Gravitational Wave Astronomy

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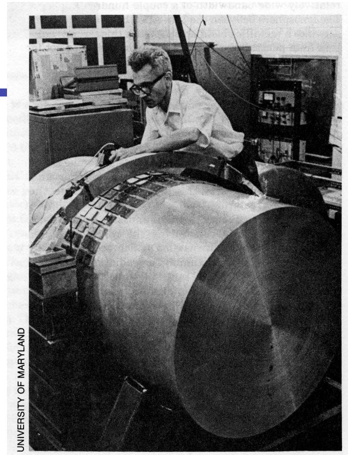
Cardiff University

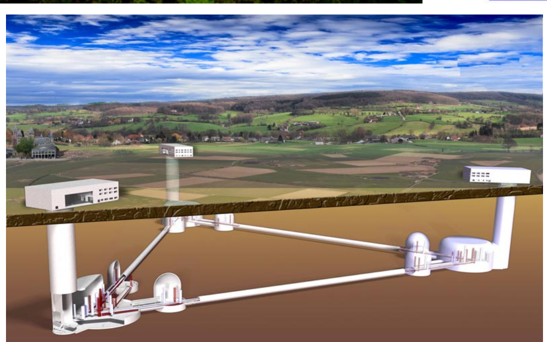
For the LIGO Scientific Collaboration
and Virgo Collaboration

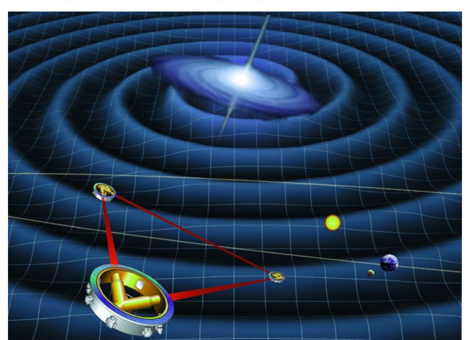
THE ROYAL SOCIETY
CELEBRATING 350 YEARS

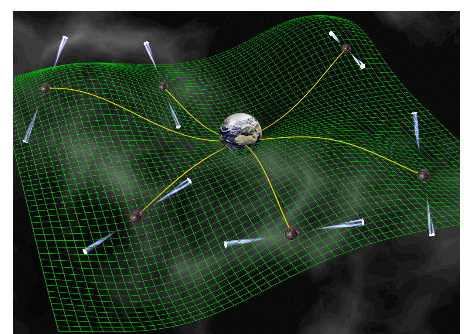
twenty ten and beyond | 350 years of excellence in science

The detectors





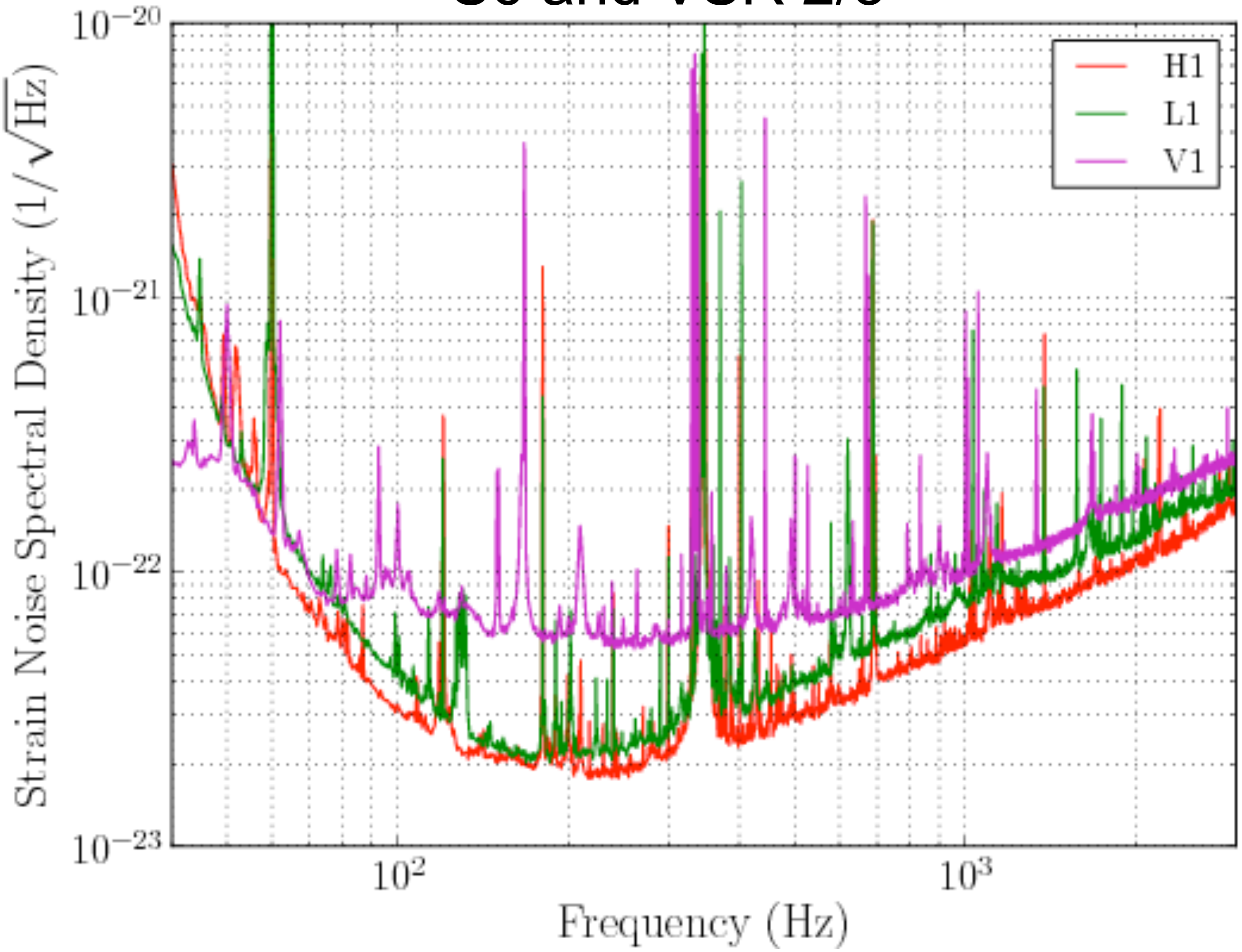




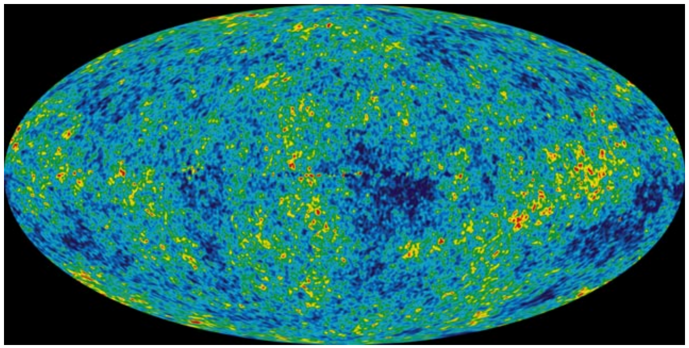
The detectors

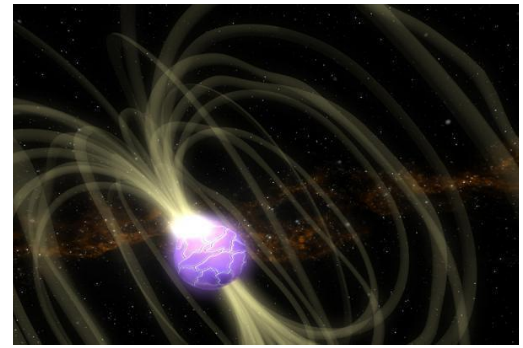
First generation detectors

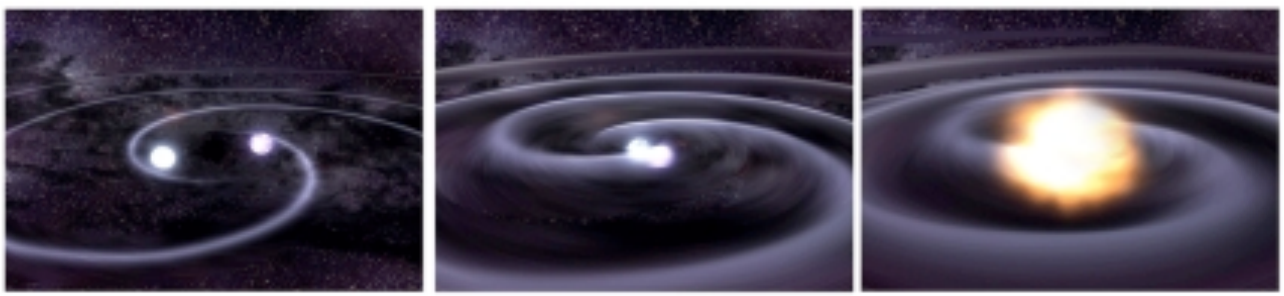
S6 and VSR 2/3

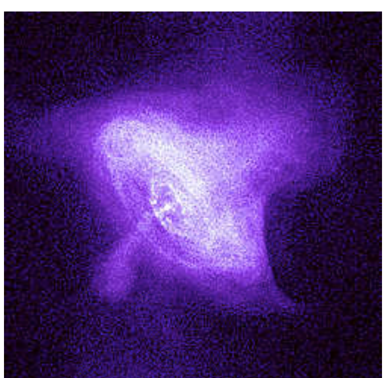


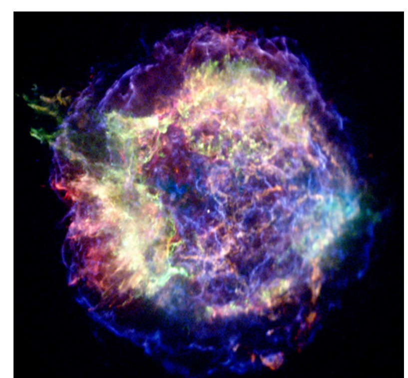
The Sources











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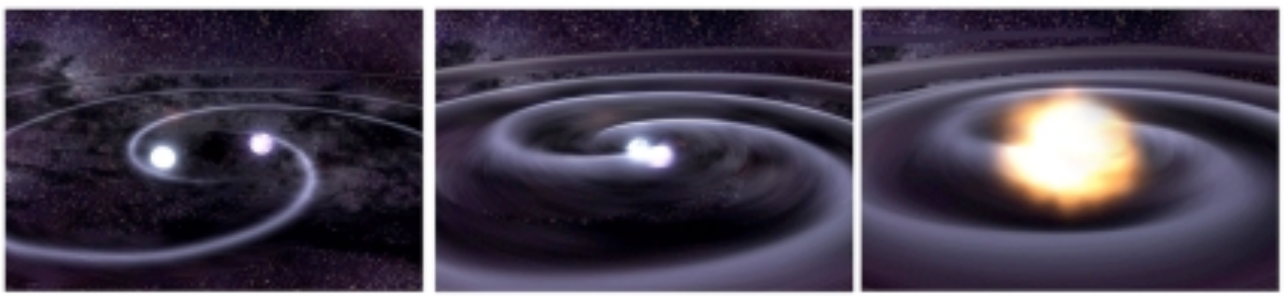
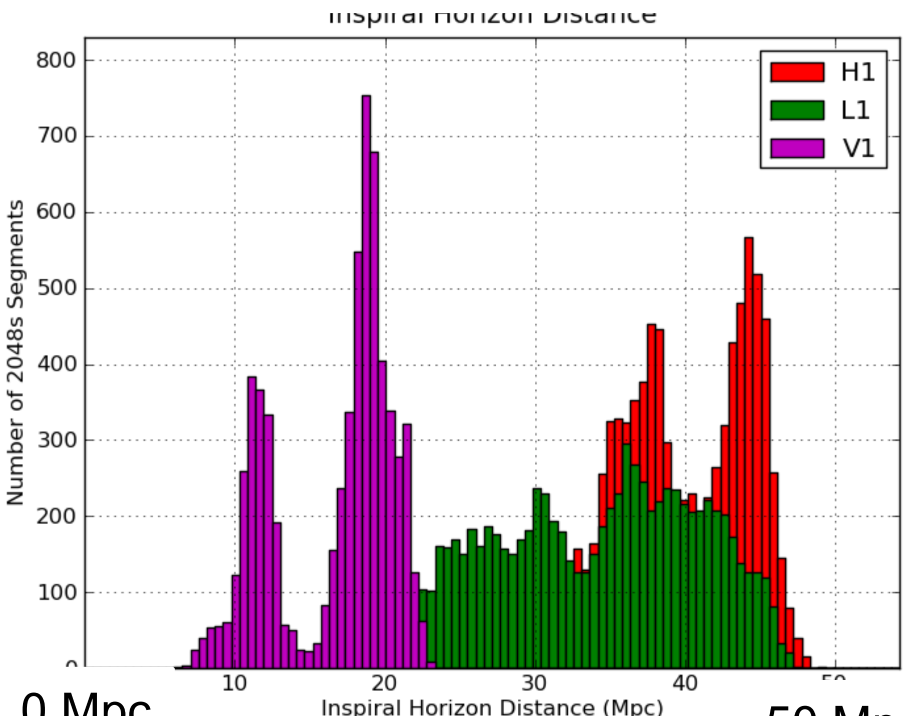


Detector sensitivity

NS-NS Horizon

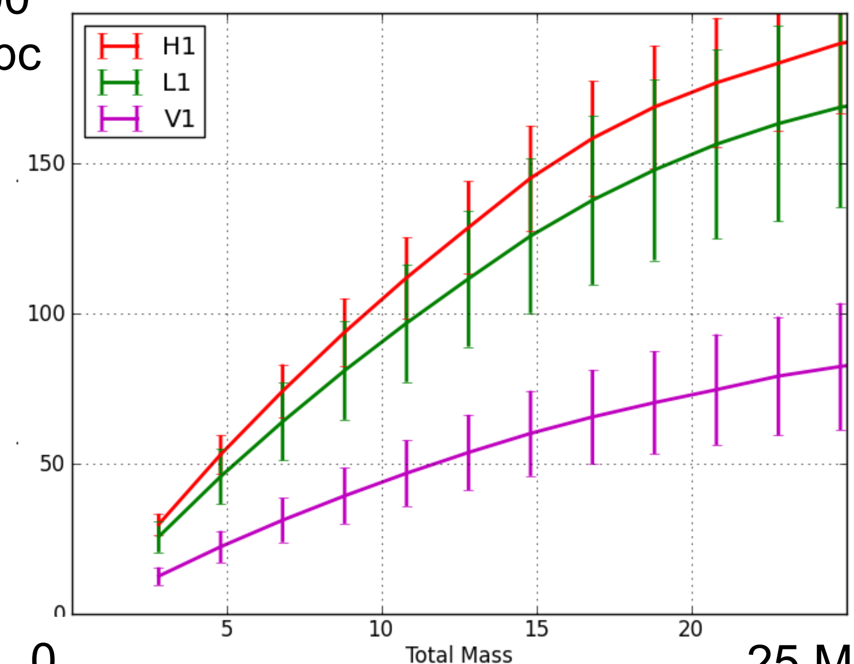


0 Mpc

50 Mpc

Horizon vs Mass

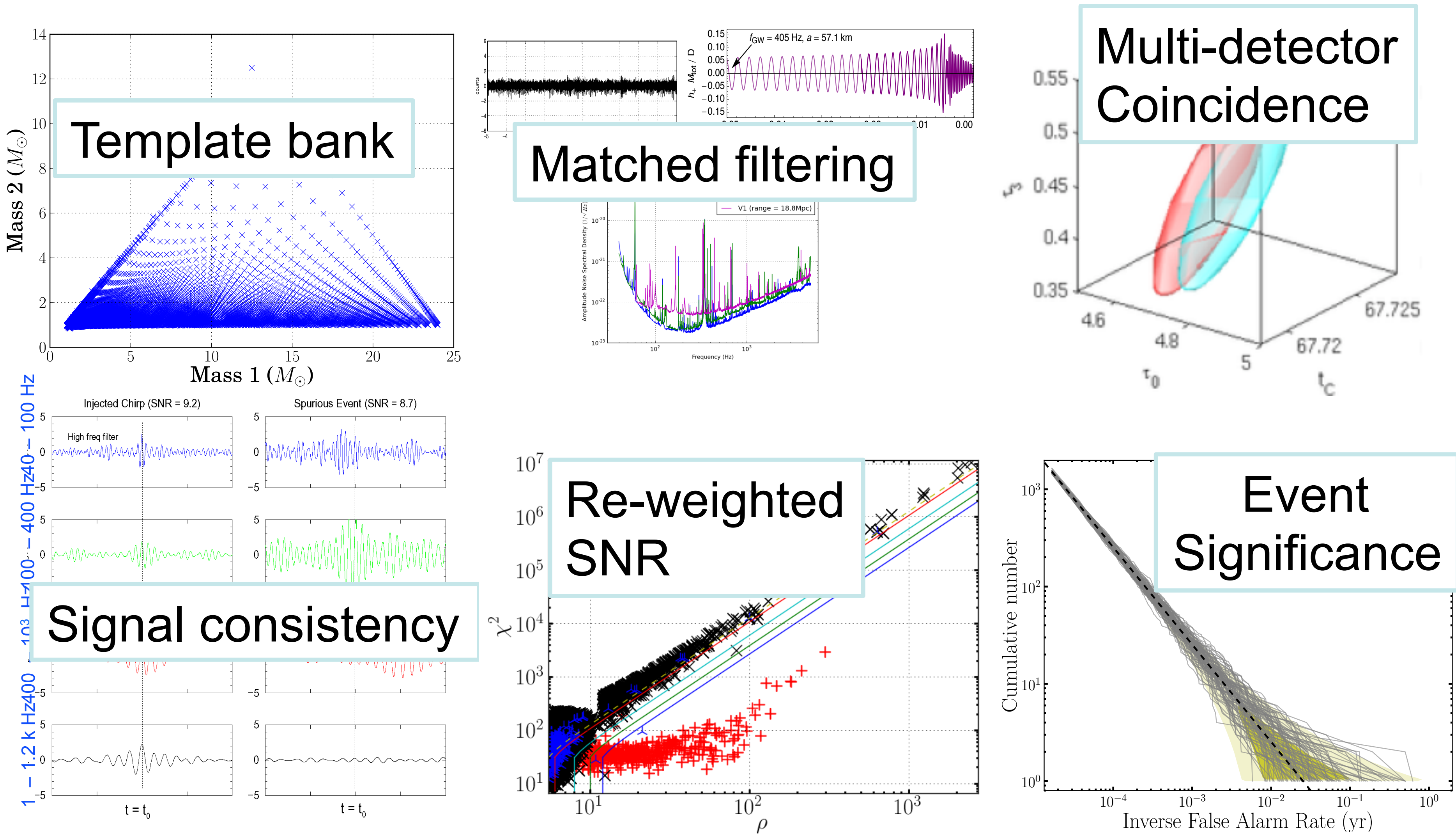
200 Mpc



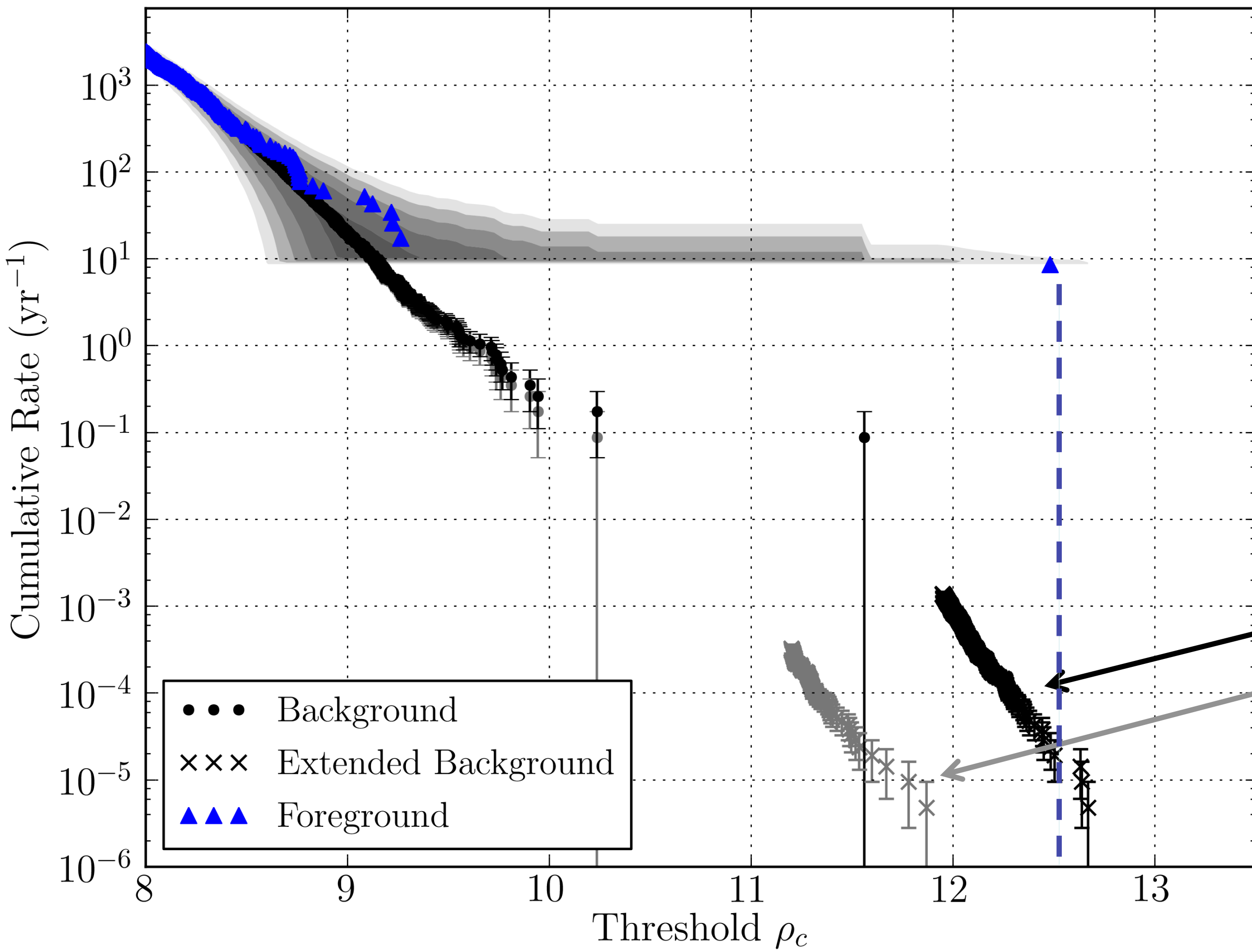
0

25 $M_\odot$

The search


Template bank
Mass 1 ($M_\odot$)
Mass 2 ($M_\odot$)
Matched filtering
f_{GW} = 405 Hz, a = 57.1 km
$h_+ M_{tot} / D$
V1 (range = 18.8Mpc)
Frequency (Hz)
Multi-detector Coincidence
τ_0
t_c
Injected Chirp (SNR = 9.2)
Spurious Event (SNR = 8.7)
High freq filter
Signal consistency
$t = t_0$
Re-weighted SNR
χ^2
ρ
Event Significance
Cumulative number
Inverse False Alarm Rate (yr)

“Blind Injection” successfully recovered

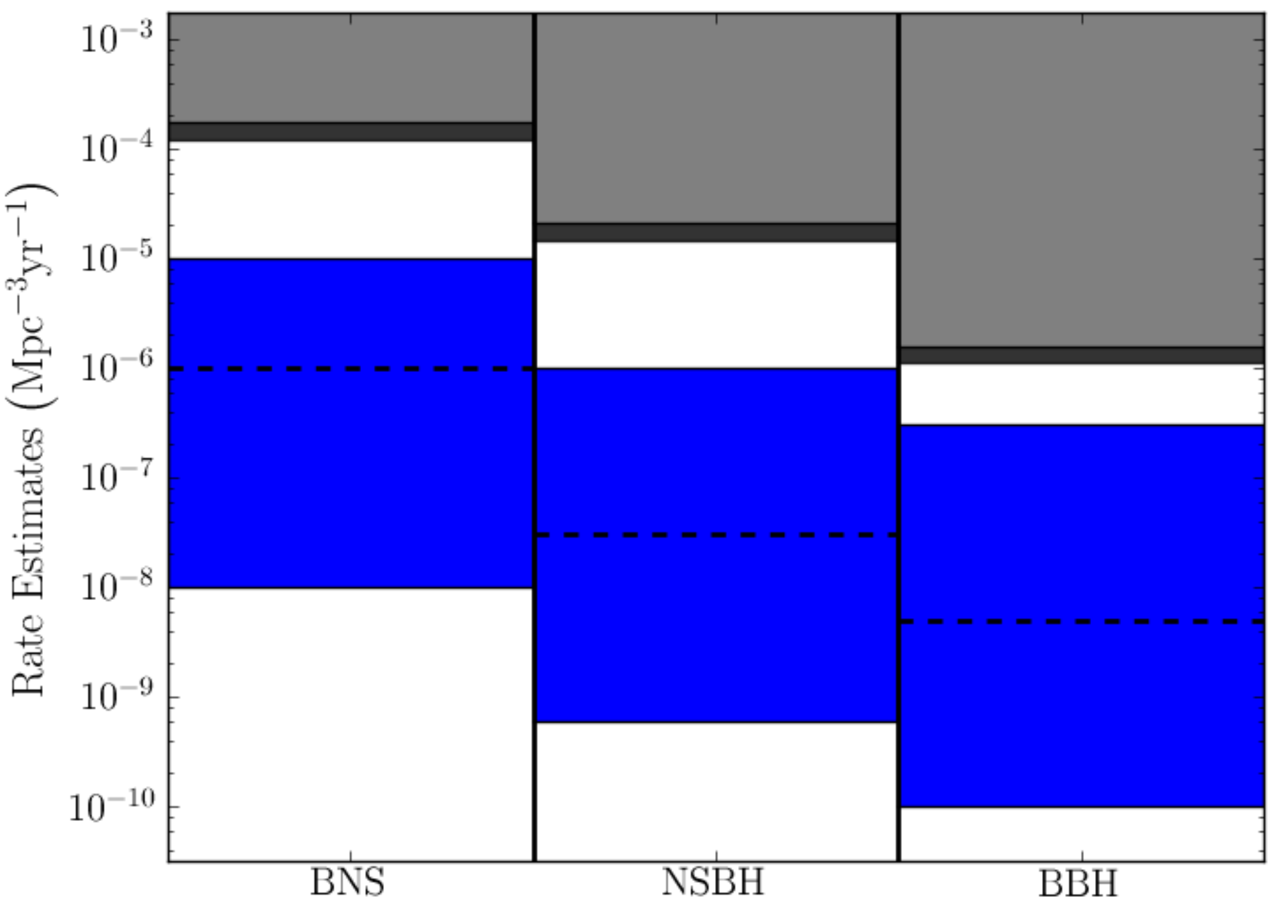


Abadie et al
PRD (2012)

Background estimate
including
excluding
time of candidate

False alarm rate (incorporating trials factor) of 1/7000 years

Coalescence Rates



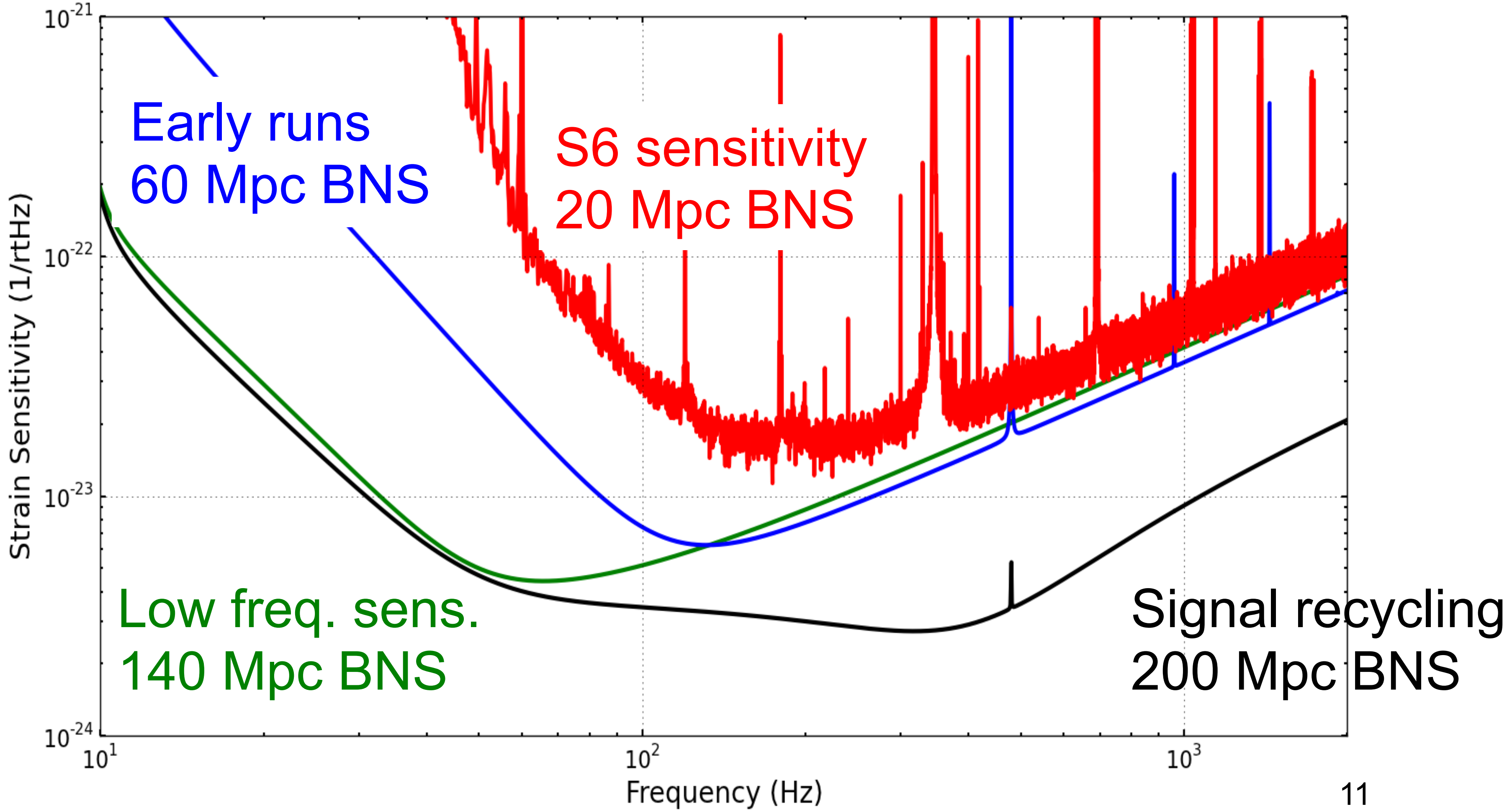
LIGO-Virgo upper limits

Abadie et al PRD (2012)

Astrophysical Predictions

Abadie et al CQG (2010)

Possible LIGO sensitivity evolution



Implication for binary mergers

- Post-Newtonian waveform

$$h(f) = A f^{-7/6} \exp[2\pi i f t + c(\pi \mathcal{M} f)^{-5/3} + \ldots]$$

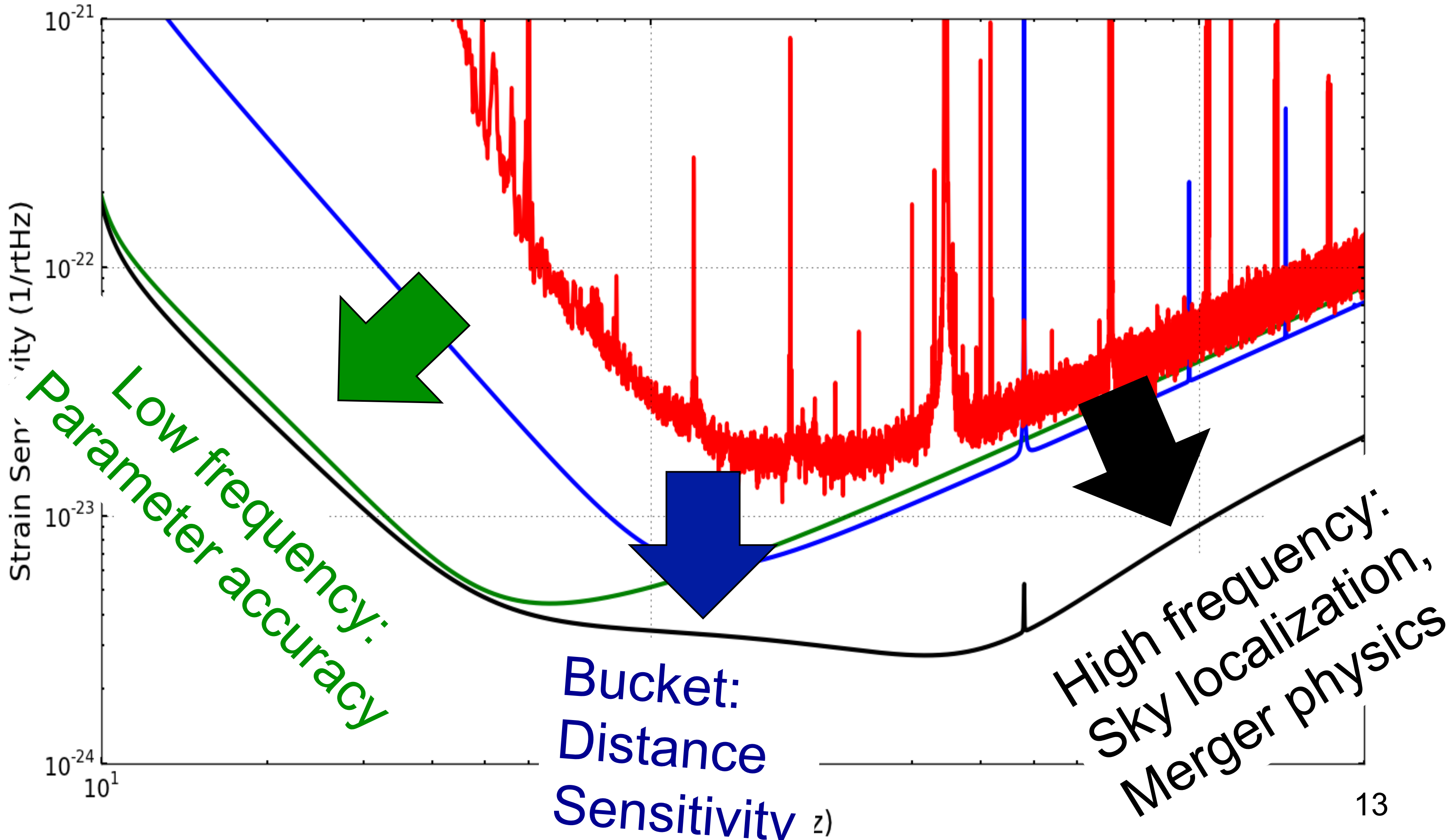
  followed by numerical merger/ringdown

- Expected signal to noise ratio $\rho = |h|$

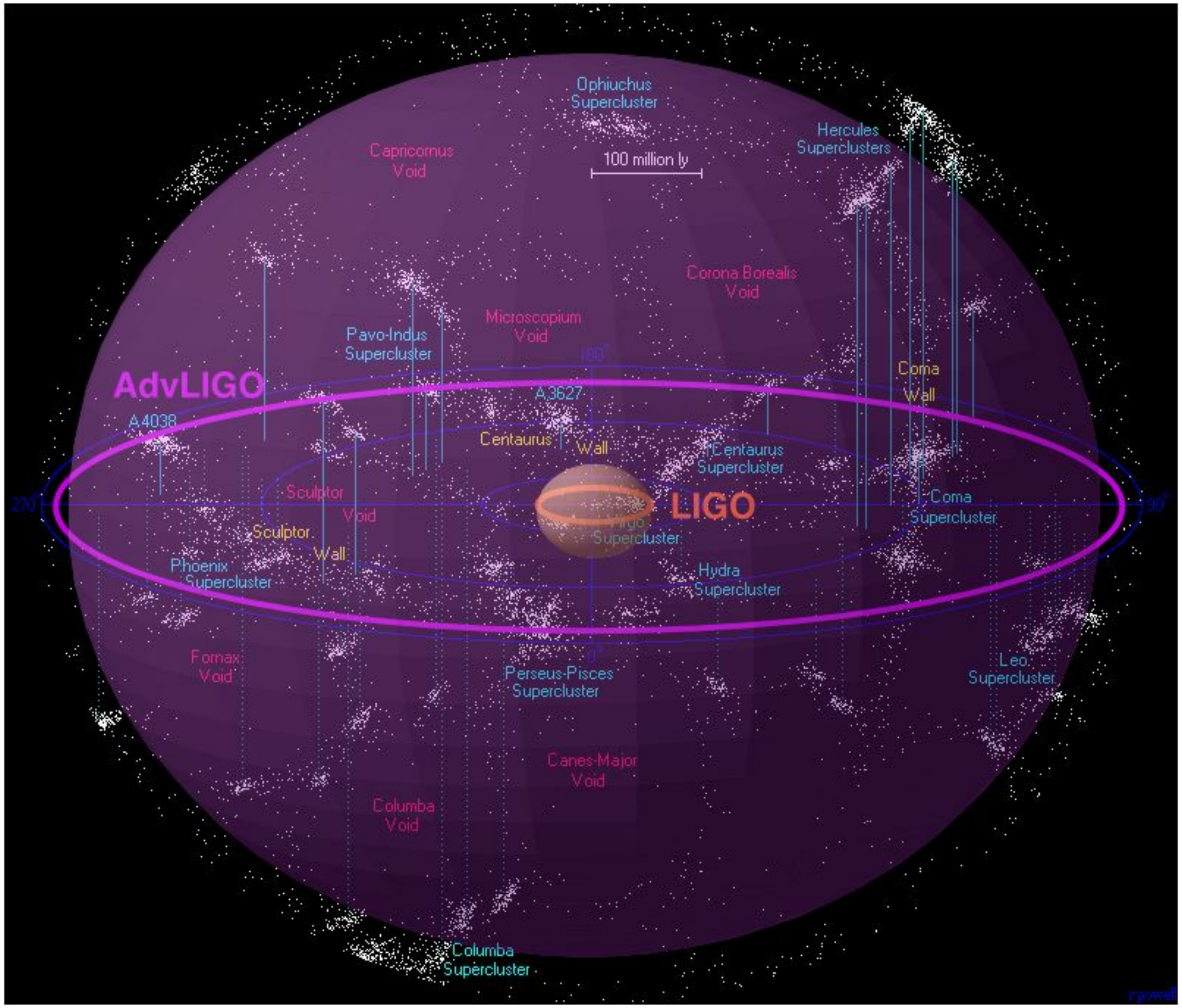
$$|h|^2 = 4\mathrm{Re} \int_0^\infty df \, \frac{|h(f)|^2}{S_n(f)}$$

- Parameter estimation: $h' = h + \delta h$ distinguishable from h provided $|\delta h| \gtrsim 3$

Implication for binary mergers

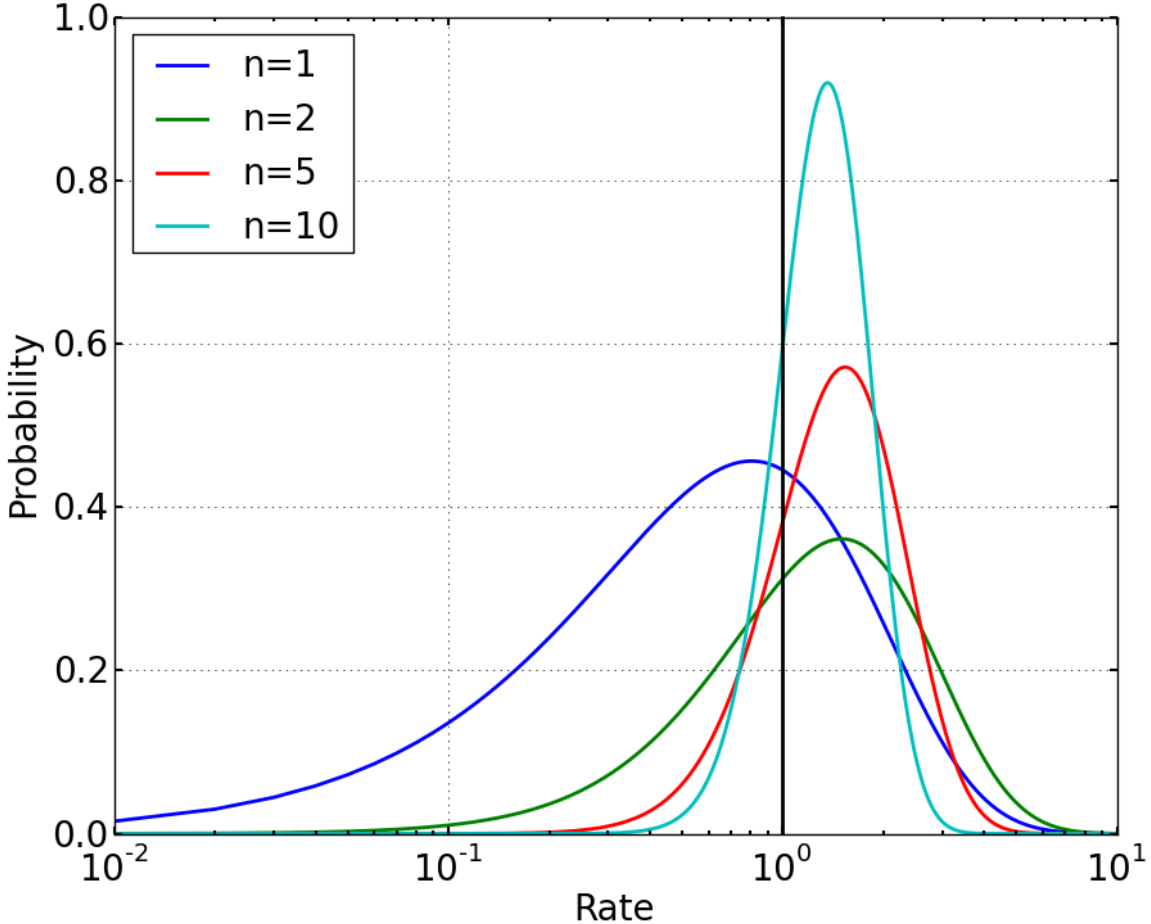


Distance Reach



Rates measurements

n: number of observed events

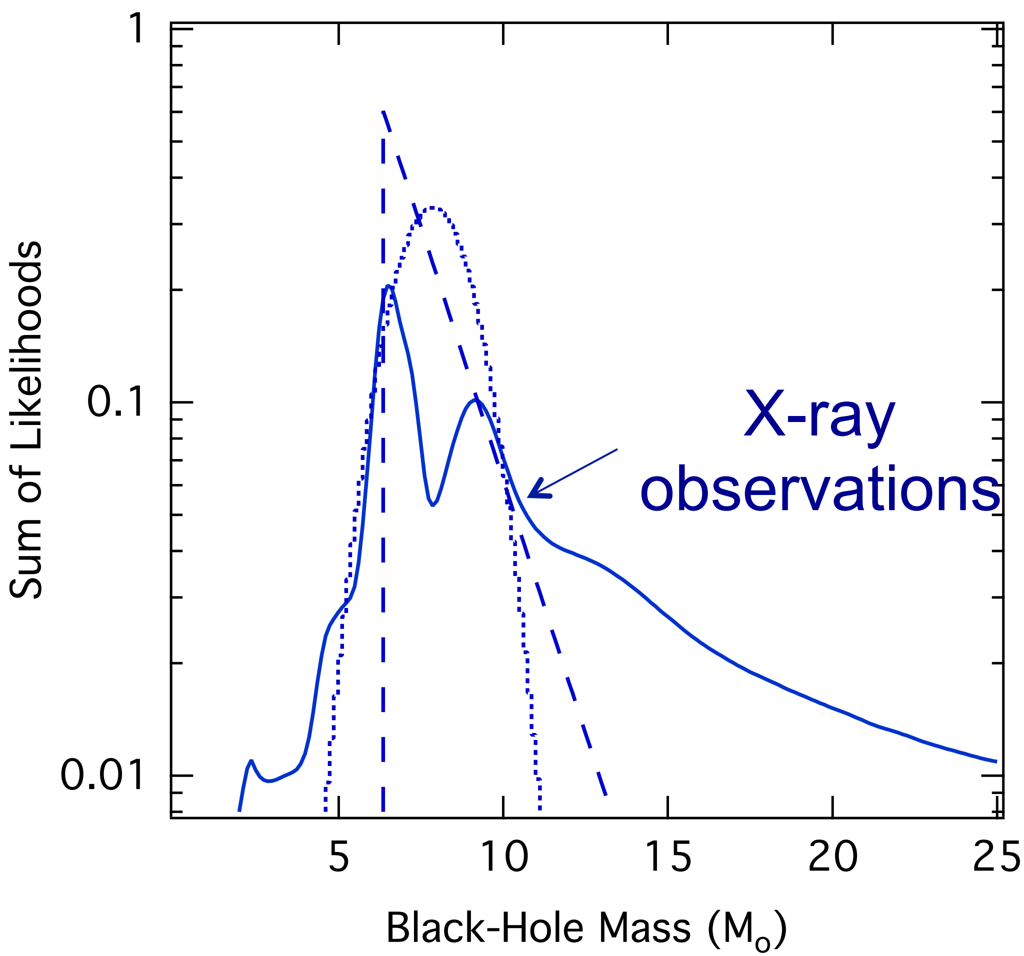


Different astrophysical models give different rates

Can measure rate accurately with only a handful of events.

Can restrict models and infer astrophysics of binary formation

Black Hole Masses

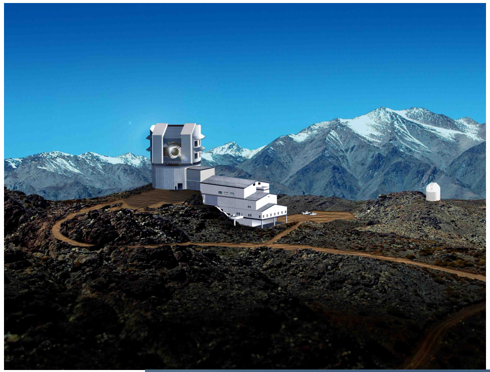


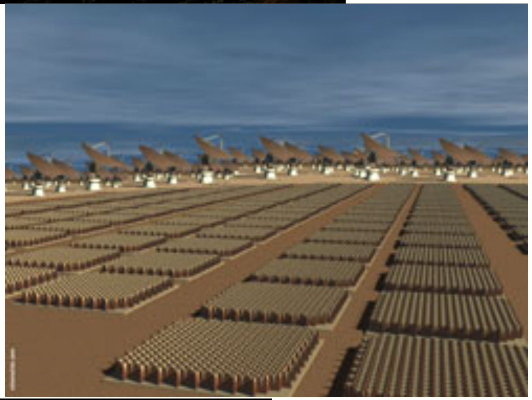
Different models also give different mass distributions

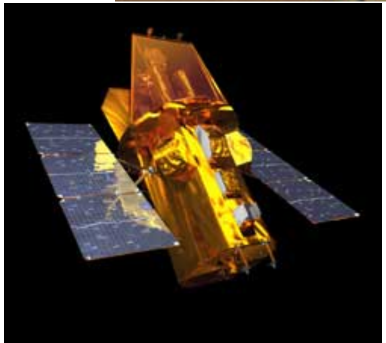
Exclude models by measuring binary masses

Ozel et al, ApJ (2012)

Multi-messenger Astronomy

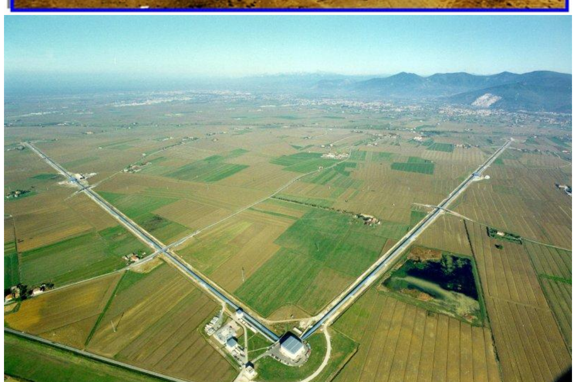
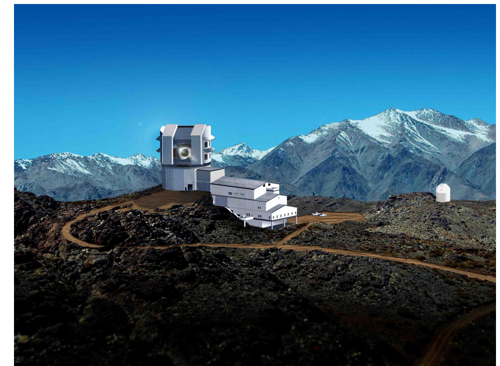


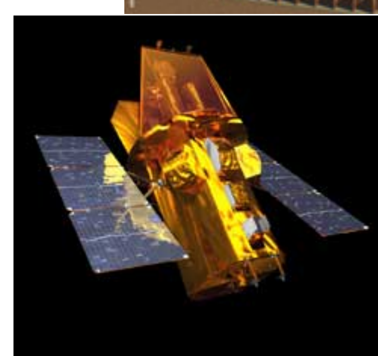




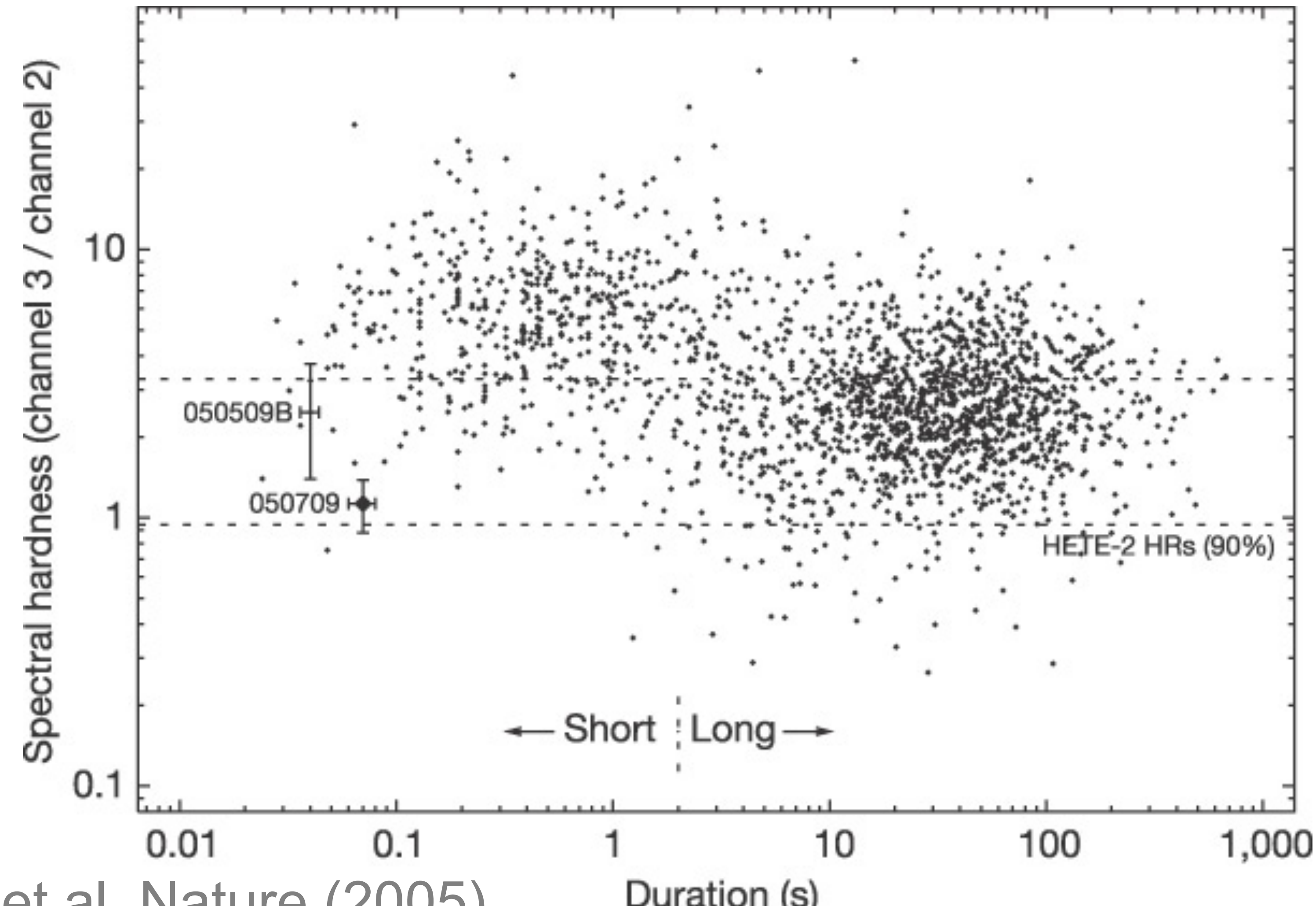
Multi-messenger Astronomy





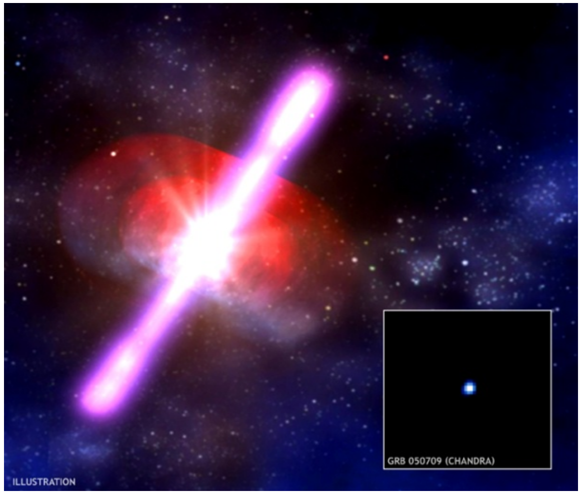
Gamma Ray Burst Classification

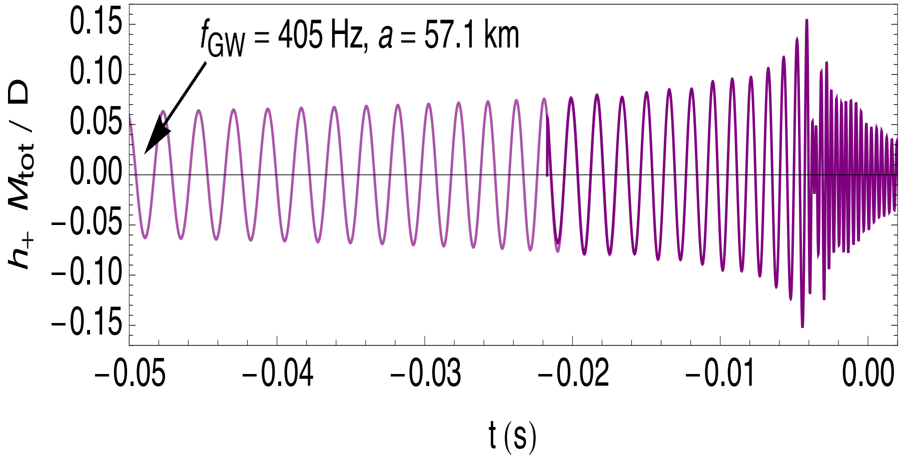


Hjorth et al, Nature (2005)

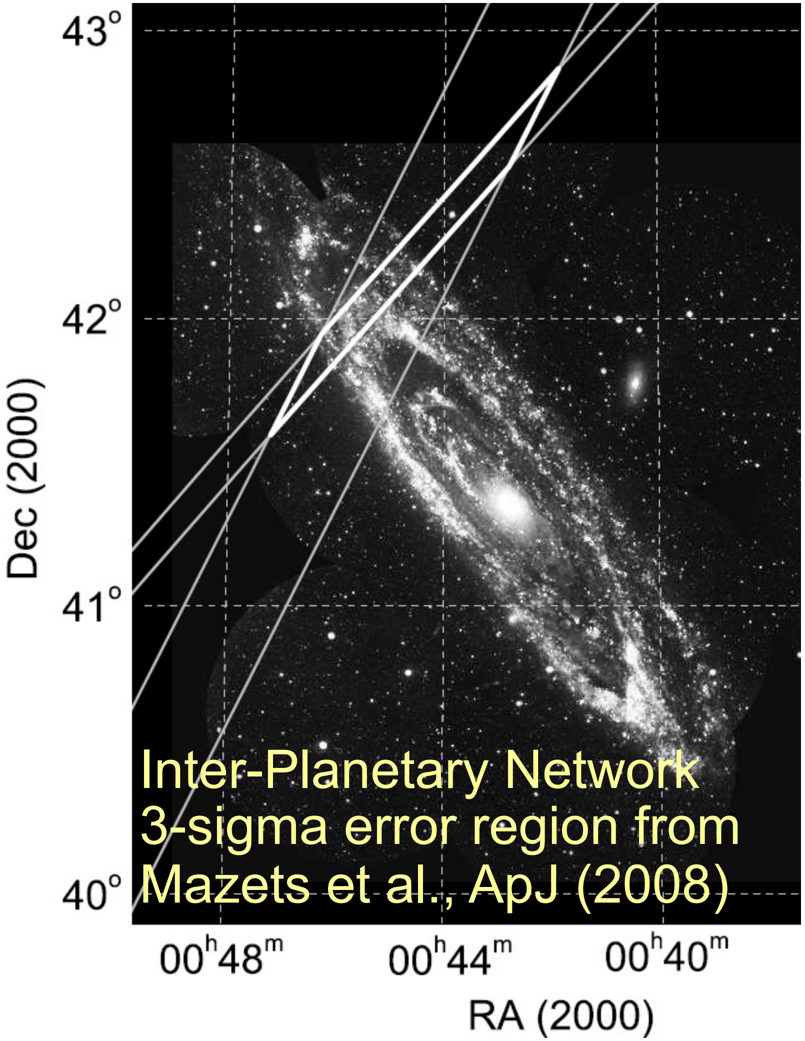
Short Gamma Ray Bursts

- Thought to be the merger of Neutron Star-Neutron Star or Neutron Star-Black Hole
- ~1000 times more likely to see a signal at GRB time than random time





GRB 070201

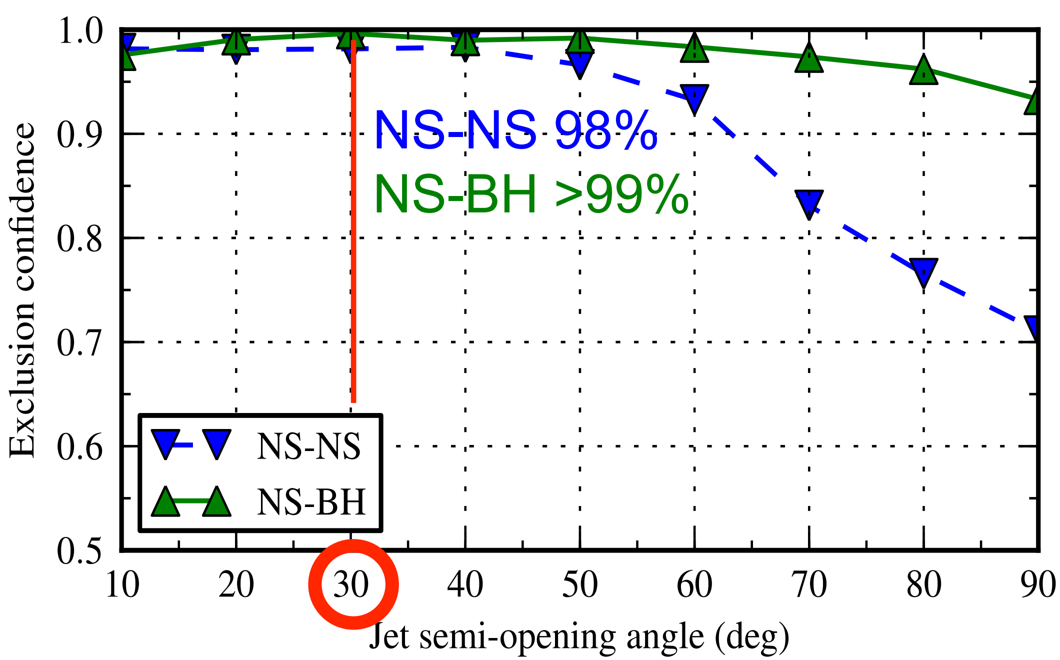


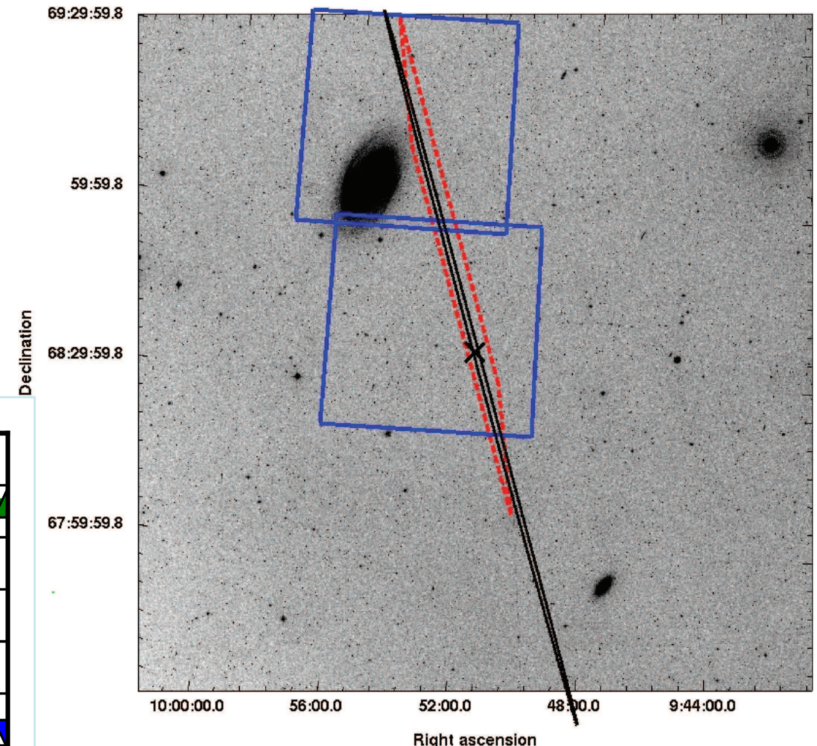
- Localization overlaps M31 (at 770 kpc)
- No GW signal observed
- Exclude NS-NS and NS-BH merger in M31 with 99% confidence
- Indirect support for hypothesis of soft gamma repeater in M31

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





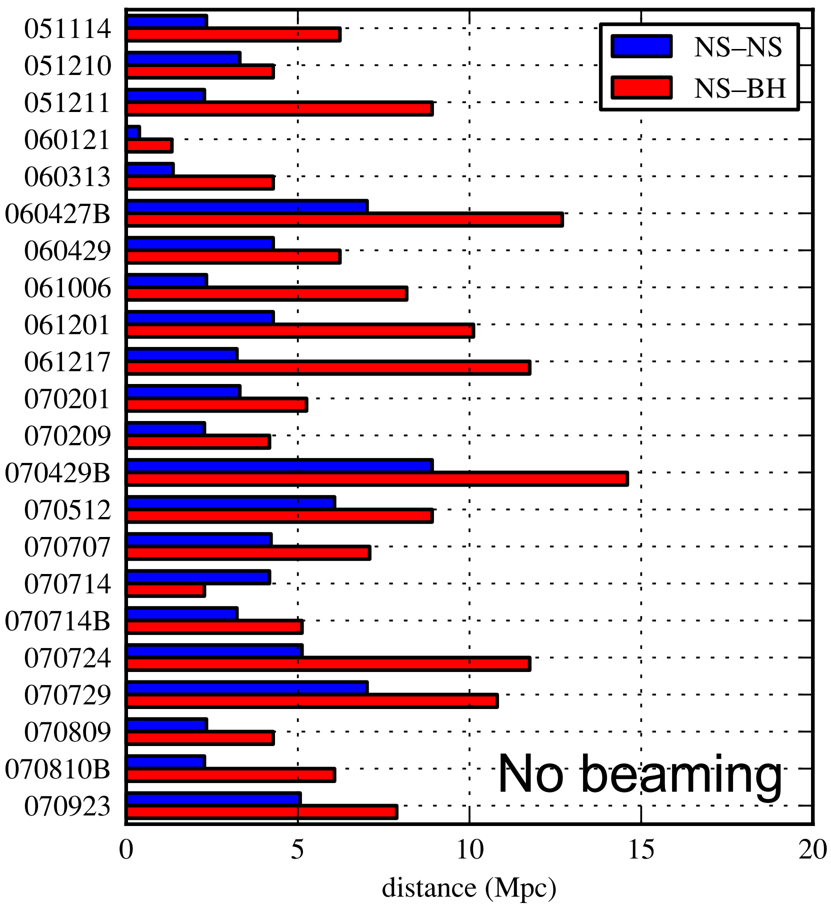
Abadie et al. 1201.1163

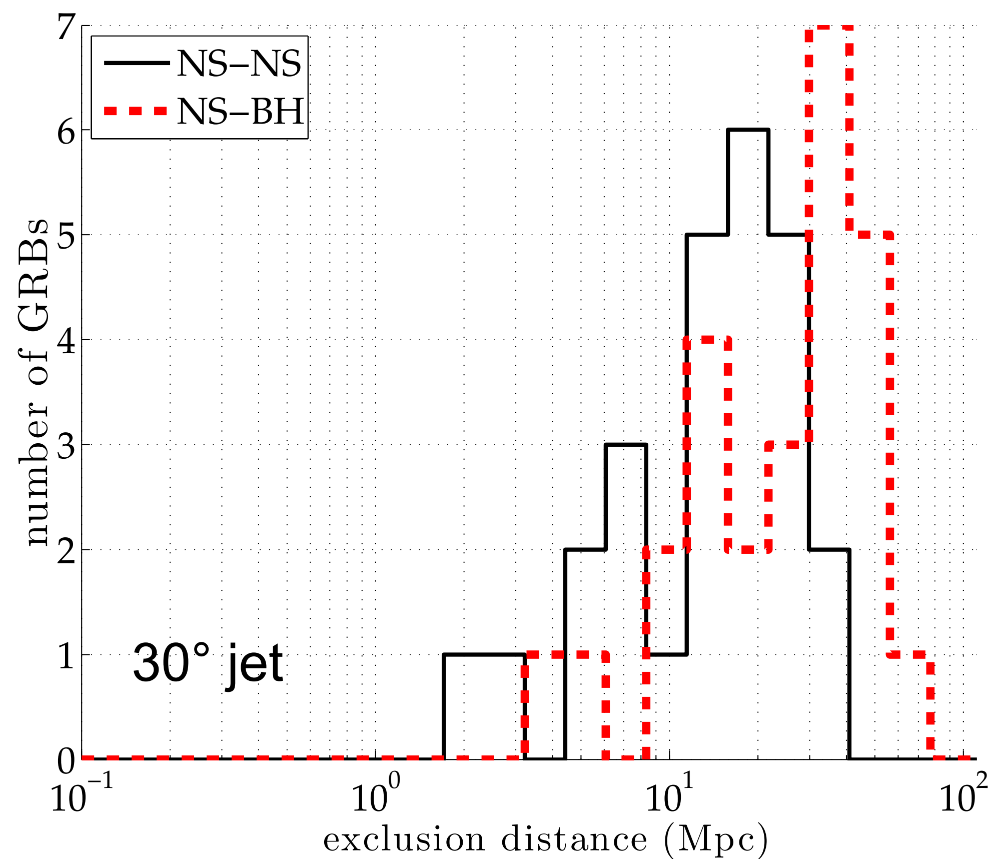
Short GRB exclusion distances

2005-7 run

Binary Merger Model

2009-10 run

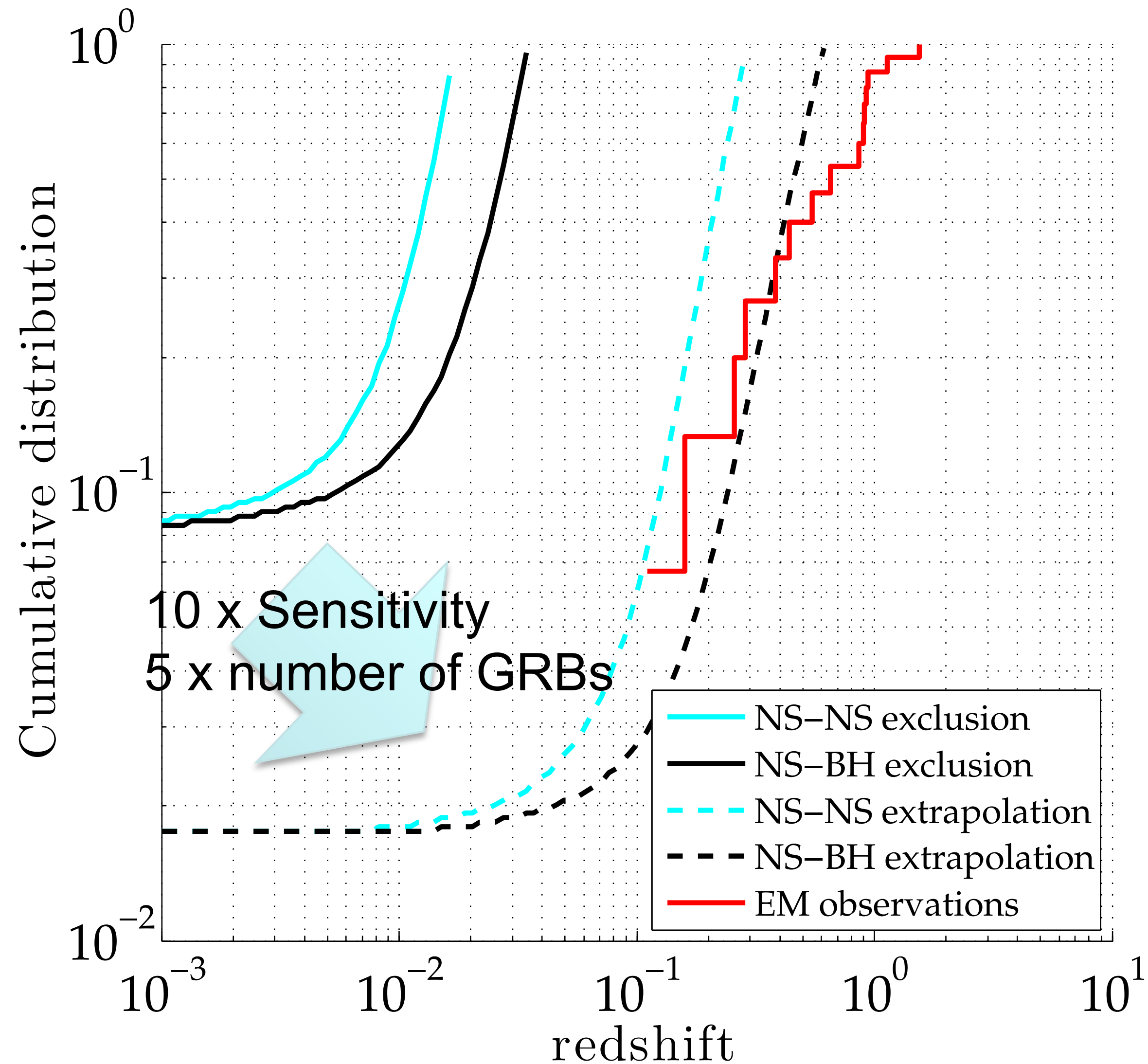




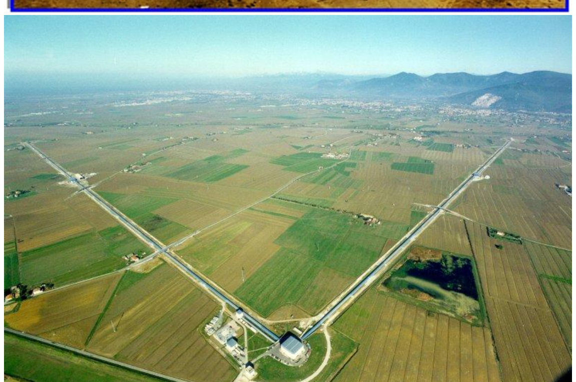
Abadie et al ApJ (2010)

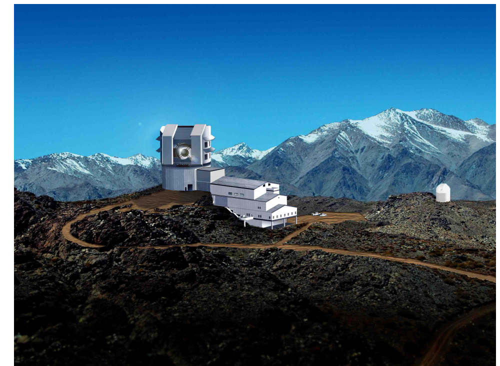
Evans et al 1205.1124

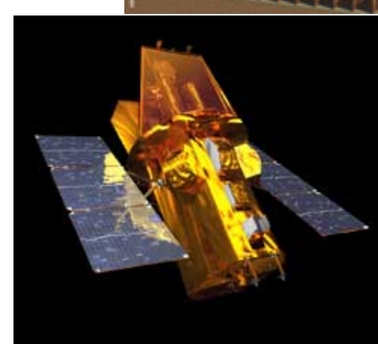
Future Prospects



Multi-messenger Astronomy







Localization

- Localization is primarily by triangulation

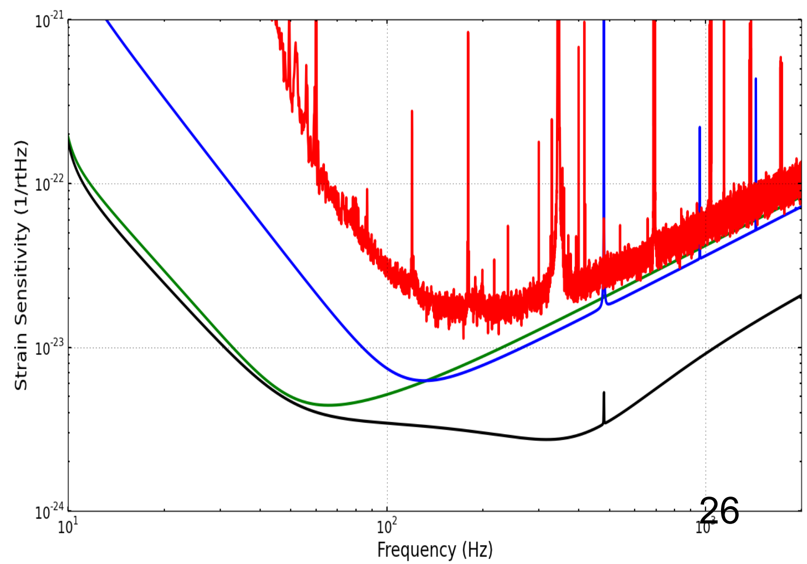
$$\text{Accuracy} \sim \frac{\sigma_t}{\Delta t}$$

Timing accuracy $(2\pi\, \rho\, \sigma_f)^{-1}$

Detector baseline

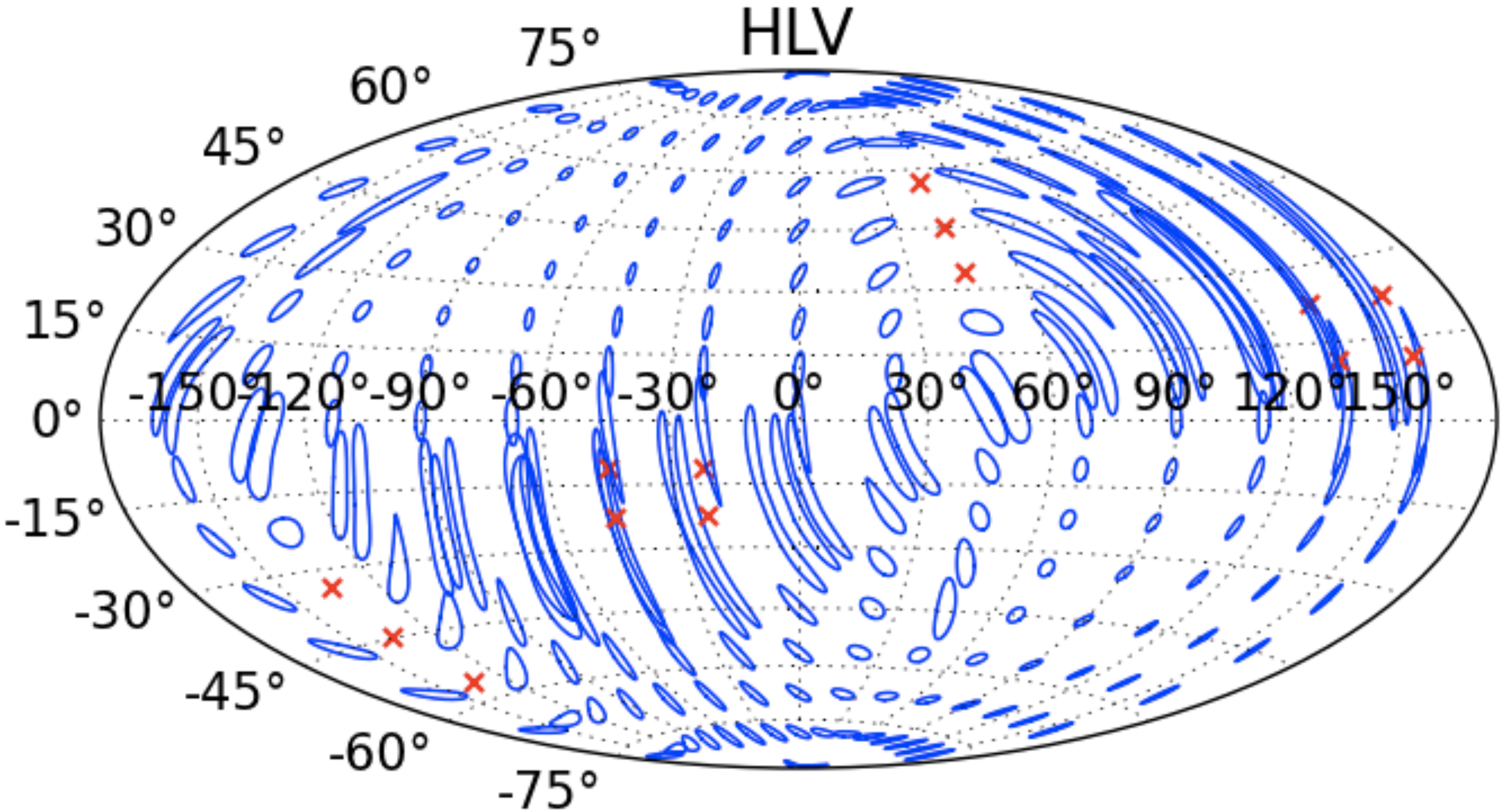
LIGO-LIGO: 10 ms
LIGO-Virgo: 27 ms
LIGO-India: 35-40ms
Virgo-India: 22ms

$\sigma_f \sim$ 100 Hz, dependent on high frequency sensitivity

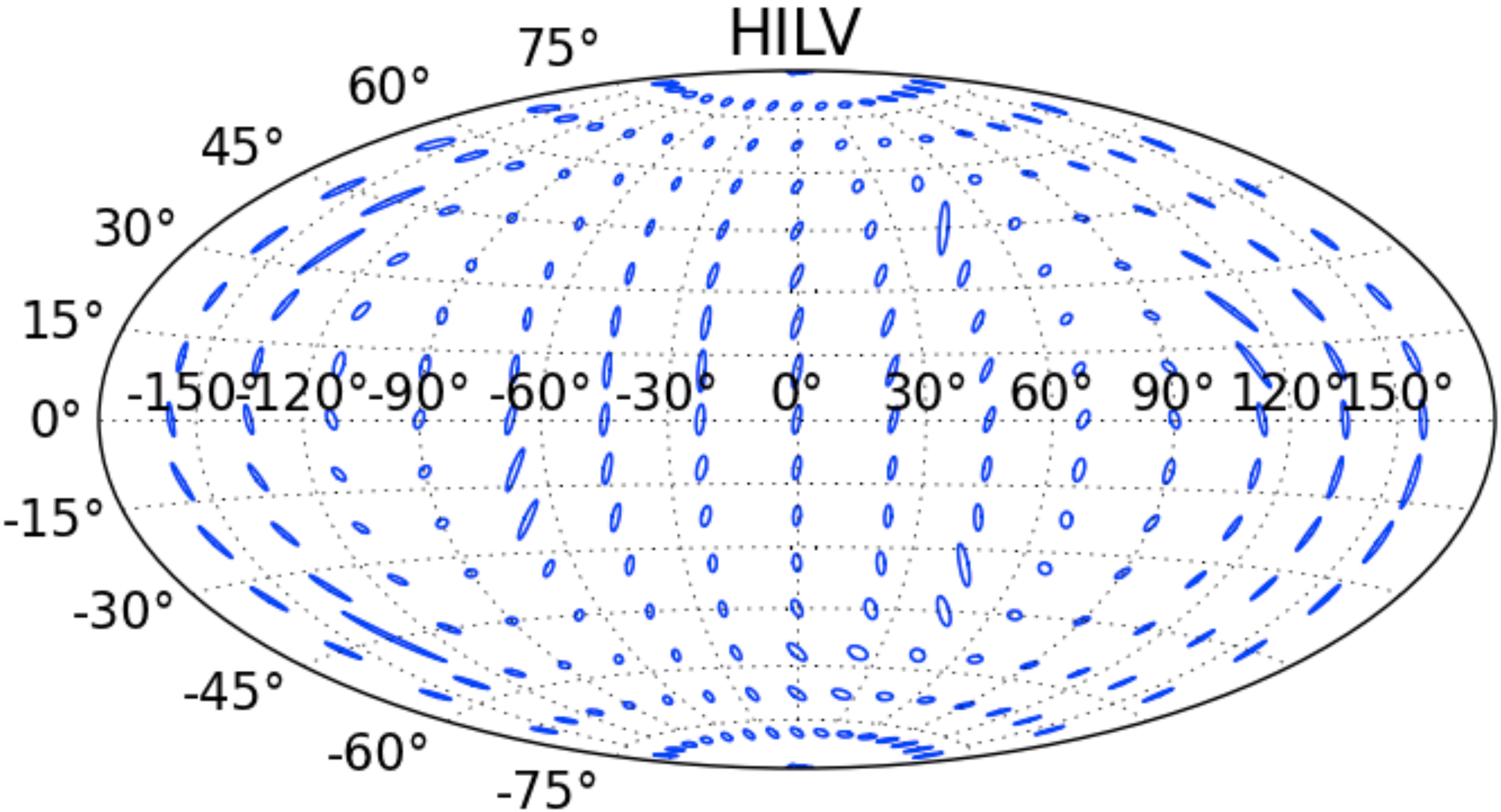


SF, NJP (2009), CQG (2011)

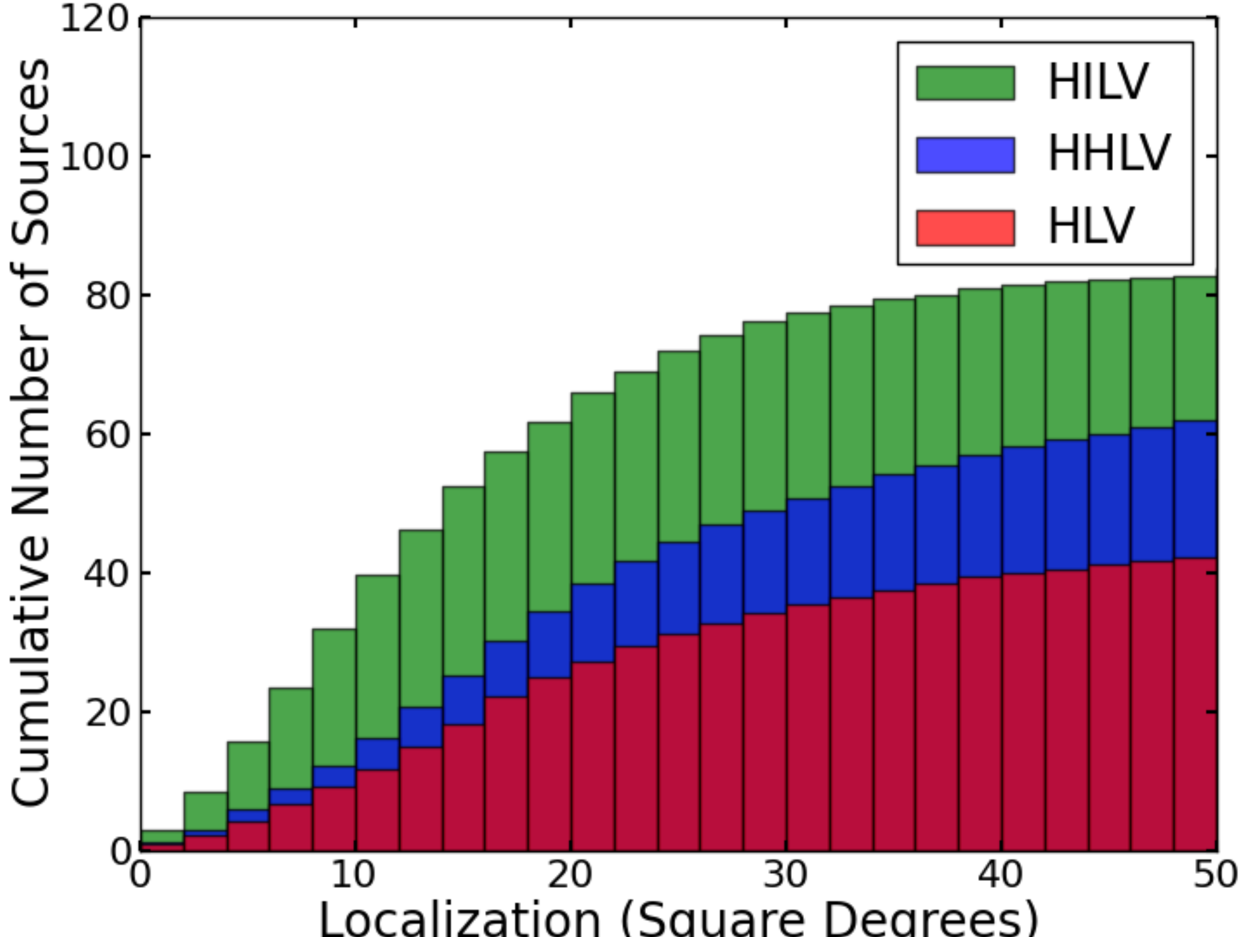
Hanford-Livingston-Virgo



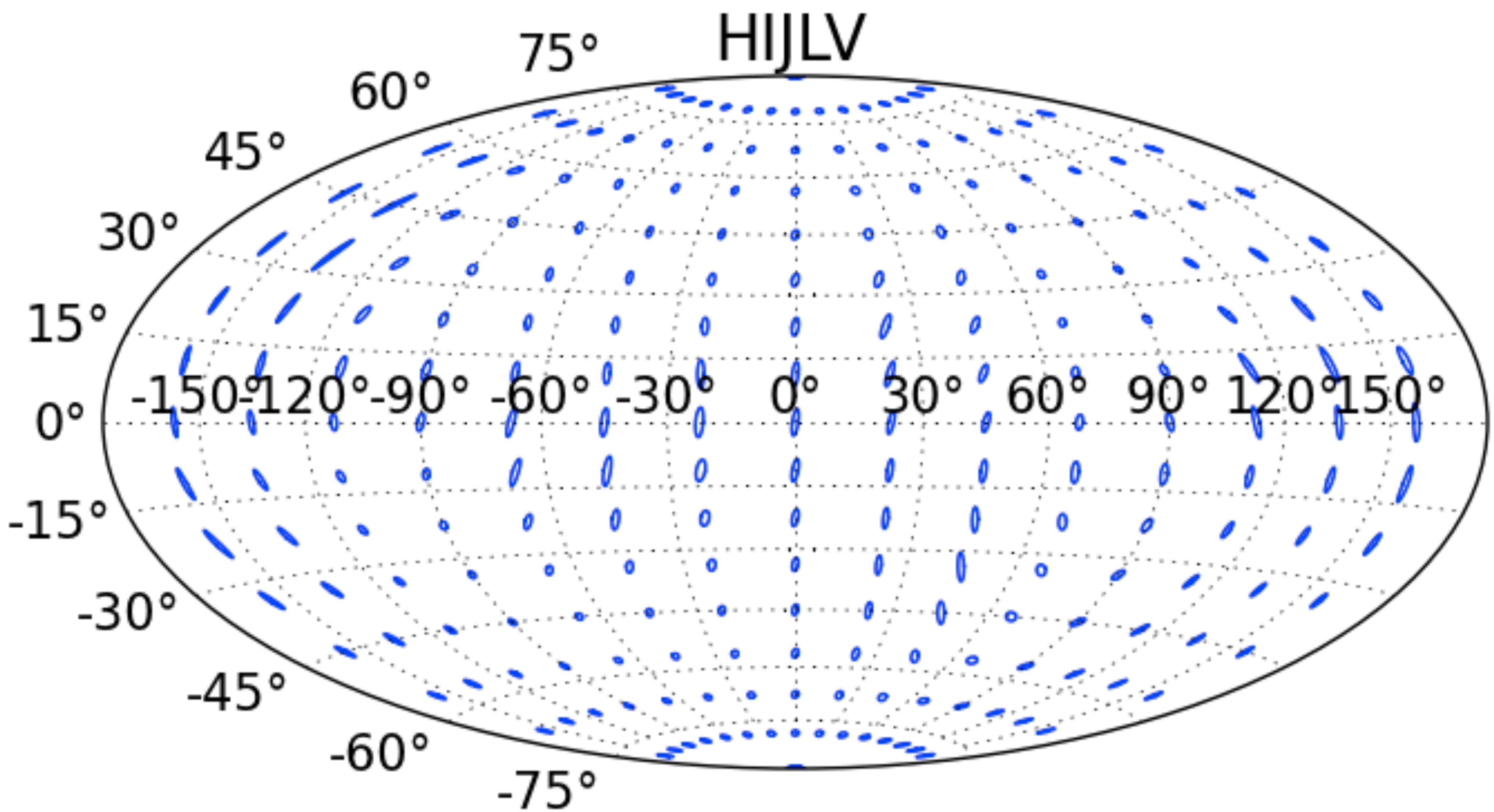
with LIGO India



Localization



5 detectors: Including KAGRA



Conclusions

- The era of GW astronomy is just around the corner
- There's much more to it than just making detections

Accurate parameter measurement and good co-ordination with EM observers required to fully take advantage