Gravitational Waves from GRBs/SN/Magnetars

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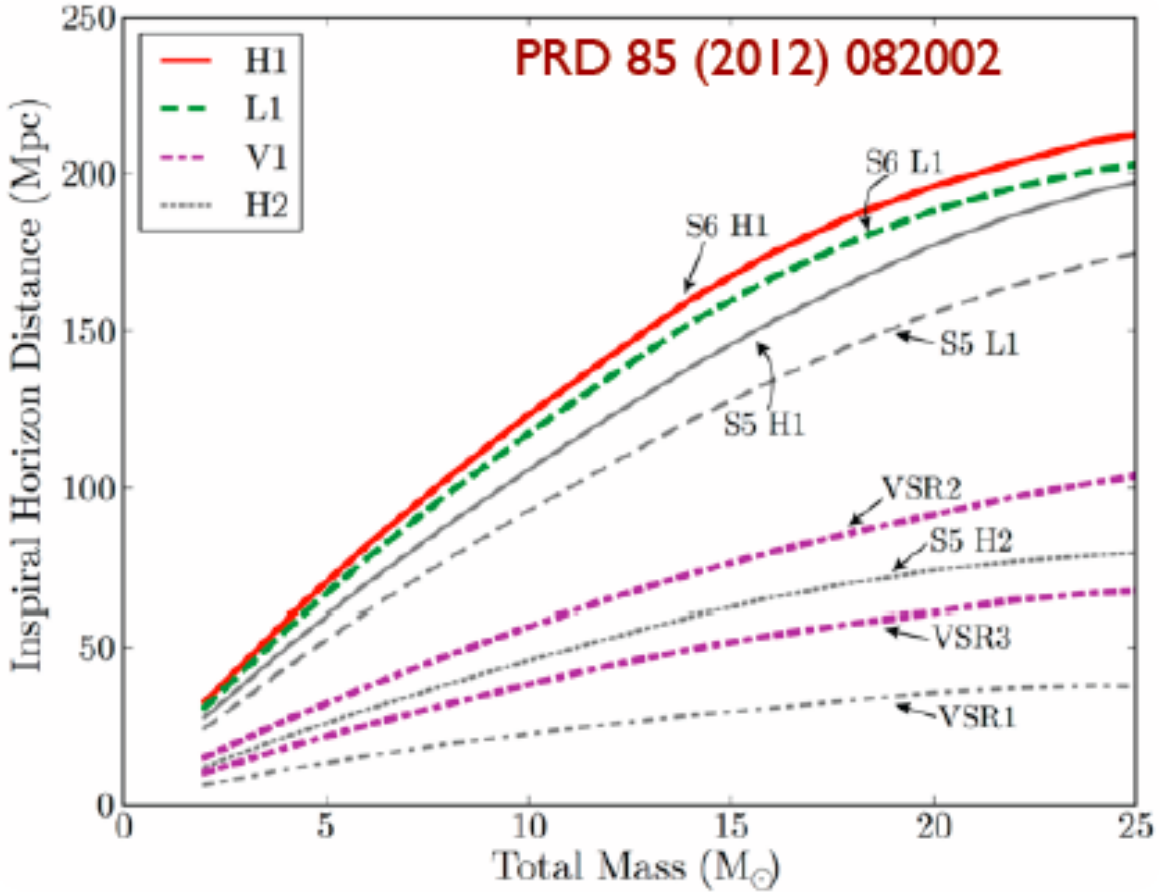
Advanced Era of GW Detector Network

Credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/ NGDC, DMSP Digital Archive

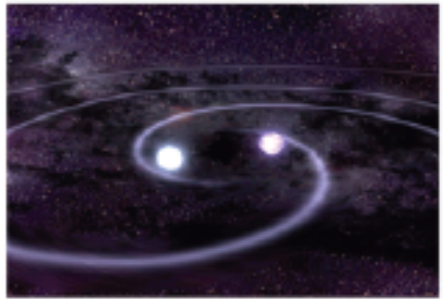
"Horizon" Distance for Binary Inspiral/Merger

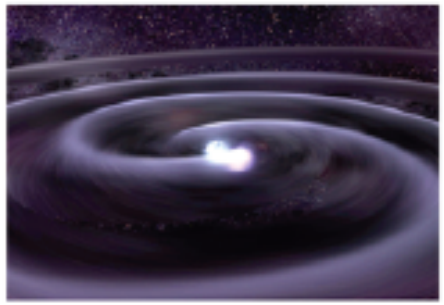
Initial LIGO and Virgo

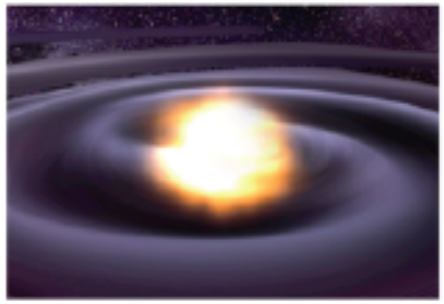
Abadie et al 2012

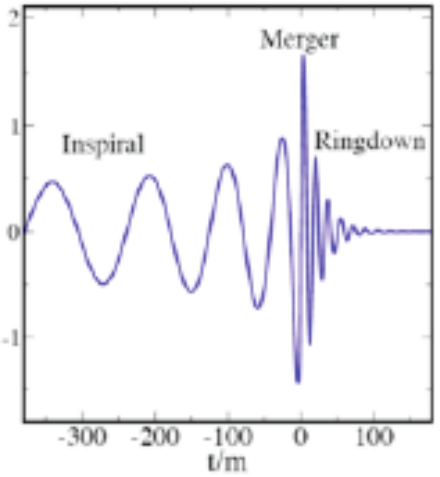


Distance at which an optimally oriented inspiral yields SNR=8







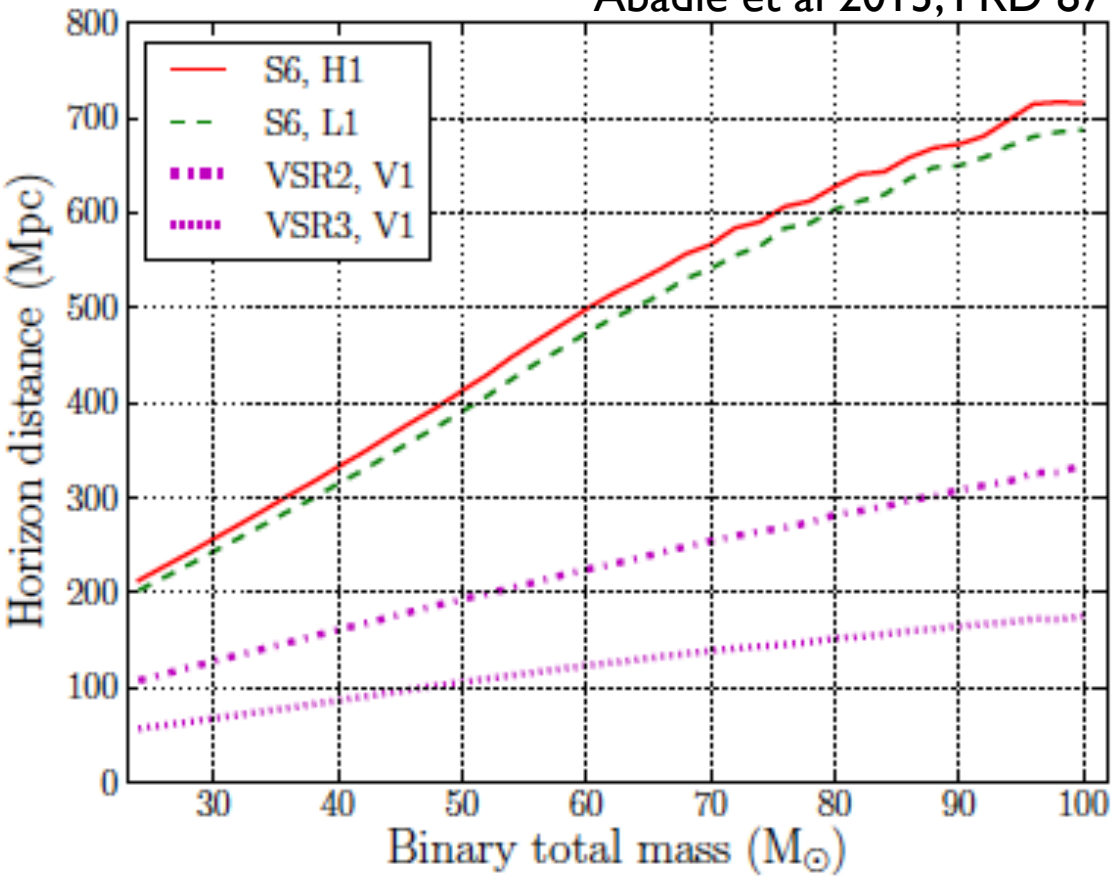


Credits: NASA/Dana Berry, Sky Works Digital

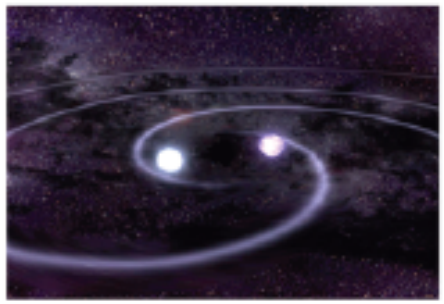
"Horizon" Distance for Binary Inspiral/Merger

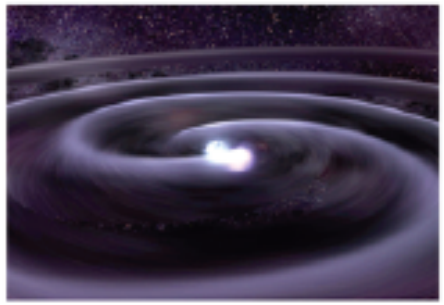
Initial LIGO and Virgo

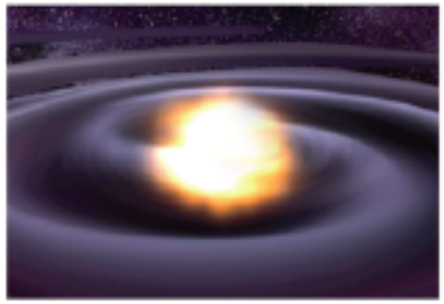
Abadie et al 2013; PRD 87

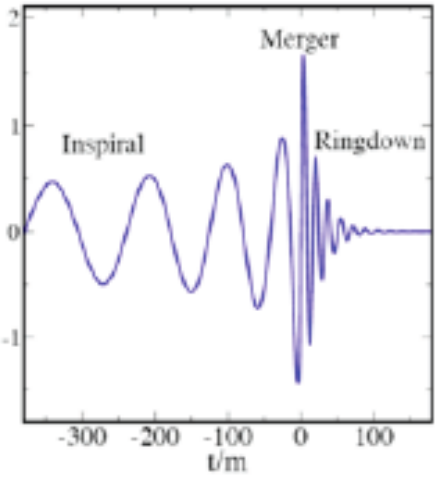


Distance at which an optimally oriented inspiral yields SNR=8



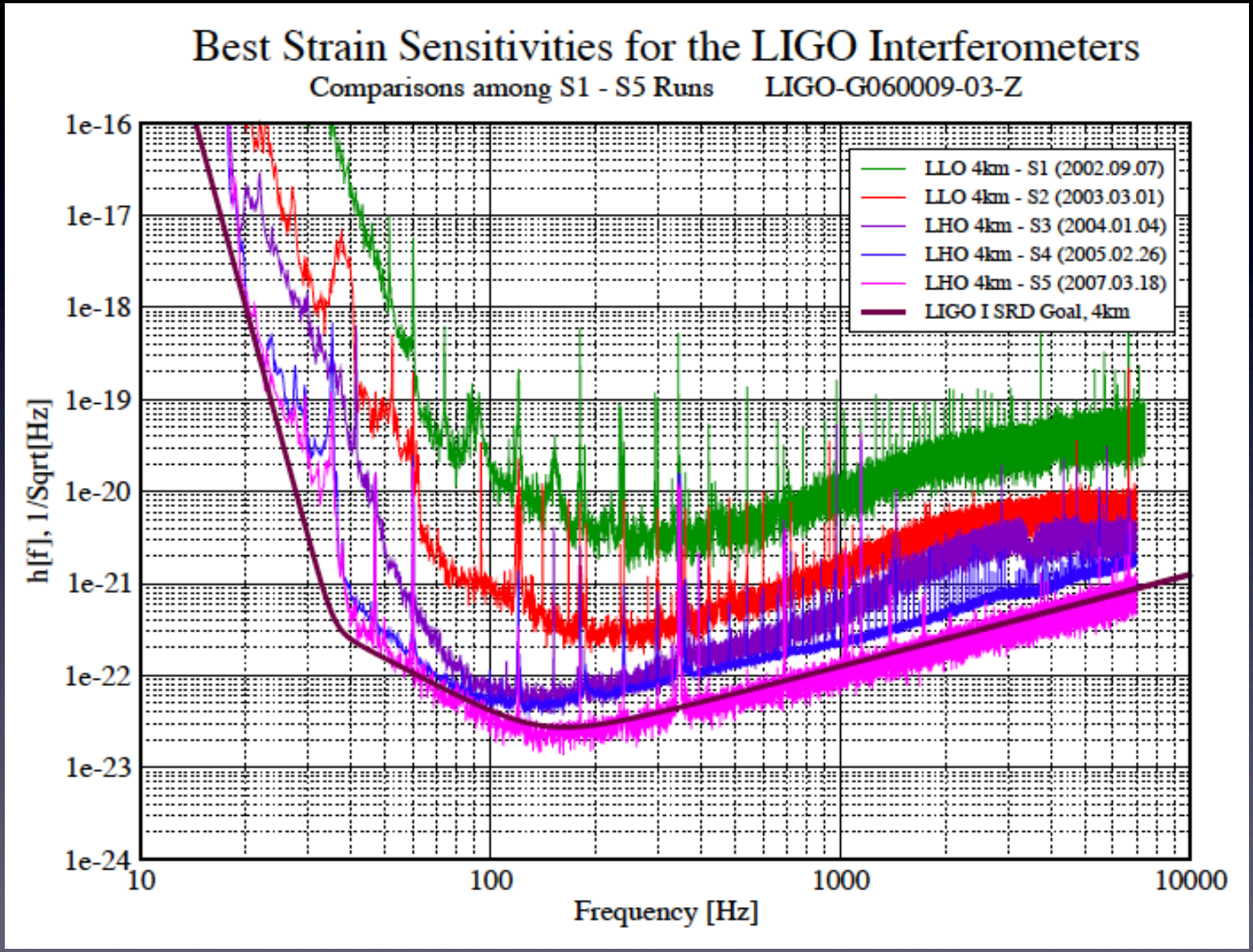




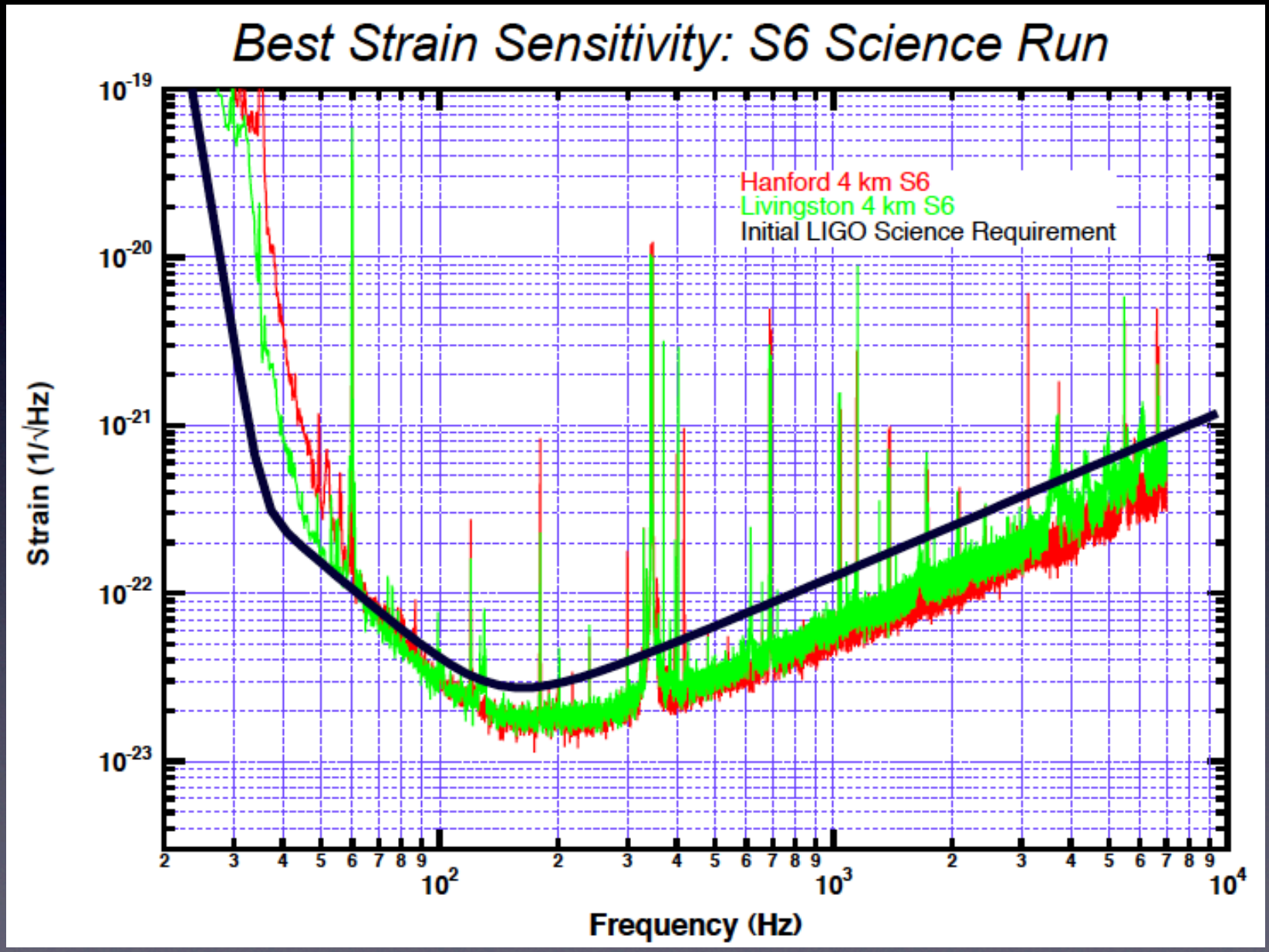


Credits: NASA/Dana Berry, Sky Works Digital

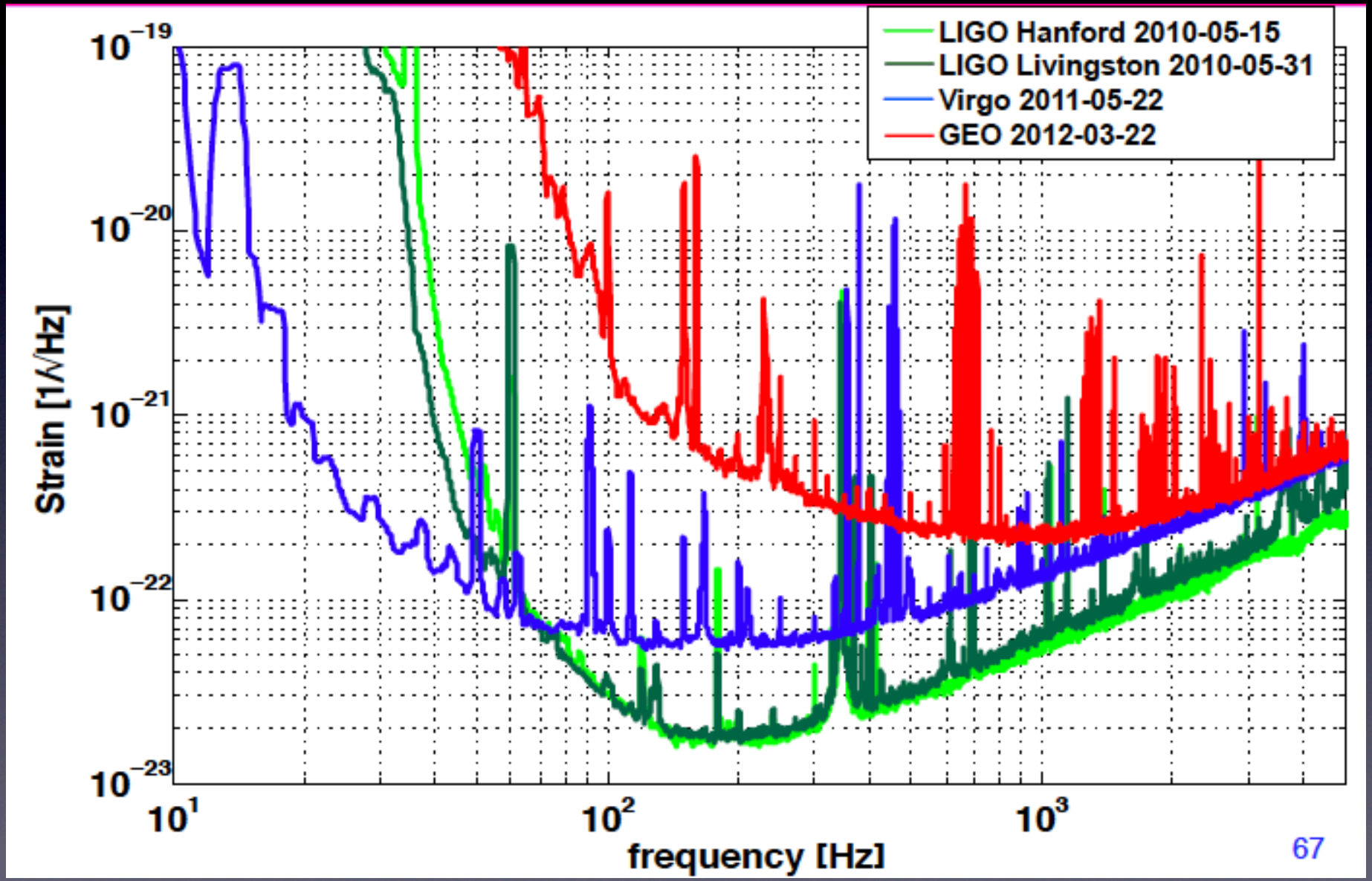
Initial LIGO: 2002 to 2007



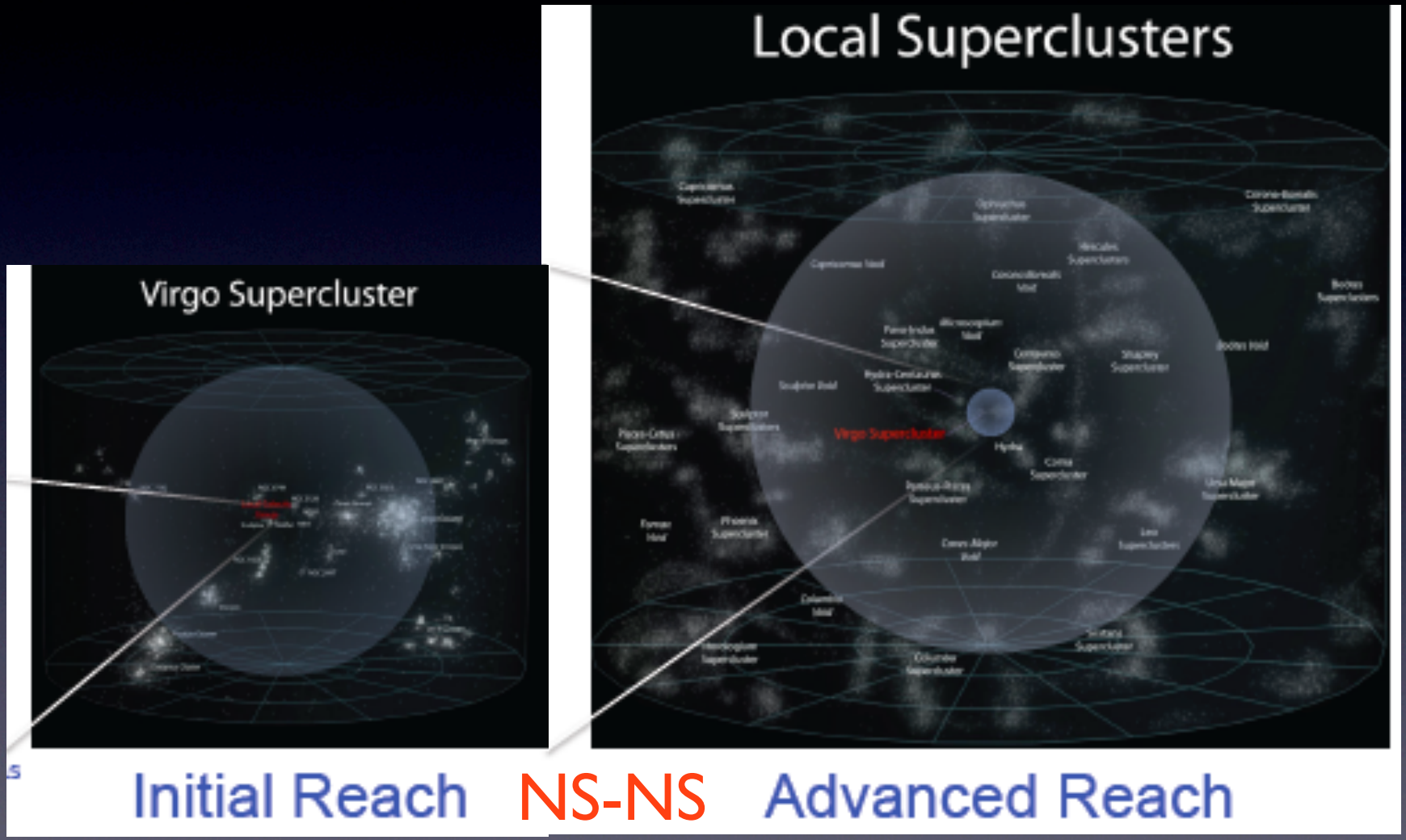
Initial LIGO: 2009 - 2010



Initial LIGO & Virgo: 2010 - 2011



From Initial to Advanced



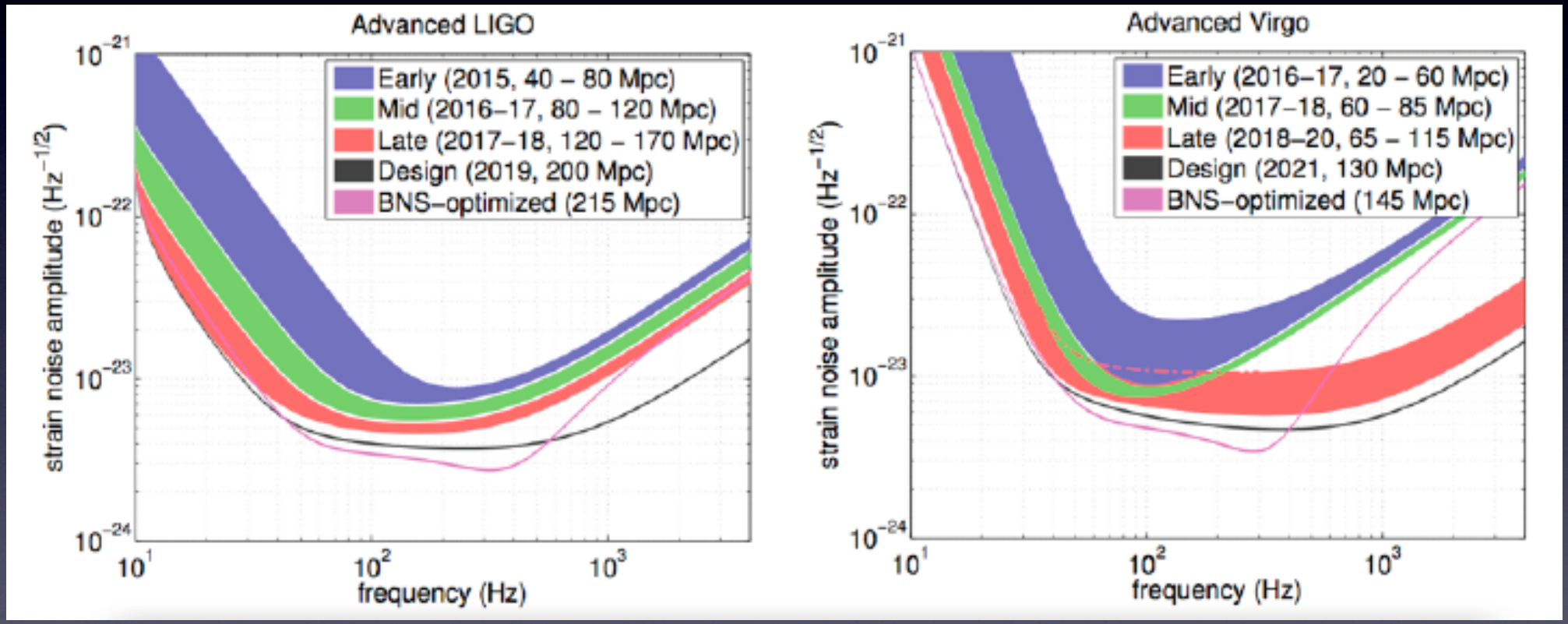
Current Rate Predictions

Abadie et al 2010; arXiv: 1003.2480

IFO	Source	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm high}$ $\rm yr^{-1}$
Initial	NS-NS	2×10^{-4}	0.2
	NS-BH	7×10^{-5}	0.1
	BH-BH	2×10^{-4}	0.5
Advanced	NS-NS	0.4	400
	NS-BH	0.2	300
	BH-BH	0.4	1000

Advanced LIGO/Virgo Sensitivity Evolution

Aasi et al 2013; arXiv: 1304.0670



Current Science Plan for Advanced Detectors

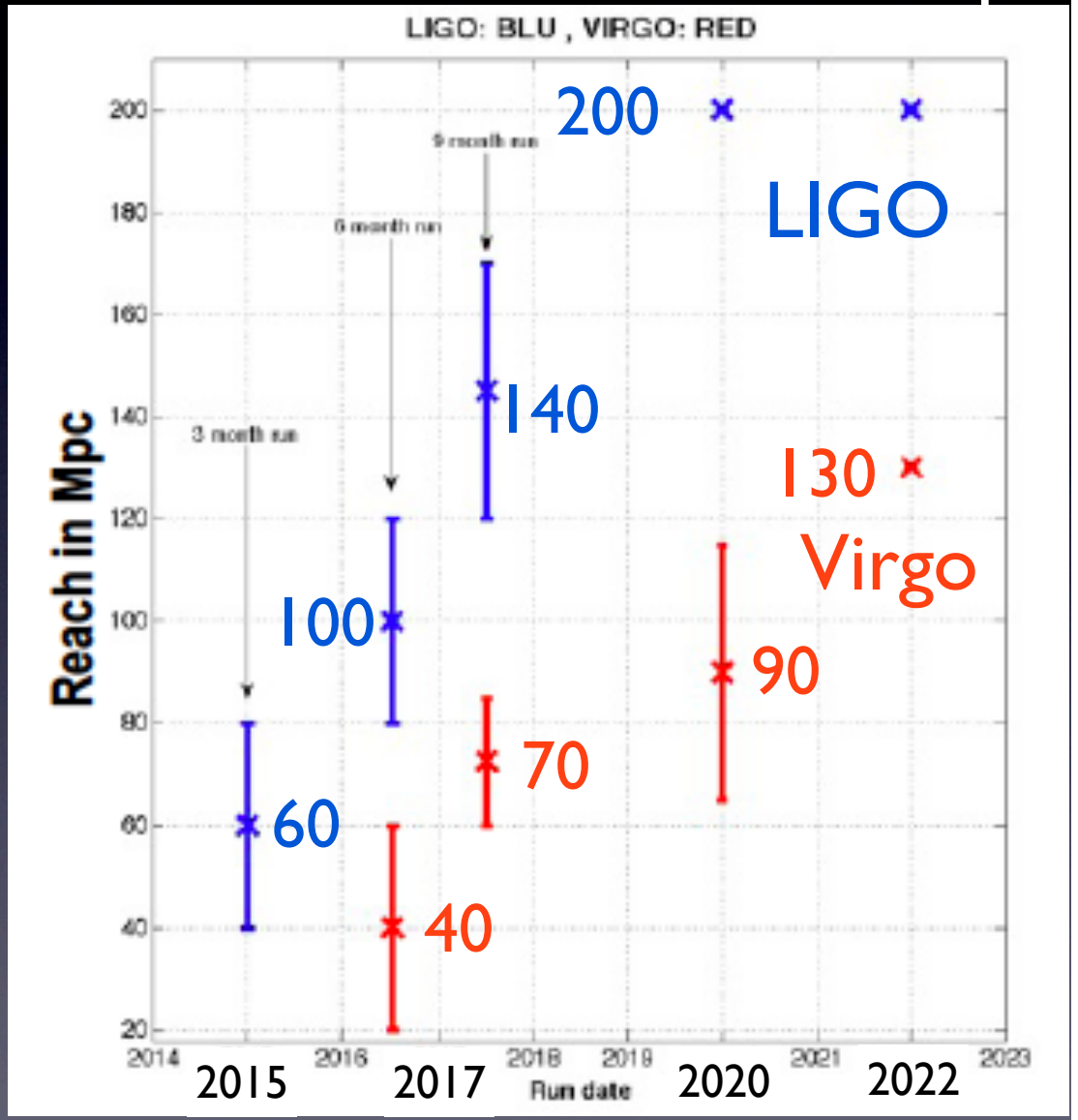
Second generation interferometers to begin science operations:

- Advanced LIGO (2 interferometers) – 2015
- Advanced Virgo (1 interferometer) – 2016

Approximate run schedule:

- **Advanced LIGO:**
  - ~ 3 month run in 2015,
  - ~ 6 month run in 2016-17
  - ~ 9 month run in 2017-18
- **Advanced Virgo:**
  - ~ 6 month run in 2016-17
  - ~ 9 month run in 2017-18
- *Modification of run schedules is likely as we learn more about the instruments*

NS-NS Reach in Mpc



Initial LIGO/Virgo Results for Transient Sources

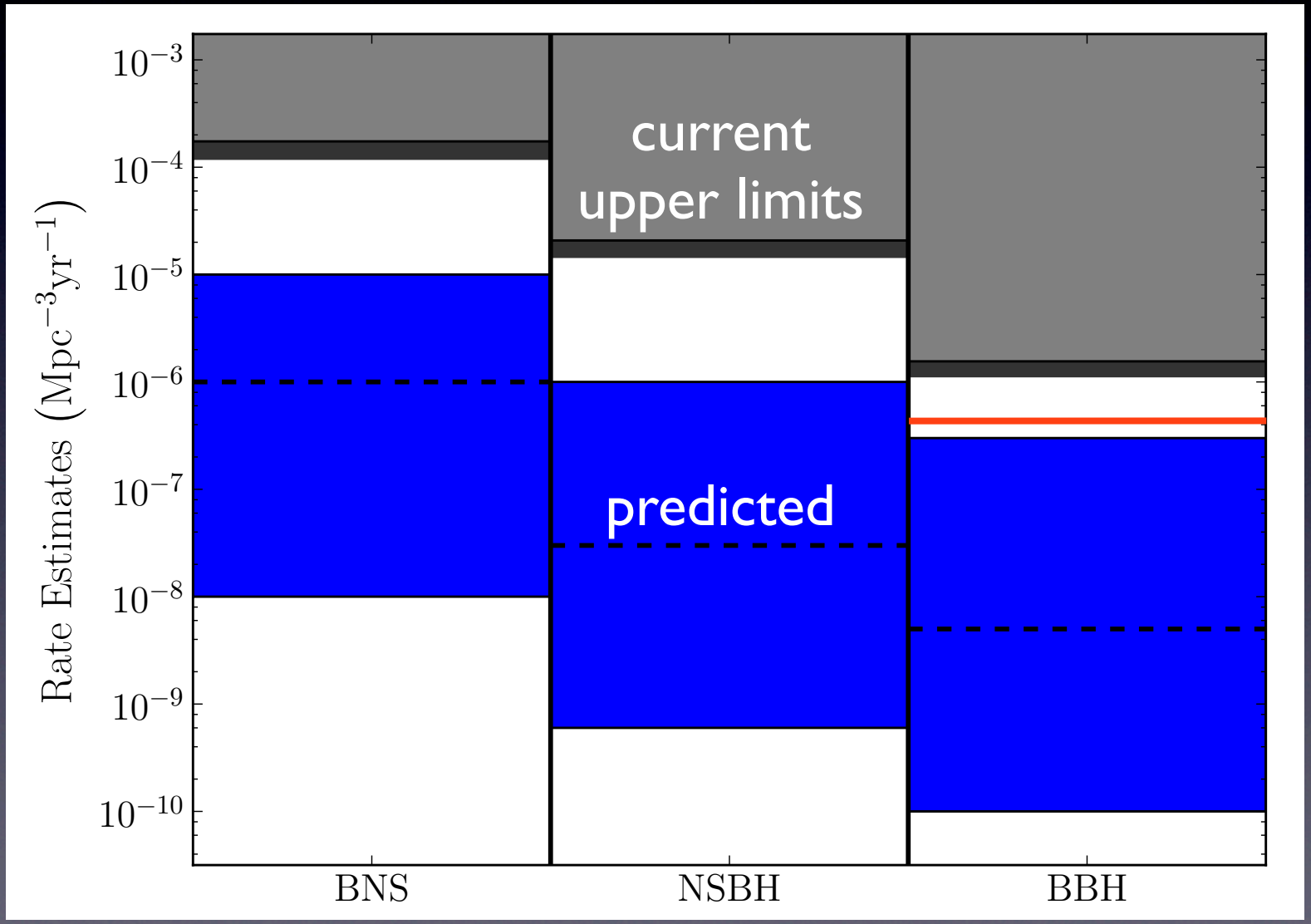
LIGO-Hanford
(H1 and H2)

LIGO-Livingston
(L1)

Virgo-Pisa
(V1)

GW Limits on Binary Inspiral/Mergers

Abadie et al 2012



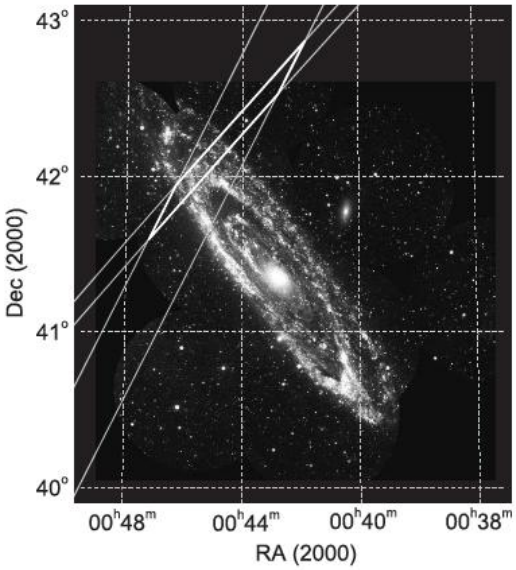
BH mass: 5 Msun

90% Upper Limits

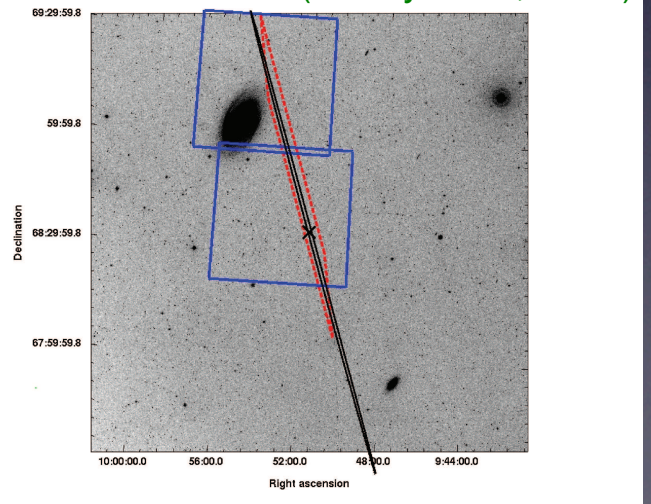
BH mass: 20 Msun

Follow-up of 2 close short GRBs

GRB070201 error box (Mazets et al., 2008)



GRB051103 error box (Hurley et al., 2010)



Significant previous non detections

- Short GRBs,
  - GRB070201 sky location overlap with M31, (Andromeda 770 kpc)
  - GRB051103 sky location overlap with M81 ($\sim$ 3.6 Mpc)
- no GW found

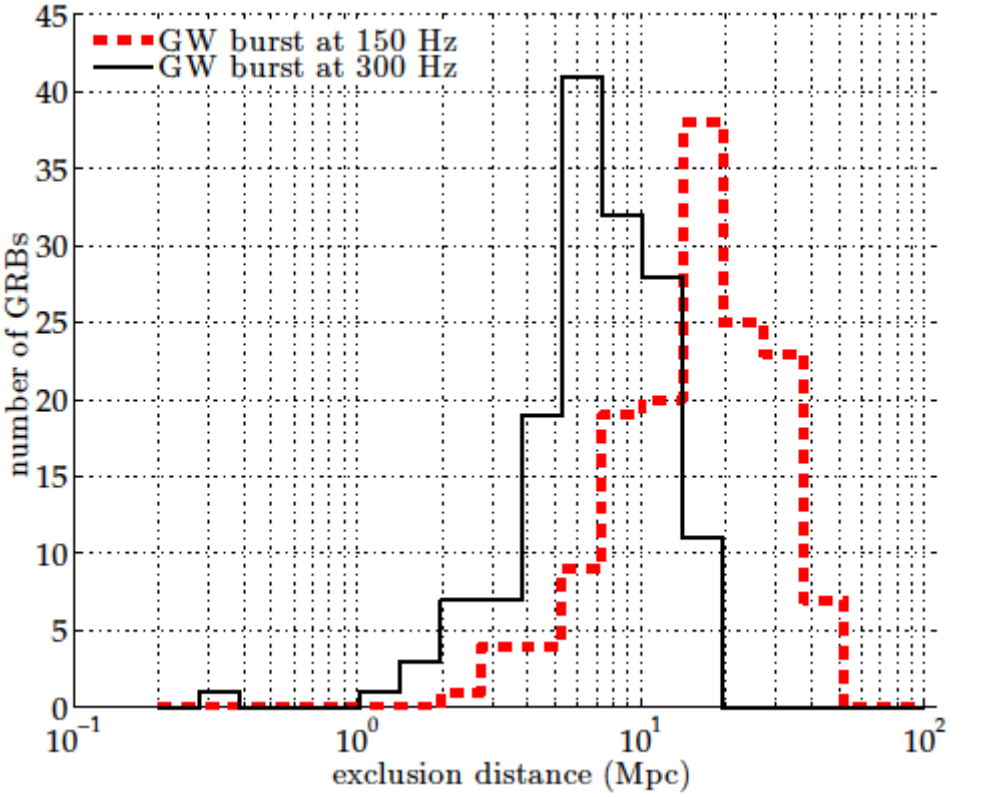
  $\Rightarrow$ Binary coalescence in M31 excluded at >99% confidence level (Abbott et al., 2008)

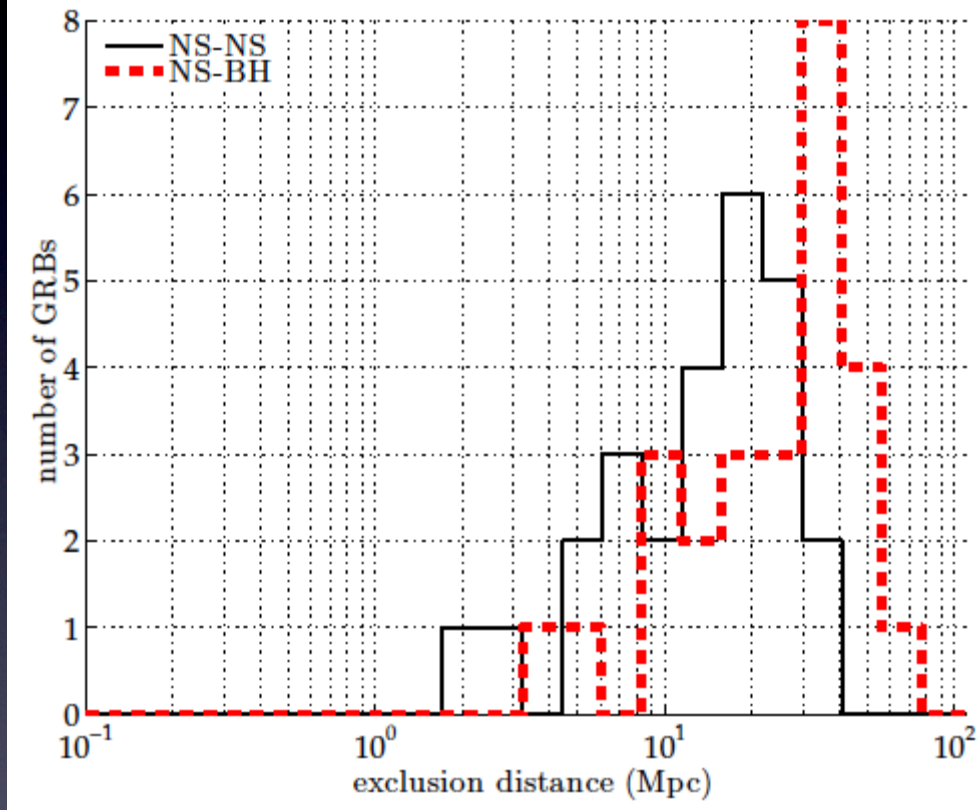
  $\Rightarrow$ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012b)
- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater) > 3.5/5.2Mpc
  - Coalescence in galaxy behind M31/M81

Follow-up of ~150 GRBs: exclusion distances

Abadie et al 2012; arXiv: 1205.2216

for 26 sGRBs



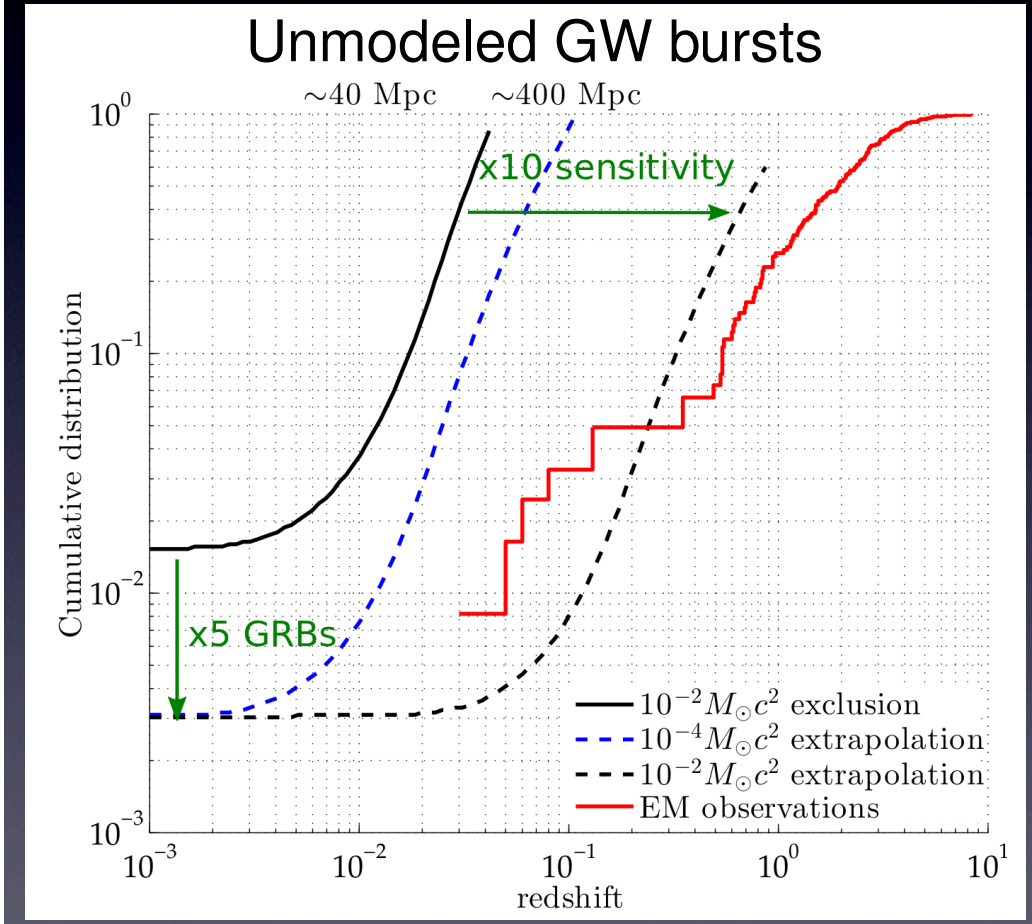


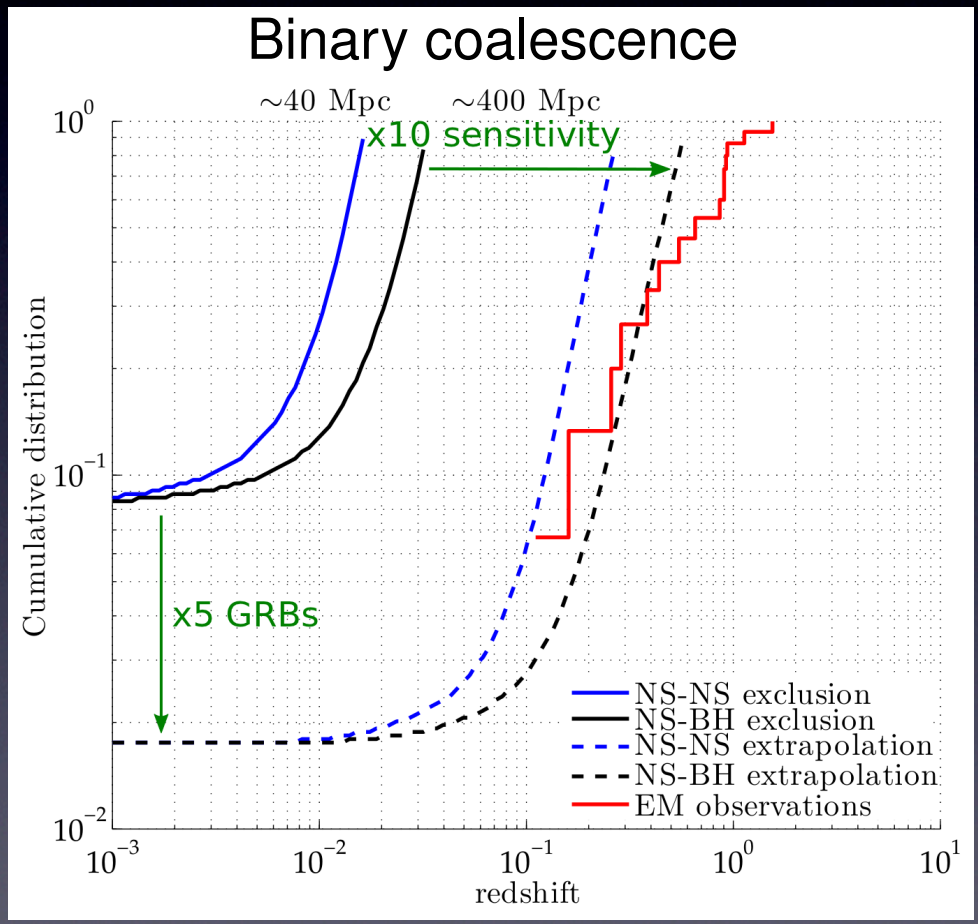
$$E_{GW} = 10^{-2} M_{\odot} c^2$$

	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	16	28

Expectations for GRB Follow-Up in the Advanced Era

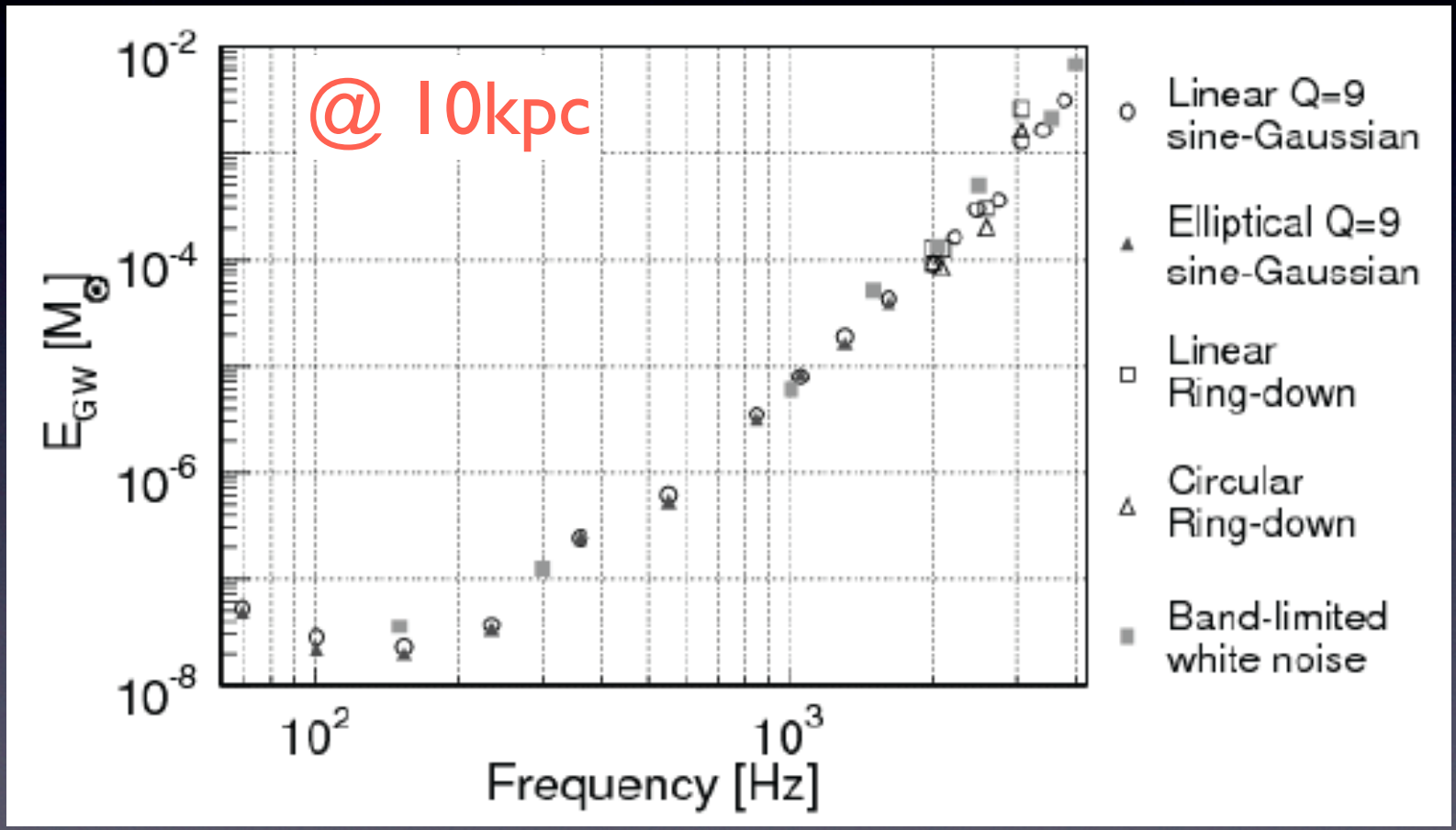
Abadie et al 2012; arXiv: 1205.2216





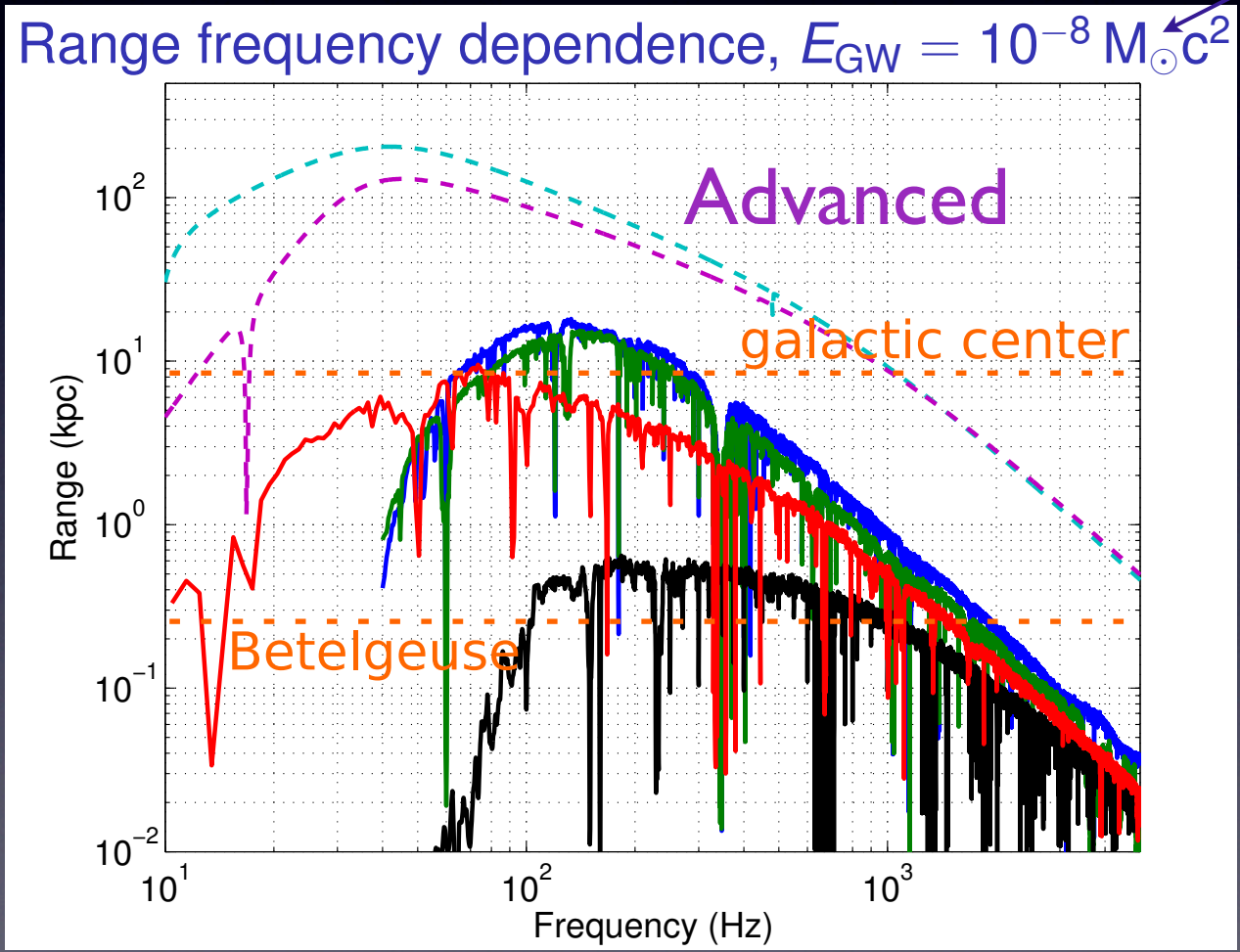
Constraints from Blind Search for Generic Bursts

Abadie et al 2012; arXiv: 1202.2788



Expectations for Advanced Searches of Generic Bursts

M. Was (priv. comm.)

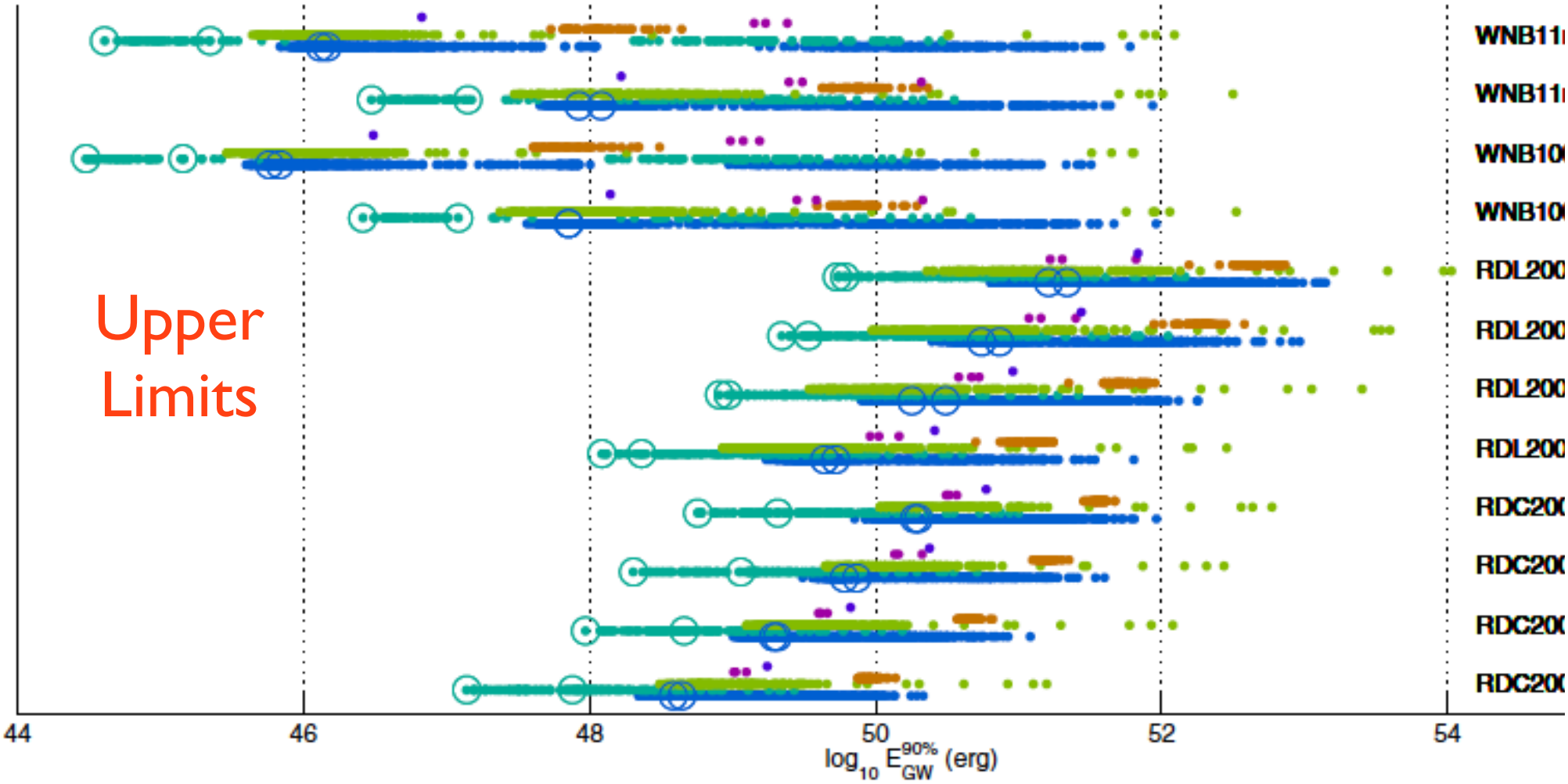


good rule of thumb?

Could GW emission efficiency be frequency dependent?

GW Emission from Magnetars

Abadie et al 2011, ApJL



6 magnetars, 1275 EM burst triggers, 1 - 3 GW detectors on

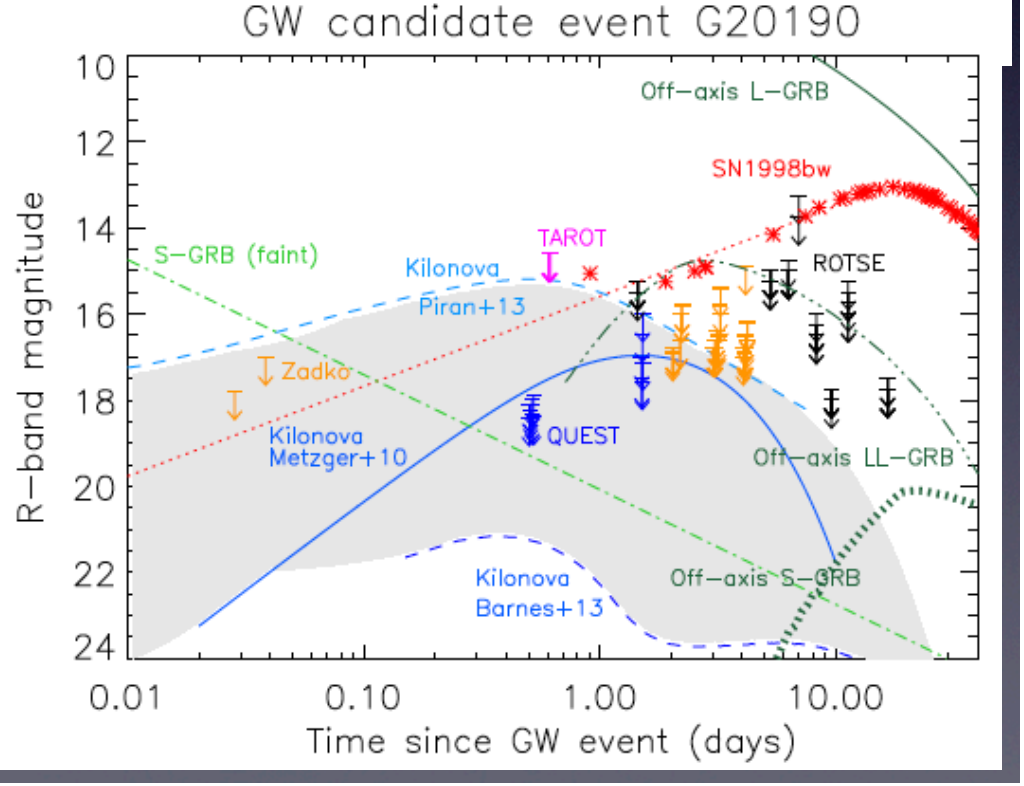
Optical Follow-Up of GW candidate events

Aasi et al 2013; arXiv: 1310.2314

ABSTRACT

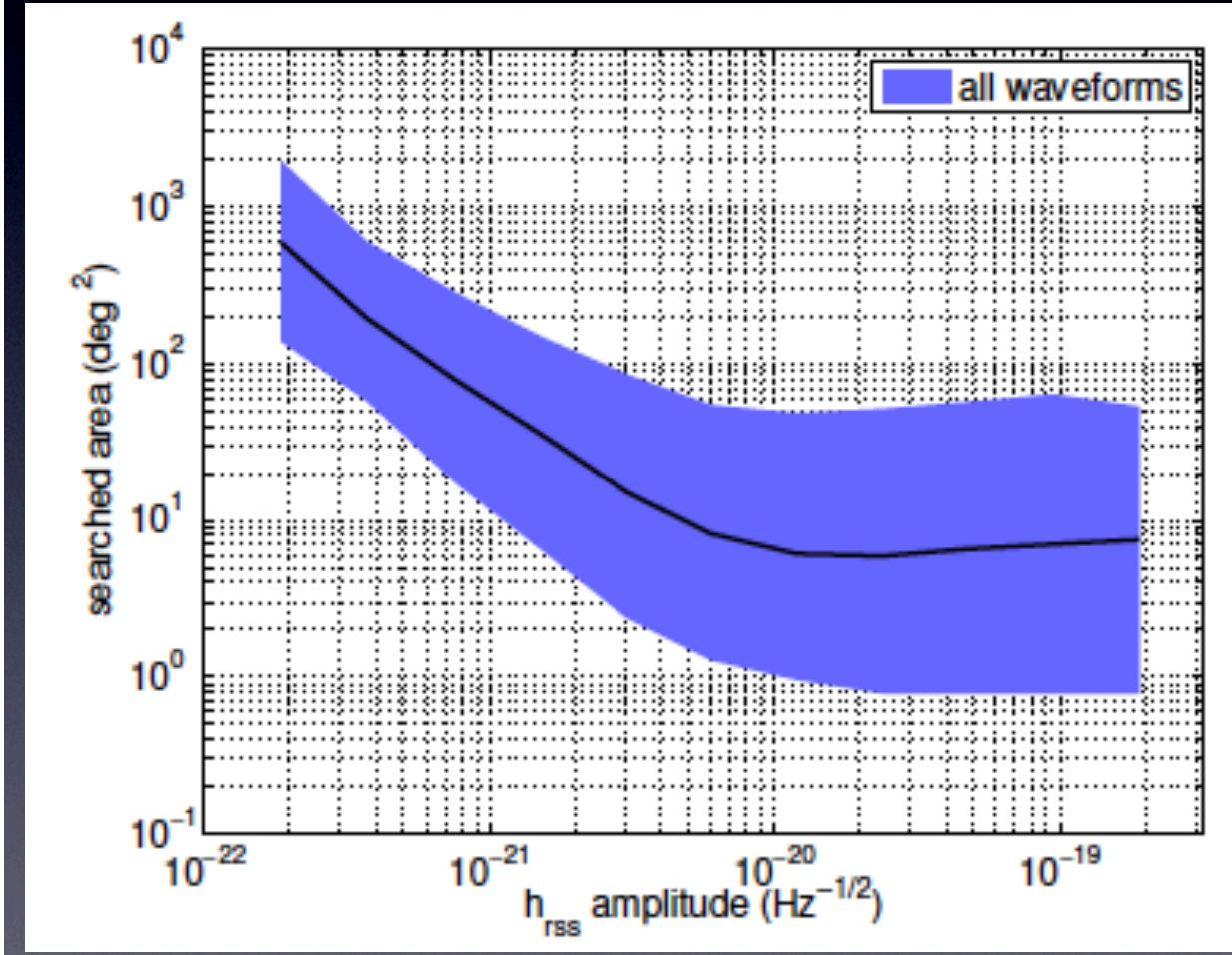
During the LIGO and Virgo joint science runs in 2009-2010, gravitational wave (GW) data from three interferometer detectors were analyzed within minutes to select GW candidate events and infer their apparent sky positions. Target coordinates were transmitted to several telescopes for follow-up observations aimed at the detection of an associated optical transient. Images were obtained for eight such GW candidates. We present the methods used to analyze the image data as well as the transient search results. No optical transient was identified with a convincing association with any of these candidates, and none of the GW triggers showed strong evidence for being astrophysical in nature. We compare the sensitivities of these observations to several model light curves from possible sources of interest, and discuss prospects for future joint GW-optical observations of this type.

Observations as soon as 40min after GW trigger out to ~10 days



Localization: Unmodelled Bursts

Aasi et al 2013; arXiv: 1304.0670



at advanced design sensitivity for both LIGO & Virgo

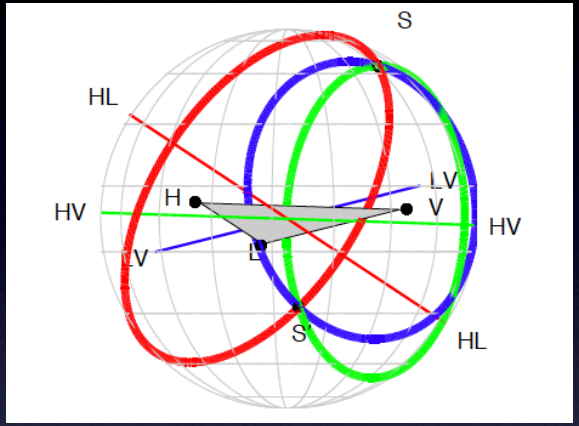
wide range of potential burst signals

median sky areas ~ 50 - 500 deg^2

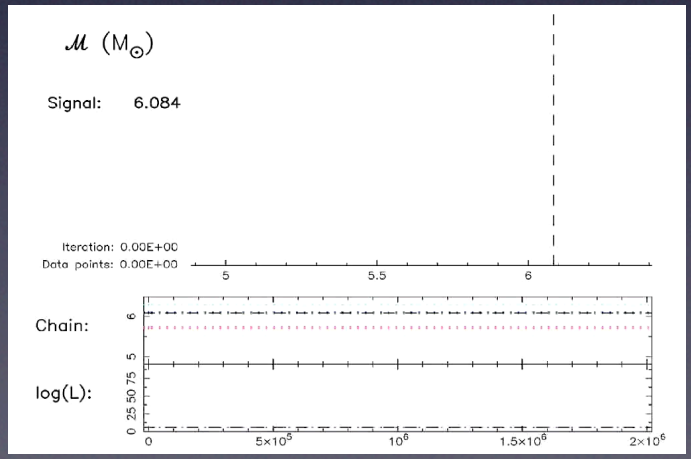
Sky Localization of GW sources

HOW ?

- Triangulation of unmodeled bursts
- Triangulation with some waveform knowledge



- Bayesian Parameter Estimation with detailed waveform knowledge eg, Markov-Chain Monte Carlo: PDFs of all signal parameters, not just sky location



Sky Localization of GW sources

HOW ?

HOW FAST ?

- Triangulation of unmodeled bursts

  ~ 1-3 minutes

- Triangulation with some waveform knowledge

- Bayesian Parameter Estimation with detailed waveform knowledge eg, Markov-Chain Monte Carlo: PDFs of all signal parameters, not just sky location

  ~ 30 minutes to hours to days

The LIGO/Virgo Parameter Estimation Team Members from NU/CIERA

- **Ben Farr** (--> UChicago)

- **Tyson Littenberg**

- **Carl Rodriquez**

- **Vivien Raymond** (now Caltech)

- **Will Farr** (now Birmingham)

- **Ilya Mandel** (now Birmingham)

NORTHWESTERN UNIVERSITY

LSC VIRGO

CIERA

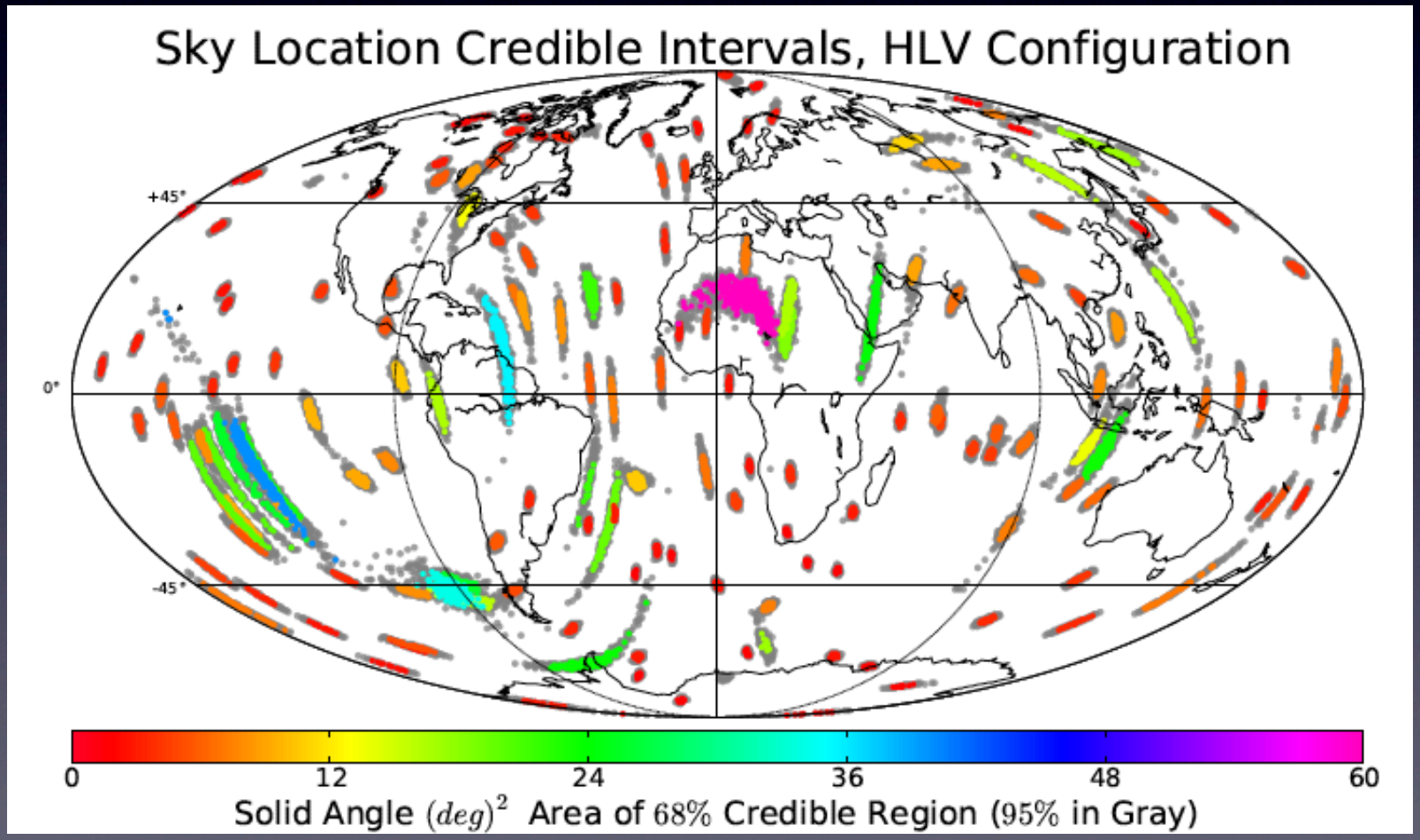
Localization: NS-NS Inspiral/Merger

Rodriguez et al 2014

- at Advanced design sensitivity for 3 detectors
- for a strong signal of SNR~20
- averaged over noise realizations
- for non-spinning NS
- with MCMC

Localization:
NS-NS Inspiral/Merger

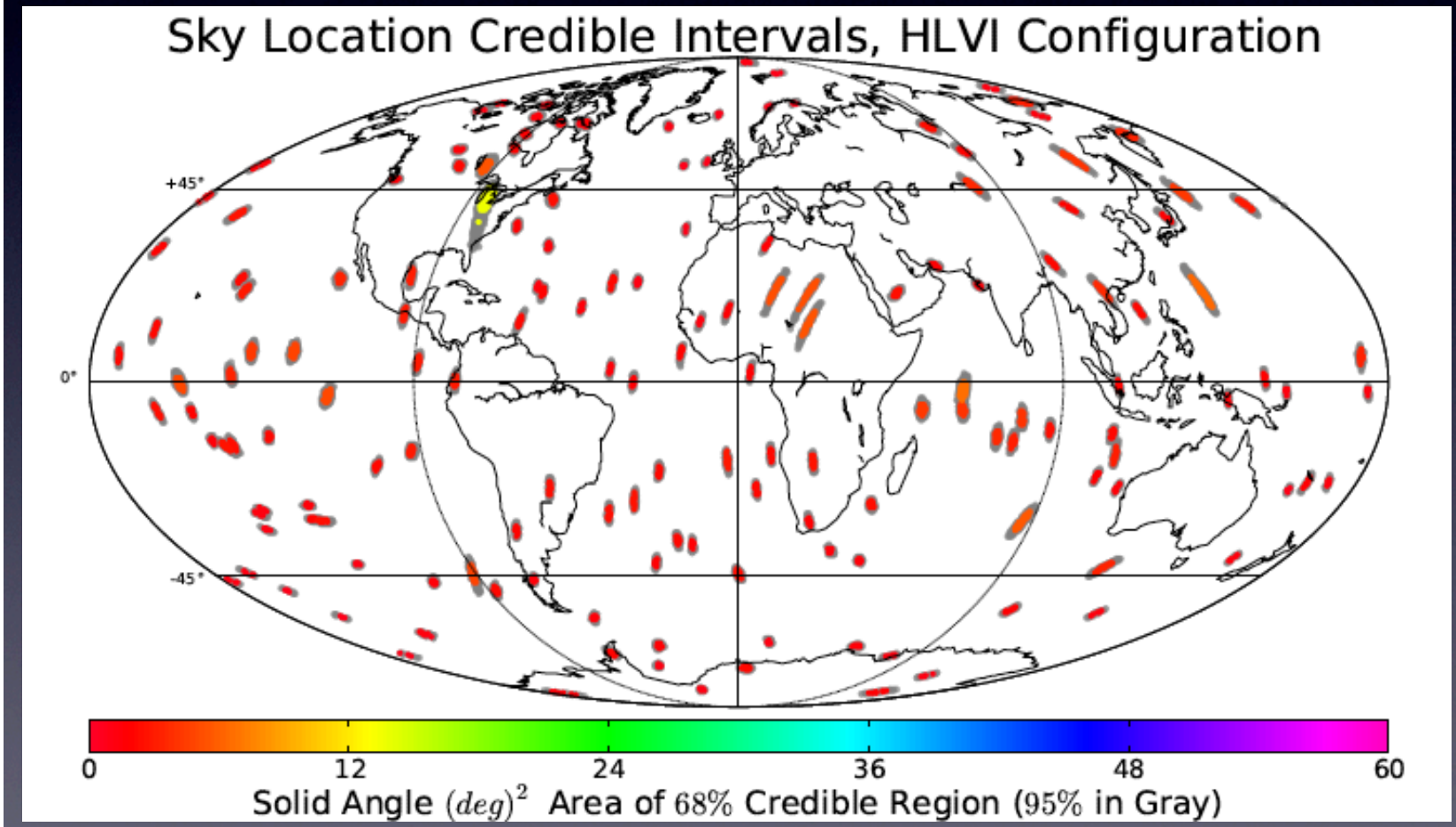
Rodriguez et al 2014



at 95% CL
median
error of
~ 10 deg^2

Localization:
NS-NS Inspiral/Merger

Rodriguez et al 2014



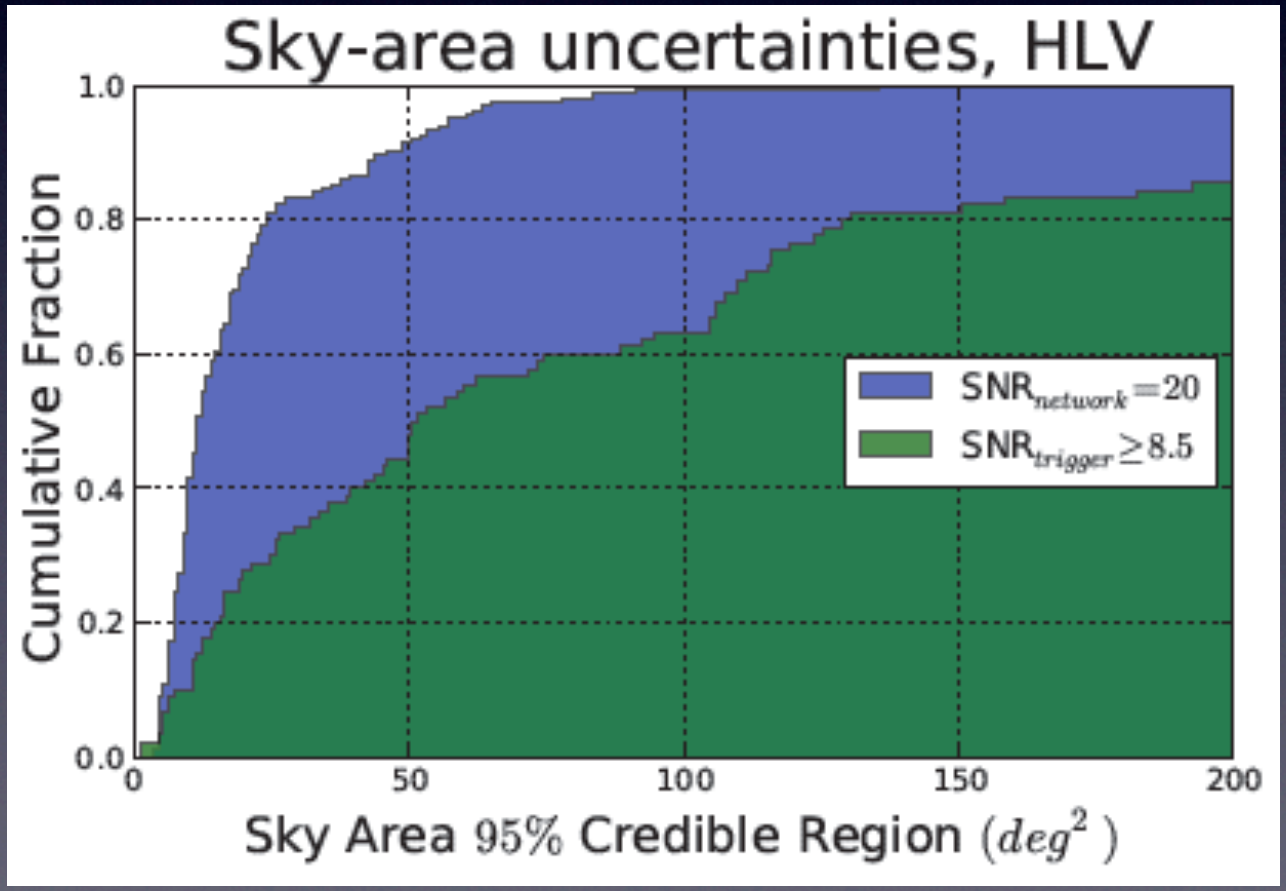
with
INDIGO

at 95% CL
median
error of
~ 5 deg^2

Localization:
NS-NS Inspiral/Merger

What about Low SNR?

Rodriguez et al 2014



at 95% CL

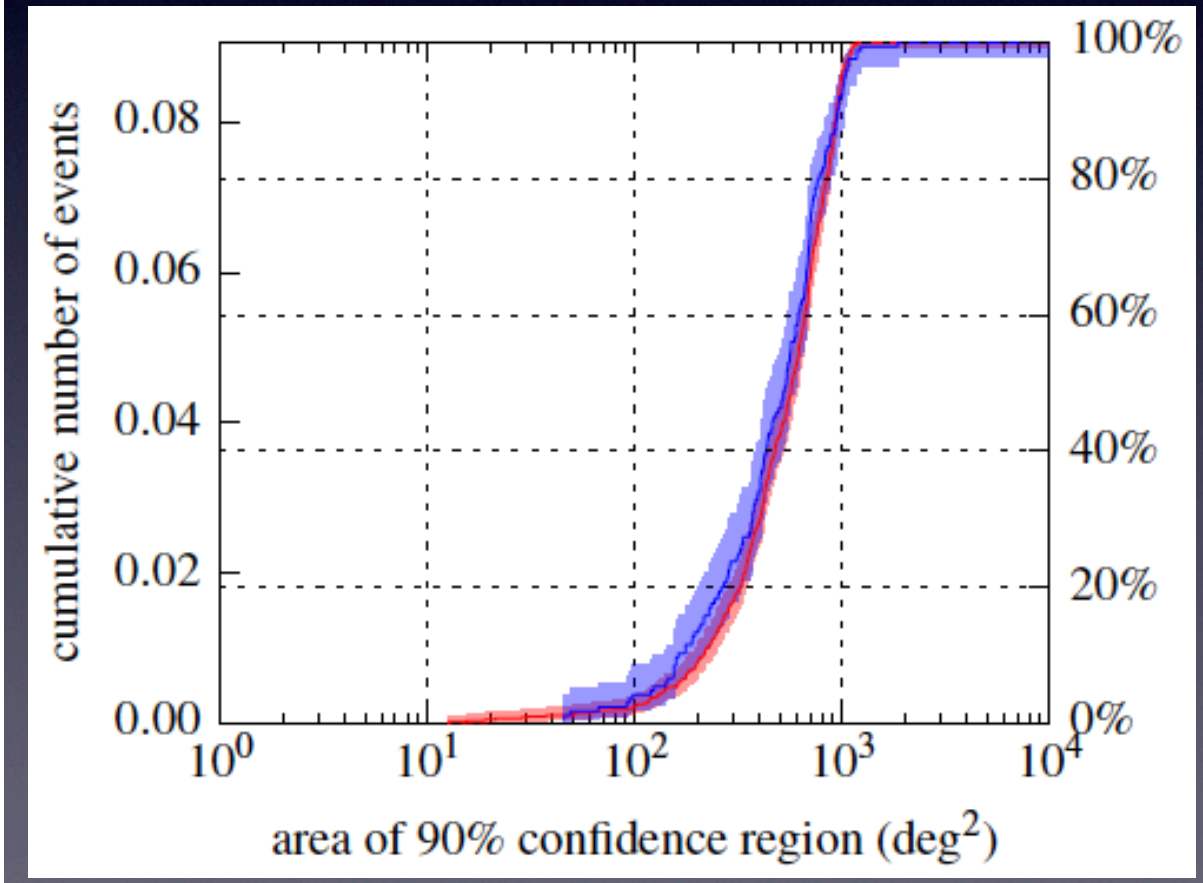
90% of error boxes
> 10 deg^2

40% of error boxes
> 100 deg^2

Localization:
NS-NS Inspiral/Merger

What about the first Ad run in 2015?

Singer et al 2014



only 2 LIGO detectors

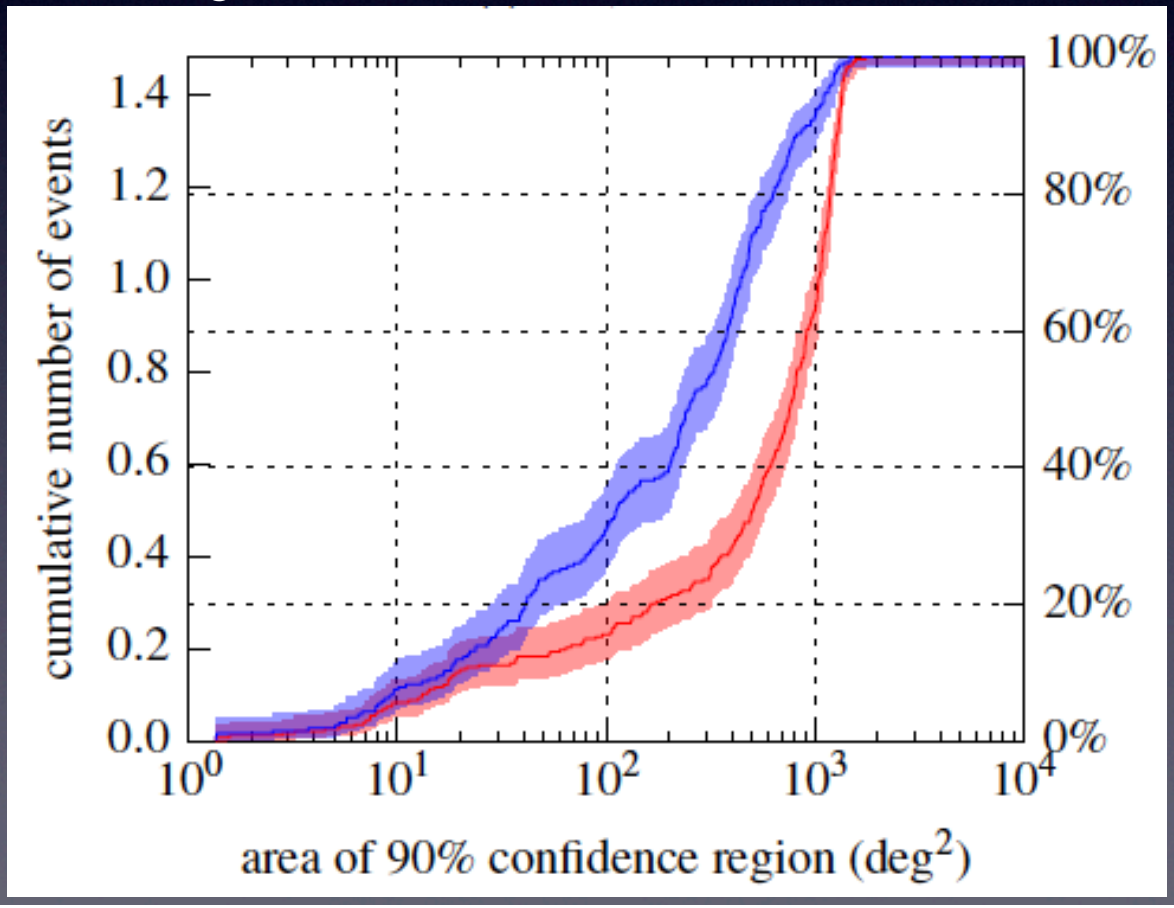
adv. triangulation comparable to MCMC

for non-spinning NS-NS

Localization:
NS-NS Inspiral/Merger

What about the Ad run in 2016?

Singer et al 2014



3 detectors:
2 LIGO & Virgo
(V less sensitive by ~3)

MCMC
decreases median area
by ~3-5

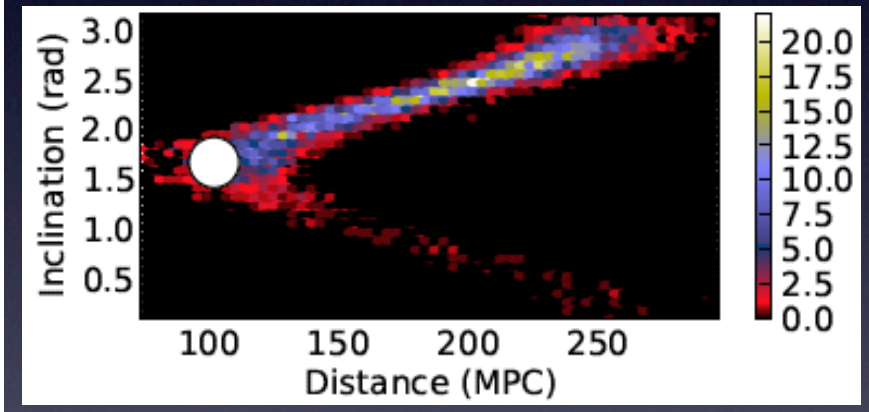
can account for
non-detection in Virgo

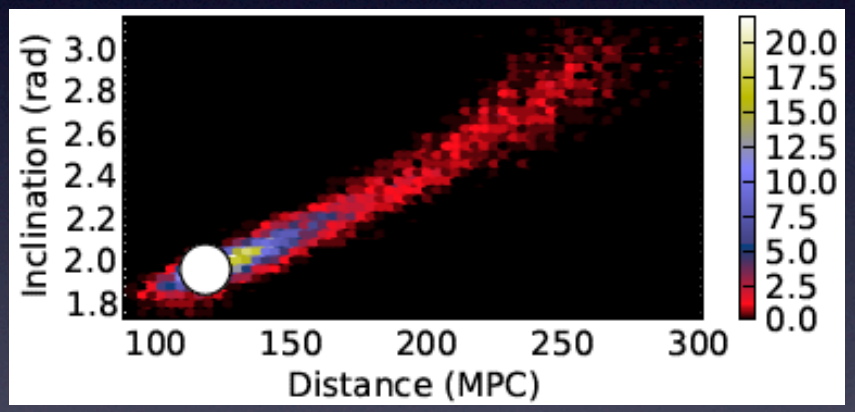
Physical Parameter Estimation: NS-NS Inspiral/Merger

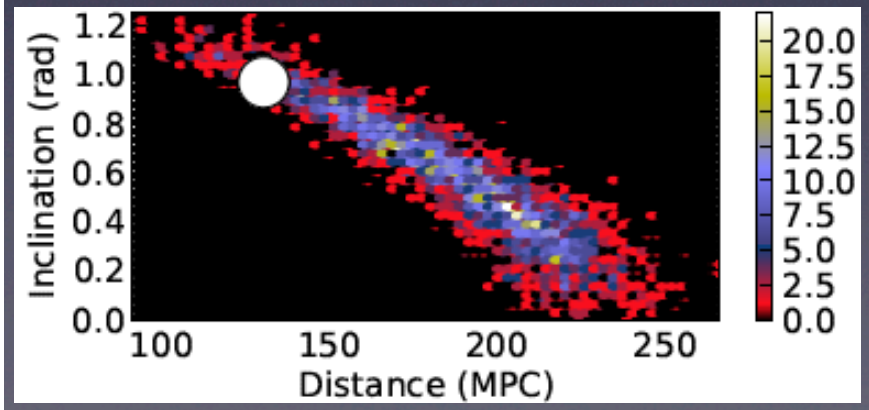
What about distance, masses, binary inclination?

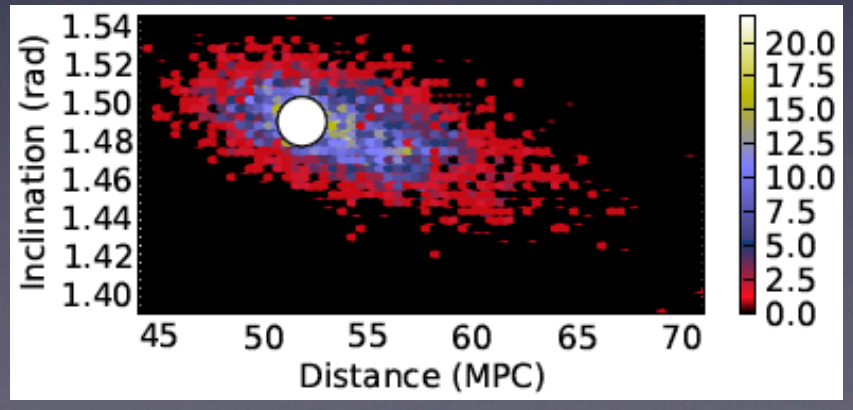
Physical Parameter Estimation: NS-NS Inspiral/Merger

What about distance, masses, binary inclination?









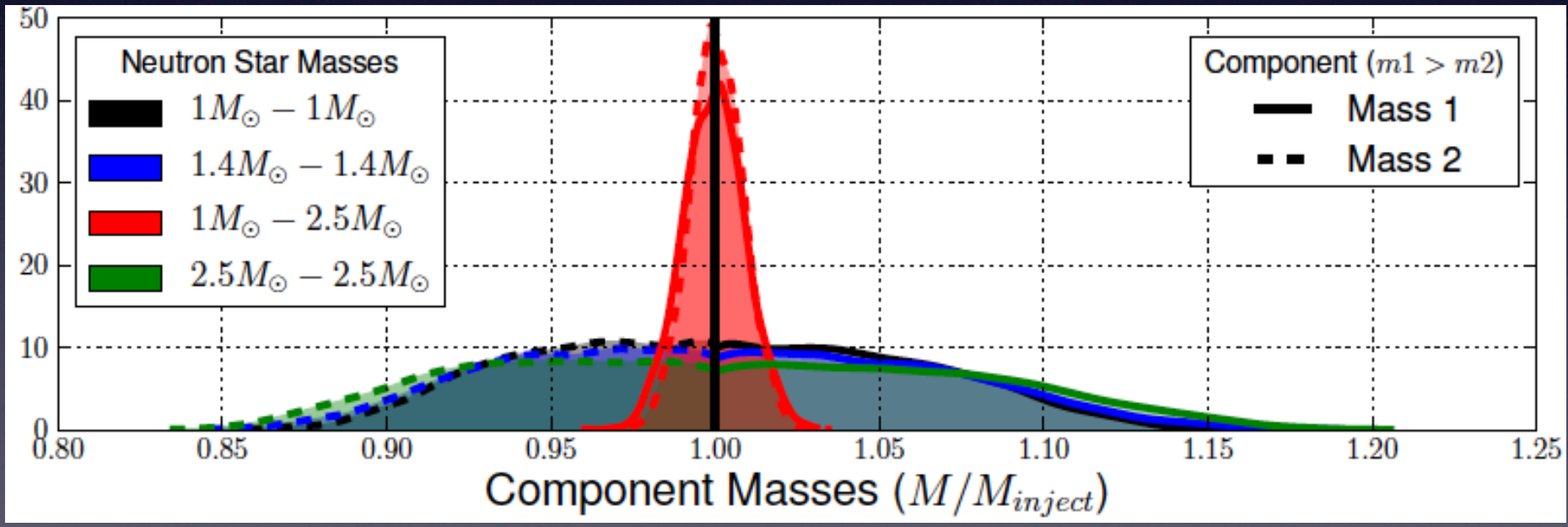
only with MCMC

Physical Parameter Estimation: NS-NS Inspiral/Merger

What about distance, masses, binary inclination?

only with MCMC

Rodriguez et al 2014

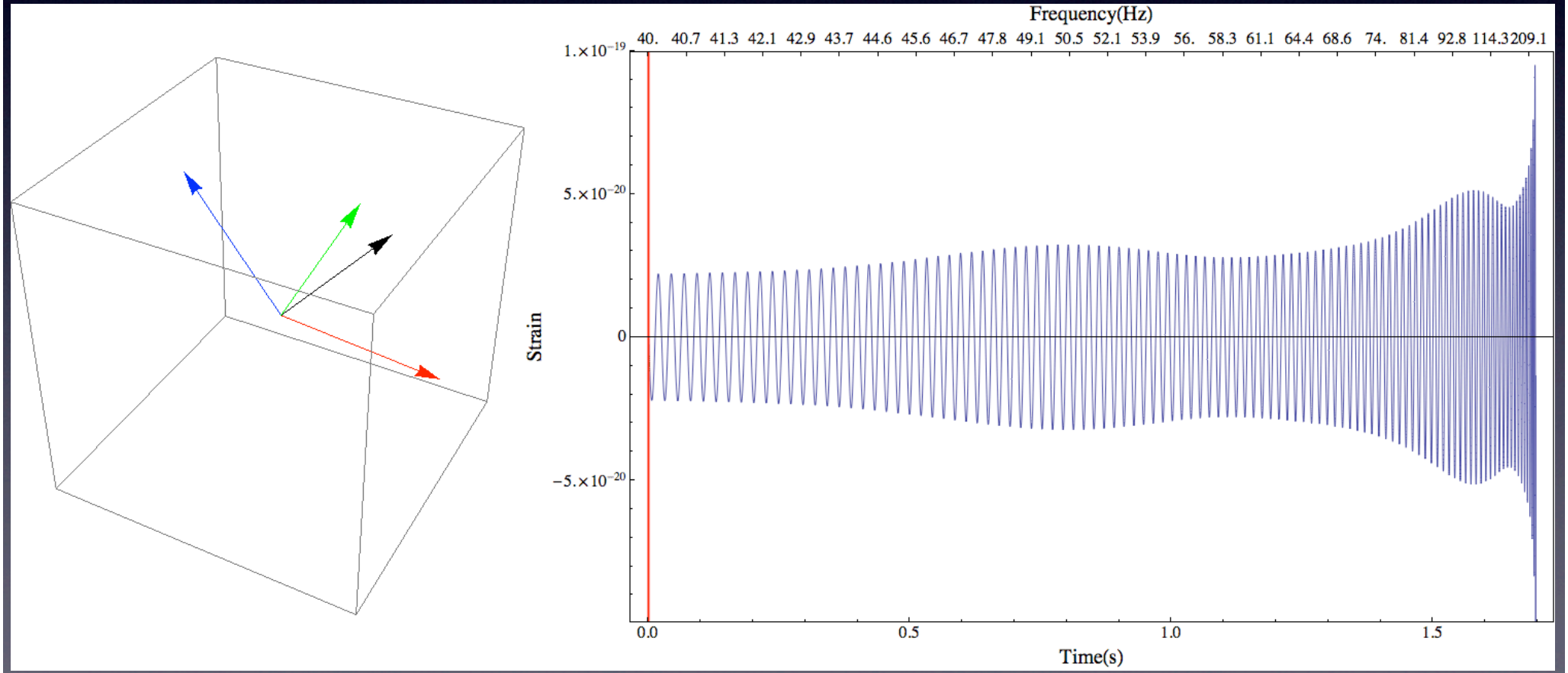


~ 10% for equal masses

~ 3% for UNequal masses

Physical Parameter Estimation: Binary Inspiral/Merger

What about spin effects ?



Physical Parameter Estimation: Spinning Binary Inspiral/Merger

- 15-dimensional space instead of 9D and strongly correlated in complex ways
  --> MCMC very challenging

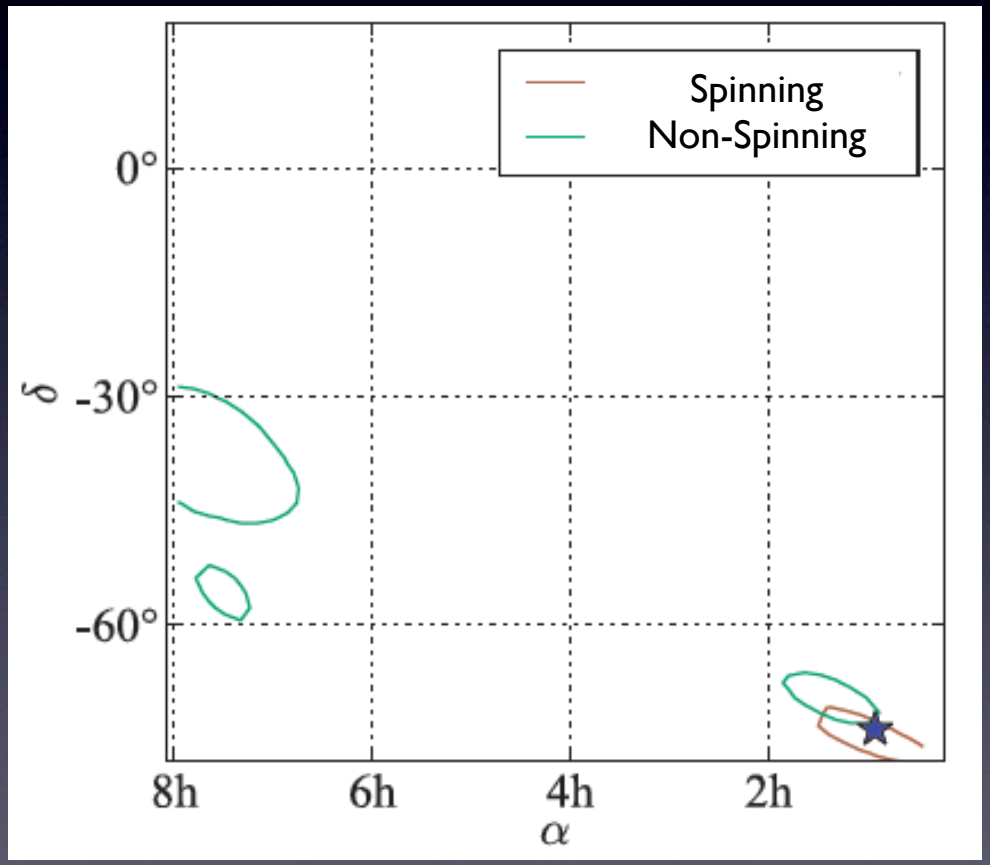
- parameter measurements are biased, if spin is ignored

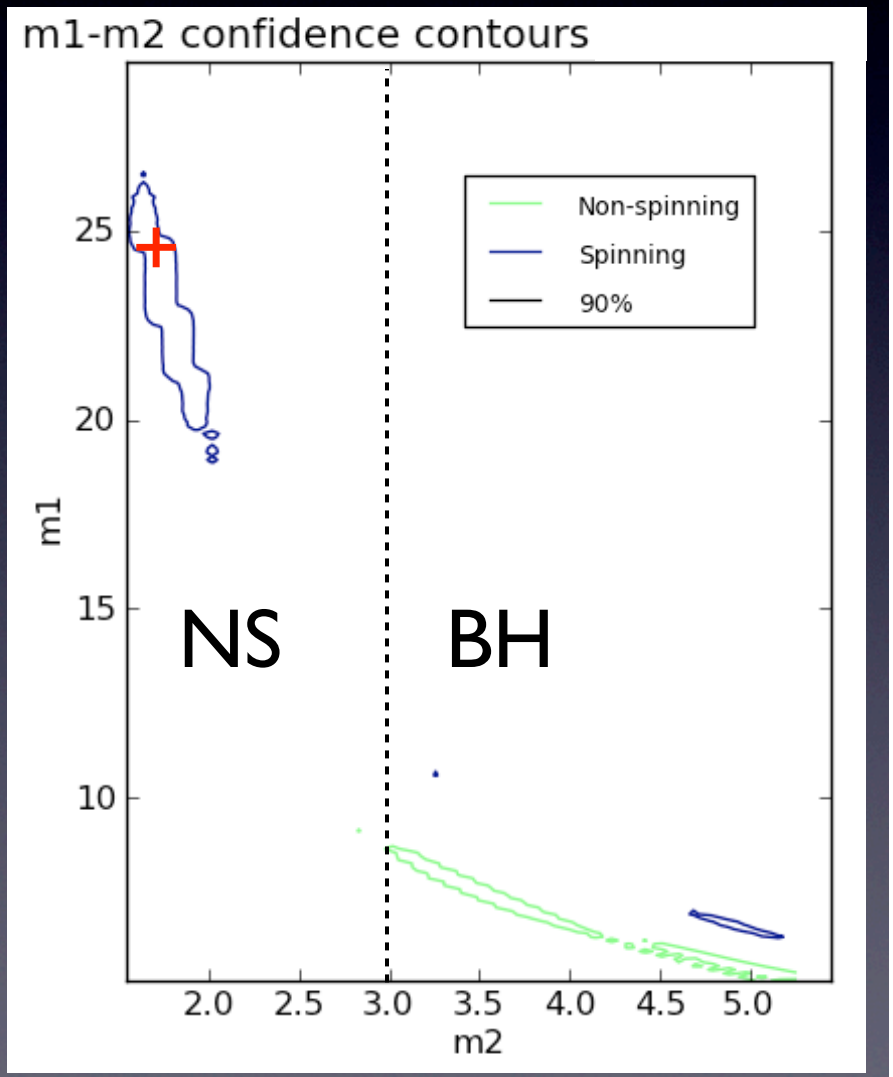
- correlations help break degeneracies, if spin is included

  --> better mass measurements
  --> better sky localization
  --> BH/NS spin measurement

Physical Parameter Estimation: Spinning Binary Inspiral/Merger

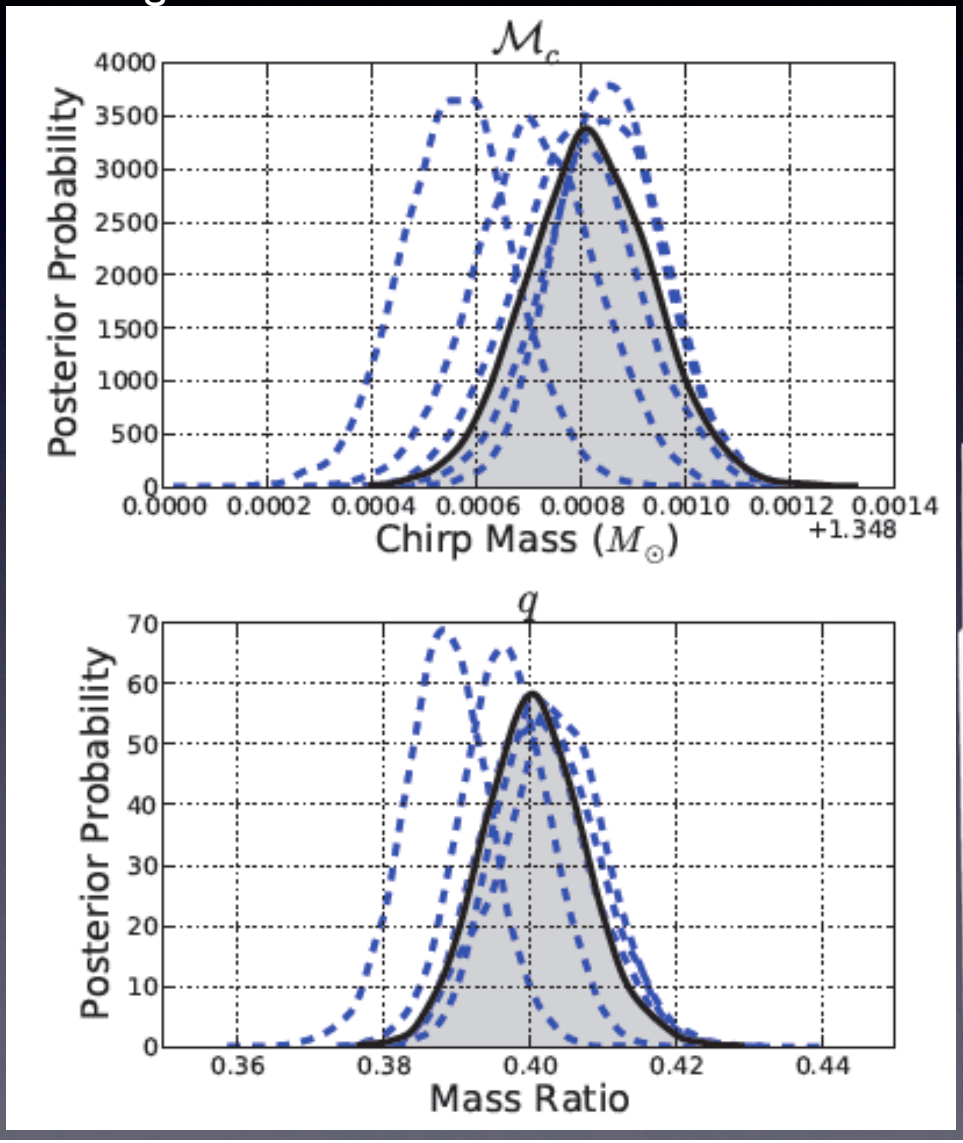
Aasi et al 2013; arXiv: 1304.1775





Physical Parameter Estimation: How Bad is the Noise?

Rodriguez et al 2014



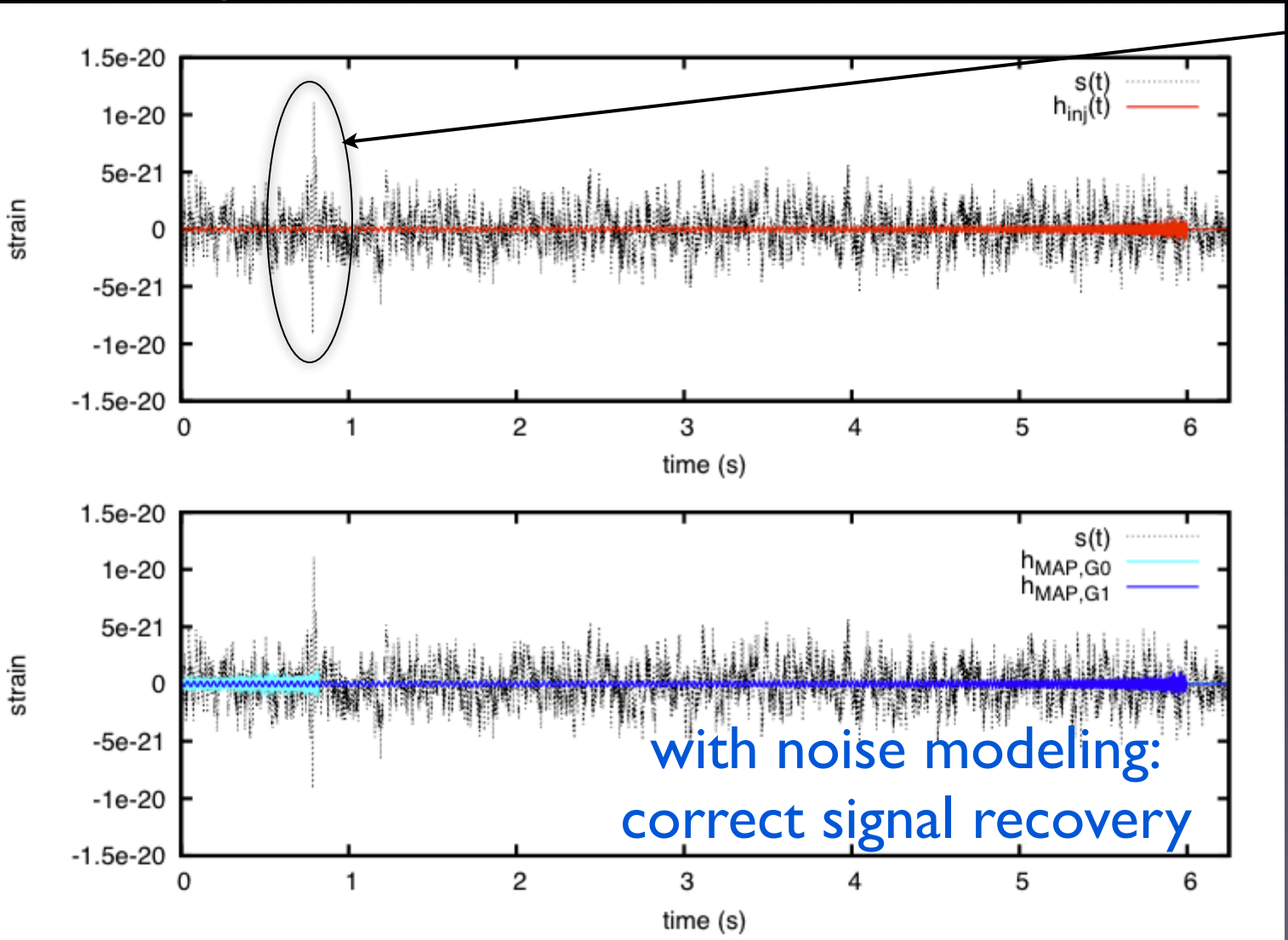
Noise systematically biases physical parameter measurements away from true values

Solution?
Noise modeling in parameter estimation:

- broadband
- lines (delta functions)
- glitches (sine-waves)
- number of noise features

Physical Parameter Estimation: How Bad is the Noise?

Littenberg et al. 2013



glitch

injected inspiral signal

with noise modeling: correct signal recovery

without noise modeling: misses true signal

Physical Parameter Estimation: Challenges in the Advanced Detector Era

- prompt, accurate, well-constrained sky localization AND distance information (new hierarchical implementation)
- smart, physically motivated MCMC implementation (machine learning, non-Markovian explorations)
- turn spin-induced modulations to our advantage
- use mass, spin, measurements for astrophysical studies

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Neutrino Status and Prospects

Target: High-Energy Neutrinos (E >> GeV)

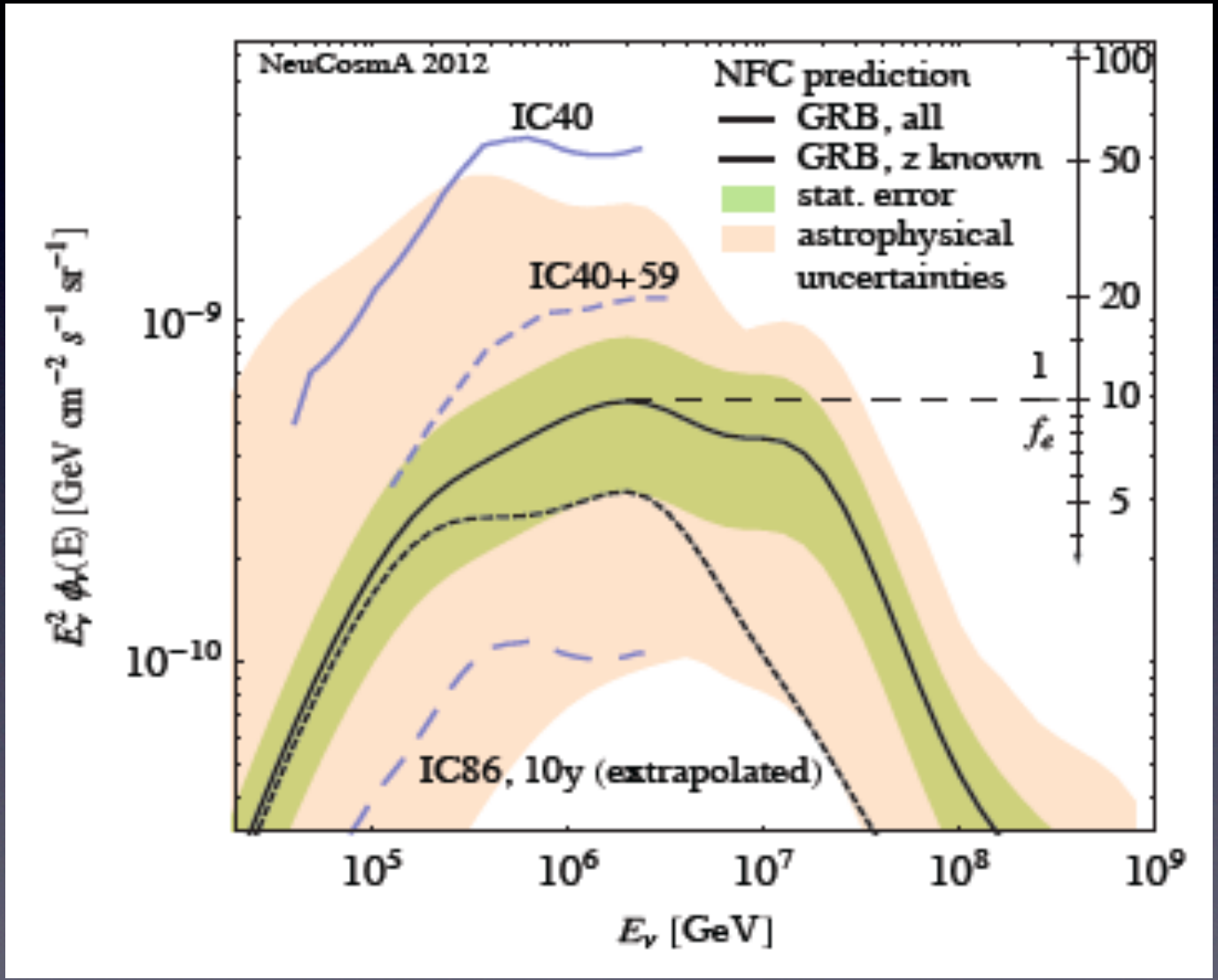
HOW ?

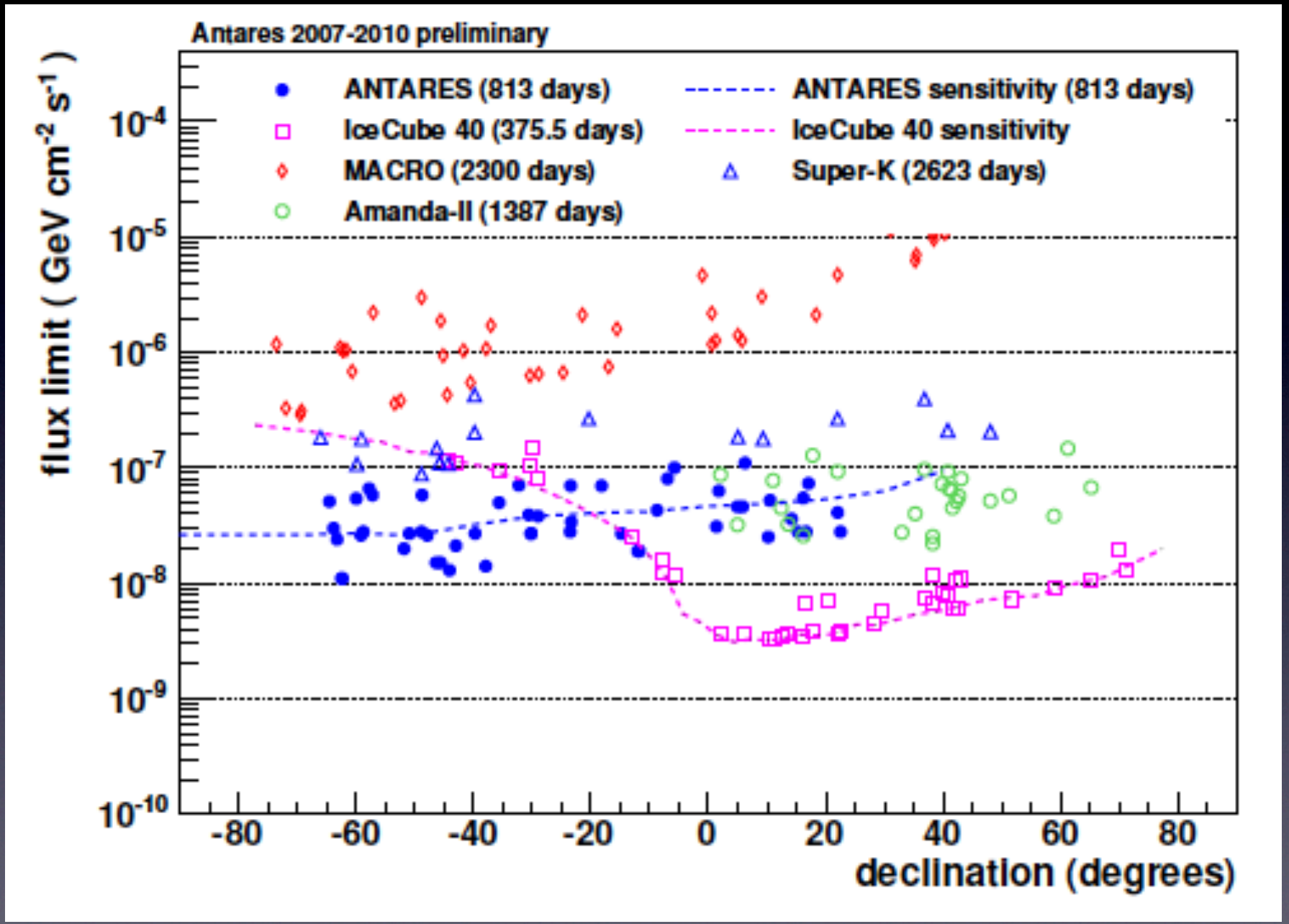
in GRBs: internal/external shock acceleration protons --> proton-proton or proton-photon --> pion or kaon --> neutrinos

also from supernovae of course

Some GRB predictions already excluded

Ando et al 2013; arXiv: 1203.5192




Antares 2007-2010 preliminary
ANTARES (813 days)
IceCube 40 (375.5 days)
MACRO (2300 days)
Amanda-II (1387 days)
ANTARES sensitivity (813 days)
IceCube 40 sensitivity
Super-K (2623 days)
flux limit (GeV cm-2 s-1)
declination (degrees)