Title: Astrphysics of coalescing compact object binaries

Date: Jun 21, 2018 01:00 PM

URL: http://pirsa.org/18060067

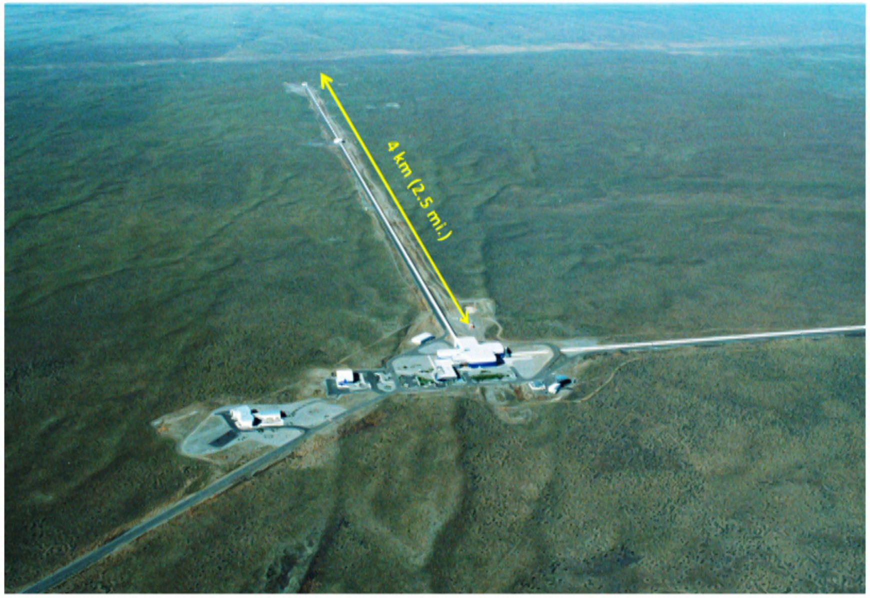
Abstract: <p>The recent detections of gravitational waves from compact object binary<br />
lead to detailed investigations of the origin of these objects. In my talk<br />
I will discuss the questions: What is the astrophysical origin of these objects?<br />
What do these detections tell us about the formation of black holes and neutron stars?<br />
What are the main problems that they pose?<br />
What to expect in the coming gravitational observations?</p>

# The plan

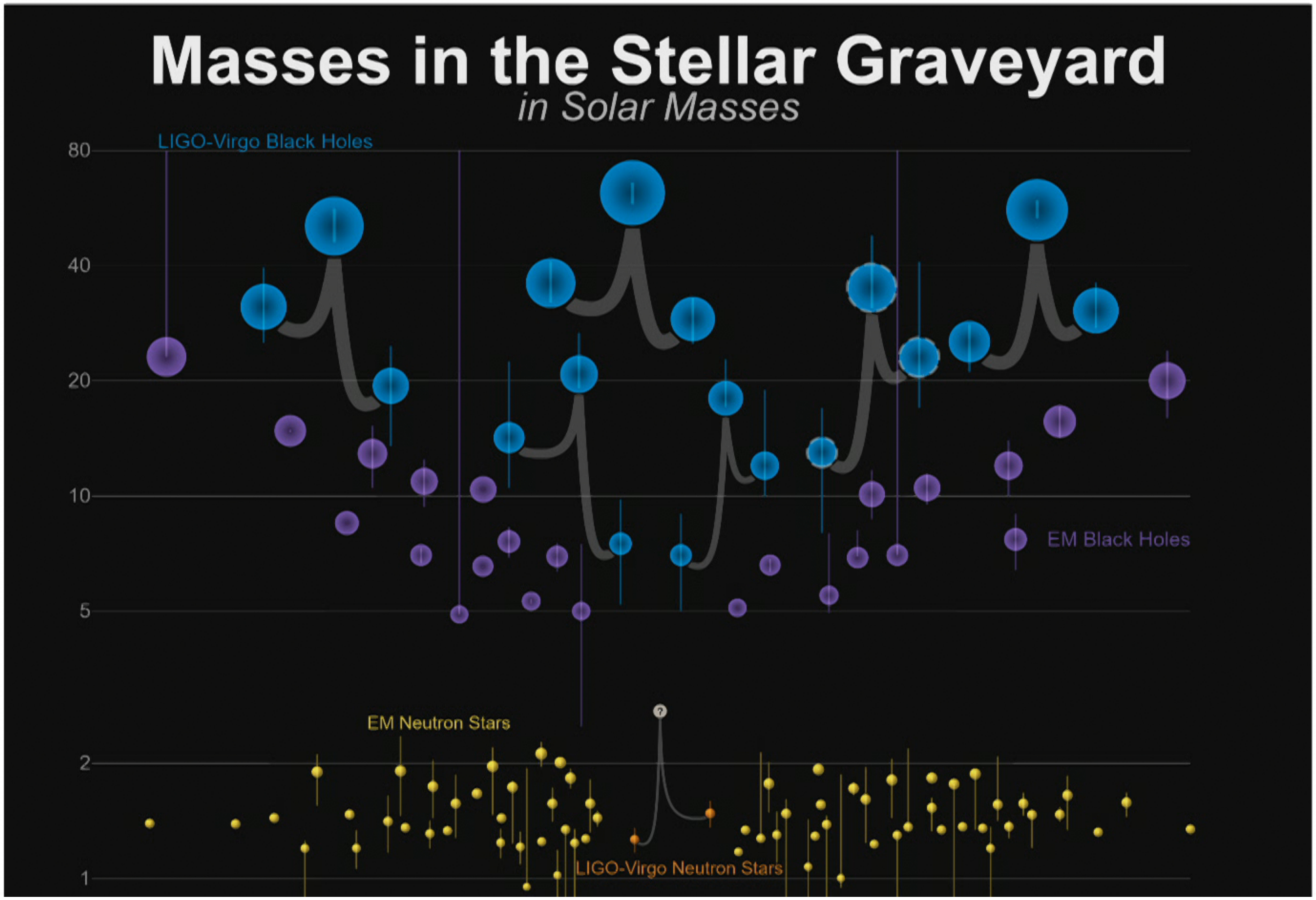
- Observations (finally!!!)
- Models to pick from (too many??)
- Constraints on the models
- Hopes and expectations

# Observations

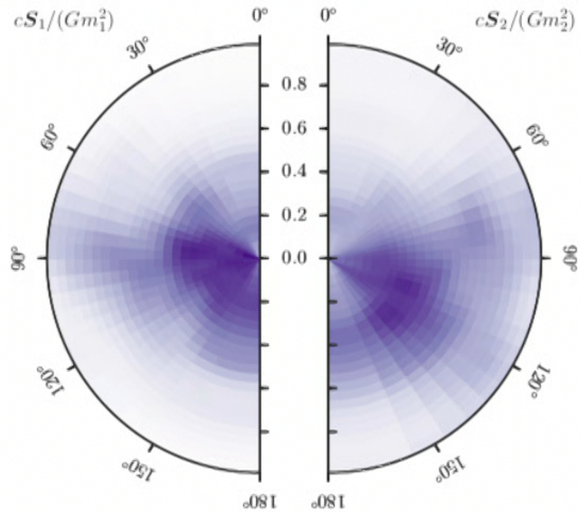
- Masses
- Spins
- Rate densities
- Locations
- Counterparts



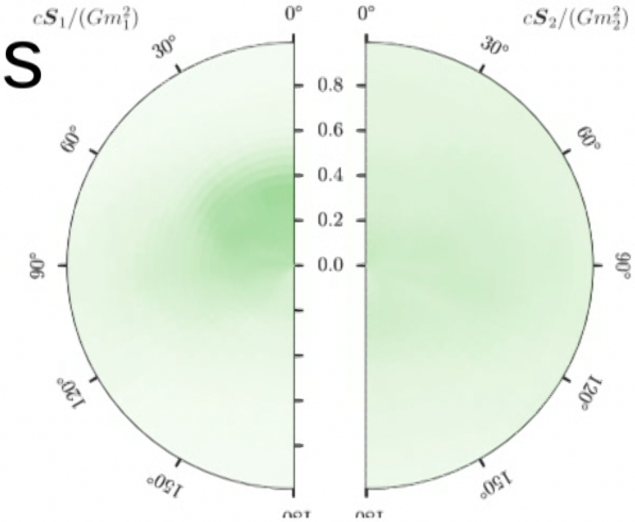
# Observations -masses



# 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

$cS_1/(Gm_1^2)$
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30°
60°
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0.8
0.6
0.4
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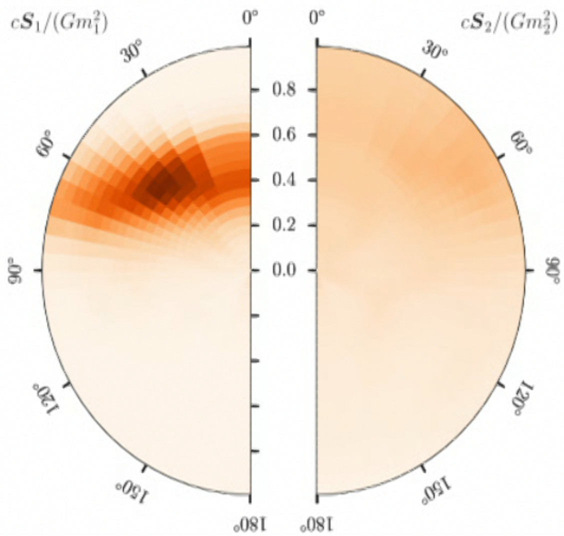
0.0

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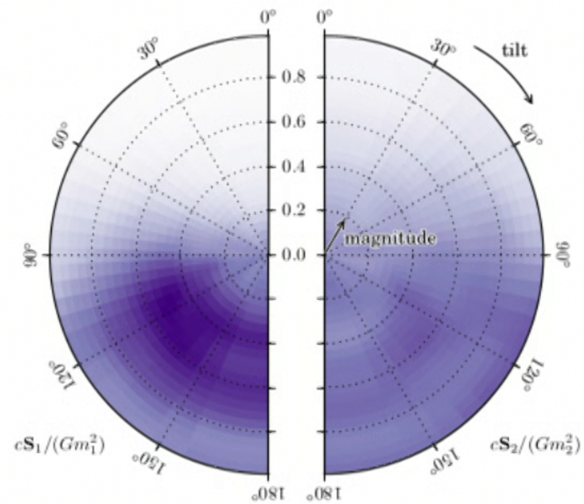
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0

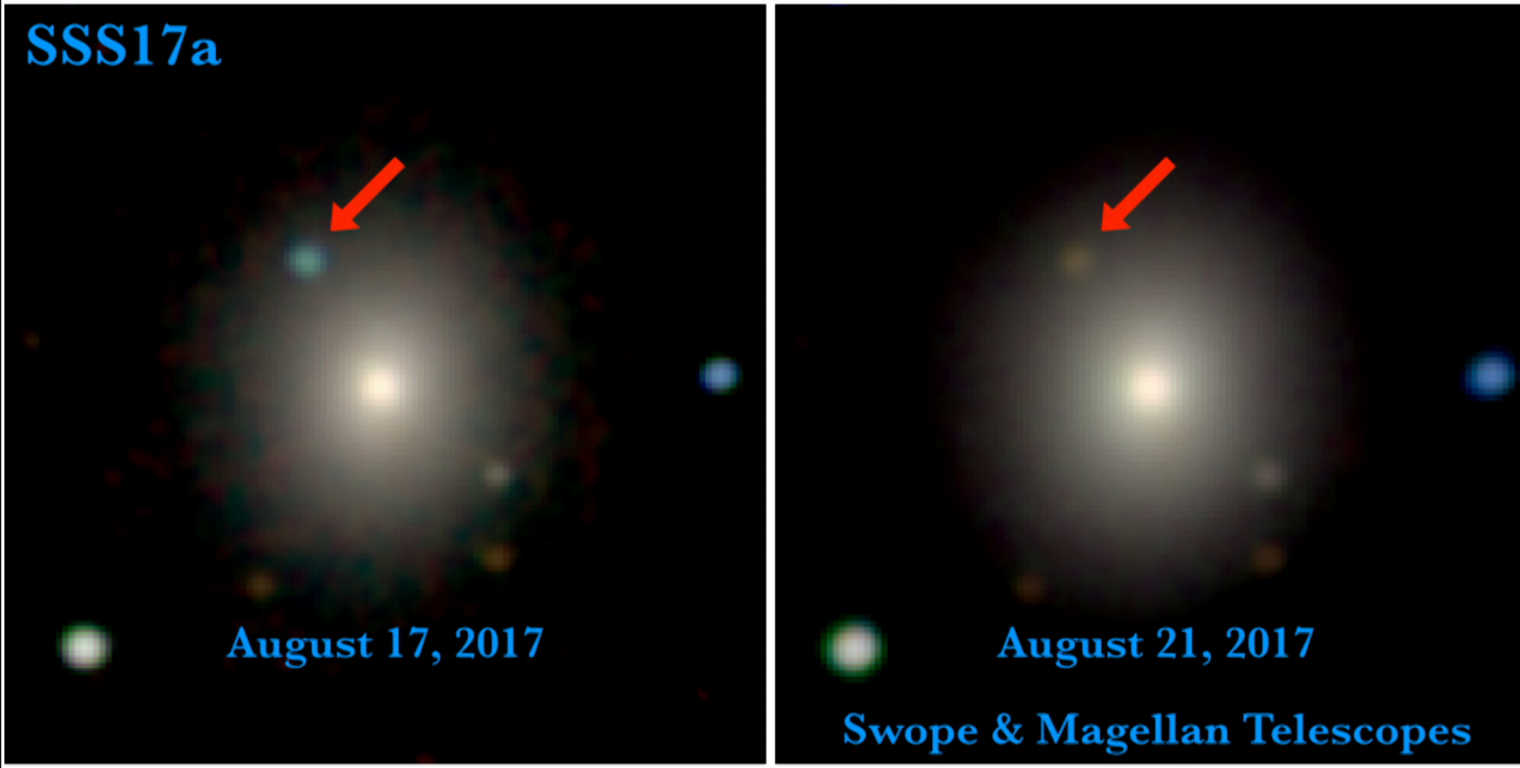
tilt
magnitude
$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0

# The merger rate densities

- BBH estimate 12-213 $Gpc^{-3}yr^{-1}$
- BNS estimate $R = 1540^{+3200}_{-1220}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

- Models have to explain these numbers!

# Host galaxy




NGC 4993 – old elliptical galaxy

# Basic challenges to the models

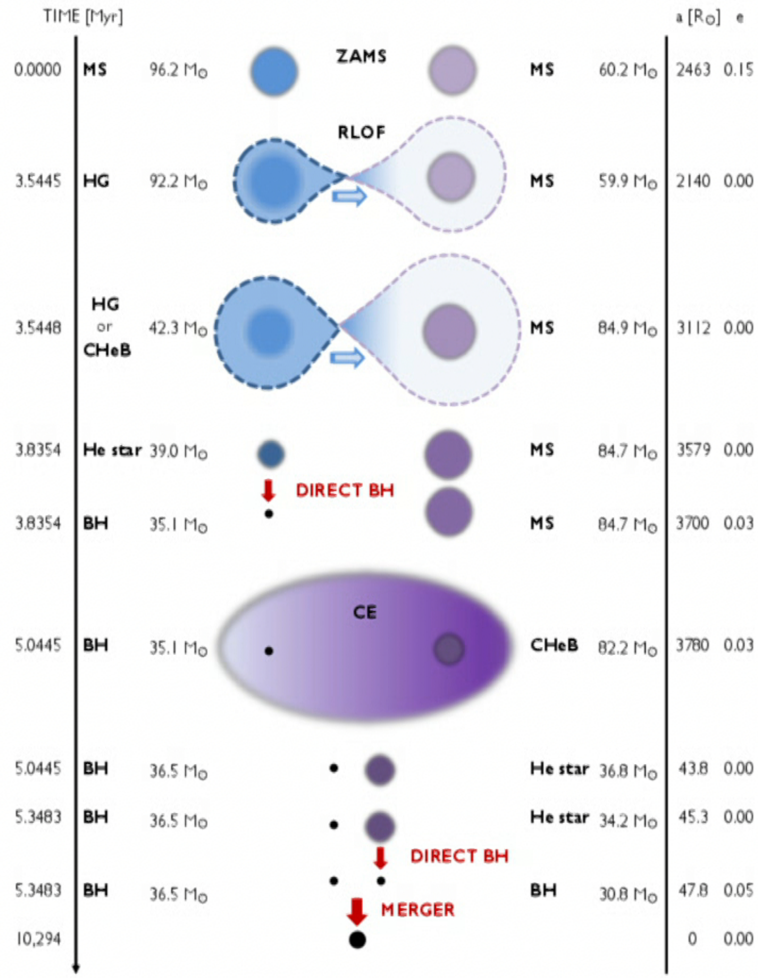
- How to make tight -merging - binaries even though the stars must have been much larger
- How to get the right mass distribution
- Be consistent with the spin constraints
- How to make the right number of binaries
- Host galaxies

# Models to pick from

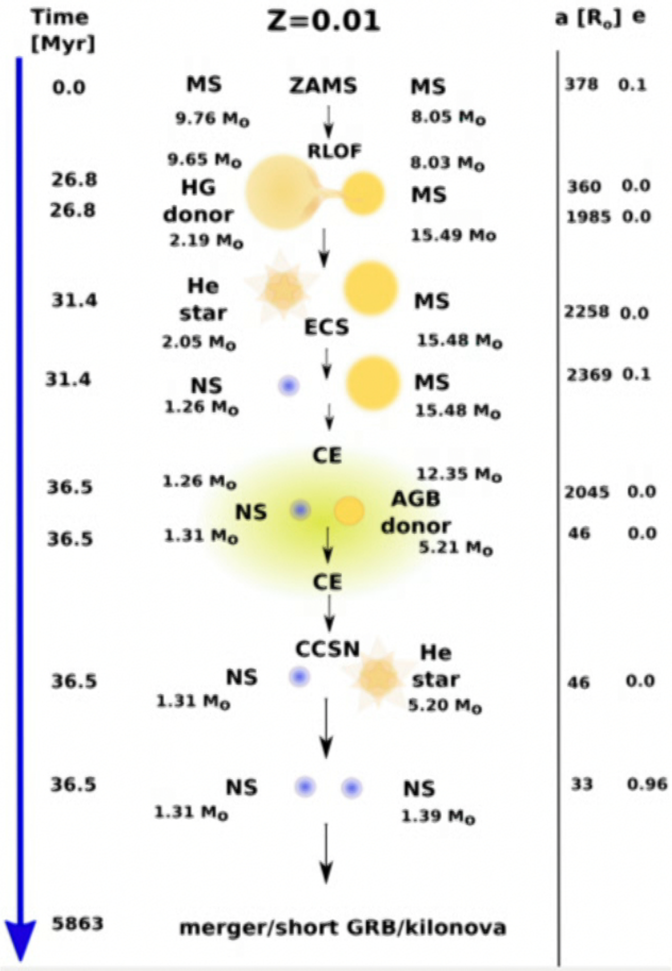
- Binary evolution
  - Standard
  - Chemically homogeneous case
- Evolution in the clusters
- Exotica
  - Pop III stars
  - Exceptional environments.

# Basic binary evolution scenario

CE →



# BNS




Delay distribution:

Typically

$$\frac{dN}{dt} \propto t^{-1}$$

for delay times above ~10Myr.

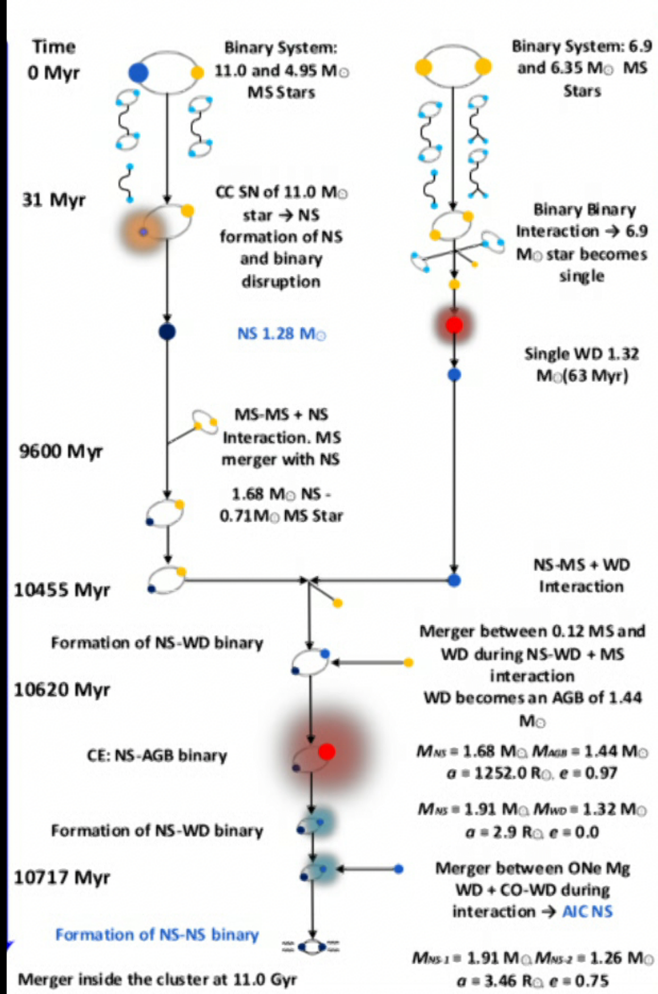
# Properties

- A generic scenario
- Most likely low metallicity needed for BHBH
- Spins tend to be aligned
- Need to pass through CE
- Delays between formation and merger.

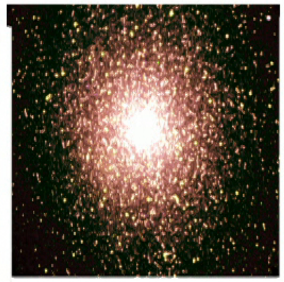
# Chemically homogeneous evolution

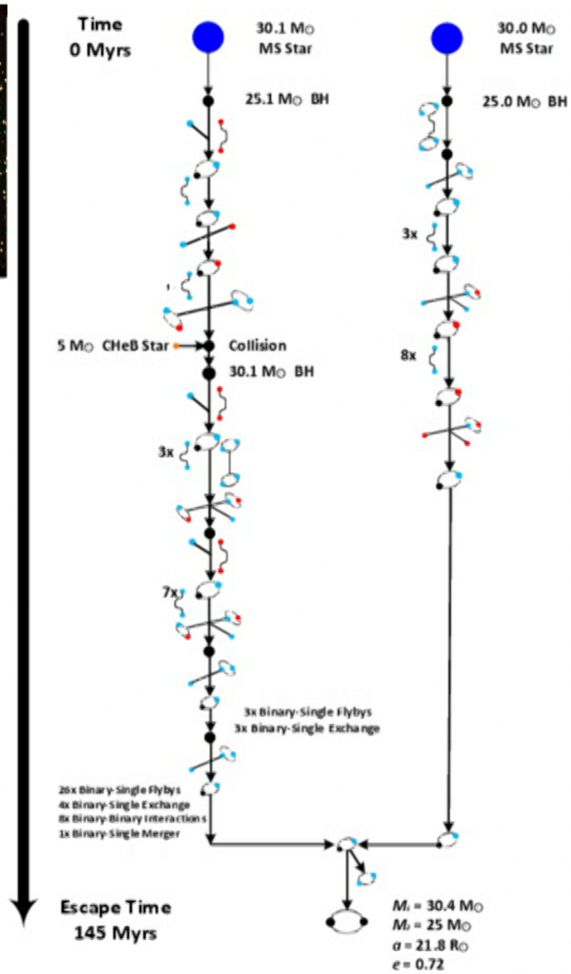
- Quick rotation mixes stellar composition
- Stars do not expand
- A close binary can stay close with no need for CE
- Nearly equal masses
- Aligned spins

# Clusters



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)
MS-MS + NS Interaction. MS merger with NS
9600 Myr
1.68 M☉ NS - 0.71M☉ MS Star
NS-MS + WD Interaction
10455 Myr
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
Formation of NS-WD binary
$M_{NS}$ = 1.91 M☉, $M_{WD}$ = 1.32 M☉
$a$ = 2.9 R☉, $e$ = 0.0
10717 Myr
Merger between ONe Mg WD + CO-WD during interaction → AIC NS
Formation of NS-NS binary
Merger inside the cluster at 11.0 Gyr
$M_{NS-1}$ = 1.91 M☉, $M_{NS-2}$ = 1.26 M☉
$a$ = 3.46 R☉, $e$ = 0.75



Time
0 Myrs
30.1 M☉ MS Star
30.0 M☉ MS Star
25.1 M☉ BH
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
$M_1$ = 30.4 M☉
$M_2$ = 25 M☉
$a$ = 21.8 R☉
$e$ = 0.72

# Properties

- Globular clusters constitute ~ 1% of stellar mass
- Exchanges facilitate making mergin binaries
- Ejections or hierachical mergers
- Spins random

# Exotica

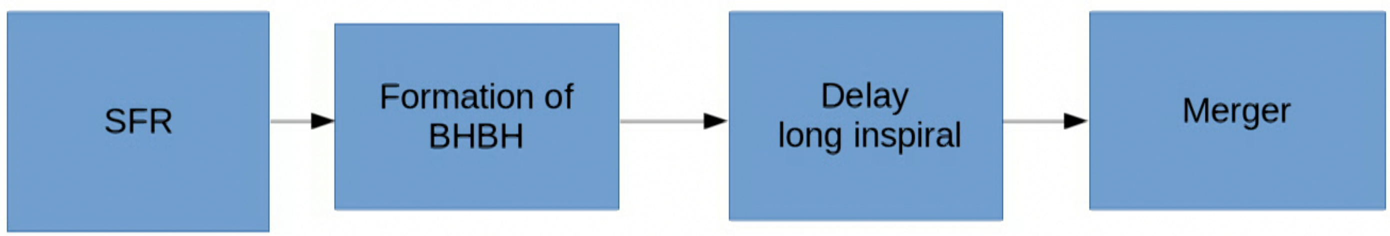
- Population III stars
  - Essentially a submodel of low metallicity binaries
- Primordial binaries
  - Why the masses?
  - Why now?

# The merger rate densities

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

# Local merger rates

- Fraction of mass processed stars
- Delays due to merger time
- Current merger rate is determined by the tail of the delay distribution for Pop III or GC models



# Rates

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

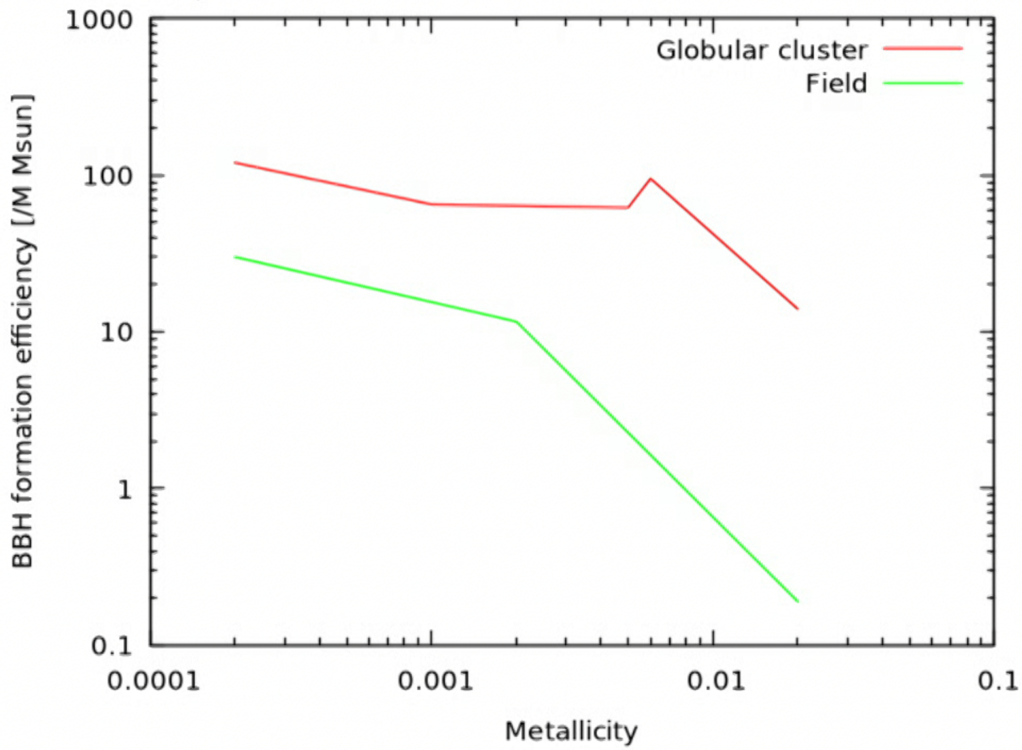
- Rate density: local and as a function of redshift

# BHBH formation efficiency

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

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

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



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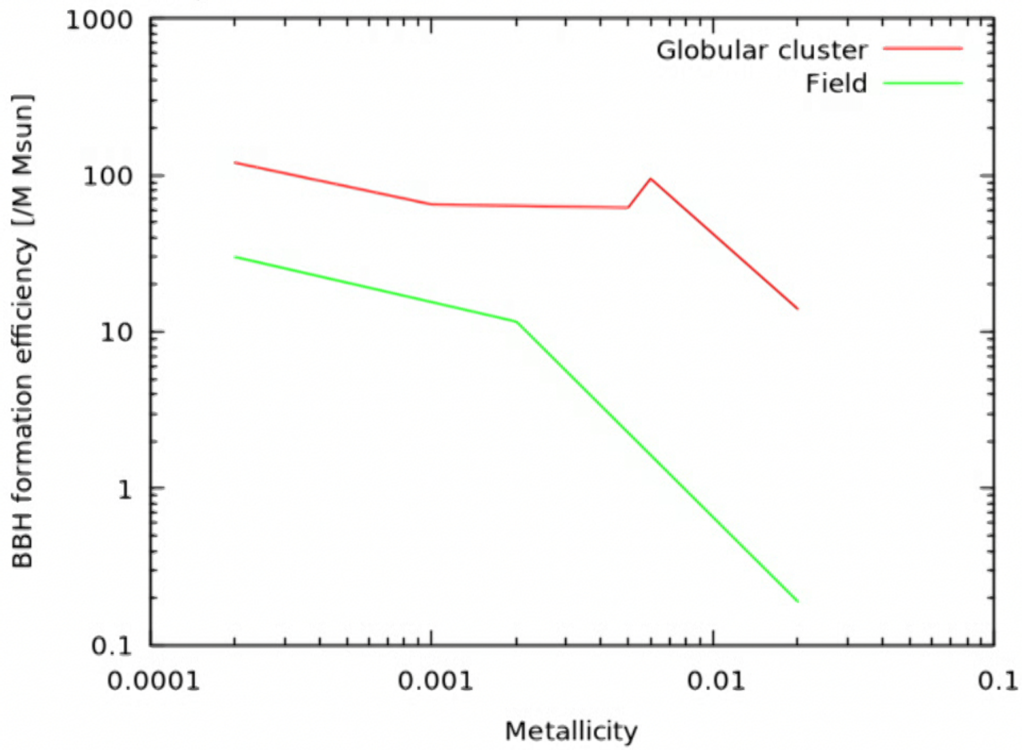
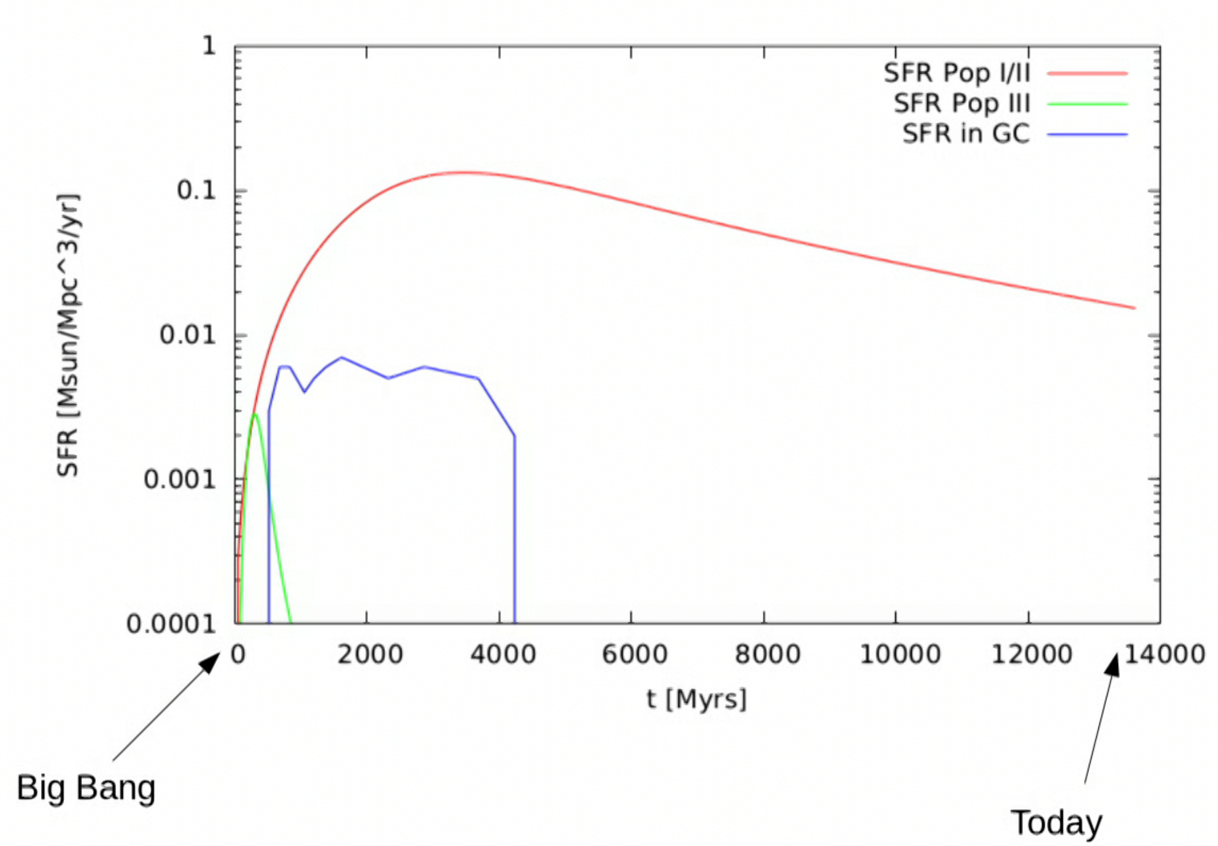
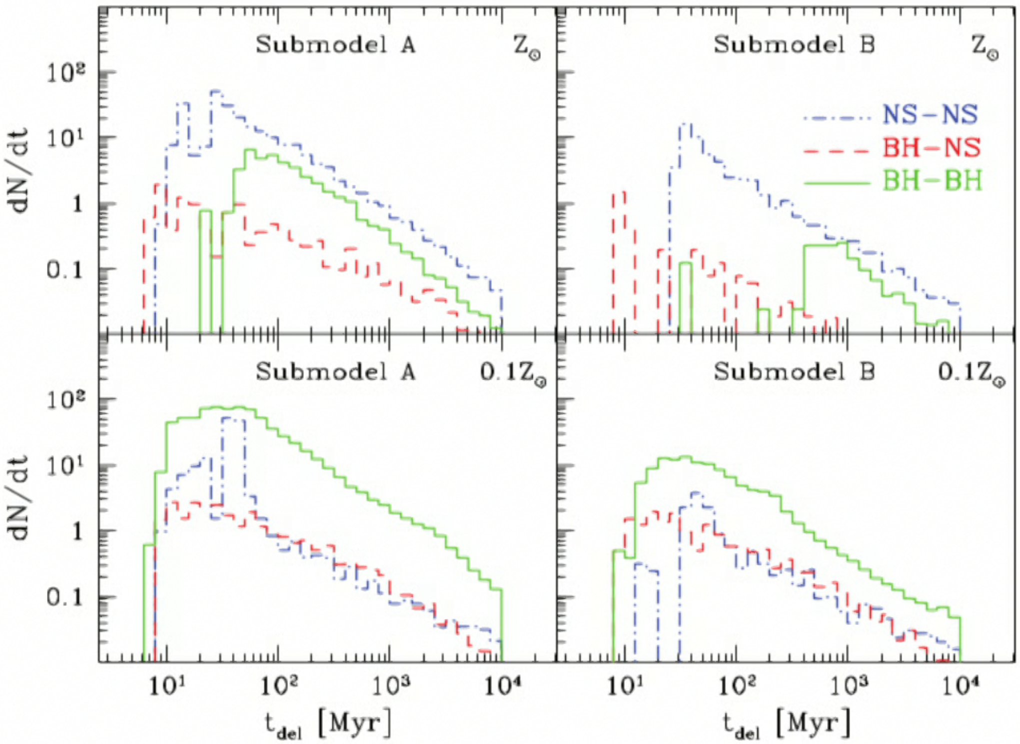


# SFR



SFR Pop I/II
SFR Pop III
SFR in GC
SFR [Msun/Mpc^3/yr]
1
0.1
0.01
0.001
0.0001
0
2000
4000
6000
8000
10000
12000
14000
t [Myrs]
Big Bang
Today

# Properties of the population – delay time distribution



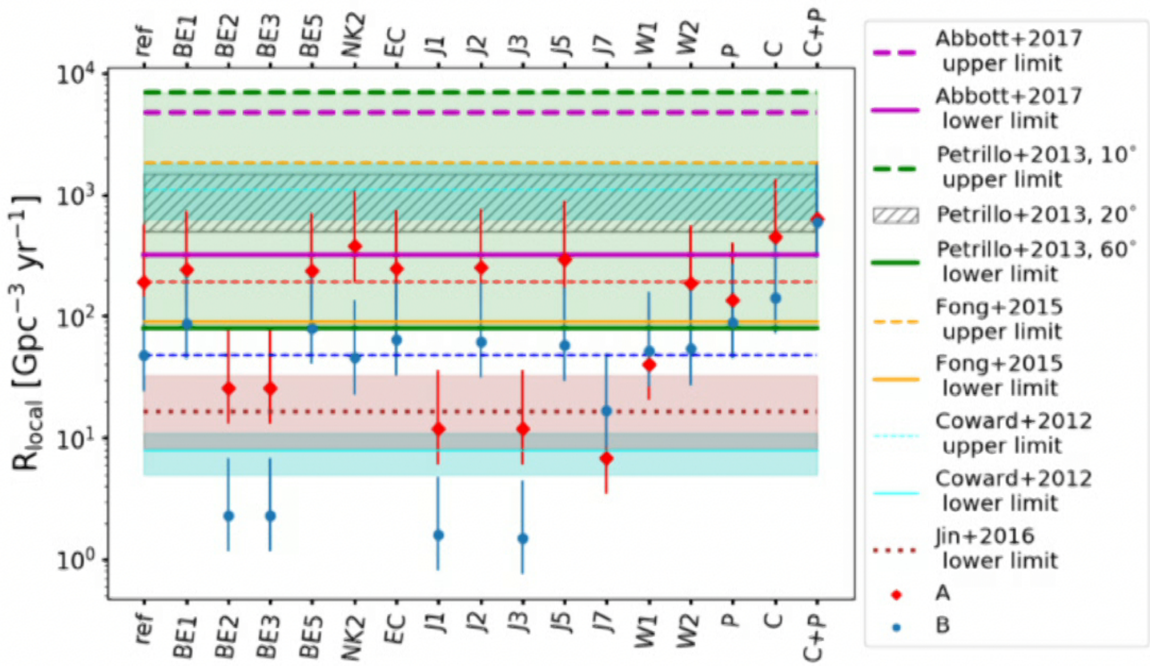

$$P_{delay}(t) \propto t^{-1}$$

Dominik et al 2012

# Basic rate arguments

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

# Local rate density of BNS mergers




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

Diamonds / cirles – different modes of Common Envelope evolution

## The rate implications

- Total GW luminosity density in the sky from NSNS mergers

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

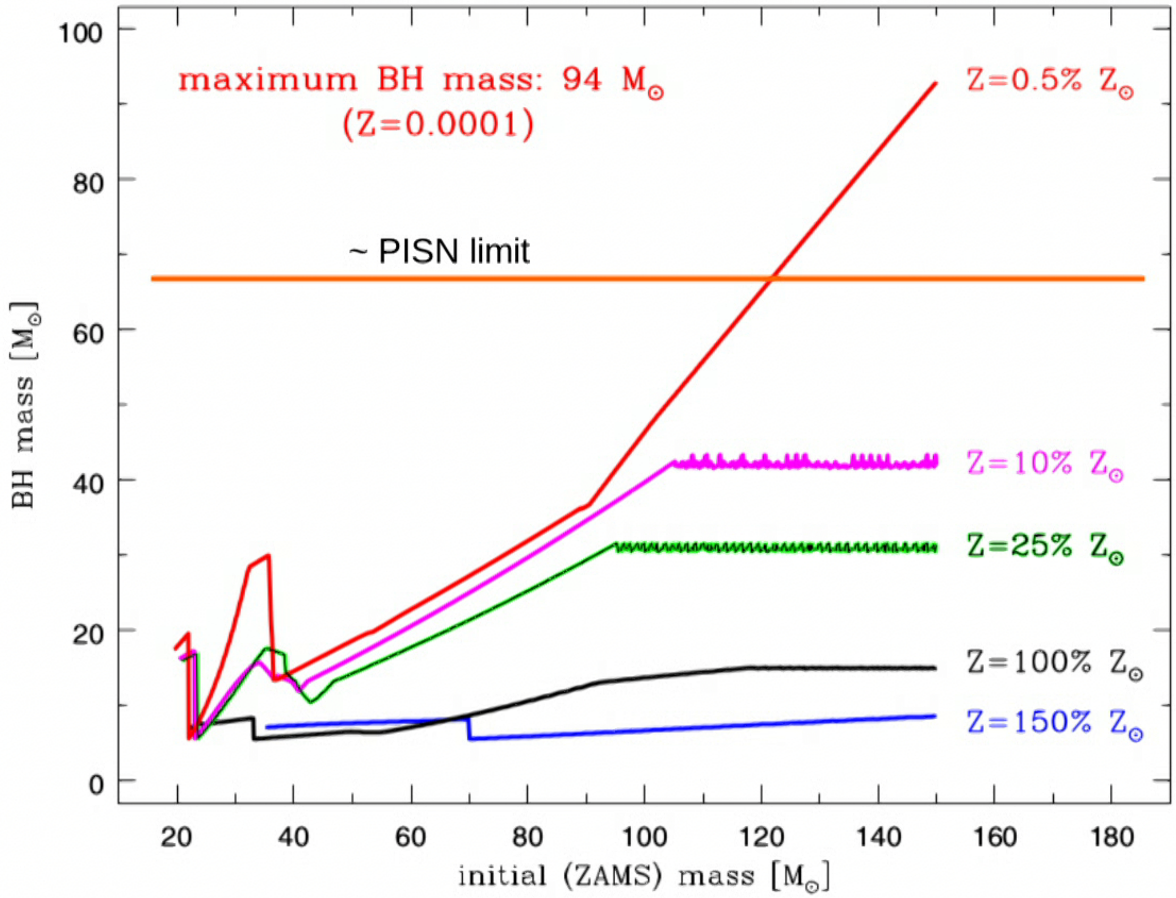
- The luminosity density of BHBH mergers is about 10 times larger

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

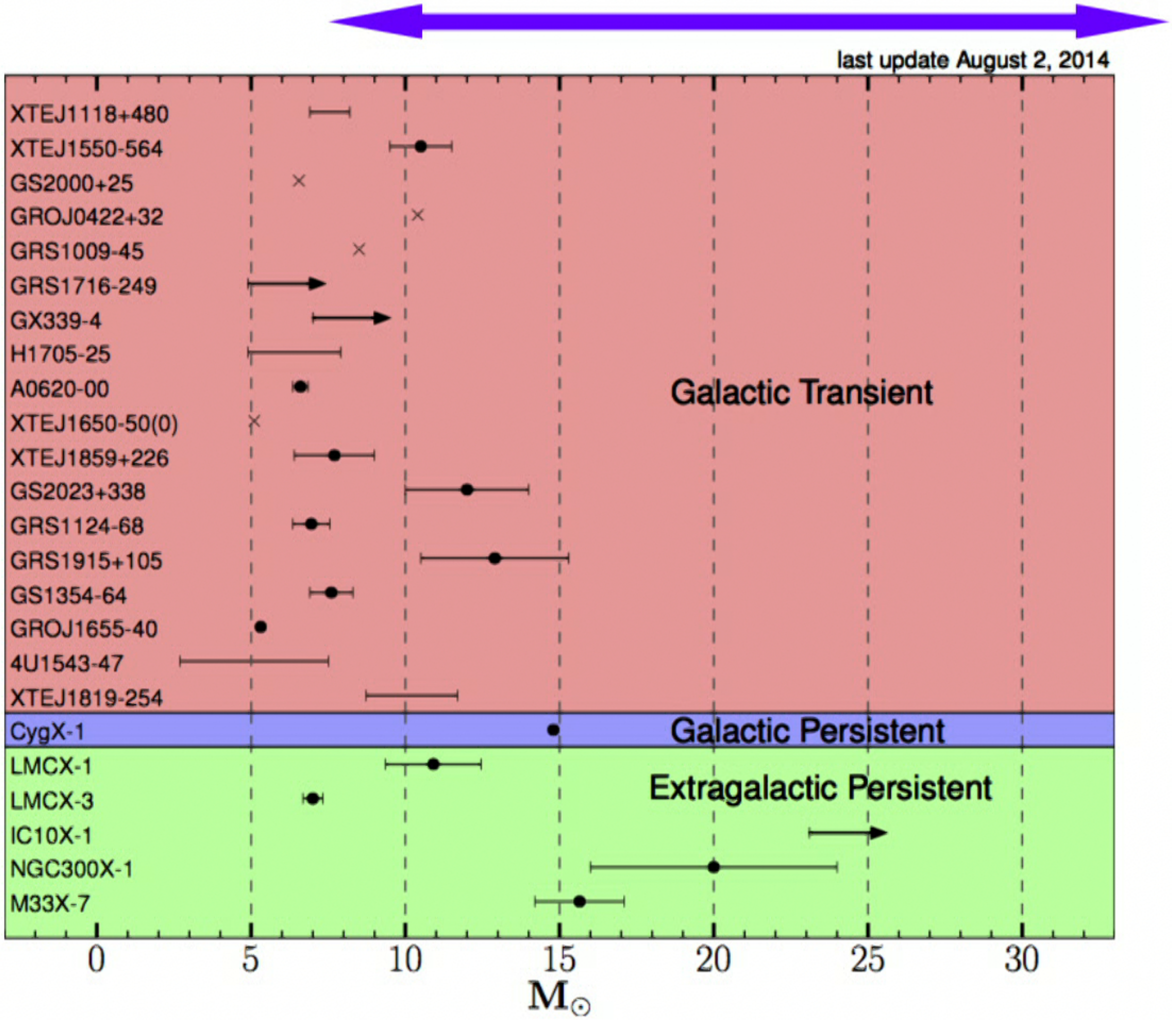
- EM luminosity density of all galaxies:

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

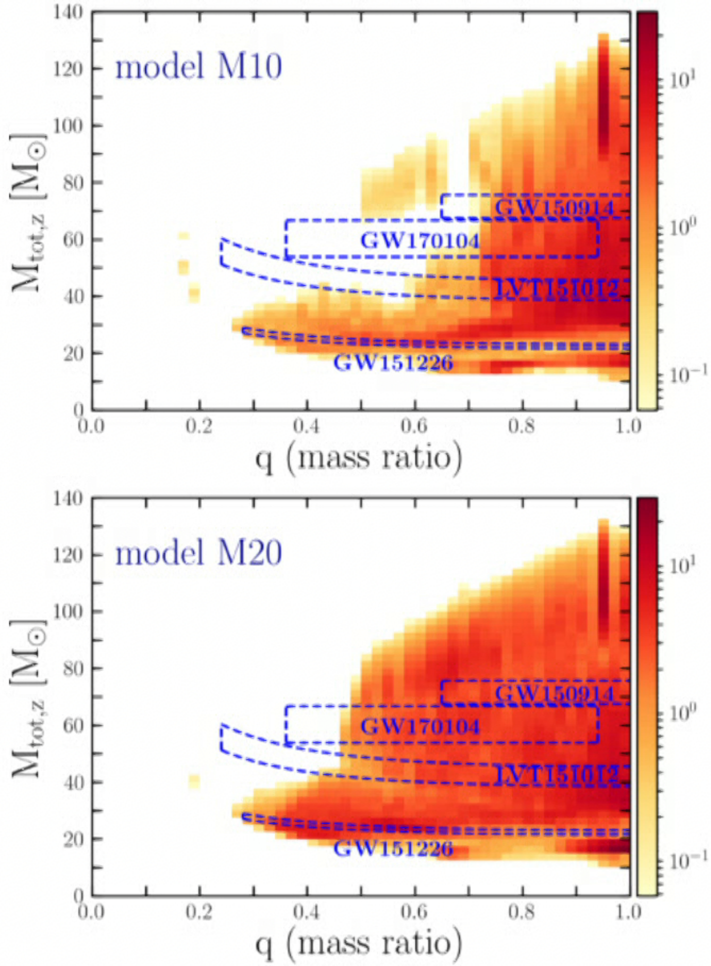
# On the maximum mass of BHs



# 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.

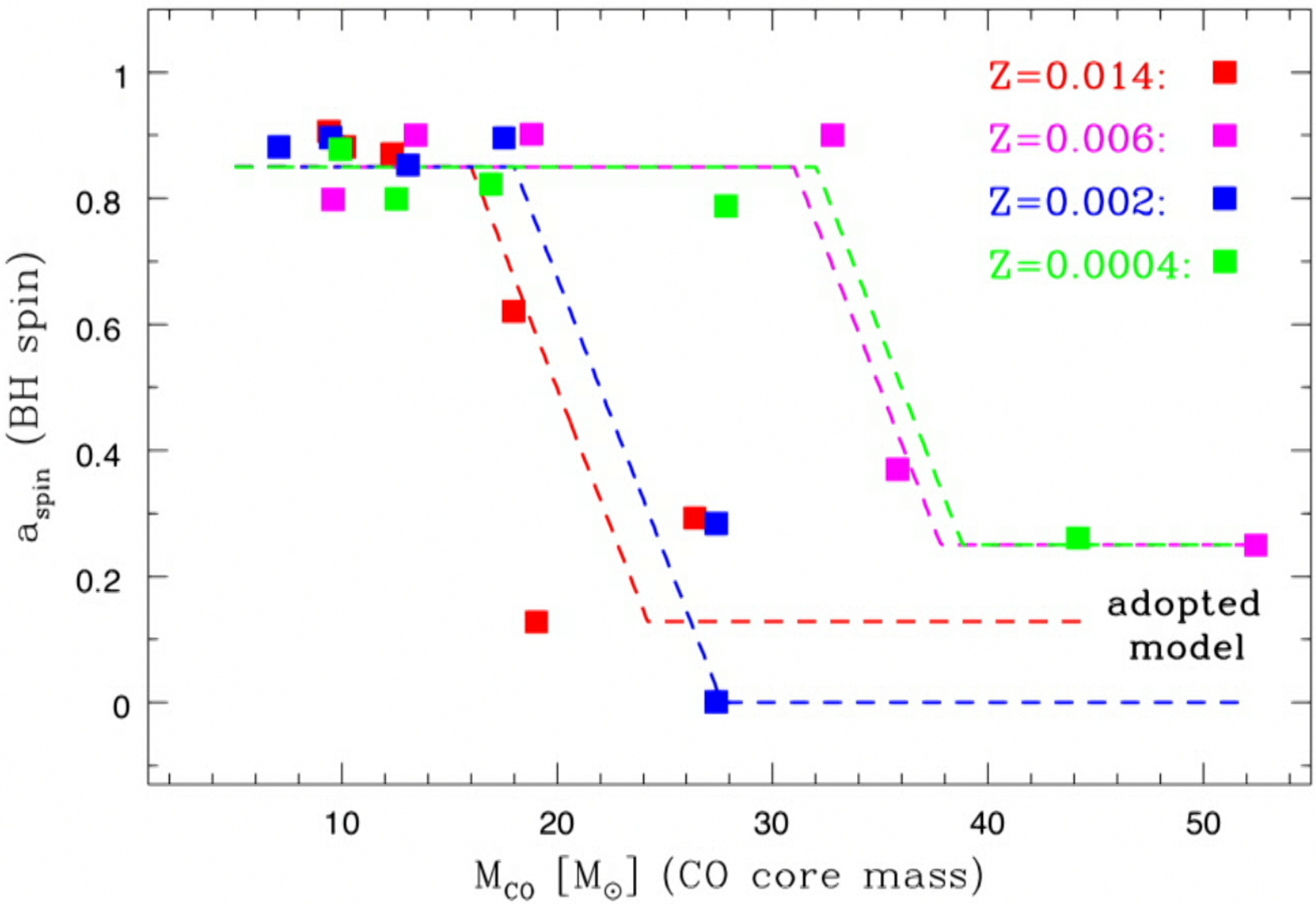
# Spin constraints

- Main question:

  What are the BH initial spins?

  Do they depend on mass, metallicity?

  Do they differ in X-rays and in GW?

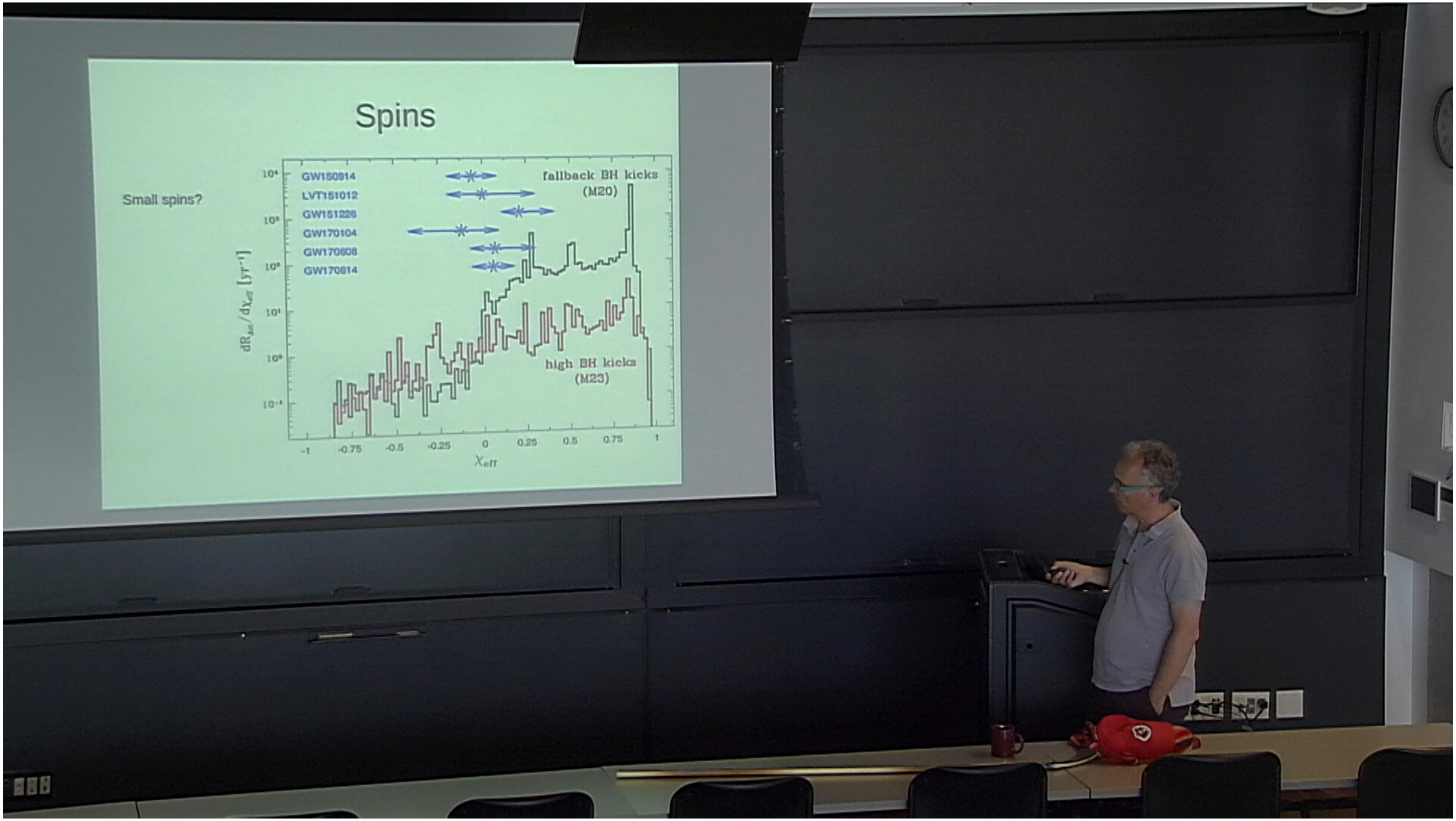


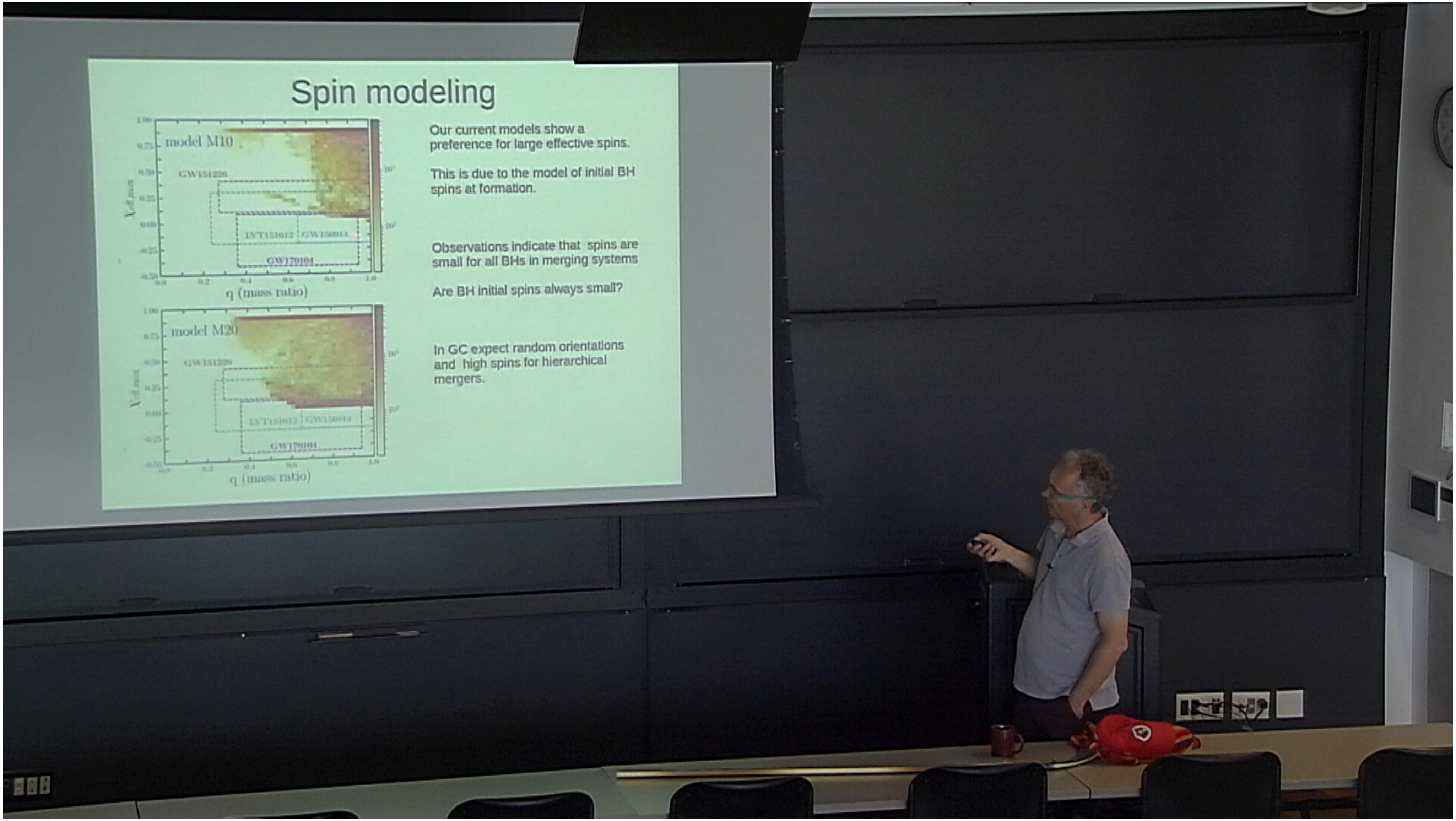
Z=0.014:
Z=0.006:
Z=0.002:
Z=0.0004:
adopted
model
1
0.8
0.6
0.4
0.2
0
$a_{spin}$ (BH spin)
10
20
30
40
50
$M_{CO}$ [$M_\odot$] (CO core mass)


Masses of
GW170817
X-ray/optical
binaries
double
neutron star
binaries
white dwarf-
neutron star
binaries
main sequence-
neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass (M☉)


Masses of
GW170817
X-ray/optical
binaries
double
neutron star
binaries
white dwarf-
neutron star
binaries
main sequence-
neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)

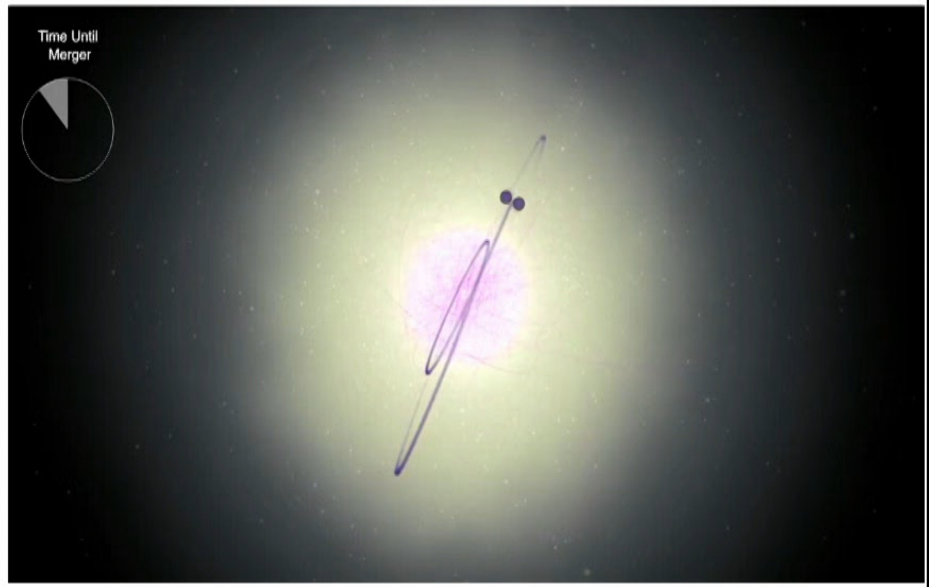

Spins
What are the BH initial spins?
How does the evolution affect them?
Binaries – tend to be aligned with angular momentum but that depends on the BH formation scenario
GC – no reason to be aligned


Spins
Small spins?
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
fallback BH kicks
(M20)
high BH kicks
(M23)
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1


Spin modeling
model M10
GW151226
LVT151012
GW150914
GW170104
q (mass ratio)
model M20
GW151226
LVT151012
GW150914
GW170104
q (mass ratio)
Our current models show a preference for large effective 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 hierarchical mergers.

# Host galaxy

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



# Host galaxy

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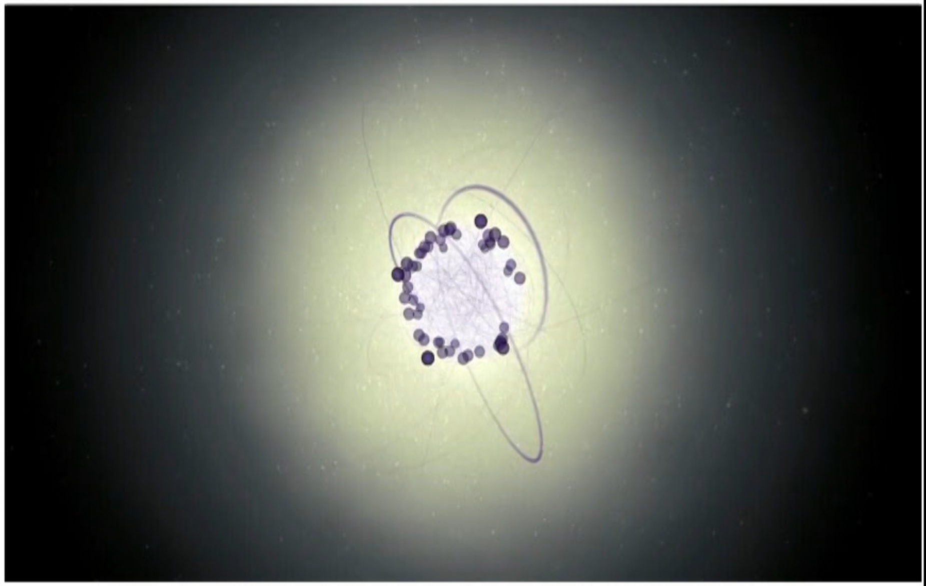
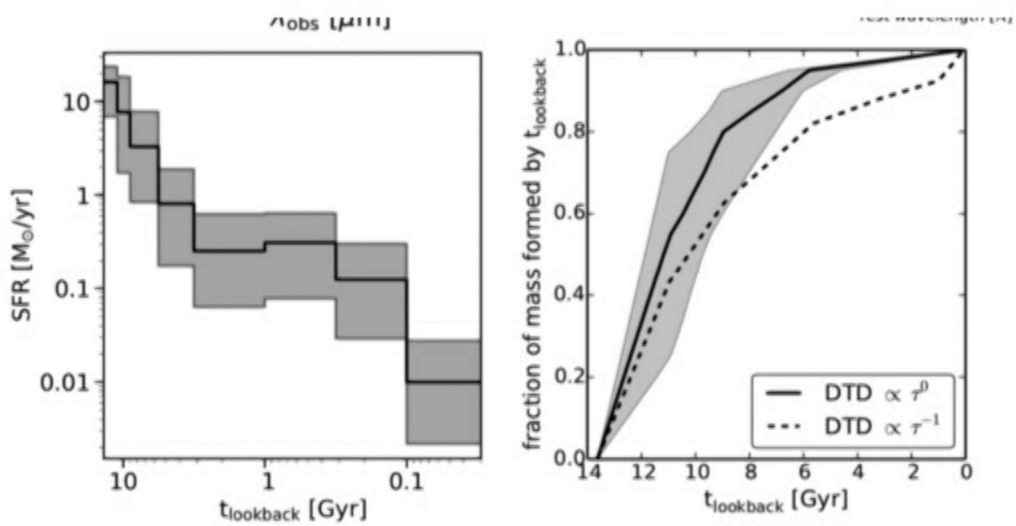


# Star formation history estimate

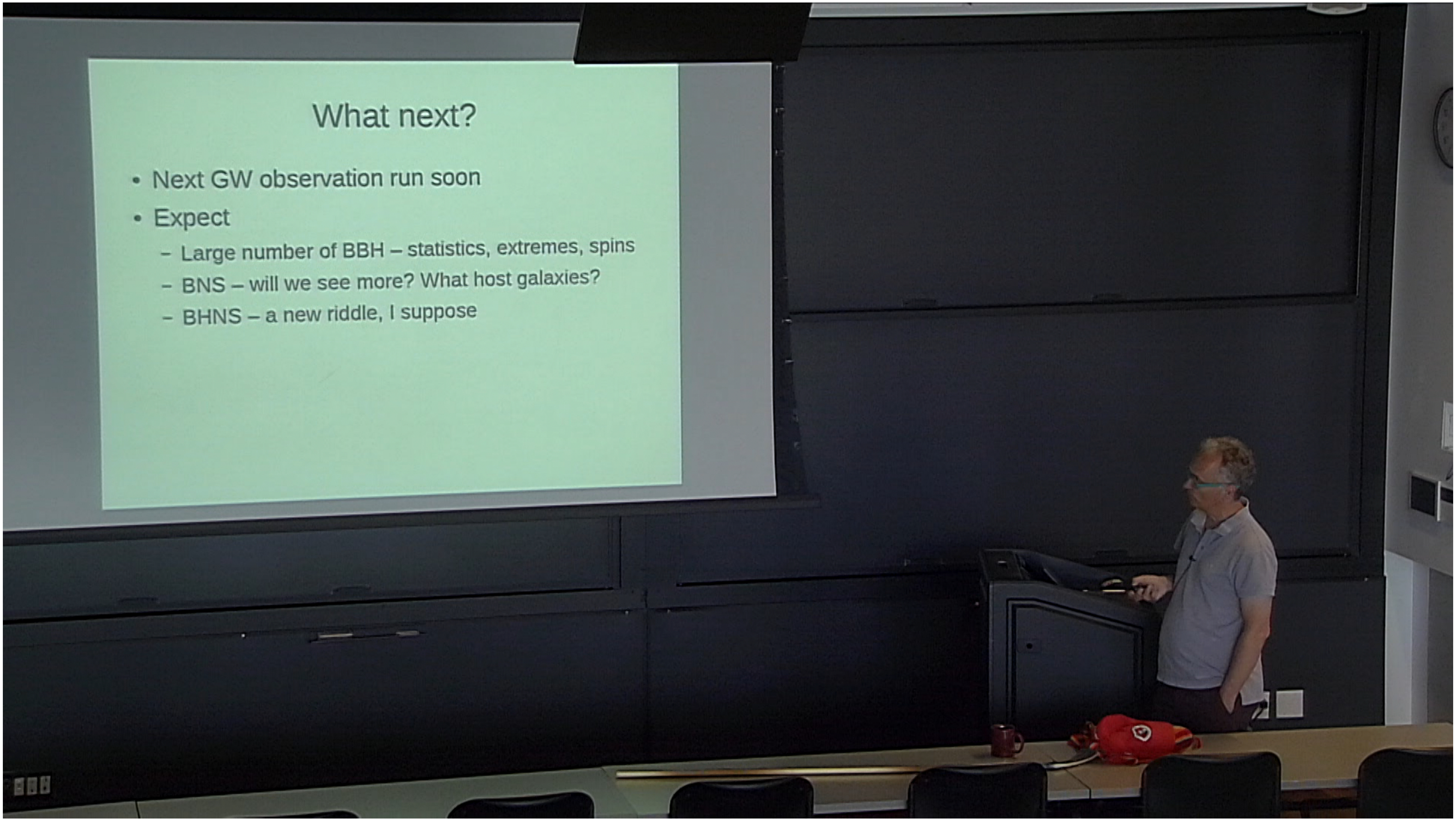


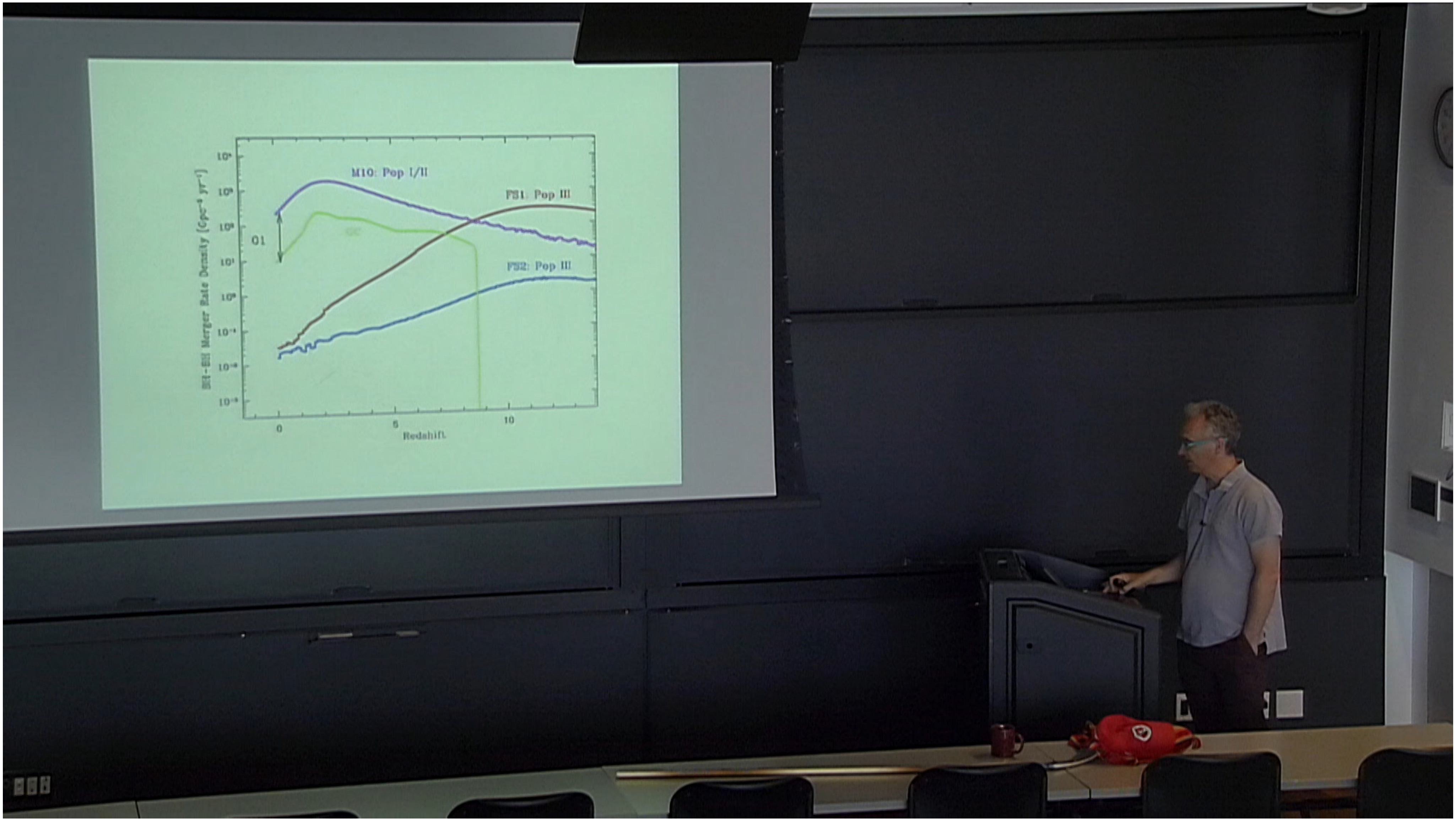

Blanchard 2017

# Open issues

- Rates seem to be high
  - There are models that are marginally consistent with the rates
  - Globular cluster origin – tough to reconcile with observations
- 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


Hopes and expectations
• Nearby future
• Far future


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


M10: Pop I/II
FS1: Pop III
FS2: Pop III
O1
BH-BH Merger Rate Density [Gpc⁻³ yr⁻¹]
Redshift
0
5
10


Conclusions
We have entered the era of gravitational wave astronomy
The interaction between observations and theory of sources is extremely interesting
Looking forward to the bright new future!

# Astrophysics of coalescing compact object binaries

Tomek Bulik (University of Warsaw)

with

K.Belczynski, D.Holz, R.O'Shaughnessy, T.Ryu, E.Berti, C.Fryer, T.Klencki, W.Gladysz, M.Chruslinska, M. Giersz, A. Askar, D.Rosinska, A.Ruiter, D.Brown, A.Heger, S.Woosley, D.Gerosa, R.Perna, T.Takamitsu, M.Benacquista