GAMMA RAY BURSTS AS SOURCES OF GRAVITATIONAL WAVES

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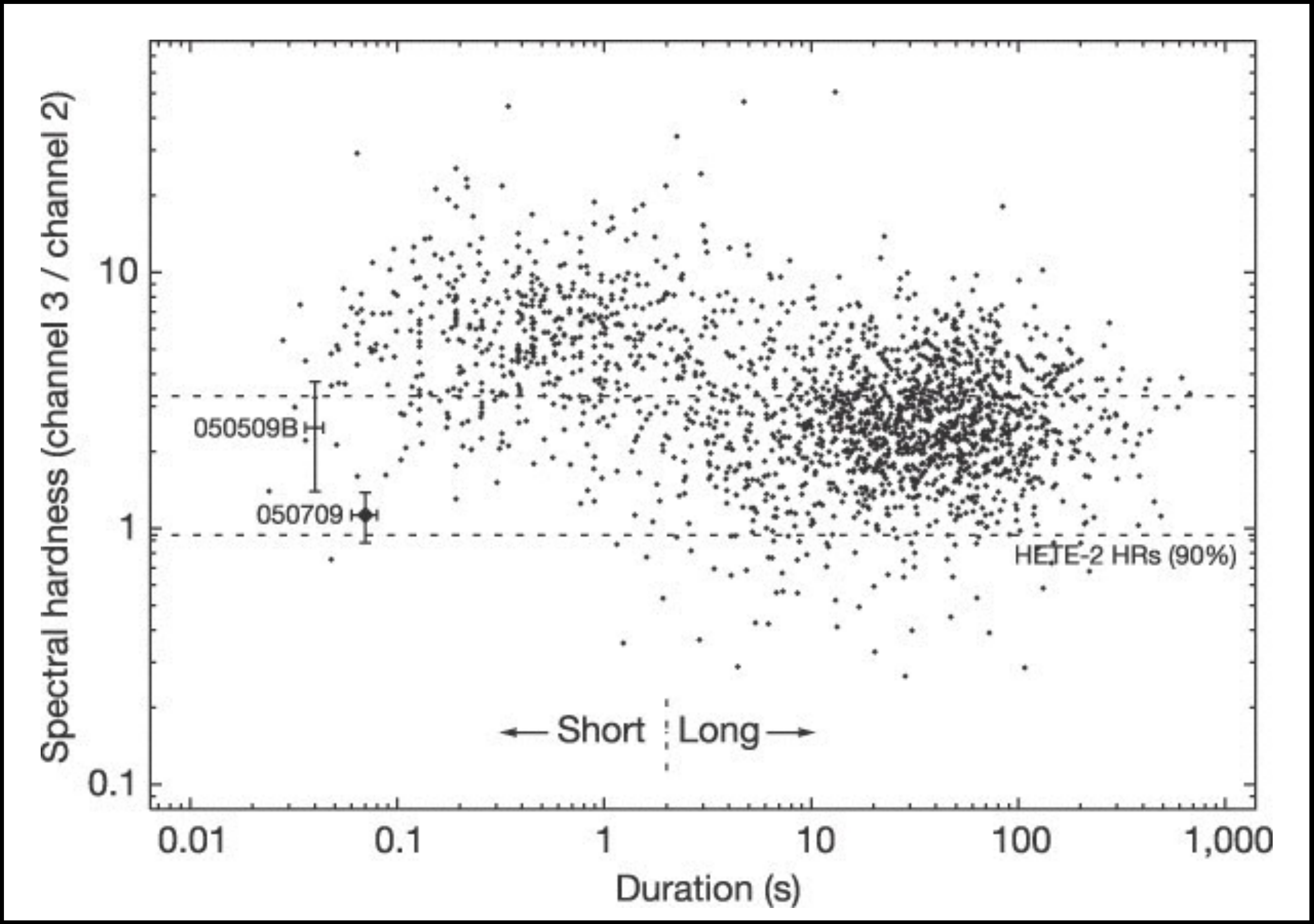
Gamma Ray Bursts in the Multi-Messenger Era, Paris

OUTLINE

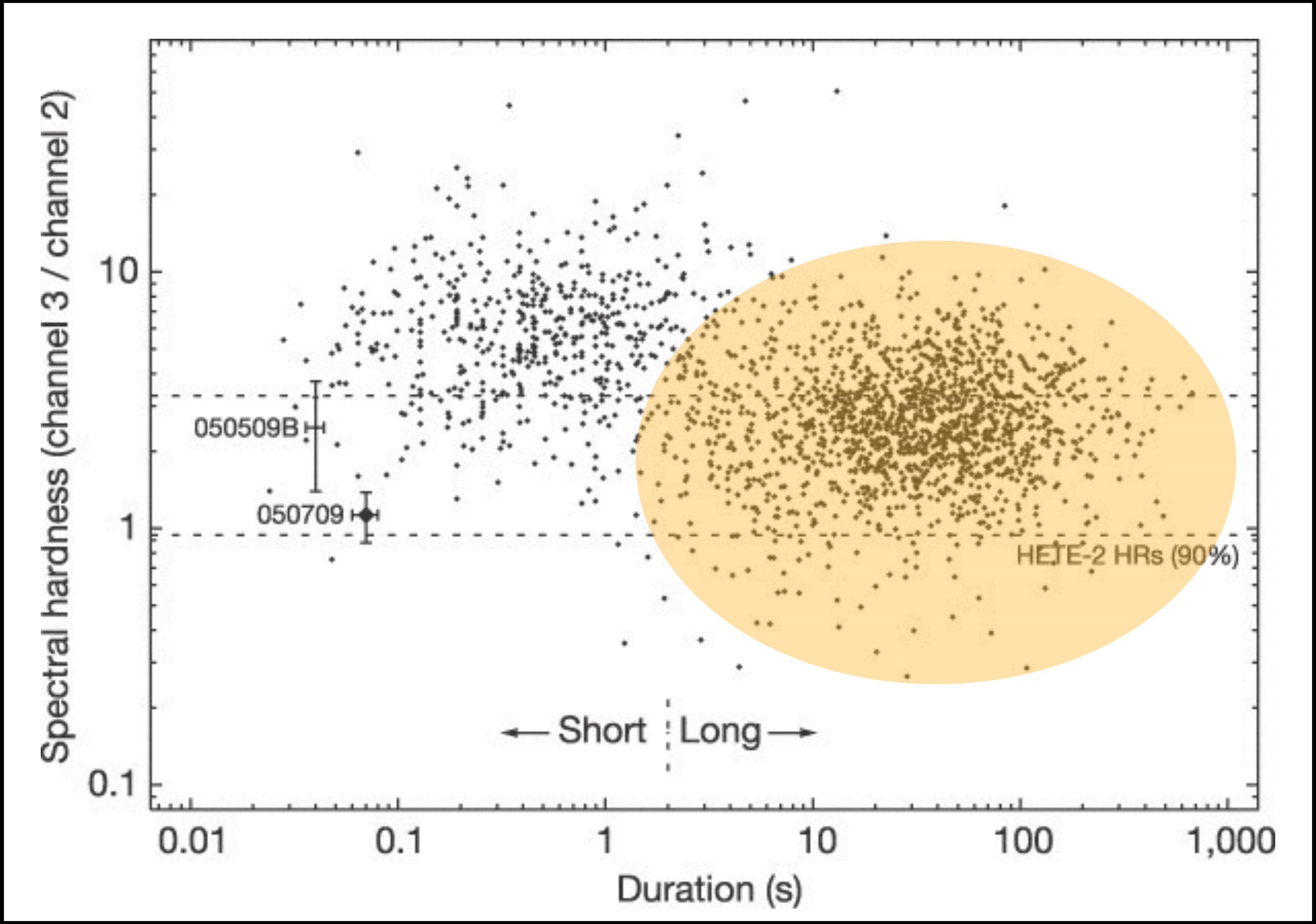
- LONG AND SHORT GRB PROGENITOR MODELS AND GW WAVEFORMS
- RESULTS FROM LIGO-VIRGO SEARCHES
- PROSPECTS FOR ADVANCED LIGO AND VIRGO
- PAYOFF FROM JOINT GW-GRB OBSERVATIONS

GRB CLASSIFICATION



Hjorth et al, Nature, 2005

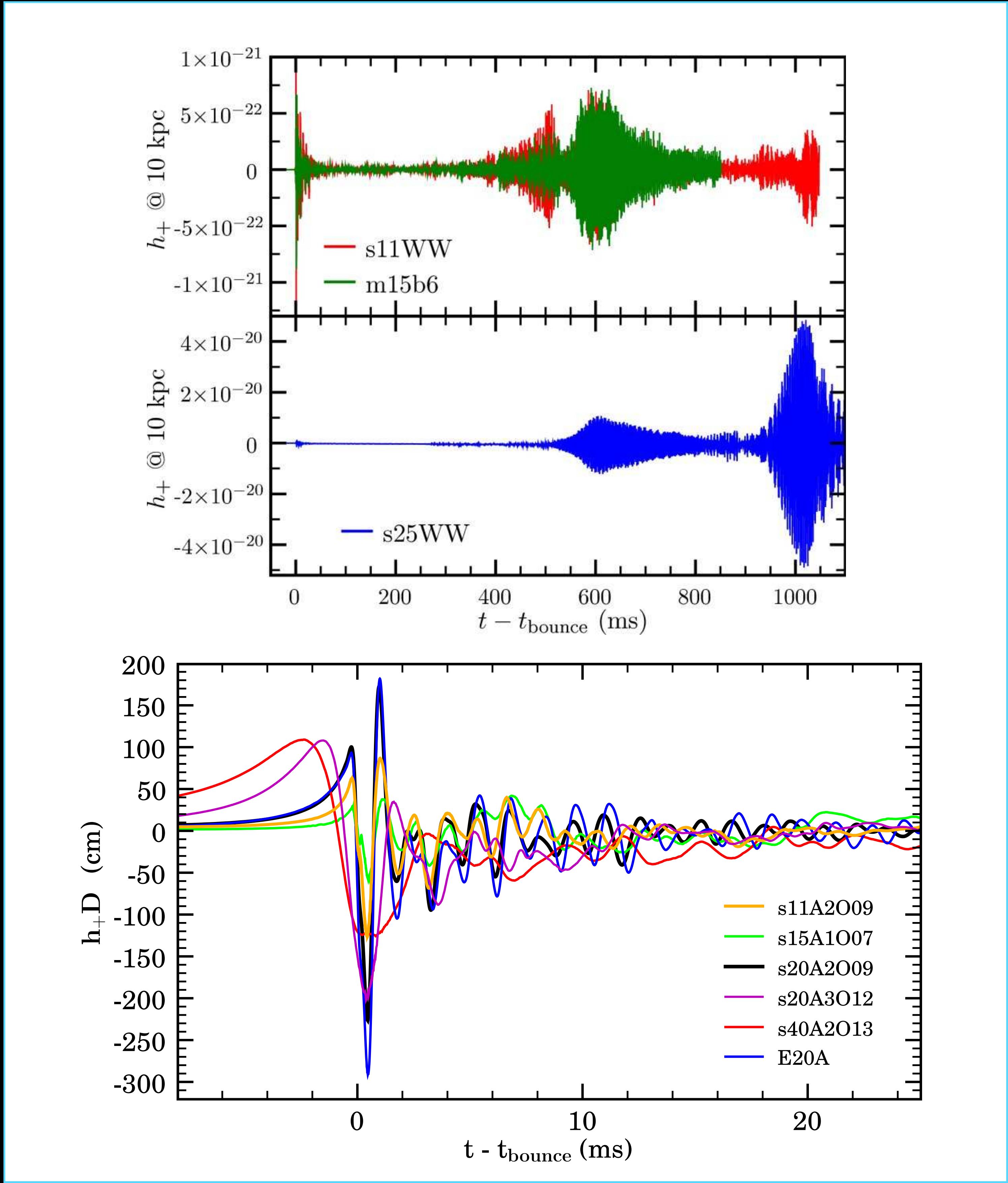
LONG GRB PROGENITORS



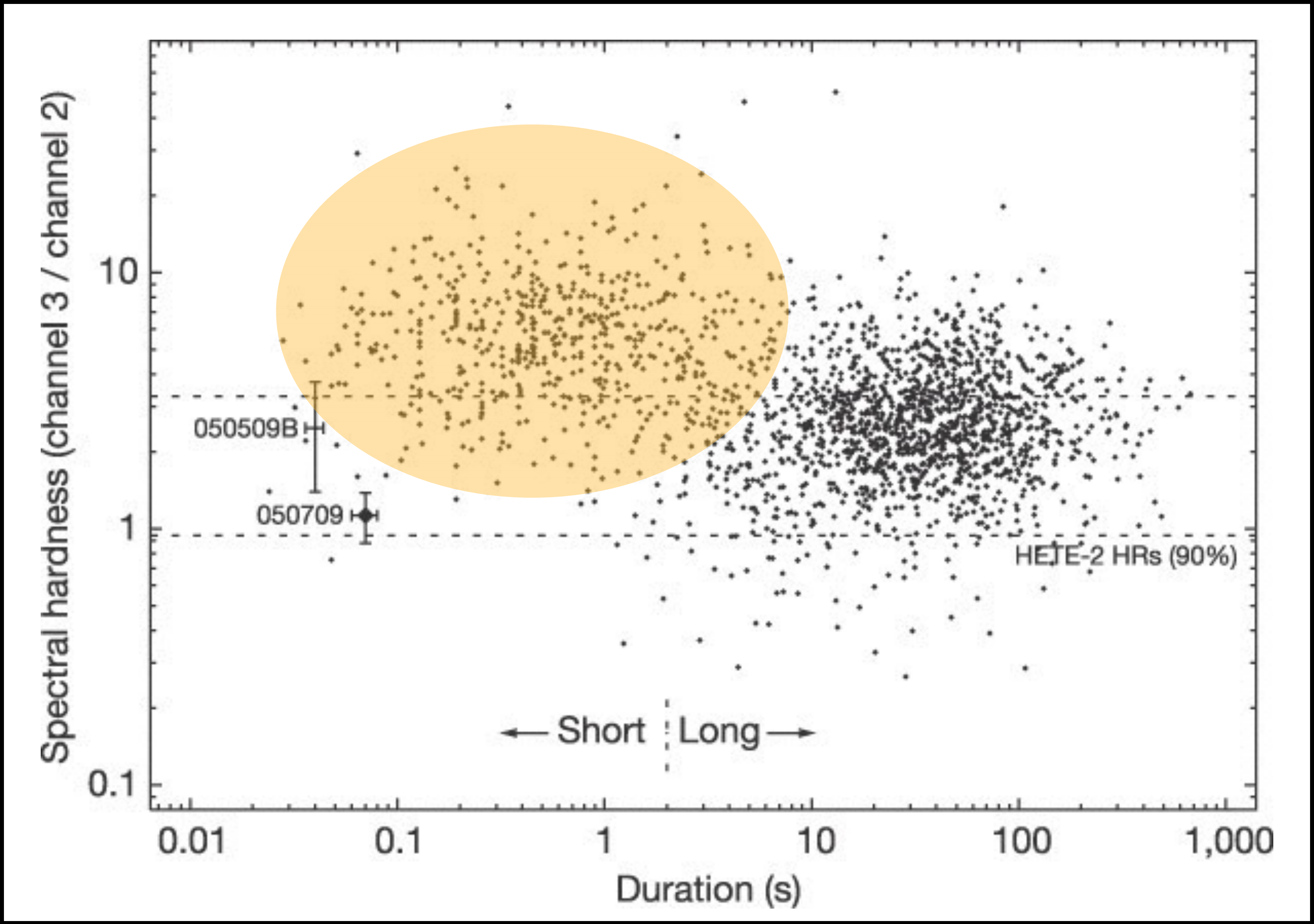
Hjorth et al, Nature, 2005

LONG GRB WAVEFORMS

- Collapsar progenitor has uncertain GW emission. Models predict:
- from $10^{-2}\ M_{\odot}c^2$ (Davies et al 2002, Piro and Pfahl 2007)
- To $10^{-8}\ M_{\odot}c^2$ (Ott 2009)

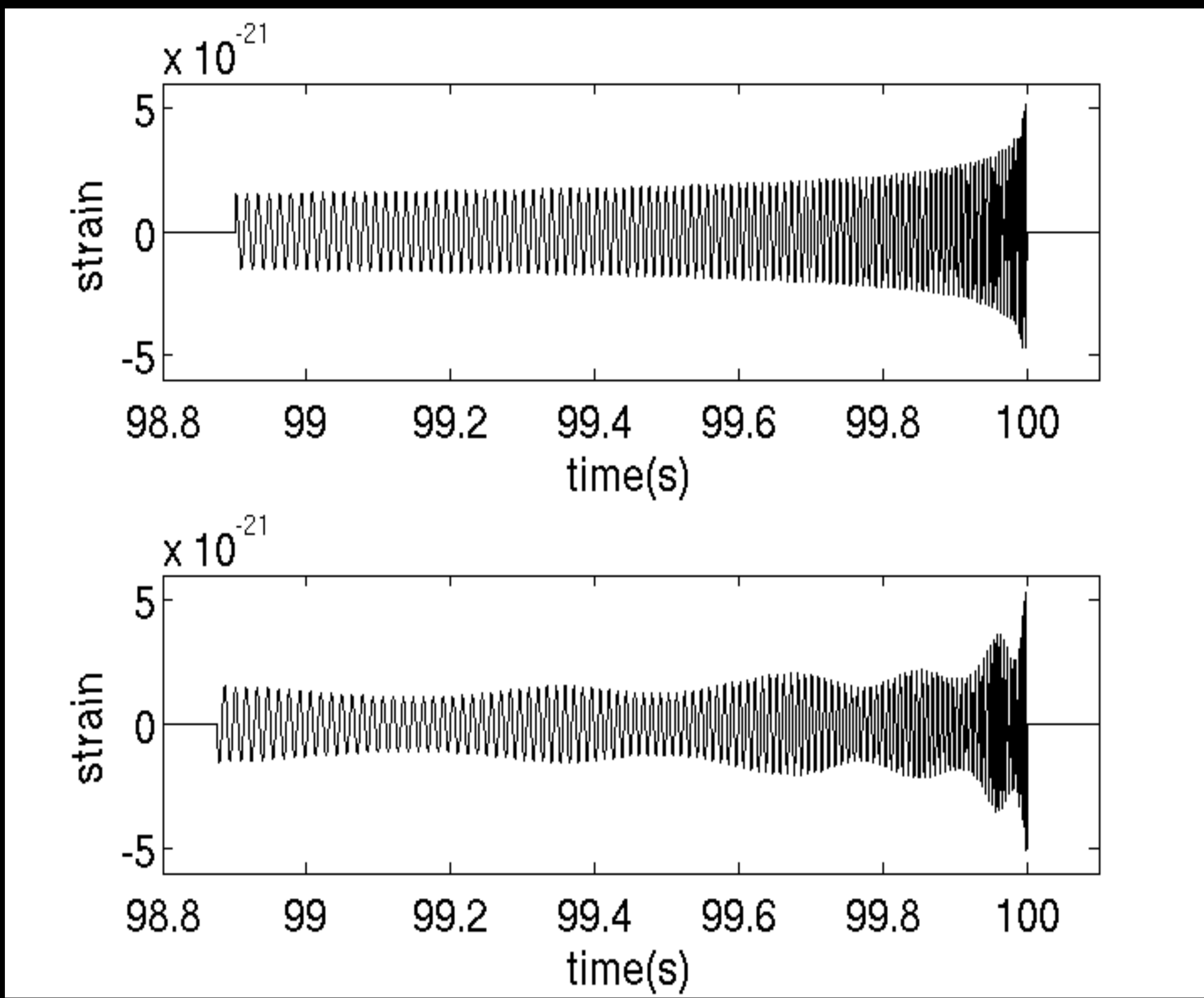


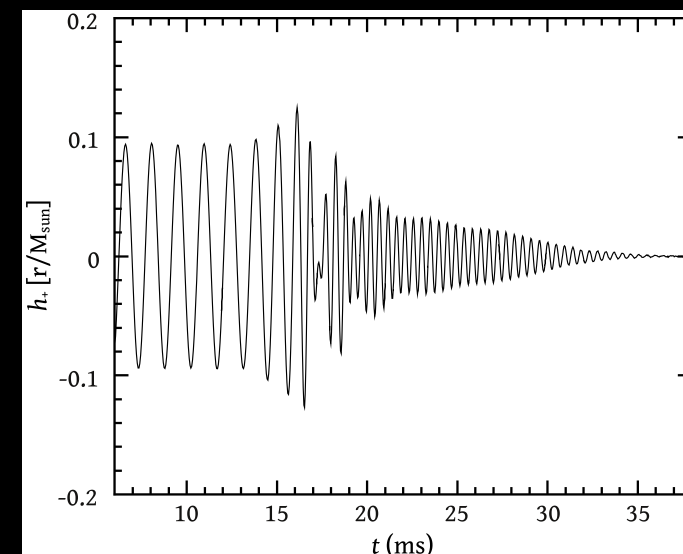
SHORT GRB PROGENITORS



Hjorth et al, Nature, 2005

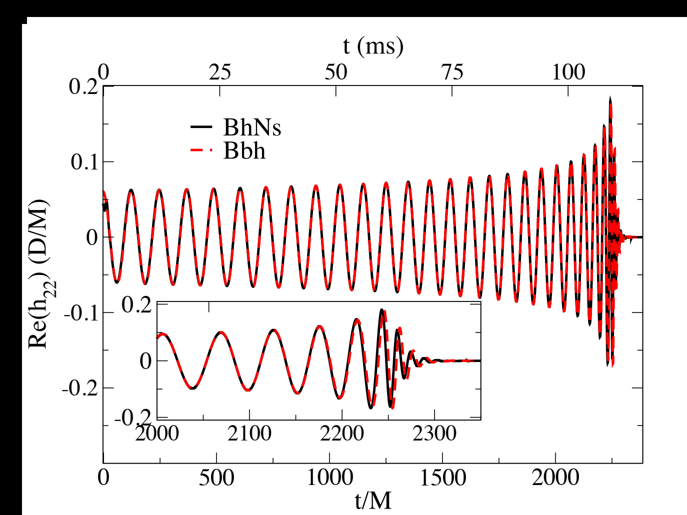
SHORT GRB WAVEFORMS





BNS Merger

Stergioulas et. al, 2011



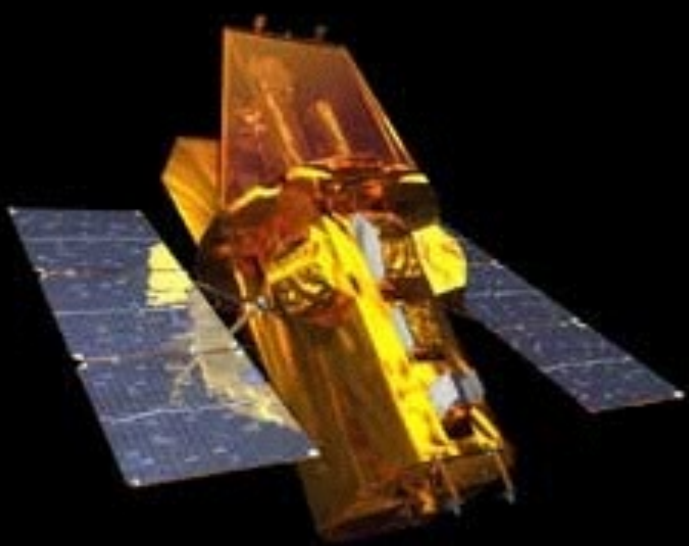
NSBH Merger

Foucart et. al, 2013

Post-Newtonian Inspiral

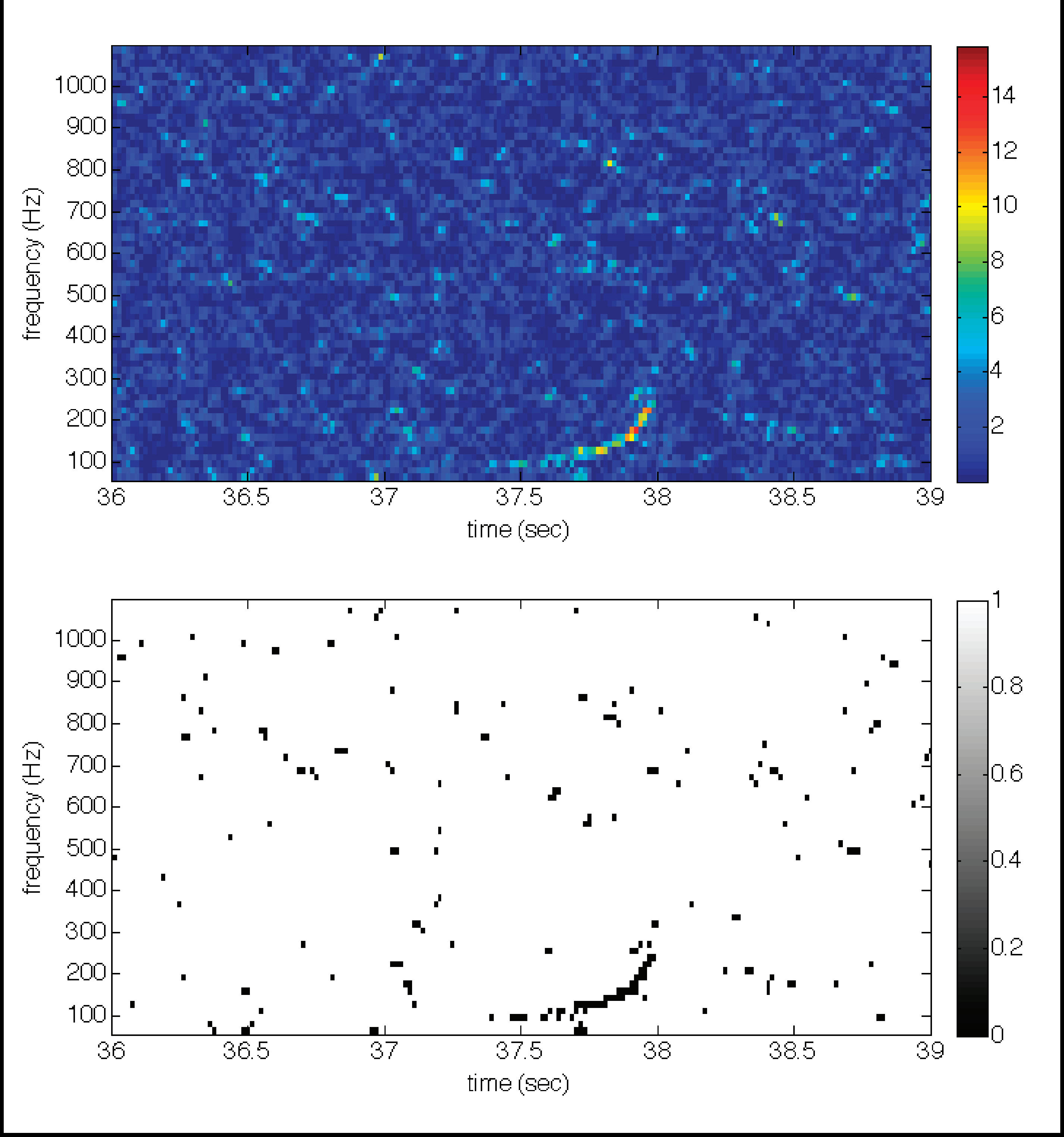
Numerical Merger

TRIGGERED GRB SEARCH



GRB SEARCH

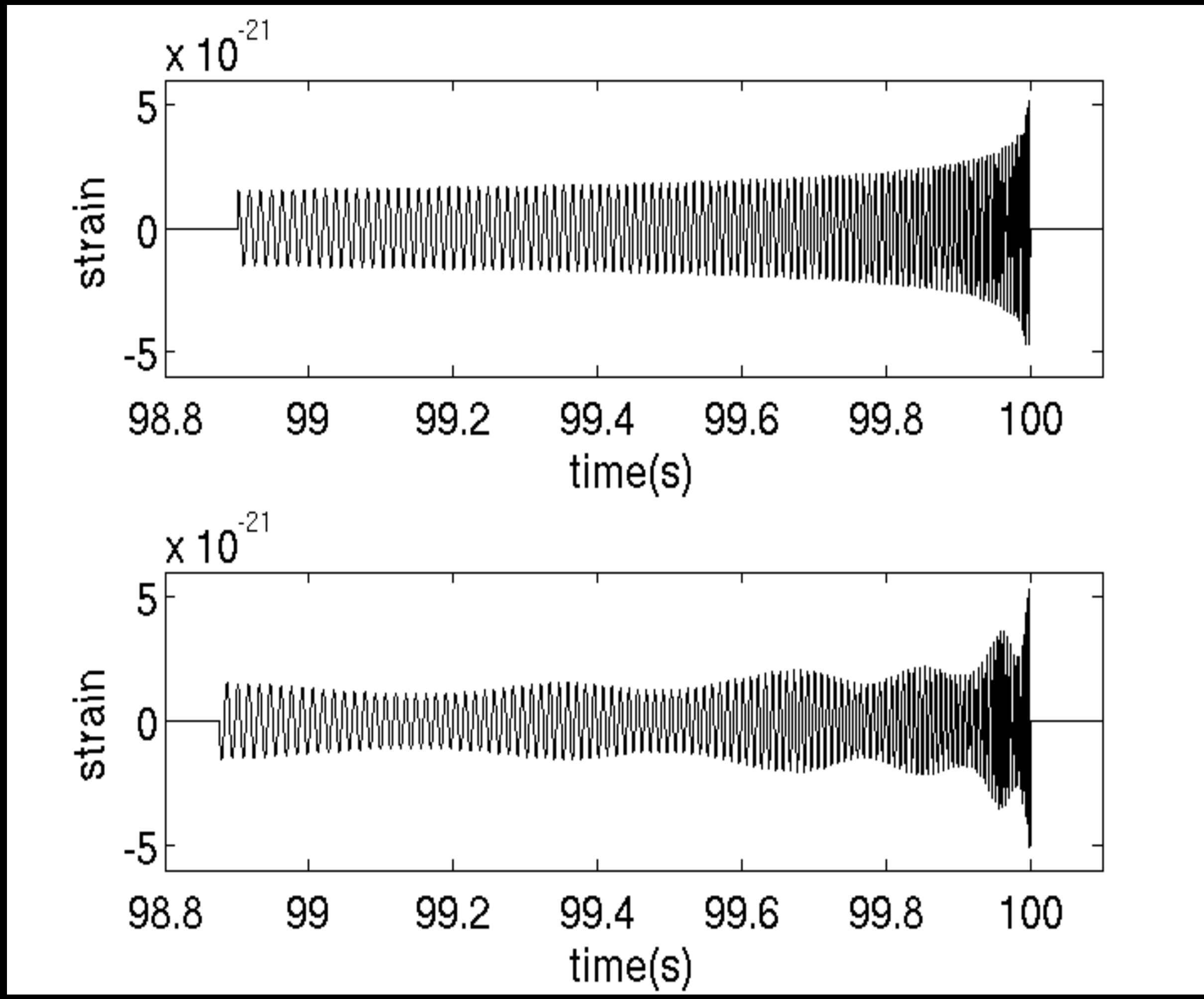
- For all GRBs, search from 600 seconds before to 60 seconds after burst
- Minimal assumptions about gravitational waveform other than known time and sky location
- About a factor of 2 improvement in sensitivity over all sky all time search



Sutton et al, NJP, 2010

SHORT GRB SEARCH

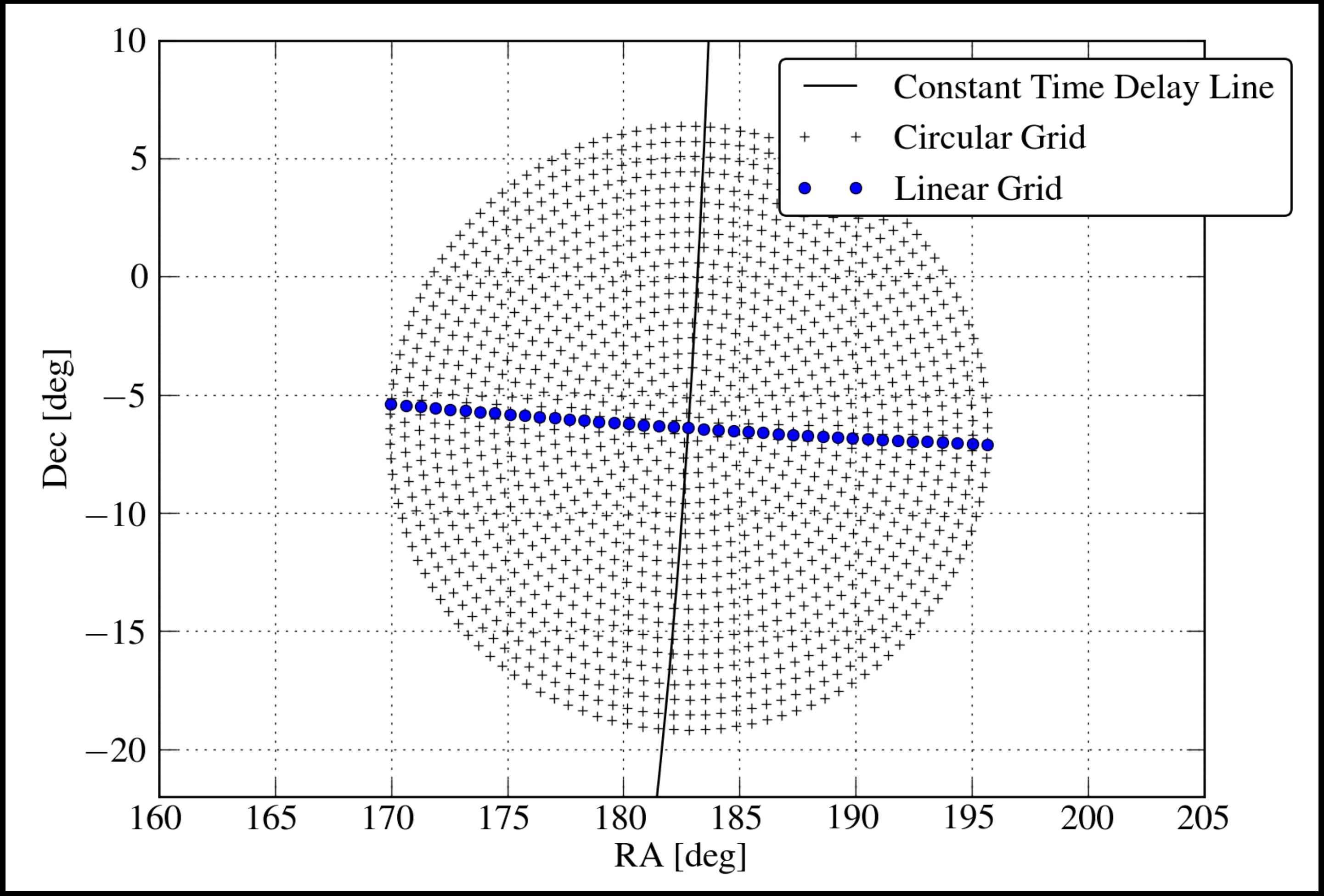
- Binary merger search — look for characteristic signal from NS-NS or NS-NH merger
- Search 5 seconds before to 1 second after burst
- Coherently combine the data from different detectors making use of the known sky location
- About a 25% increase in sensitivity over all sky all time search



Babak et al, PRD, 2013
Harry and SF, PRD, 2011

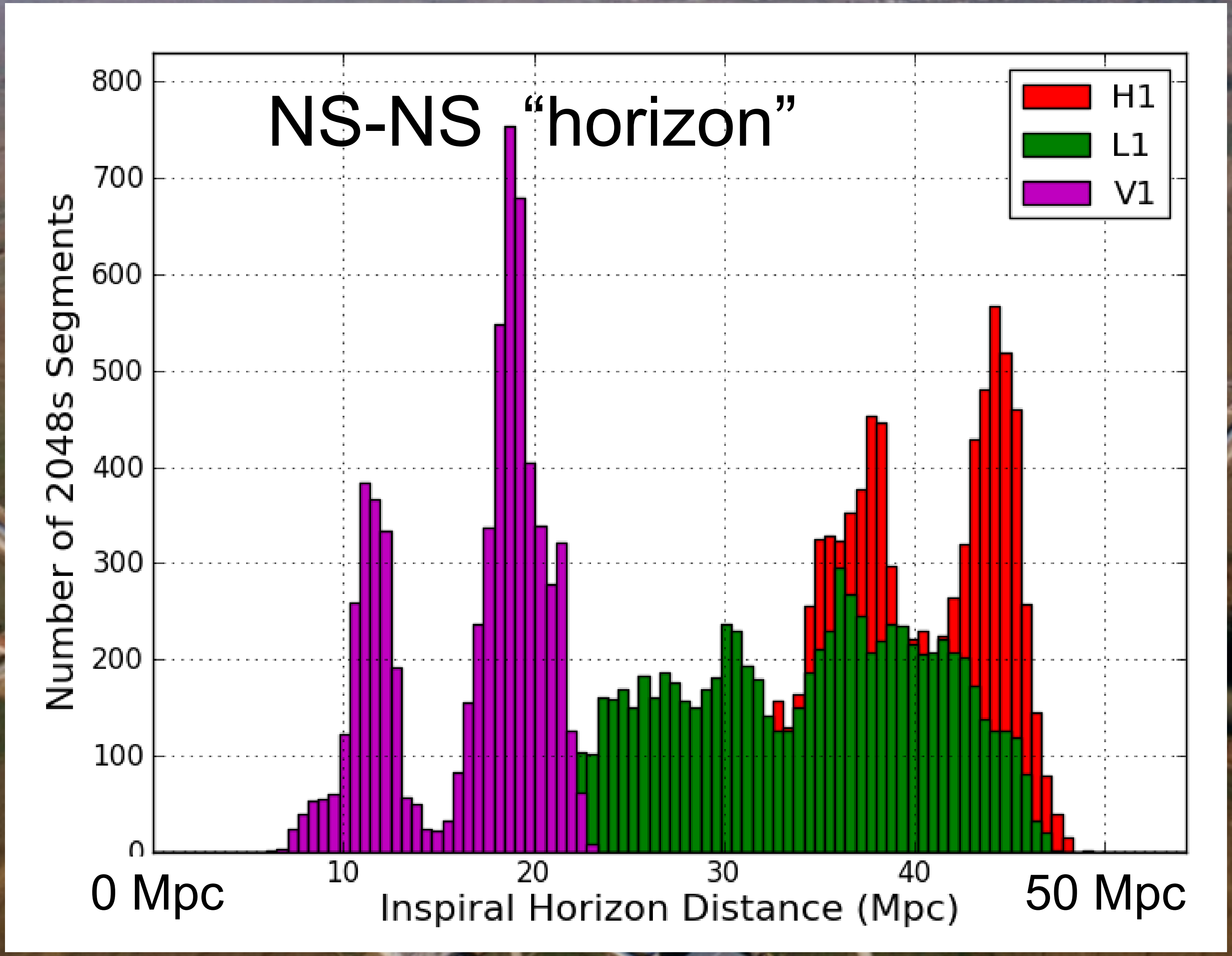
COVERING SKY PATCHES

- Swift BAT bursts localized to a single point (from GW perspective)
- Fermi GBM and Interplanetary Network bursts not so well localised: tile the sky area

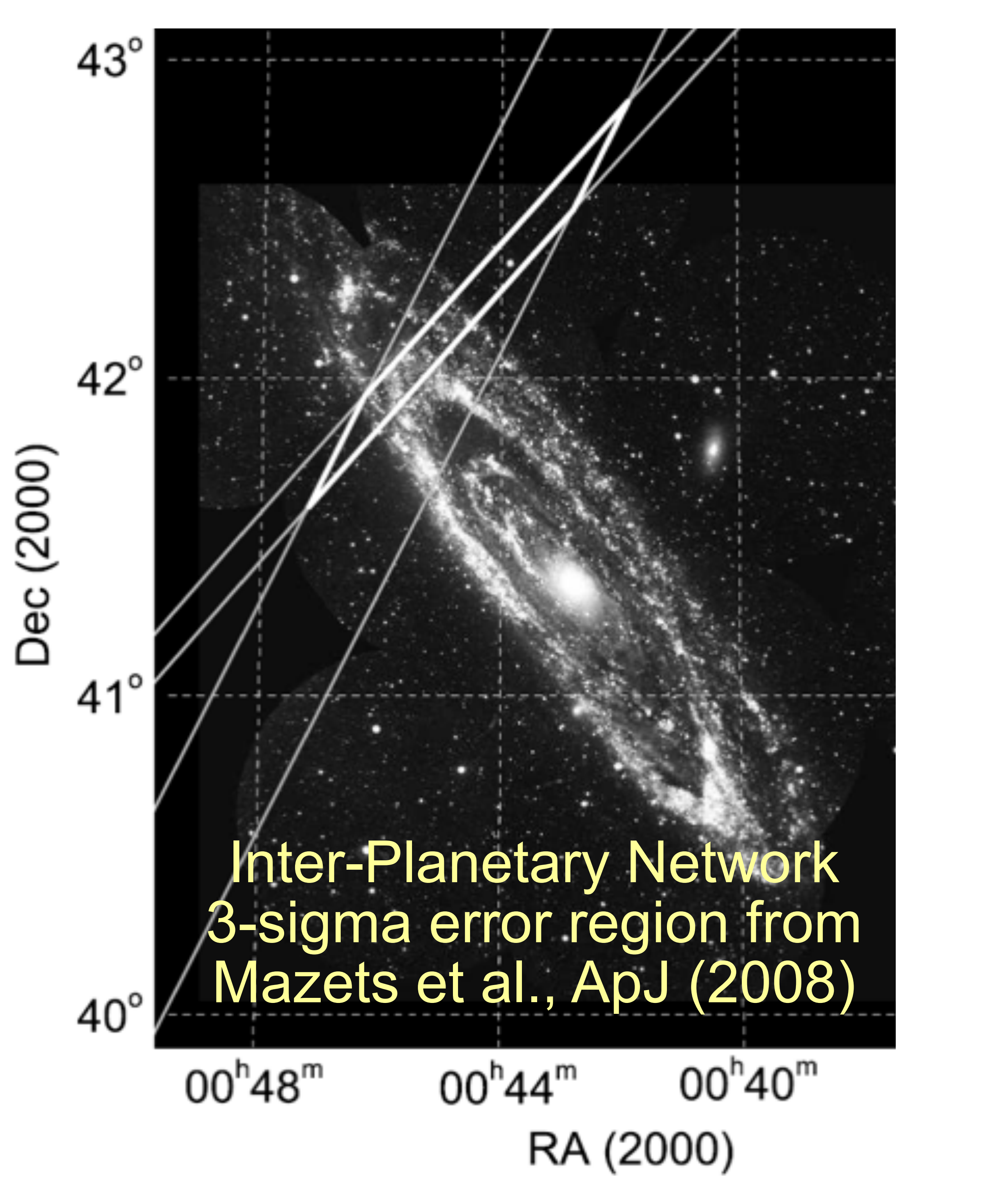


Aasi et al, 2014

INITIAL LIGO-VIRGO RESULTS



GRB 070201

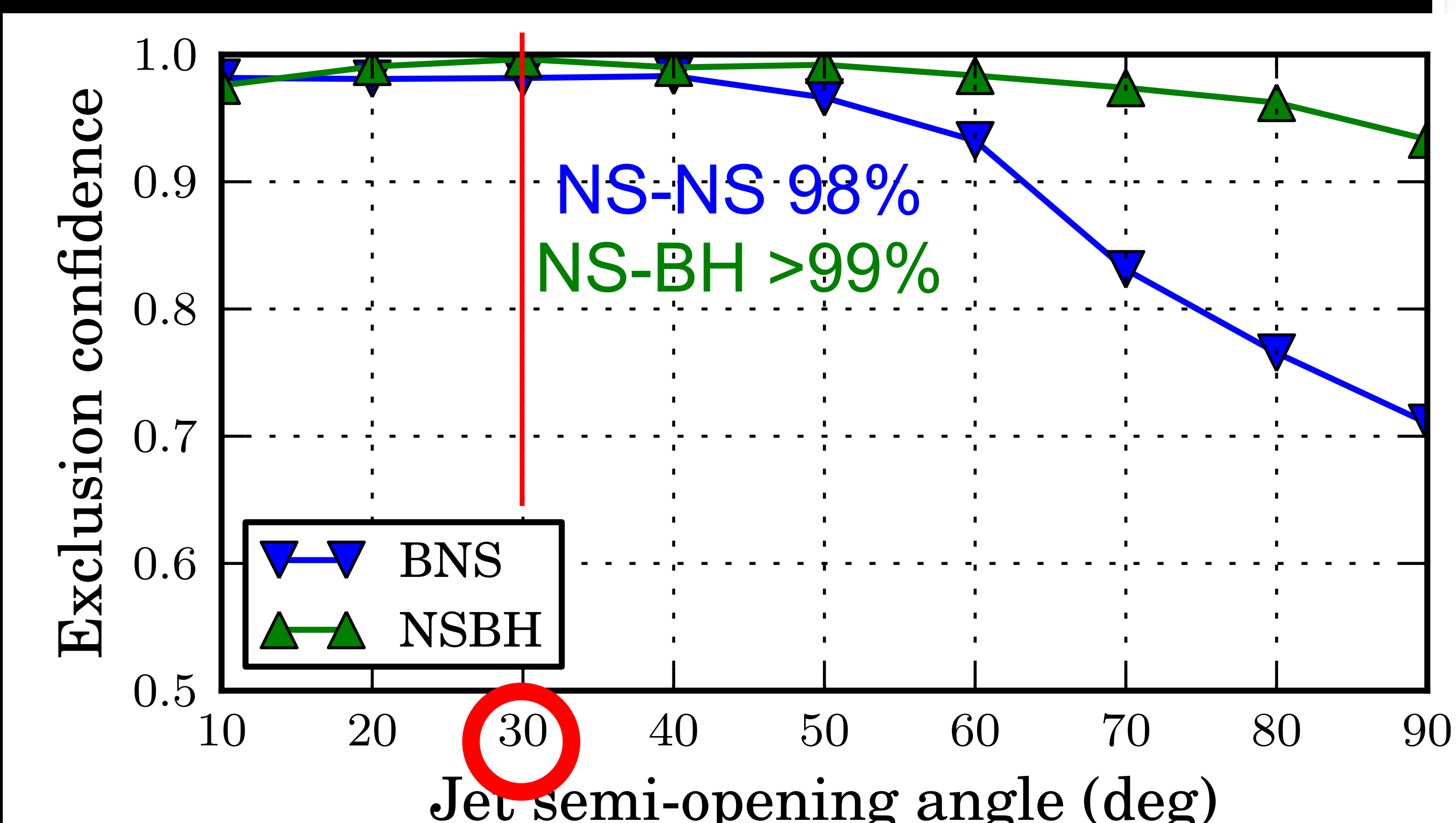


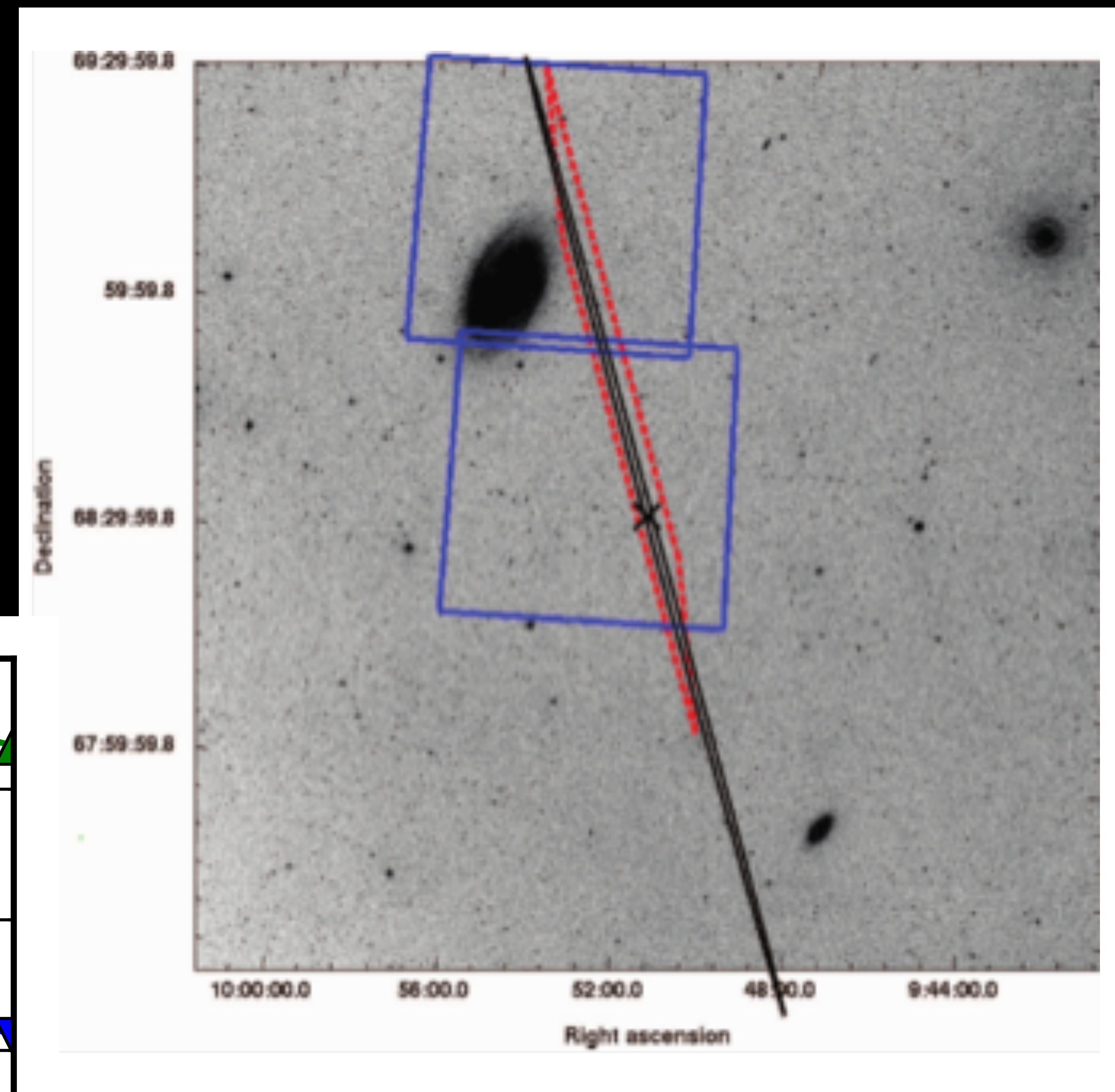
- Localization overlaps M31 (at 770 kpc)
- No GW signal observed
- Exclude NS-NS and NS-BH merger in M31 with 99% confidence
- Indirect support for hypothesis of soft gamma repeater in M31

Abbott et al. ApJ 2008

GRB 051103

- Localization overlaps M81 (at 3.6 Mpc)
- No GW signal observed
- Exclude binary merger progenitor as function of opening angle

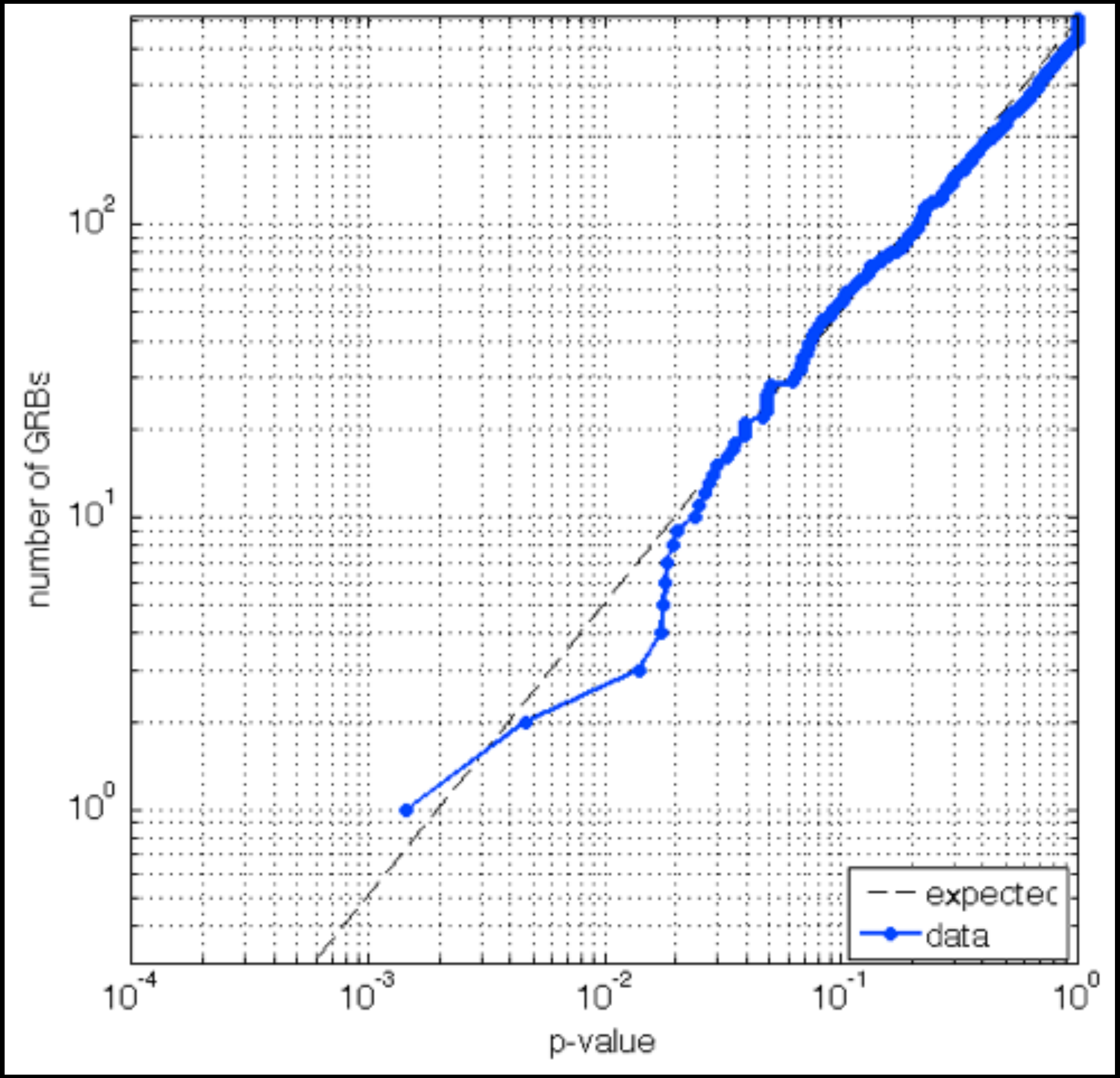




Abadie et al, ApJ, 2012

SEARCH RESULTS: ALL GRB

- Search for gravitational wave signal from 508 GRBs observed between 2005 and 2010.
- No evidence of a signal for single event or population
- Place exclusion limits assuming a GW emission model
- Also see V.Predoi poster

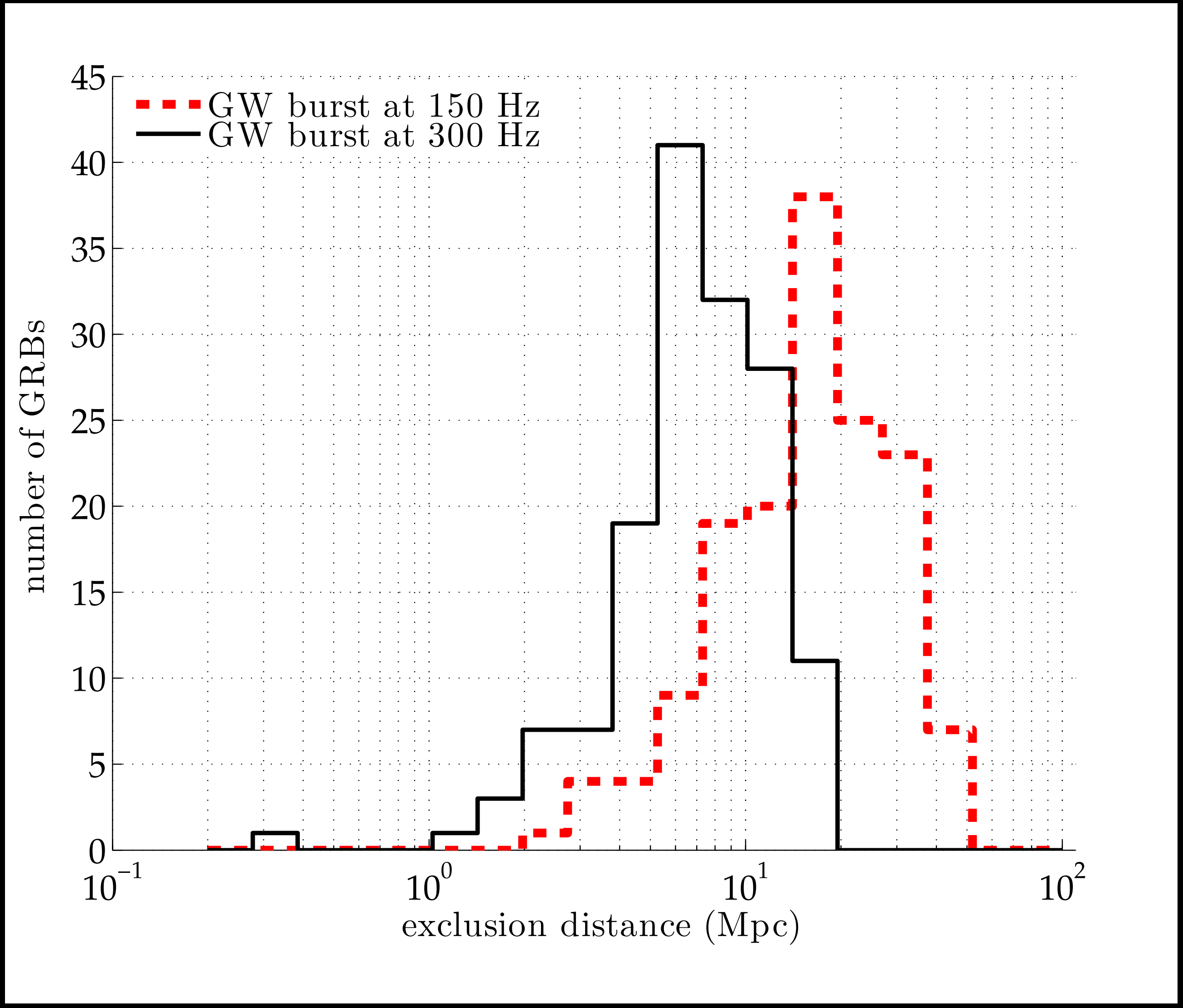


Aasi et al, 2014

EXCLUSION DISTANCES: ALL GRB

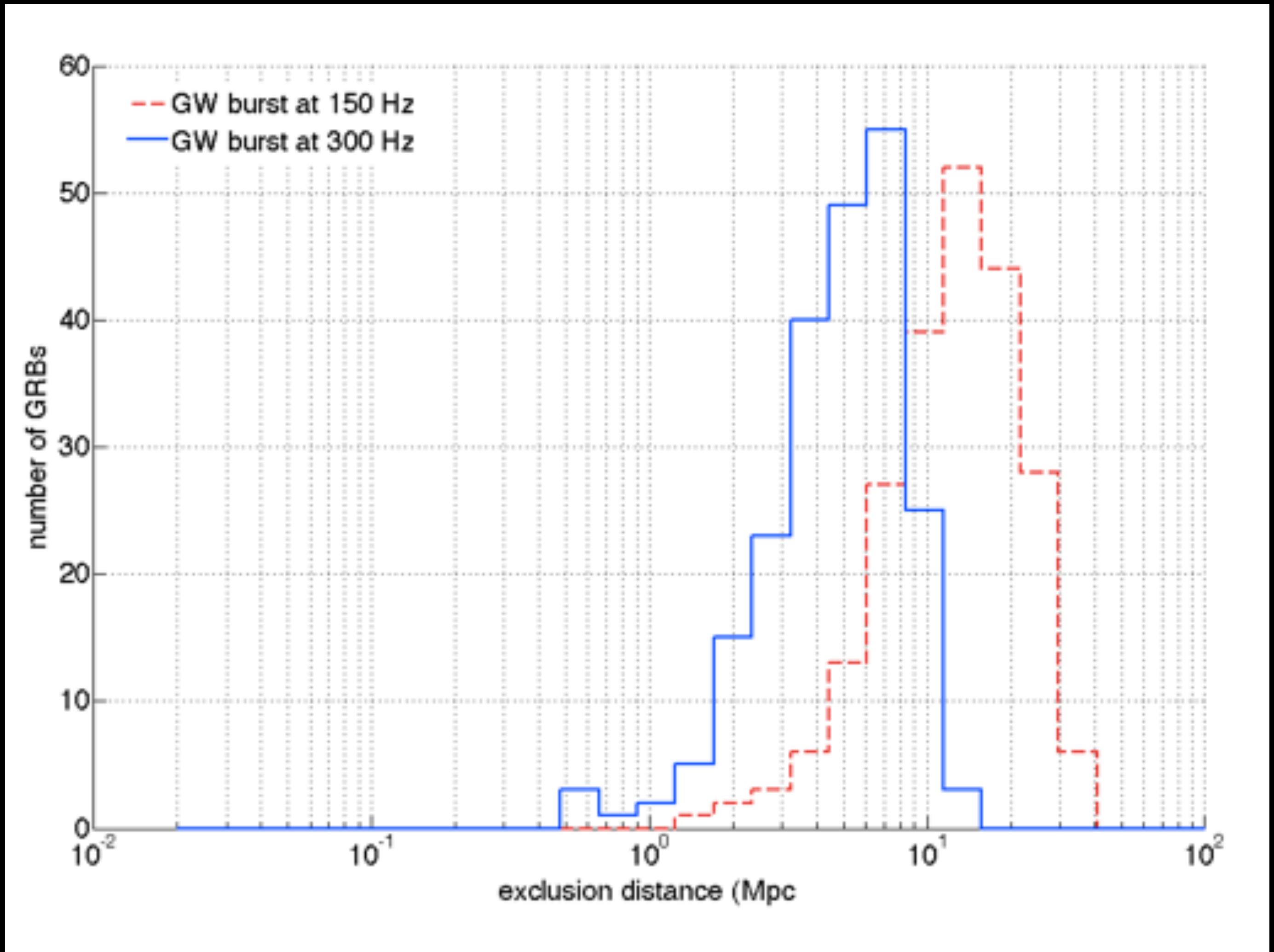
Assuming $10^{-2}\ M_\odot c^2$ in GW; emitted in small frequency band

Swift/Fermi Bursts



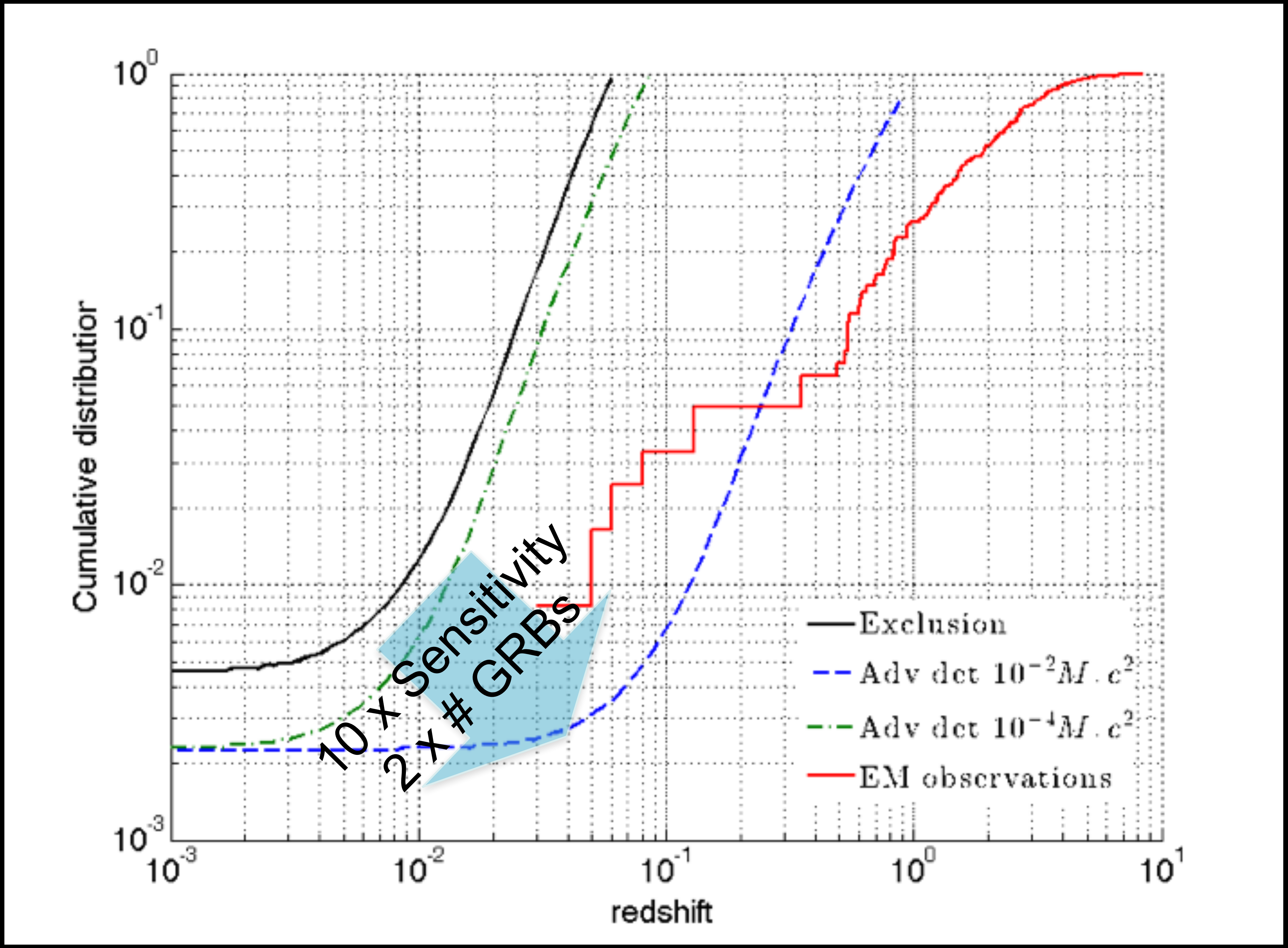
Briggs et al, 2012

IPN Bursts



Aasi et al, 2014

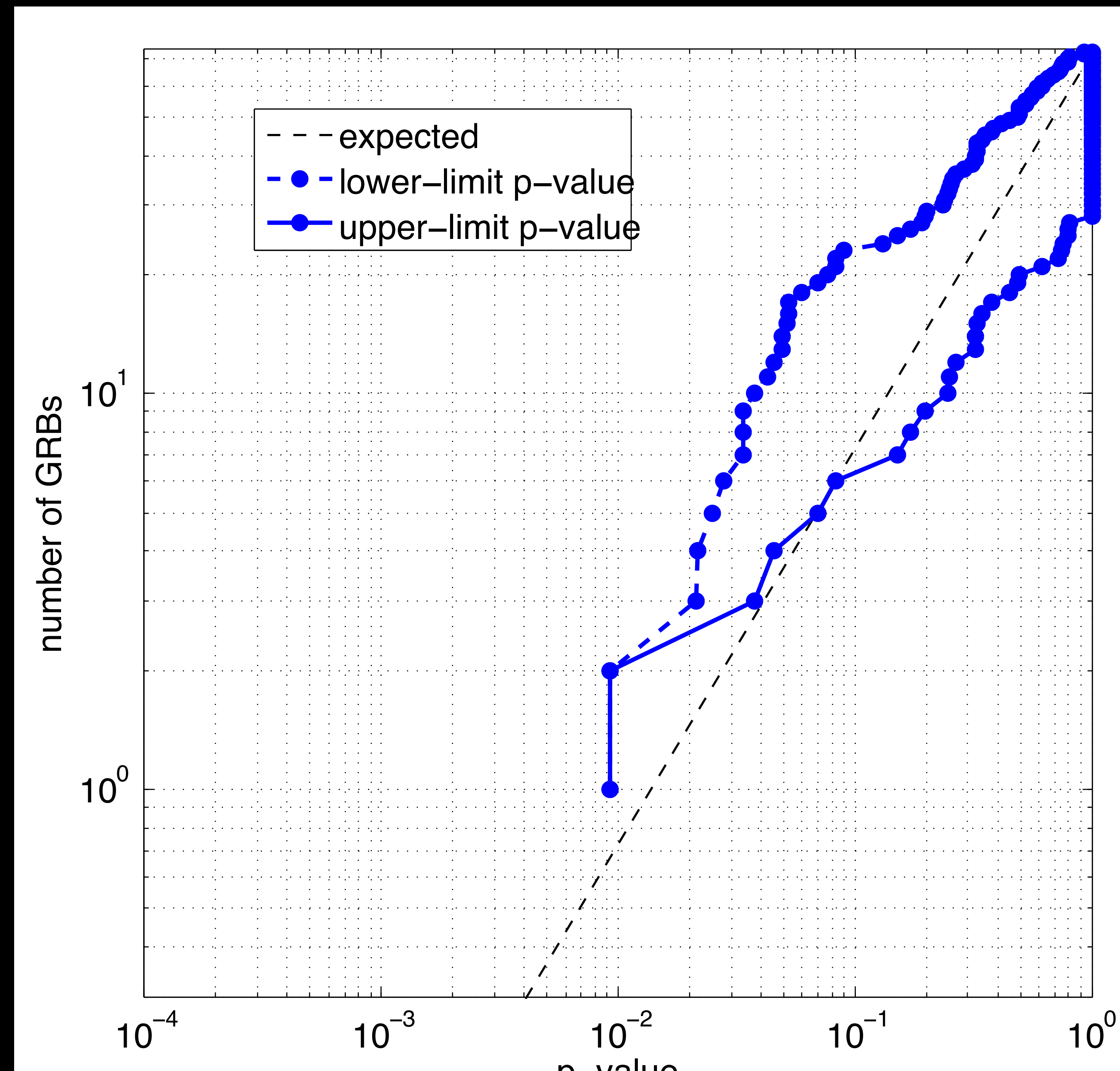
POPULATION EXCLUSION



Aasi et al, 2014

SEARCH RESULTS: SHORT GRB

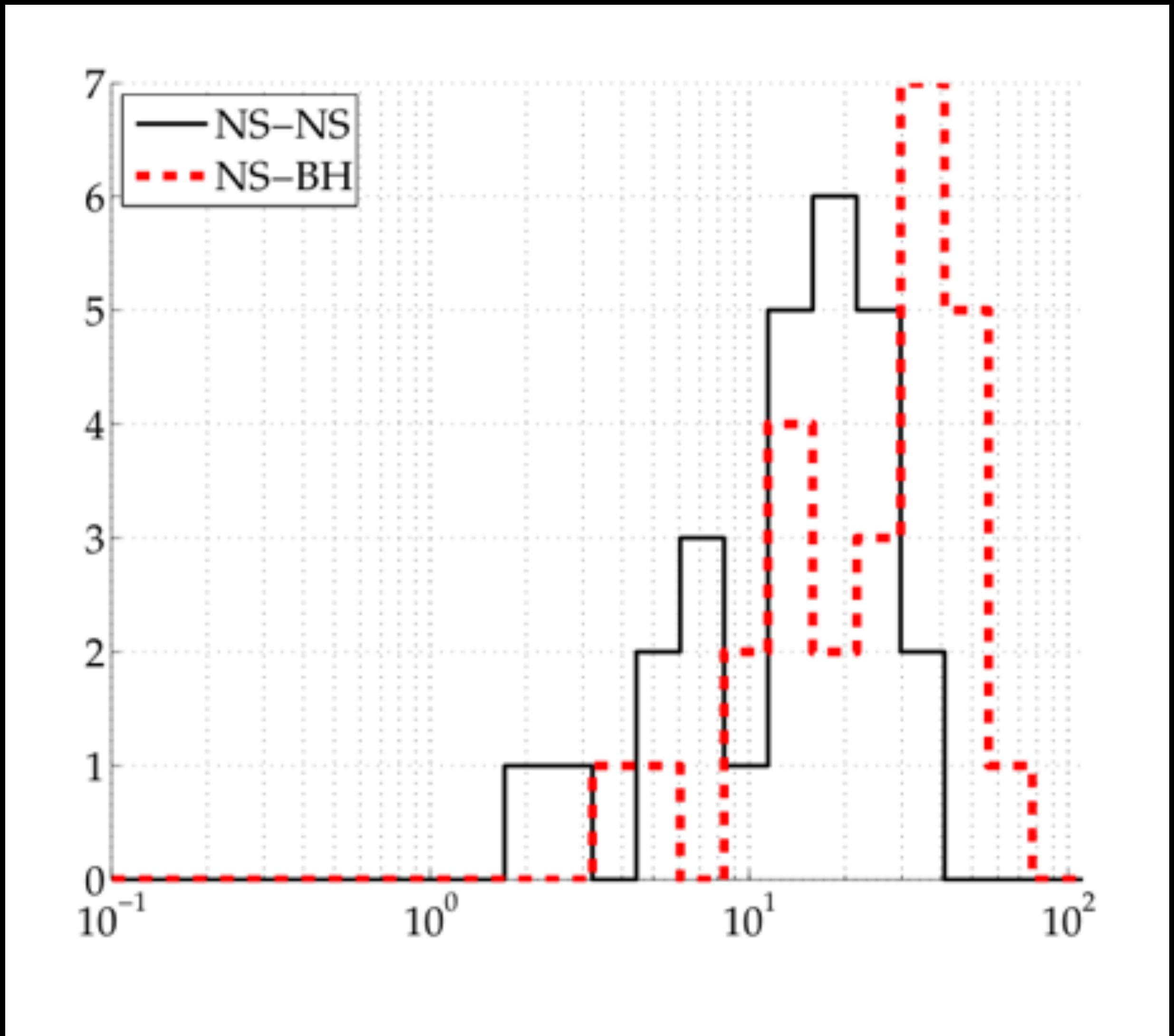
- Search for gravitational wave signal from 69 short GRBs observed between 2005 and 2010.
- No evidence of a signal for single event or population
- Place exclusion limits assuming NS-NS and NS-BH progenitor model



Aasi et al, 2014

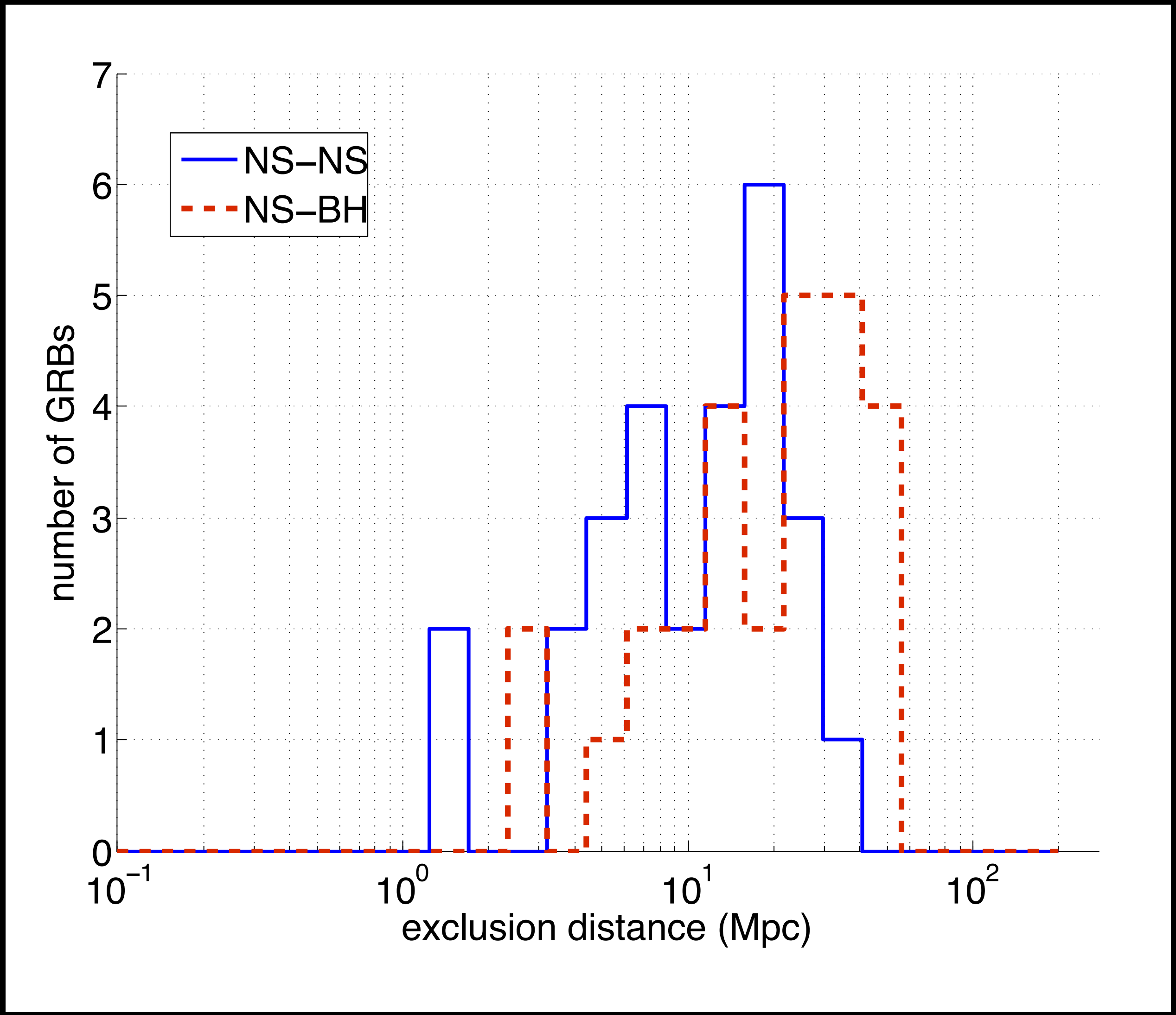
EXCLUSION DISTANCES: SHORT GRB

Swift/Fermi Bursts



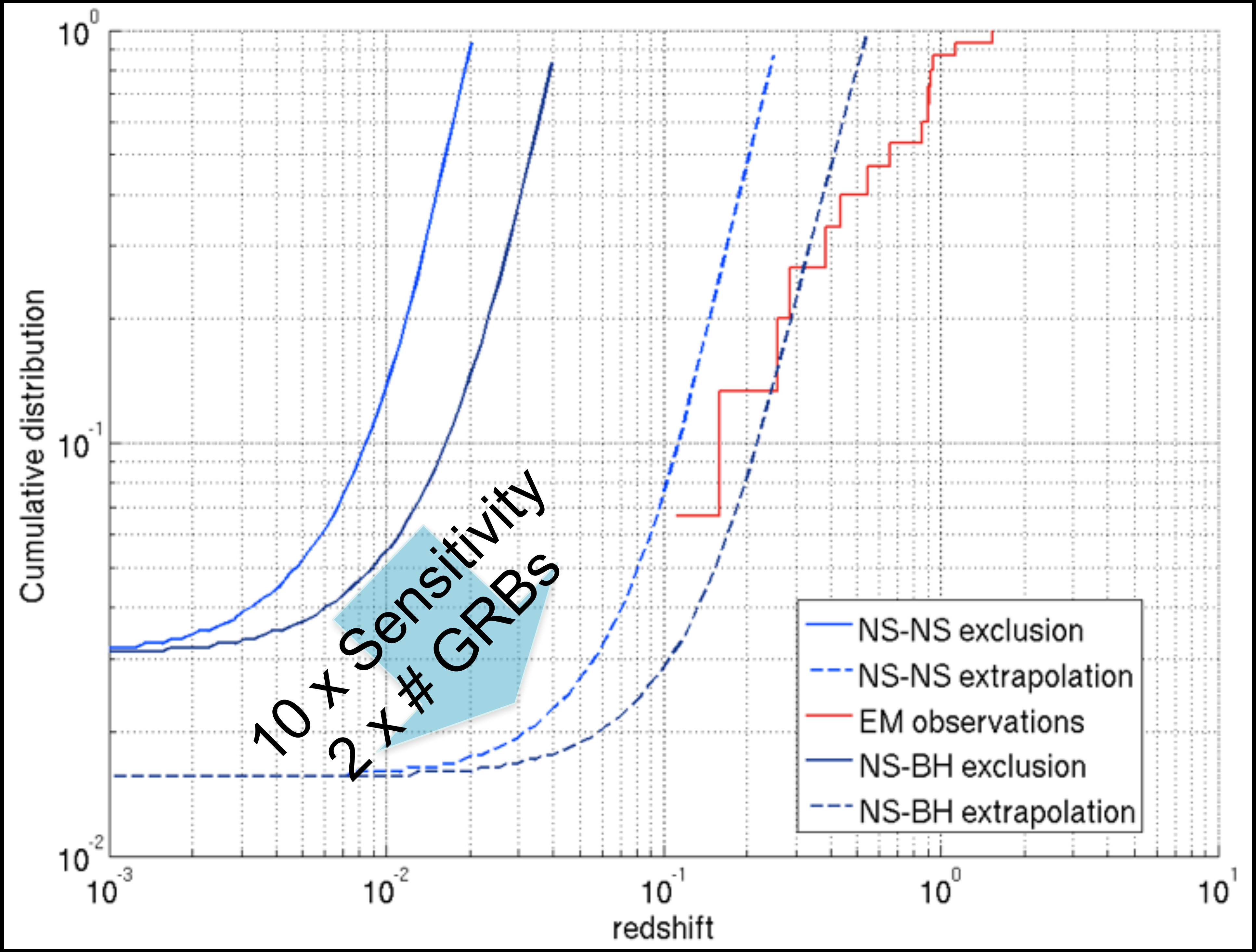
Briggs et al, 2012

IPN Bursts



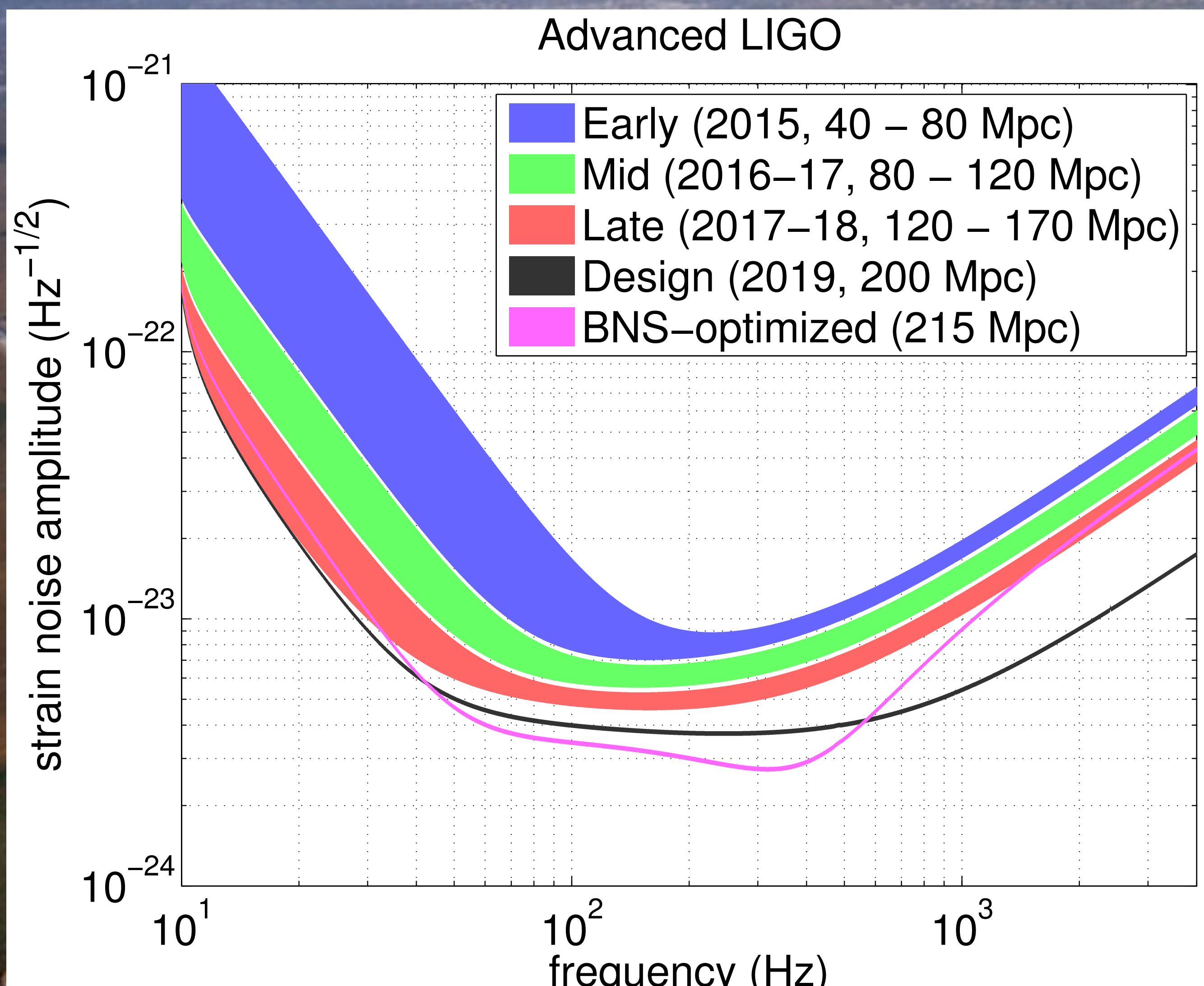
Aasi et al, 2014

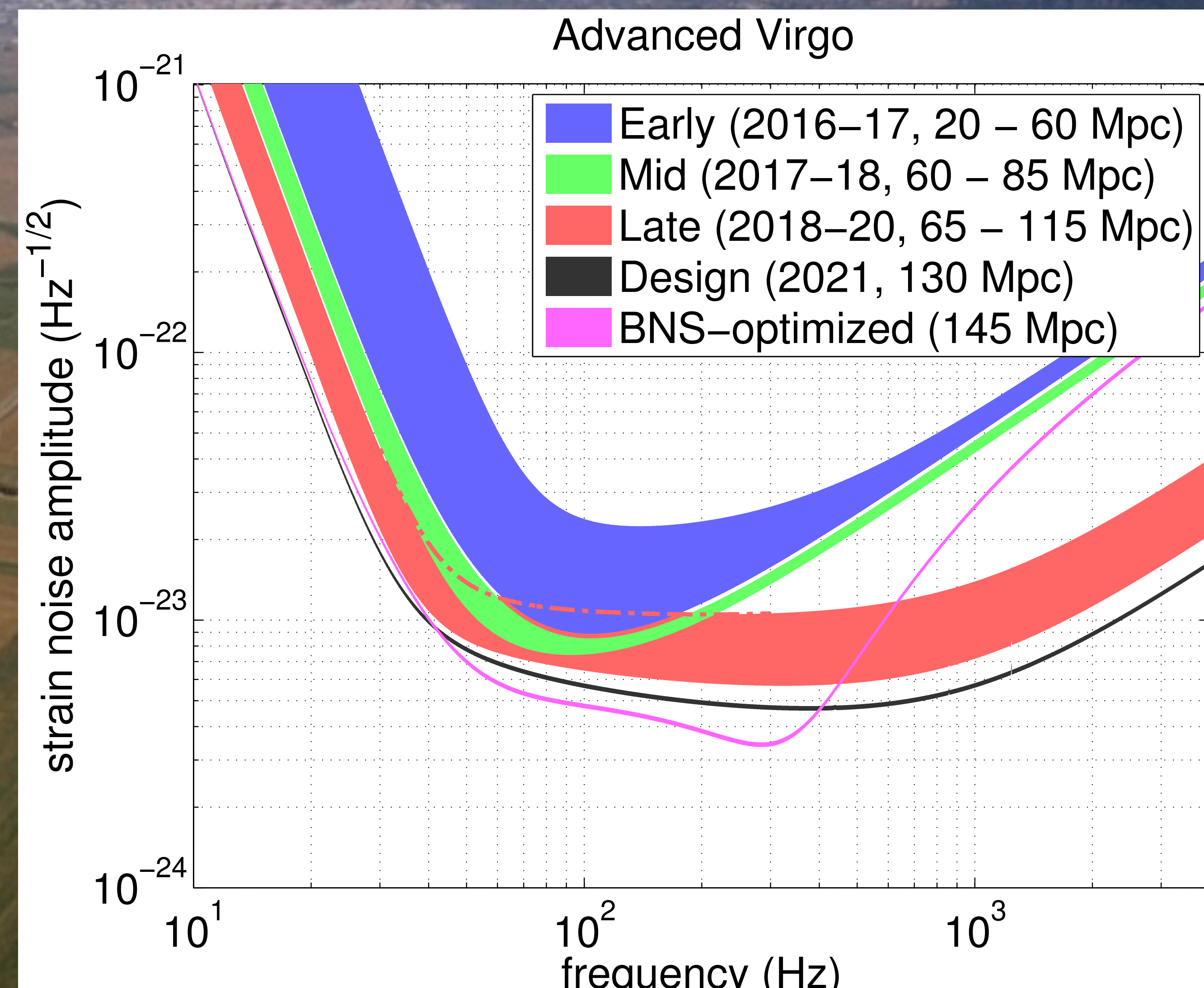
POPULATION EXCLUSION



Aasi et al, 2014

ADVANCED DETECTOR PROSPECTS

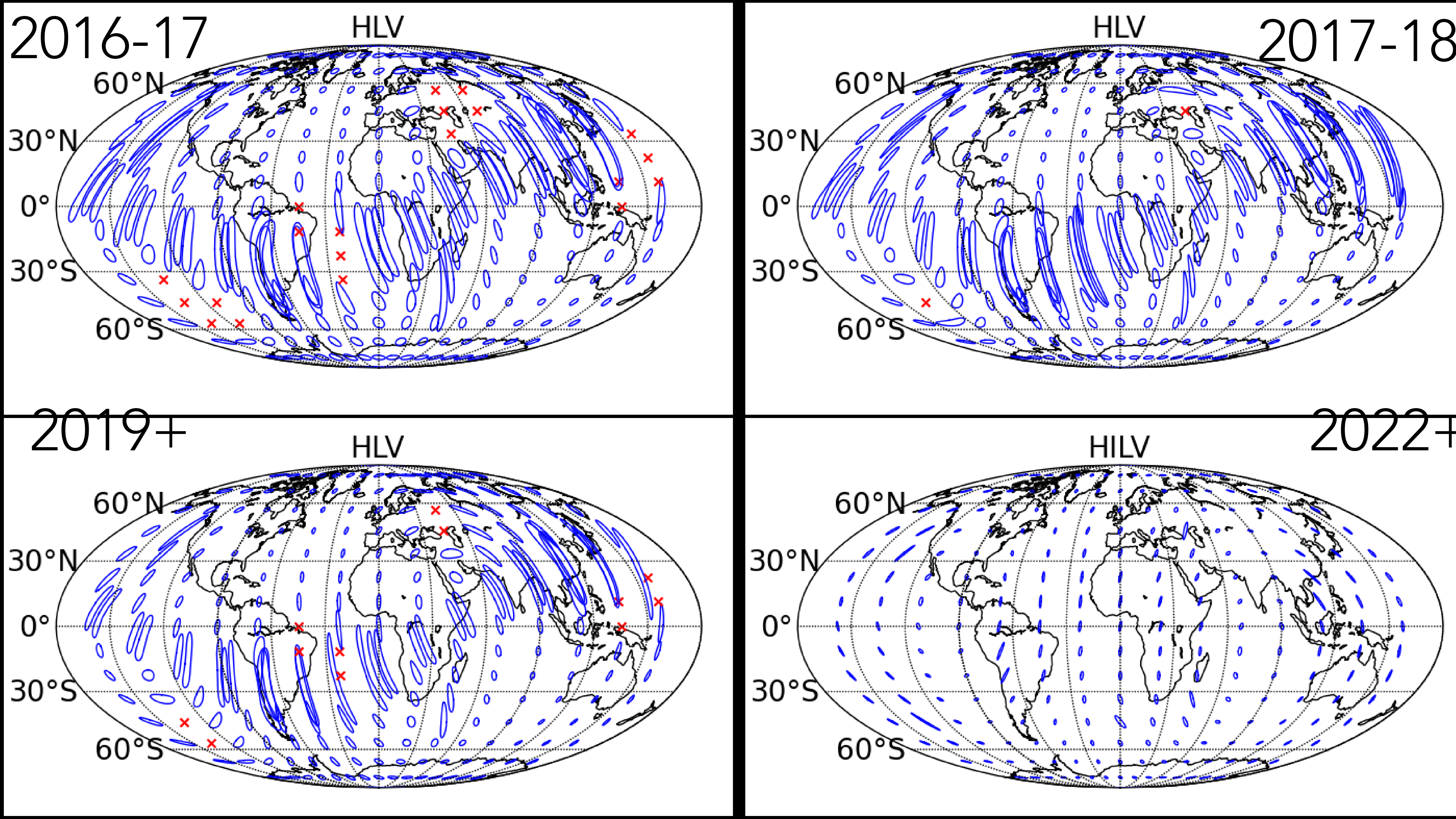




Aasi et al, 2013

SOURCE LOCALIZATION

Face on BNS at 80 Mpc



Face on BNS at 160 Mpc

Aasi et al, 2013

RATE EXPECTATIONS

Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

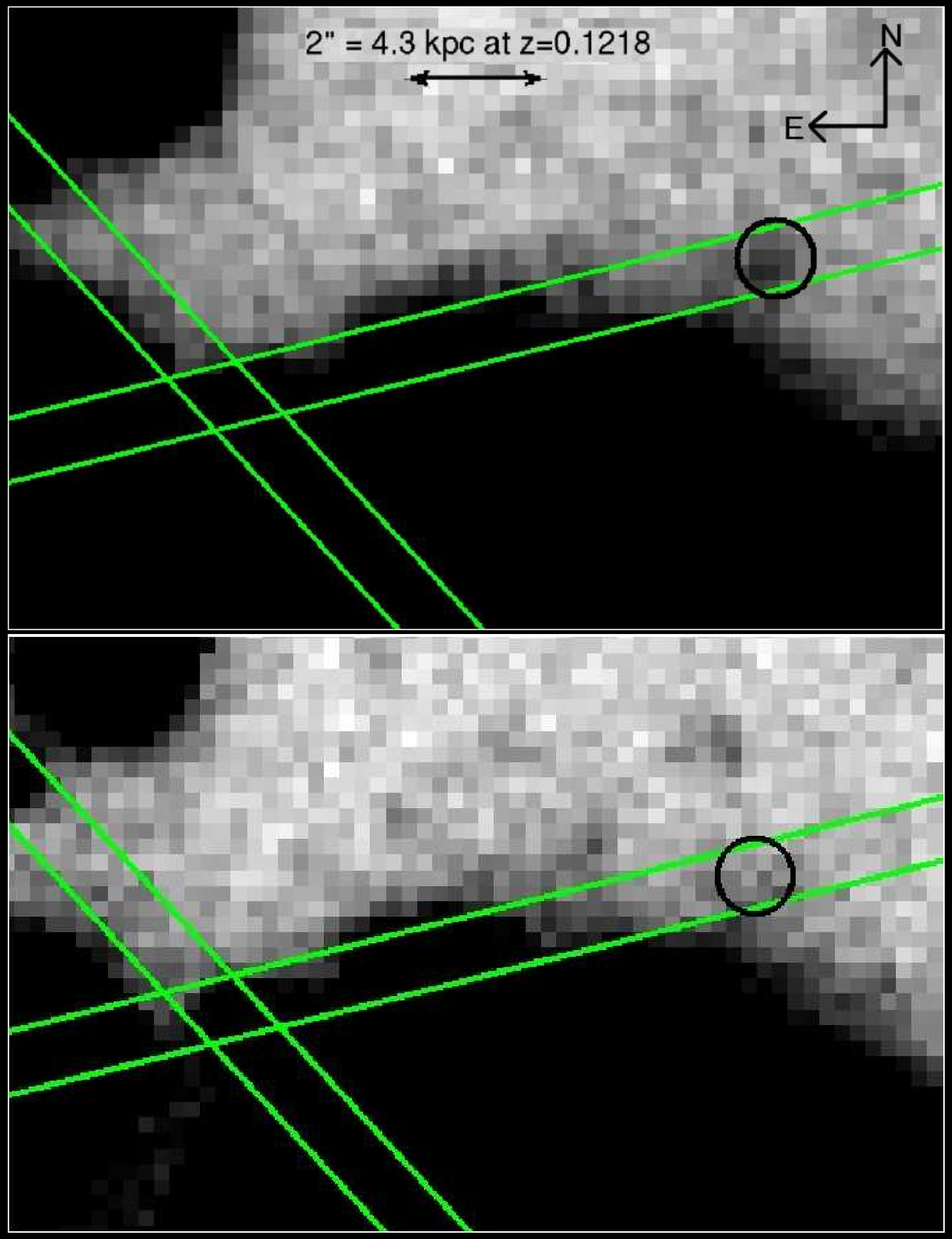
Aasi et al, 2013

WHAT ABOUT GRBS?

- Hard to make a prediction for long bursts — unknown gravitational wave emission
- Focus on short bursts, assuming NS-NS progenitor
  - Reasonable to assume binary is (close to) face on — gives strongest gravitational wave signal
  - About a 25% increase in sensitivity over all sky all time search
  - Sky averaged sensitivity ~400 Mpc for network at design sensitivity

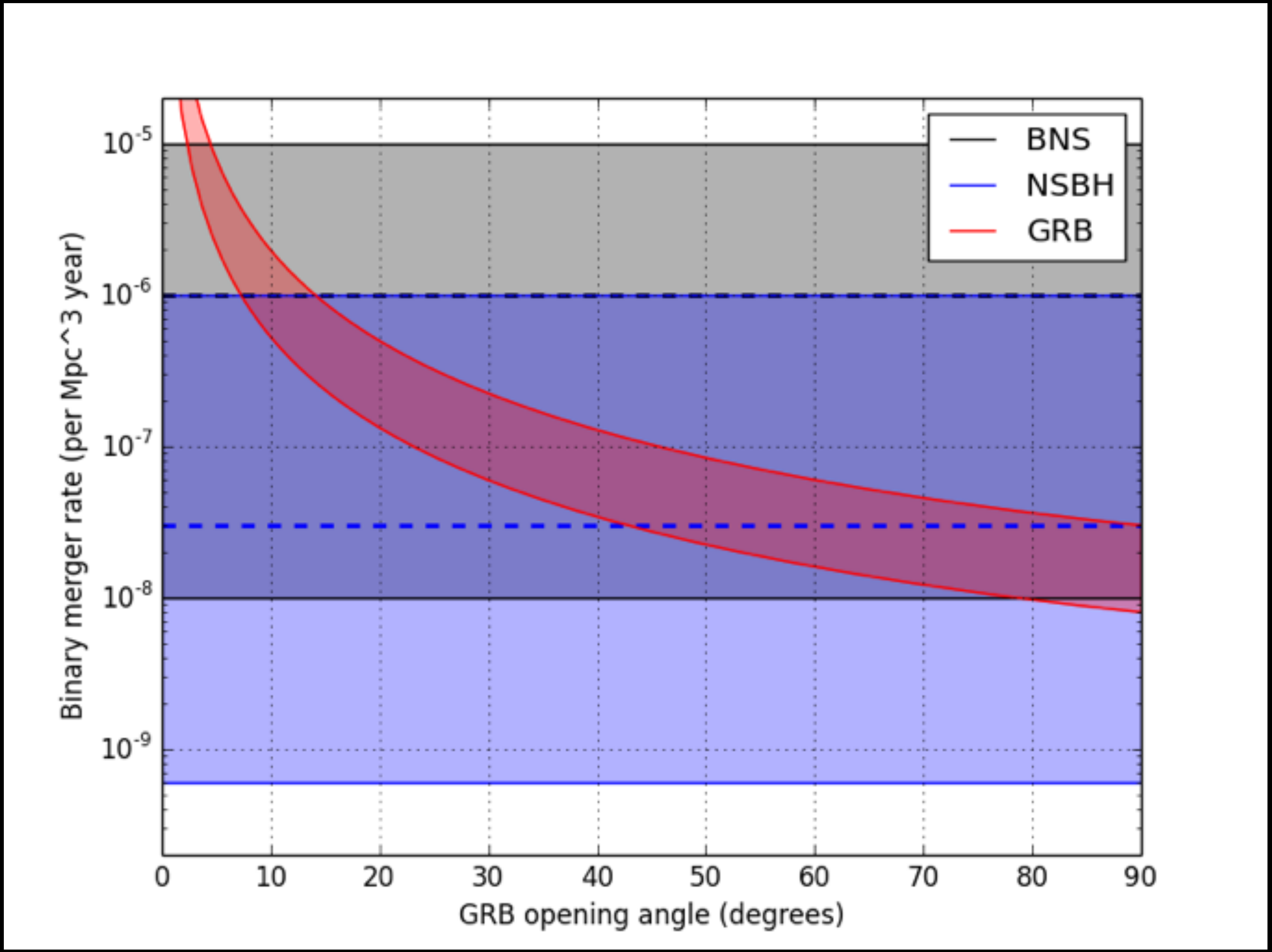
ANOTHER GRB080905A?

- Closest short GRB
  - z = 0.12
  - D~550 Mpc
- For advanced LIGO-Virgo network
  - NS-NS progenitor:
    - expected SNR~7.7
    - about a 1% false alarm probability
  - NS-BH progenitor:
    - strong signal
    - either detected or progenitor excluded



Rowlinson et al, MNRAS, 2010

GW-GRB PREDICTIONS



GRB rate of 8-30 per Gpc^3 per year
from Guetta and Piran, Astron.Astrophys, 2006
NS-NS and NS-BH rates from Aasi et al, CQG, 2010

GRB EXPECTATIONS

Epoch	Run Duration	BNS Range (Mpc)		Number of GW–GRB detections		
		LIGO	Virgo	All Sky	Fermi GBM	Swift BAT
2015	3 months	40 - 80	-	0.0005 - 0.07	0.0003 - 0.05	0.0001 - 0.01
2016–17	6 months	80 - 120	20 - 60	0.01 - 0.6	0.01 - 0.4	0.002 - 0.1
2017–18	9 months	120-170	60 - 85	0.09 - 3	0.05 - 2	0.01 - 0.4
2019+	(per year)	200	65 - 130	0.5 - 6	0.3 - 4	0.07 - 1
2022+	(per year)	200	130	0.9 - 10	0.6 - 6	0.1 - 2

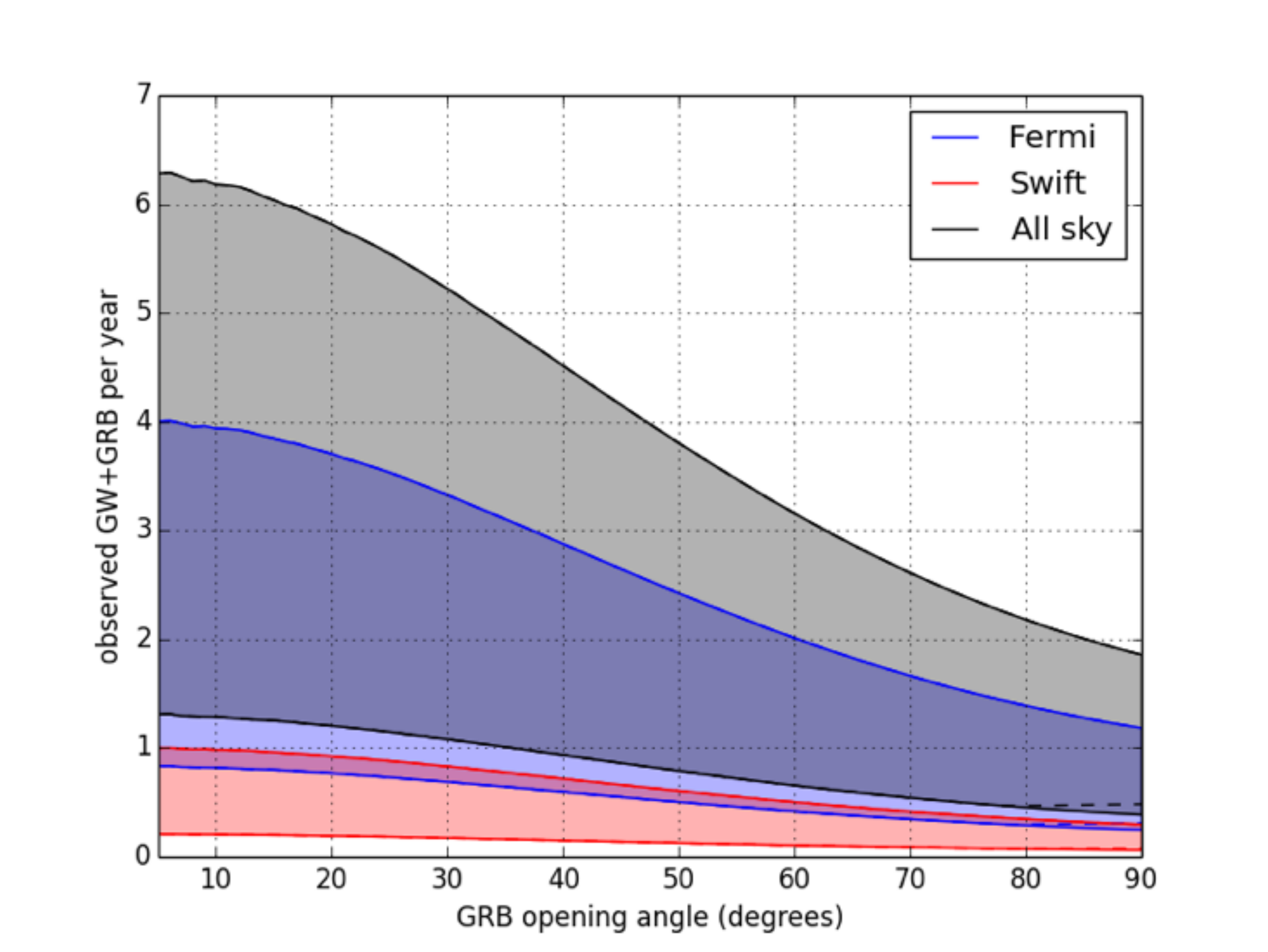
Clark et al, in prep.

Assume that:

- All short GRBs produced by BNS mergers and
- Detectors sensitive to all GRBs within LIGO/Virgo range

Rate doubles if 20% of short GRBs have NSBH progenitor

RATES AT DESIGN SENSITIVITY



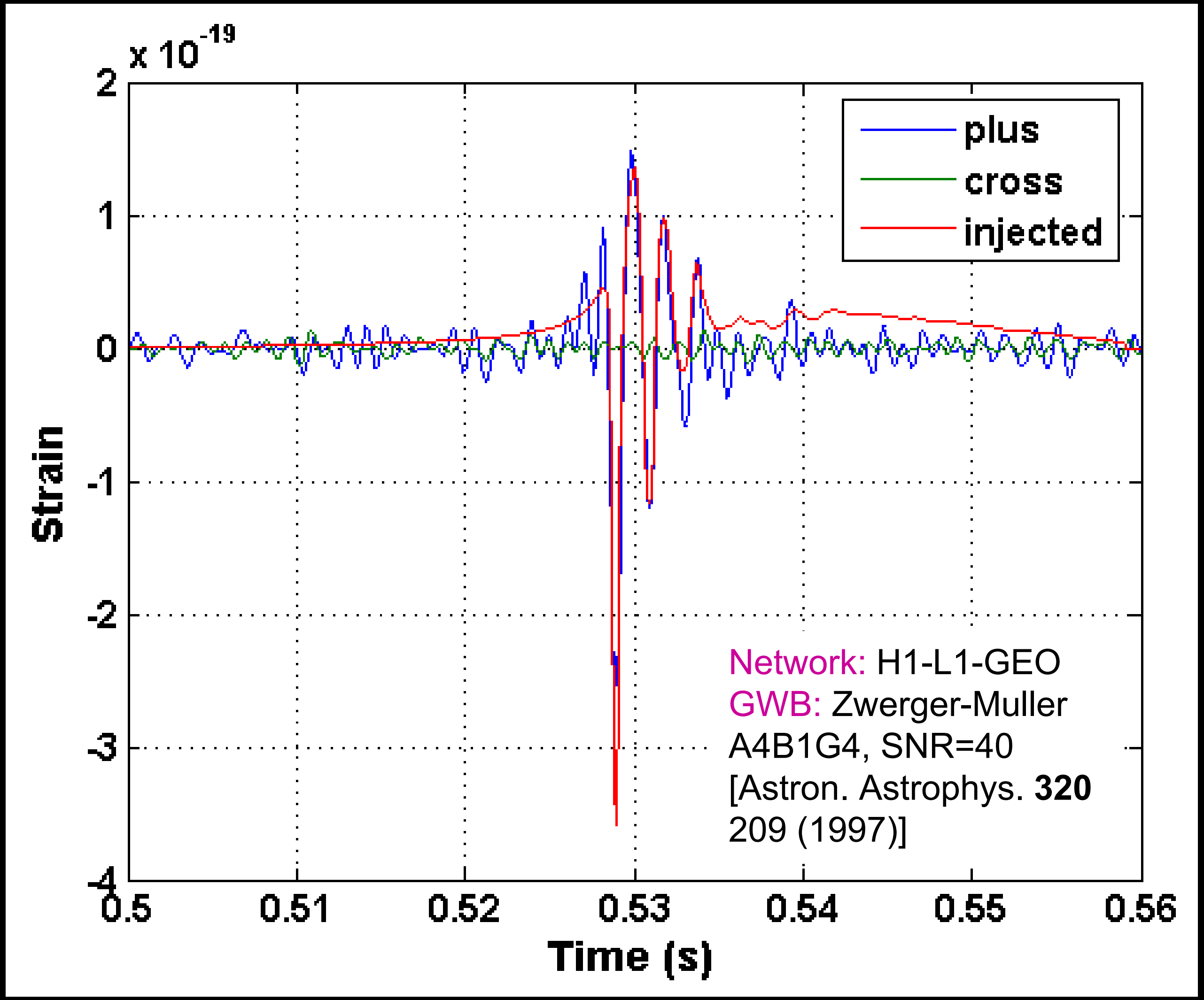
Clark et al, in prep.

PAYOFF FROM GW-GRB OBSERVATIONS

- New insights into GRB progenitor
- GW "standard sirens" as tools for cosmology
- Constrain GRB beaming angles
- Constrain NS equation of state
- Measure "speed of gravity"

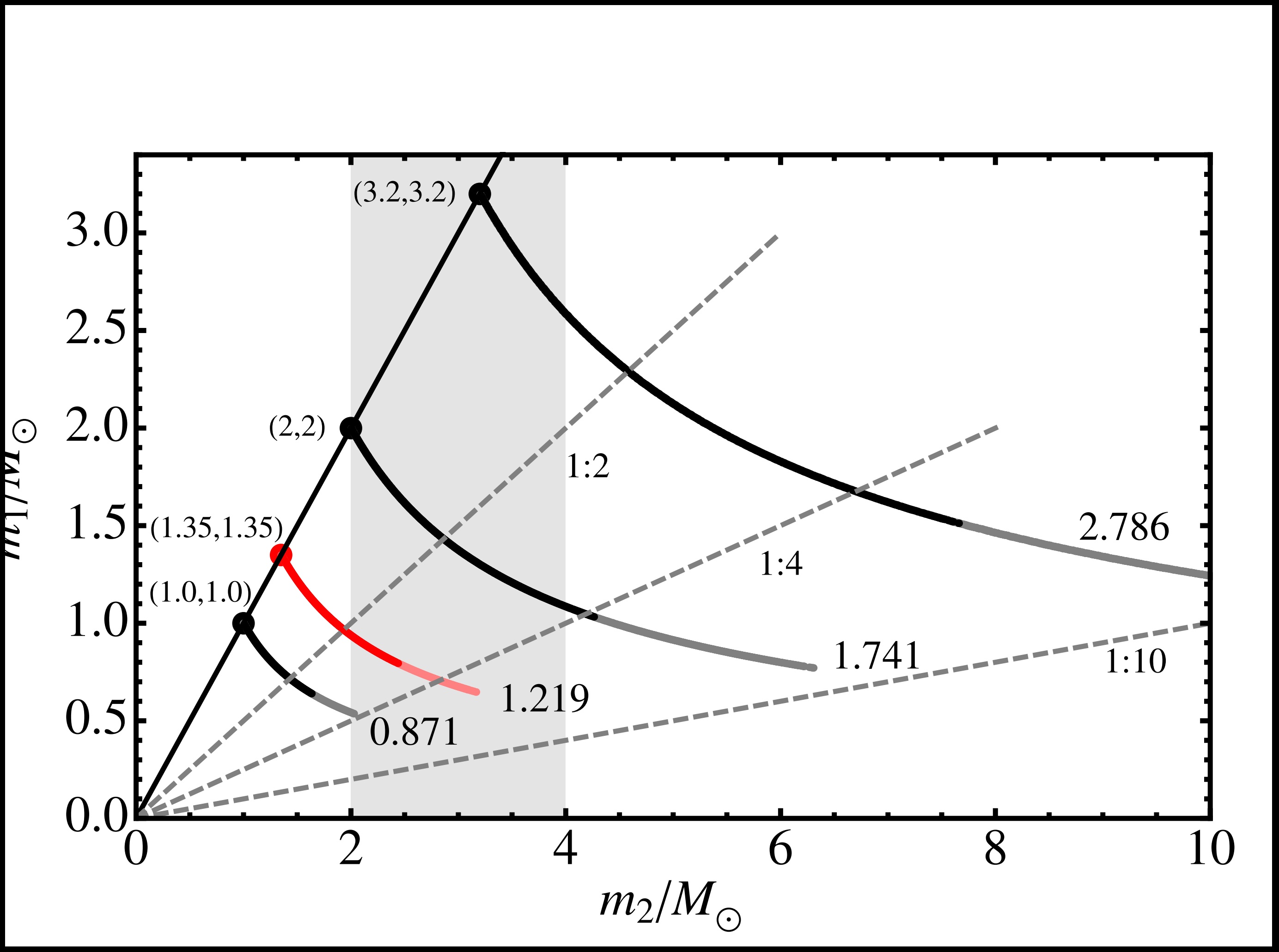
EXTRACTING THE WAVEFORM

- Un-modelled search can extract the gravitational waveform, even though it's buried in noise
- Distinguish between progenitor models

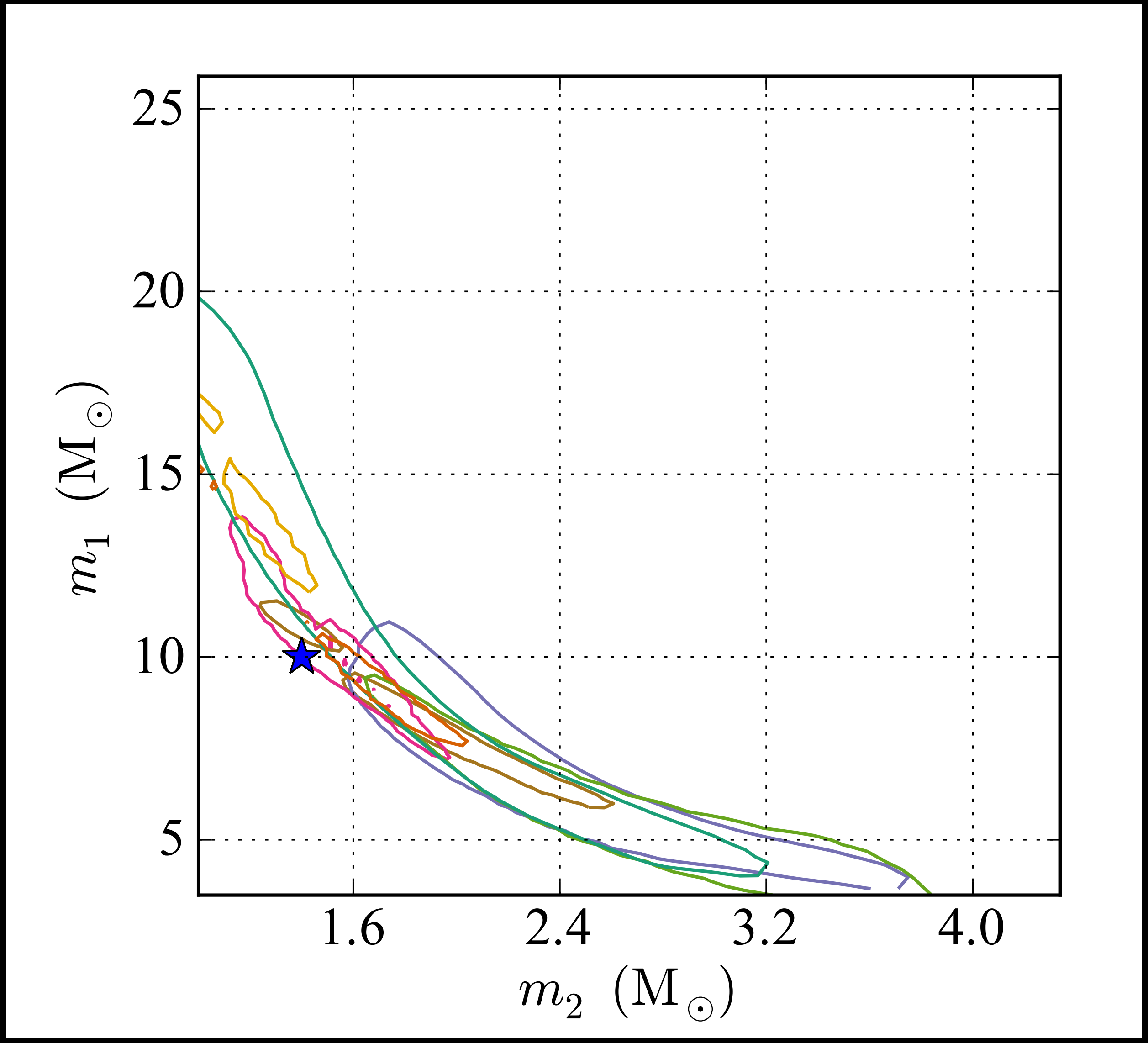


Toy example: provided by P. Sutton

NS-NS OR NS-BH?



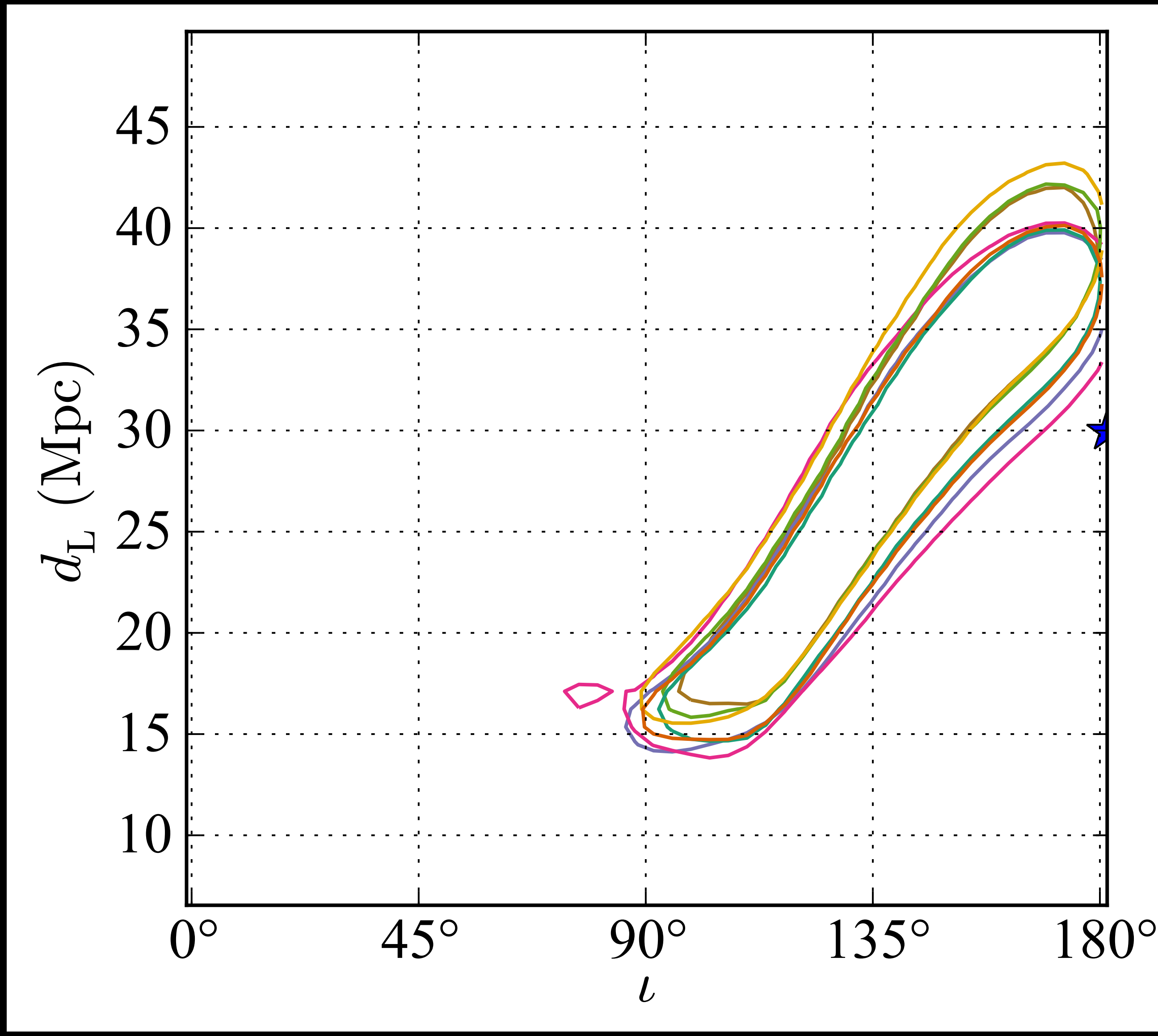
From Hannam et al, ApJL, 2013



From Aasi et al, PRD 2013

MEASURING THE DISTANCE

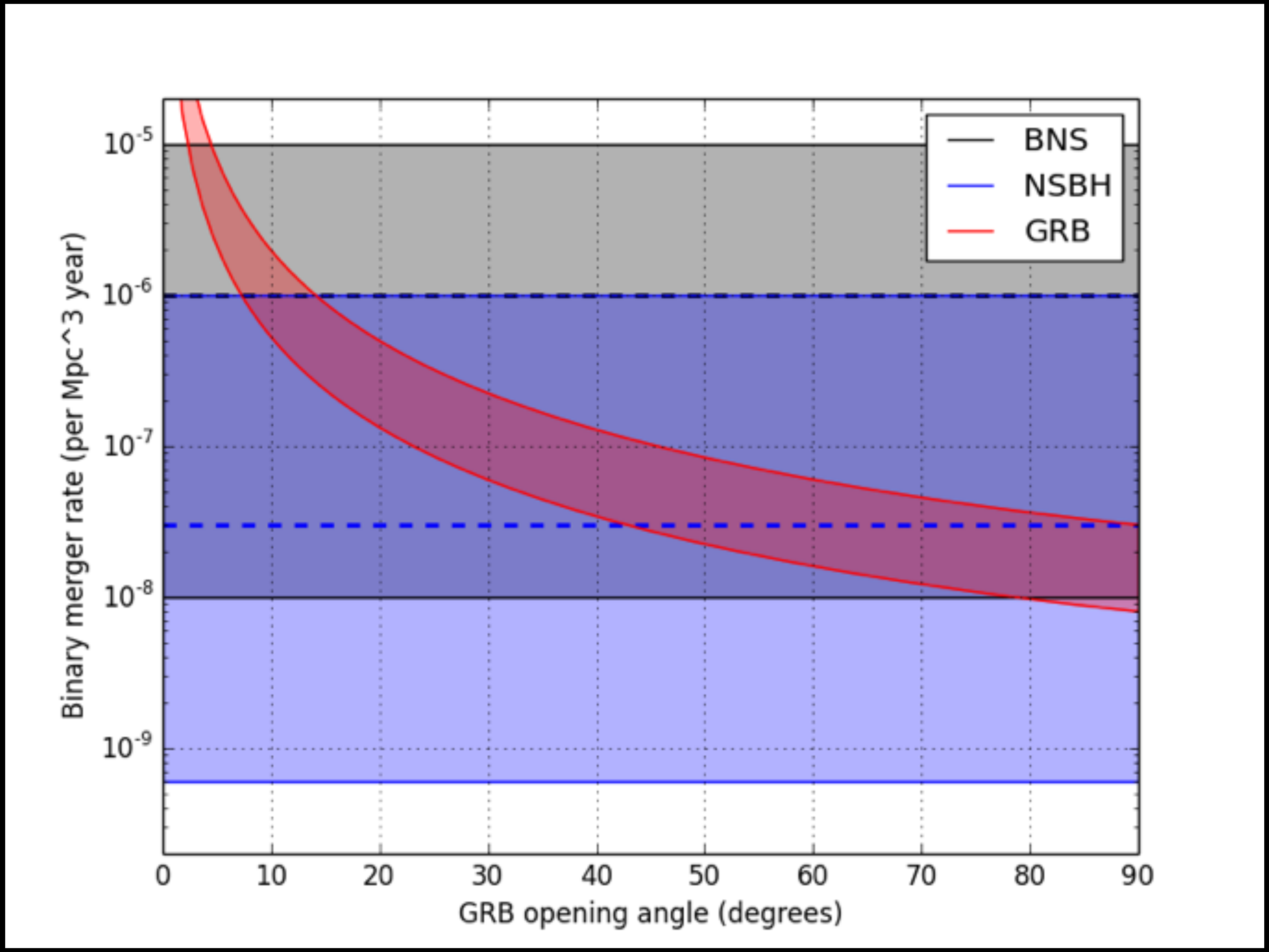
- Degeneracy between distance and binary inclination makes it hard to extract either with great accuracy
- Assuming small opening angle, likely to measure distance to ~10% accuracy
- With redshift measurements, start to probe cosmological models, Schutz, Nature, 1986



From Aasi et al, PRD, 2013

CONSTRAINING THE OPENING ANGLE

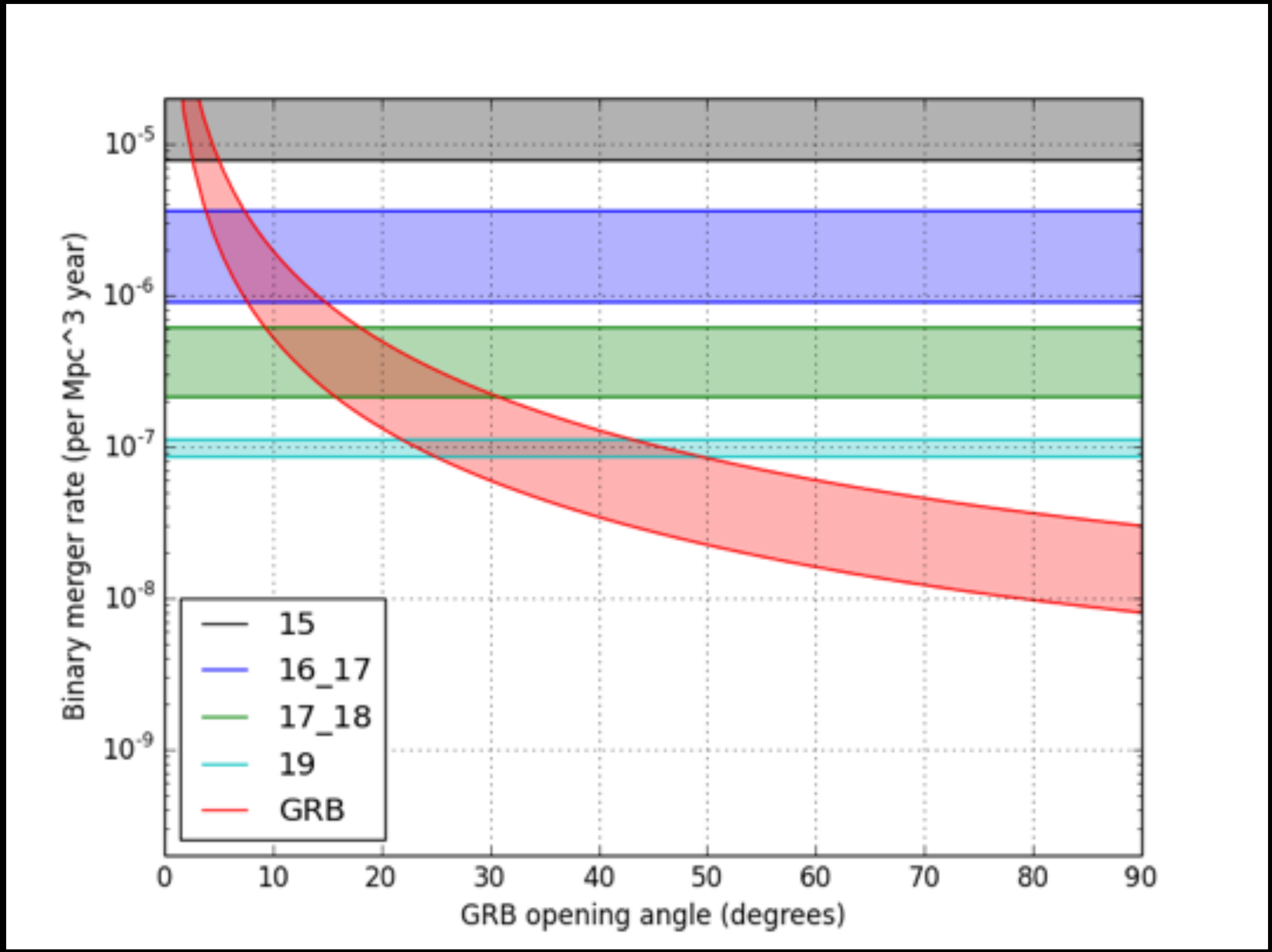
- Challenging from single GRB observations
- Measurement of NS-NS and GRB rates will allow us to constrain the opening angle



CONSTRAINING THE OPENING ANGLE

- Use all sky GW search to give lower limit on opening angle.
- Assume all NS-NS give sGRB
- In absence of GW a detection: lower limit on opening angle
- With GW detection, merger rate measured within a factor of a few: estimate of GRB opening angle

Expected NS-NS rate limits from observing runs



Clark et al, in prep.

SUMMARY

- Long and short GRBs are potentially strong gravitational wave sources.
- Restricting time and sky location of searches leads to increased GW search sensitivity.
- LIGO and Virgo have performed numerous GRB searches: no detection from single events (including 051103 and 070201) or population.
- Good prospect for joint GW-GRB observations in coming years.
- Gravitational wave signal will give unique insights into central engines.