Cosmological Heavy Ion Collisions:

Colliding Neutron Stars and Black Holes

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Comparison

	RHIC	**BH-NS Merger**
Temperature	O(GeV)	O(keV)
Size	O(nm)	O(km)
Time Scale	10 ^(-23) second	milli second
Number of Particles	O(100)	O(10^57)
Outcome	Fundamental Particles	Gravitational Wave + GRB
Hydrodynamics	Special Relativity	General Relativity
Tools	Collider	Satellite, Telescope

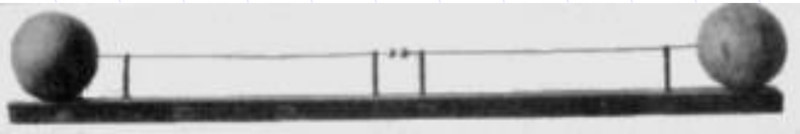
Contents

- Gravitational Waves
- Short Hard Gamma-ray Bursts
- Current Observations & Prospect

Introduction

EM wave

- Theory: Maxwell (1873)
- Acceleration of electric charge
- Detection : H. Hertz (1888)



Grav. wave

- Theory : Einstein (1916)
- Acceleration of matter (transverse & spin 2)
- Evidence : Taylor & Hulse ('79)
- Detection : K. Thorne(?)

LIGO(?)

?

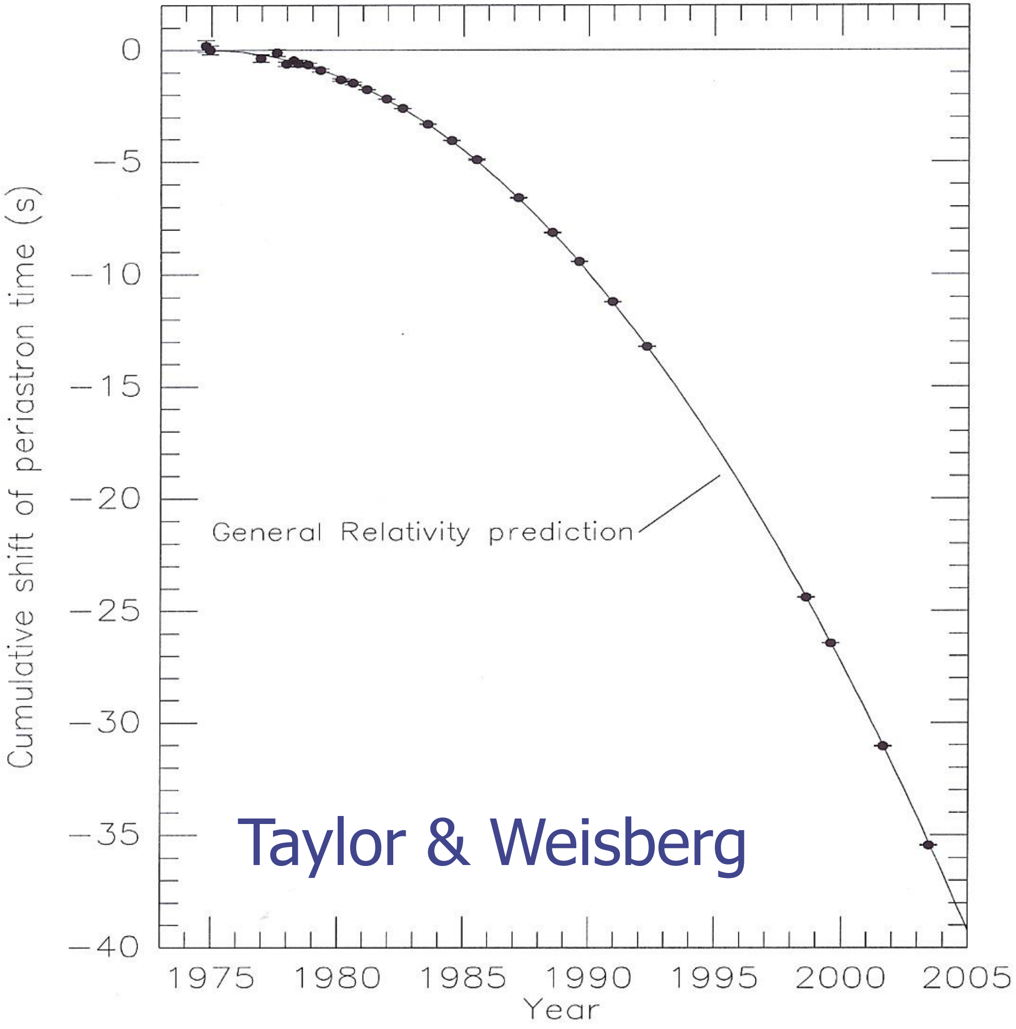
Gravitation Wave from Binary Neutron Star

B1913+16
Hulse & Taylor (1975)

Effect of Gravitational Wave Radiation

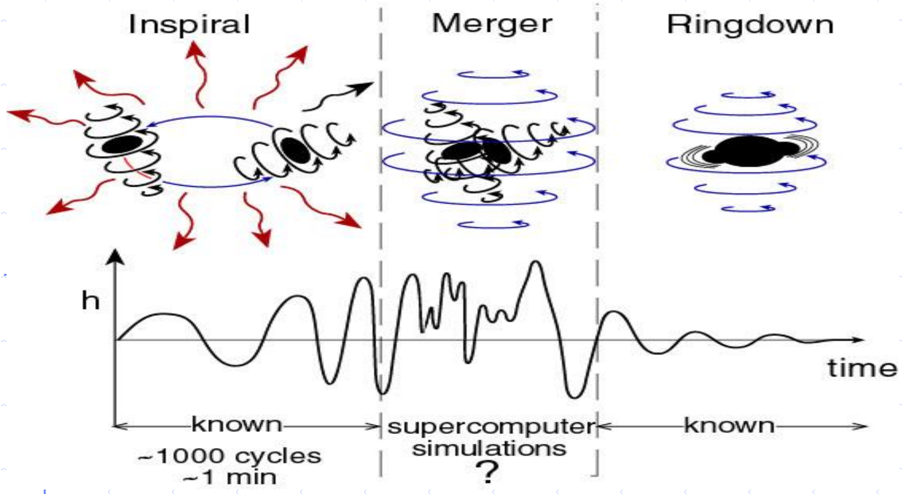
1993 Nobel Prize
Hulse & Taylor

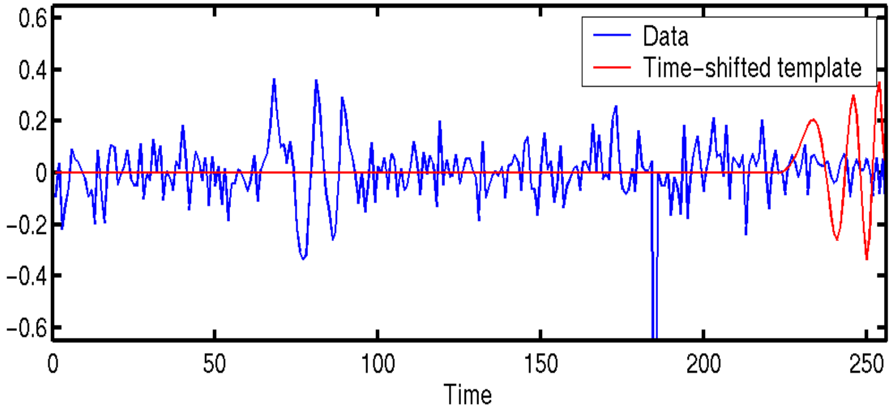
LIGO was based on one DNS until 2002

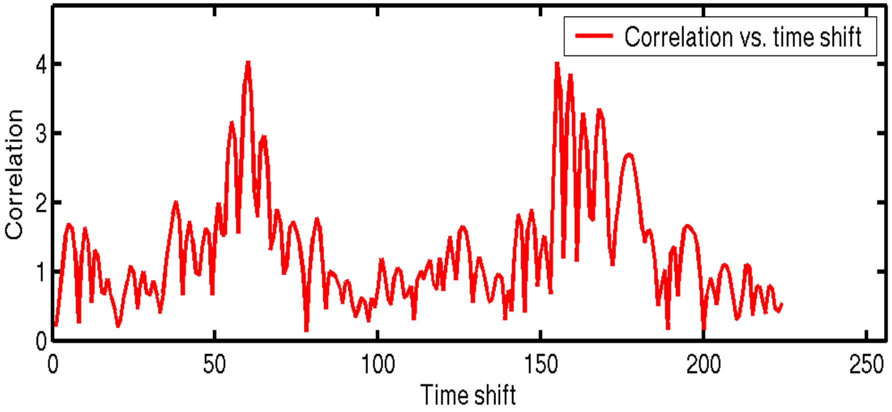


Taylor & Weisberg

Introduction







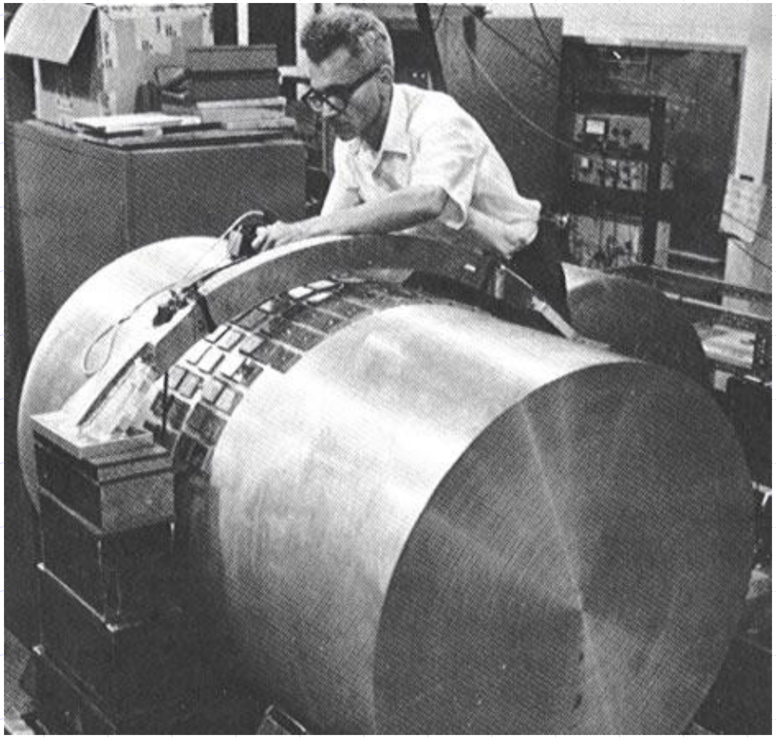
◆ GW Sources

- BH-BH, NS-NS mergers
- Cosmological perturbations
- Supernovae

◆ Grav. wave pattern:

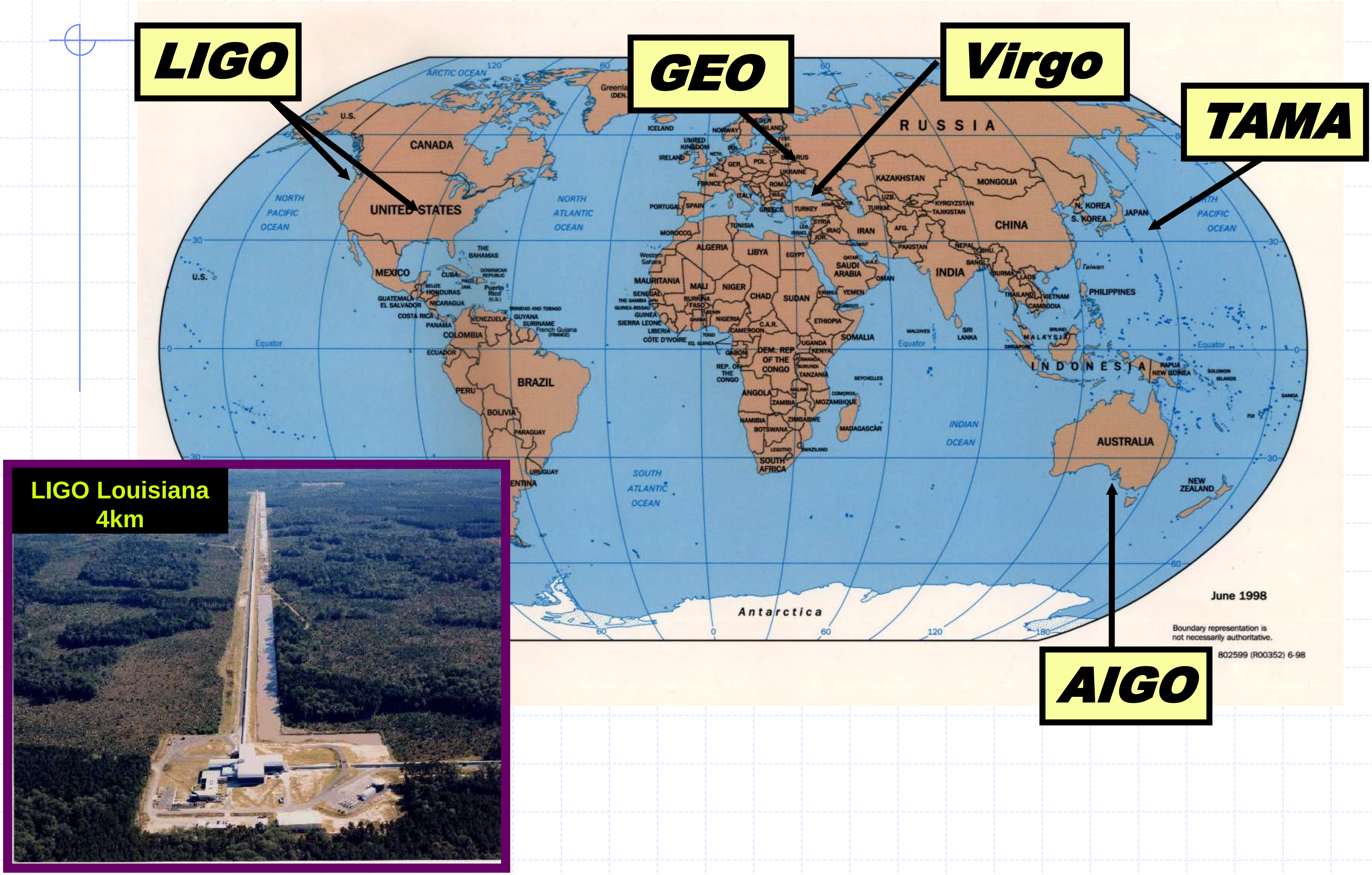
"Urgent Demand For GW Detection !!"

NR and Gravitational Wave Detection

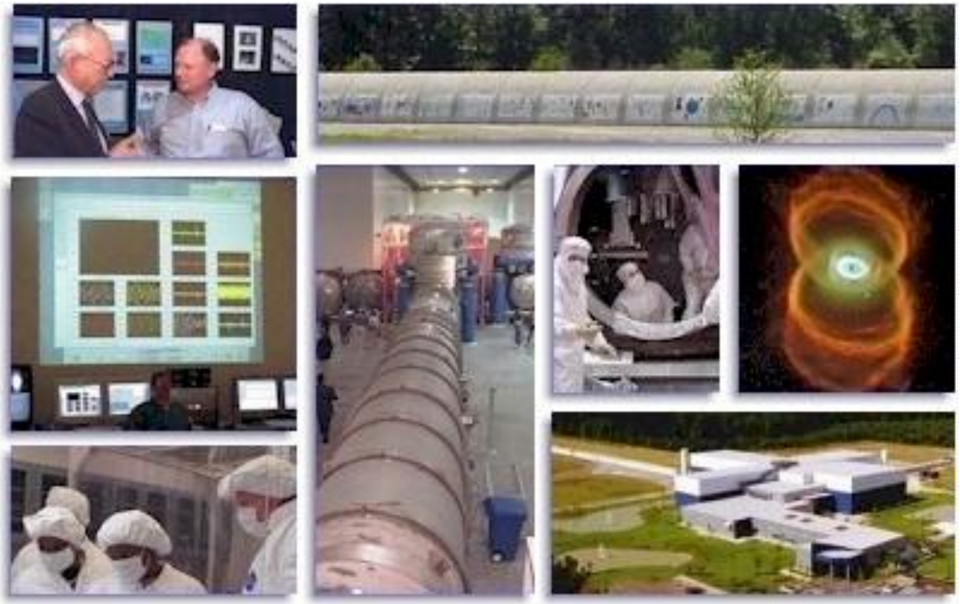


Joseph Weber (1960)

Network of Interferometers



Laser Interferometer Gravitational Wave Observatory



LIGO I : in operation
(since 2004)

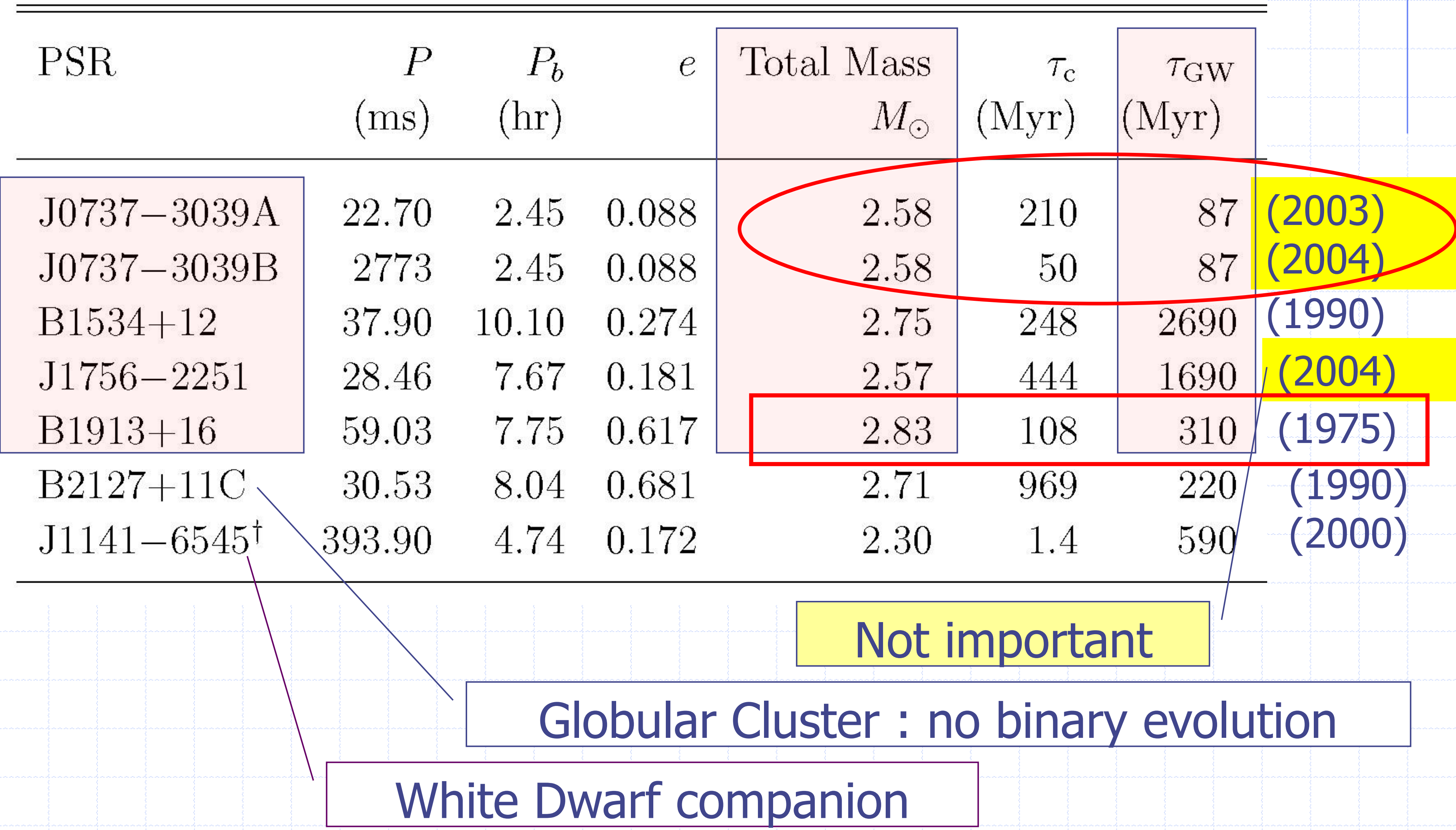
LIGO II: in progress
(2010 ?)

NS-NS, NS-BH, BH-BH Binaries as sources for LIGO

(*Laser Interferomer Gravitational Wave Observatory*)

Observations

NS (radio pulsar) which coalesce within Hubble time

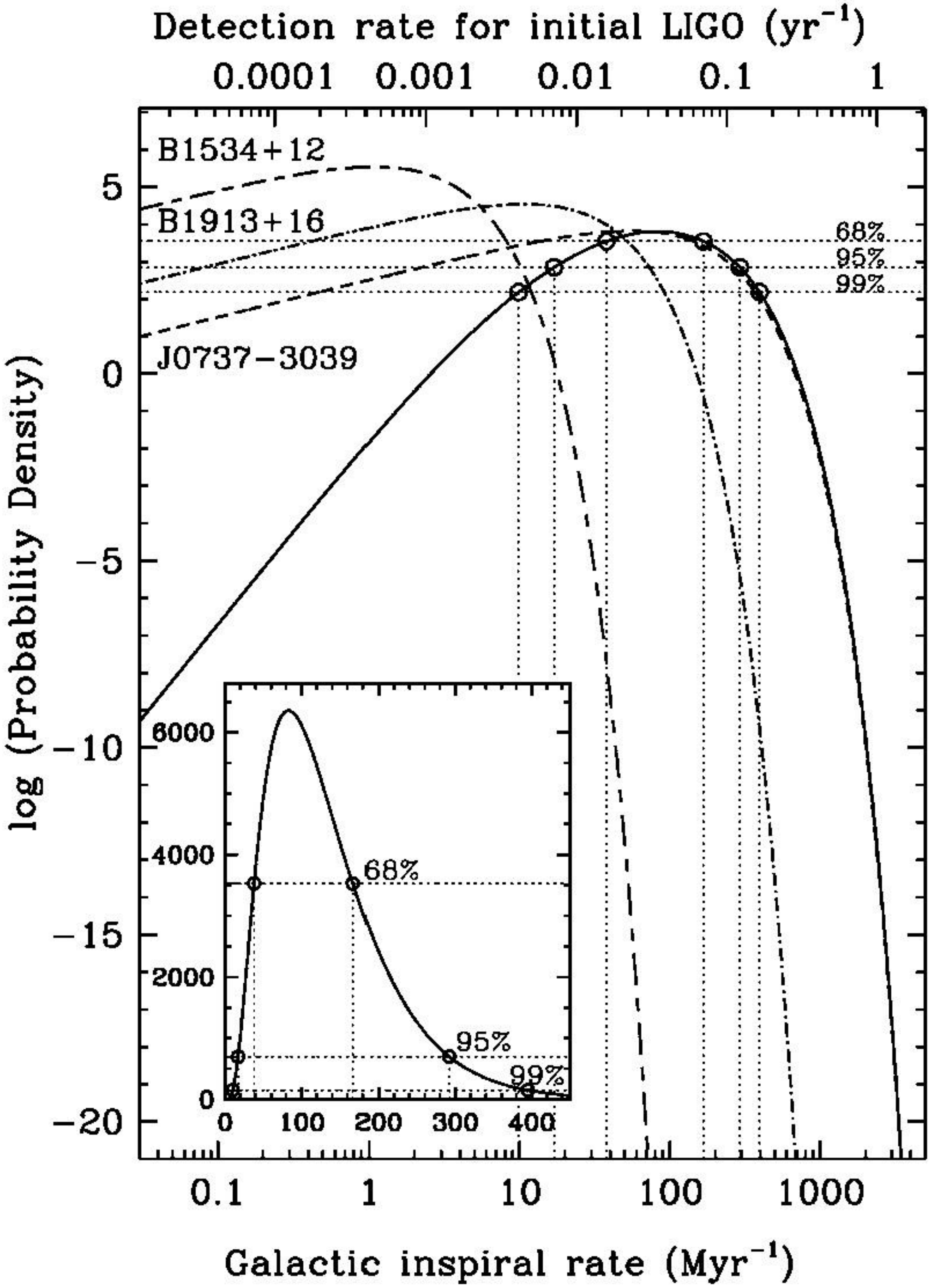


PSR	P (ms)	P_b (hr)	e	Total Mass $M_\odot$	τ_c (Myr)	τ_{GW} (Myr)	
J0737−3039A	22.70	2.45	0.088	2.58	210	87	(2003)
J0737−3039B	2773	2.45	0.088	2.58	50	87	(2004)
B1534+12	37.90	10.10	0.274	2.75	248	2690	(1990)
J1756−2251	28.46	7.67	0.181	2.57	444	1690	(2004)
B1913+16	59.03	7.75	0.617	2.83	108	310	(1975)
B2127+11C	30.53	8.04	0.681	2.71	969	220	(1990)
J1141−6545[†]	393.90	4.74	0.172	2.30	1.4	590	(2000)

Not important

Globular Cluster : no binary evolution

White Dwarf companion



Due to J0737-3039 LIGO detection rate was increased by 8 !

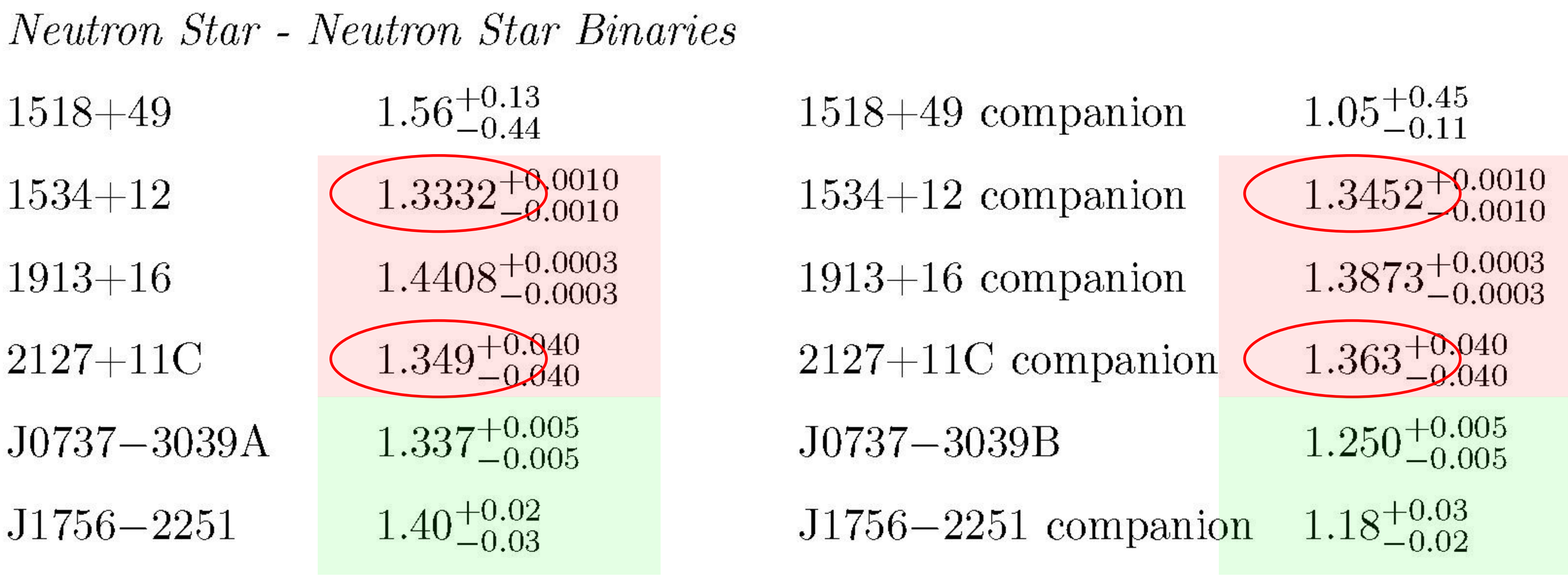
- ➢weak radio signal: 1/6 of B1913+16
- ➢short coalesce time: 1/2 of B1913+16

Initial LIGO
0.035 event/year

Advanced LIGO
187 event/year

Kalogera et al. (2004)

Introduction

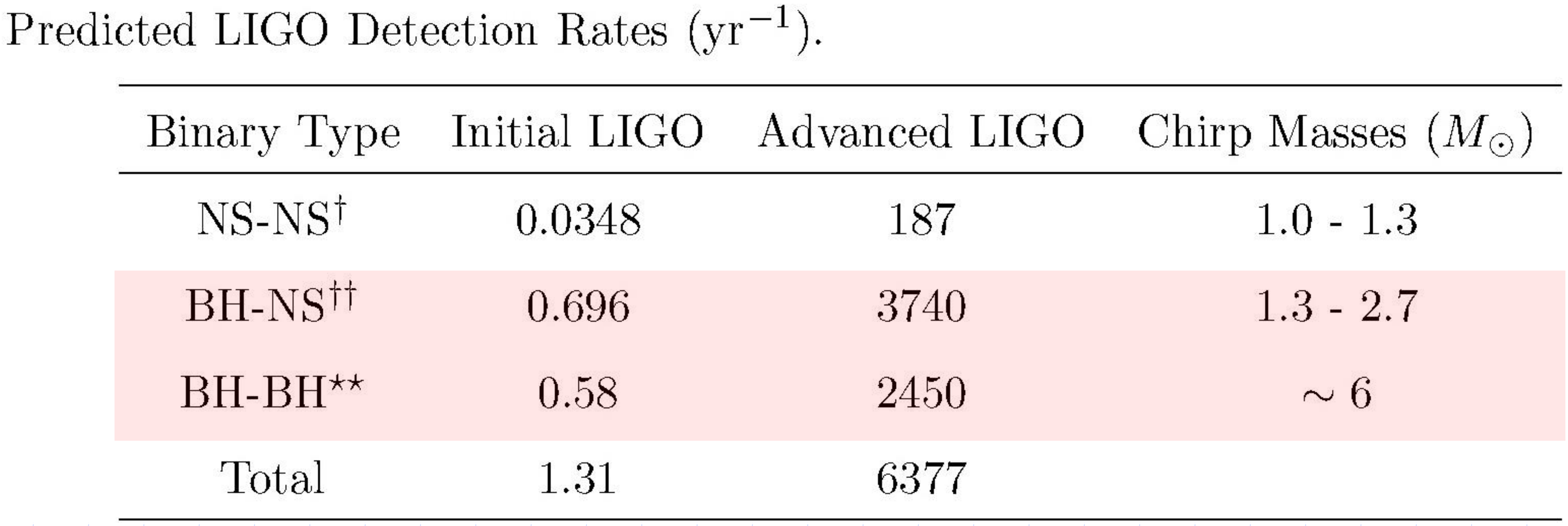


Neutron Star - Neutron Star Binaries

1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$

- All masses are < 1.5 $M_\odot$
- 1534, 2127: masses are within 1%
- J0737, J1756: ΔM = 0.1 - 0.2 $M_\odot$

Introduction

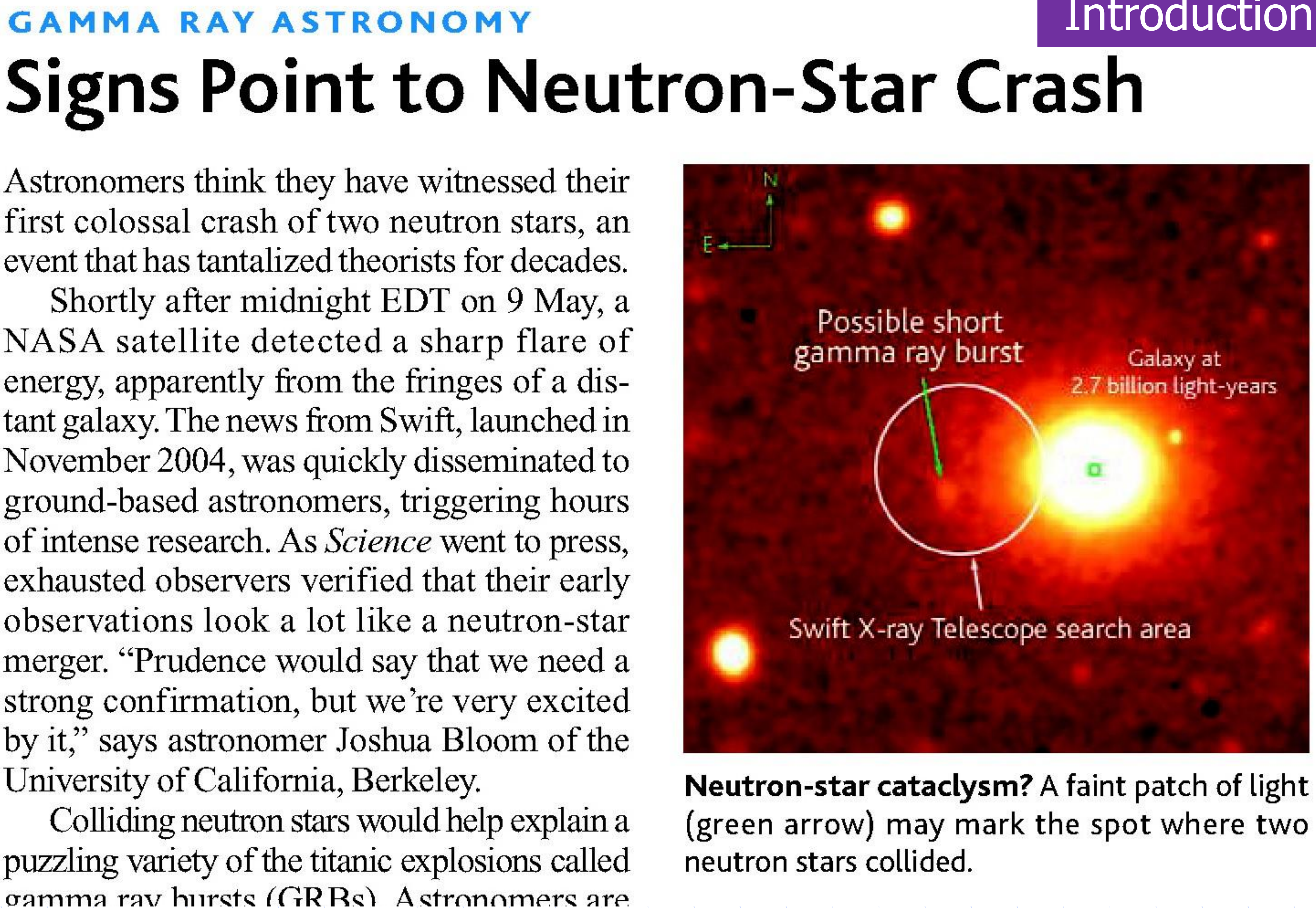


Predicted LIGO Detection Rates (yr^{-1}).

Binary Type	Initial LIGO	Advanced LIGO	Chirp Masses ($M_\odot$)
NS-NS†	0.0348	187	1.0 - 1.3
BH-NS††	0.696	3740	1.3 - 2.7
BH-BH**	0.58	2450	~ 6
Total	1.31	6377	

$$R_{\mathrm{eff}} = R_0 \left(\frac{M_{\mathrm{chirp}}}{M_\odot} \right)^{5/6}, \qquad M_{\mathrm{chirp}} = \mu^{3/5} M_{\mathrm{tot}}^{2/5}$$

- R_0=17 Mpc (initial LIGO), 280 Mpc (advanced LIGO)



GAMMA RAY ASTRONOMY

Signs Point to Neutron-Star Crash

Astronomers think they have witnessed their first colossal crash of two neutron stars, an event that has tantalized theorists for decades.

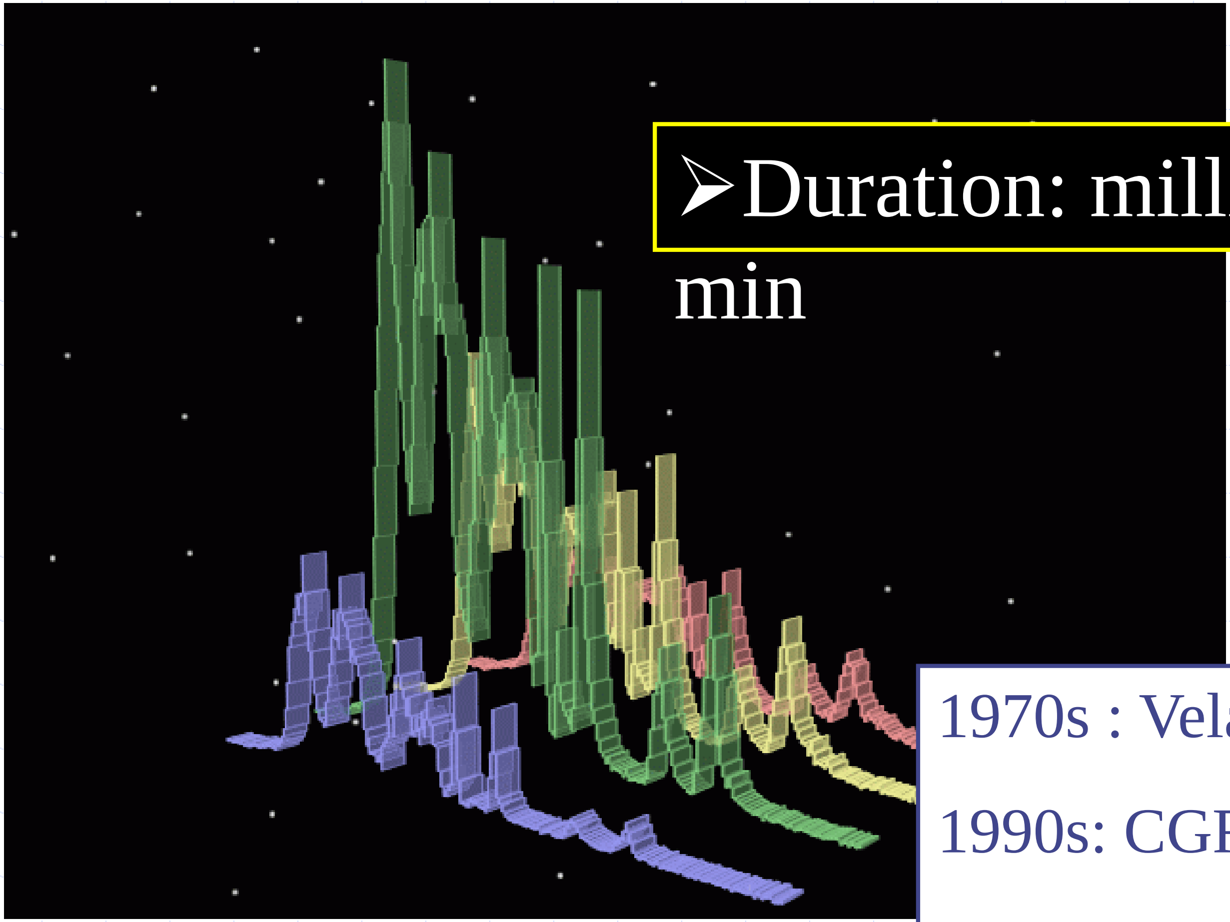
Shortly after midnight EDT on 9 May, a NASA satellite detected a sharp flare of energy, apparently from the fringes of a distant galaxy. The news from Swift, launched in November 2004, was quickly disseminated to ground-based astronomers, triggering hours of intense research. As *Science* went to press, exhausted observers verified that their early observations look a lot like a neutron-star merger. "Prudence would say that we need a strong confirmation, but we're very excited by it," says astronomer Joshua Bloom of the University of California, Berkeley.

Colliding neutron stars would help explain a puzzling variety of the titanic explosions called gamma ray bursts (GRBs). Astronomers are

Neutron-star cataclysm? A faint patch of light (green arrow) may mark the spot where two neutron stars collided.

Science 308 (2005) 939

Gamma-Ray Burst



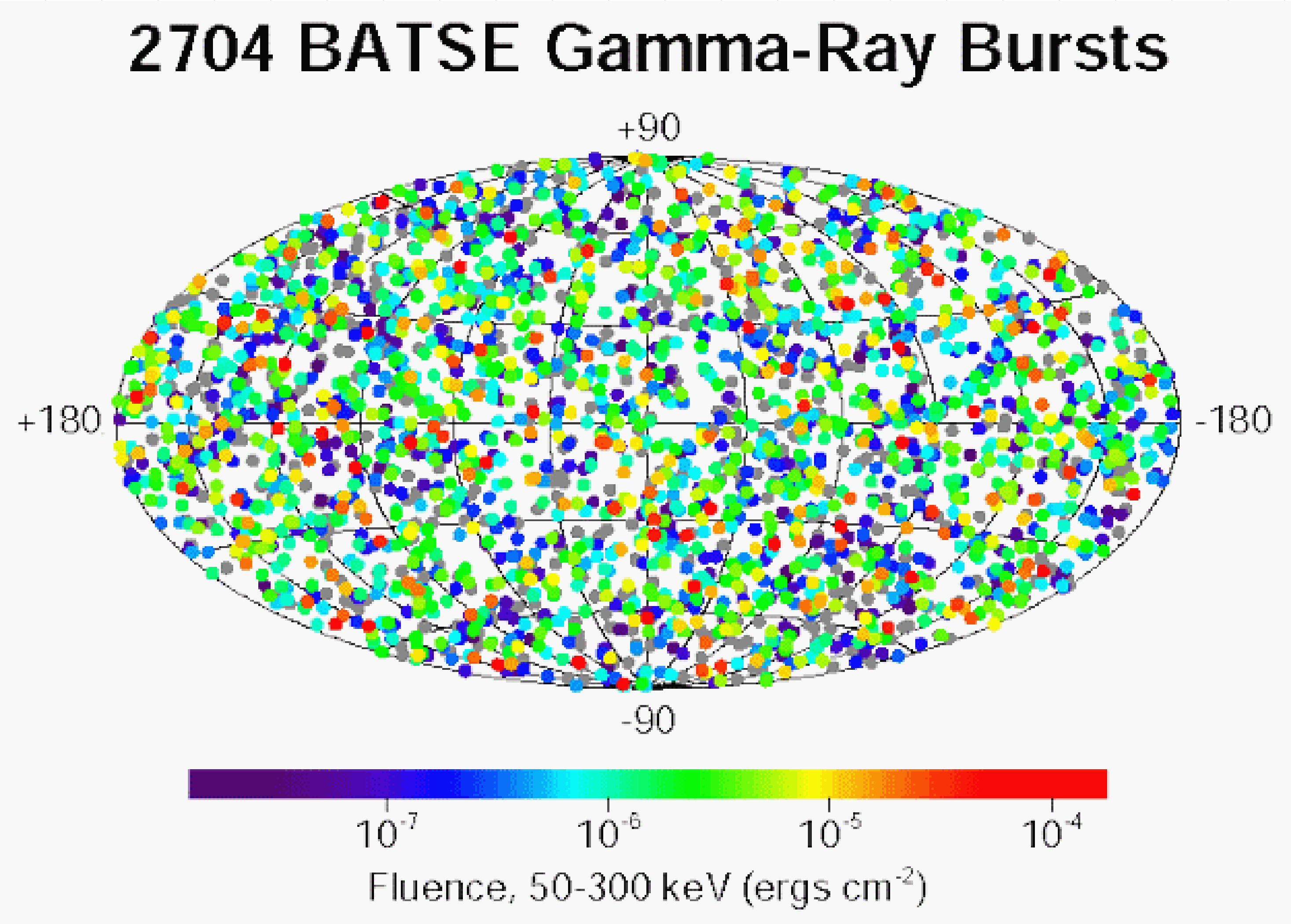
- Duration: milli sec - min

1970s : Vela Satellite

1990s: CGRO, Beppo-SAX

2000s: HETE-II, Swift

GRB


2704 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10^-7
10^-6
10^-5
10^-4
Fluence, 50-300 keV (ergs cm^-2)

Two groups of GRBs

- Short Hard Gamma-ray Bursts:
  Duration time < 2 sec
  NS-NS, NS-LMBH mergers
- Long-duration Gamma-ray Bursts:
  from spinning HMBH

HMBH (High-mass black hole)

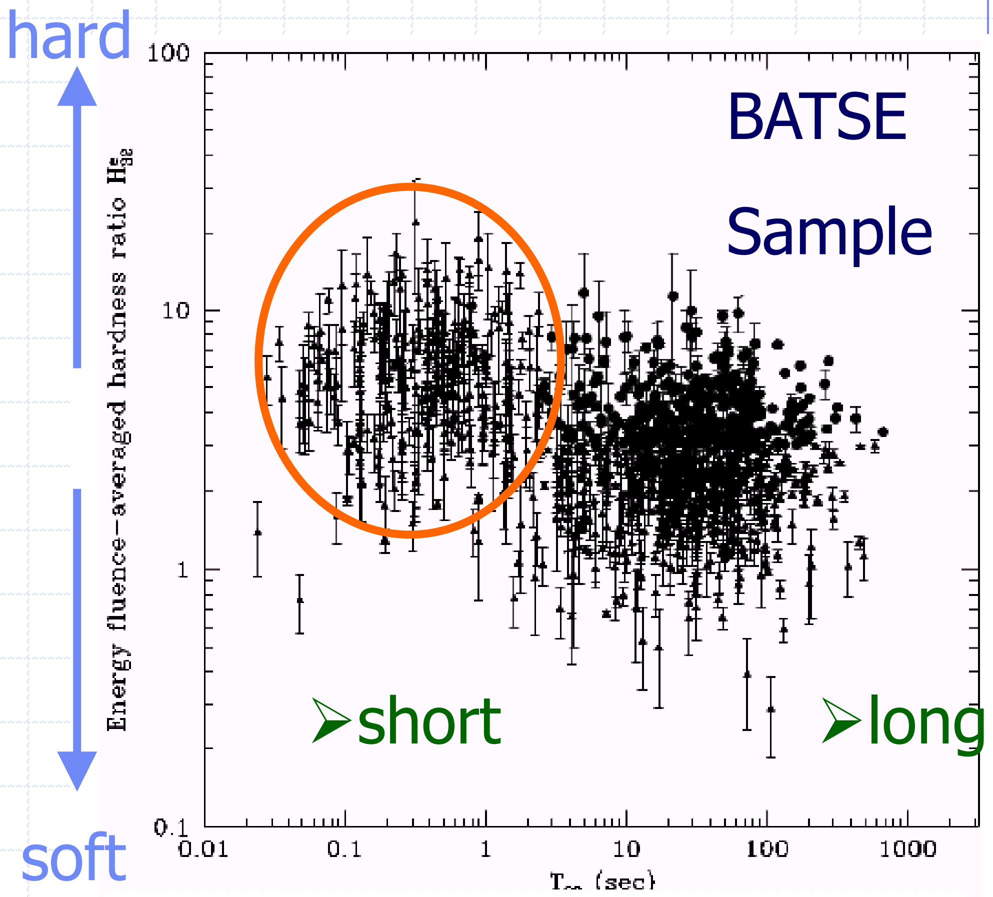
5-10 solar mass

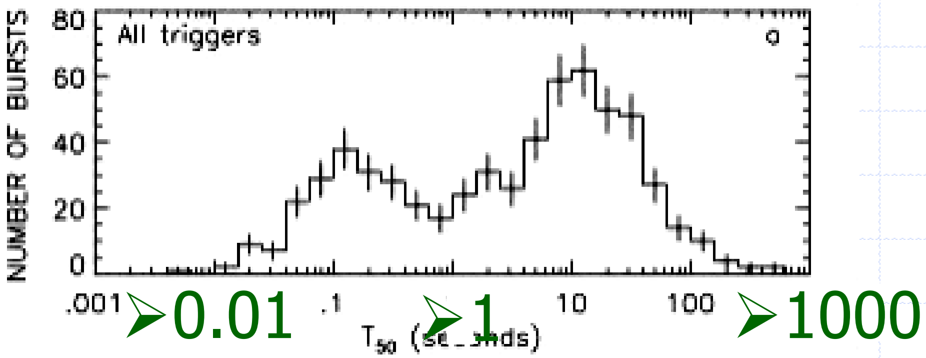
Short-hard GRBs

No optical counterpart (?)

Origin

- Neutron star merger?
- Magnetar flare?
- Supernova?



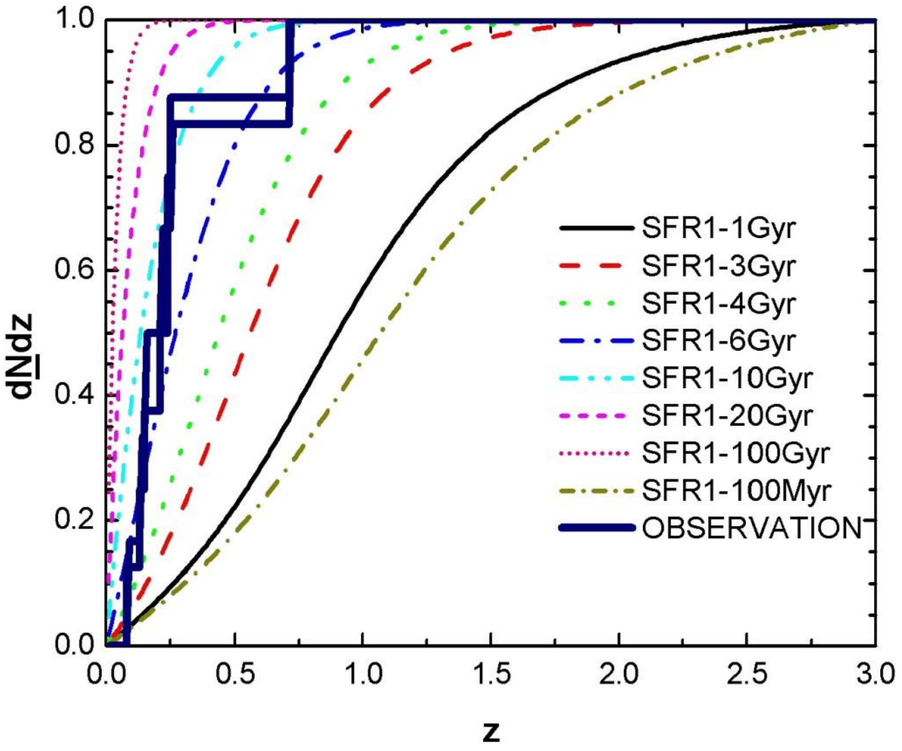


Short-Hard Gamma-ray Bursts (SHBs)

Observed NS-NS binaries are inconsistent with SHBs

Invisible old (> 6 Gyr) NS binaries are responsible for short-hard gamma-ray bursts (SHBs)

Nakar et al.



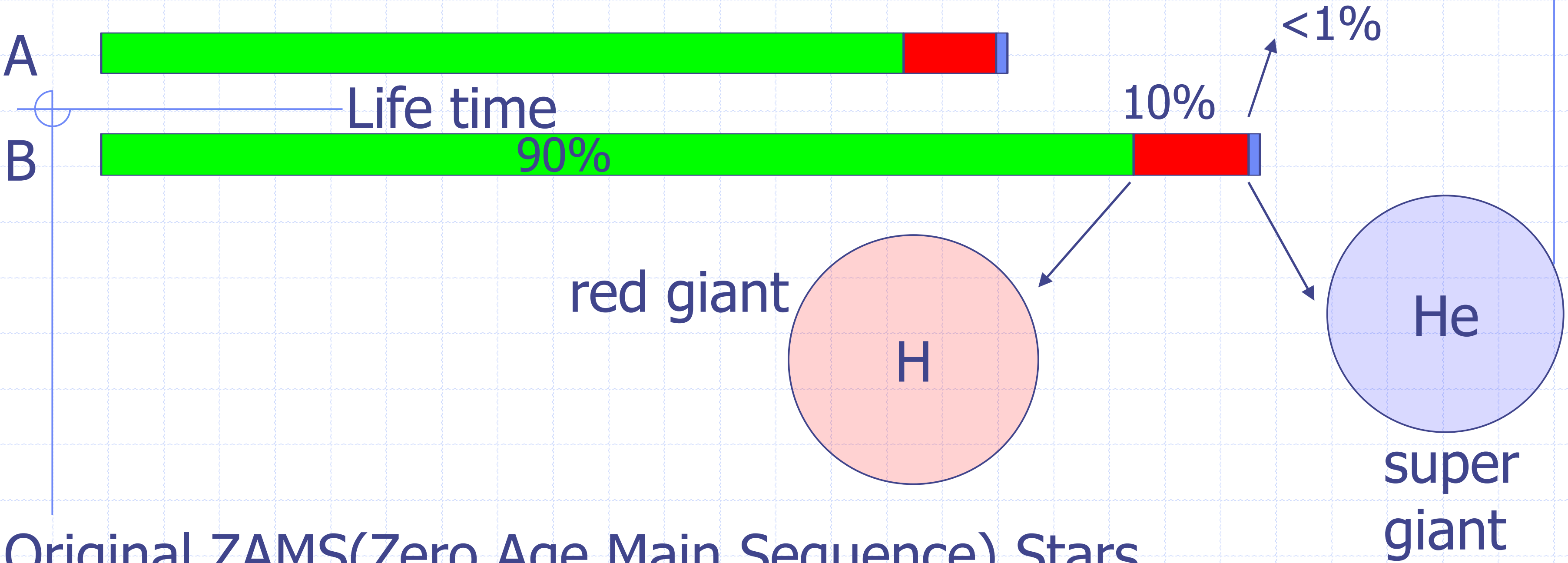
What are the *invisible* old NS binaries ?

Jeong & Lee

Invisible NS/BH binaries by Bethe/Brown/Lee

- NS/LMBH is 5 times more dominant than NS/NS due to hypercritical acctetion.
- NS/LMBH will increase LIGO detection rate by factor of 10.

Evolution of binary NS



A

Life time

B

90%

10%

<1%

red giant

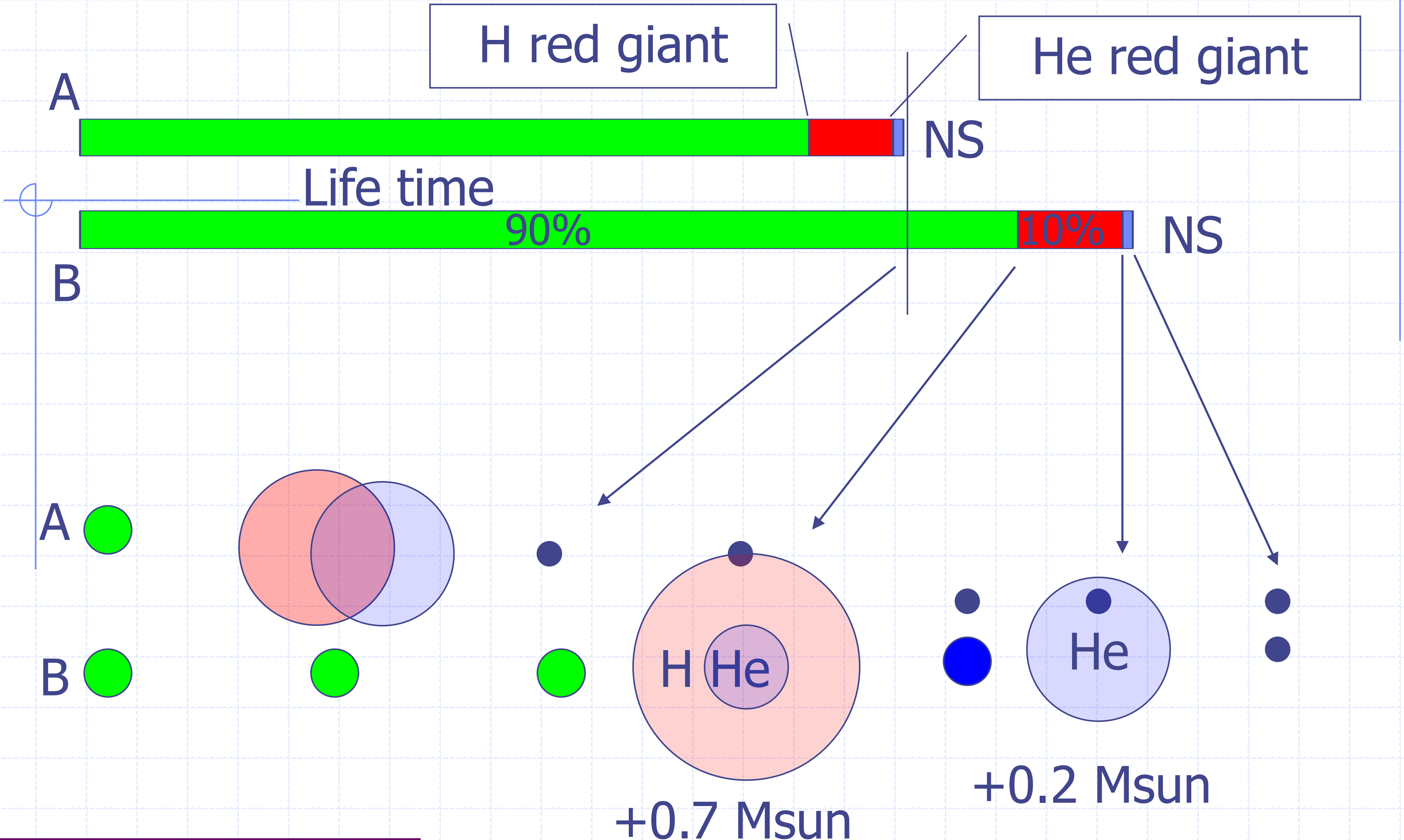
H

He

super giant

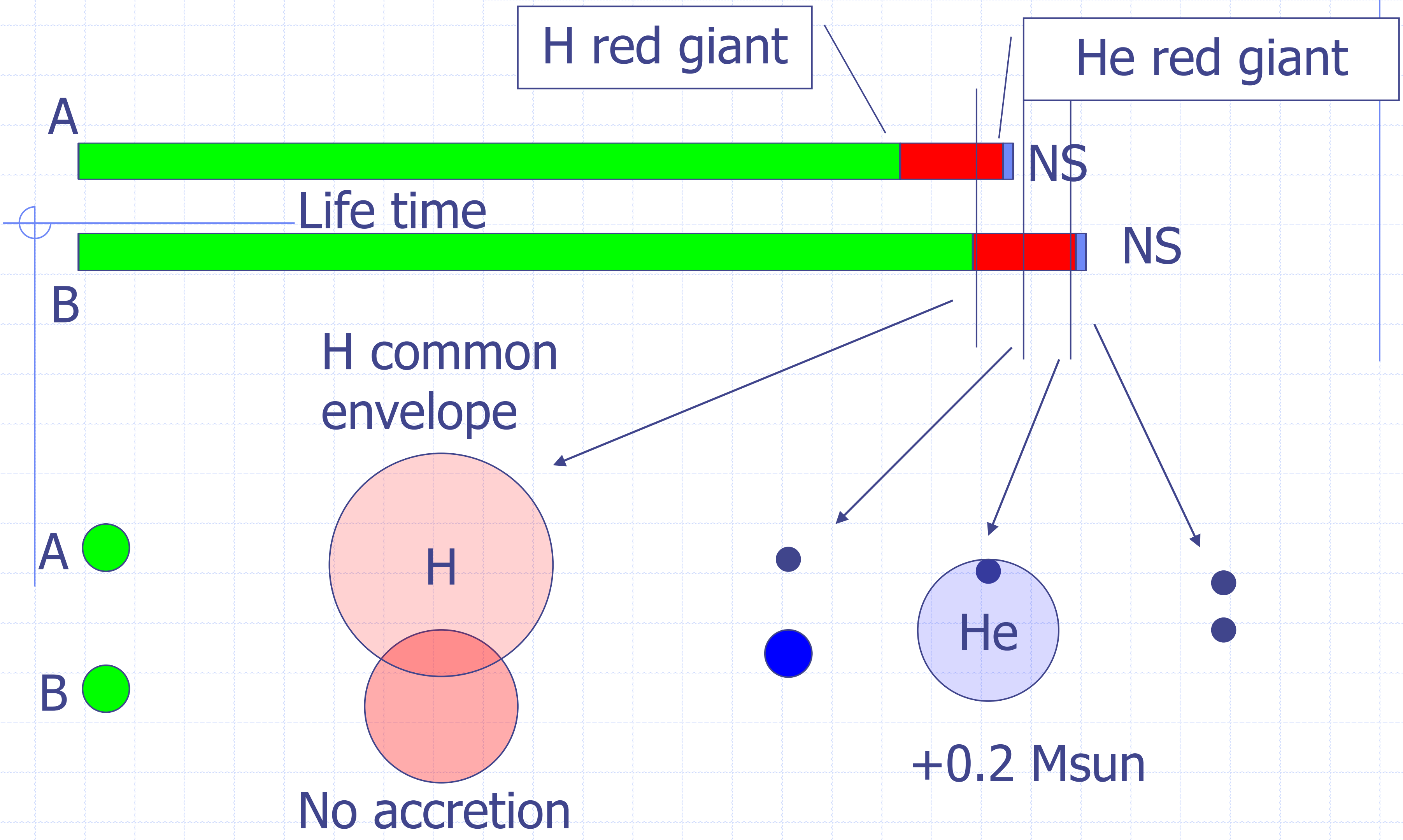
Original ZAMS(Zero Age Main Sequence) Stars

- Probability = $1/M^{2.5}$
- Life Time = $1/M^{2.5}$
- $\Delta M=4\%$,
  $\Delta T_{life}=(1 - 1/1.04^{2.5})= 10\%$,
  $\Delta P=10\%$ (population probability)



Case 1 : ΔT > 10%

Hypercritical Accretion:
First born NS should accrete 0.9 $M_\odot$!



H red giant

He red giant

A

NS

Life time

NS

B

H common envelope

A

B

H

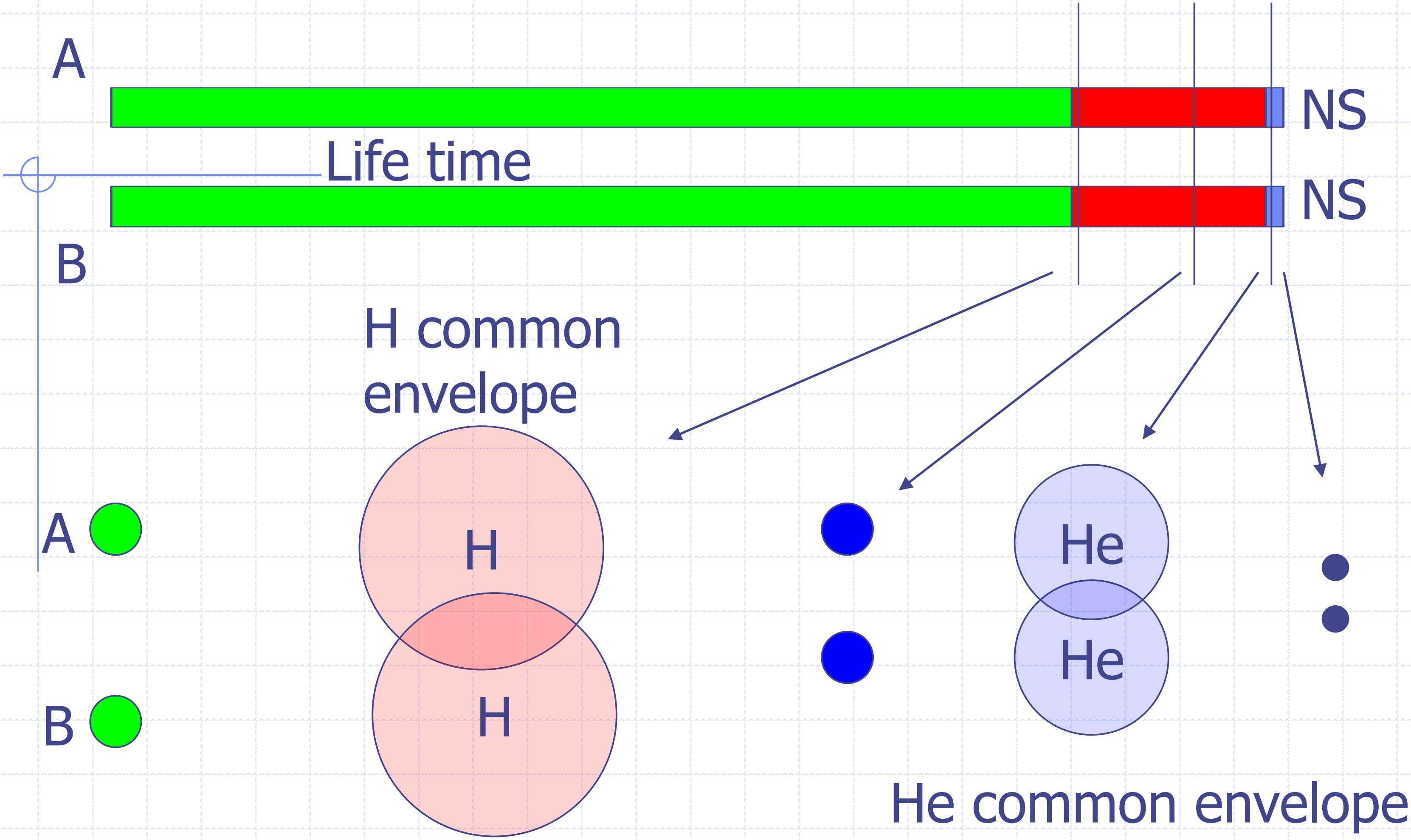
He

No accretion

+0.2 Msun

Case 2 : $\Delta T < 10\%$

First born NS should accrete only 0.2 $M_\odot$!



A

NS

Life time

NS

B

H common envelope

A

H

H

B

He

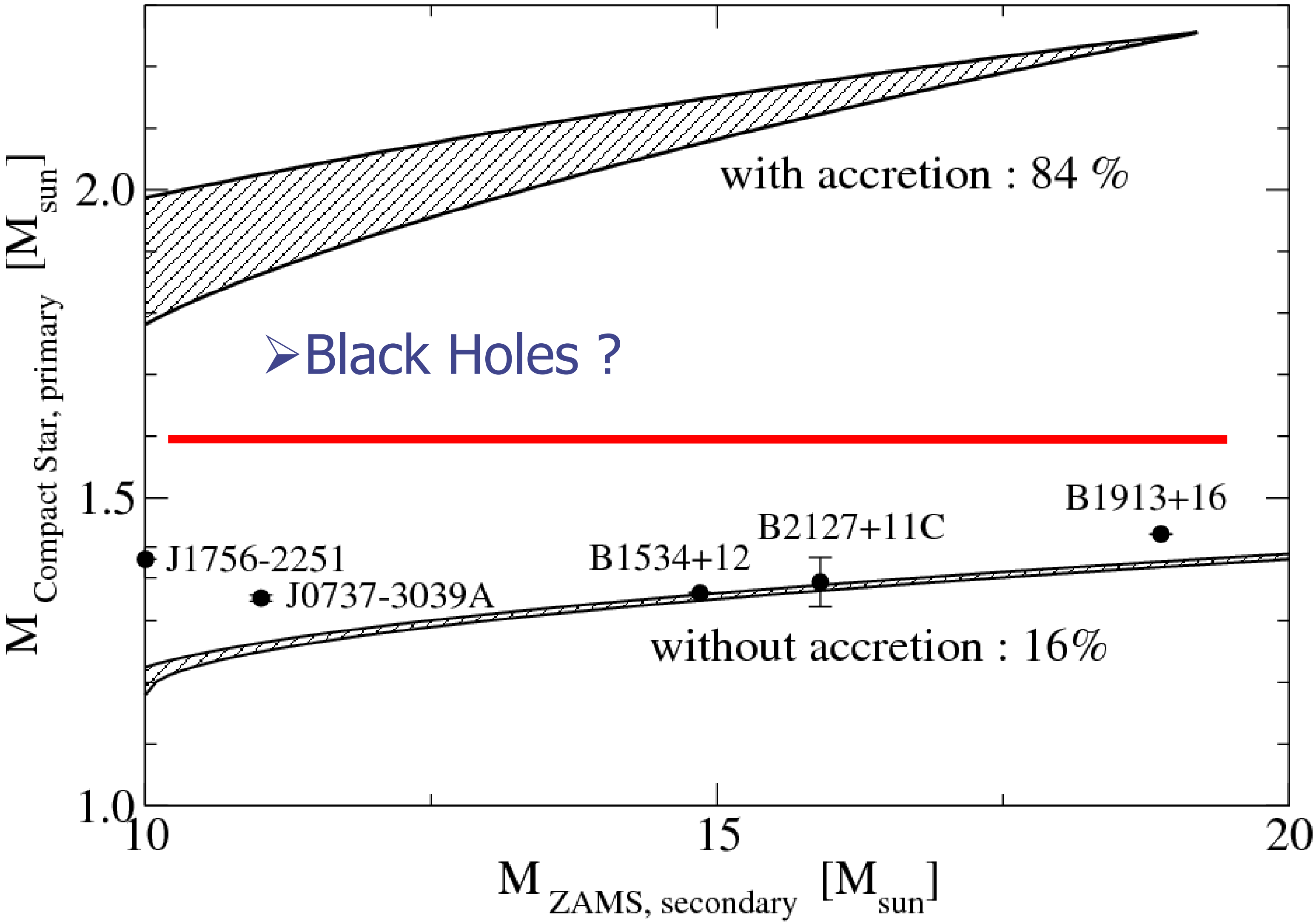
He

He common envelope

Case 3 : $\Delta T < 1\%$

No accretion : same mass pulsars !

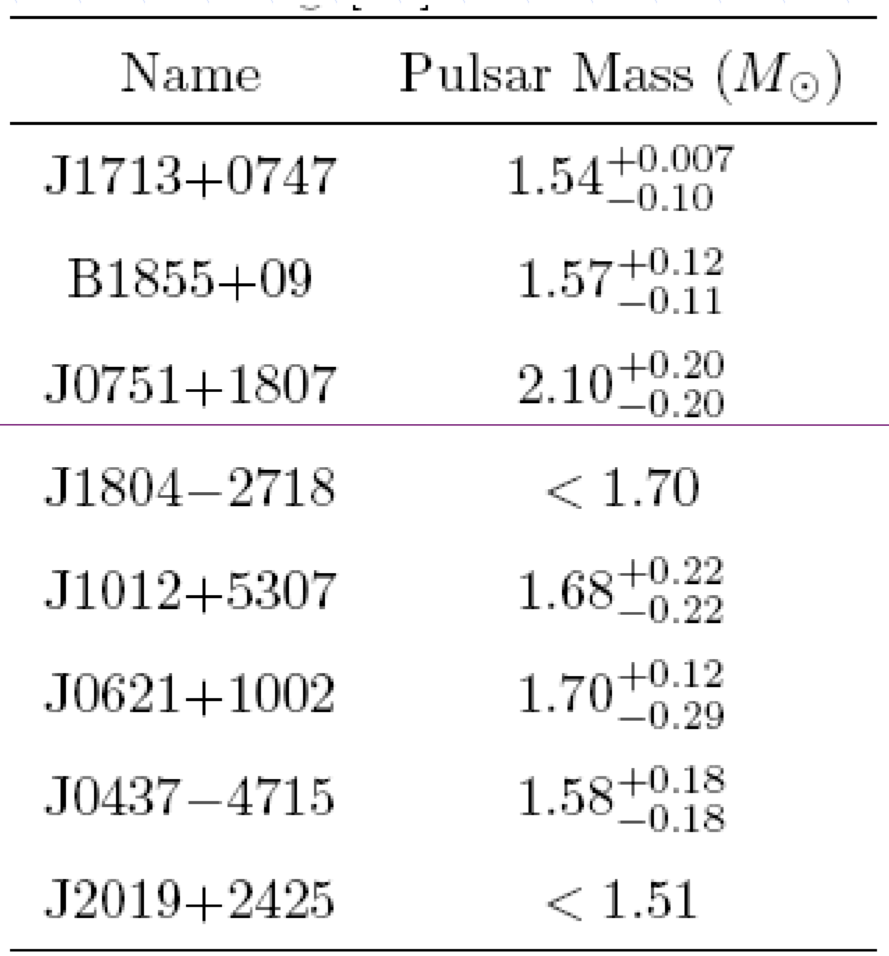
Binary Neutron Stars : Observation vs Prediction



- Black Holes ?

Lee et al., ApJ 670, 741 (2007)

NS-WD binaries



Name	Pulsar Mass ($M_\odot$)
J1713+0747	$1.54^{+0.007}_{-0.10}$
B1855+09	$1.57^{+0.12}_{-0.11}$
J0751+1807	$2.10^{+0.20}_{-0.20}$
J1804−2718	< 1.70
J1012+5307	$1.68^{+0.22}_{-0.22}$
J0621+1002	$1.70^{+0.12}_{-0.29}$
J0437−4715	$1.58^{+0.18}_{-0.18}$
J2019+2425	< 1.51

Pulsar J0751+1807

2.1 ± 0.2 solar mass

Nice et al., ApJ 634 (2005) 1242.

Nice, talk@40 Years of Pulsar, McGill, Aug 12-17, 2007

$1.26^{+0.14}_{-0.12}$ solar mass

Loop-hole in Bayesian analysis for WD mass

SHB

Predicted LIGO Detection Rates (yr^{-1}).

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R_0=17 Mpc (initial LIGO), 280 Mpc (advanced LIGO)

Introduction

- NS-NS binaries : several
- NS-BH binaries : some clues
- BH-BH binaries : expected in globular clusters where old-dead stars (NS, BH) are populated.

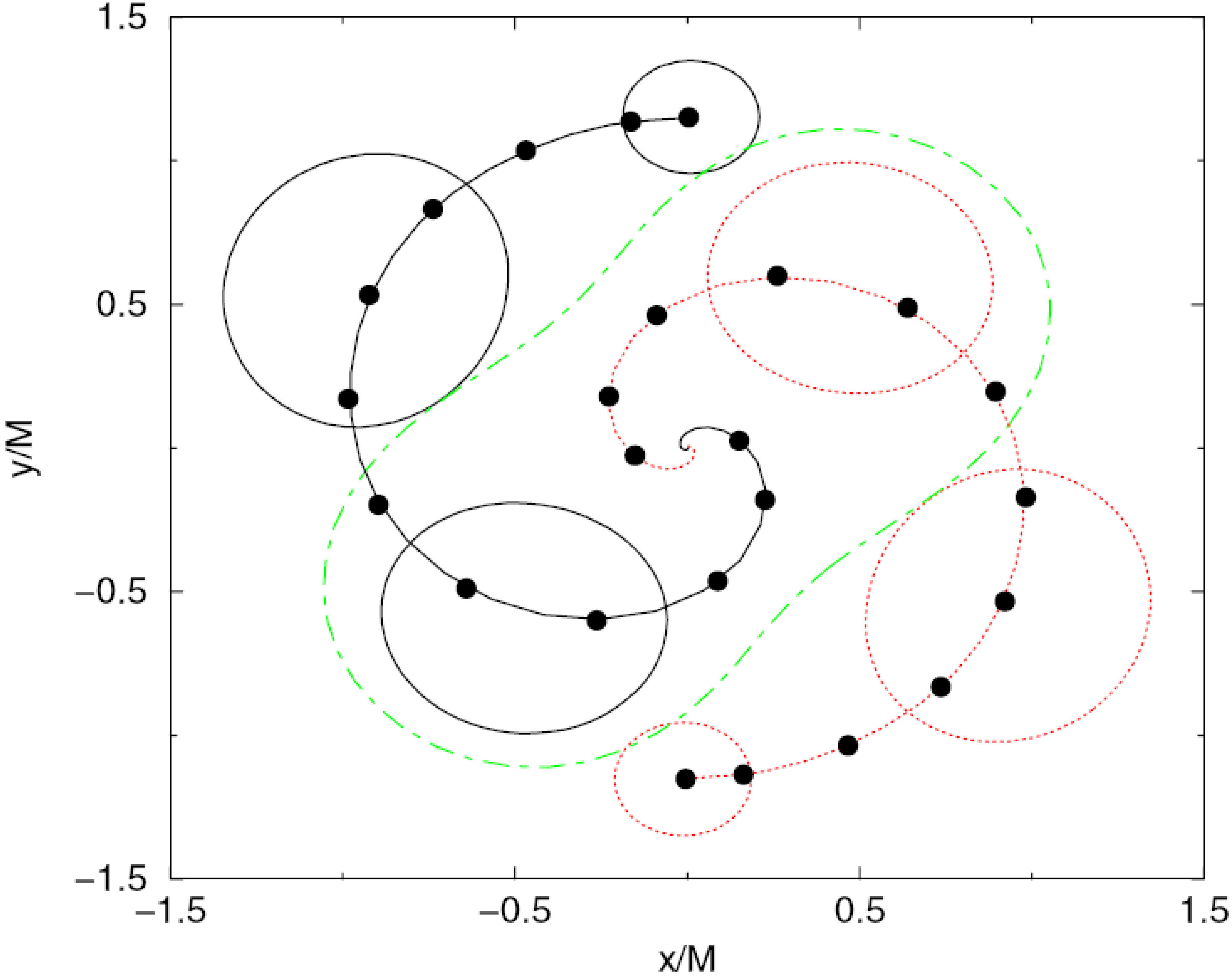
Wanted

- How to distinguish sources from GW observations?
- What is the GW pattern ?

Why numerical approach ?

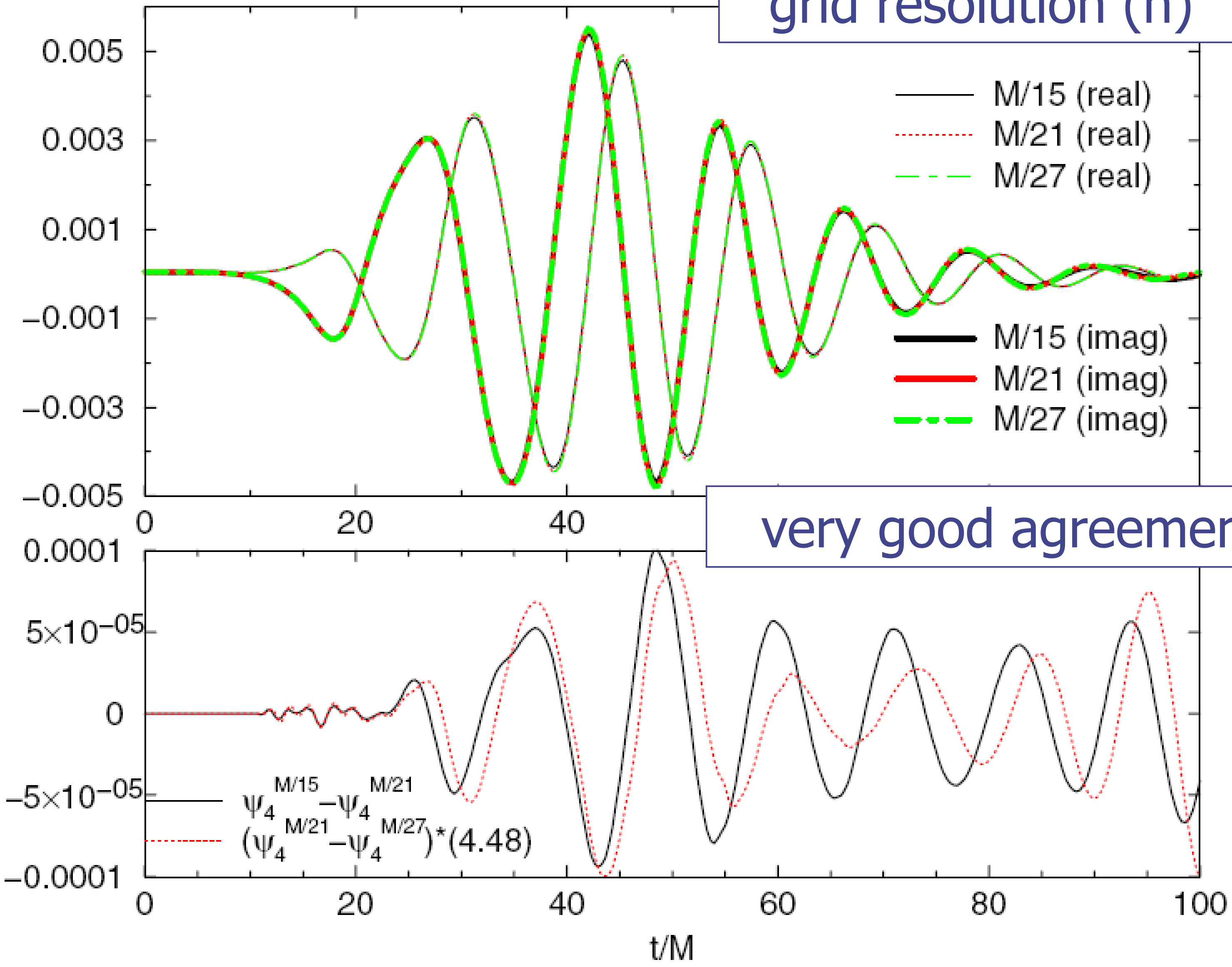
- Perturbative analytic method:
  good during the early stages of a merger & later stages of ringdown.
- Numerical solution is essential:
  during last several orbits, plunge, early stages of ring down.
- Problem:
  no code to simulate a nonaxisymmetric collisions through coalescence & ringdown

2006



trajectories from t=0 to 18.8 M (in 2.5 M step)

2006



grid resolution (h)

very good agreement

Weyl scalar $(\ell = 2,\ m = 2)$ mode of ψ_4 at $r = 15M$

Prospects

- Recent works give stable (reliable) results !!
- Future possibilities in numerical relativity !
- Colliding Neutron Stars:
  - Equation of States
  - QGP formation in the process of collision (?)

Physics of Heavy Ion Collisions

Thank You