Population synthesis and binary black hole merger rates

Richard O'Shaughnessy

Vicky Kalogera, Chris Belczynski

LSC

8-19-2004

LIGO-G040405-00-Z

BBH rate from Population Synthesis

- No known BBH sample → rates from astrophysical theory

- Population synthesis:
  - Representative sample [masses, orbits]
  - Evolve, modulo (many!) **parameters**:
    - → Each fairly well-constrained
    - → **vary 7** (=for Milky Way: SN kicks, CE efficiency, ..)

- Slow evaluations:
  - ~ 40 cpus
  - 1270 binaries/hour/cpu
  - 10^5-10^7 binaries needed per model

  } ~ O(3-30) days/model/cpu

- Context: Previous PS calcualtions
  - Explore *dependence*, not *likelihood*

Astrophysical uncertainties: Supernovae

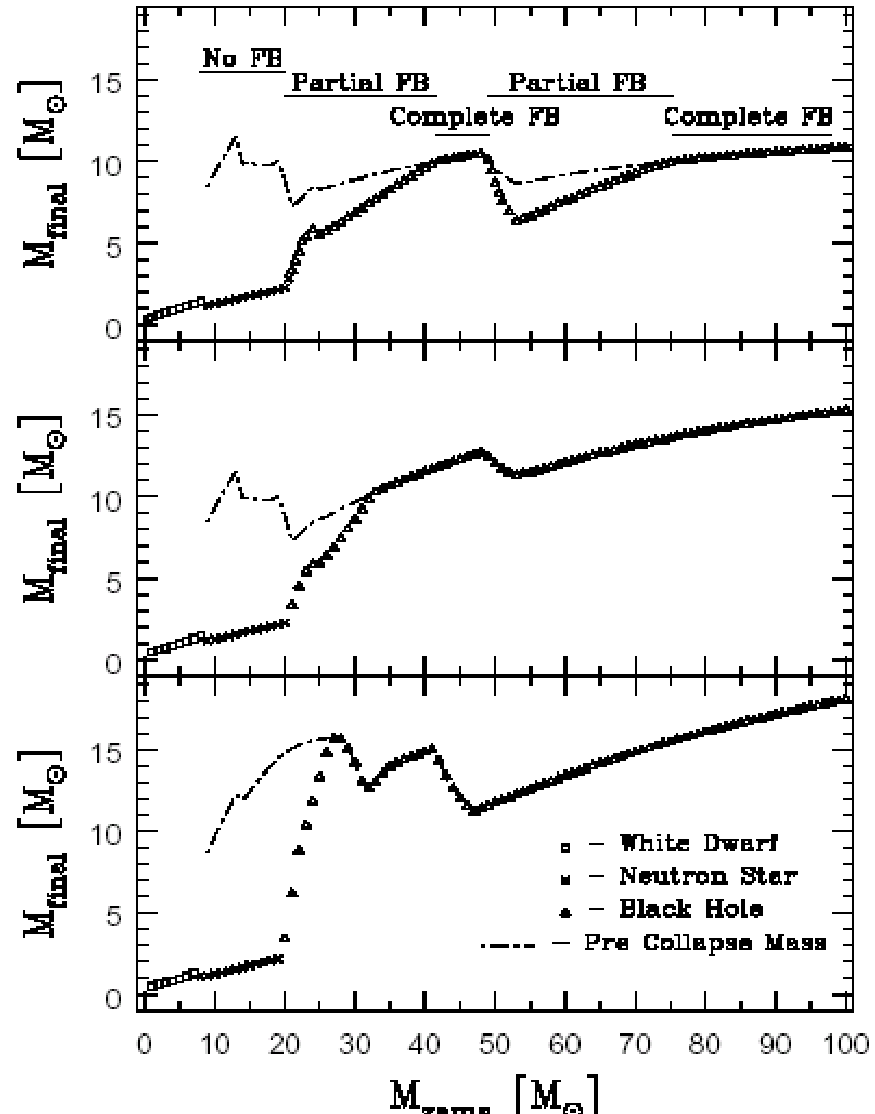
- What is remnant?
  - $M_{before} > M_c \rightarrow$ BH
  - $M_{before} < M_c \rightarrow$ NS

… we use $M_c = 22\ M_o$

(e.g., Heger et al 2003, …)

- Kicks imparted to remnant BH
  – Evidence for explosions in BH systems (XRB)

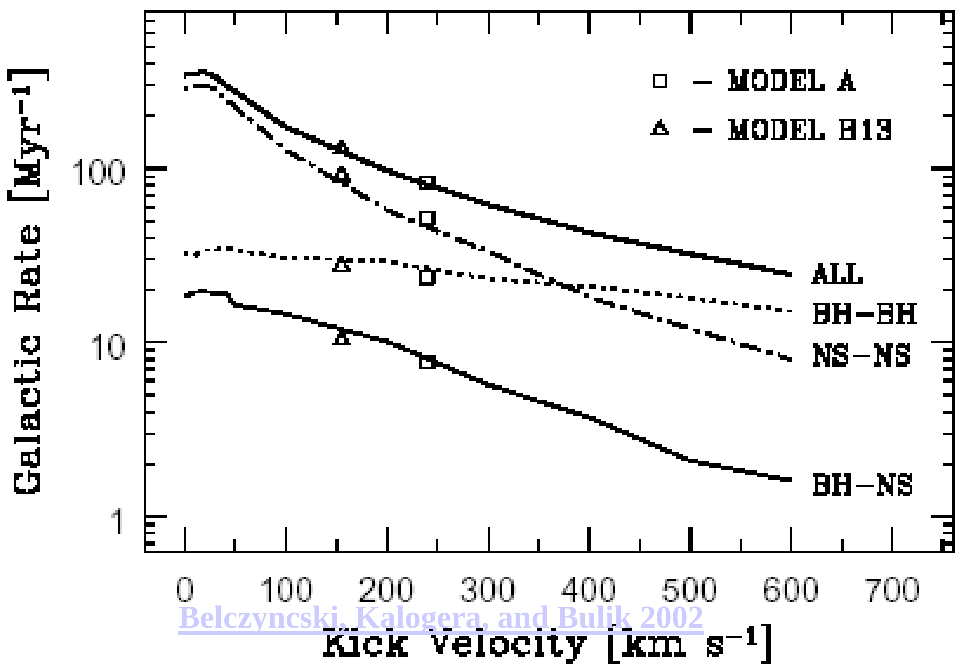
  – Zero BH kicks *unlikely* a priori



Population Synthesis:
Parameter dependence

Despite best constraints on models

→ broad range of compact object merger rates, even versus one parameter



Belczyncski, Kalogera, and Bulik 2002

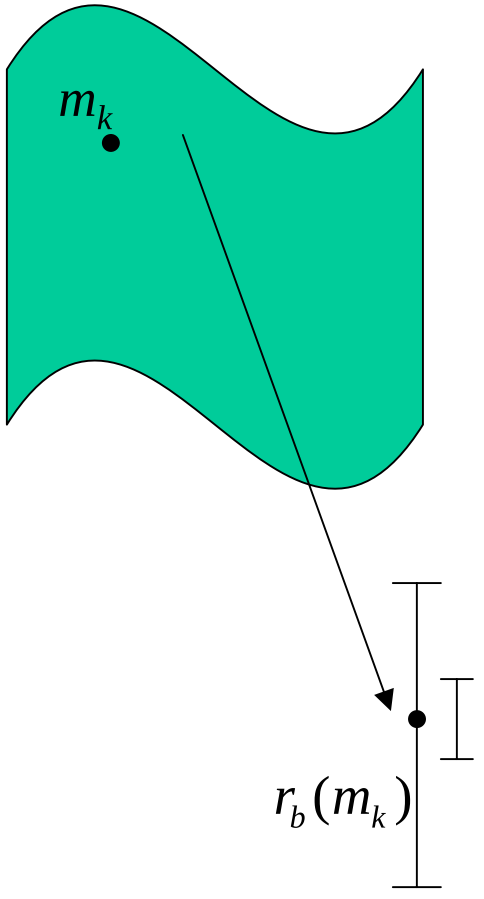
Example:

Rate versus peak

SN kick strength

BH-BH rate distribution

<u>Monte carlo</u>:



- <u>Method</u> : Histogram
  - sample points m_k
  - find $r(m_k)$, bin

→ *possible* only with faster code!

Population Synthesis:
Directed searches

- Targeted search

  → **speedup**

  1) Fixed relative accuracy:

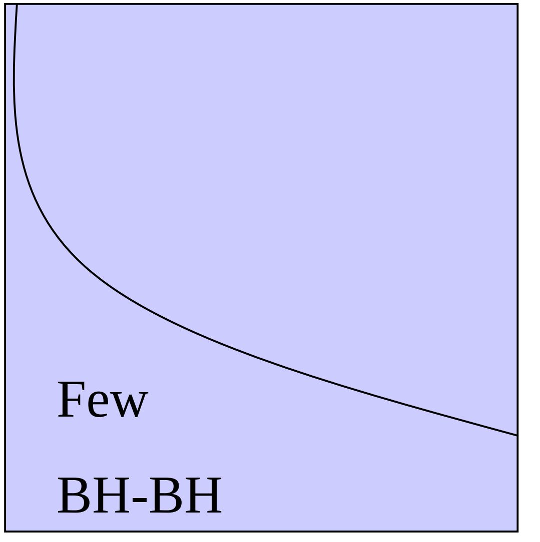
     …run until BBH rate known to O(30%)

  2) Ignore systems:

     - Runtime [when become irrelevant]
     - Initially [based on *experience*]
       - Early runs → what progenitors are likely always irrelevant (non-BBH)
       - Later runs → ignore?

Population Synthesis:
Directed searches

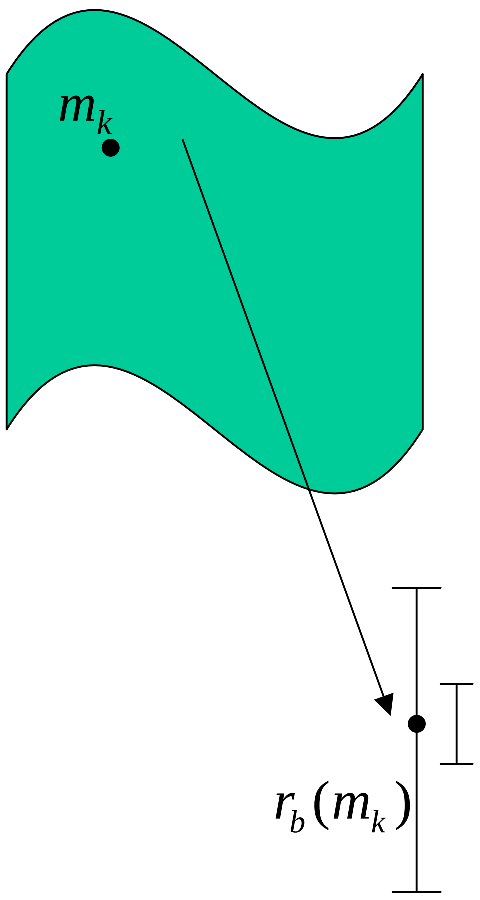
- <u>Practical optimization</u>:
  - <u>Partition surface</u>:
    …separate progenitors of BH-BH from others
    …plan to **ignore** all progenitors on one side of the cutoff
    [for **all** PS parameters]
  - <u>Genetic algorithms</u>
    →search for optimal cutoff
    →use early runs as reference



Speedup (from just this cut)	Error probability (average)	Error probability (worst case)
x 10	0.14%	12%

BH-BH rate histogram

Monte carlo:



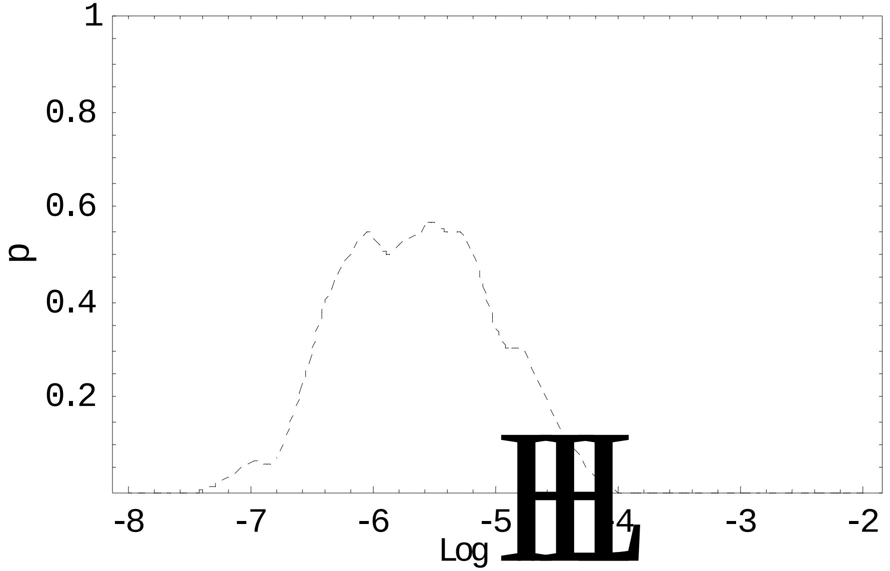
- Method :

  312 sample points m_k

  → Find $r(m_k)$

  Histogram

BH-BH rate histogram



R = rate/year/MW

1 merger/Myr/(Milky way)galaxy

312 sample points:

…first rate distribution

Normalization:

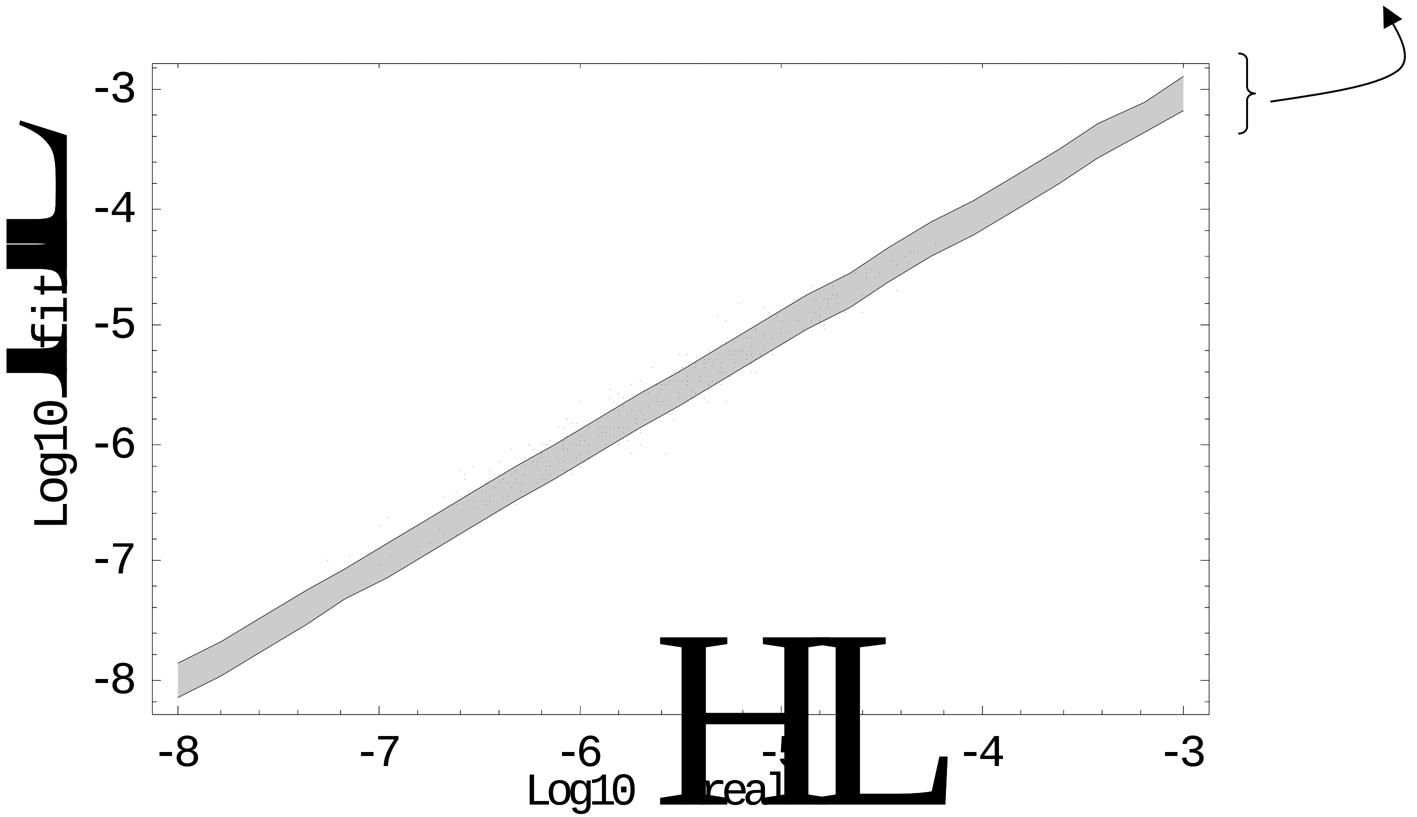
$$\int \rho(r) d \log_{10} r = 1$$

BH-BH rate histogram

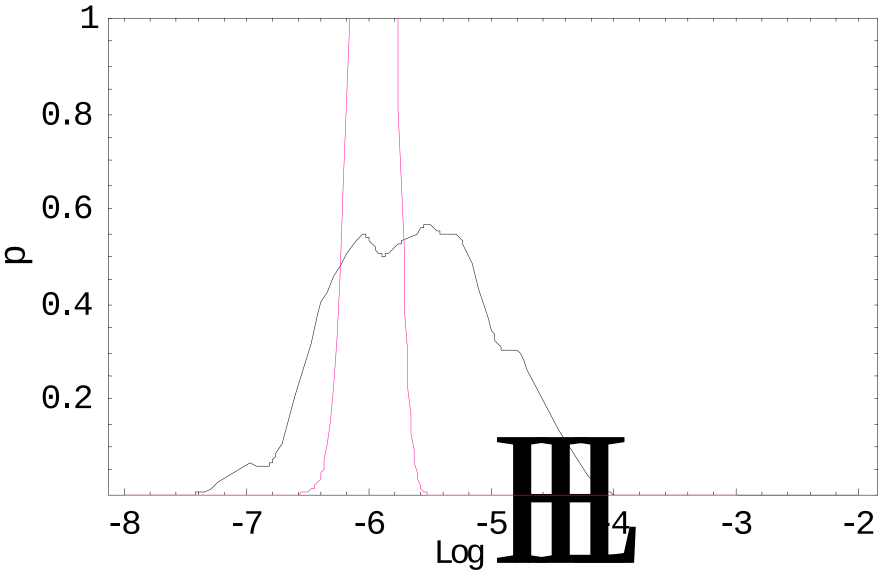
- <u>Adequate sampling:</u>

  We have enough points to **fit** rate in 7d

Fit near limit of 30% uncertainty in each data point



BH-BH rate histogram



R = rate/year/MW

smallest resolvable rate

- Well-resolved:

  -Sensitive to low rates

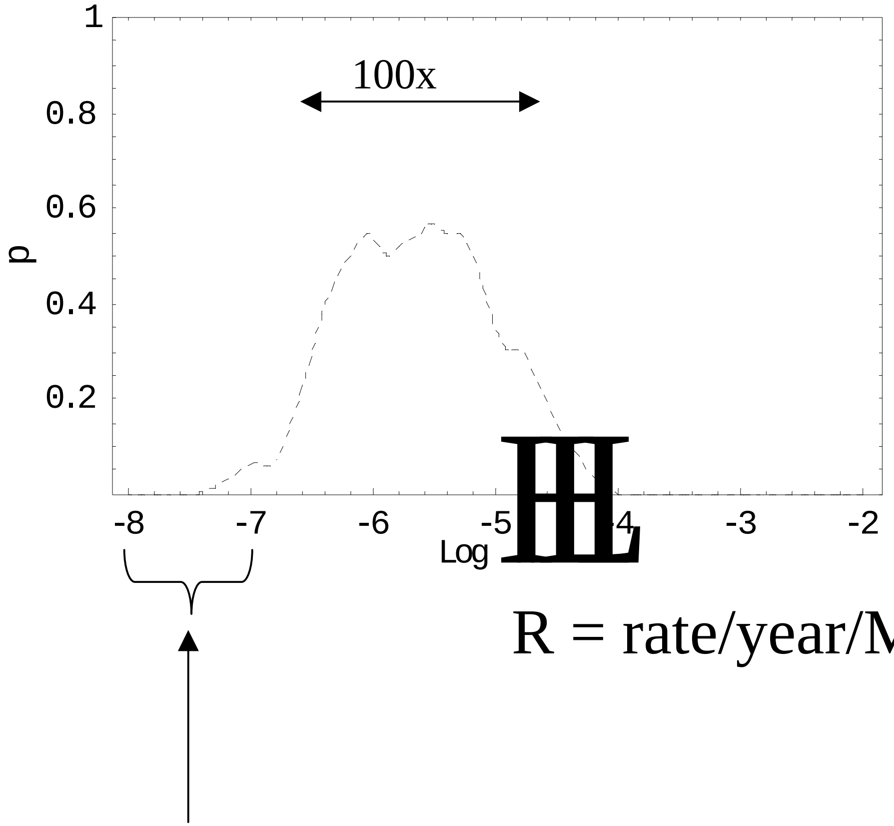
  (> 10^{-8}/yr/Milky Way)

  -Low intrinsic errors

  - Rates known to 30%
  - Example: Purple curve

    expected result given rates = 10^{-6} always

BH-BH rate histogram



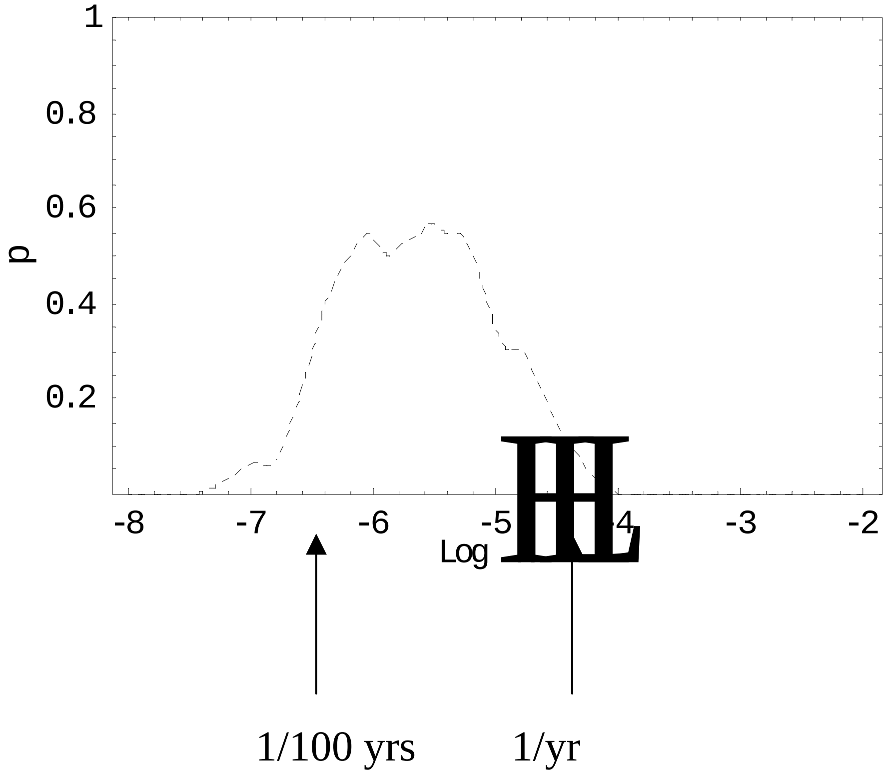
R = rate/year/MW

no rates here…

<u>Results</u>:

- Bounded:
  - – no evidence for very low rates (yet)
- Broad range:
  - > 100x uncertainty

BH-BH rate histogram



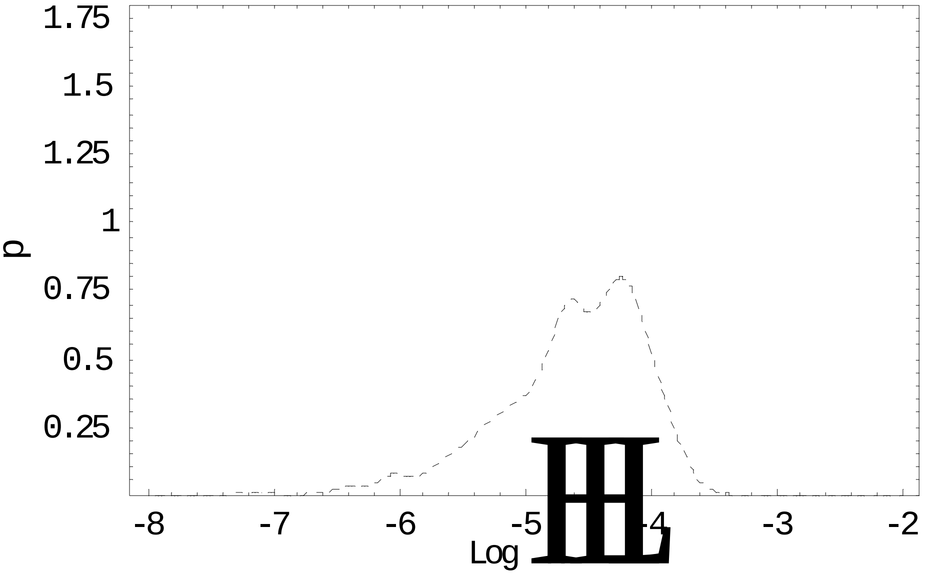
- <u>LIGO-I detection rates:</u>
  - M=10 M_o
  - D_{BH}= 100 Mpc

$$R_{LIGO} = R\rho 4\pi D^3 / 3$$

…Then add more **constraints**

Example: NS-NS merger rate

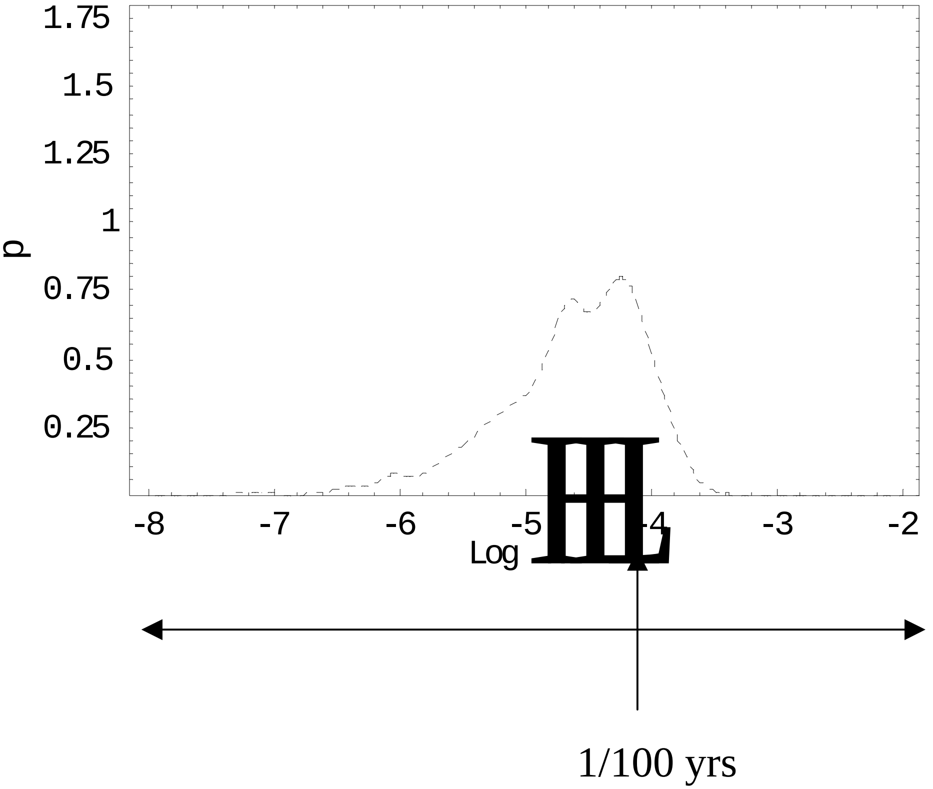
NS-NS rate distribution



Poor constraint:

>O(50x) uncertain

NS-NS rate distribution



Poor constraint:

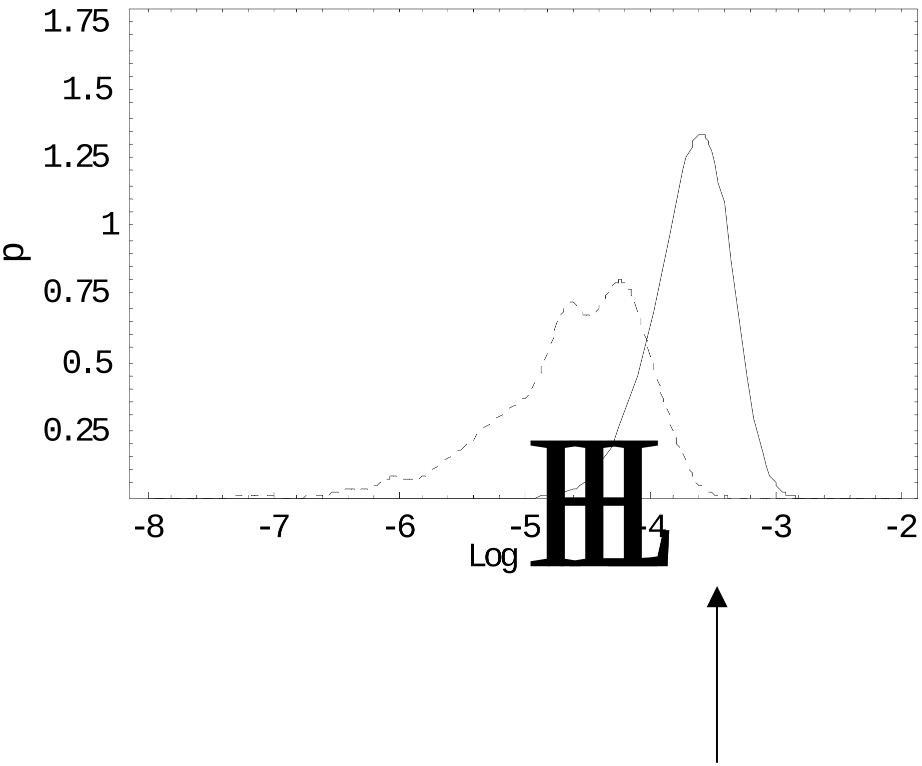
>O(50x) uncertain

LIGO rates:

- $M=1.4\ M_o$
- D_{ns}= 20Mpc?, 350 Mpc ?

  [network range, 1+1+1/2; **ref??**]

NS-NS rate distribution

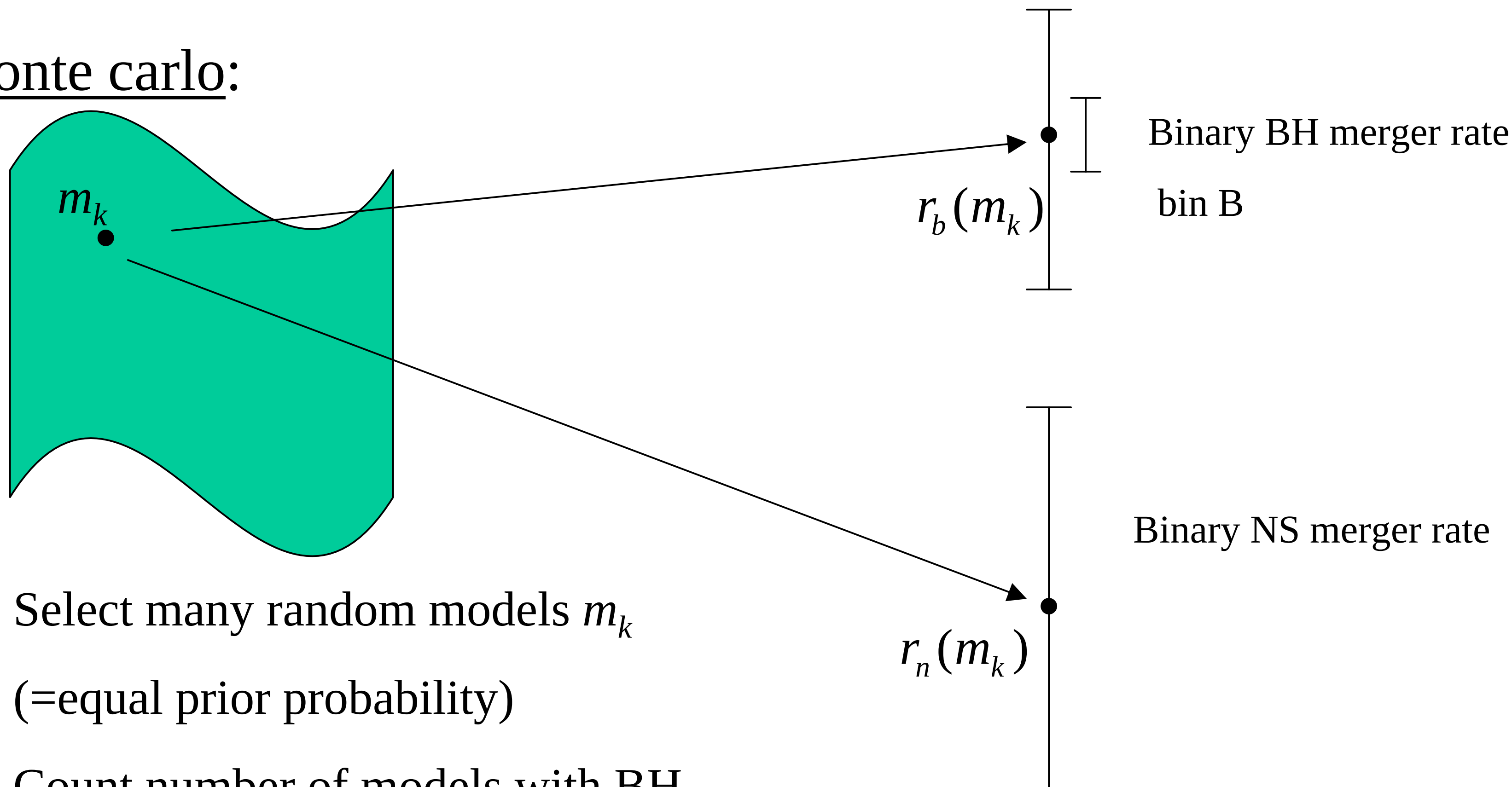


- Binary pulsar sample:
  - 4 in our galaxy
    [B1913, B1534, J0737, J1756]
- Selection effects
  → *Likelihood* distribution for NS-NS merger rate
  [Kalogera, Kim, Lorimer ApJ **584** 985 : astro-ph/0207408]

…empirical rate > prior rate

NS-NS rate as constraint: method

Monte carlo:



1. Select many random models m_k

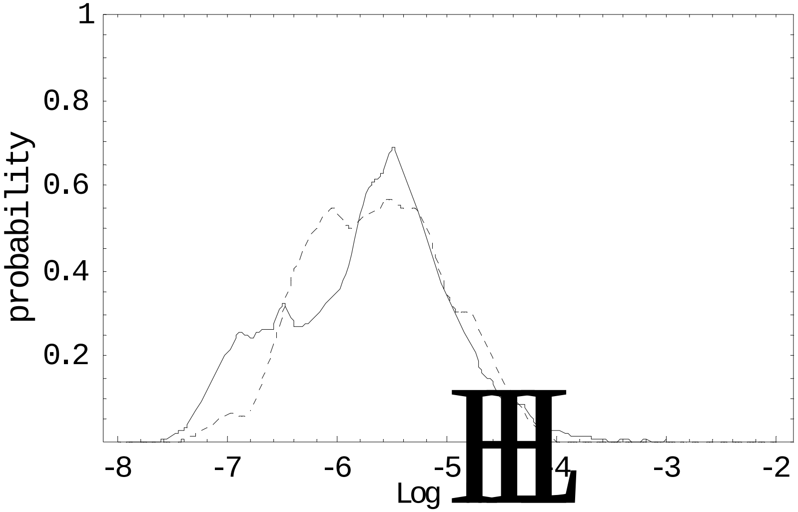
   (=equal prior probability)

2. Count number of models with BH merger rates in a bin B, **weighted** by binary NS rate:

$$count(B) = \sum_k \Theta\left(r_b(m_k) \in B\right) \frac{p_n(r_n(m_k))}{const}$$

→ **Histogram** of BBH rate

BBH distribution II



- Result: (preliminary)

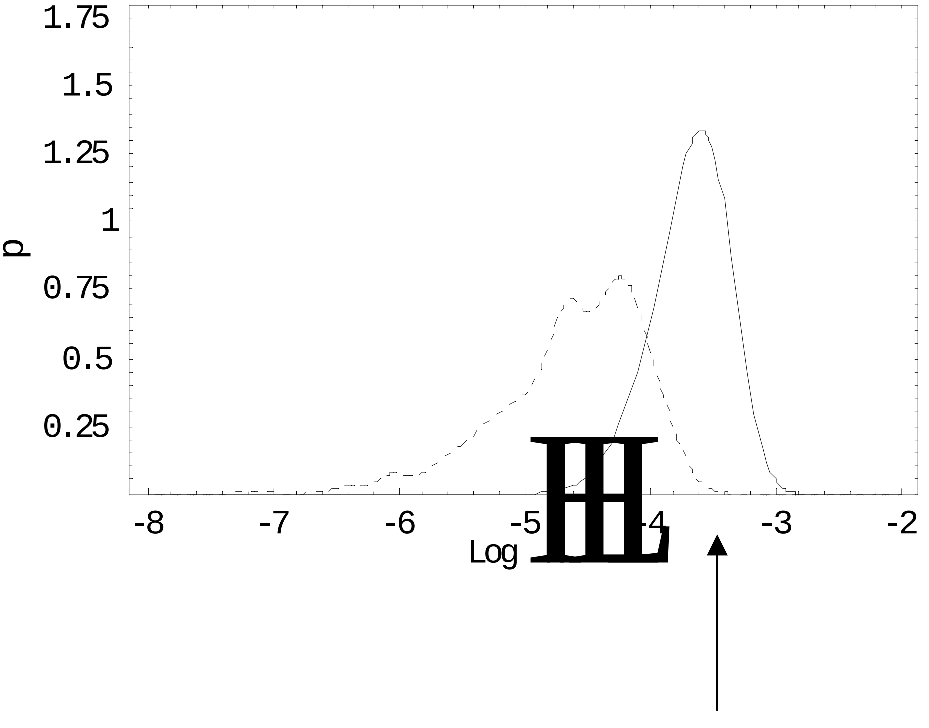
  Similar ….

- Reason:

  -NS-NS and BH-BH

  rates not strongly correlated

BBH distribution: Sampling



- <u>Sampling problem</u>:

…few models known with such high rates!

Summary and future directions

- Summary
  - BBH rate distribution from a priori PS…
  - (preliminary) BBH distribution from NS-NS
  - …*proof of principle* for further similar work

- Future directions
  - better sampling (of course!)
    - …check high-rate tail of NS-NS
  - fit rate functions?
  - distributions [not flat] for parameters (e.g., kicks)
  - more constraints (e.g, SN rate, XRBs, NS+WD binaries, …)

LIGO <u>detection rate</u> distribution?

Beware:

our result is for the merger rate, **not** the LIGO detection rate

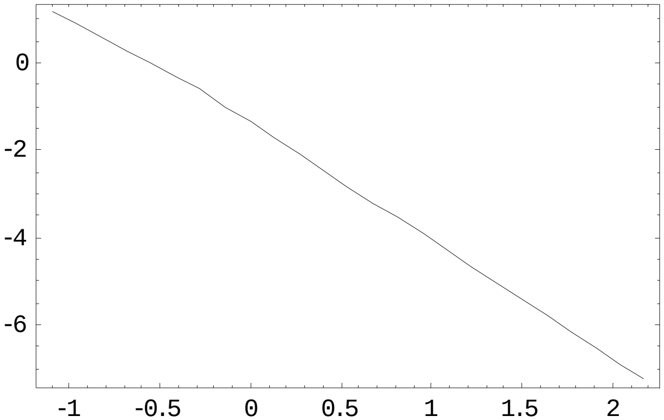
→ black holes are not all of one mass

Can reconstruct the LIGO detection rate (but haven't yet)

StarTrack and merger rates

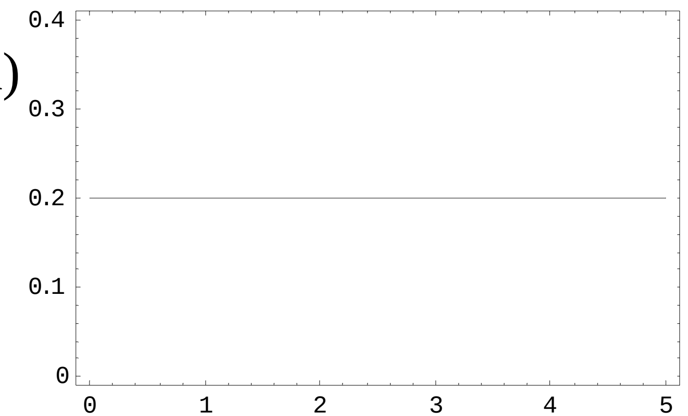
- Pick N stellar systems

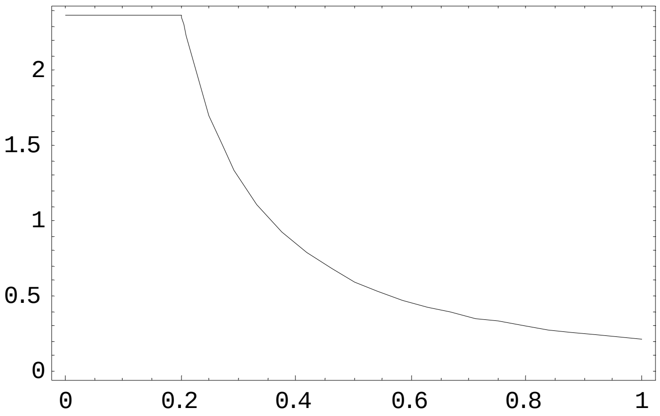
  from orbital parameter distributions (m1,m2=q*m1,a,e):



$\rho(m_1)dm_1$

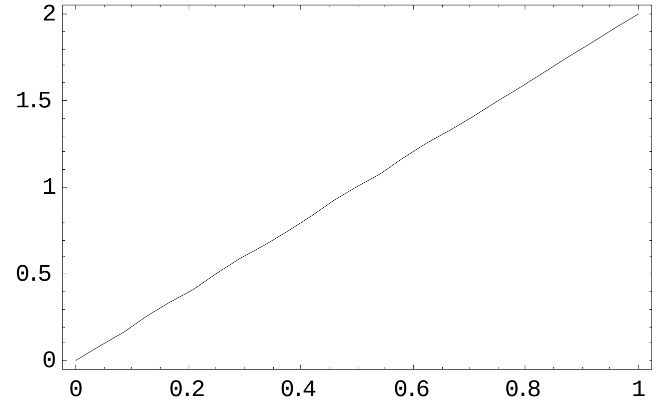
$\rho(a)d(\log_{10}a)$





$\rho(q)dq$

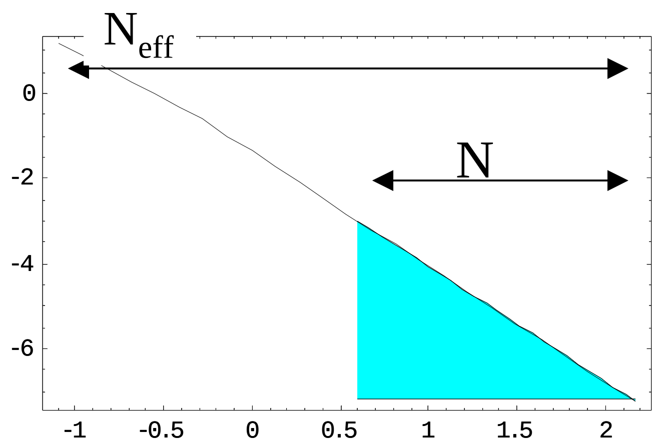
$\rho(e)de$



StarTrack and merger rates

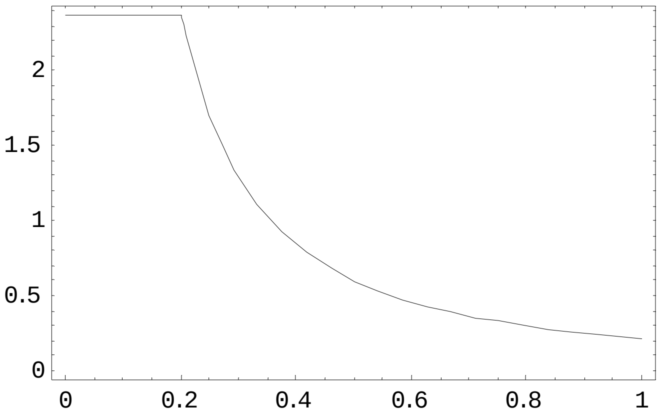
- Pick N stellar systems

from orbital parameter distributions (m1,m2=q*m1,a,e):



$\rho(m_1)dm_1$

$\rho(a)$



$\rho(q)dq$

Speedup (example):

Only pick N

high-mass

systems (m1, m2 > 4)…

Corresponds to a larger effective population size N_{eff}

StarTrack and merger rates

- Pick N stellar systems
- Follow them in time

evolution depends on unknown *parameters* – including

-common-envelope efficiency ($\alpha \in [0,1]$)

-wind strength ($w \in [0,1]$)

-companion mass ratio distribution ($r \in [0,3]$)

-bimodal kick distribution

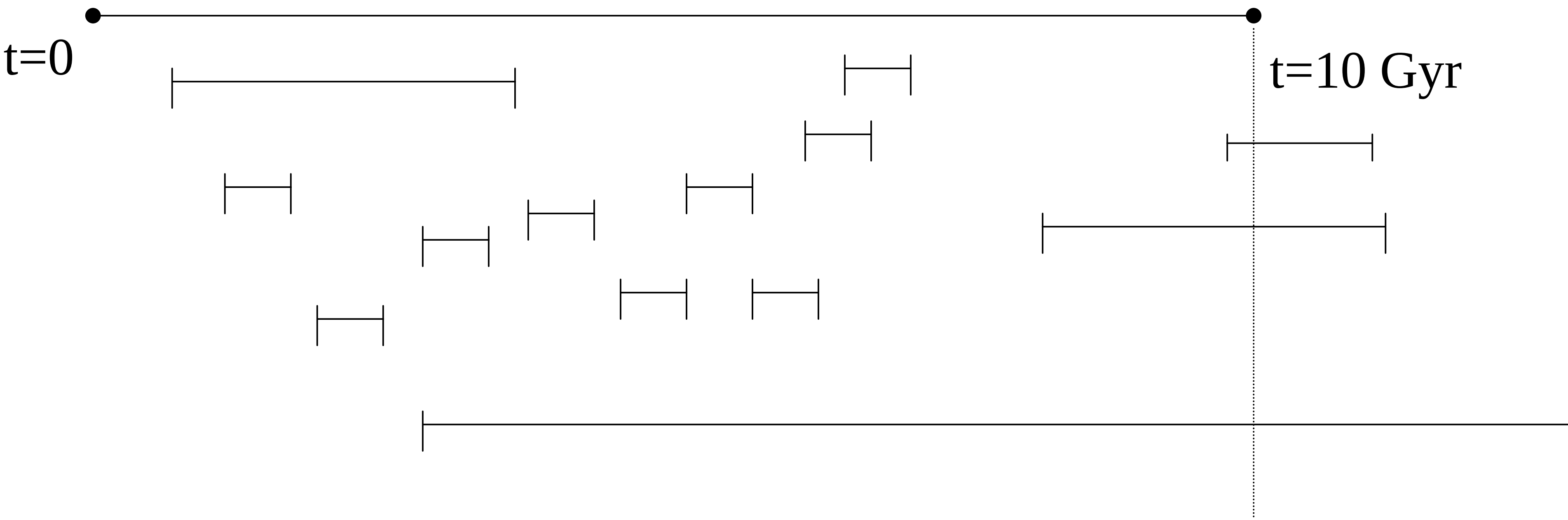
($v1 \in [0,200]$, $v2 \in [200,100]$, weight $\in [0,1]$)

-mass loss during nonconservative mass transfer ($f_a \in [0,1]$)

…and others we do not vary yet (e.g. metallicity)

StarTrack and merger rates

- Pick N stellar systems
- Follow them in time
- Place them uniformly in time over T=10Gyr



StarTrack and merger rates

- Pick N stellar systems
- Follow them in time
- Place them uniformly in time over T=10Gyr
- Find total number of mergers (n)
- Calculate physical (*average*) merger rate R

$$R = \frac{n}{T} \frac{N_g}{N_{eff}}$$

where N_g is the number of stellar systems born in the milky way (e.g. found using some normalization *consistent* with the model parameters)

PS: Parameter problems

Models

Probabilities, rates, …

Binary BH merger rate

S merger rate

ation rate

a rate

n+1 dimensi

Scale factor
number of stars

Properties at format
metallicity of gal
initial mass distri
…

Models for binary e
supernova kick m
common envelope efficiency
…

constraint
actor);

e predictions

Many parameters…

but

1) many have **narrow** ranges

2) dependence is smooth

Survey: Constraining BH rate using predictions for NS rate (II)

- Explicit formula:

$$A_n(m) = \int d\overline{m}\,\delta\left(r_n(\overline{m}) - r_n(m)\right)$$

$$p_m(m) = \frac{p_n(r_n(m))}{A_n(m)}$$

$$\boxed{p_b(R_b) = \int d\overline{m}\,p_m(\overline{m})\,\delta\left(R_b - r_b(\overline{m})\right)}$$

Key

$r_n(m)$	rate of binary NS merger for model *m*
$r_b(m)$	
$p_n(r)dr$	probability for binary NS rate to be in [r,r+dr]

Accumulating data: Results

NS-NS runs

Simulations	Merging NS-NS (per sim)
~ 488	10
~ 130	100

BH-BH runs

Simulations	Merging BH-BH
~ 312	10

Accumulating data: “Focused” runs

- Motivation:
  1. Most progenitors are *not* progenitors of NS-NS binaries (or BH-BH binaries)
  2. Many progenitors *cannot* produce these binaries, *independent* of model parameters and random events

- Idea: “partitions” which reject irrelevant objects (=which can’t make a *particular* class of event)

- Examples:
  - Mass cutoff (m1,m2>4)
  - Can search for additional, better ones (e.g. correlated in m1, m2, a, e)…with some “training” data

Accumulating data: “Focused” runs

NS runs

Type	Prob
NS-NS	0.987
All other	0.088

BH runs

Type	Prob
BH-BH	0.9986
NS-NS	0.0215