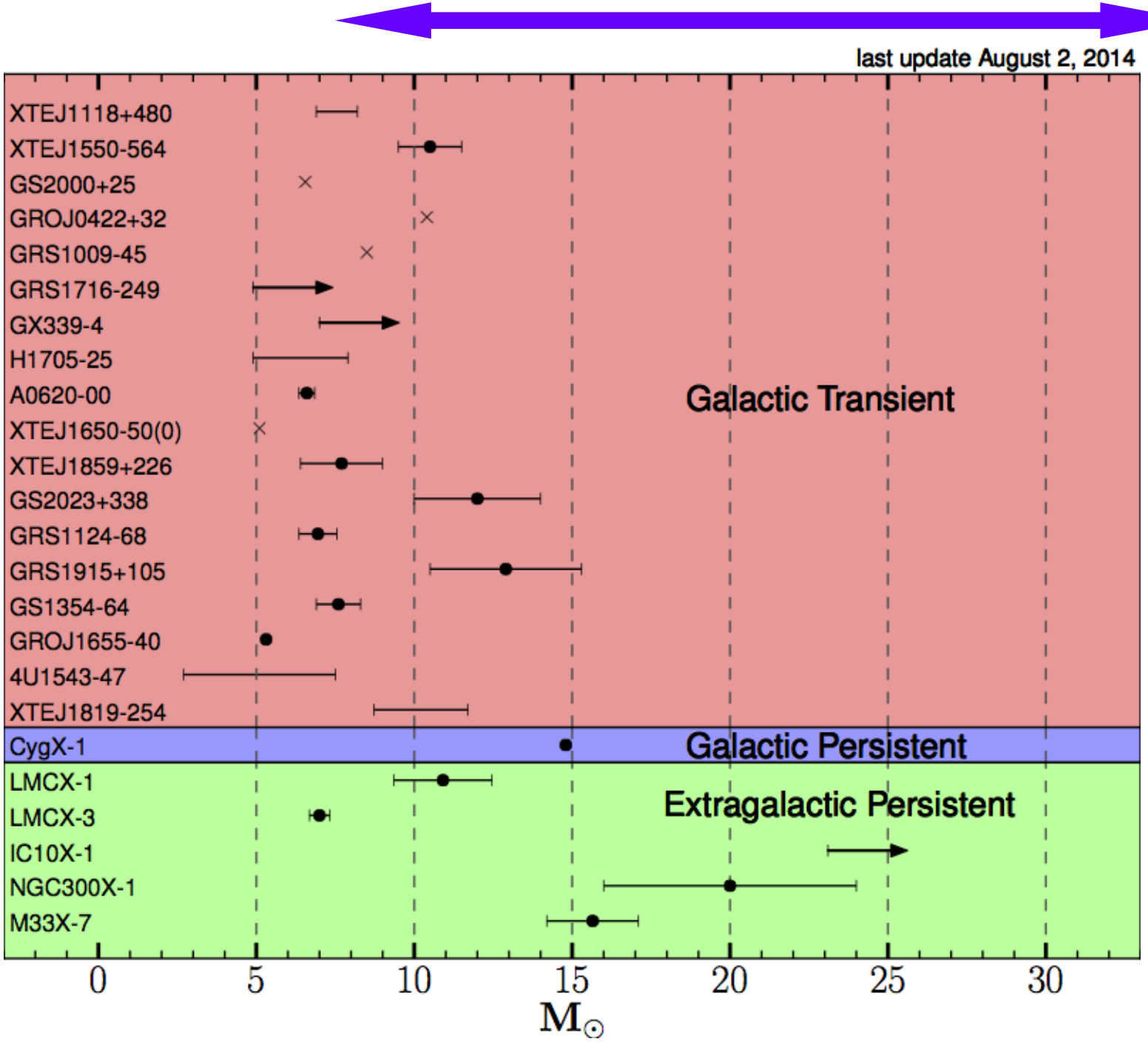
- EM luminosity density of all galaxies:

$$\mathcal{L}_{EM} \approx 10^{50} \mathrm{erg\,s}^{-1} \mathrm{Gpc}^{-3}$$

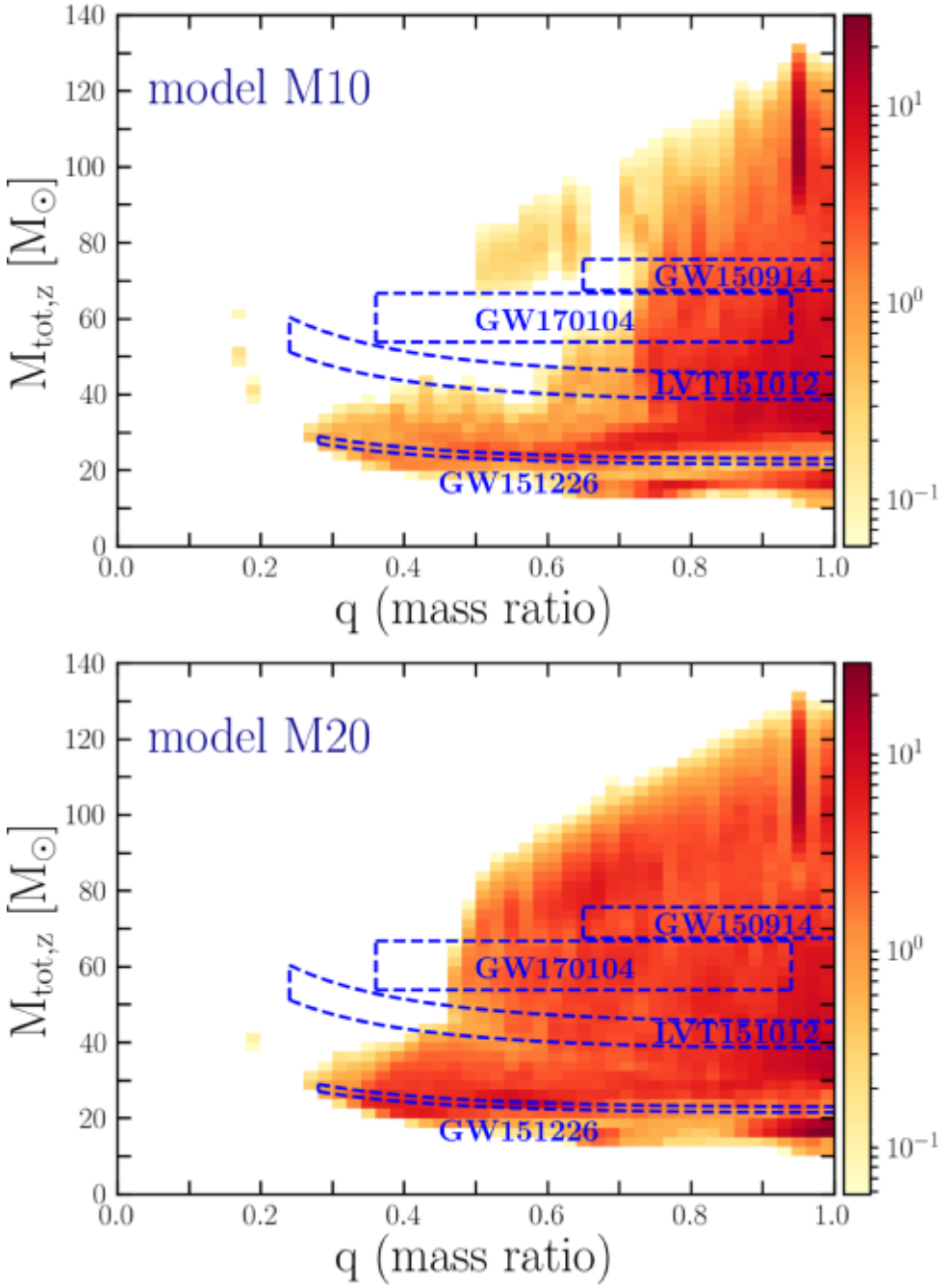
On the maximum mass of BHs



Range of masses in GW binaries



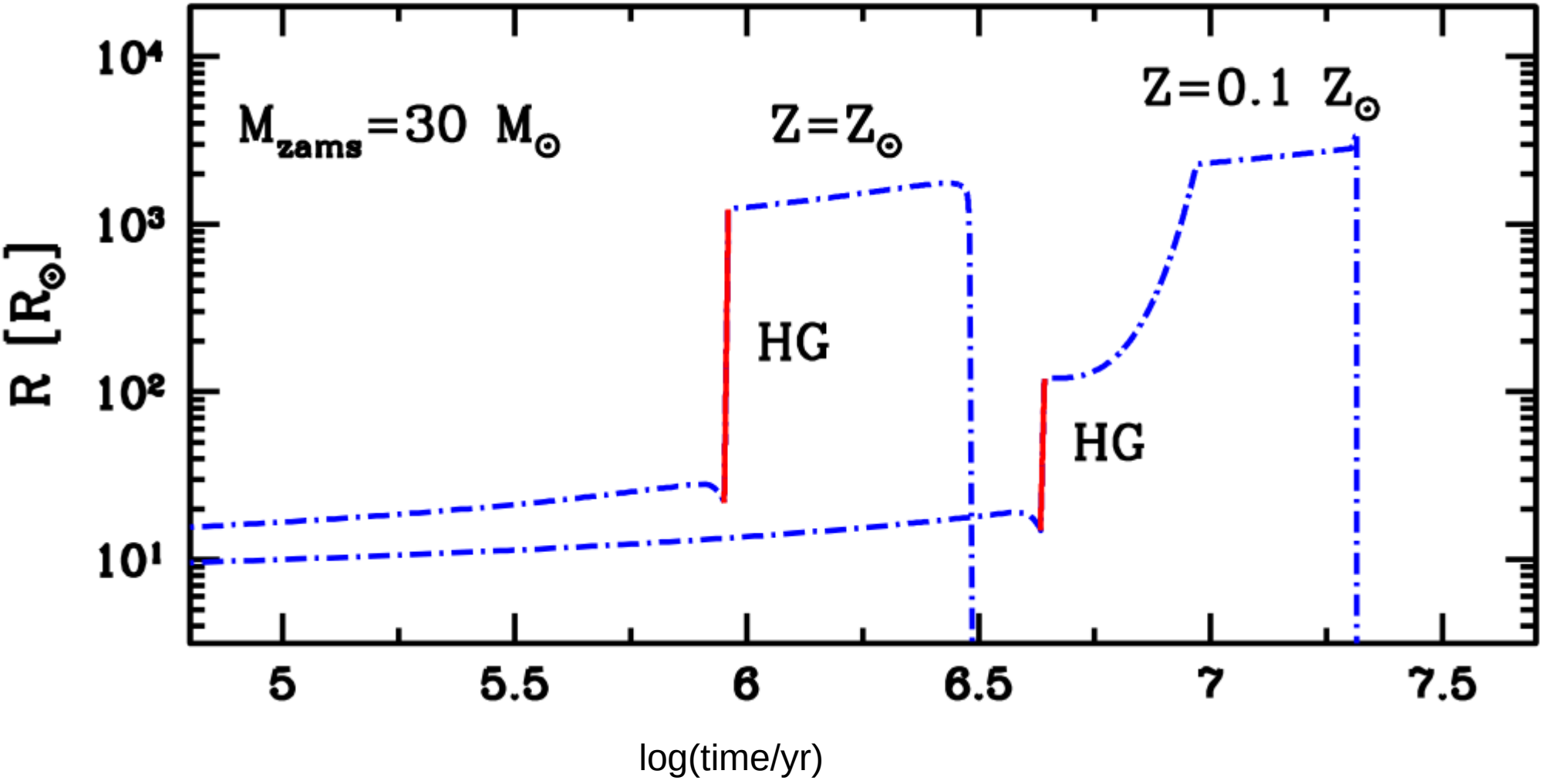
Mass distribution



Detailed modeling can reproduce observed masses

In GC the mass distribution is similar unless there is a significant number of hierachical mergers.

Low metallicity – helps with CE



Spin constraints

- Main question:

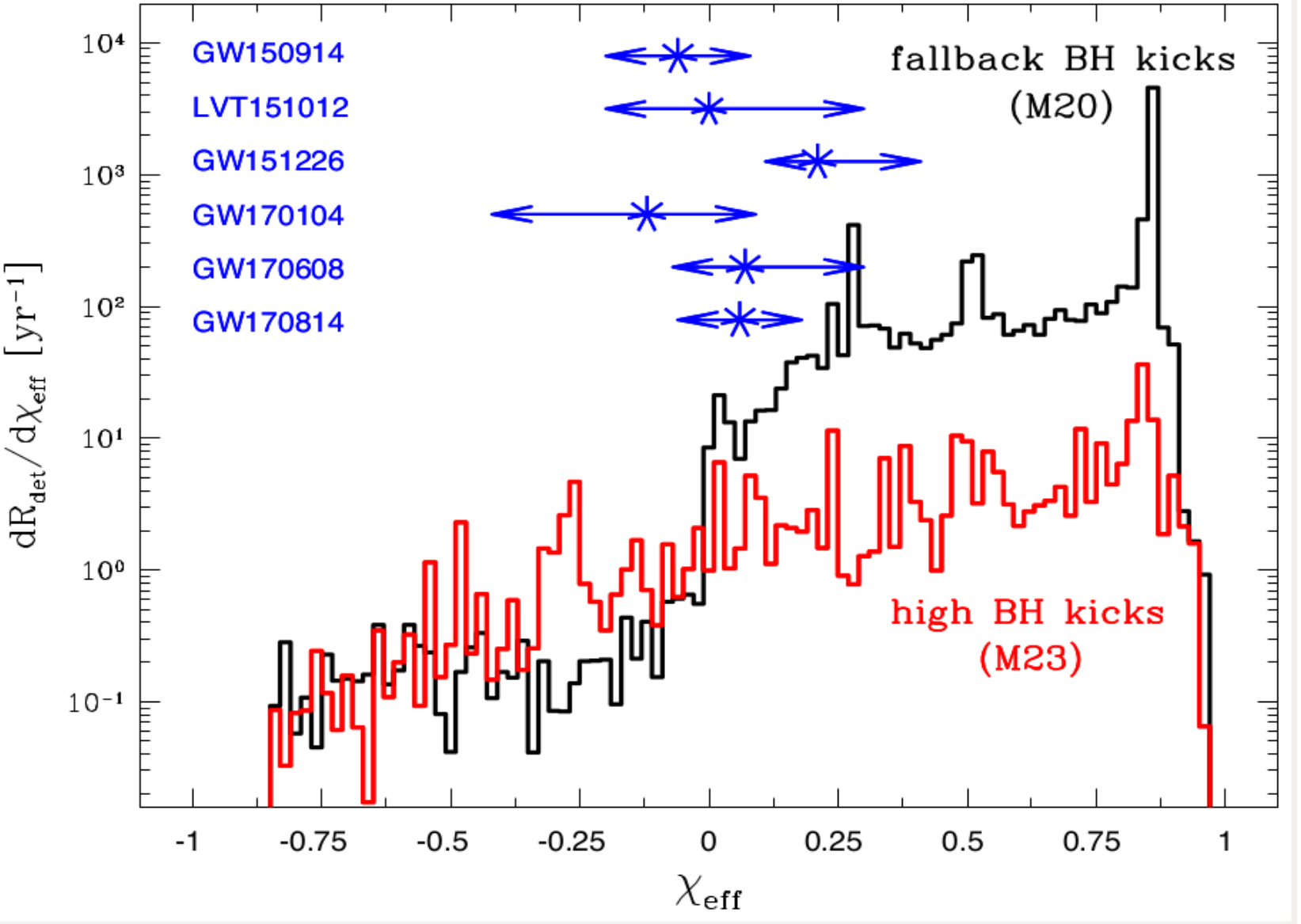
  What are the BH initial spins?

  Do they depend on mass, metallicity?

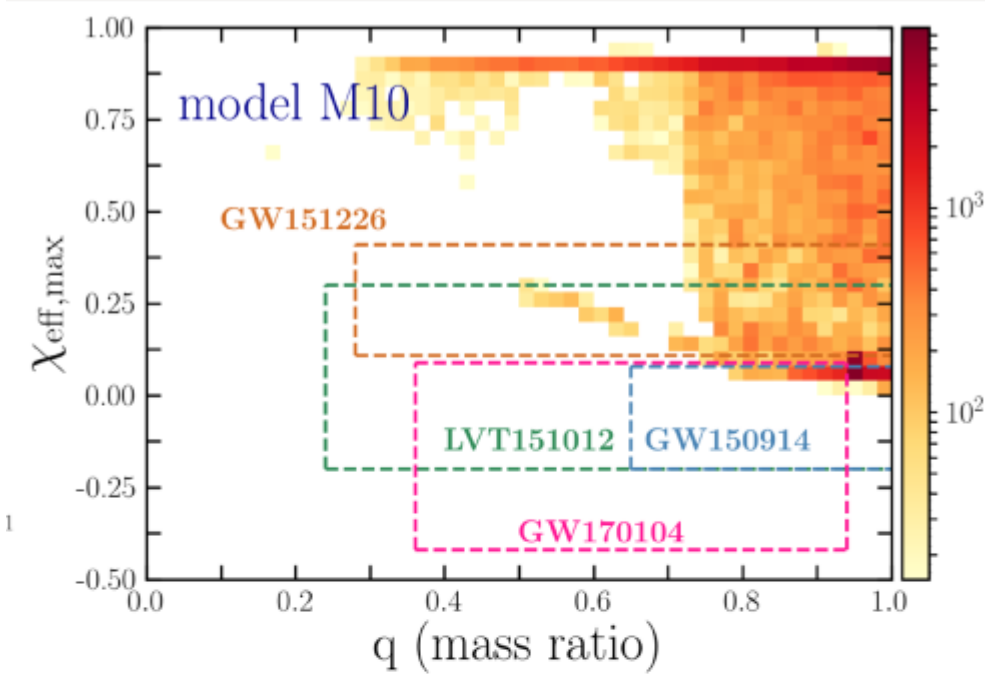
  Do they differ in X-rays and in GW?

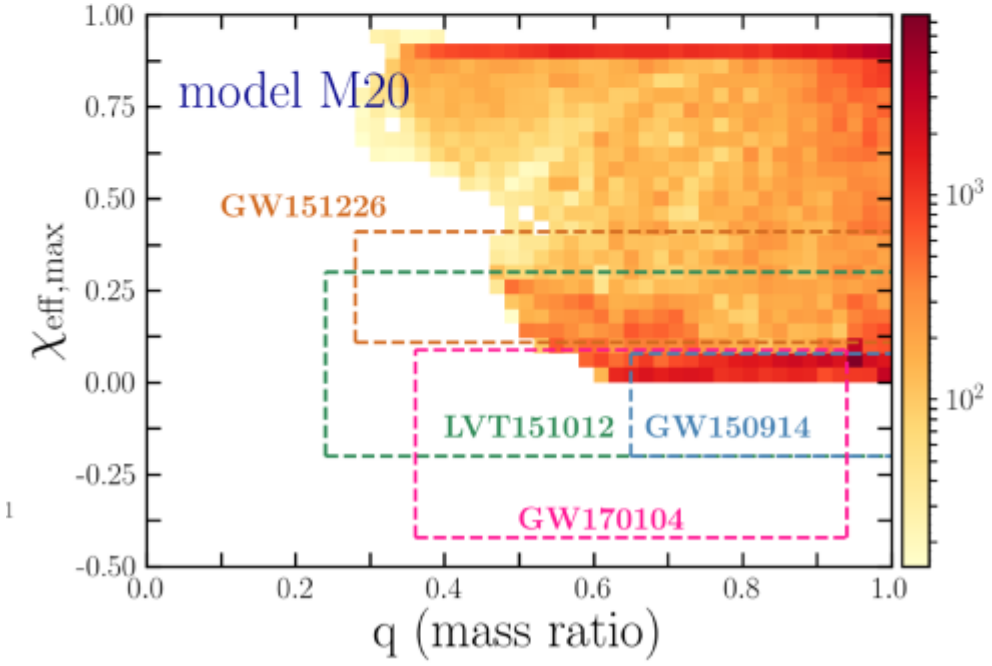
Spins – effective spins

Small spins?



Spin modeling





Our current models show a preference for large effectove spins.

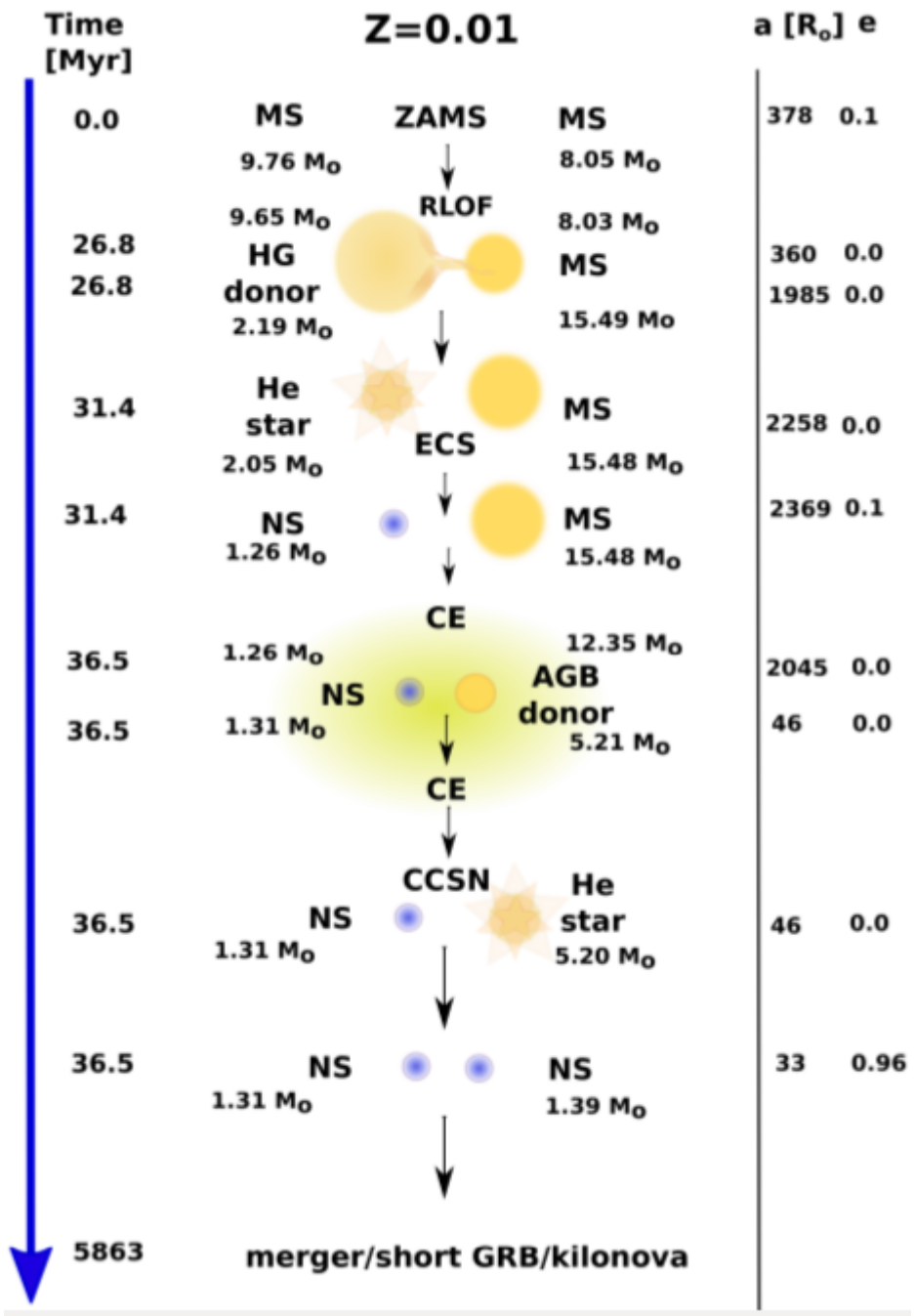
This is due to the model of initial BH spins at formation.

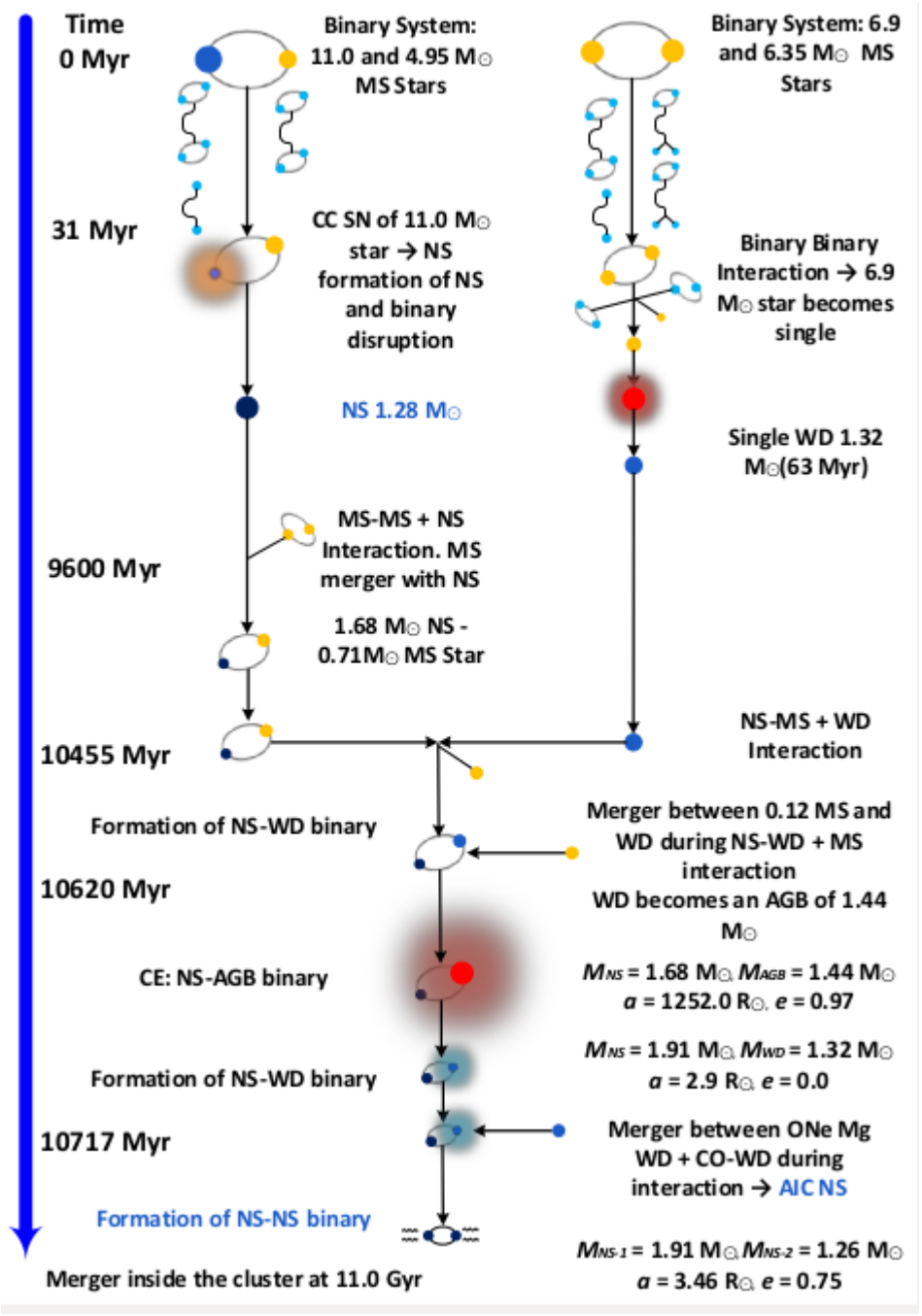
Observations indicate that spins are small for all BHs in merging systems

Are BH initial spins always small?

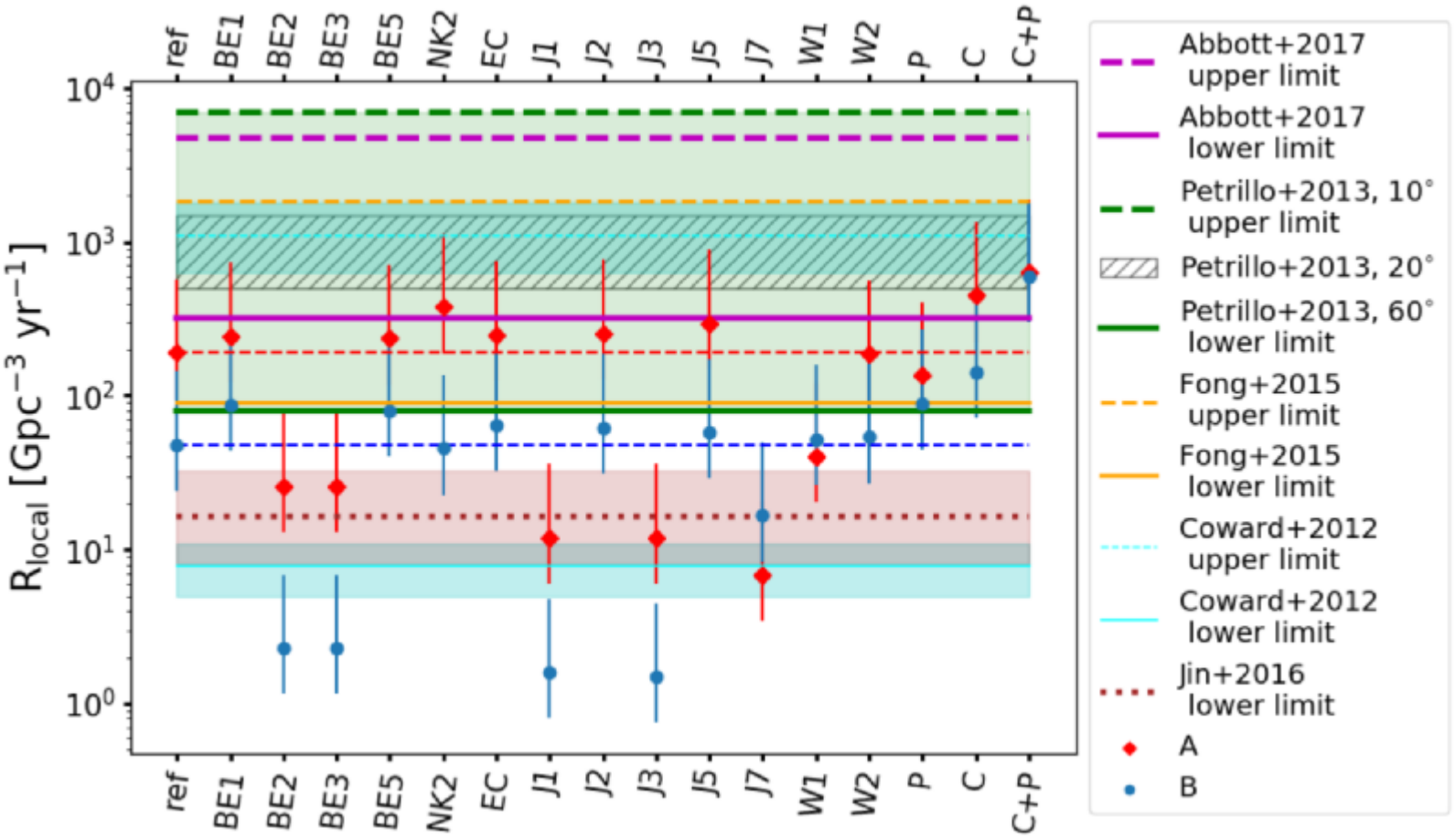
In GC expect random orientations and high spins for hierachical mergers.

BNS


Time [Myr]
Z=0.01
a [R$_o$] e
0.0
MS
9.76 M$_o$
ZAMS
MS
8.05 M$_o$
378 0.1
9.65 M$_o$
RLOF
8.03 M$_o$
26.8
HG donor
2.19 M$_o$
MS
15.49 Mo
360 0.0
26.8
1985 0.0
31.4
He star
2.05 M$_o$
ECS
MS
15.48 M$_o$
2258 0.0
31.4
NS
1.26 M$_o$
MS
15.48 M$_o$
2369 0.1
CE
1.26 M$_o$
12.35 M$_o$
36.5
2045 0.0
NS
1.31 M$_o$
AGB donor
5.21 M$_o$
36.5
46 0.0
CE
CCSN
36.5
NS
1.31 M$_o$
He star
5.20 M$_o$
46 0.0
36.5
NS
1.31 M$_o$
NS
1.39 M$_o$
33 0.96
5863
merger/short GRB/kilonova


Time
0 Myr
Binary System: 11.0 and 4.95 M⊙ MS Stars
Binary System: 6.9 and 6.35 M⊙ MS Stars
31 Myr
CC SN of 11.0 M⊙ star → NS formation of NS and binary disruption
Binary Binary Interaction → 6.9 M⊙ star becomes single
NS 1.28 M⊙
Single WD 1.32 M⊙(63 Myr)
9600 Myr
MS-MS + NS Interaction. MS merger with NS
1.68 M⊙ NS - 0.71M⊙ MS Star
10455 Myr
NS-MS + WD Interaction
Formation of NS-WD binary
Merger between 0.12 MS and WD during NS-WD + MS interaction
WD becomes an AGB of 1.44 M⊙
10620 Myr
CE: NS-AGB binary
M_{NS} = 1.68 M⊙ M_{AGB} = 1.44 M⊙
a = 1252.0 R⊙, e = 0.97
M_{NS} = 1.91 M⊙ M_{WD} = 1.32 M⊙
a = 2.9 R⊙ e = 0.0
Formation of NS-WD binary
10717 Myr
Merger between ONe Mg WD + CO-WD during interaction → AIC NS
Formation of NS-NS binary
M_{NS-1} = 1.91 M⊙ M_{NS-2} = 1.26 M⊙
a = 3.46 R⊙ e = 0.75
Merger inside the cluster at 11.0 Gyr

Rates

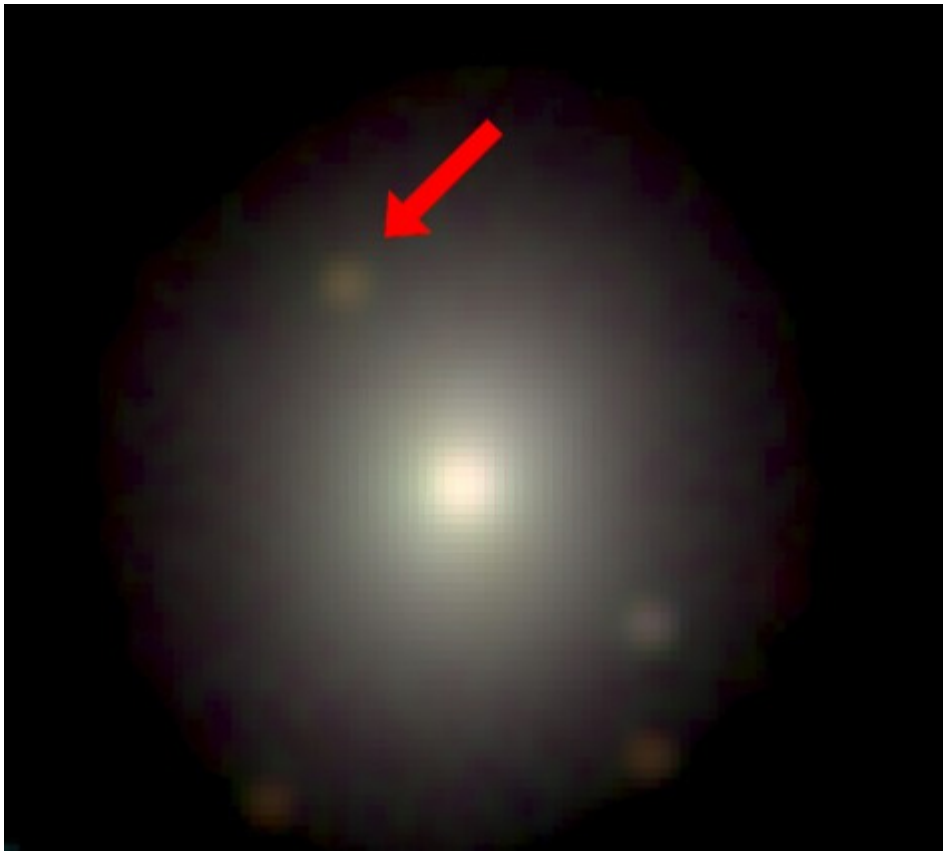


NS-NS rates up 1000/Gpc^3/yr but overpduction of BHBH

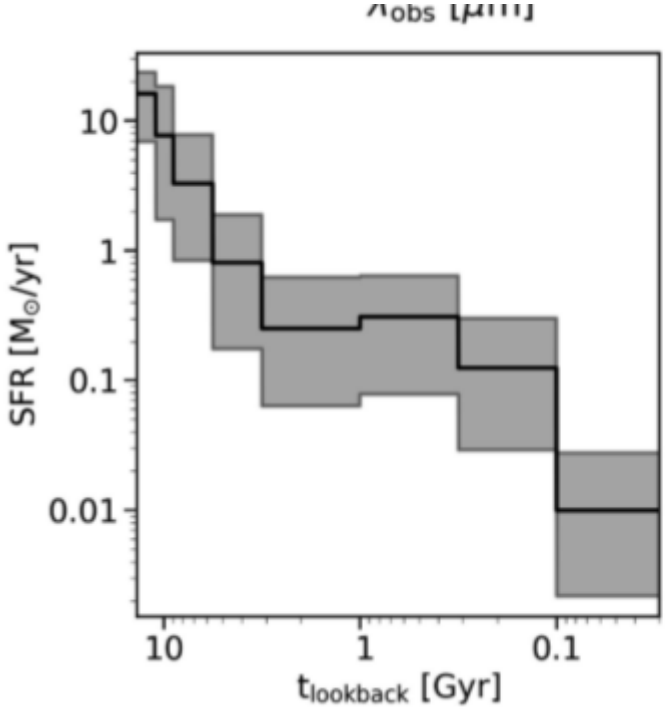
Diamonds / cirles – different modes of Common Envelope evolution

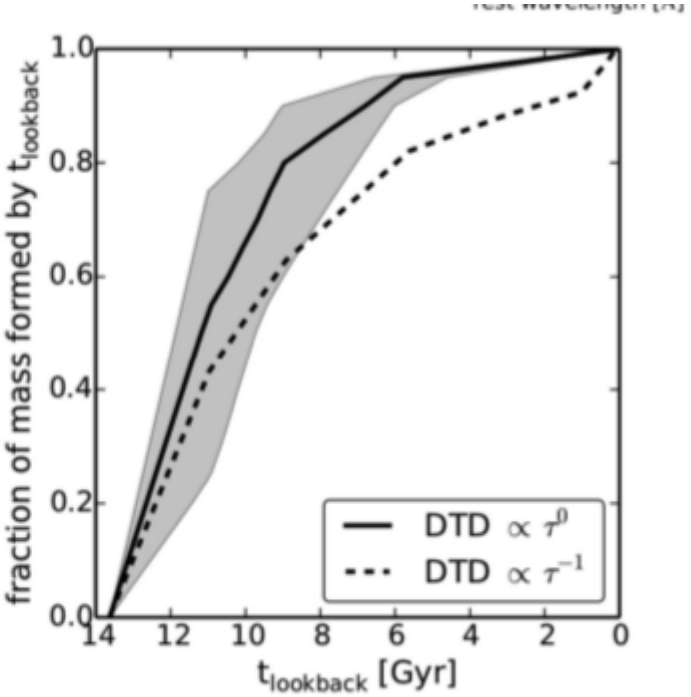
Host galaxy

- Quite a challenge
- No SFR - long delay time ~2Gyrs
- Simulations and observations indicate short delay times < 100 Myrs



Star formation history estimate





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Open issues

- Place the scenarios within astrophysical landscape
- Rates seem to be high
  - There are models that are marginally consistent with the rates
  - Globular cluster origin – tough to reconcile with all observations
  - Many paths may contribute
- Value of BH spins
  - Are spins small? - binary evolution origin
  - Do they have random orientations? - GC origin
- How exceptional was GW170817?
  - Long delay time
  - Unusual GRB

What next?

- Next GW observation run soon
- Expect
  - Large number of BBH – statistics, extremes
  - BNS – will we see more? What host galaxies?
  - BHNS – a new riddle, I suppose