UNIVERSITY of WISCONSIN
UWMILWAUKEE

Center for Gravitation and Cosmology

Gravitational-Wave Astronomy

Current Status and Future Prospects

Patrick Brady

Gravitational Waves in GR

Spacetime interval can be written as

$$ds^2 = (\eta_{\alpha\beta} + h_{\alpha\beta})dx^\alpha dx^\beta$$

where $\eta_{\alpha\beta}$ is the Minkowski metric and $h_{\alpha\beta}$ is a metric perturbation

For weak gravitational fields, the leading order solution is

$$h_{ij} = \frac{2G}{c^4}\frac{1}{r}\frac{d^2Q_{ij}}{dt^2} \sim \frac{G}{c^4}\frac{mv^2}{r}$$

Mass Quadrupole

$$Q_{ij} \approx \int \rho(x_i x_j - \frac{1}{3}\delta_{ij}x^2)d^3x$$

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velocity of the quadrupole variation

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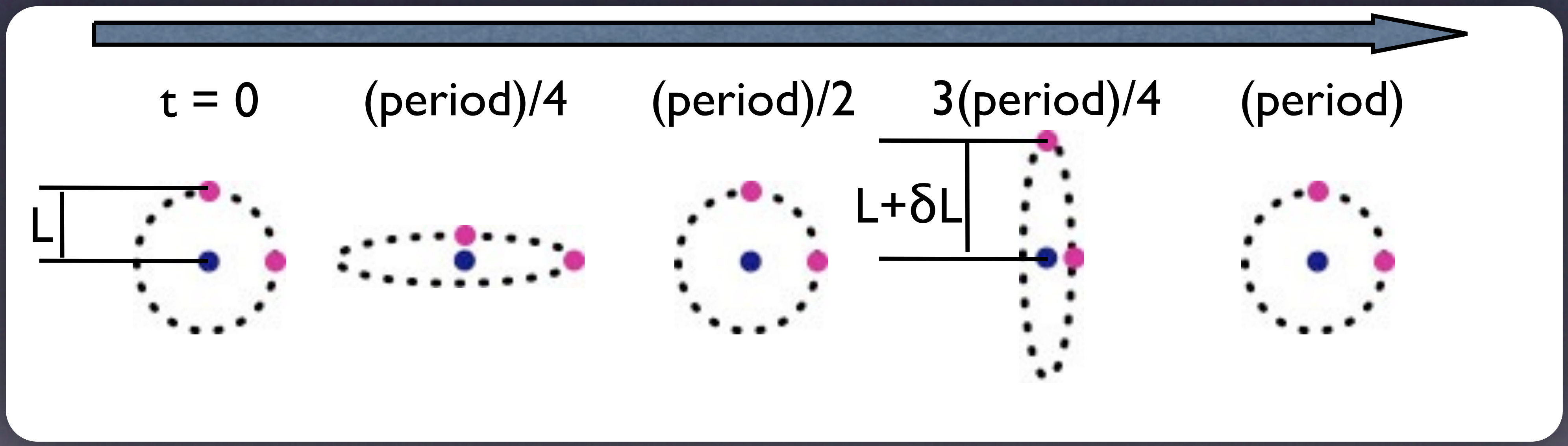
Physical Effects of the Waves

- As gravitational waves pass, they change the distance between neighboring bodies
- GR predicts two polarizations

Animations: Warren Anderson

- Fractional change in distance is the strain given by h = δL / L



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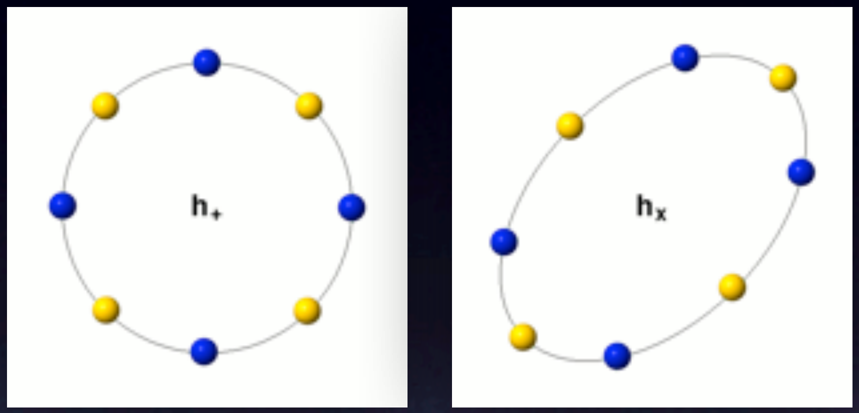

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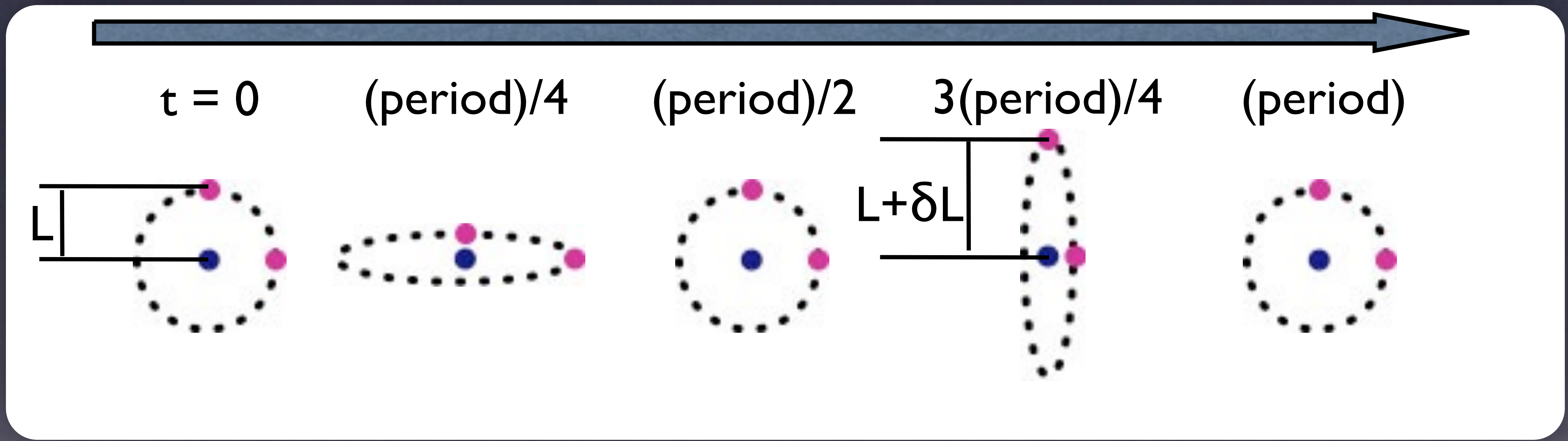
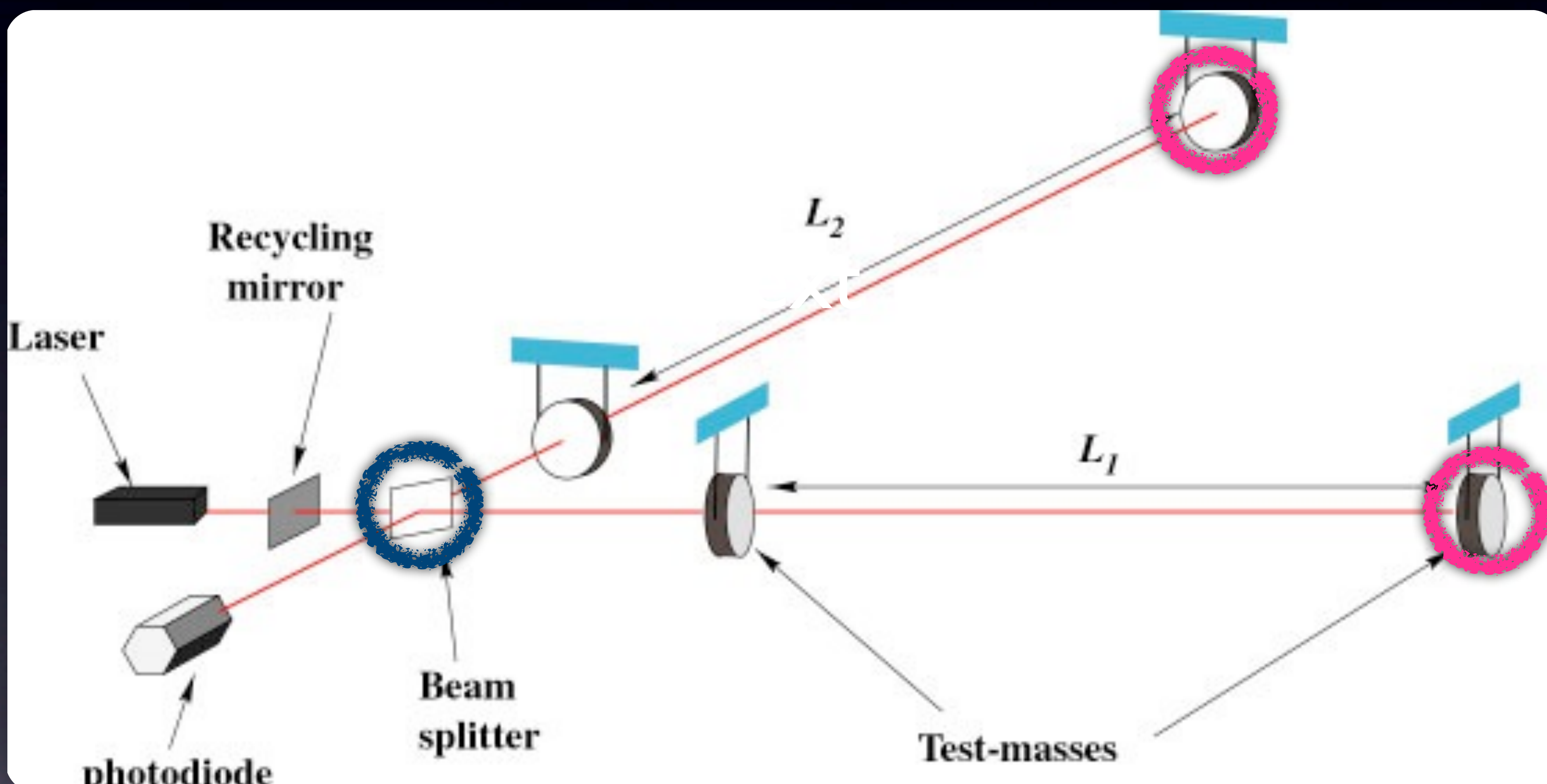


Schematic Detector

As gravitational waves pass, they change the distance between neighboring bodies…



…causing the interference pattern to change at the photodiode

Global Network of Gravitational-wave Detectors

LIGO Hanford

LIGO Livingston

GE600

Virgo

Global Network of Gravitational-wave Detectors

LIGO Hanford

LIGO Livingston

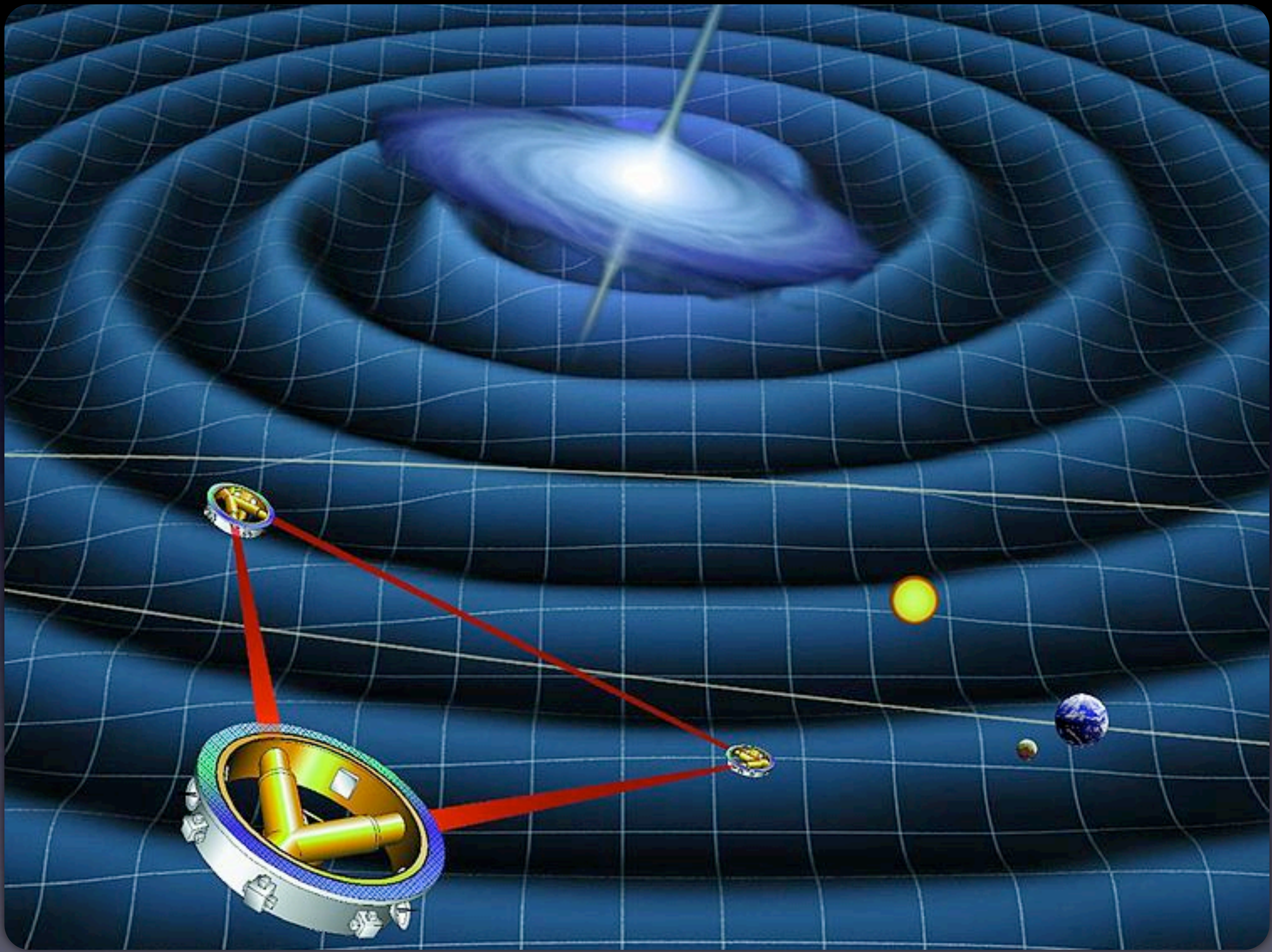
GE600

Virgo

LIGO India

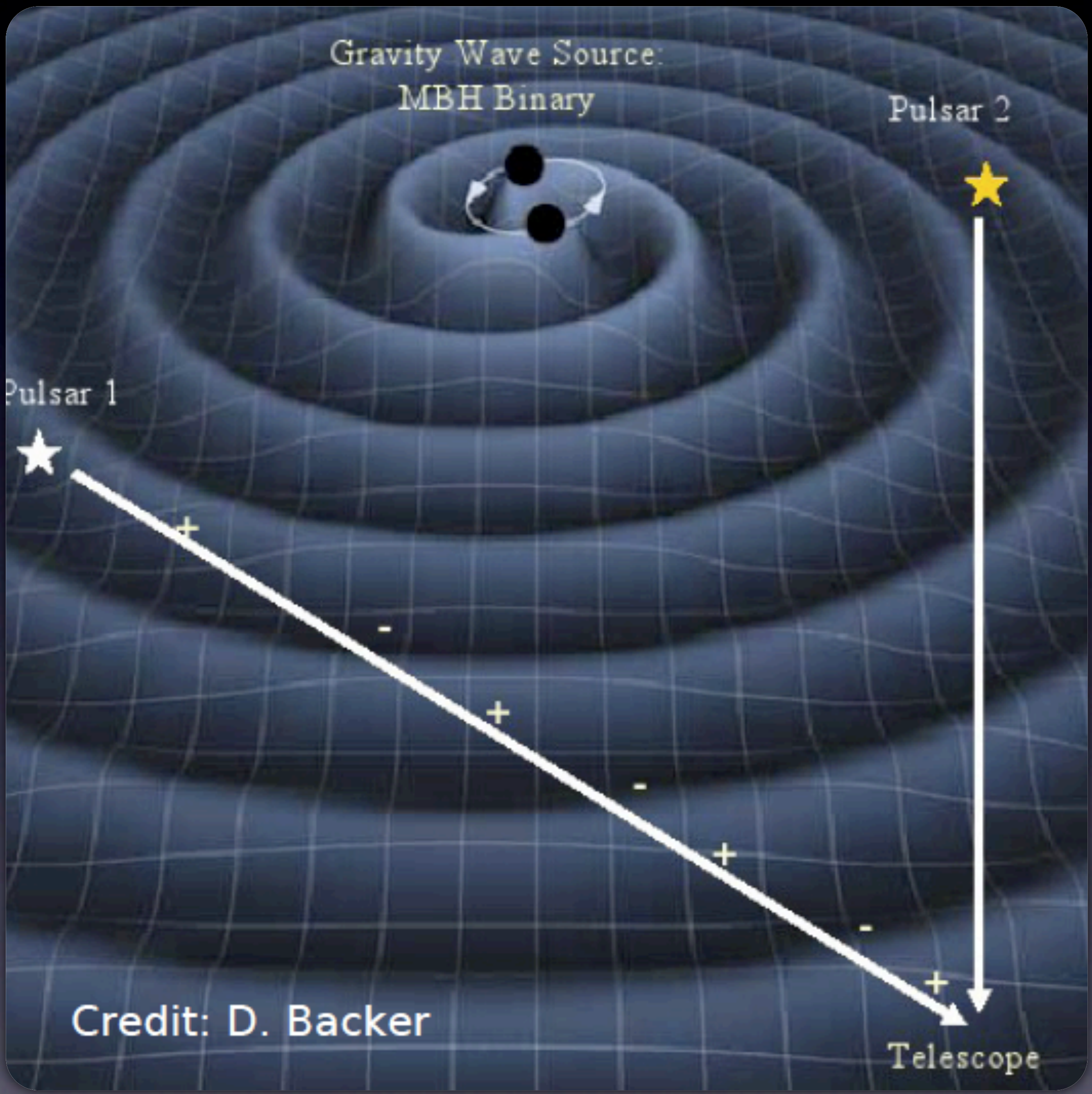
Kagra

Space-Based Detectors



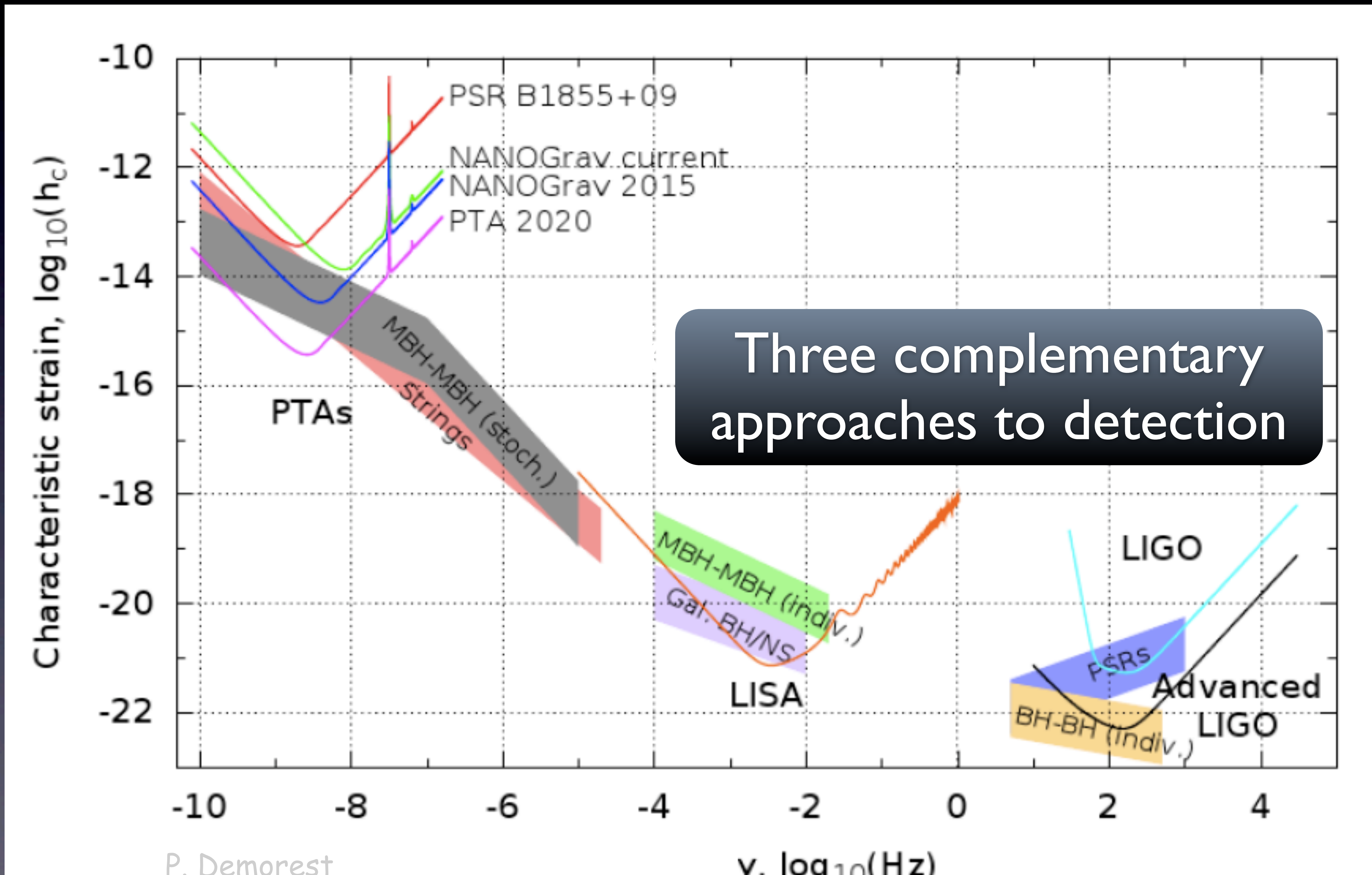
DECIGO & LISA

Pulsar Timing



International Pulsar Timing Array (IPTA)
includes NANOGrav, EPTA, ...

Gravitational-Wave Spectrum



Courtesy: NanoGrav, M. McLaughlin, P. Demorest

Motivation

- To test relativistic gravity and to develop gravitational wave detection as an astronomical probe
- Anticipated gravitational-wave signals
  - Transient signals: compact binary coalescence, supernovae, cosmic string kinks, black-hole ringdown.
  - Continuous signals: spinning neutron stars in isolation & in binaries.
  - Stochastic signals from cosmological sources.
  - Serendipitous signals: unanticipated sources in all these categories
- Gravitational waves carry information about the structure and dynamics of the sources

LIGO

LIGO-Virgo Collaboration

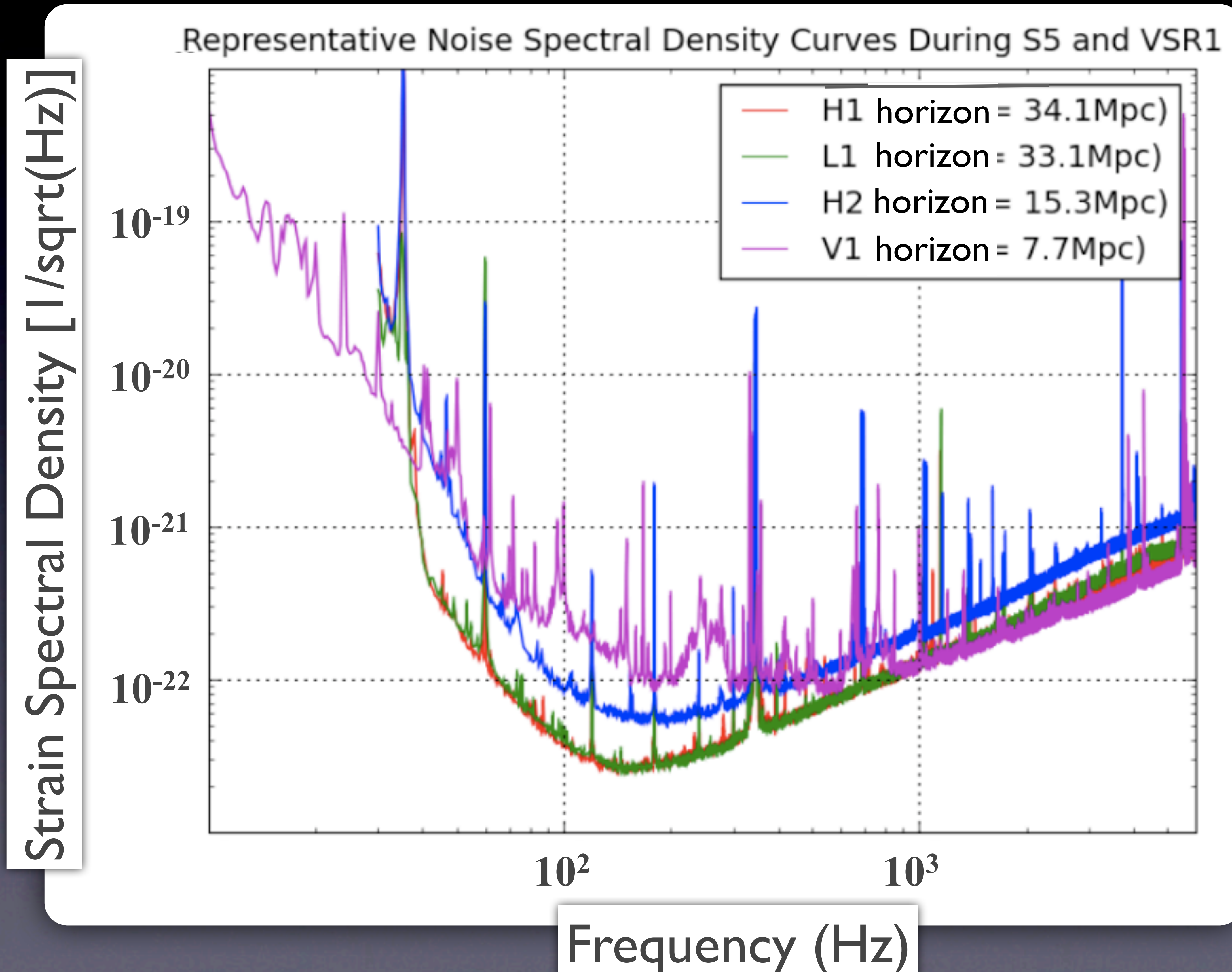
VIRGO

LSC

University of Maryland 1856
Michigan
University of Strathclyde
ACIGA
Leland Stanford Junior University 1891
Montana State University
PAH
University of Washington
Loyola University New Orleans
Syracuse University Founded AD 1870
清華大學
Tsinghua University
Trinity University
San José State University
University of Wisconsin Milwaukee
ANU
The Australian National University
LSU
UTB TSC
R·I·T
부산대학교
Pusan National University
The University of Western Australia
University of Glasgow
NASA
Goddard Space Flight Center
Università degli Studi del Sannio
The University of Melbourne
KiSTi
Andrews University
Massachusetts Institute of Technology
Southeastern Louisiana University
Moscow State University
California Institute of Technology 1891
Northwestern University
Hanyang University 한양 1939
University of Cambridge
The University of Adelaide Australia
PAN
The University of Texas at Austin
GEO 600
Embry-Riddle Aeronautical University
University of Massachusetts Amherst 1863
Lund University
ISI
University of New Hampshire
PennState 1855
Carleton College Northfield, Minn. AD 1866
Cardiff University
California State University Fullerton
Washington State University
국가수리과학연구소
National Institute for Mathematical Sciences
The University of Mississippi 1848
Charles Sturt University
UIB Universitat de les Illes Balears
UF University of Florida
Perimeter Institute
CITA-ICAT
Seoul National University
University of Rochester
NAOJ
University of Southampton
Hobart and William Smith Colleges
University of Minnesota
Universität Hannover
Southern University and Agricultural & Mechanical College
Science & Technology Facilities Council
Rutherford Appleton Laboratory

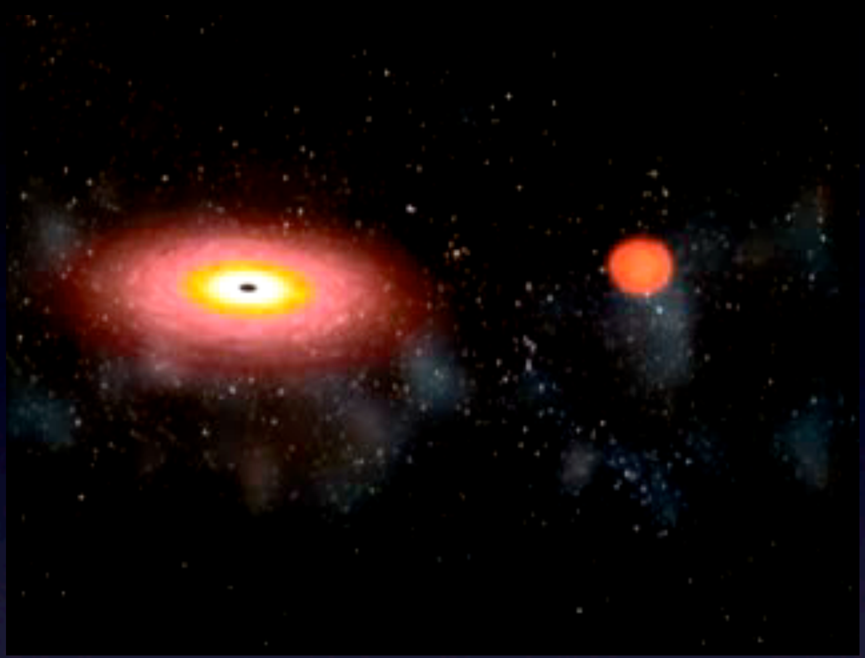
LIGO & Virgo Observing Runs

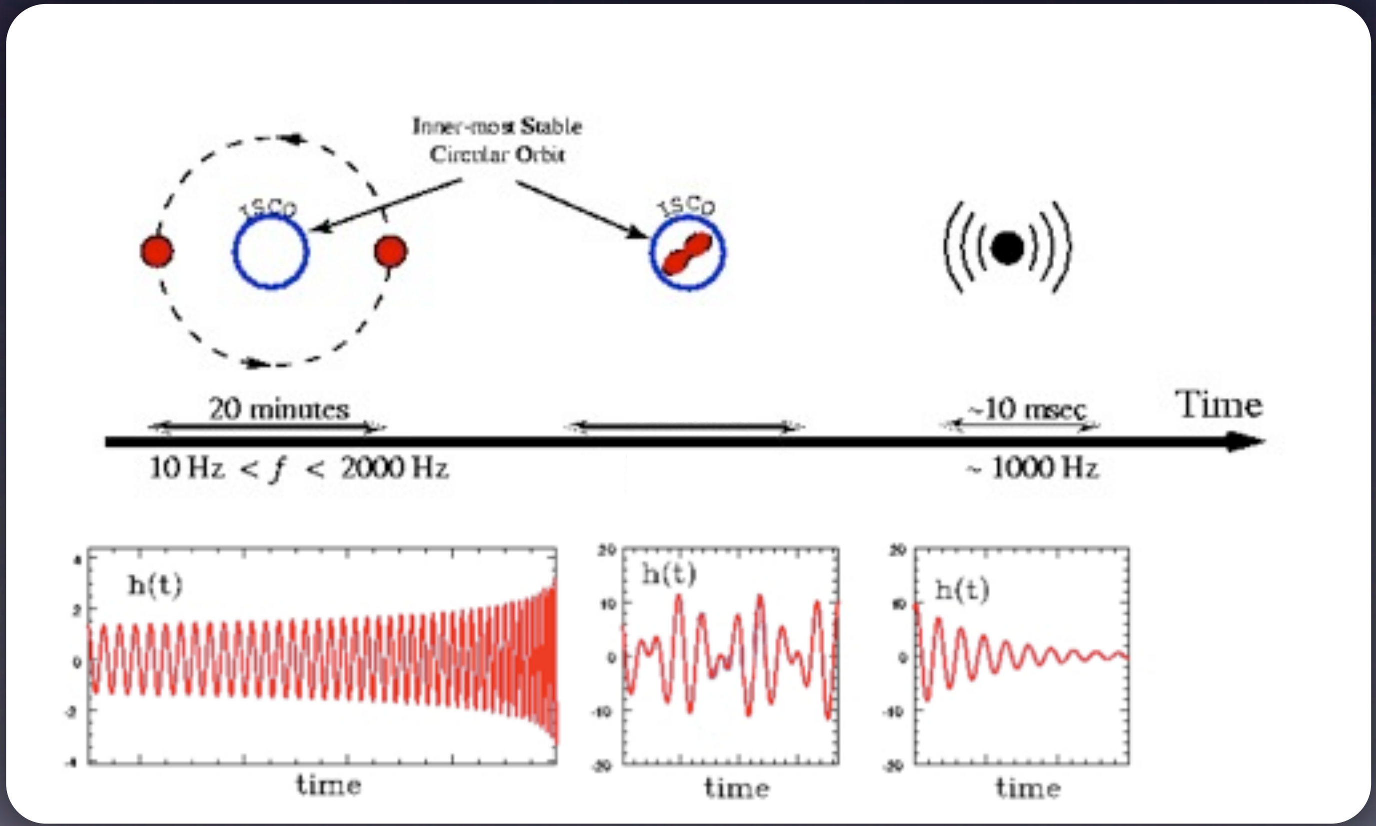
S5/VSR1 Sensitivity



Compact Binaries

- Pairs of black holes, neutron stars, or a black hole and neutron star
- As they orbit one another, they emit gravitational waves causing the objects to get closer together, eventually merging

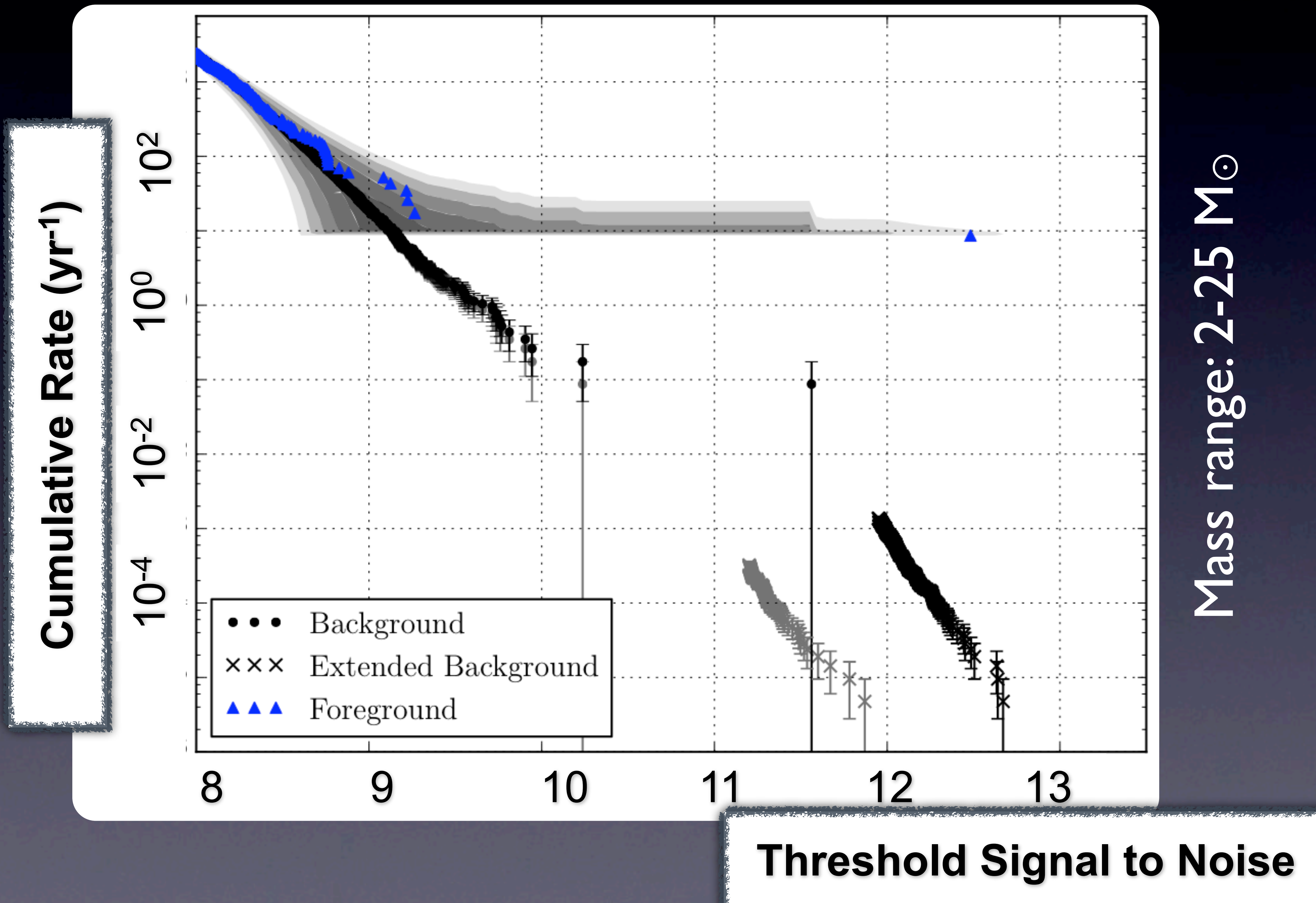

Credit: Dana Berry, NASA



$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$

S6/VSR2 Compact Binary Foreground

(Includes blind injection signal)



Mass range: 2-25 $M_\odot$

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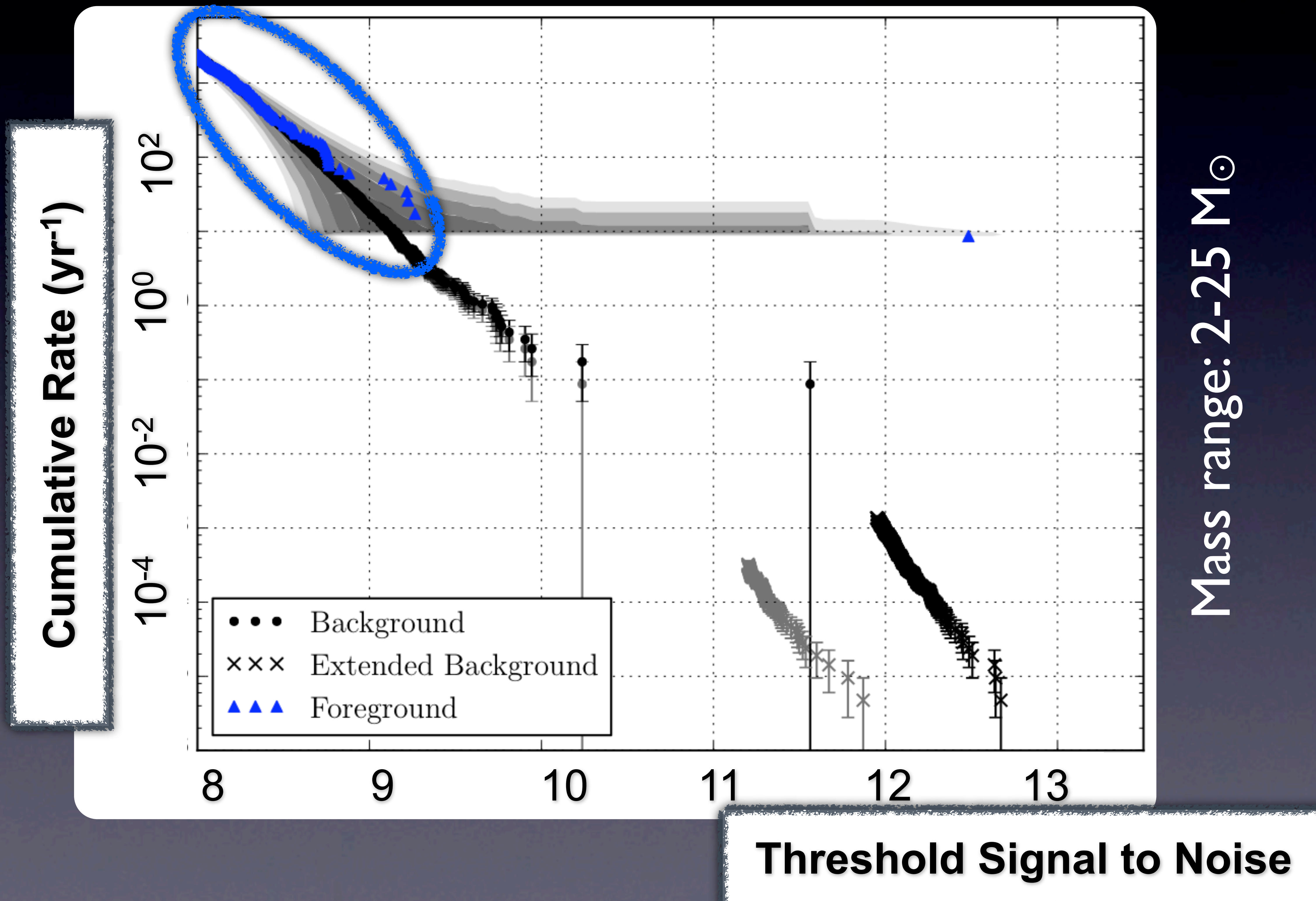
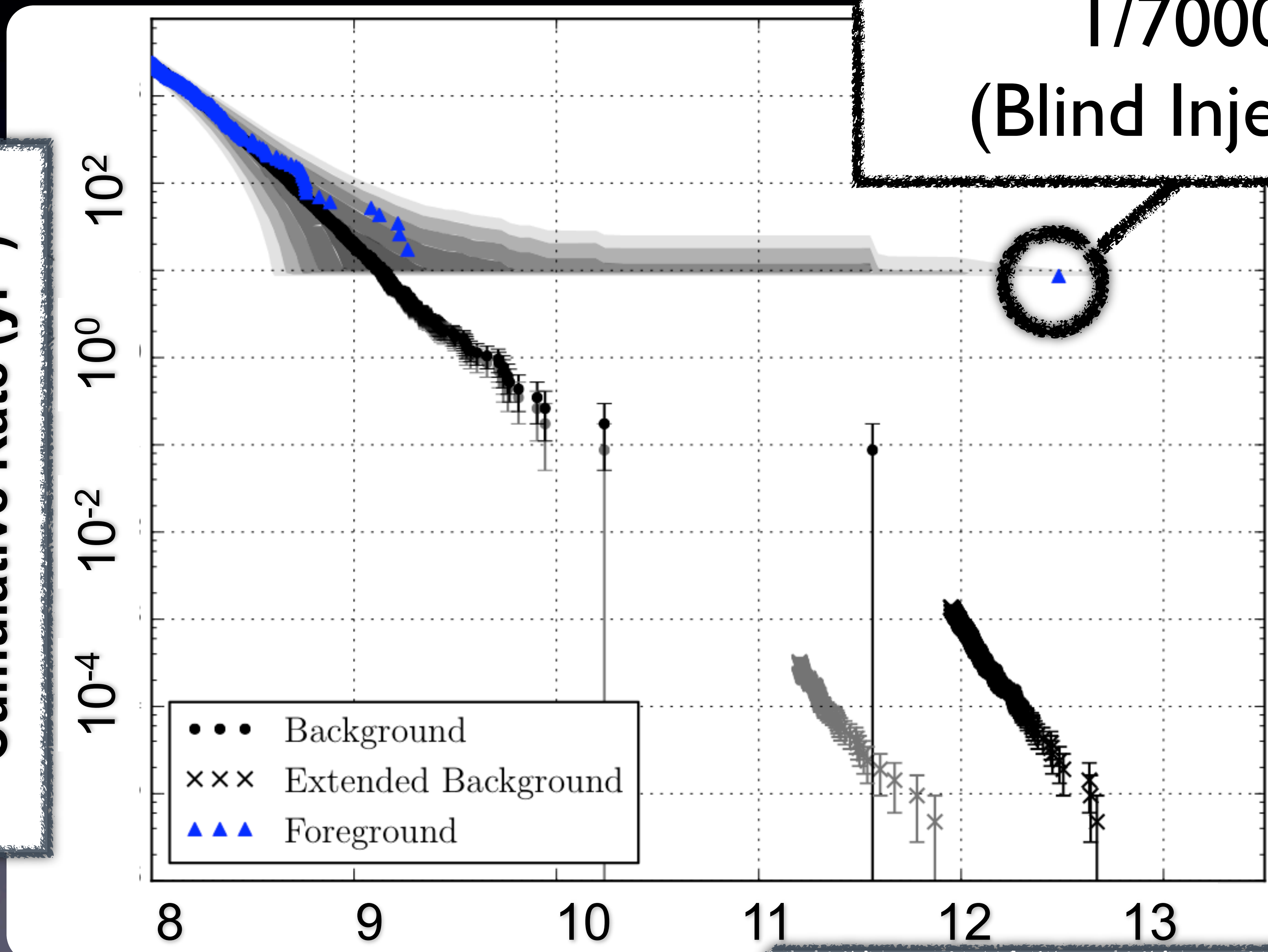


S6/VSR2 Compact Binary Foreground

(Includes blind injectic

Big Dog Event:
1/7000yr
(Blind Injection)

http://ligo.org/science/GW100916/



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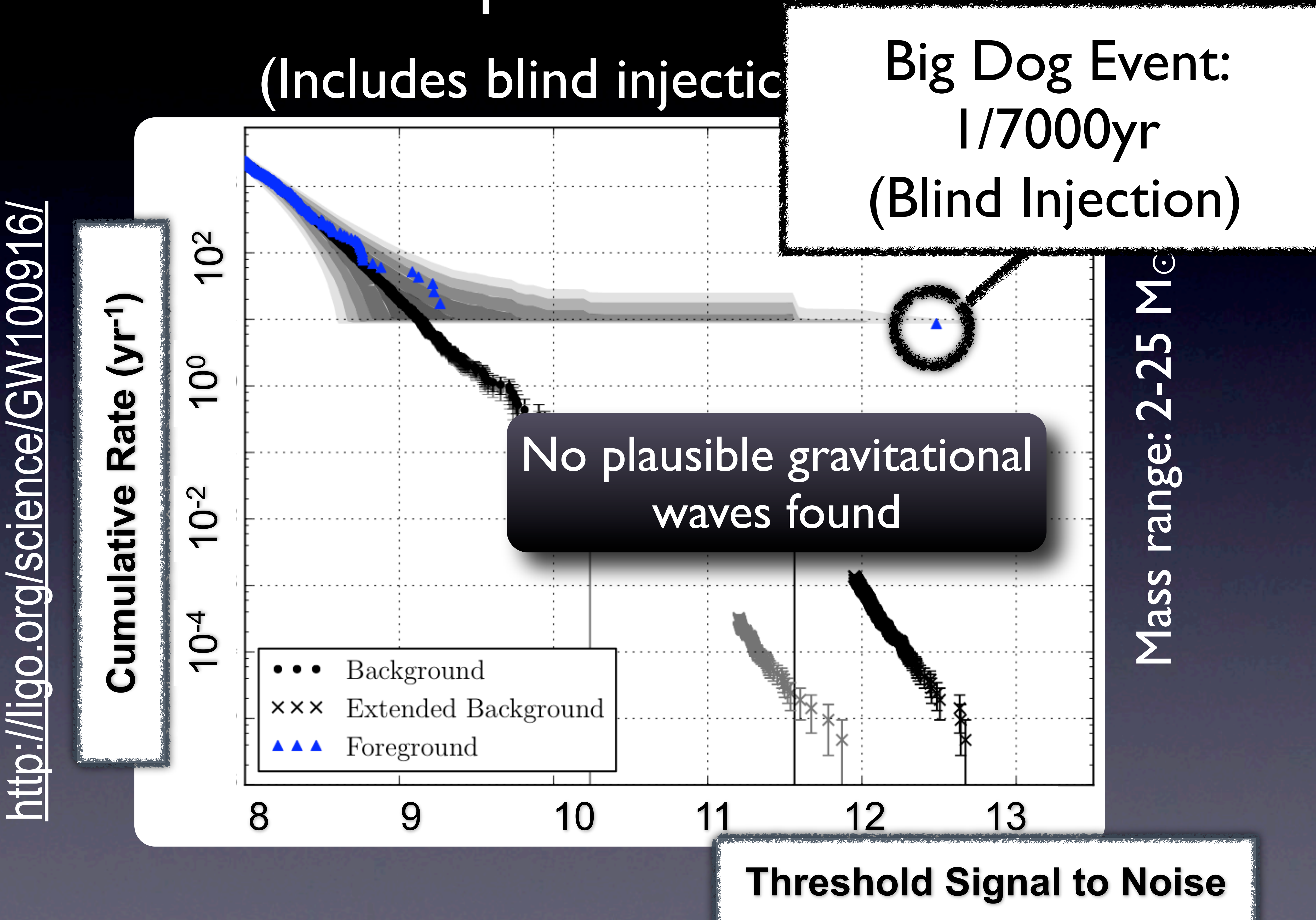
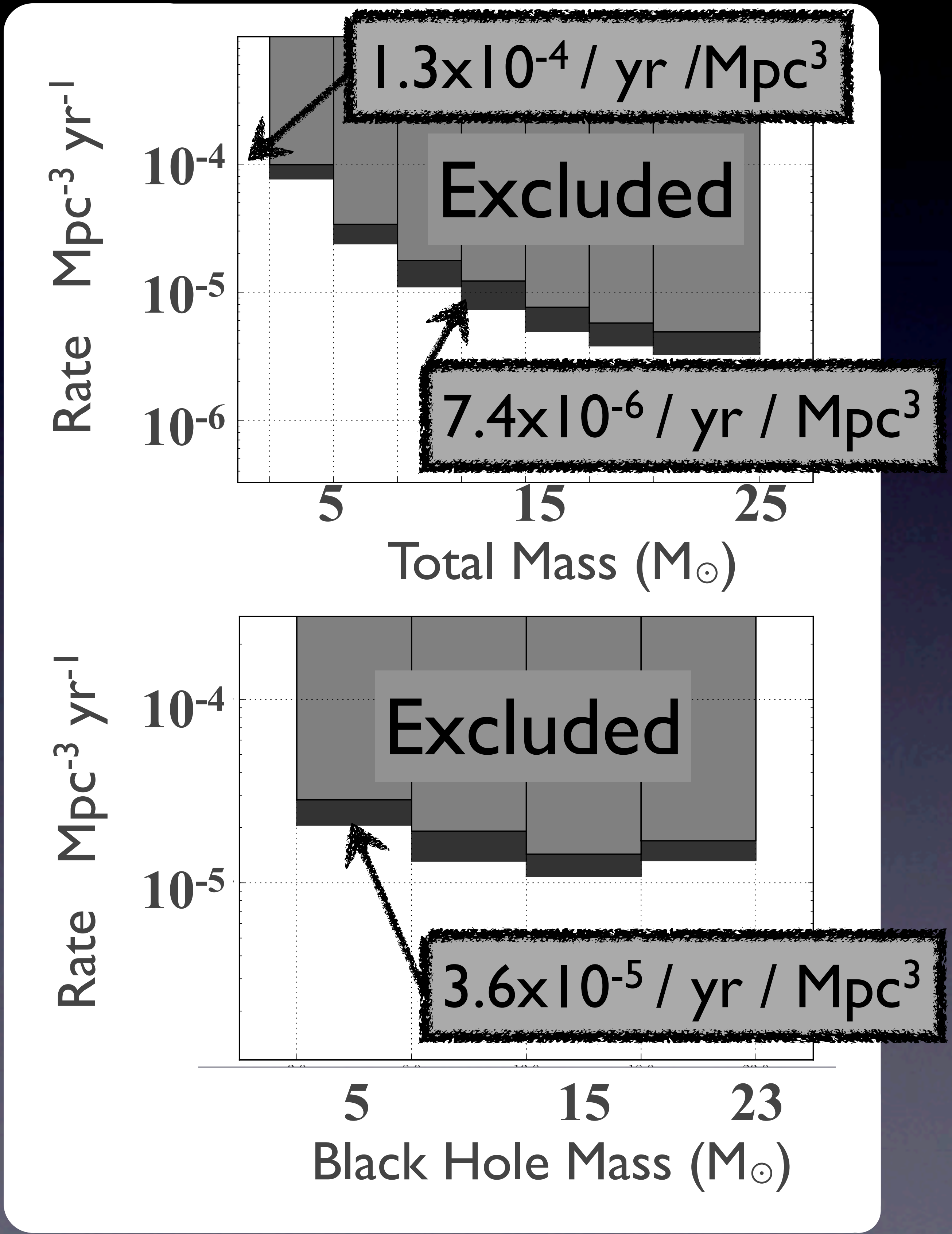


Searches for compact binaries

No plausible gravitational waves found

- Reasonable rate estimate for binary neutron stars is ~ 1×10^{-6} / yr / Mpc^3
- Neutron star black hole rates are ~3×10^{-8} / yr / Mpc^3
- Black hole binaries are ~ 5×10^{-9} / yr / Mpc^3

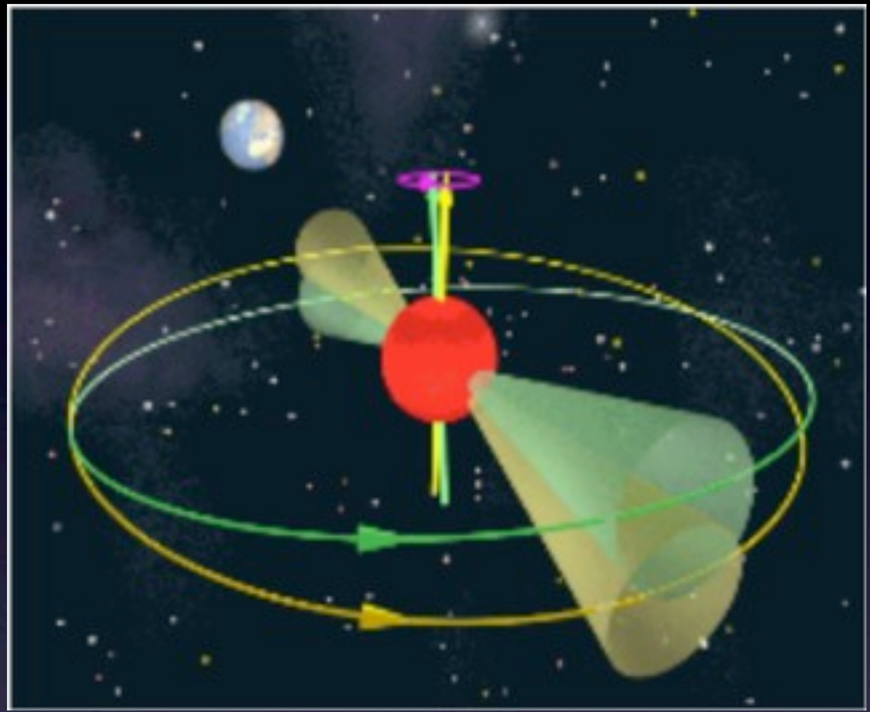
LIGO-Virgo, Phys Rev D85 (2012) 082002
[arXiv:1111.7314]



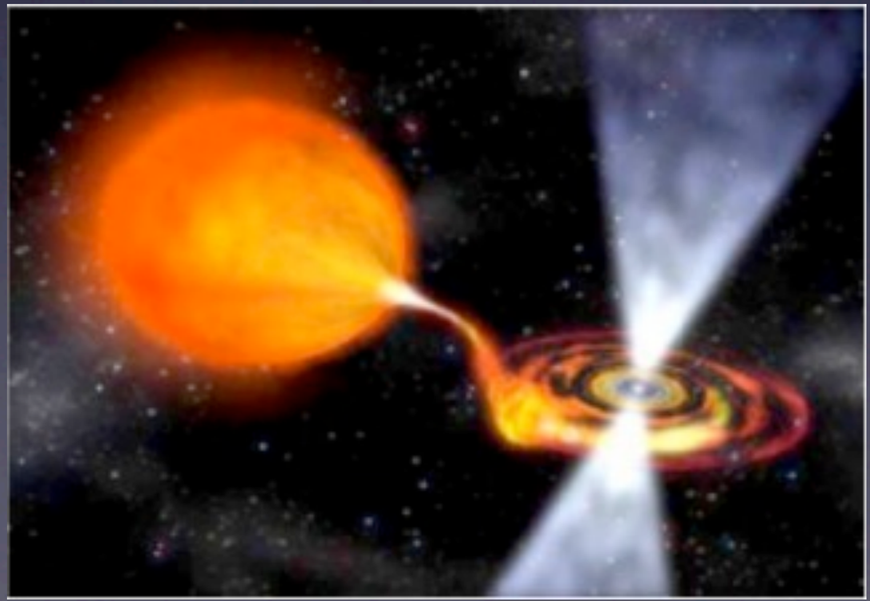
Continuous Signals

- Signals last as long as, or longer than, the observation time
- Known radio pulsars could also emit gravitational waves
- Unknown radio pulsars that are not beamed toward earth
- Signal strength is given by

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f^2}{r}$$



Credit: M. Kramer



Credit: Dana Berry/NASA

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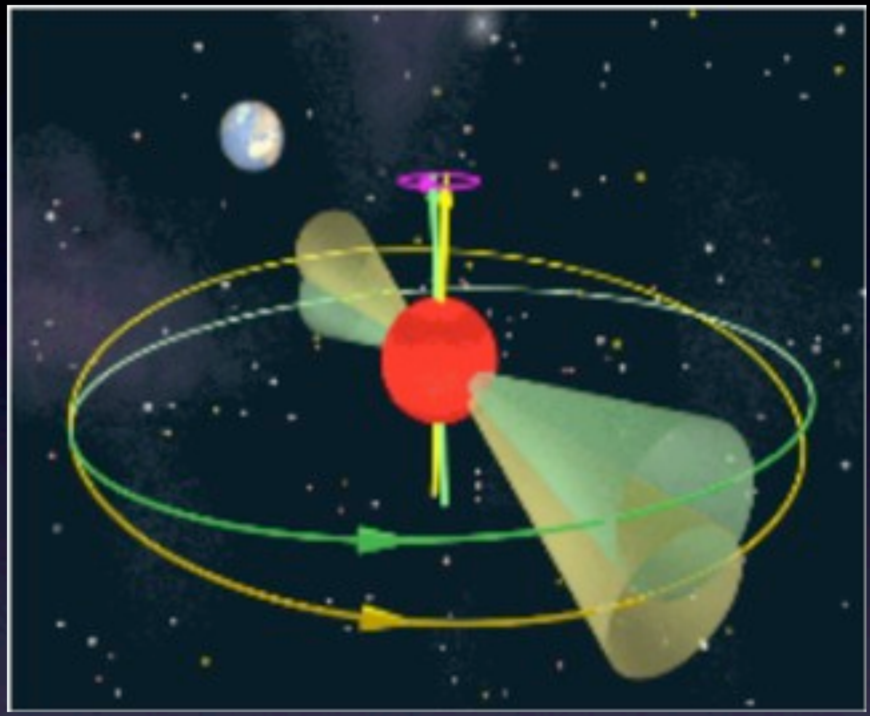
gravitational ellipticity



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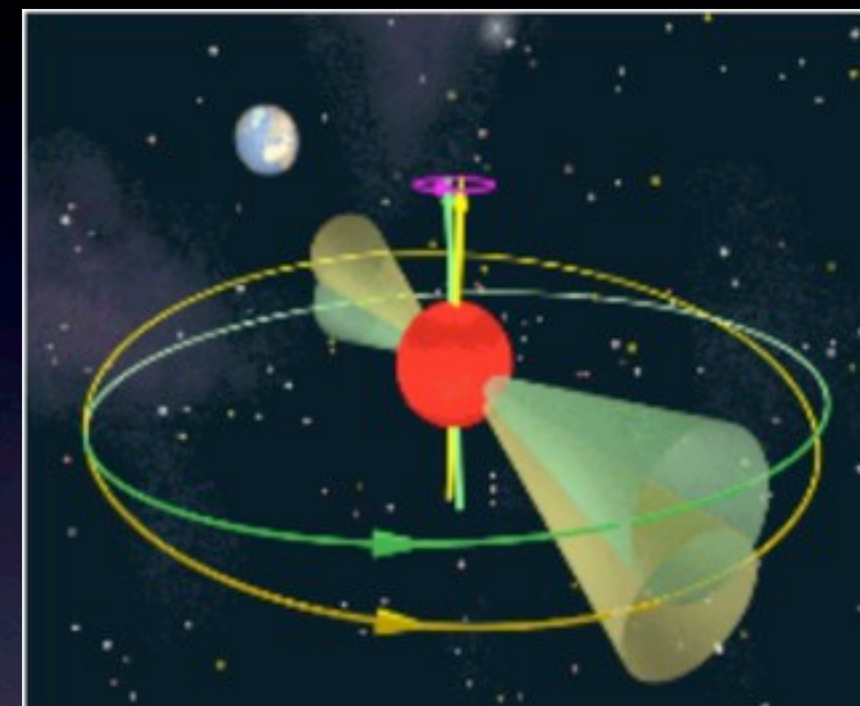
moment of inertia



Credit: M. Kramer

Credit: Dana Berr

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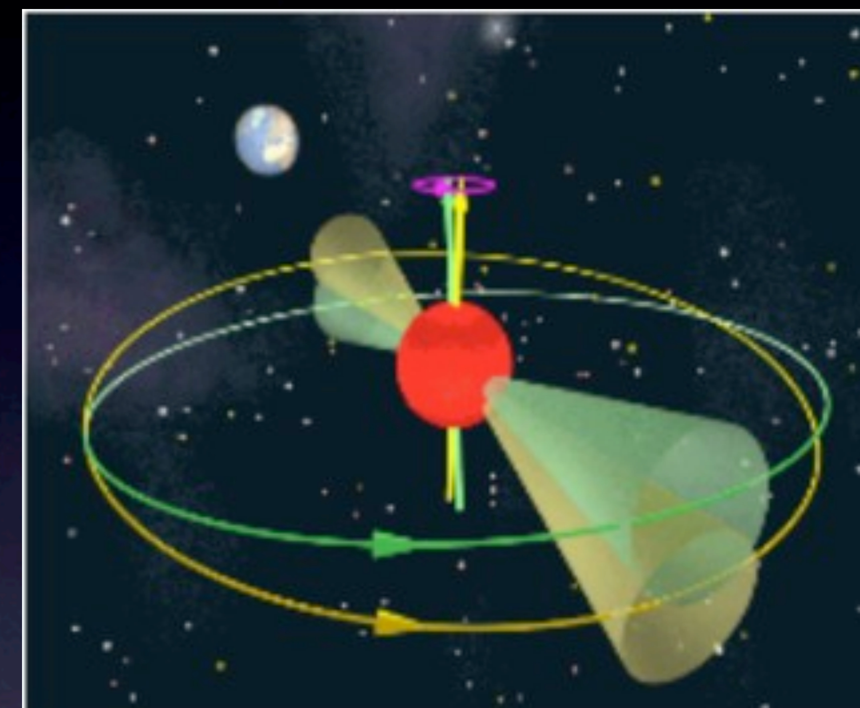
rotational frequency



Credit: M. Kramer

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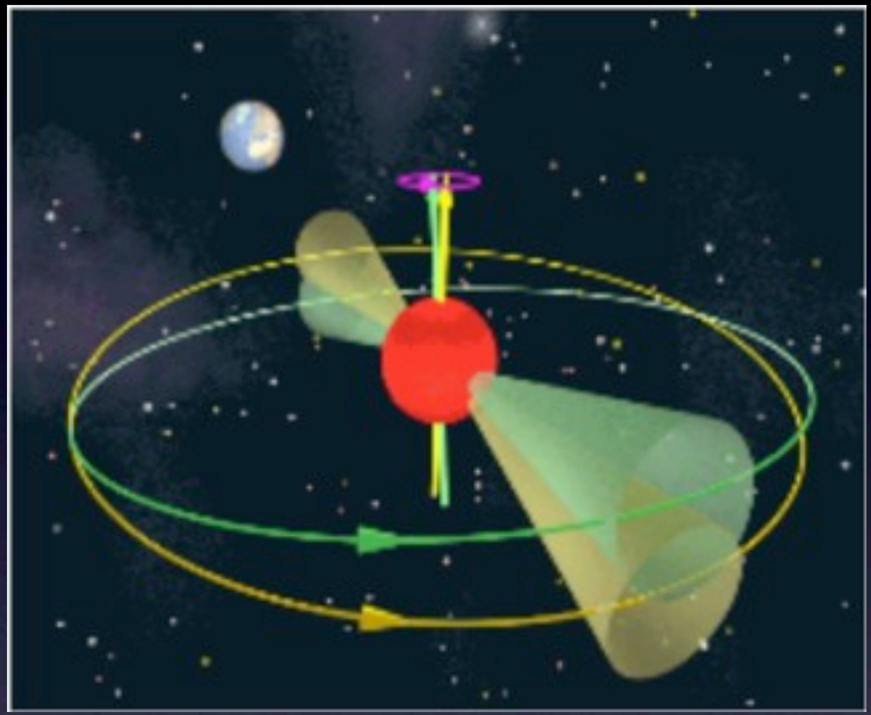
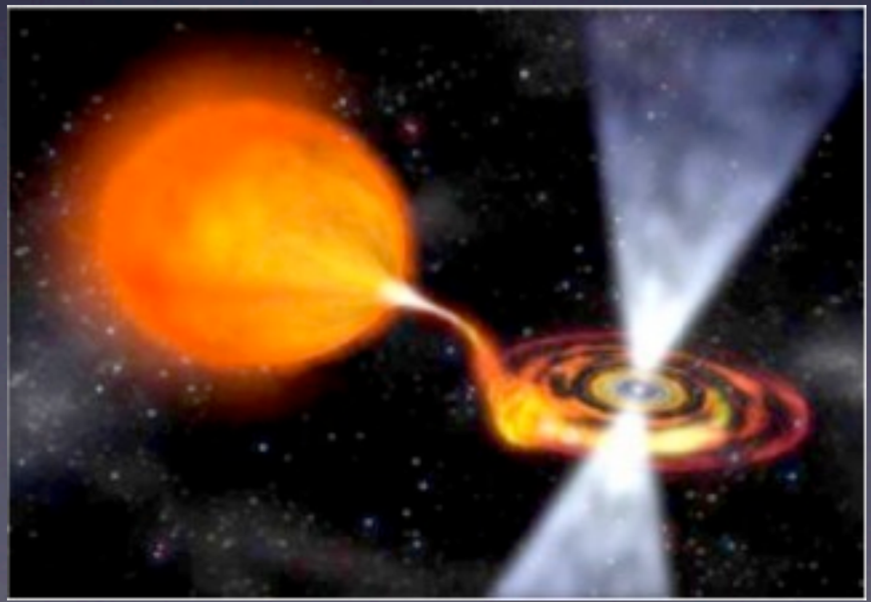


Credit: M. Kramer

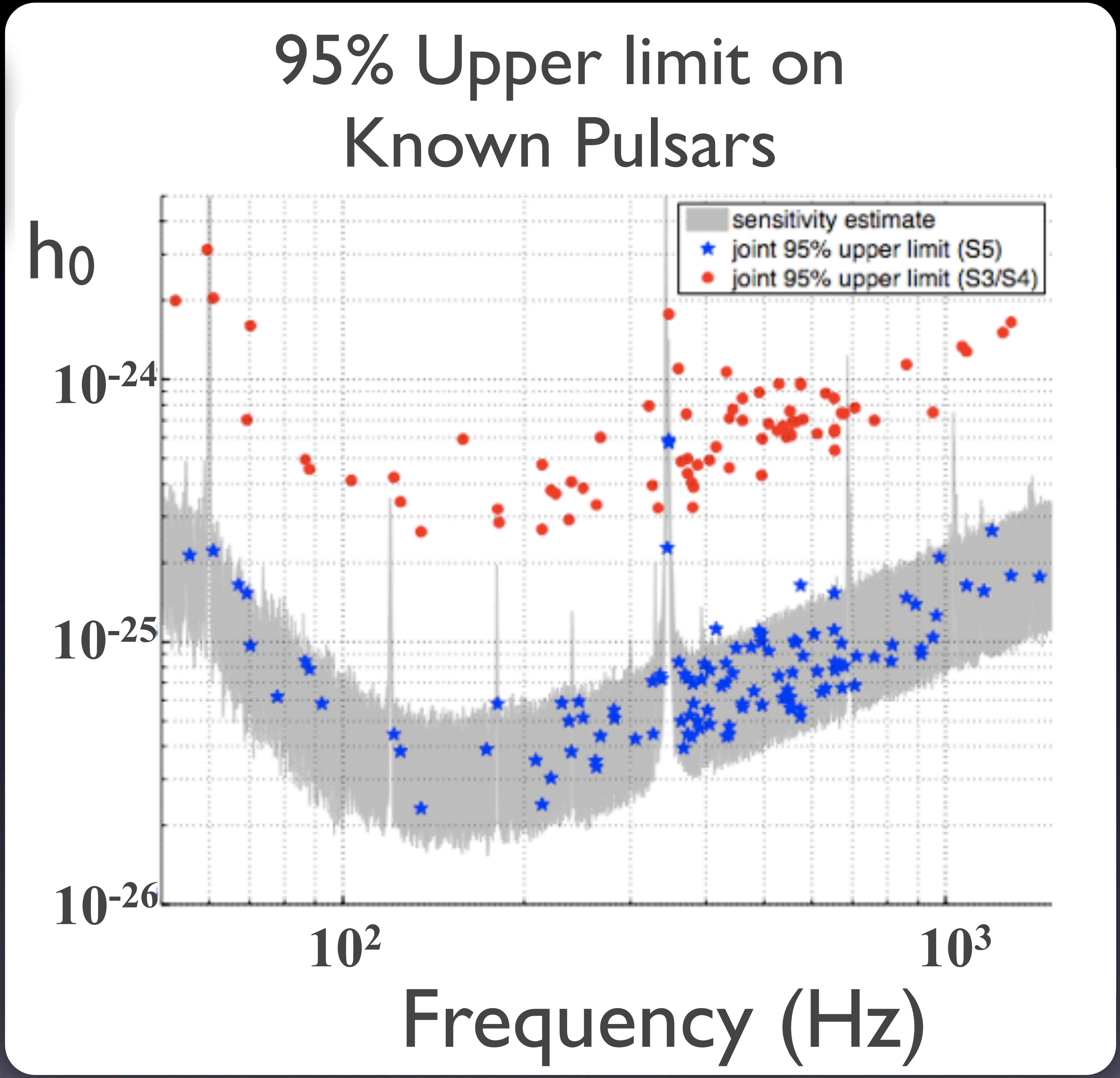


Credit: Dana Berry/NASA

Searches for continuous waves

No plausible gravitational waves found

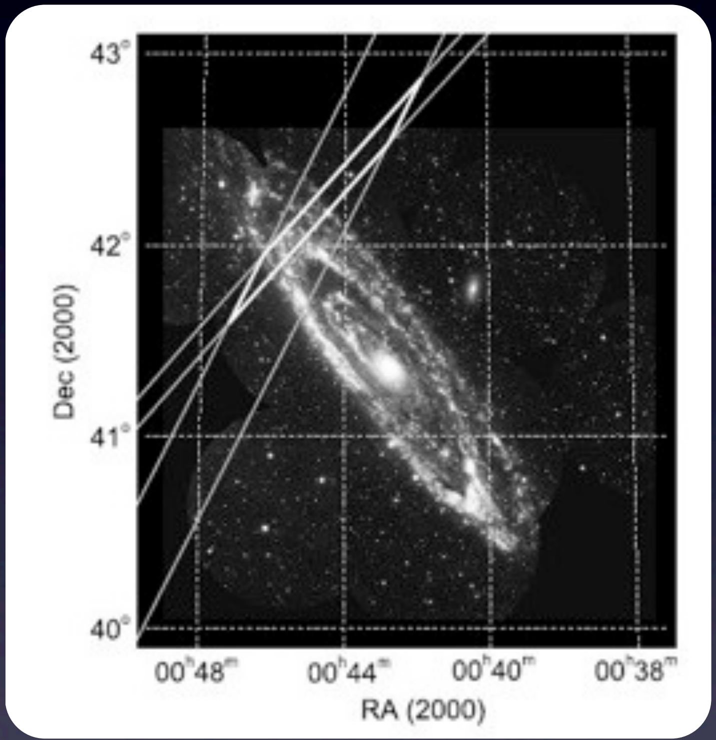
- Strength of gravitational waves depends on gravitational ellipticity
- Radio observations of Crab pulsar spindown constrain maximum gravitational ellipticity around 10^{-3}
- LIGO-Virgo non-detection of gravitational waves constrains gravitational ellipticity of Crab at $\sim 10^{-4}$

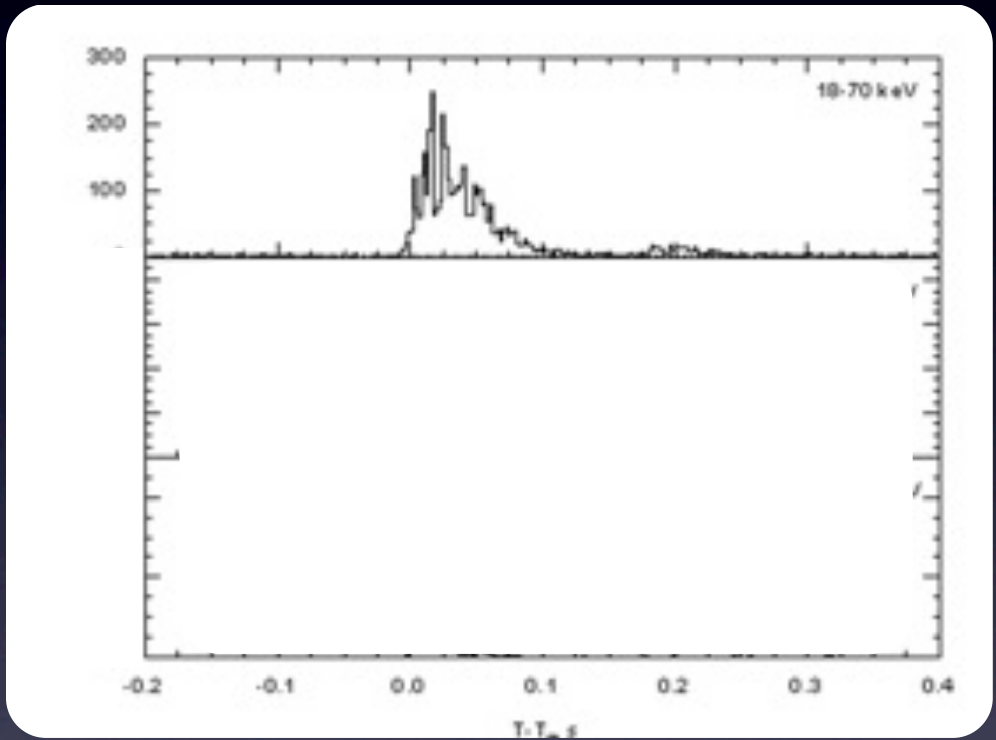


LIGO-Virgo, "Searches for gravitational waves from known pulsars with S5 LIGO data," Astrophys. J. 713 (2010) 671 [arXiv:0909.3583]

GW Astronomy

Trying to add a soundtrack to astronomical events





- Soft-gamma Repeaters. LSC, Phys. Rev. D 76 (2007) 062003 [astro-ph/0703419]; Astrophys. J. 701 (2009) L68-L74. [arXiv:0905.0005]
- Gamma-ray Bursts. LSC, Phys. Rev. D 77 (2008) 062004 [arXiv:0709.0766]; Astrophys. J. 681 (2008) 1419 [arXiv:0711.1163].
- Gamma-ray Bursts. LIGO-Virgo, Astrophys. J. 715 (2010) 1438 [arXiv:0908.3824]; Astrophys. J. 715 (2010) 1453 [arXiv:1001.0165]; Astrophys. J. 760 (2012) 12 [arXiv:1205.2216]

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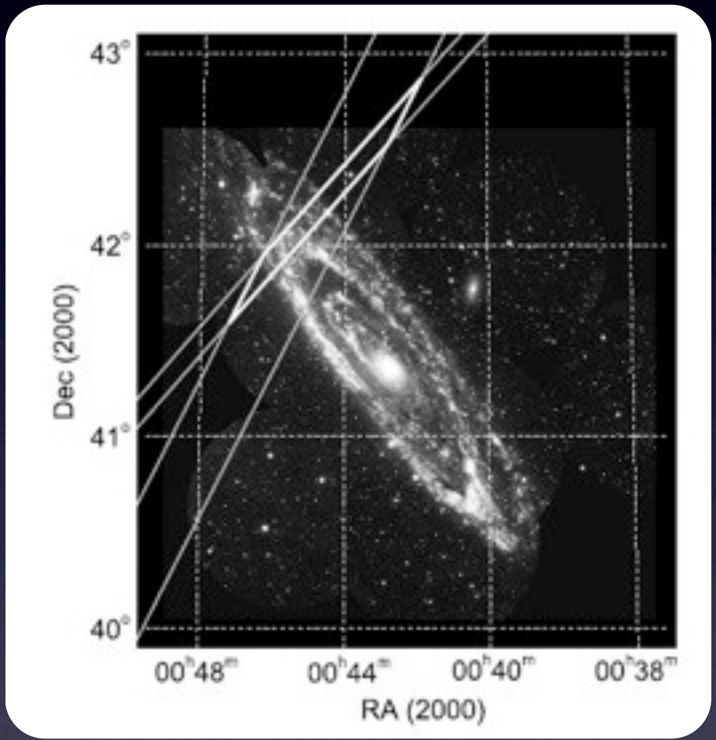

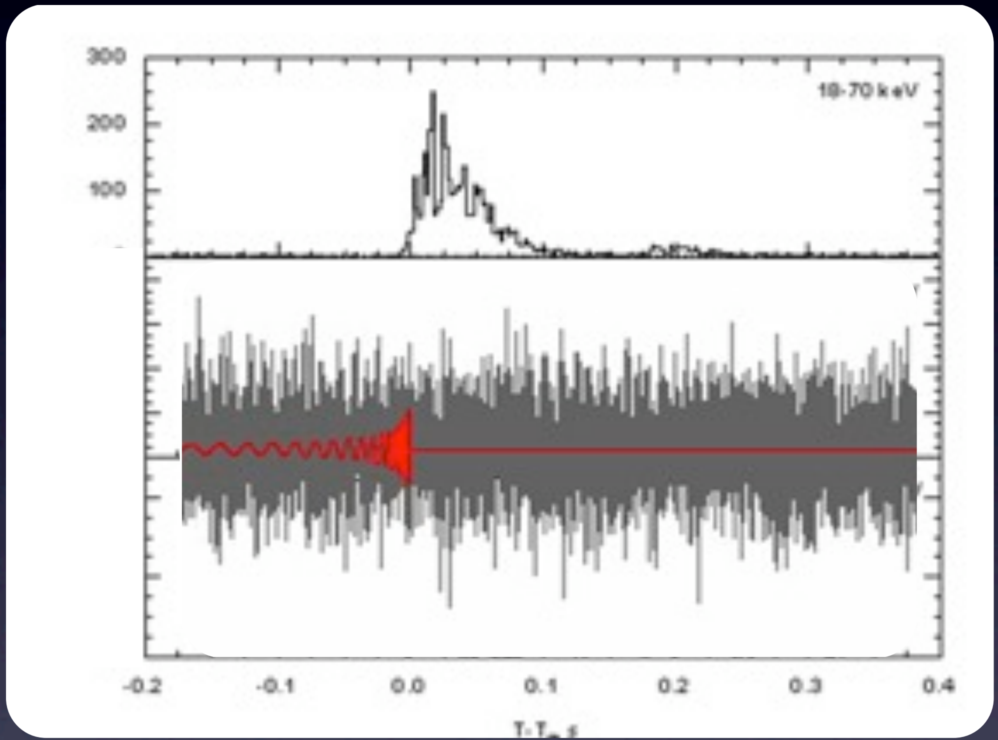

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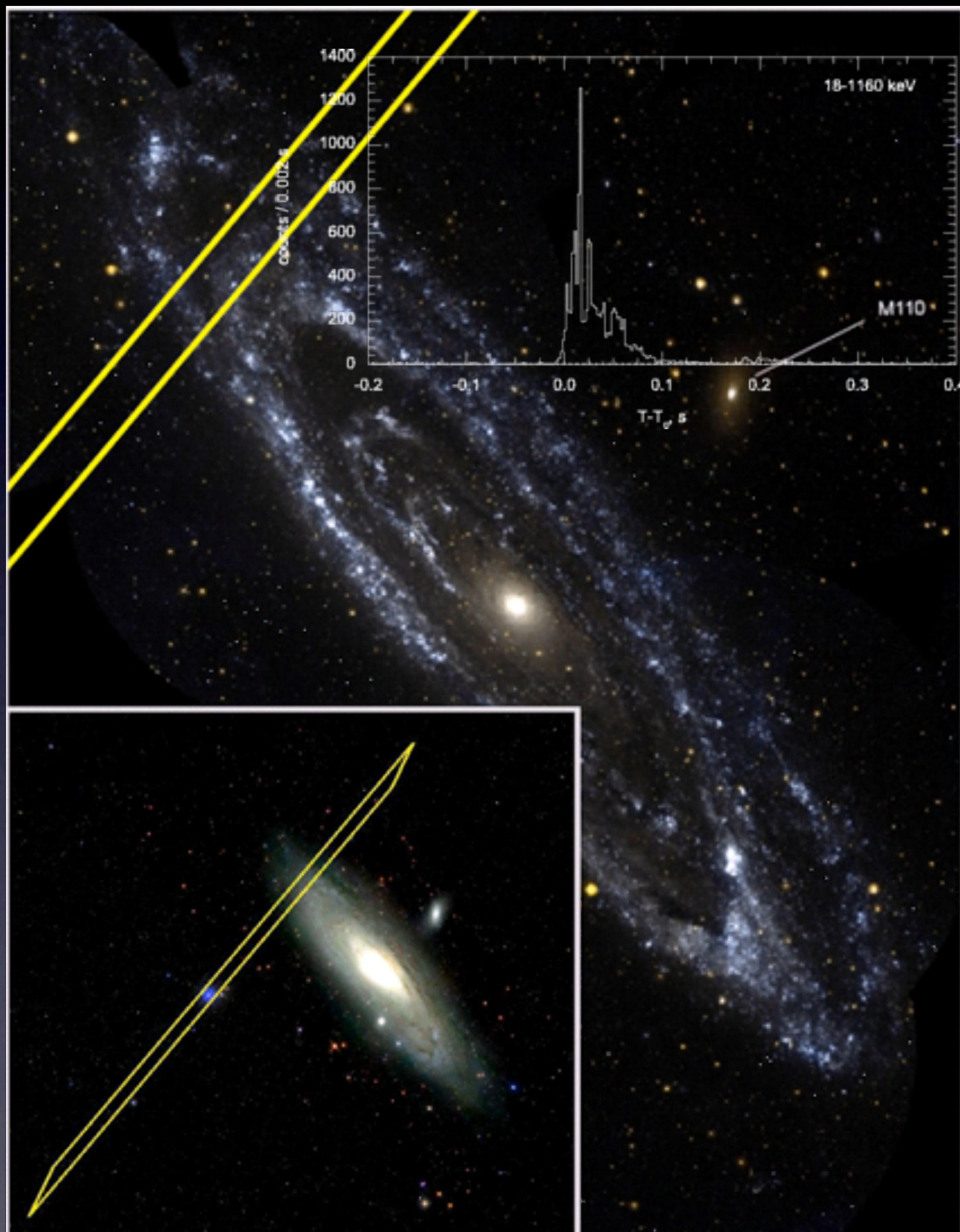
Example: GRB 070201



- Short gamma-ray burst
- Interplanetary Network error box included M31 at ~700 kpc!
- Ruled out compact binary progenitor in M31, but could not rule out SGR.

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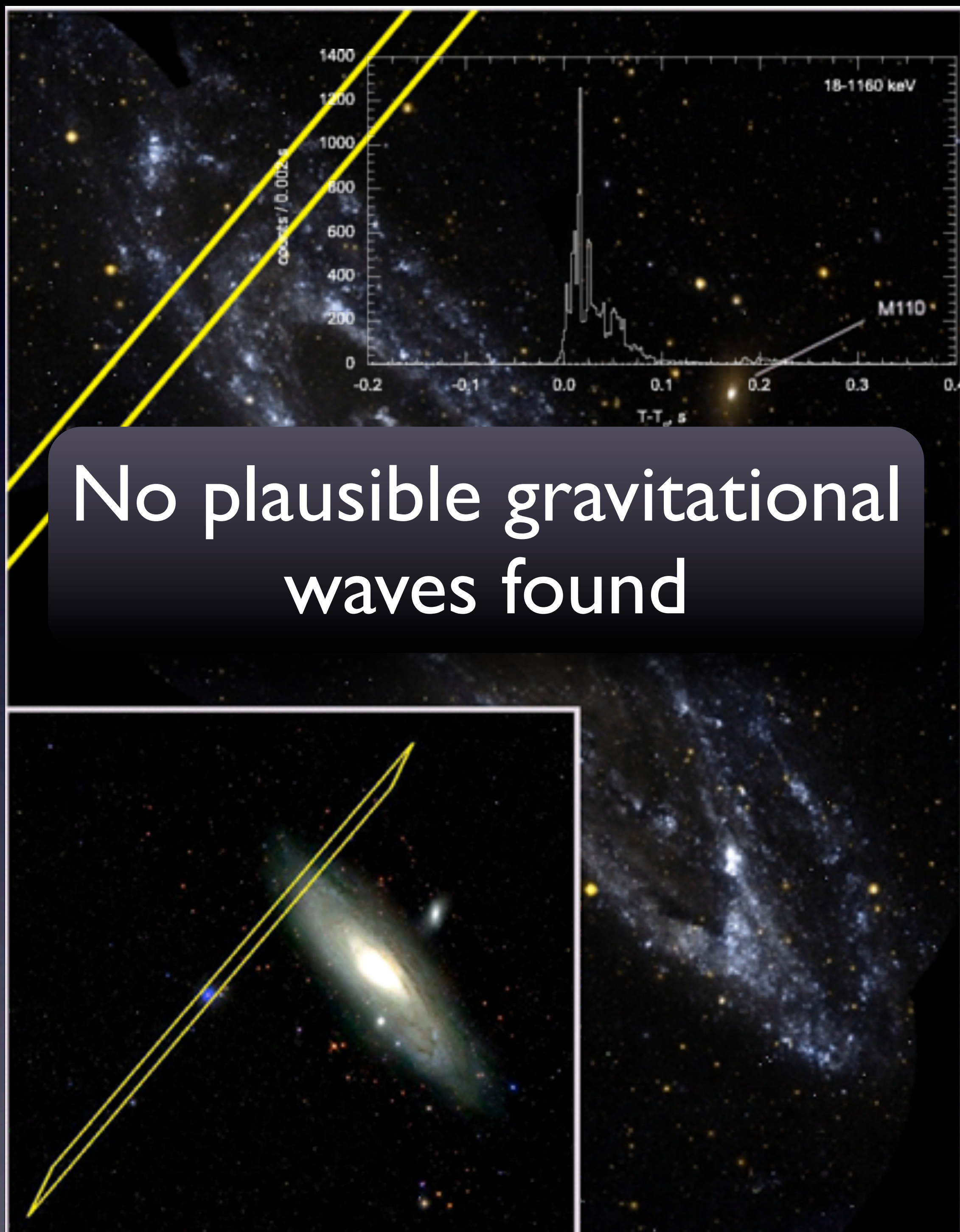

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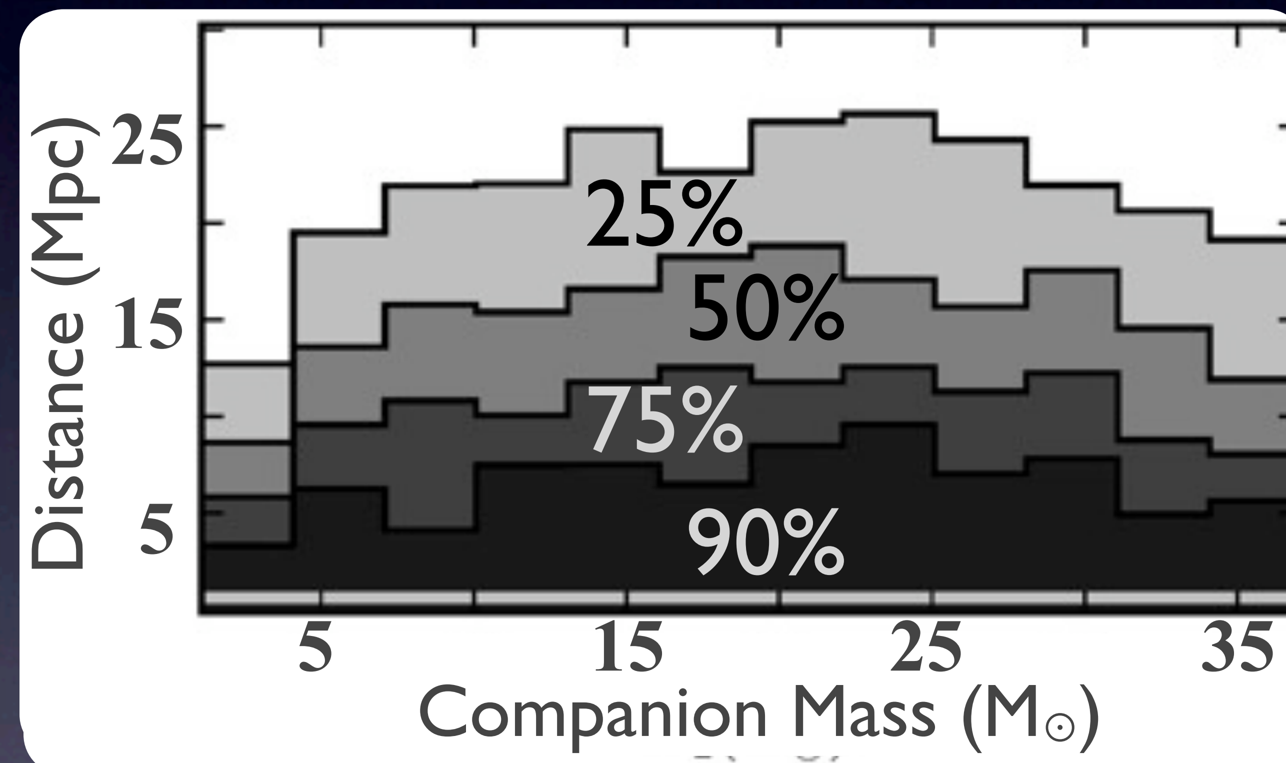

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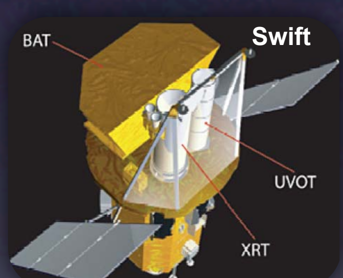
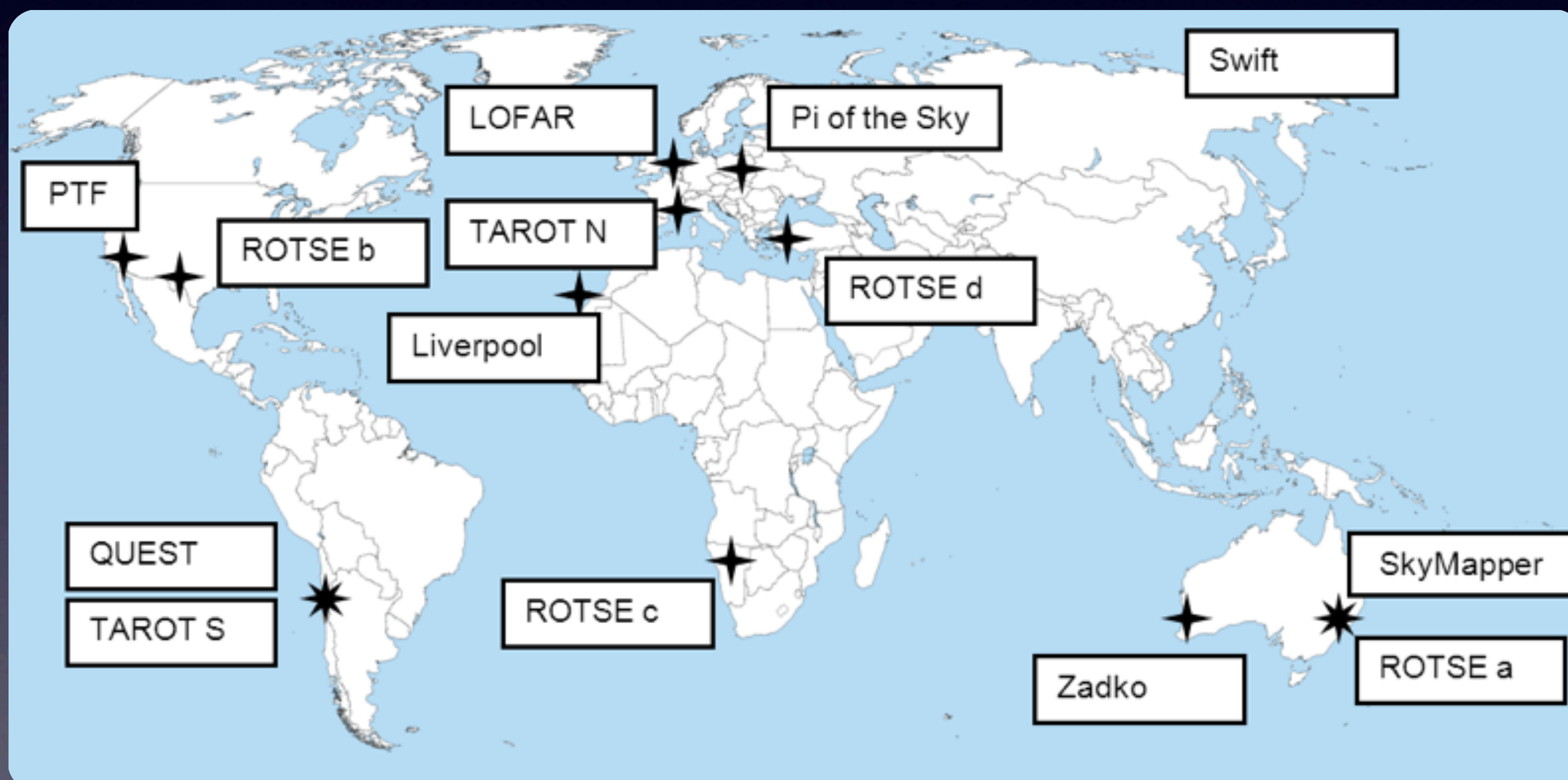
LSC. "Implications for the Origin of GRB 070201 from LIGO Observations", Ap. J., 681:1419–1430 (2008). arXiv:0711.1163

Connecting GW and EM observations



- LIGO-Virgo partners for the S6/VSR2/VSR3 science runs



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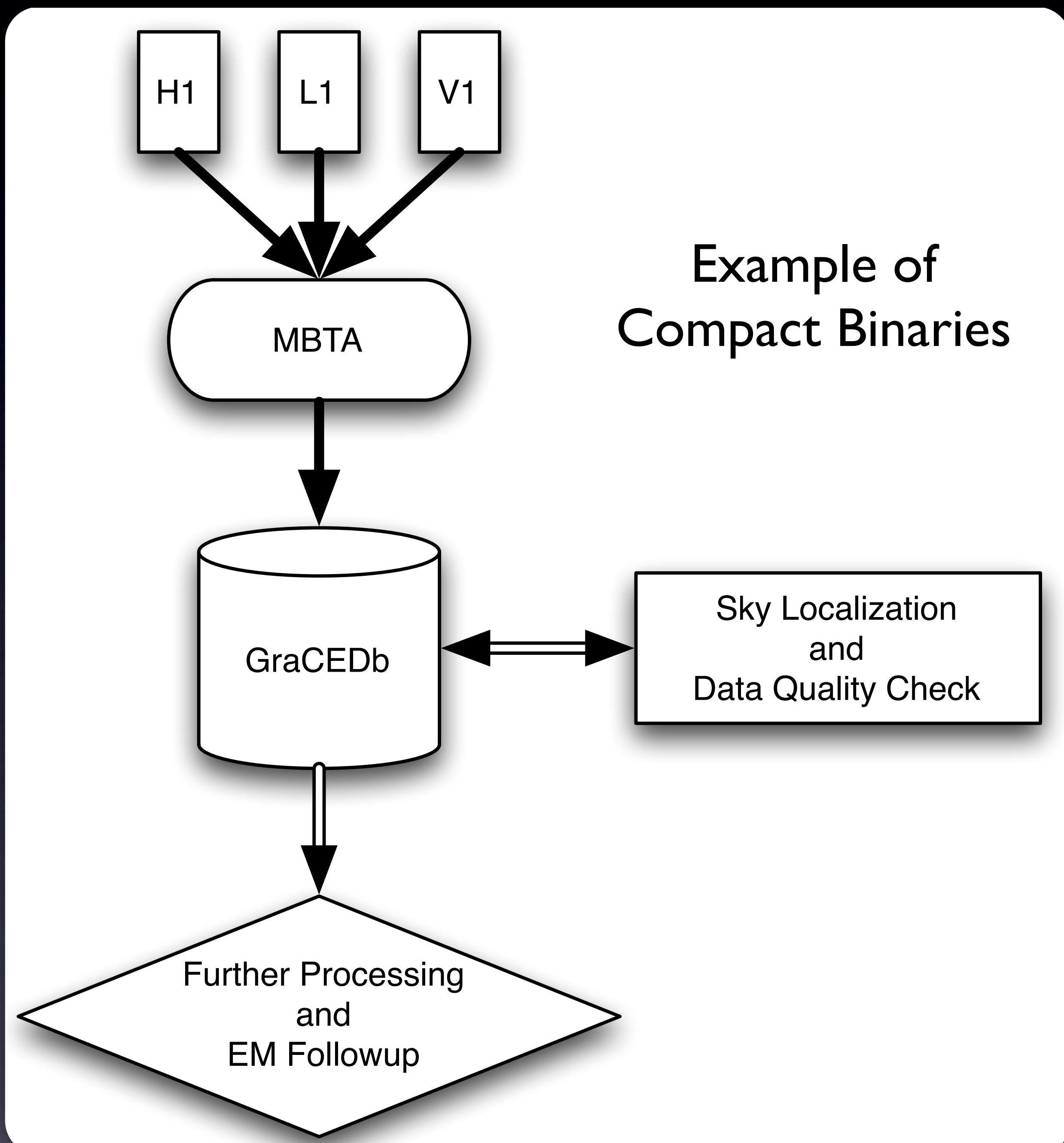
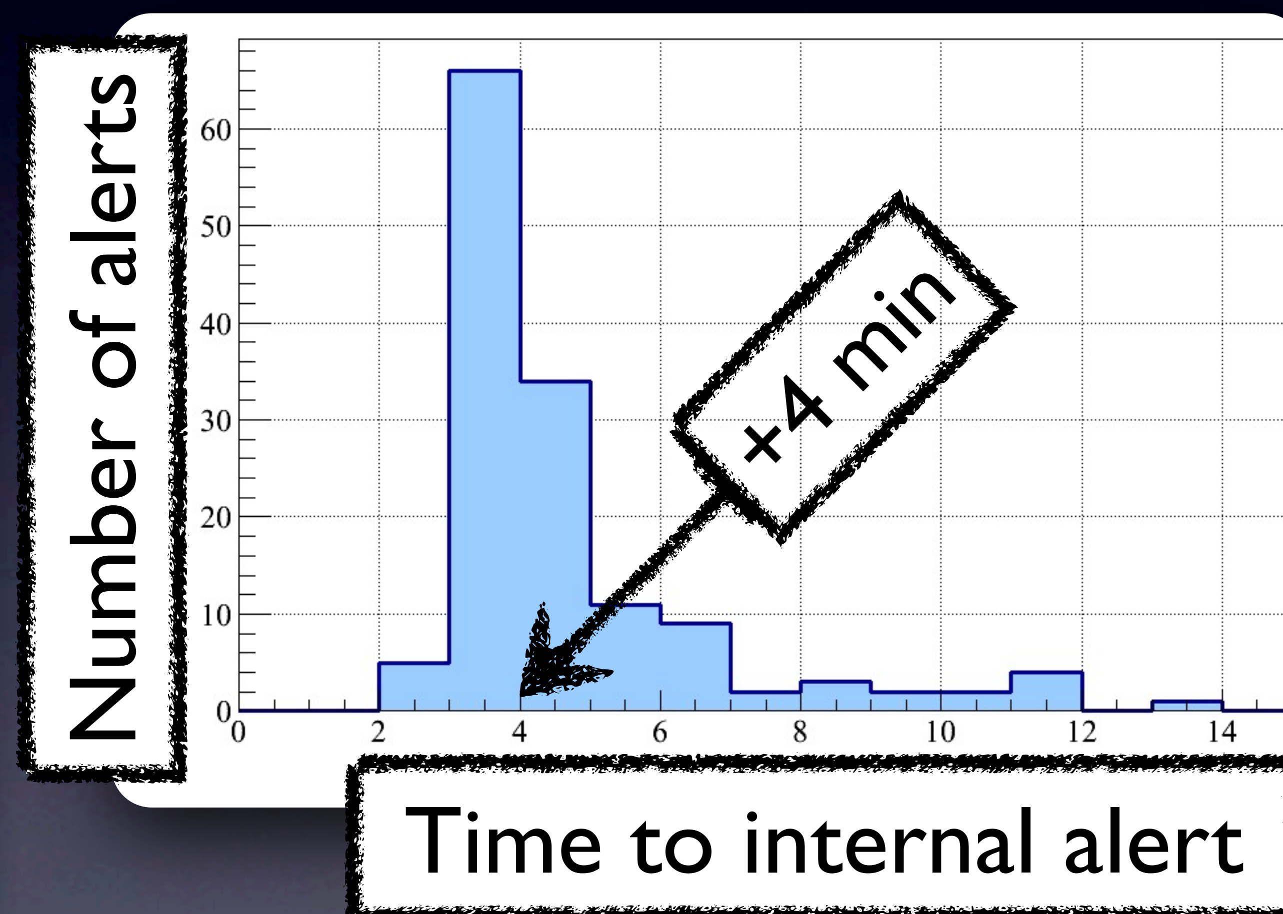
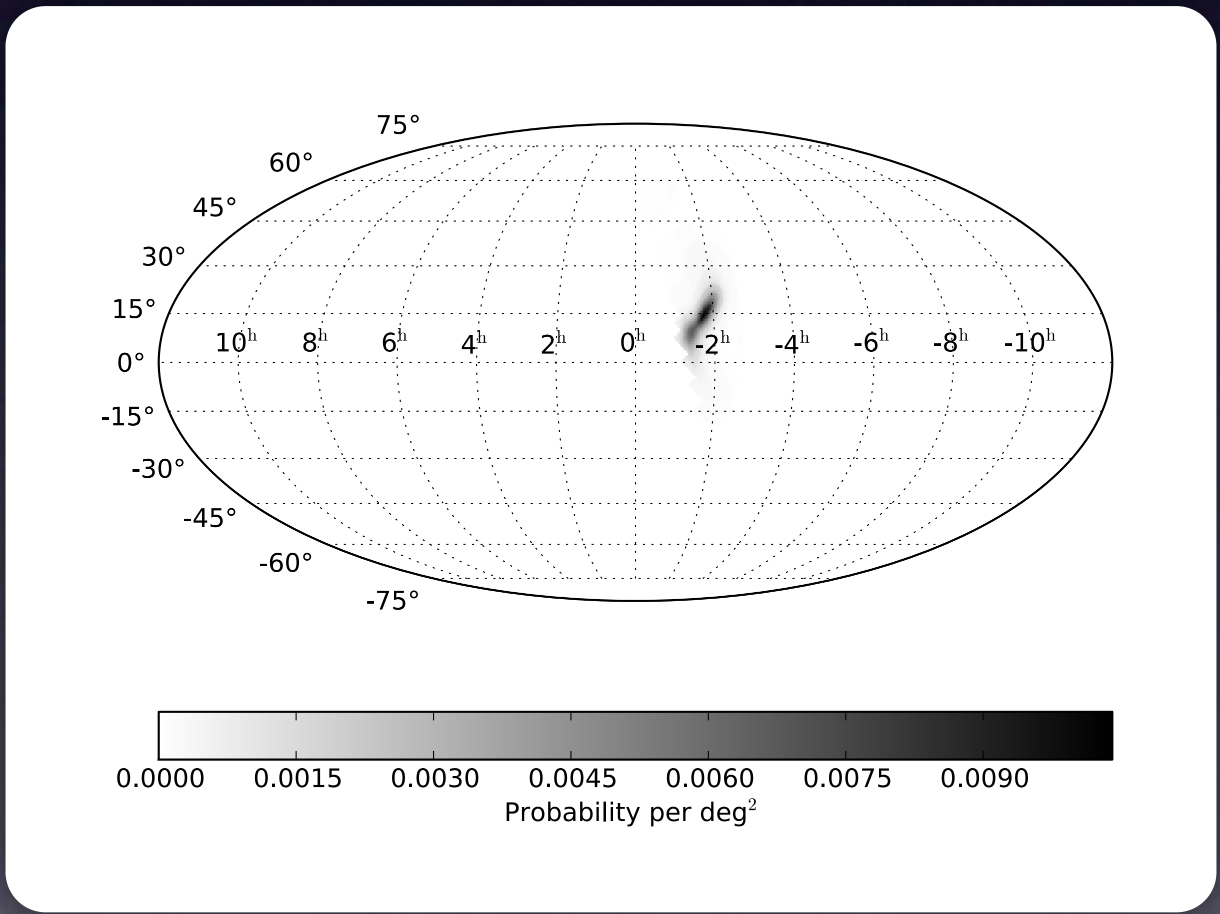
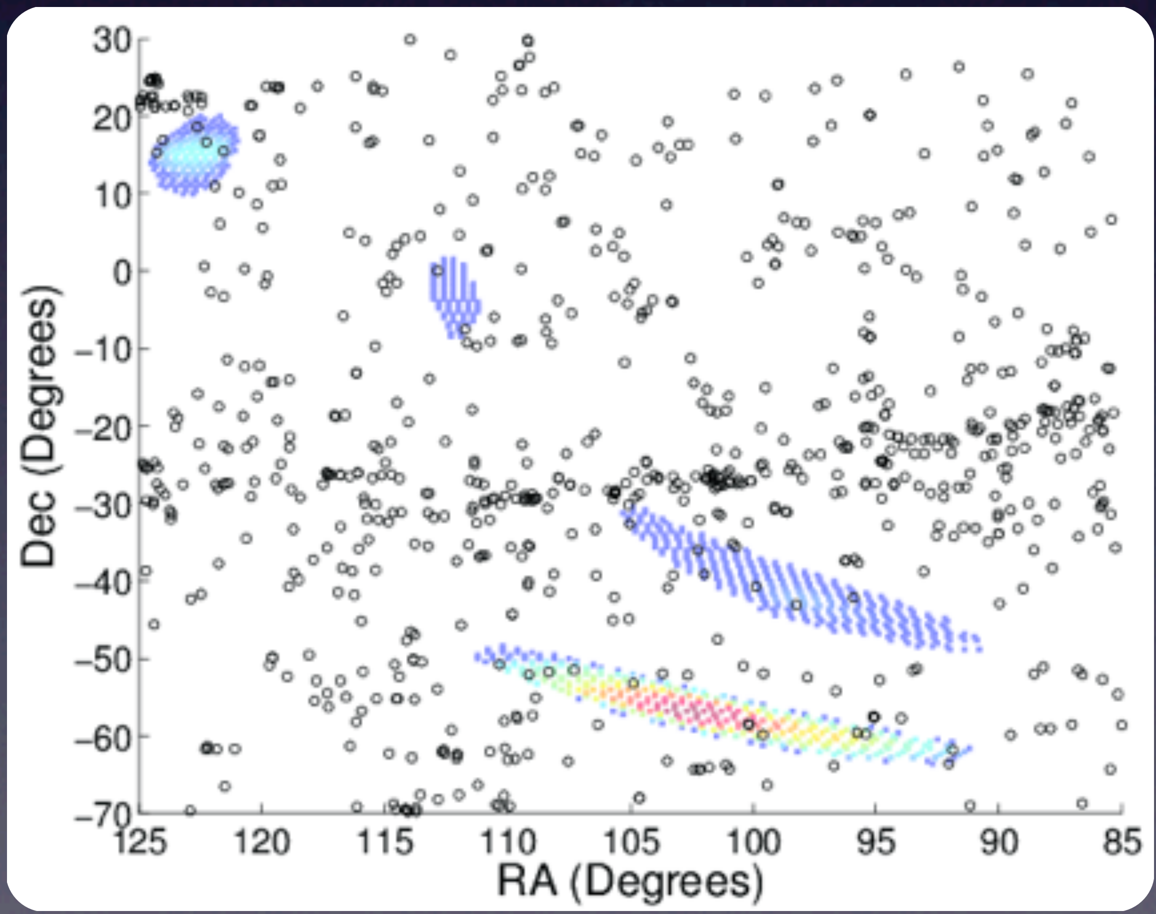




+45min

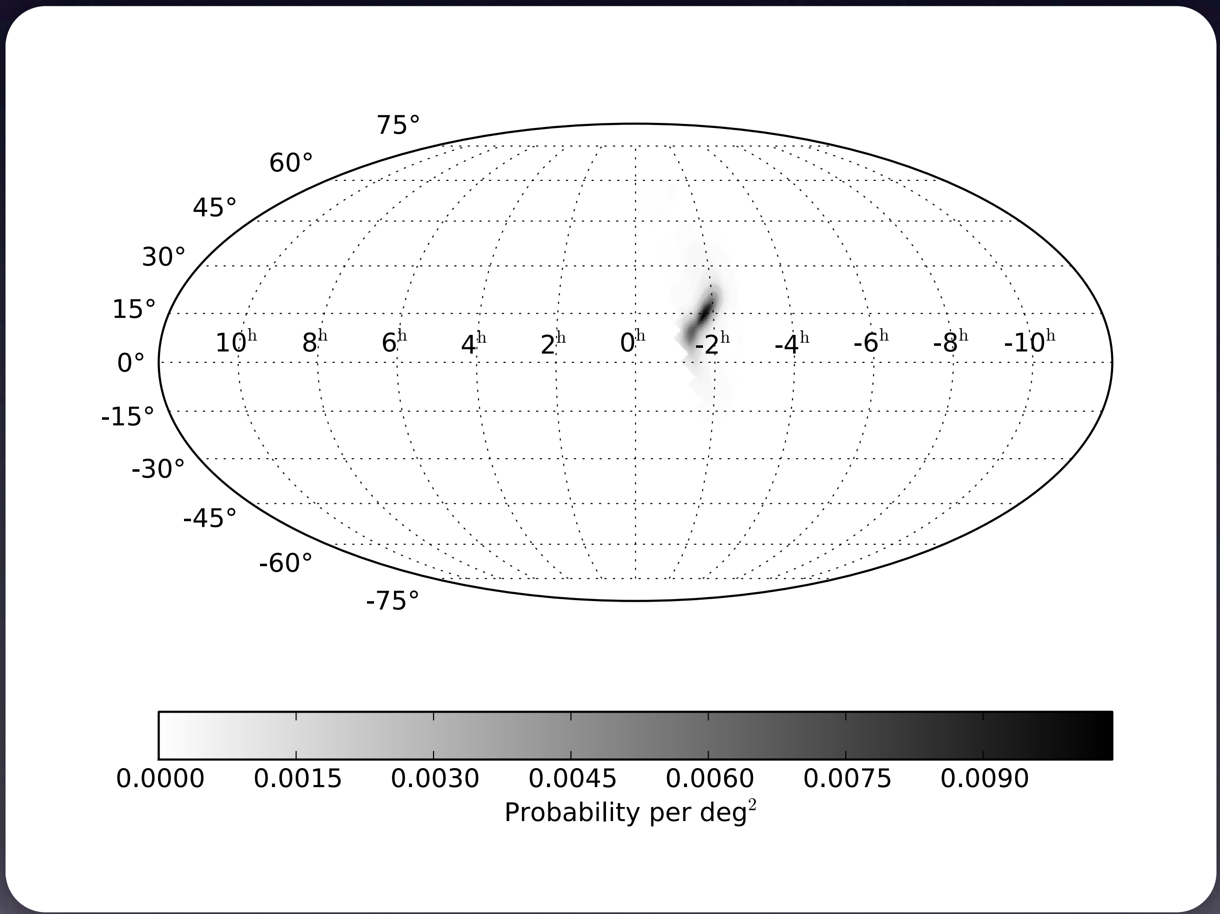
Sky Maps

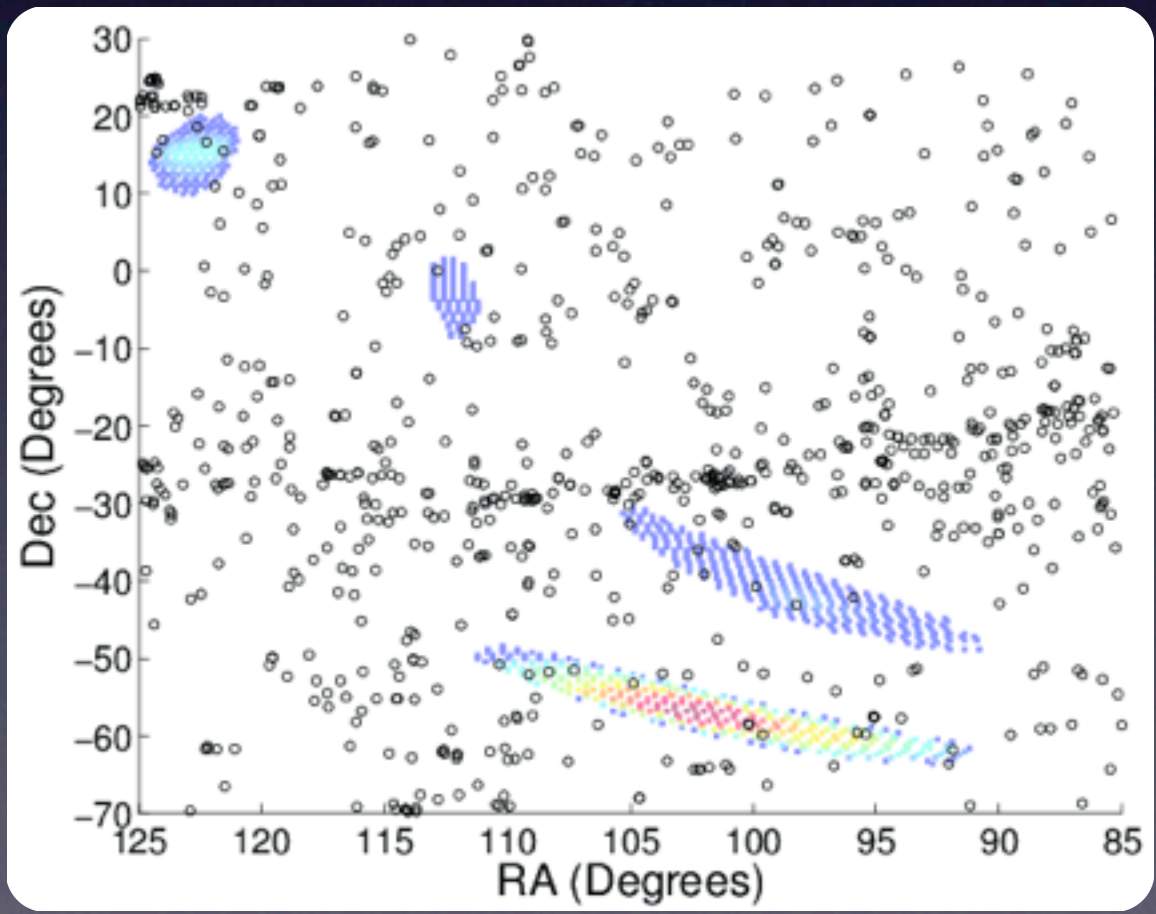

75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
10h 8h 6h 4h 2h 0h -2h -4h -6h -8h -10h
0.0000 0.0015 0.0030 0.0045 0.0060 0.0075 0.0090
Probability per deg2


Dec (Degrees)
30 20 10 0 −10 −20 −30 −40 −50 −60 −70
125 120 115 110 105 100 95 90 85
RA (Degrees)

Sky Maps

No plausible gravitational waves found

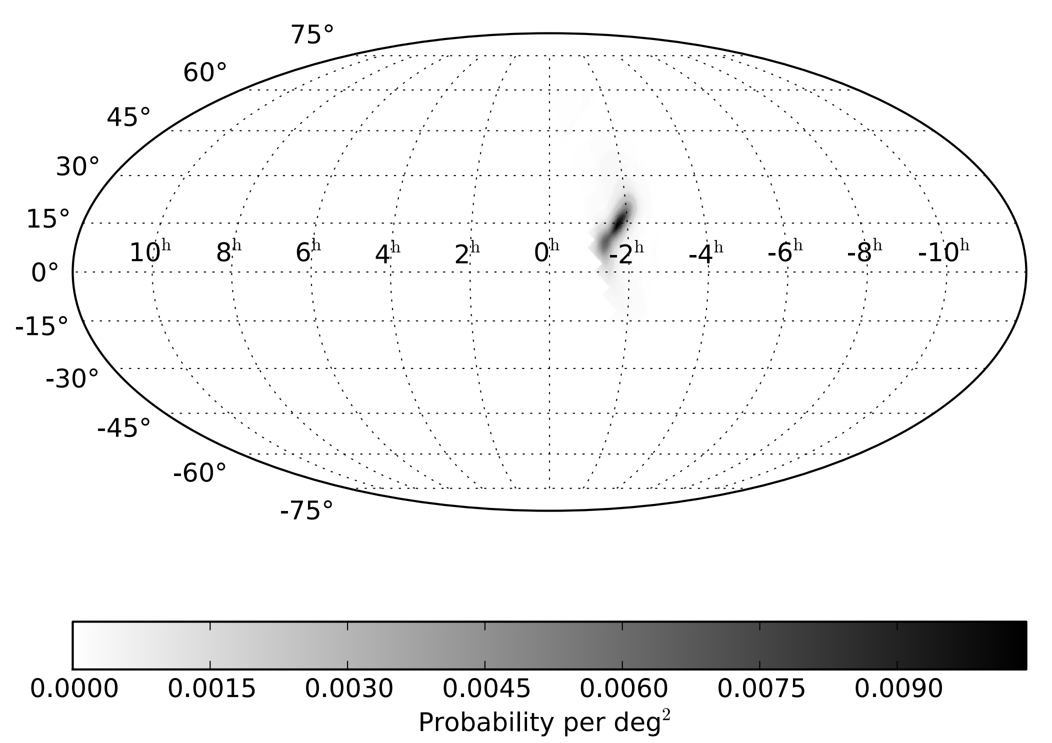


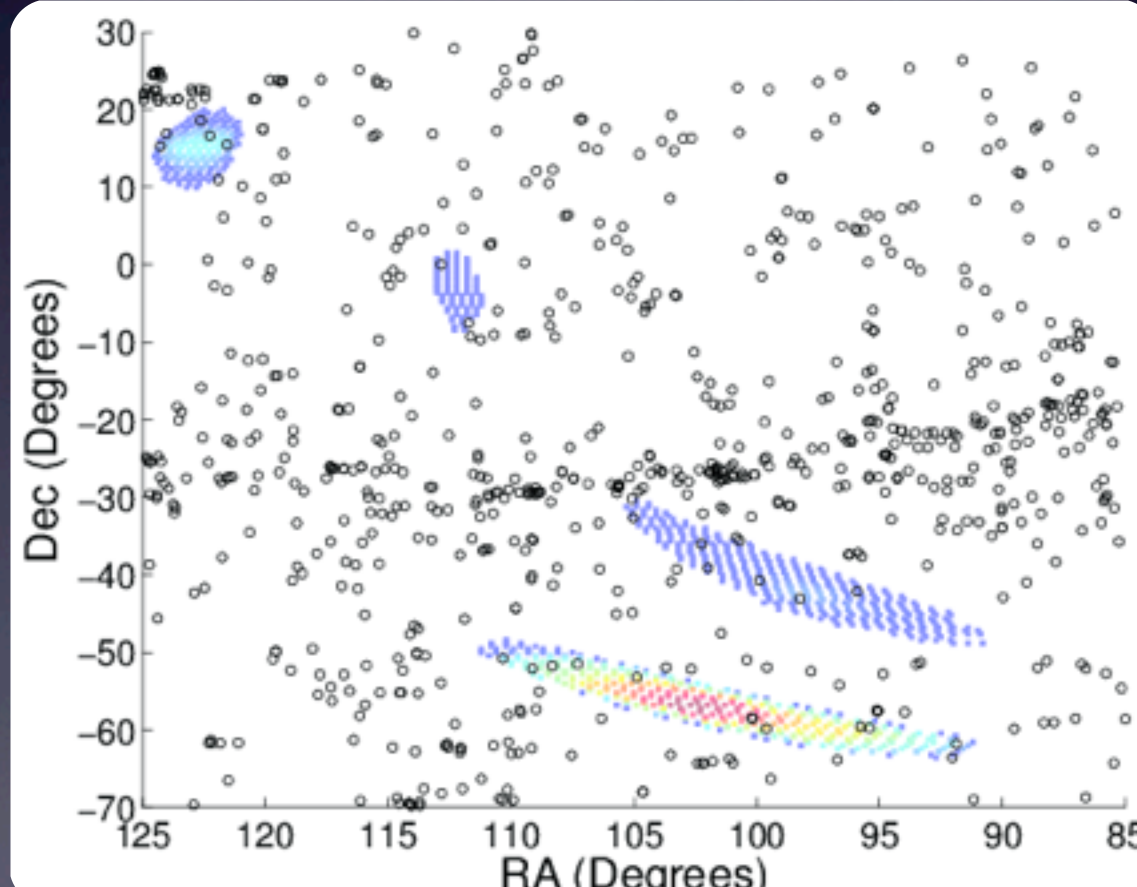


Sky Maps

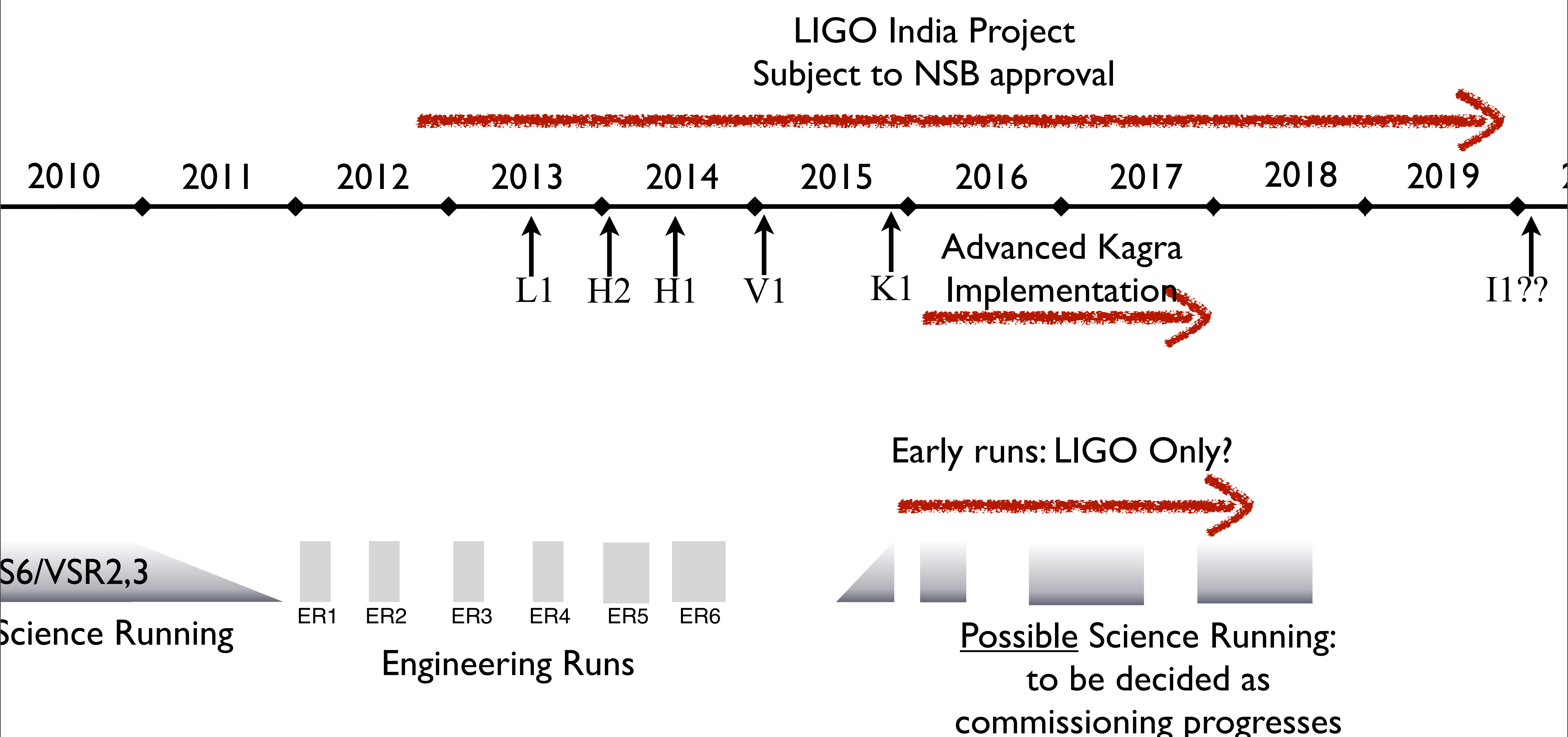
No plausible gravitational waves found

Analysis of EM data forthcoming

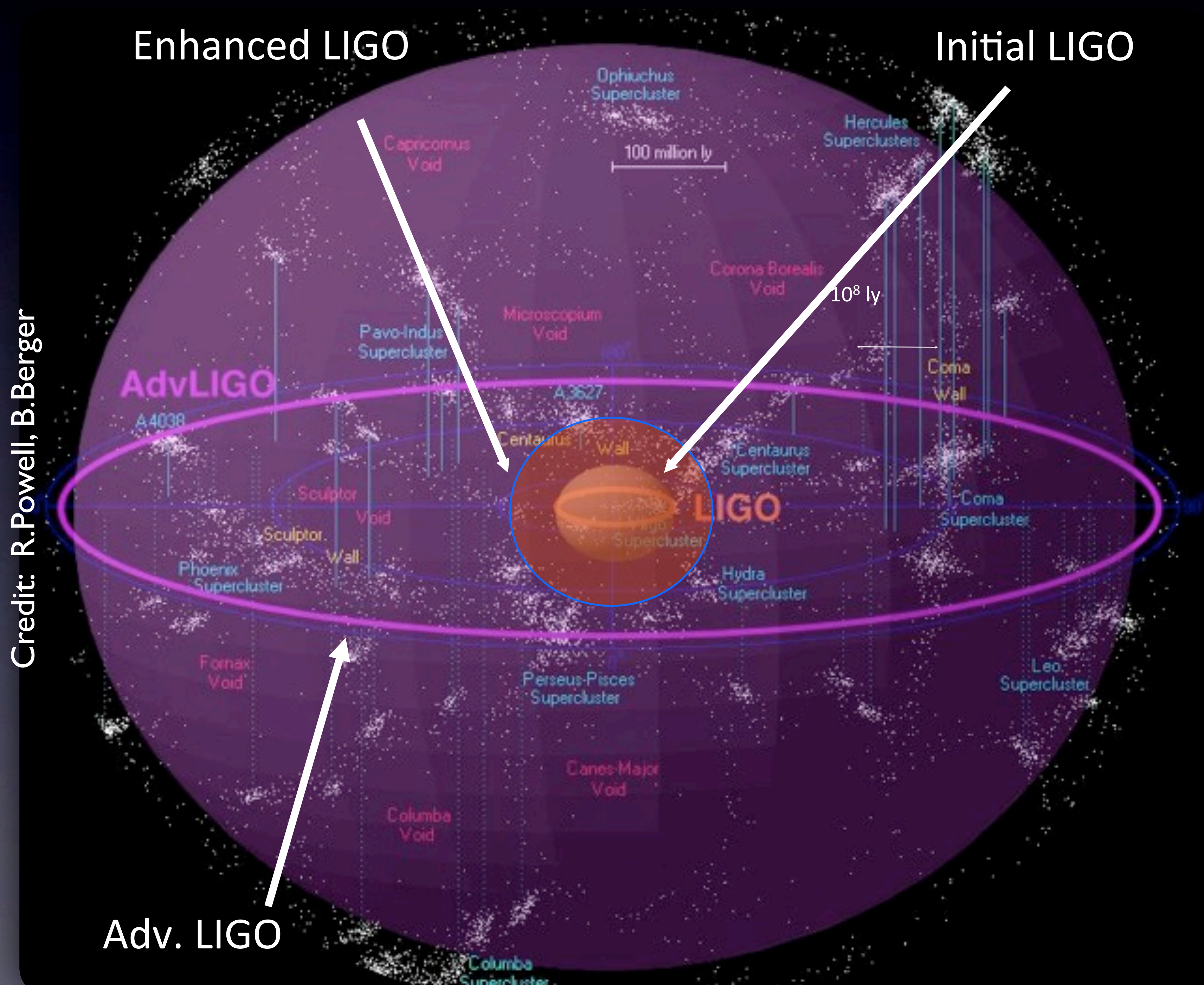




Tentative Timing



Looking forward to 2016



- Advanced LIGO
    - project in full swing
    - acceptance 2014/15
- 10 x Initial LIGO
- 1000 x more sources
- 40 BNS per year