Gravitational Waves: A New Frontier in 21st Century Astrophysics

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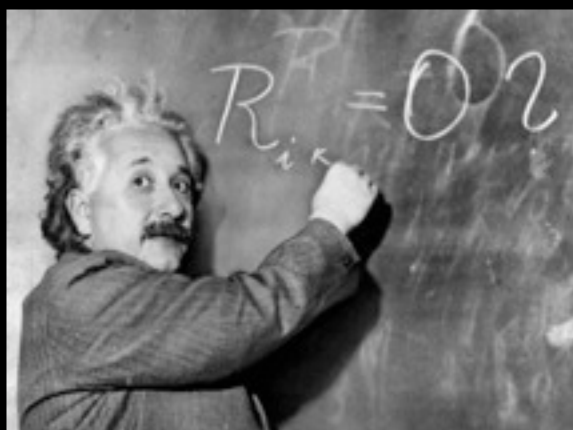
Fundamental questions that gravitational-wave observations can answer



Is general relativity the correct theory of gravity?

What is the nature of one of the four fundamental forces?

What happens when two black holes collide?

Do black holes really have no hair?

What are the progenitors of short gamma ray bursts?

What is the engine that powers them?

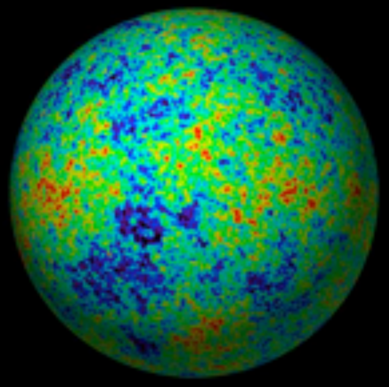
Fundamental questions that gravitational-wave observations can answer

How does core collapse power a supernova?

Is there a mass gap between neutron stars and black holes?

What is the maximum mass of a neutron star?

What is the nuclear equation of state at very high densities?

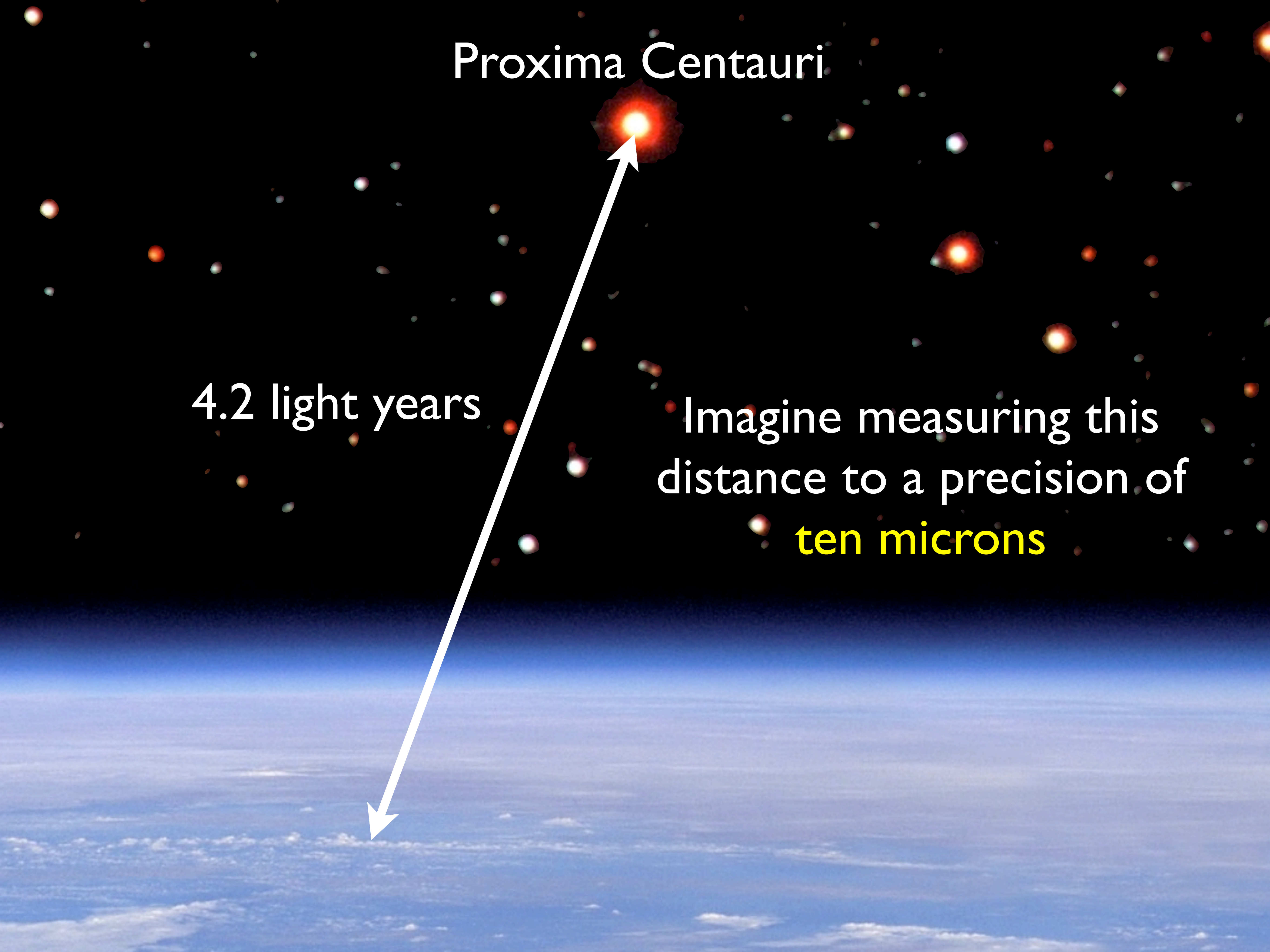


What new physics lies beyond the microwave background?

What happened in the earliest moments of creation?

- Typical strains on Earth for astrophysical sources are

$$h \sim \frac{G}{c^4}\frac{E_{\rm NS}}{r} \sim 10^{-21}$$



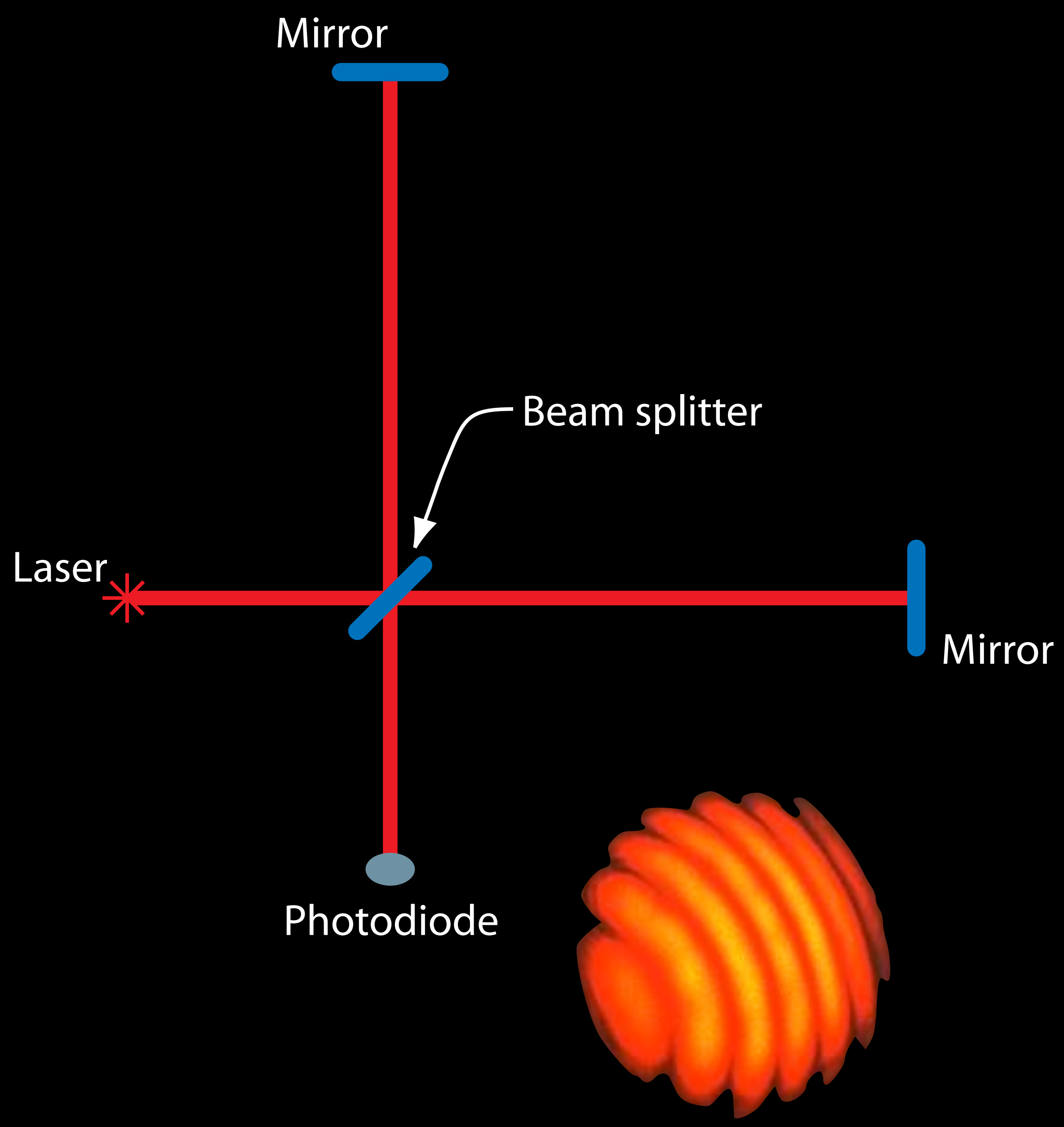
Proxima Centauri
4.2 light years
Imagine measuring this distance to a precision of ten microns

- The radiated energy is enormous

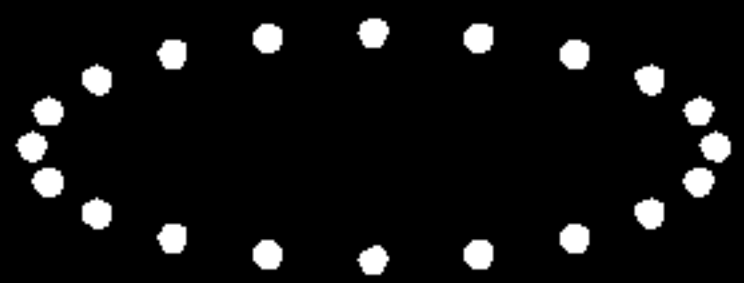
$$L_{\mathrm{GW}} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\mathrm{S}}}{r}\right)^2 \sim 10^{59}\mathrm{erg/s}$$

- Compare to
  - Solar luminosity L ~ 10^{33} erg/s
  - Gamma Ray Bursts L ~ 10^{49-52} erg/s

Laser Interferometers

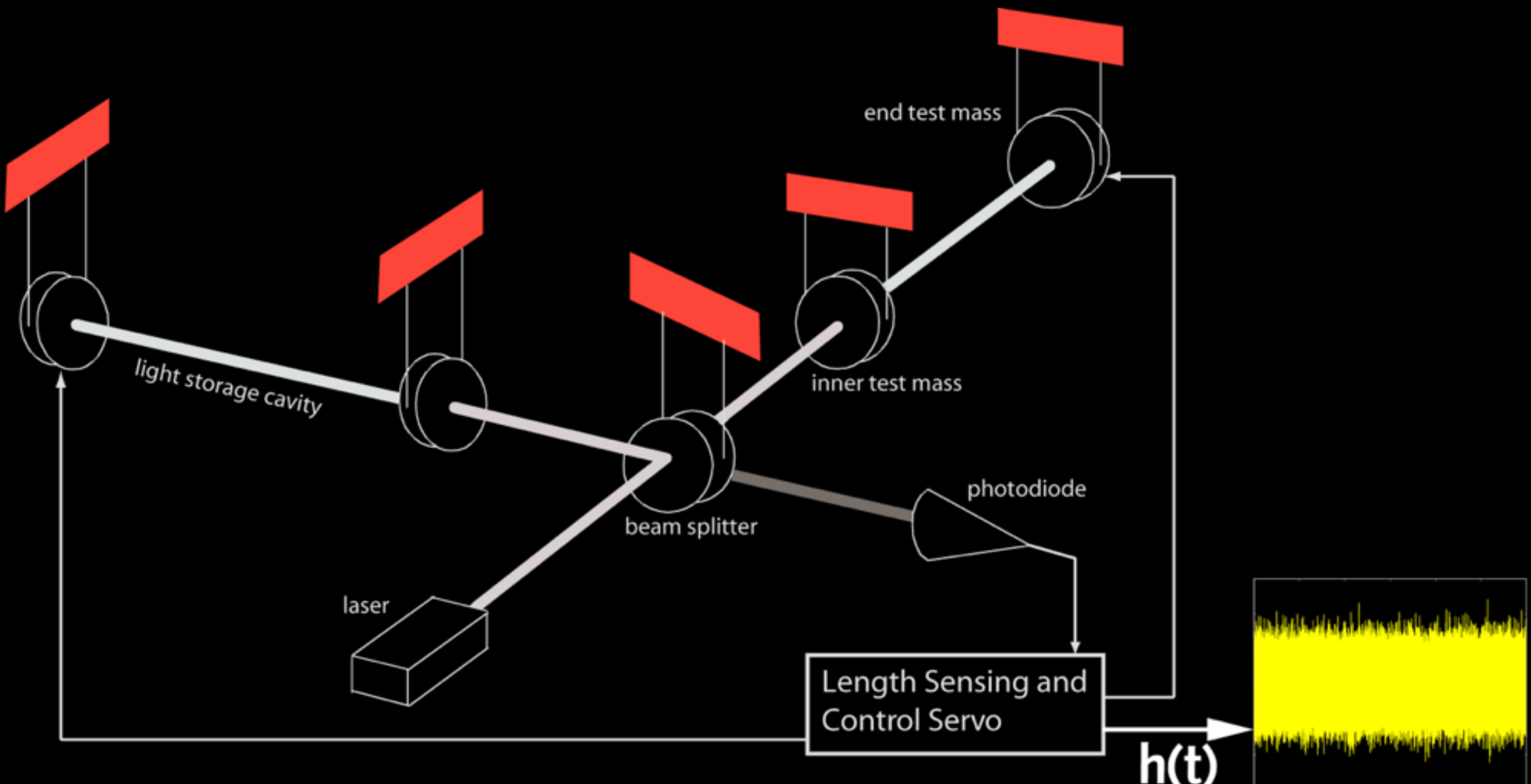


Michelson interferometer



Gravitational waves stretch and squeeze the detector’s arms

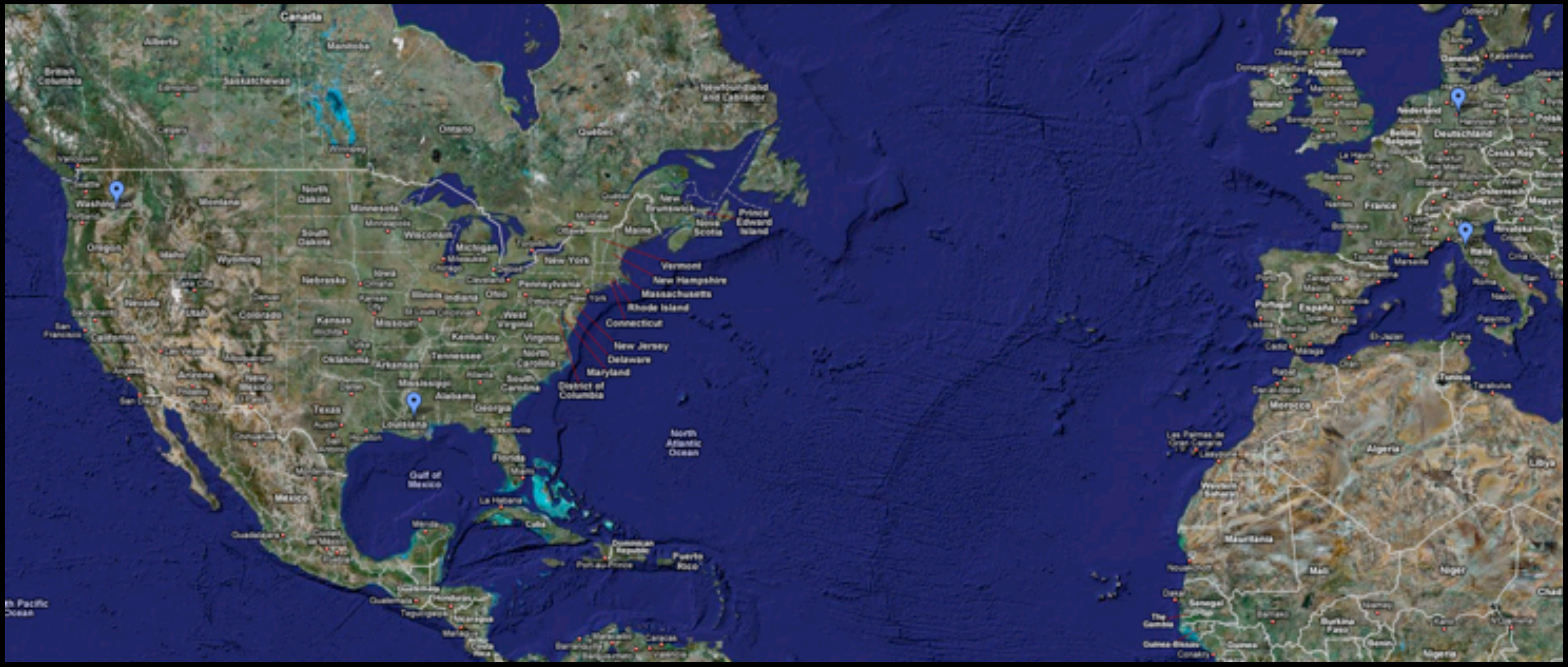
The Laser Interferometer Gravitational-wave Observatory: LIGO



LIGO Livingston Observatory

LIGO Hanford Observatory

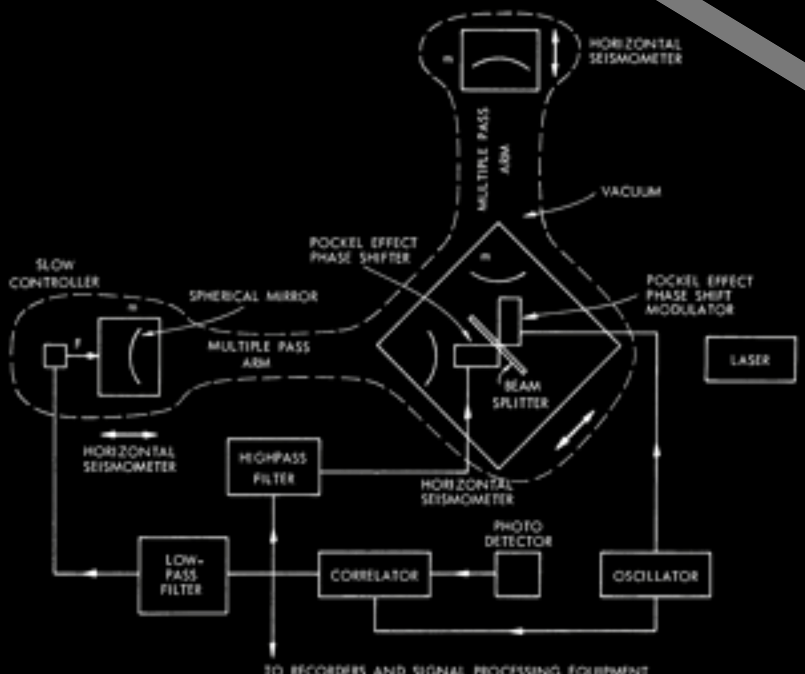
Virgo
Near Pisa, Italy



Three detectors on two continents

Decades of work in gravitational-wave detector science is about to pay off

1972



Weiss' design for a first-generation gravitational-wave interferometer: LIGO

Construction of LIGO facilities

1994

2005

Initial LIGO reaches design sensitivity

Initial LIGO Sensitivity

Neutron star binaries visible in

Milky Way (~ 50 kpc)	Andromeda (~700 kpc)	Virgo Cluster (20 Mpc)
September 2002	March 2003	September 2005+
Abbott, ..., DAB, et al. PRD **69** 122001 (2004)	Abbott, ..., DAB, et al. PRD **72** 082001(2005)	Abbott, ..., DAB, et al. PRD **79** 122001 (2009) Abbott, ..., DAB, et al. PRD **80** 047101(2009) Abadie, ..., DAB, et al. PRD **82**102001 (2010)

- All LIGO and Virgo data up to October 20, 2010 has been searched for binary neutron stars and binary black holes
- No gravitational-wave candidates found

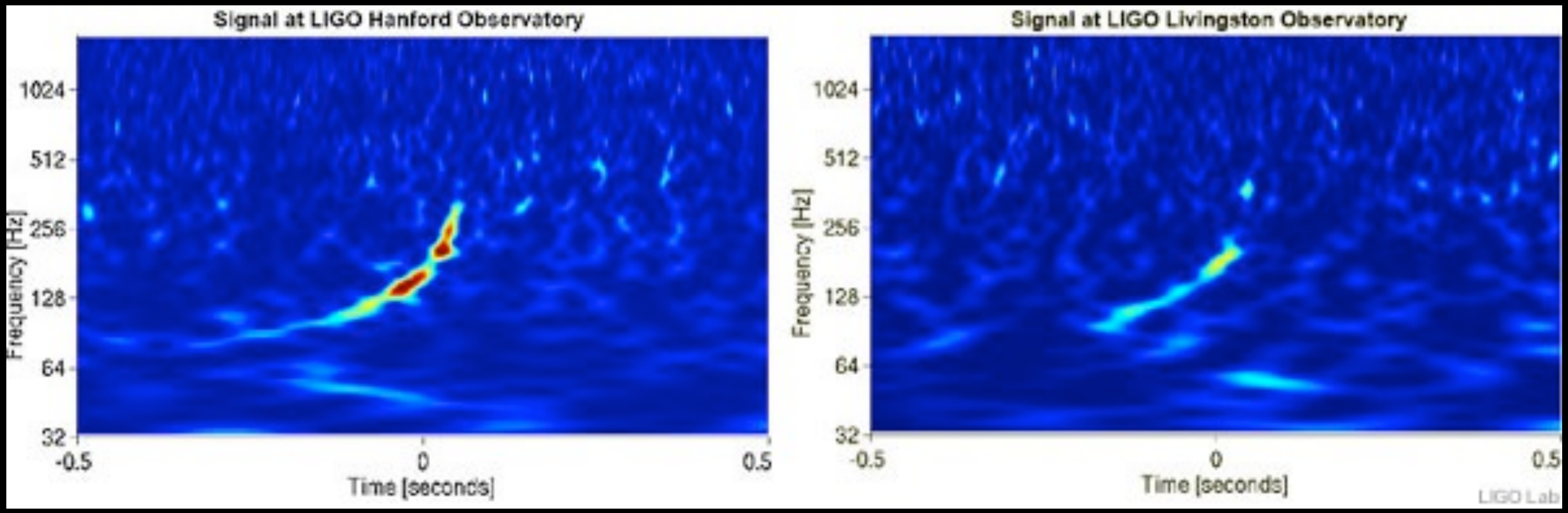
Abadie, ..., DAB, et al. PRD **85** 082002 (2012)
Aasi, ..., DAB, et al., PRD **87** 022002 (2013)

Blind Injection Challenge

- A loud candidate was found by the search
- False alarm rate was 1 in 7000 years
- A detection paper was written and approved for submission to Physical Review Letters
- Then we found out it was an injection...

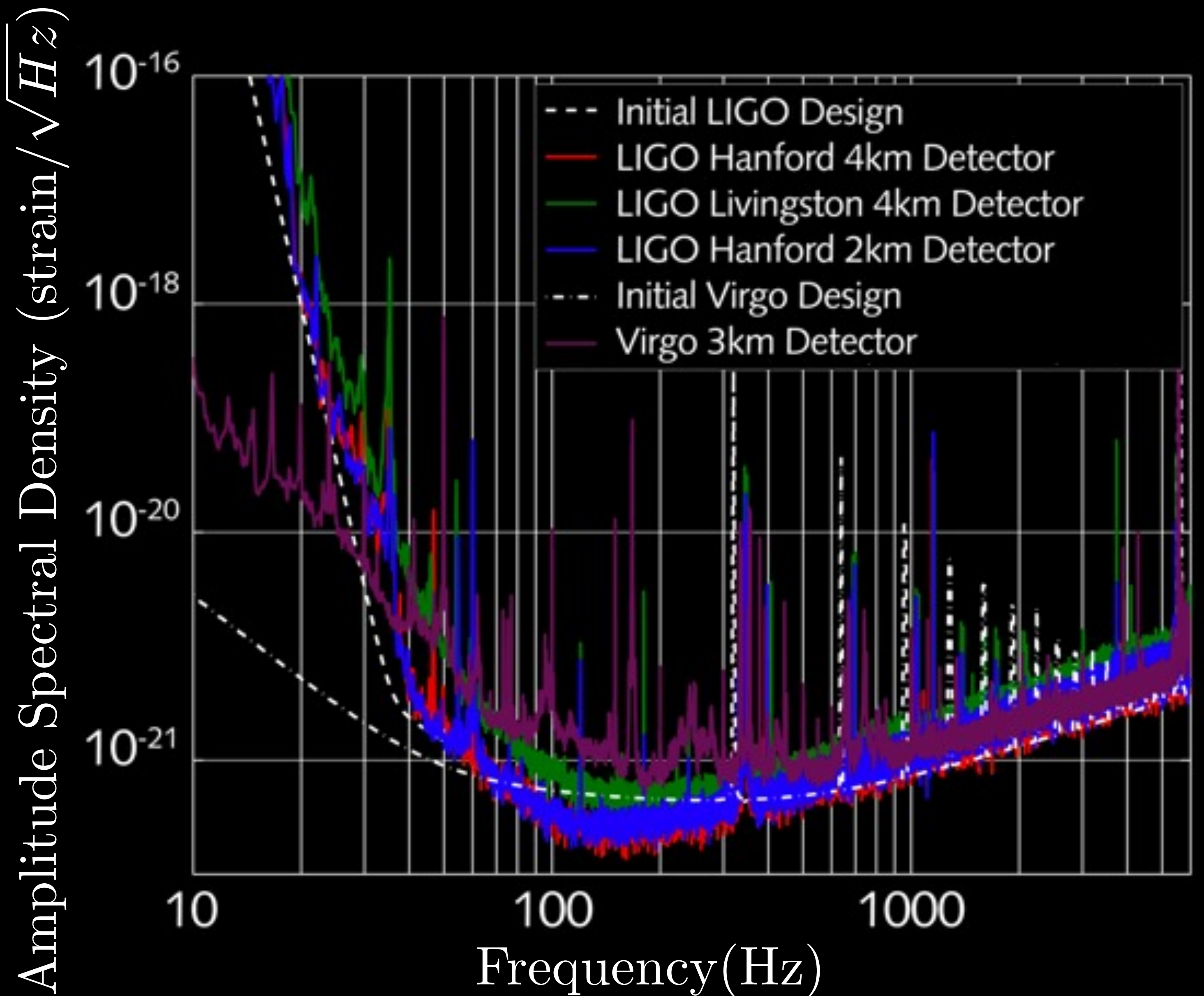
Blind Injection Challenge

- End-to-end test of detection capability in LSC-Virgo collaborations
- An inspiral signal was injected into the data without the knowledge: only three people in the collaboration knew



http://www.ligo.org/news/blind-injection.php

Opening a new field of physics



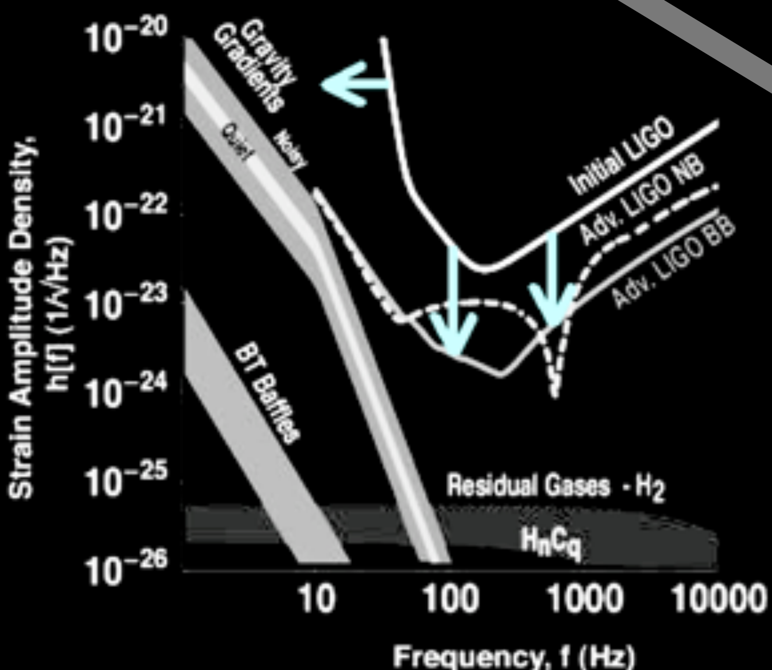
Initial LIGO demonstrated that we can measure displacements of 10^{-19} m

"Scientists now have ground-based interferometric detectors that are on a path to reaching the sensitivity at which the detection of gravitational waves is virtually assured."

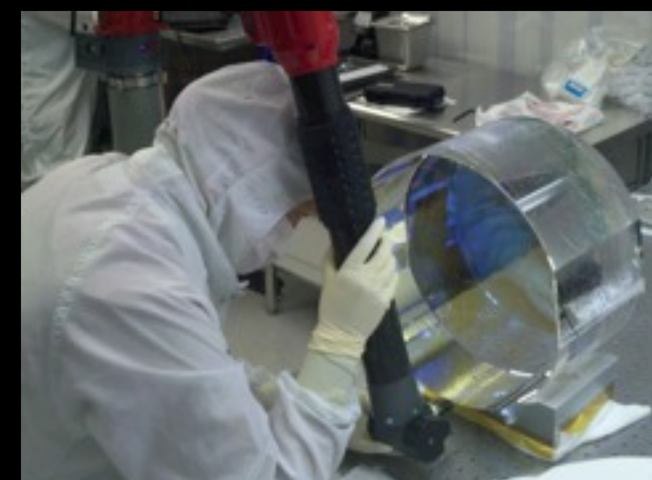
National Academy of Sciences 2010 Decadal Survey of Astronomy and Astrophysics

Advanced LIGO will detect gravitational waves from astrophysical sources

1996



Planning of second-generation detectors begins: Advanced LIGO



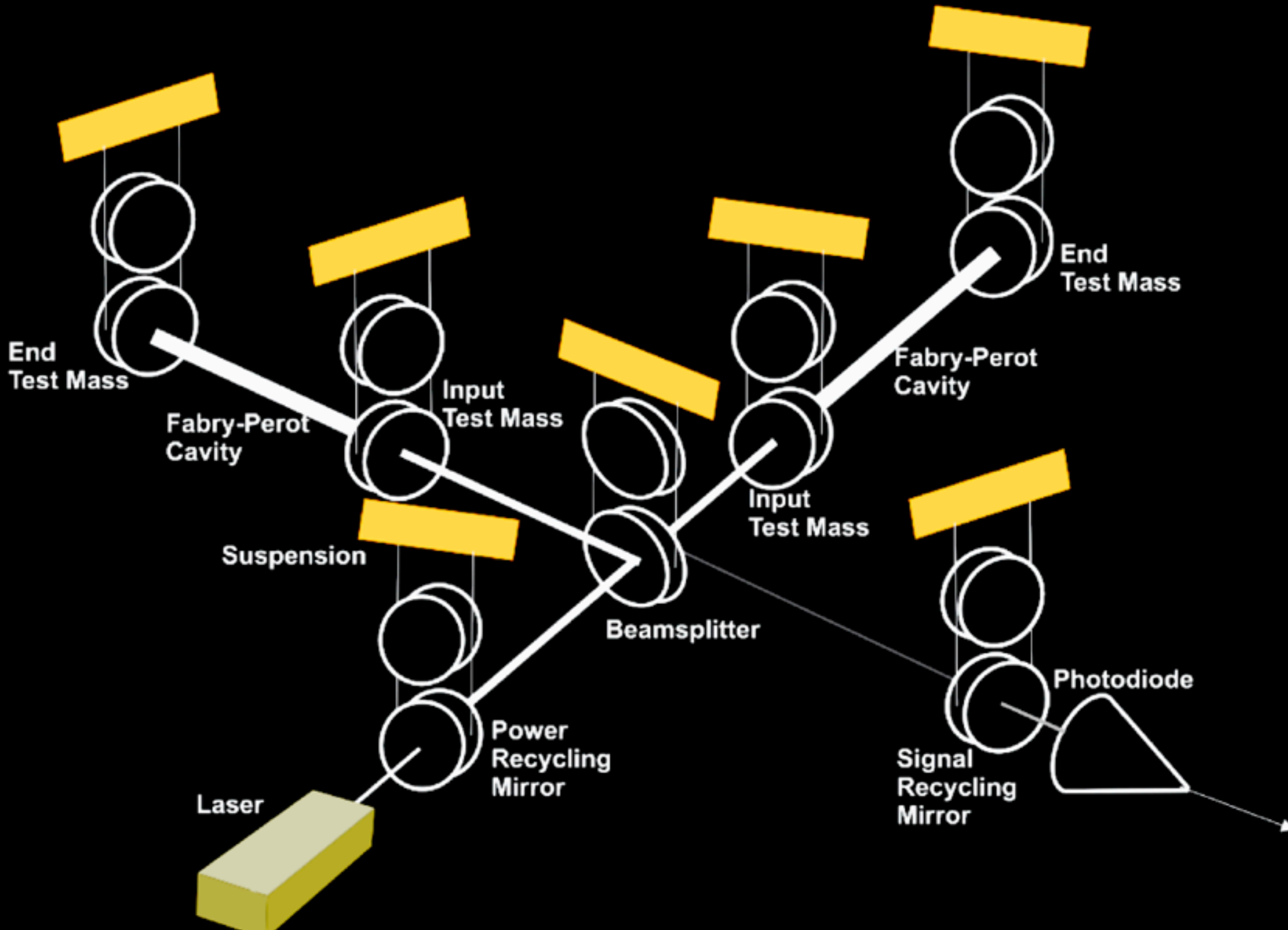
Advanced LIGO funded: construction begins

2008

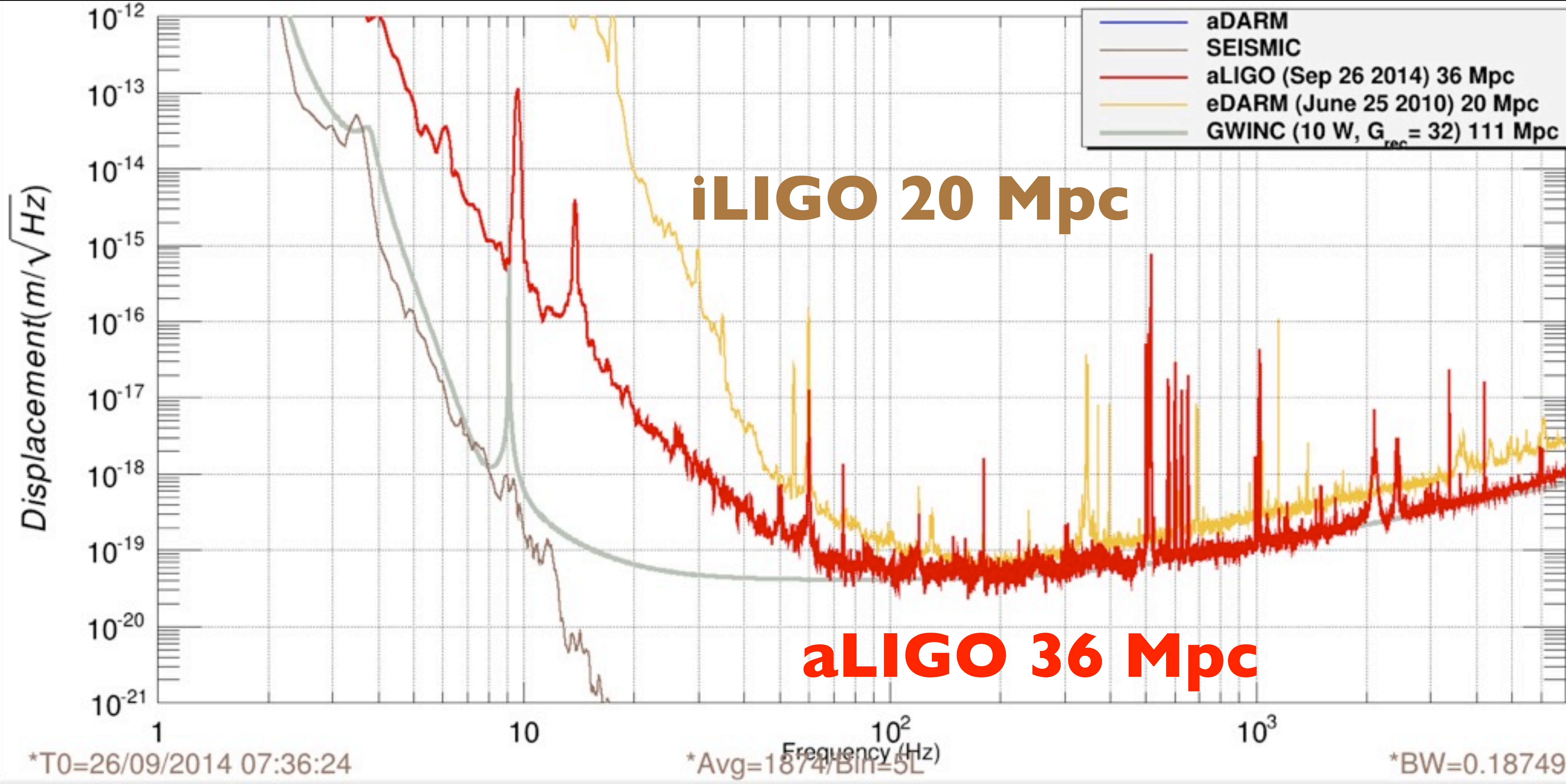
2015

Advanced LIGO begins observations of the gravitational-wave sky

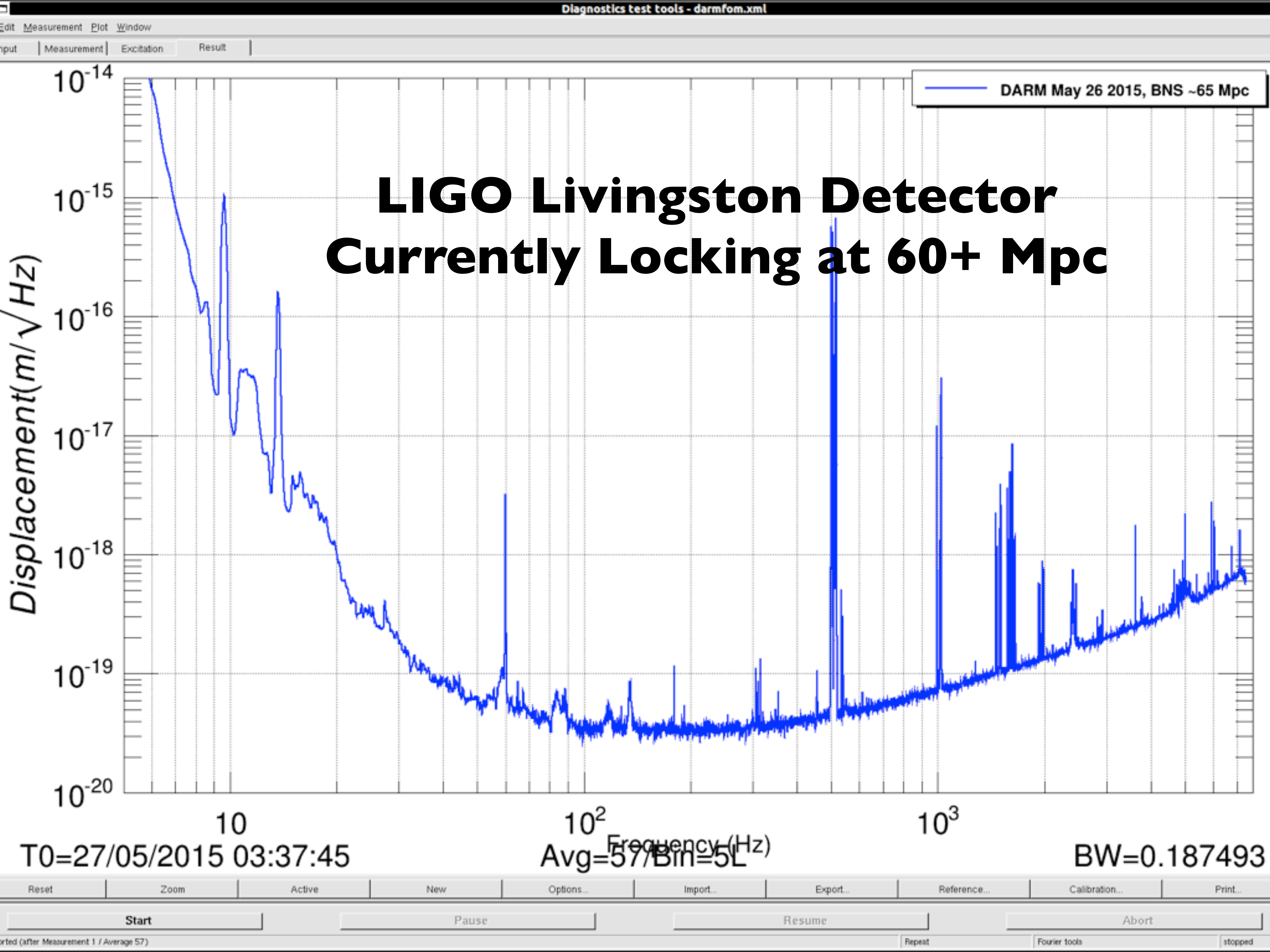
Advanced LIGO

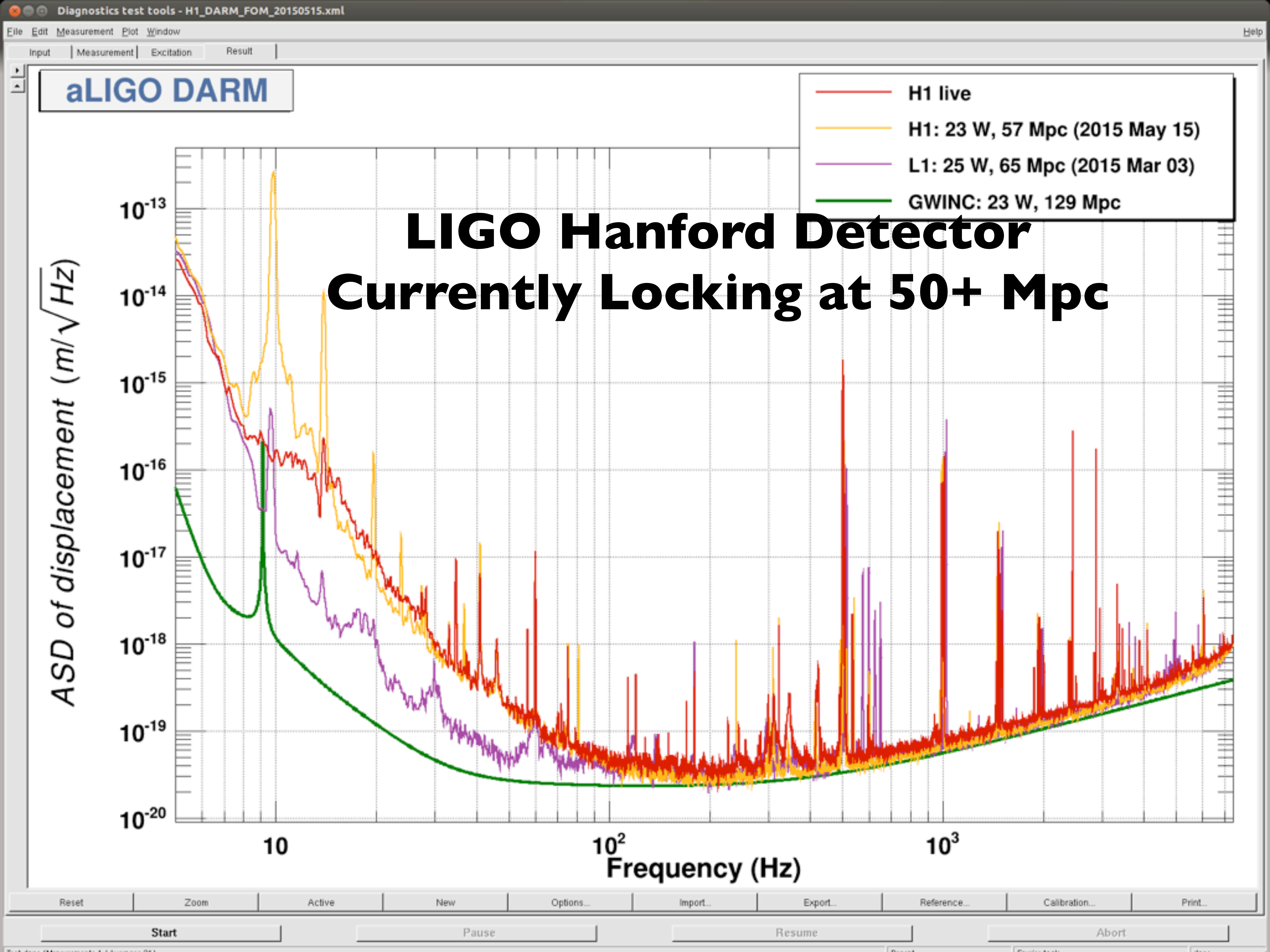


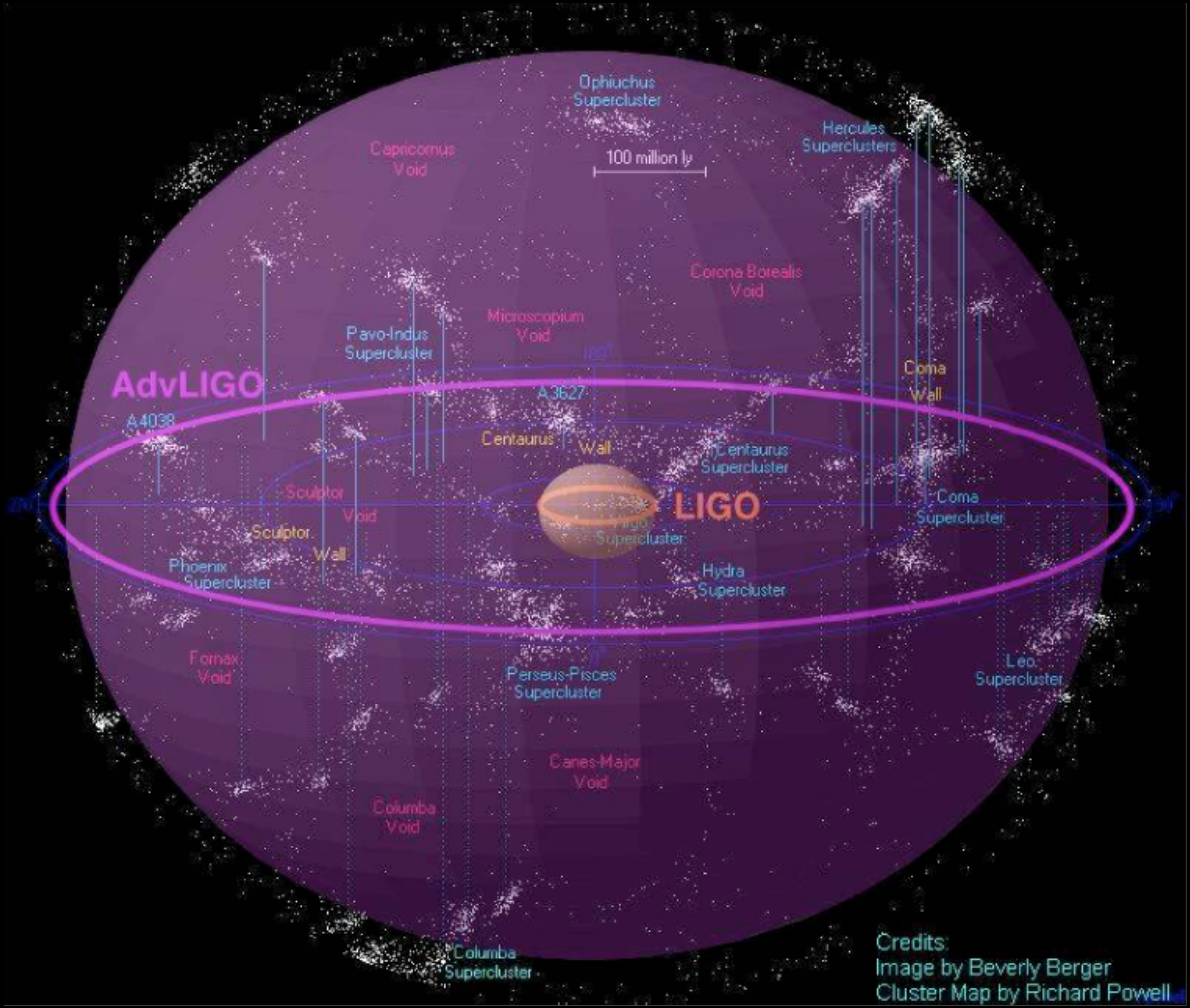
Advanced LIGO's sensitivity has already significantly exceeded that of Initial LIGO



LIGO Livingston Detector Currently Locking at 60+ Mpc

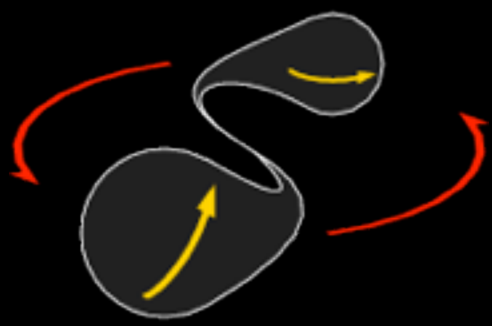



Diagnostics test tools - H1_DARM_FOM_20150515.xml
File Edit Measurement Plot Window
Help
Input
Measurement
Excitation
Result
aLIGO DARM
H1 live
H1: 23 W, 57 Mpc (2015 May 15)
L1: 25 W, 65 Mpc (2015 Mar 03)
GWINC: 23 W, 129 Mpc
LIGO Hanford Detector
Currently Locking at 50+ Mpc
ASD of displacement (m/√Hz)
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10
10^2
10^3
Frequency (Hz)
Reset
Zoom
Active
New
Options...
Import...
Export...
Reference...
Calibration...
Print...
Start
Pause
Resume
Abort

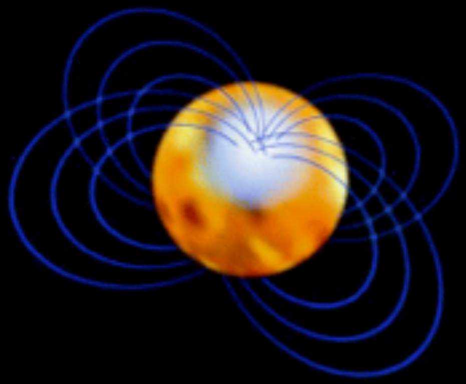


Ophiuchus Supercluster
100 million ly
Hercules Superclusters
Capricornus Void
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
AdvLIGO
A3627
Coma Wall
A4038
Centaurus Wall
Centaurus Supercluster
Sculptor Void
LIGO
Virgo Supercluster
Coma Supercluster
Sculptor Wall
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes-Major Void
Columba Void
Columba Supercluster
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Sources of Gravitational Waves

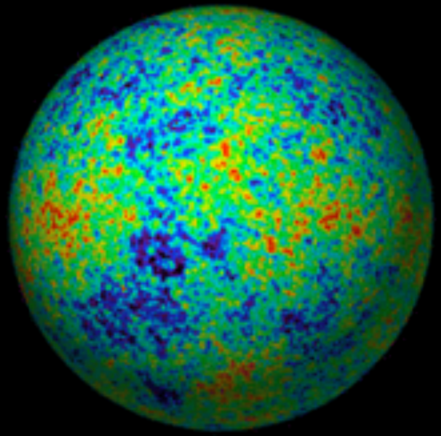


Compact binary coalescence (CBC): inspiral, merger and ringdown of black holes and neutron stars



Continuous Sources: spinning neutron stars

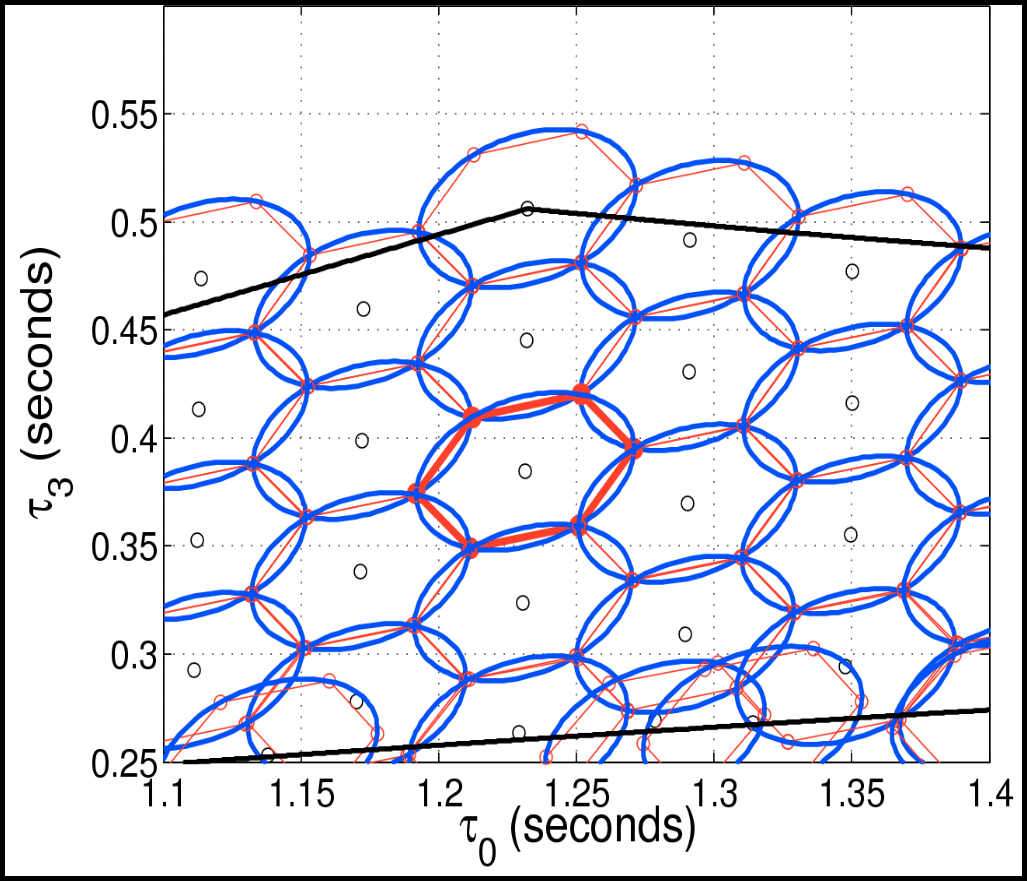
Short bursts: supernovae, unmodeled transient sources



Stochastic sources: gravitational wave background from the big bang

Binary Neutron Stars

Binary neutron star searches for aLIGO are well in hand: we know the waveforms, and how to construct filters to detect signals

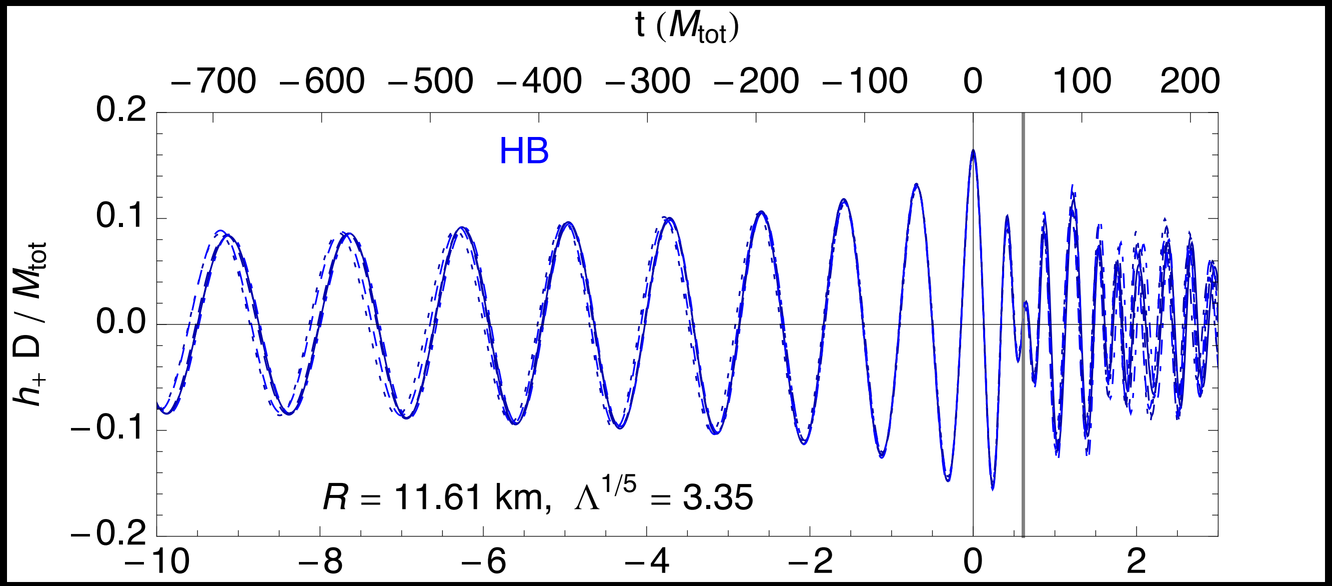


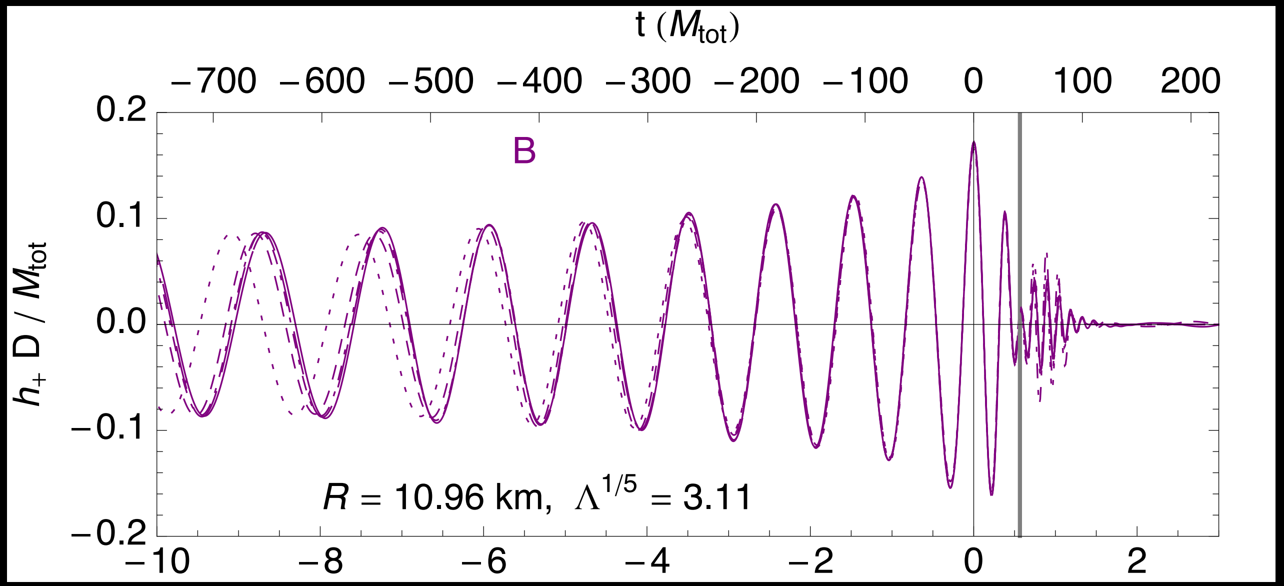
$$\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}} \qquad \langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\,df$$

Owen and Sathya PRD 60, 022002 (1999)
Babak et al. Class.Quant.Grav. 23 5477 (2006)
Allen, Anderson, Brady, DAB, Creighton Phys Rev D **85** 122006 (2012)
Babak,..., DAB, et al. Phys Rev D **87** 024033 (2013)
DAB, Harry, Lundgren, Nitz PRD **86** 084017 (2012)

Nuclear Astrophysics

- Matter effects imprint on the waveform as post-merger signatures or changes to the inspiral phase due to tidal effects
- Currently exploring how to extract these signatures from detected signals

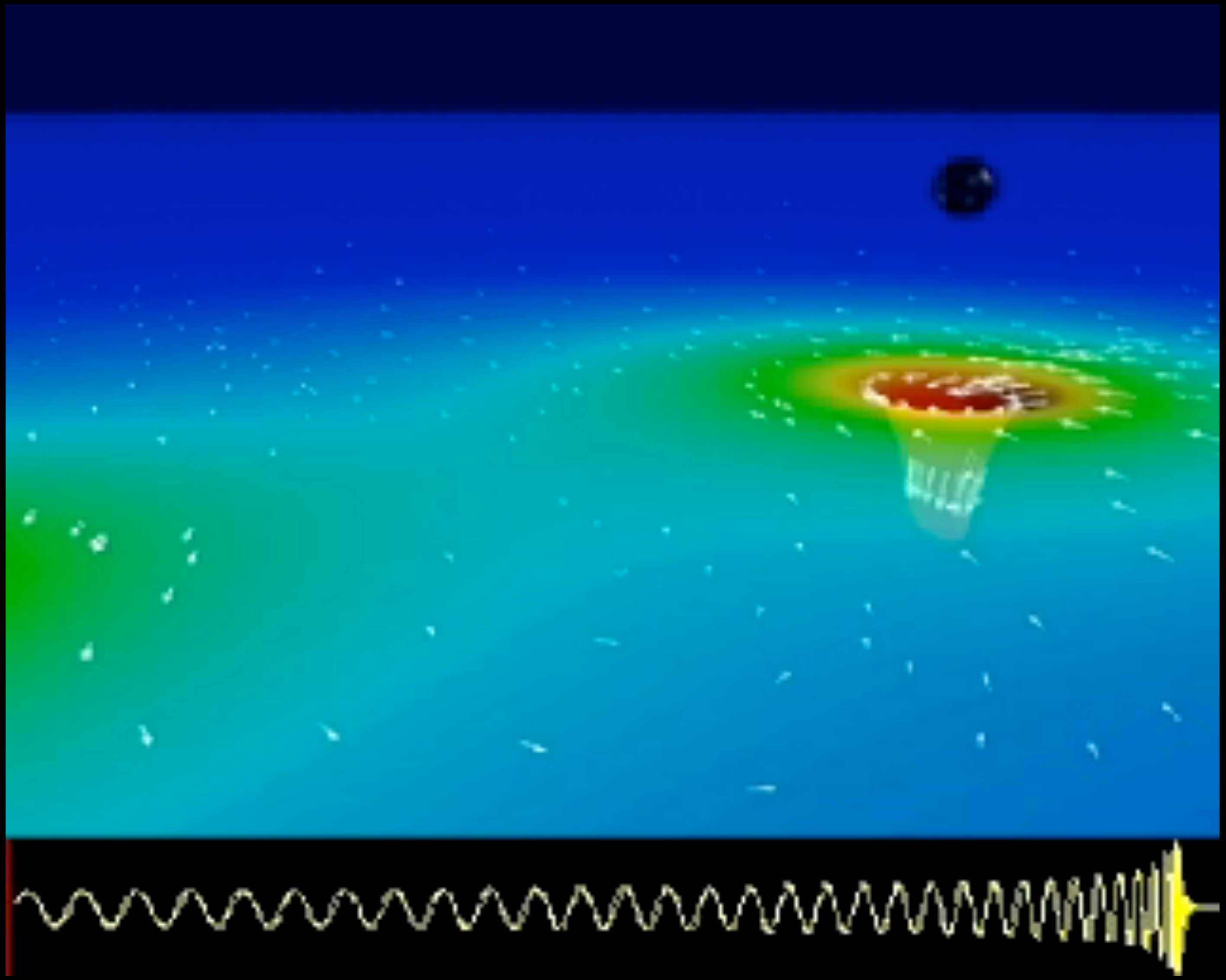




Read et al., PRD **88** 044042 (2013)

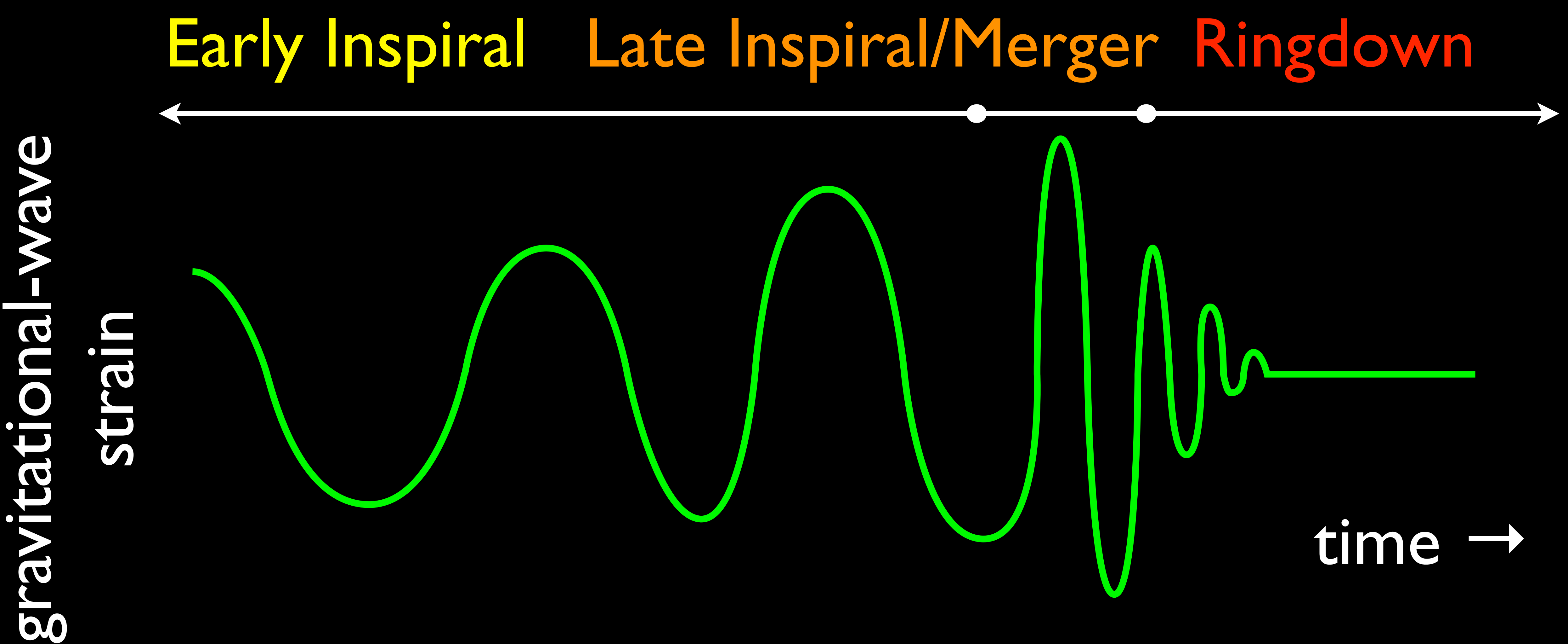
Simulating Extreme Spacetimes

At high masses, high mass ratios or if the black holes are spinning, the approximations used to model BNS break down: need full numerical solution of Einstein Equations



Boyle, DAB, Kidder, Mroue, Pfeiffer, Scheel, Teukolsky, PRD **76** 124038 (2007)
Scheel, Boyle, Chu, Kidder, Matthews, Pfeiffer PRD **79** 024003 (2009)

We can construct searches using waveforms modeled by a combination of post-Newtonian theory, EOB, numerical relativity and perturbation methods

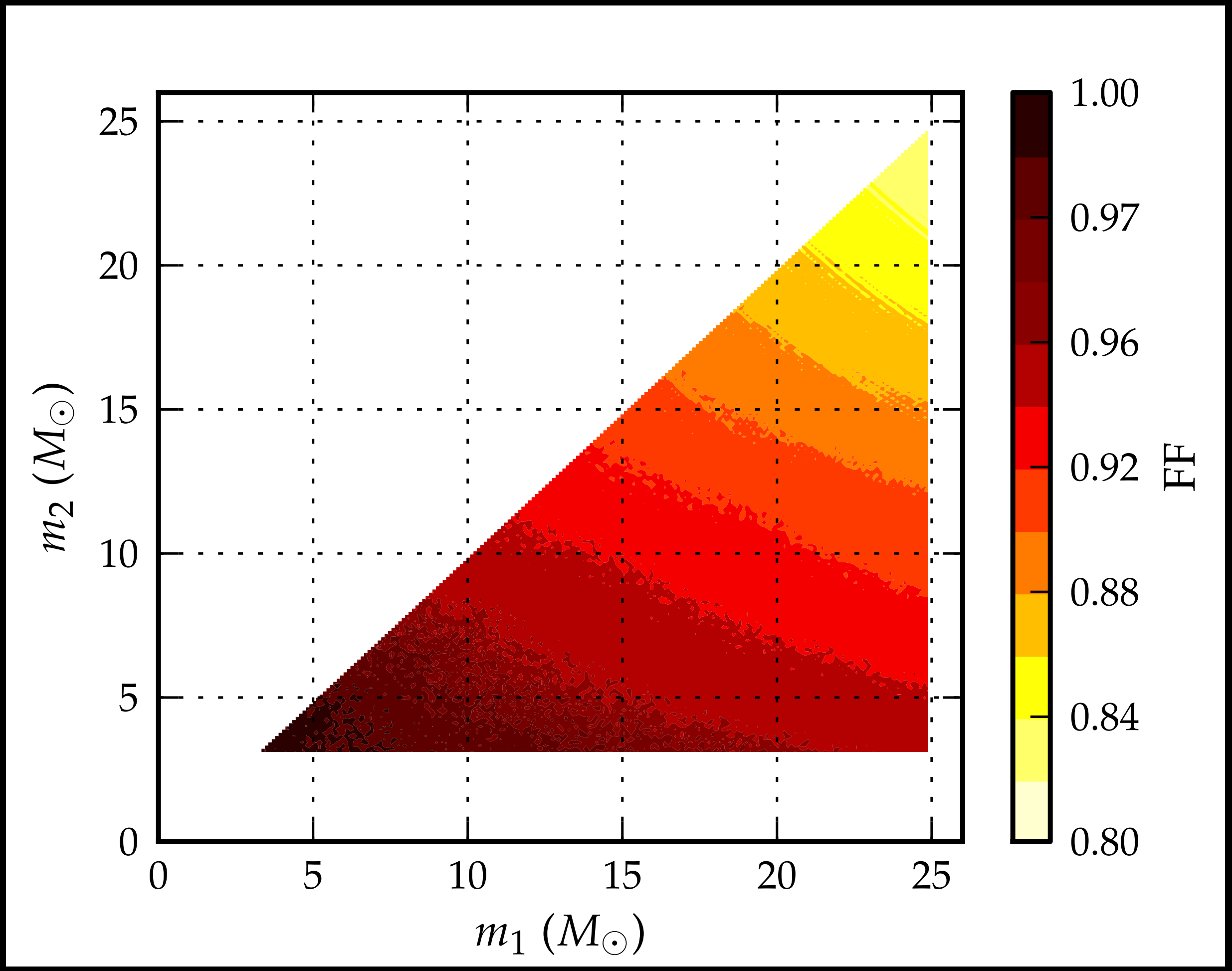


Blanchet, Living Reviews in Relativity **9** 4 (2006)
Buonanno and Damour, PRD **59** 084006 (1999)
Pan et al. PRD **84** 124052 (2011)
Taracchini et al. PRD **86** 024011 (2012)

Post-Newtonian waveforms are Taylor series with the binary's velocity as the expansion parameter

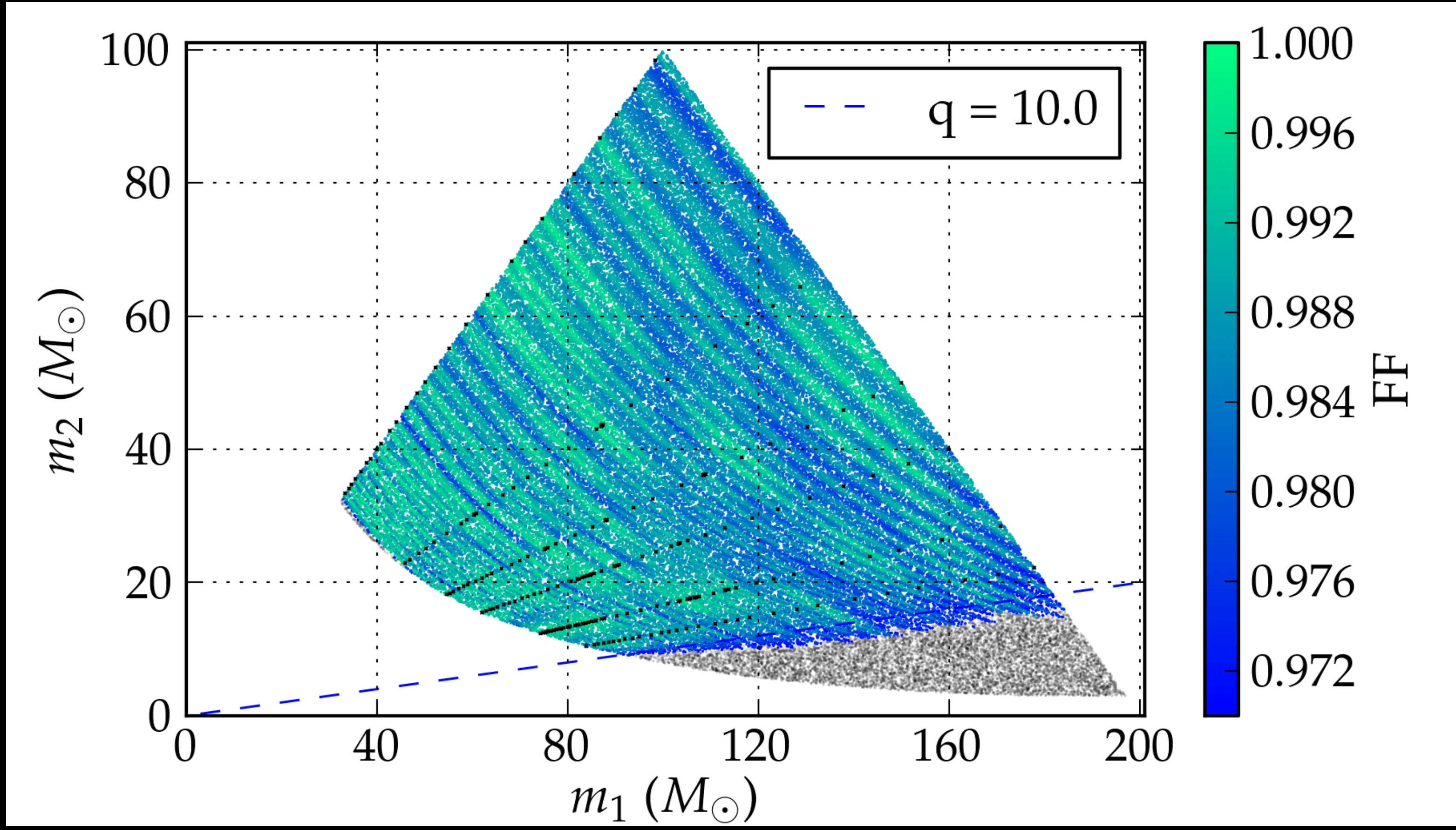
$$\Psi = 2\pi f_0 x t_c - \phi_c + \lambda_0 x^{-5/3} + \lambda_2 x^{-1} + \lambda_3 x^{-2/3} + \lambda_4 x^{-1/3} + \lambda_{5L}\log(x) + \lambda_6 x^{1/3} + \lambda_{6L}\log(x) x^{1/3} + \lambda_7 x^{2/3}$$

These waveforms are sufficient to capture the non-spin part of the waveform physics in Advanced LIGO for $m_1 + m_2 < 12\ M_{sun}$

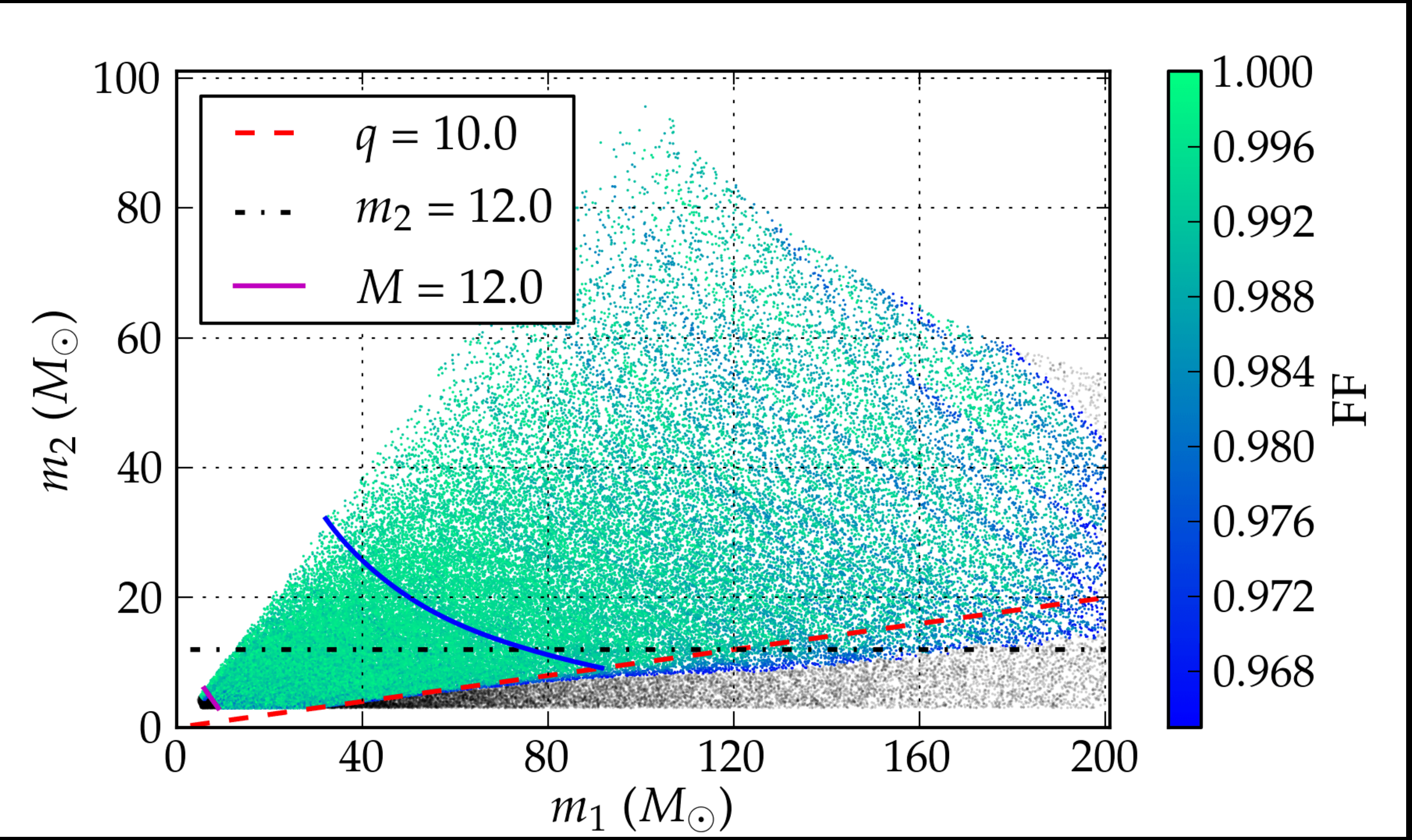


DAB, Kumar, Nitz, PRD **87** 082004 (2013)

What regions do numerical relativity simulations cover?



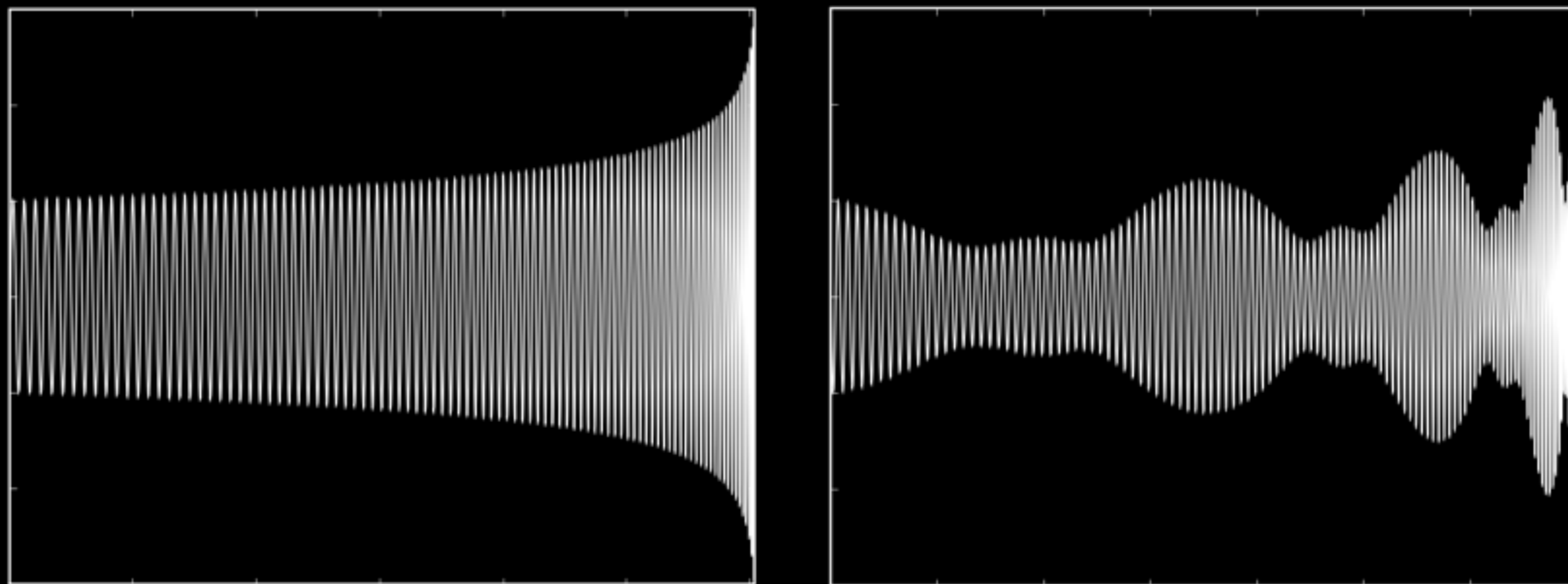
With 30 NR simulations of length ~ 50 orbits, we can cover the entire mass plane for non-spinning binary black holes



Kumar, MacDonald, DAB, Pfeiffer, Cannon et al. PRD **89** 042002 (2014)

Non-spinning | Spinning

$h(t)$



t | t

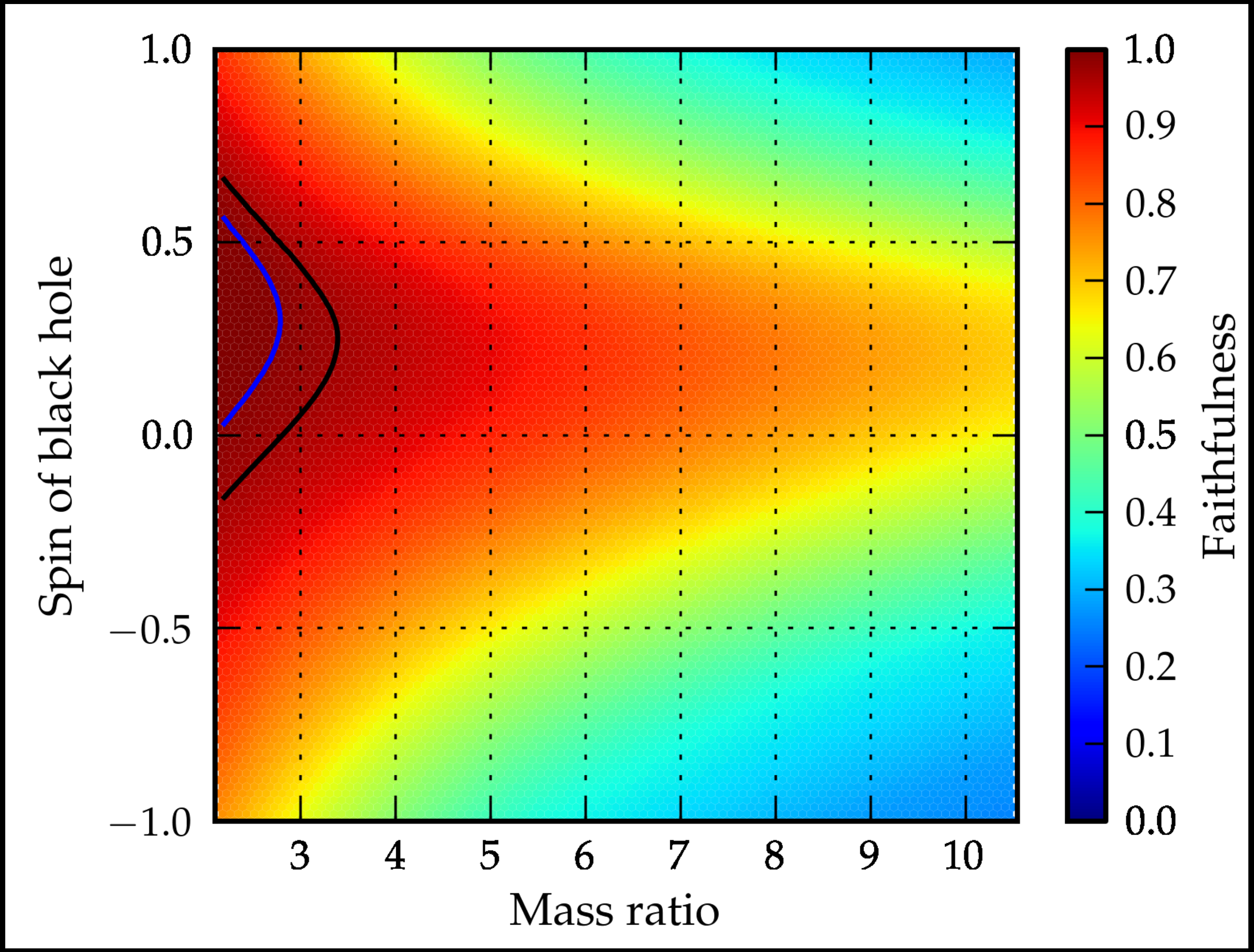
$(M = m_1 + m_2,$
$\eta = m_1 m_2 / M^2)$

$(M, \eta, \vec{s}_1, \vec{s}_2, \hat{L}_N, \alpha, \delta, \ldots)$

Apostolatos, Cutler, Susssman, Thorne PRD **49** 6274 (1994)
Apostolatos PRD **52** 605 (1995)
Kidder PRD **52** 821 (1995)
Buonanno, Chen, Vallisneri PRD **67** 104025 (2003)
Pan, Buonanno, Chen, Valisneri PRD **69** 104017 (2004)
DAB, Lundgren, O'Shaugnessy PRD **86** 064020 (2012)

Spin-orbit (and spin-spin) coupling can cause significant change in waveform phase.

Example: TaylorT4 vs SEOBNRv2

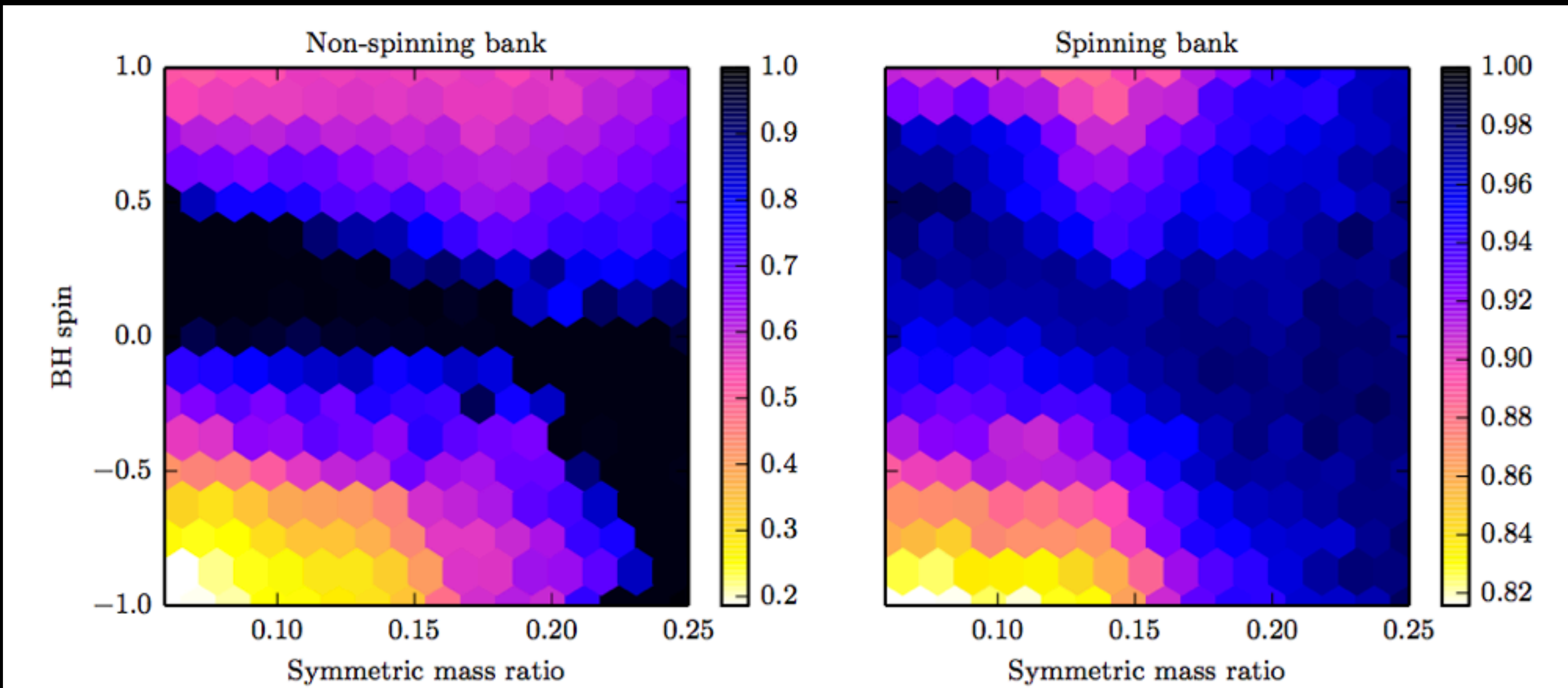


Post-Newtonian waveforms have not yet converged in this regime

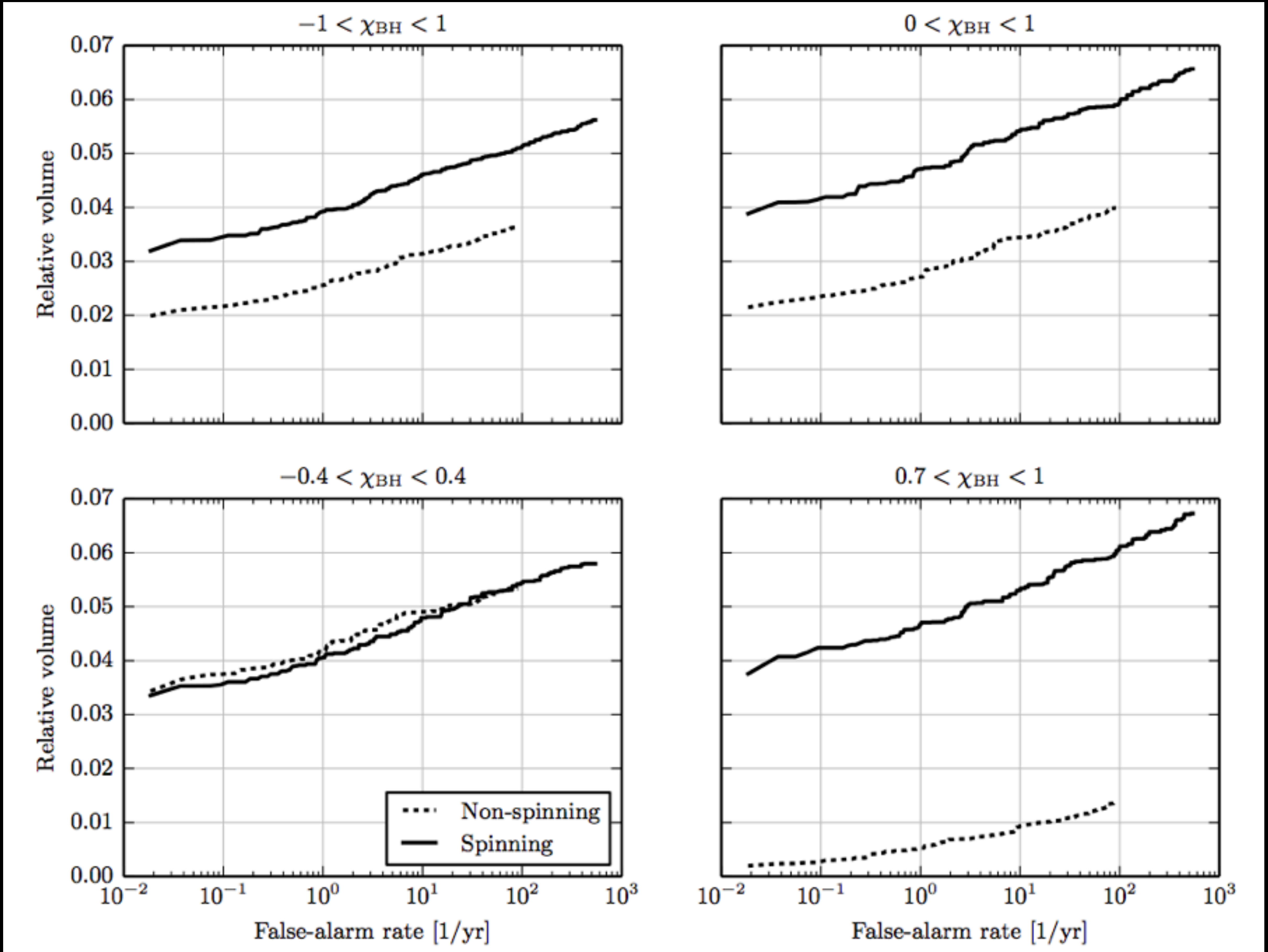
Still need information from NR even in the vacuum case

Kumar, Barkett, Bhagwat, Afshari, DAB, Lovelace, Scheel, Szilagyi, (in prep)

Searches for NSBH binaries must include spin

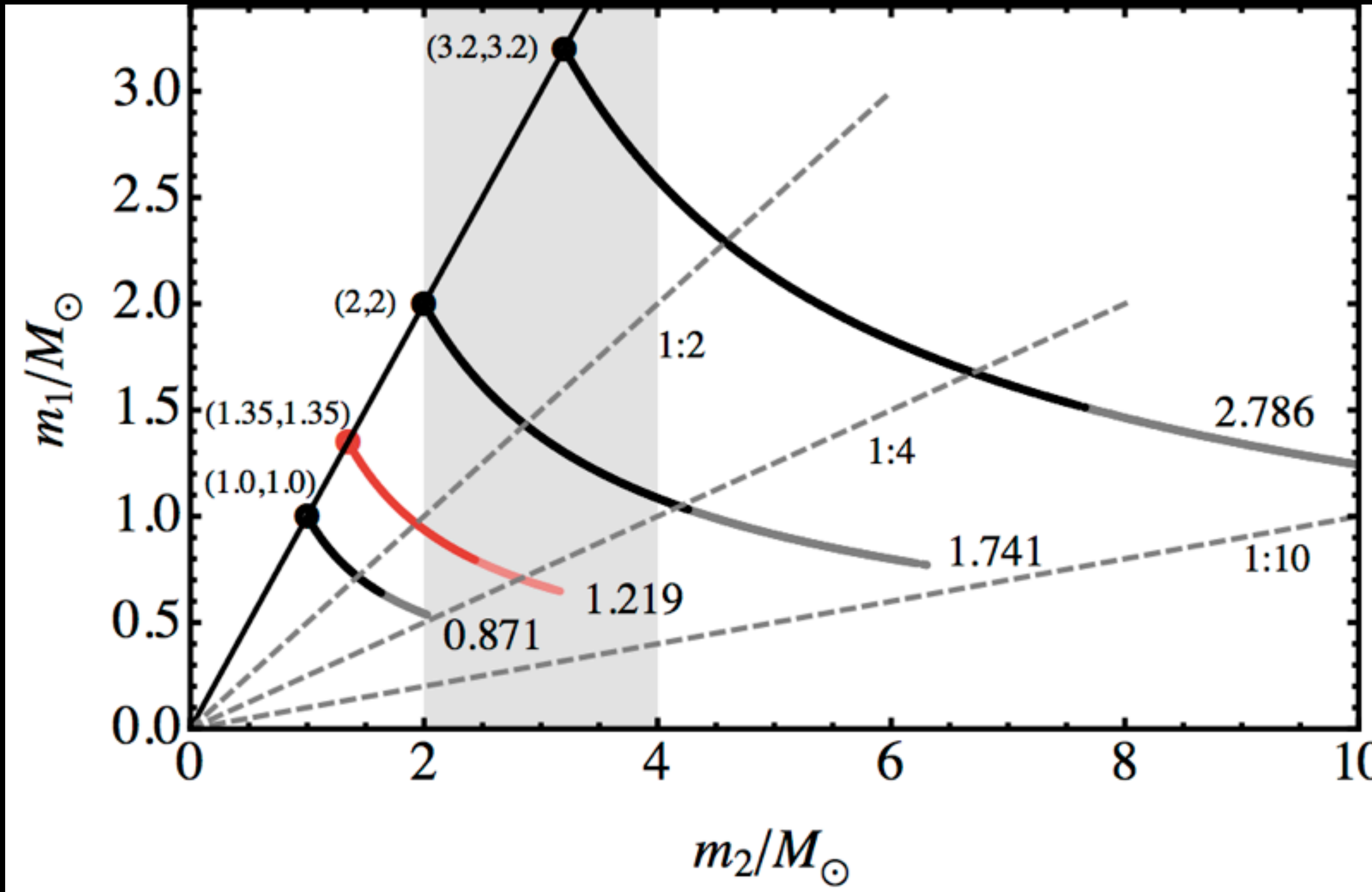


Dal Canton, Nitz, Lundgren, Nielsen, DAB, Dent, Harry, Krishnan, Miller, Wette, Wiesner, Willis, PRD **90**, 082004, 2014



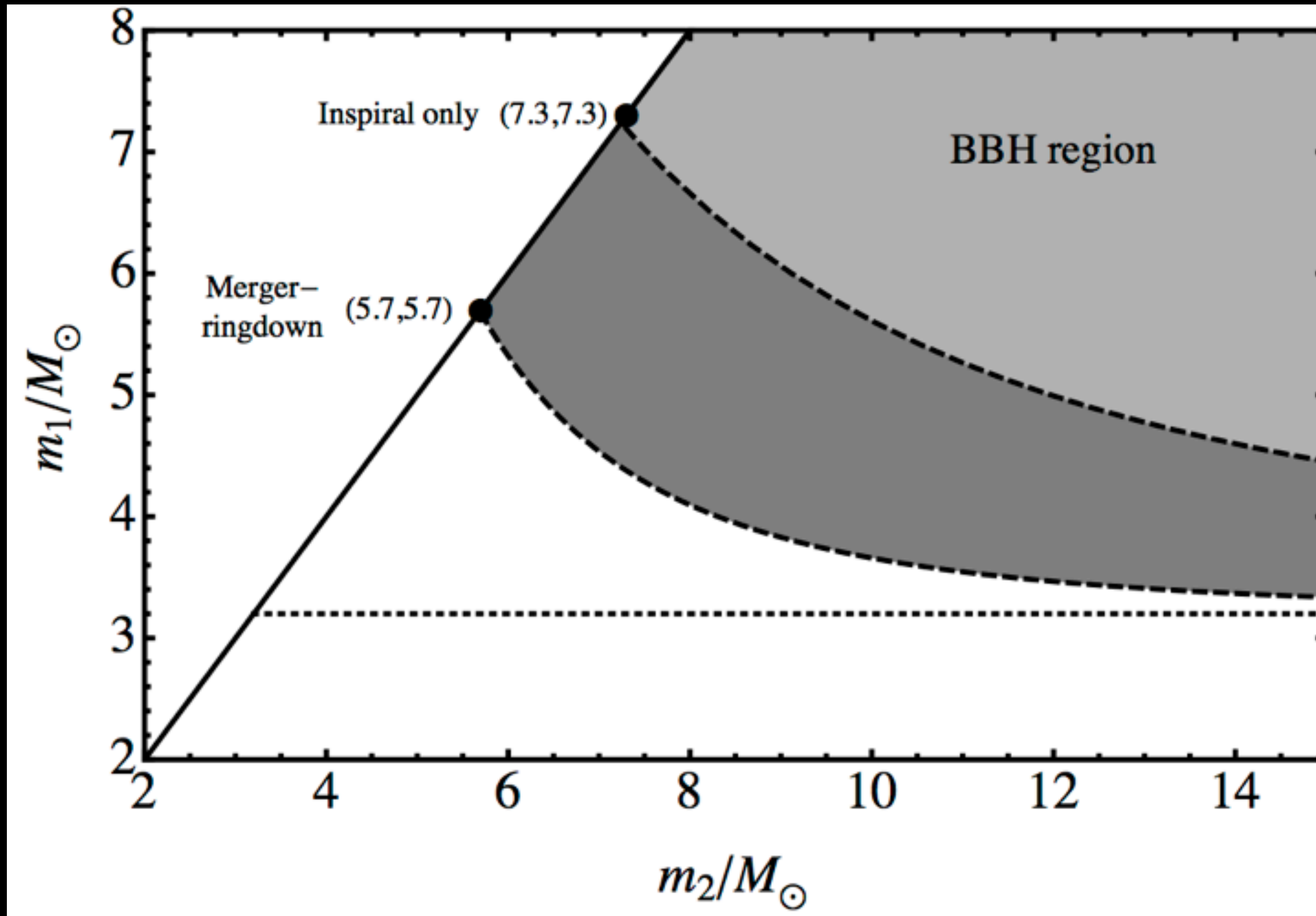
Dal Canton, Nitz, Lundgren, Nielsen, DAB, Dent, Harry, Krishnan, Miller, Wette, Wiesner, Willis, PRD **90**, 082004, 2014

- We know that we measure the chirp mass most accurately (~0.01% for BNS) and symmetric mass ratio less accurately (~1.3% for non-spinning BNS systems)
- Spin and mass ratio can be degenerate in the phase evolution and this can impact our ability to measure the mass ratio



- There is a degeneracy between BNS, NSBH, and BBH

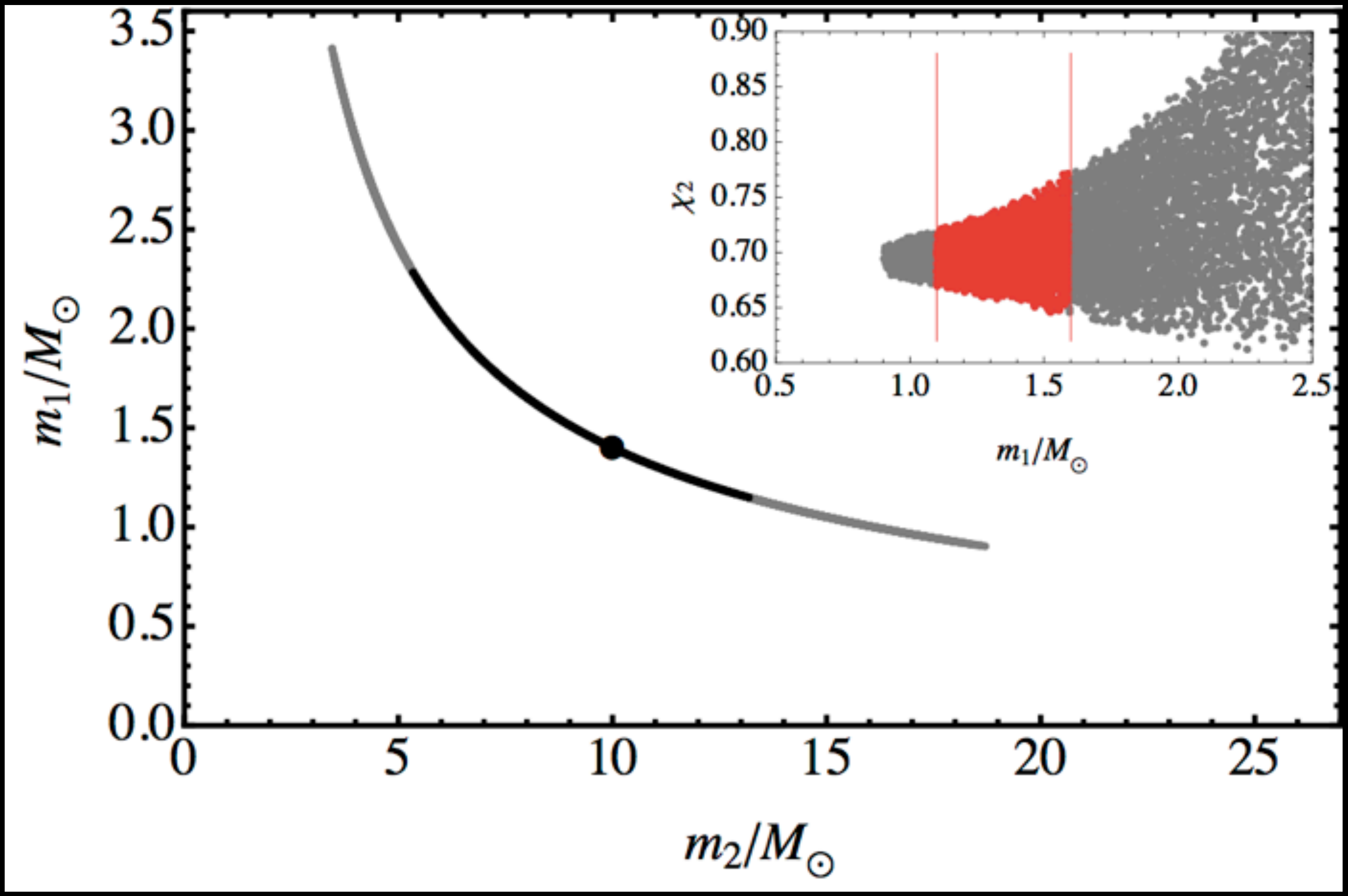
Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)



- Merger-ringdown can help break the NSBH/BBH degeneracy, but we need an accurate waveform to do this

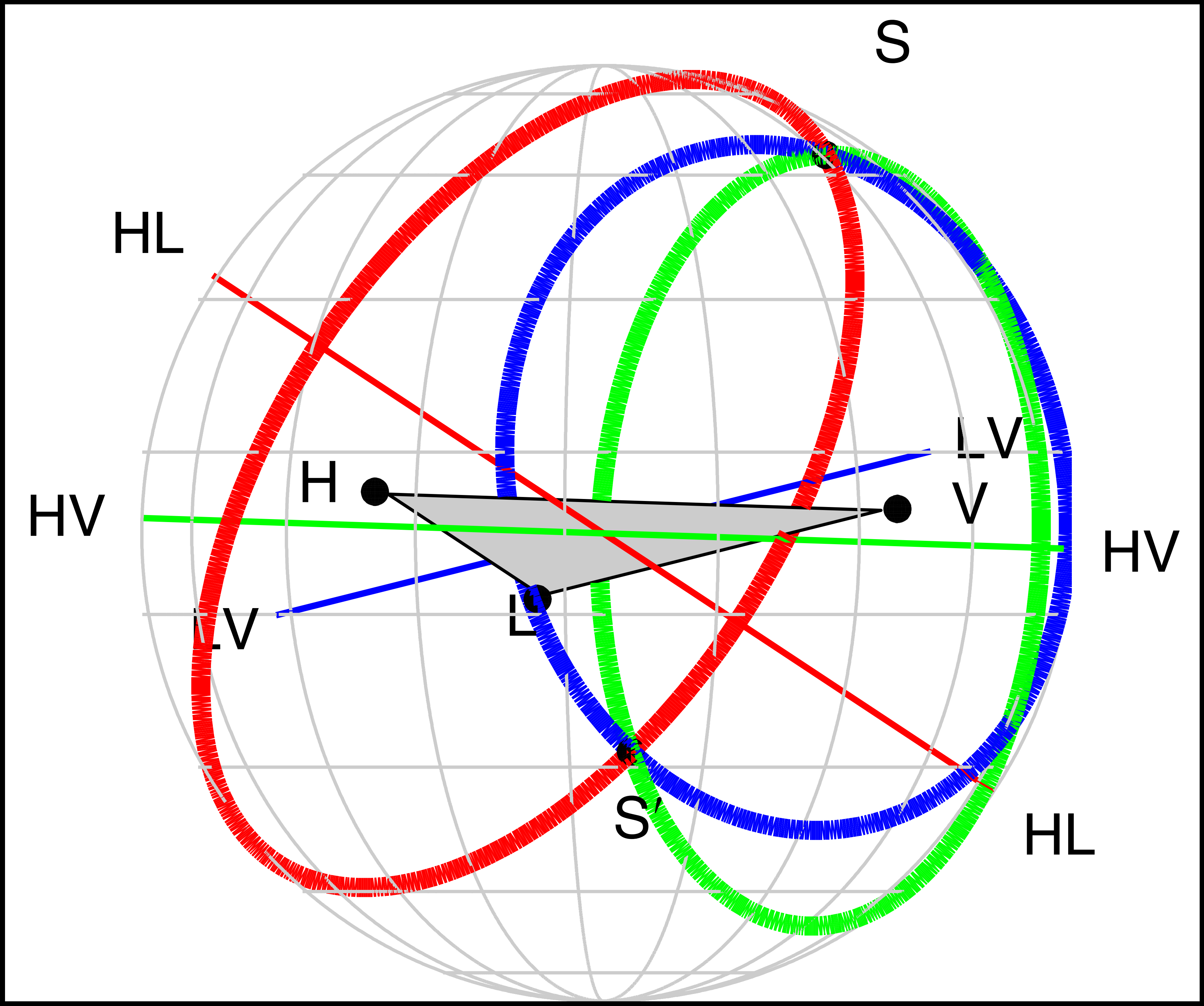
Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)

- Observing an EM counterpart would help break degeneracy



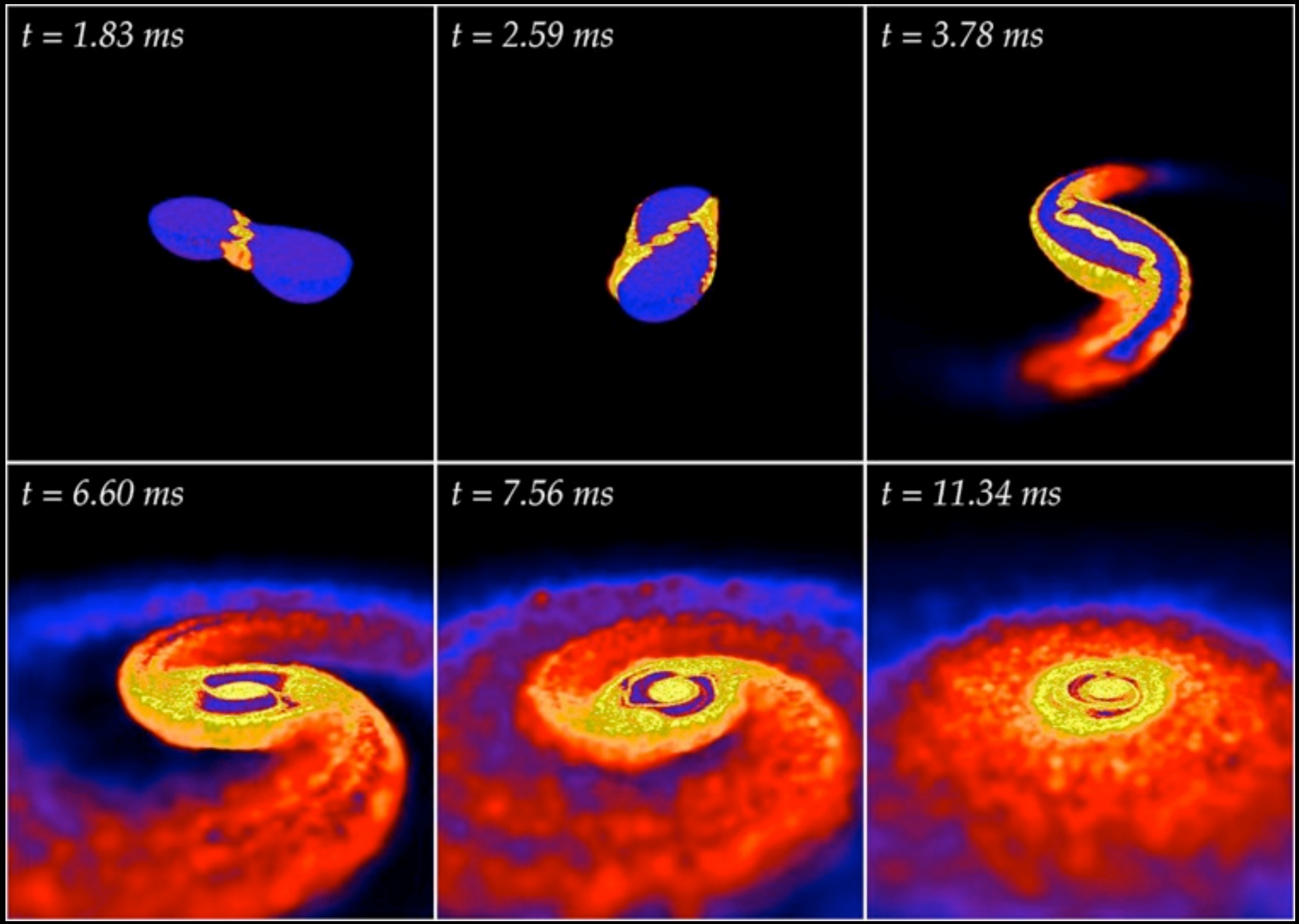
Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)

Source Localization with a network



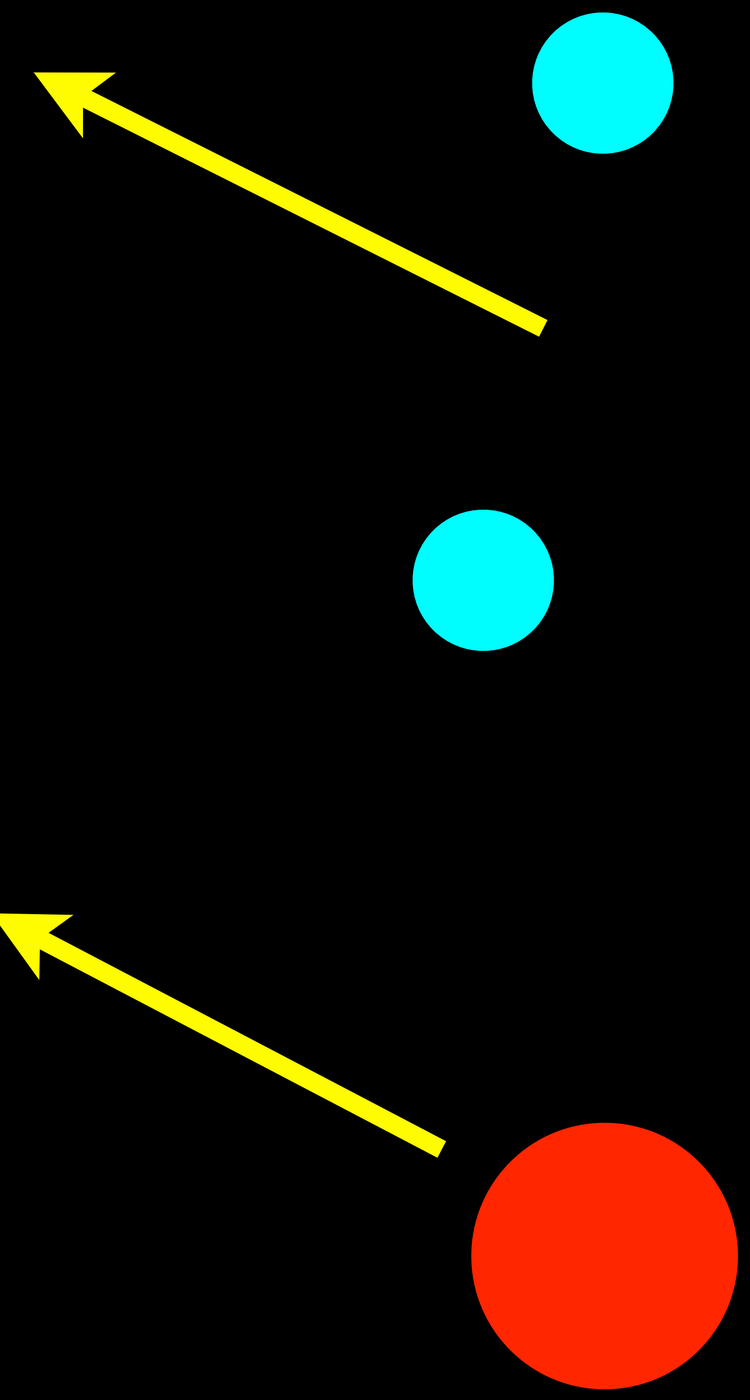
Chatterji et al. Phys Rev D **74** 0802005 (2006), Fairhurst New J.Phys. **11** 123006 (2009)

Kilonova: neutron rich matter ejected in tidal tails and disk wind leads to EM emission



Li and Paczynski (1998); Kulkarni (2005); Rosswog (2005); Metzger et al. (2010)

- GWs come directly from bulk motion of the source
- EM emission is highly reprocessed
- Lots of complementary information for us to extract from observations

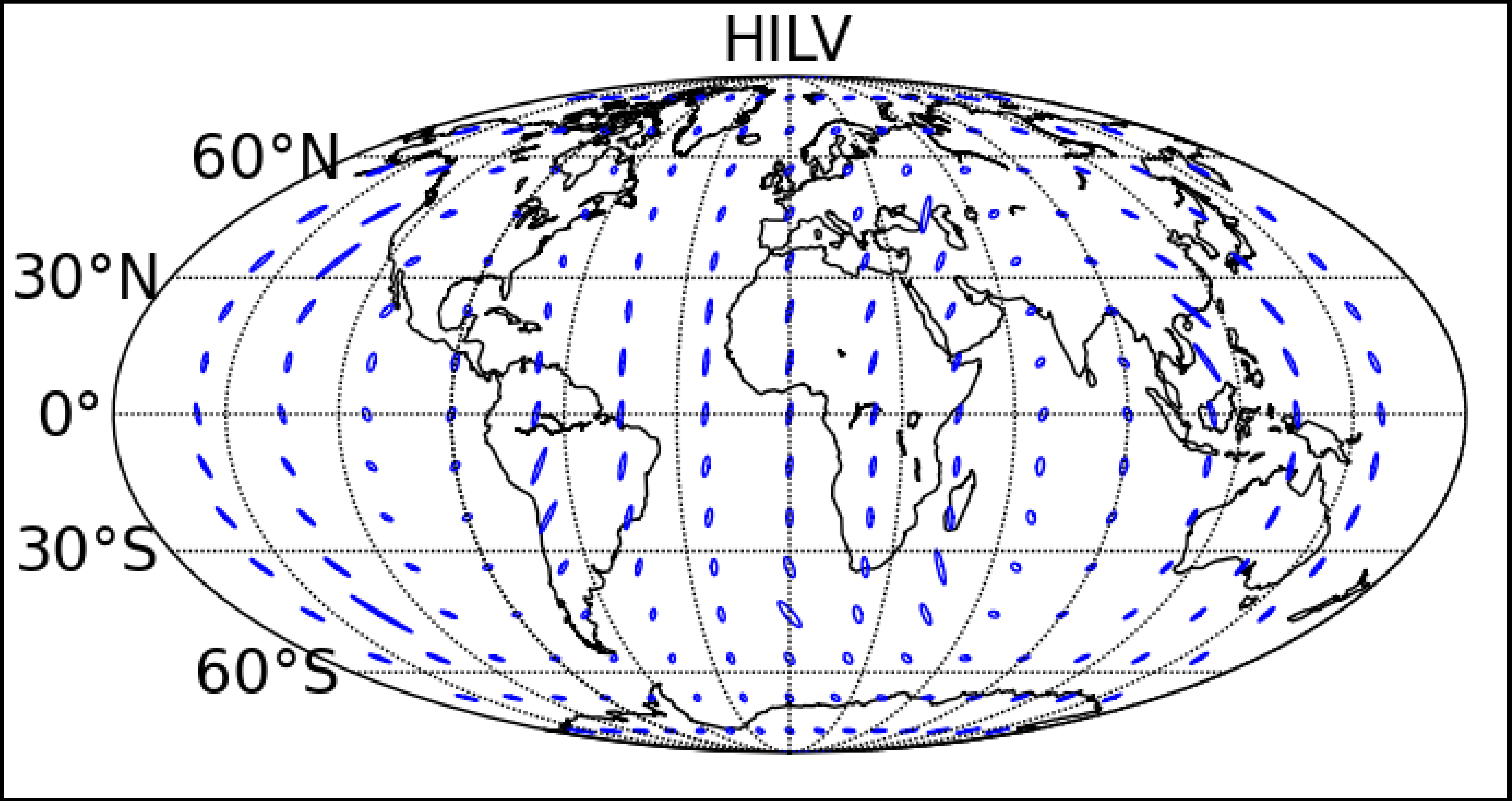


Joint EM-GW observations will give us the host galaxy, association with stellar population, accurate distance, merger hydrodynamics, jet formation, etc.

	Number of BNS detections	Localized to 5 deg sq	Localized to 20 deg sq
2015	0.0004 - 3	-	-
2016-7	0.006 - 20	2%	5 - 12%
2017-8	0.04 - 100	1 - 2%	10 - 12%
2019	0.4 - 400	3 - 8 %	8 - 28 %

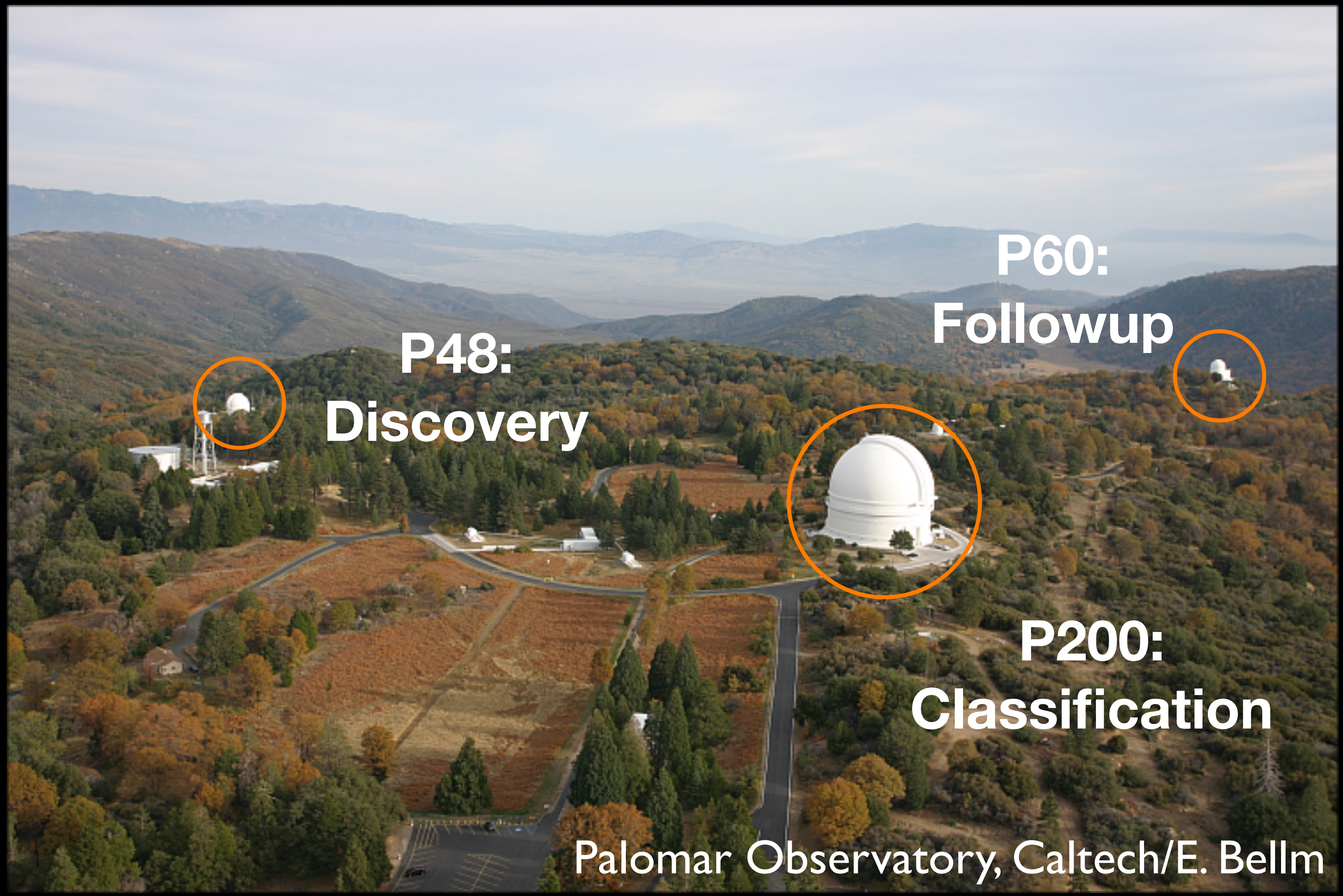
Aasi, ..., DAB, et al. (LSC and Virgo) arXiv:1304.0607

LIGO India: 17% (48%) of sources located to 5 (20) deg sq



Aasi, ..., DAB, et al. (LSC and Virgo) arXiv:1304.0607

Palomar Transient Factory

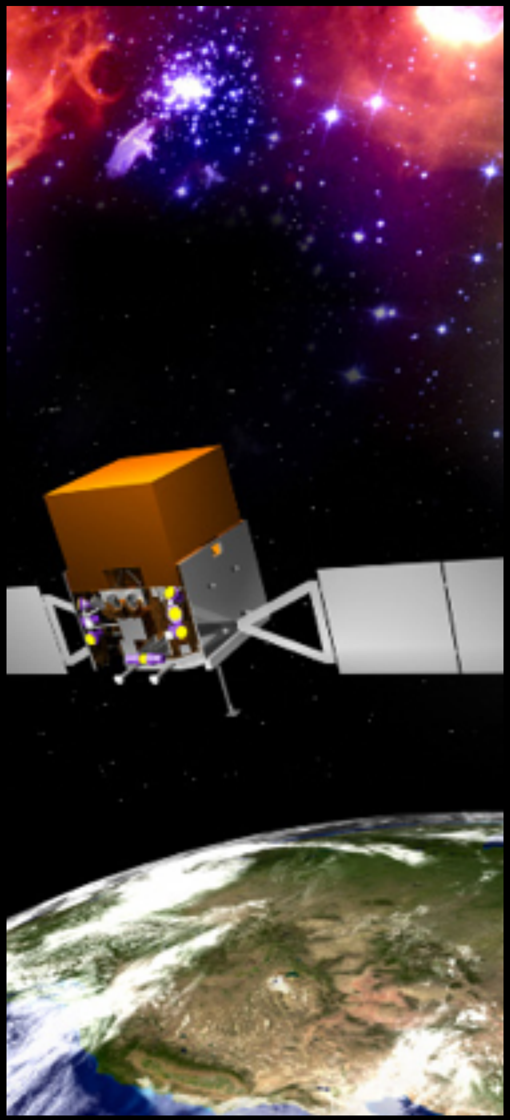


P48 Survey telescope ($\approx$7 deg^2 FOV, R$\approx$20.6 mag in 60 s)

P60 Robotic, photometric follow-up

P200 Spectroscopy, classificatioN

Fermi Gamma Ray Bursts

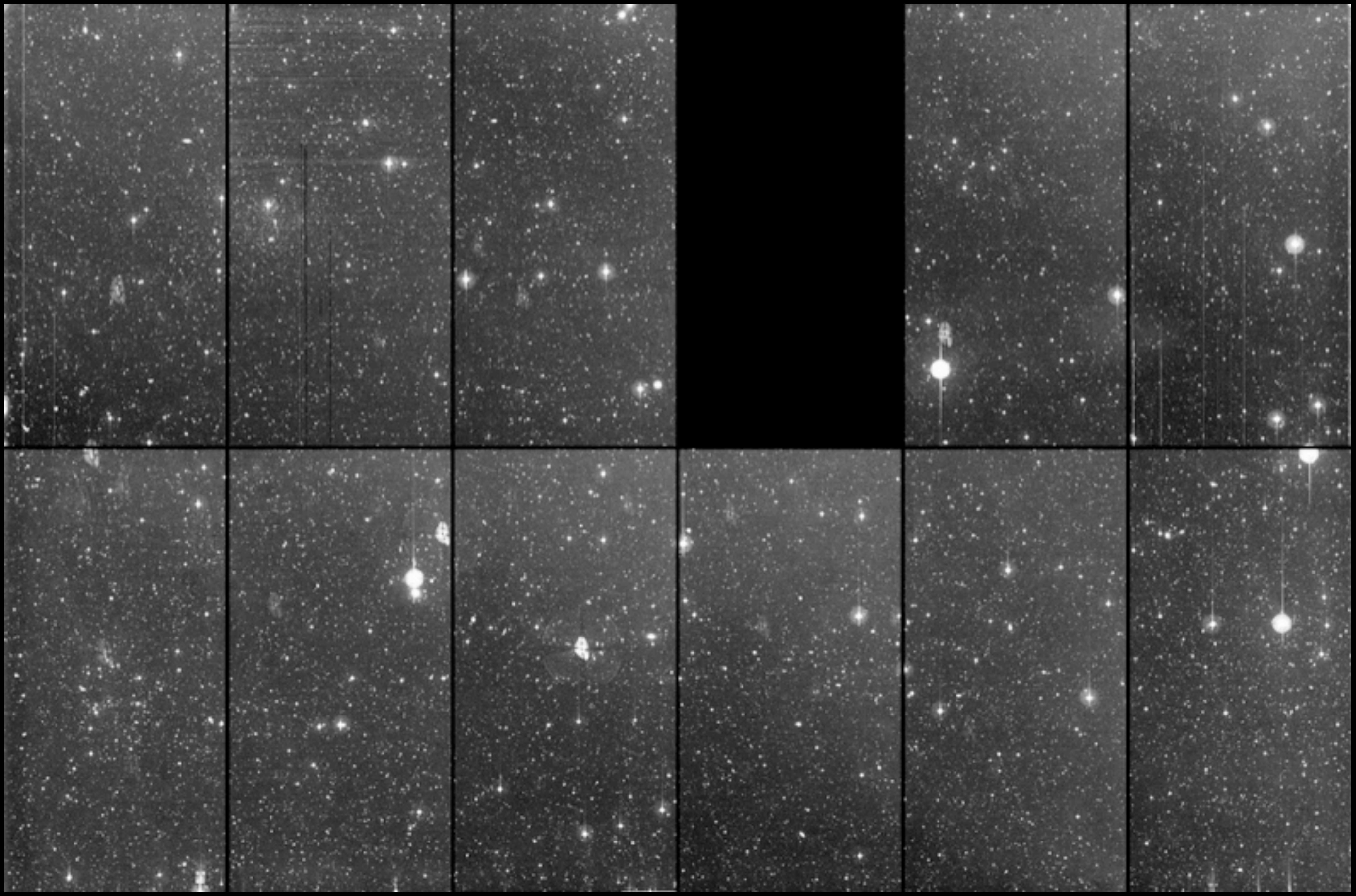


NASA/GSFC

Fermi GBM has twice the detection rate of Swift BAT

70% of sky and better for short GRBs

But very coarse localization, so very hard to follow up and observe afterglows



P48 has ~ 7 square degree field of view

Tile the Fermi error box and follow up GBM GRBs

Fermi trigger on July 2, 2013

27,004 transient/variable candidates found by real-time iPTF analysis

26,960 not known minor planets

2740 sources without SDSS detections brighter than r'=21

43 sources detected in both P48 visits, presented to human scanners

7 sources saved by humans

3 afterglow-like candidates scheduled for follow-up

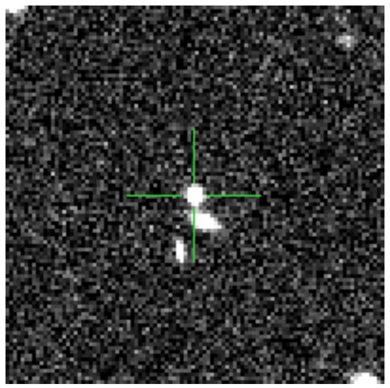
13bxl

14:29:14.78 +15:46:26.4
217.311582 +15.774013

View another

OVERVIEW PHOTOMETRY SPECTROSCOPY FOLLOWUP OBSERVABILITY FINDING CHART EXAMINE PAGE

NEW



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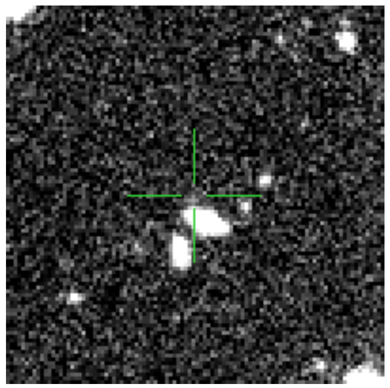
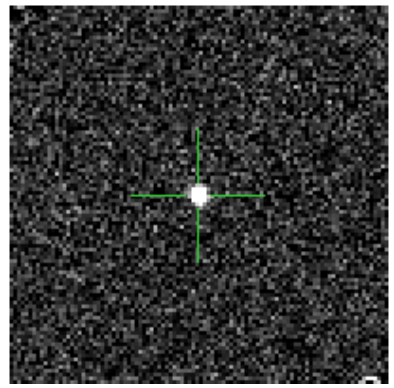
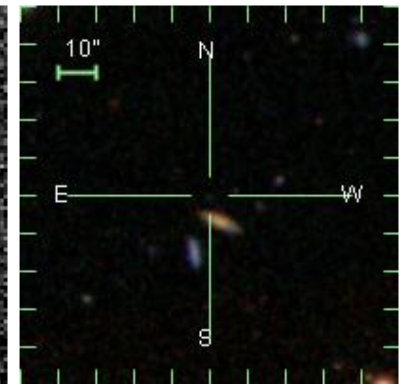
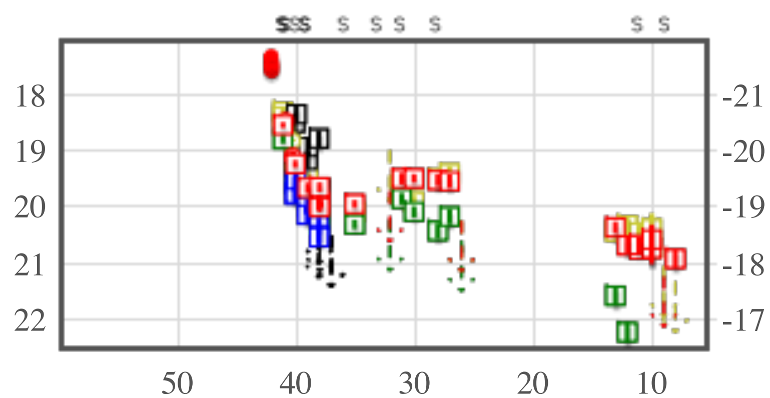


SUB

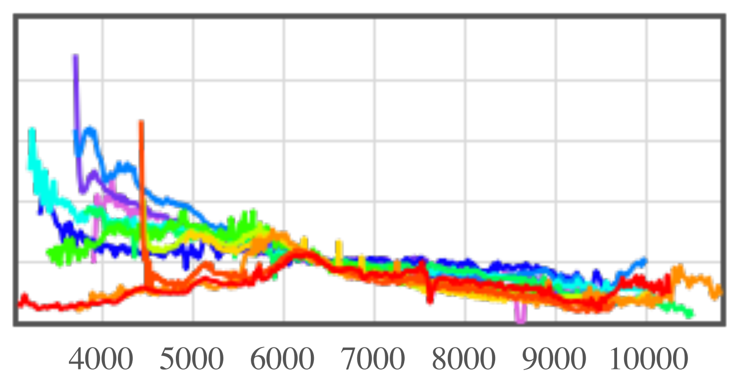


SDSS





r = 17.6 (42.2 d) | Upload New Photometry



z = 0.145 | Upload New Spectroscopy
DM (approximate) = 39.19

ADDITIONAL INFO

NED | SIMBAD | VizieR | HEASARC | SkyView | PyMP | Extinction
IPAC | DSS | WISE | Subaru | VLT | Variable Marshal (Search) | ADS

Add to Cart

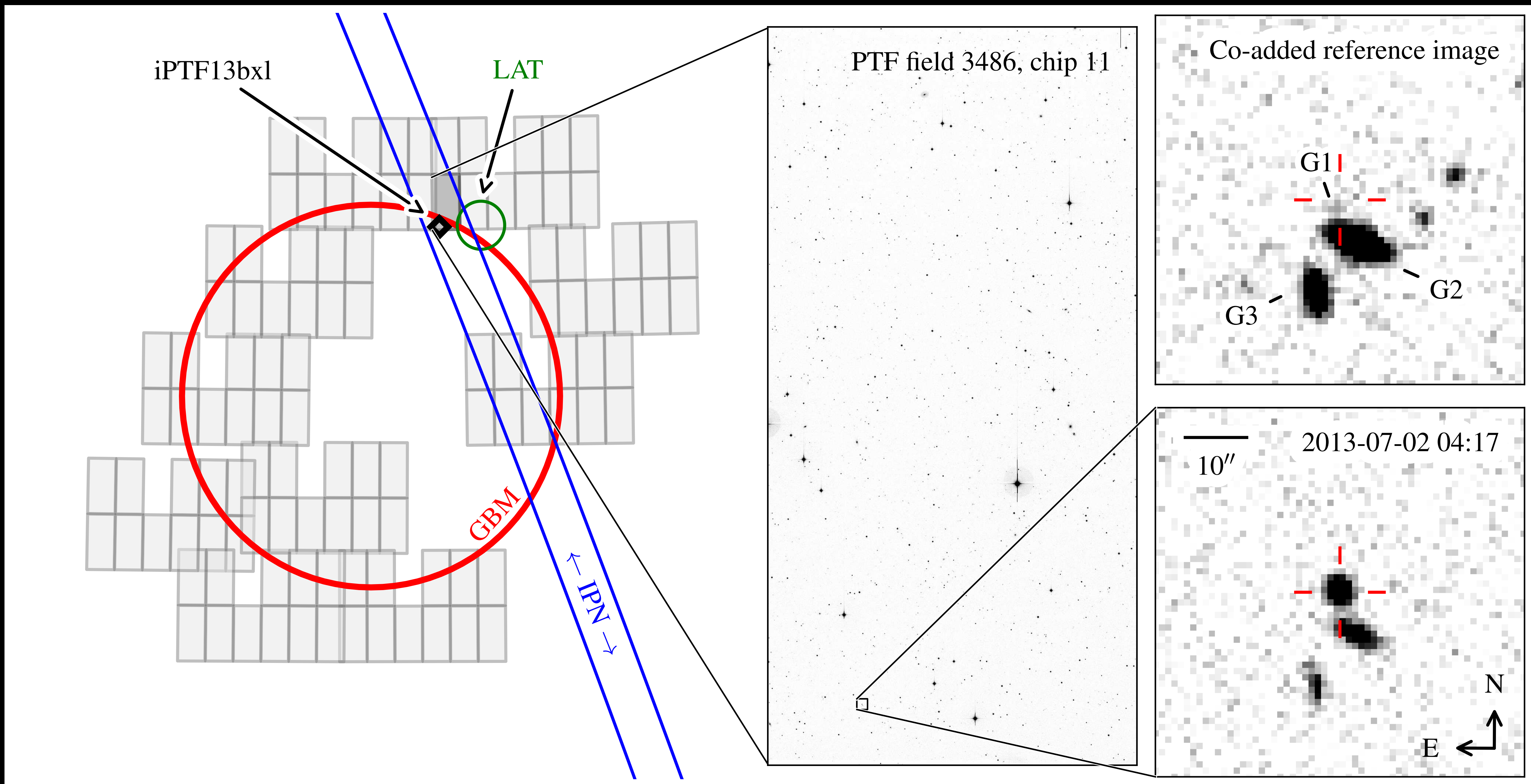
FOLLOW UP

PROGRAMS

COMMENTS

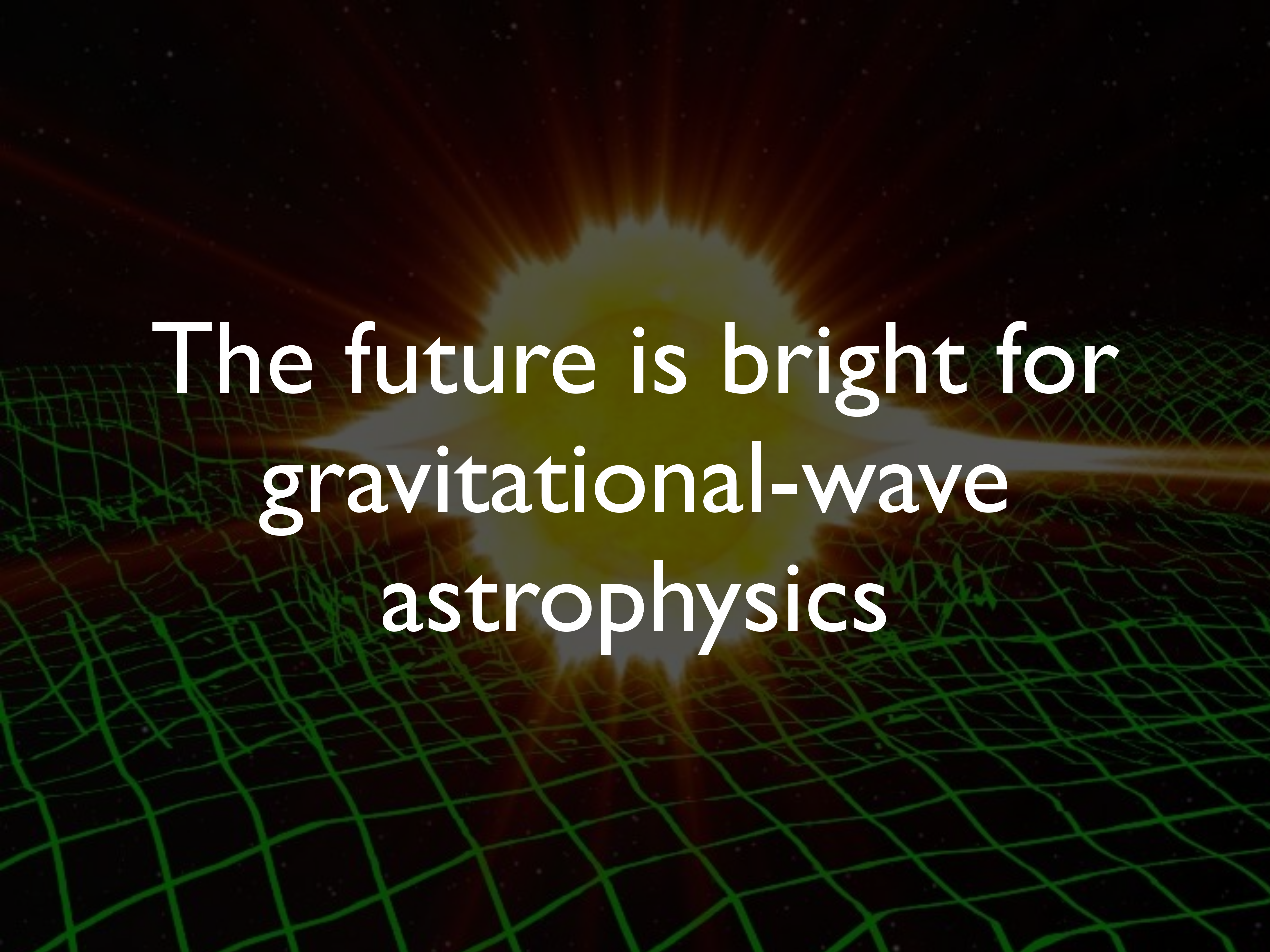
2013 Aug 04 sumin [info]: observed with LRIS
2013 Jul 15 iair [info]: Observed at P200+DBSP (PA 166.1)
2013 Jul 14 jesper [info]: Latest Keck spectrum (July 11) looks like 2006aj close to Max. The fit with 98bw is less good.
2013 Jul 11 sumin [info]: observed with lick 3-m kast, g-band and R-band images
2013 Jul 11 sumin [info]: observed with Lick Kast g-band image, 130711
2013 Jul 09 brad [info]: Broad features identified in NOT spectrum (GCN 14994) are clearly visible. But it doesn't look like an exact match to 98bw to me (see attached). [view attachment]
2013 Jul 08 robert [info]: Light curve is still fading as a powerlaw (see attached plot). Could have been a break in the LC before 10^5 seconds. [view attachment]
2013 Jul 06 jesper [info]: interesting features, and about right timing. Although some structure also in earlier spectra. SNID attached. /jesper [view attachment]
2013 Jul 06 avishay [info]: SN signatures seem to be already emerging, as light curve decline slows down. Comparison with SN 1998bw and SN 2006aj attached. [view attachment]
2013 Jul 05 ofer [comment]: Quick reduction (to be compared with final one)
2013 Jul 04 mansi [redshift]: 0.145
2013 Jul 04 iair [info]: Observed with P200+DBSP
2013 Jul 03 iair [redshift]: 0.145
2013 Jul 03 iair [comment]: possible redshift based on narrow H, O I, O III
2013 Jul 03 eric [info]: Observed with P200-DBSP 130703
2013 Jul 03 duncan [info]: There is a Fermi/LAT detection (GRB130702A). The best LAT on-ground location is found to be: RA, DEC = 216.4, 15.8 (J2000), with an error radius of 0.5 deg (90% containment, statistical error only) This position is 4 deg from the best GBM position (RA, Dec = 218.81, +12.25 with a 4 deg radius), and 0.8 deg from the position of the optical afterglow.
2013 Jul 02 eric [info]: Observed with P200-DBSP 130702
2013 Jul 02 duncan [info]: Final Fermi GBM position: +14h 35m 14s, +12d 15' 00" (218.810d, +12.250d) (J2000) Error 3.99 [deg radius, statistical only]

iPTF 13bxl: Discovery of Optical Counterpart in 71 deg sq



Singer, Cenko, Kasliwal, Perley, Ofek, DAB, et al. Astrophys J Letters **766** L34 (2013)

- The convergence of
  - Gravitational-wave experiments
  - Numerical and analytical relativity
  - Modeling of electromagnetic counterparts
  - Wide-field optical telescopes
- will give us the tools to revolutionize our astrophysical knowledge of the universe



The future is bright for gravitational-wave astrophysics