Gravitational Waves: Celestial Soundtrack

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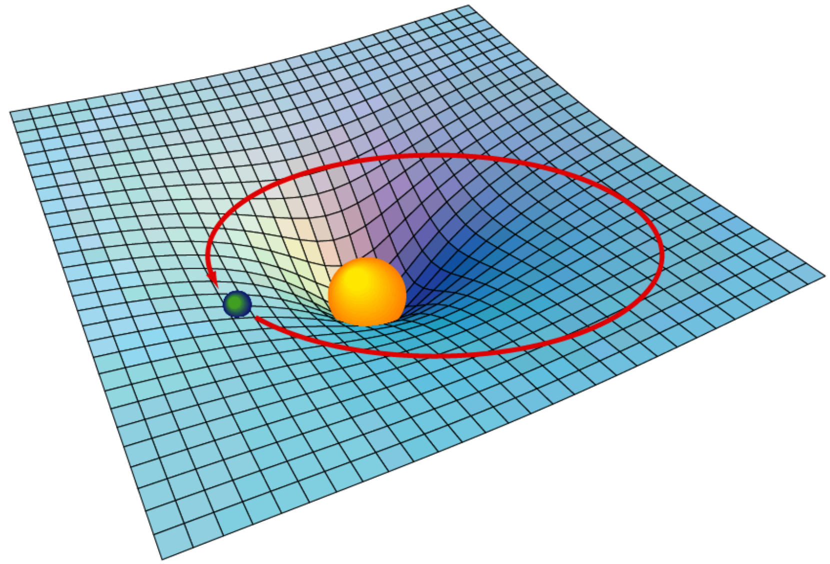
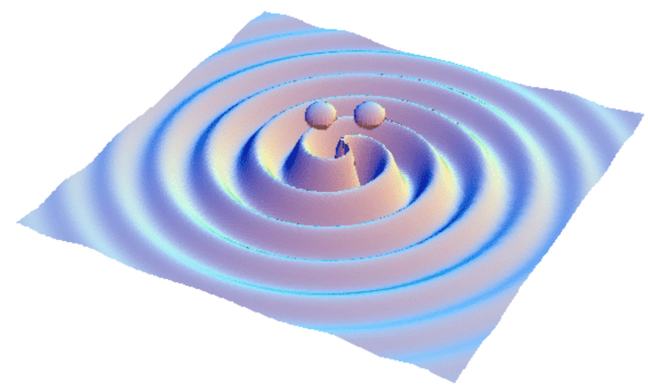
LIGO-G1300099

Gravitational waves

- General Relativity: massive objects curve the space-time and it tells the objects how to move



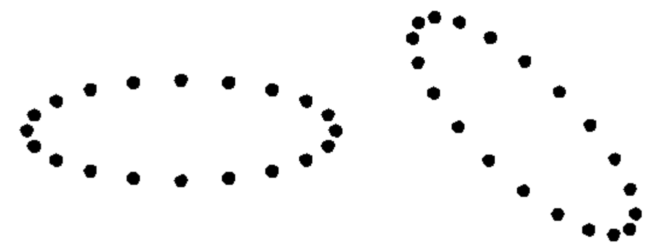
- Gravitational Waves: predicted by Theory of General Relativity (1915). Einstein doubted GW physical reality until the end of his life.



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Experimental Study of GWs

- Felix Pirani (1957): reception of gravitational waves - in the presence of a gravitational wave, a set of freely-falling particles would experience genuine motions with respect to each another.



$$h = \frac{\Delta L}{L}$$

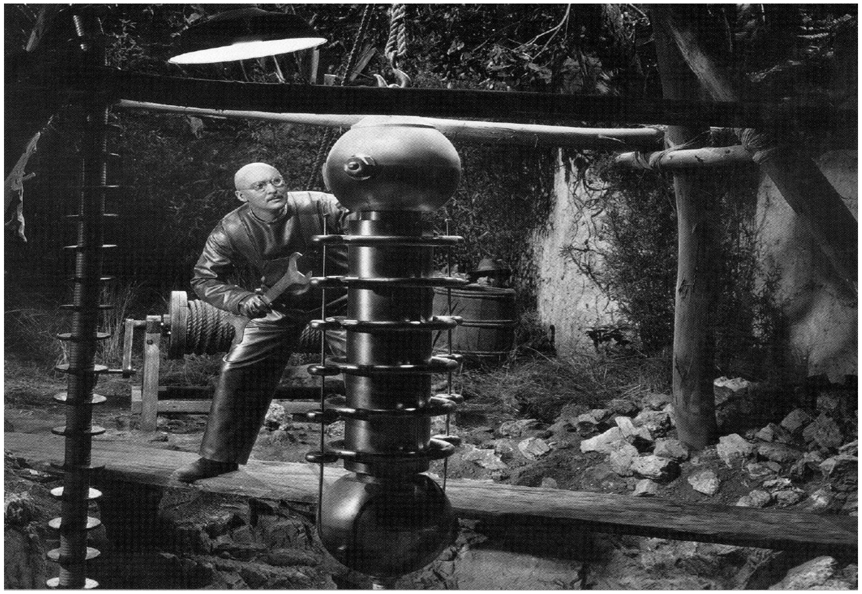
- **Detection and Generation of Gravitational Waves***

J. Weber
University of Maryland, College Park, Maryland
(Received February 9, 1959; revised manuscript received July 20, 1959)

Methods are proposed for measurement of the Riemann tensor and detection of gravitational waves. These make use of the fact that relative motion of mass points, or strains in a crystal, can be produced by second derivatives of the gravitational fields. The strains in a crystal may result in electric polarization in consequence of the piezoelectric effect. Measurement of voltages then enables certain components of the Riemann tensor to be determined. Mathematical analysis of the limitations is given. Arrangements are presented for search for gravitational radiation.

PhysRev. 117, 1 (1960)

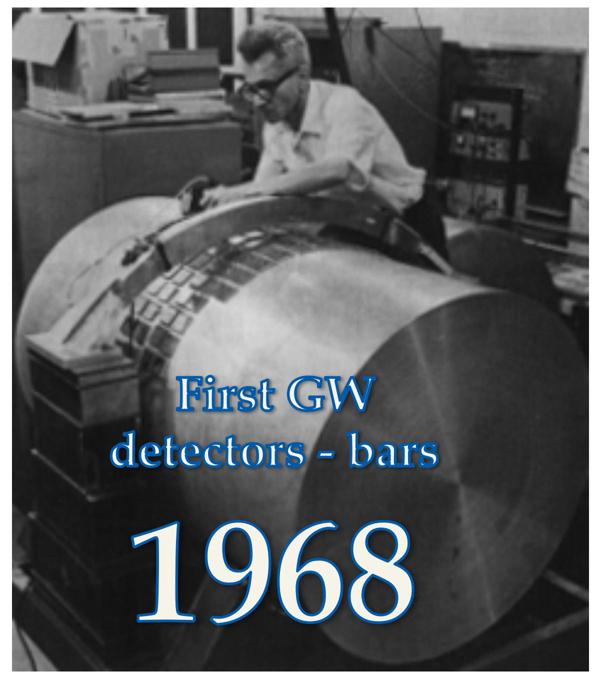
First GW detectors: Cryogenic Bars



$$h = \frac{\Delta L}{L} \approx \frac{4\pi^2 G M R^2 f^2}{r c^4}$$

R = 1m, f=1kHz,
M=1t, r=30m
h ~ 10^{-35}

$$10^{-35} \cdot 1m \sim \text{Plank length}$$



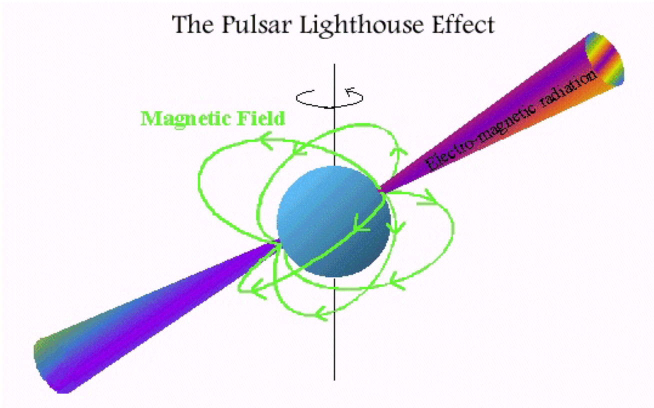
- J.Weber: "When I decided to search for gravitational waves some 14 years ago, most physicists applauded our courage, but felt that success – detection of gravitational radiation – would require a century of experimental work." (Popular Science May 1972)

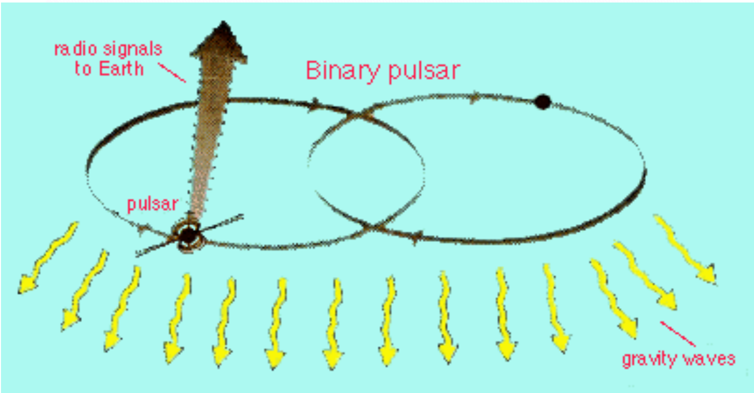
Gravitational Waves: *the evidence*

PSR 1913 + 16 Neutron Binary System

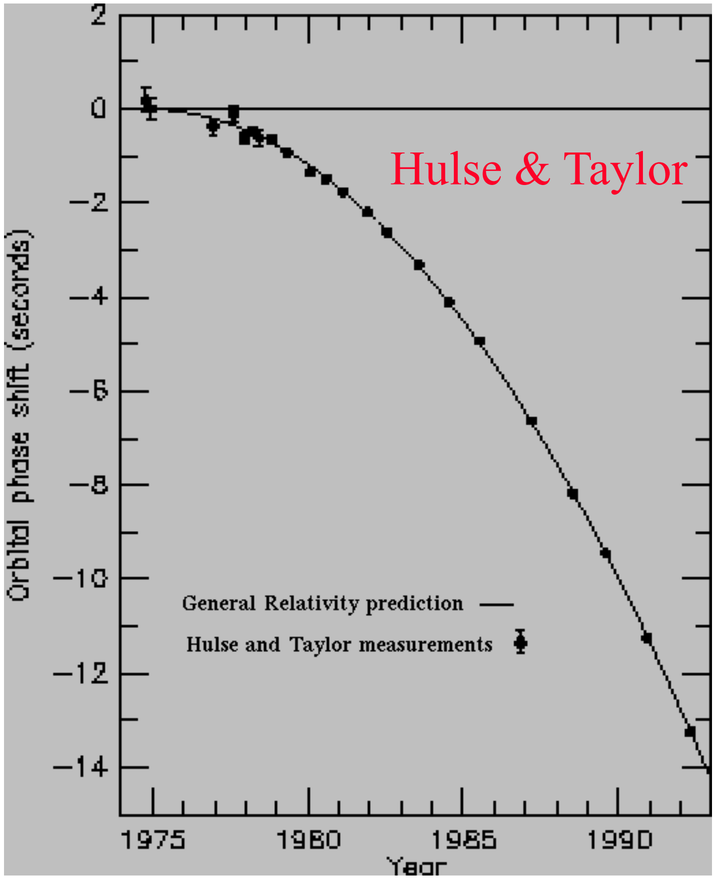
Separated by 10^6miles,

$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$;





Emission of gravitational waves

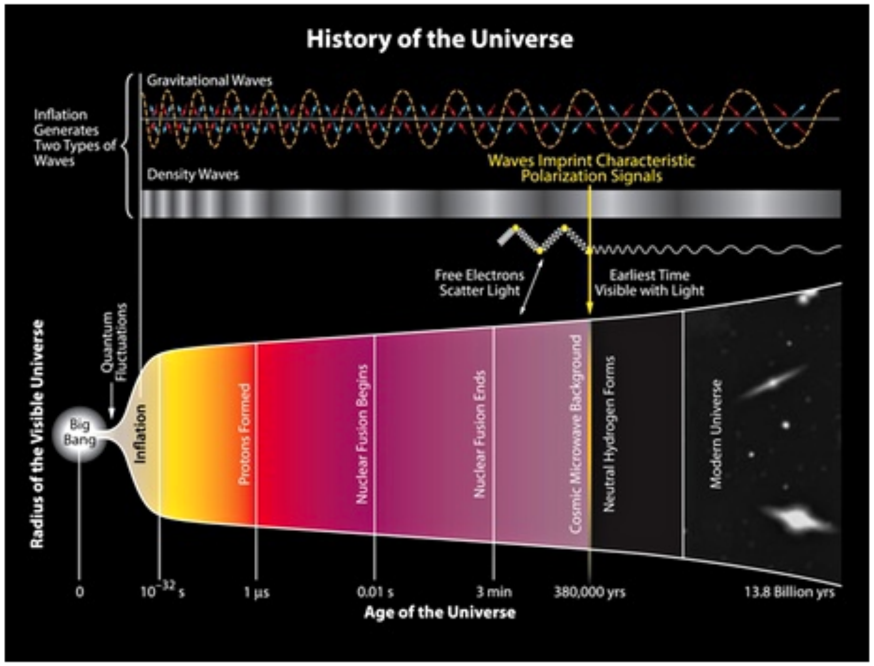


Prediction from general relativity

- spiral in by 3 mm/orbit
- merge in 300 million years

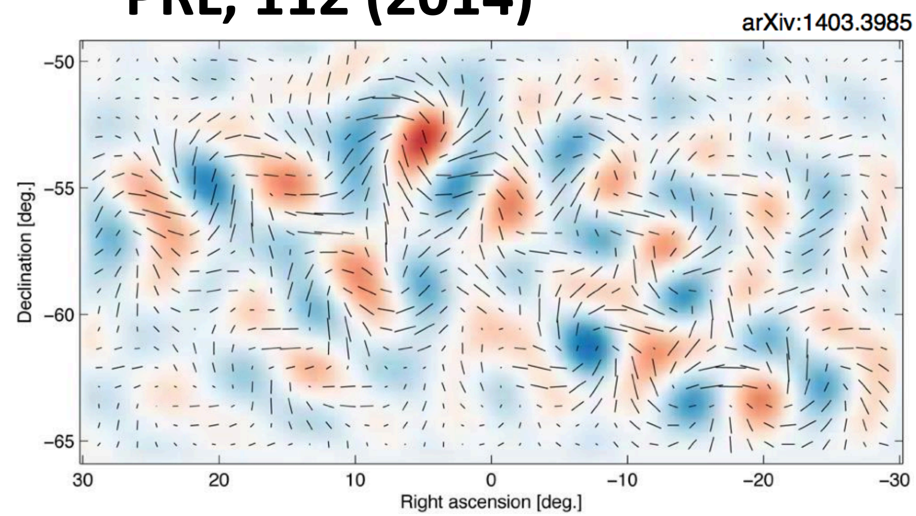
time of periastron relative to that expected if the orbital separation remained constant.

BICEP2: CMB B-modes



Photograph: The BICEP2 Collaboration/PA

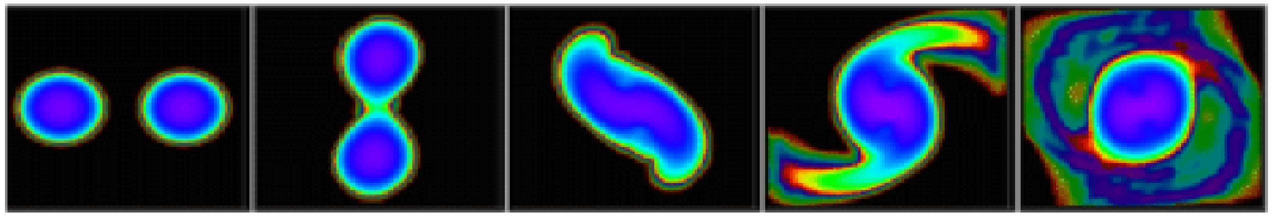
PRL, 112 (2014)



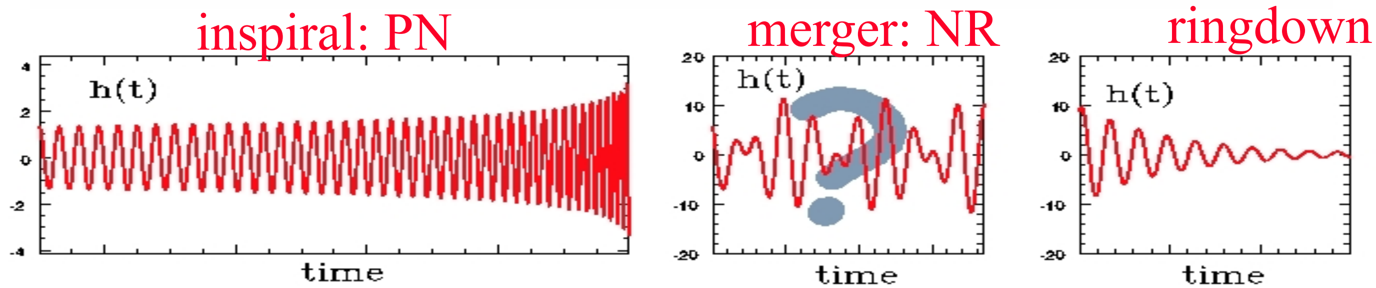
- Observe B-modes, interpreting it as GW "fossil" imprinted in CMB by tensor density fluctuations (as opposed to E-modes – scalar fluctuations [Nature 420, 2002])
- Could be also due to galactic dust foreground - recent Plank results do not look good for BICEP2

PSR1913+16 300 million years later…

- Neutron star – neutron star (Centrella et al.)



R = 20km, f=1kHz,
M=1.4Mo, r=10Mpc
h ~ 10^{-21}

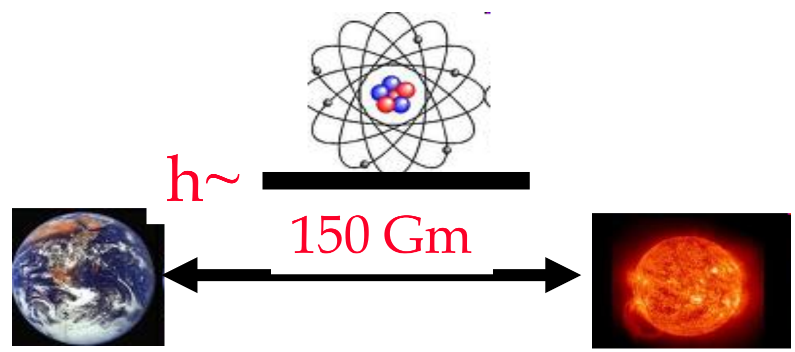


~1kHz

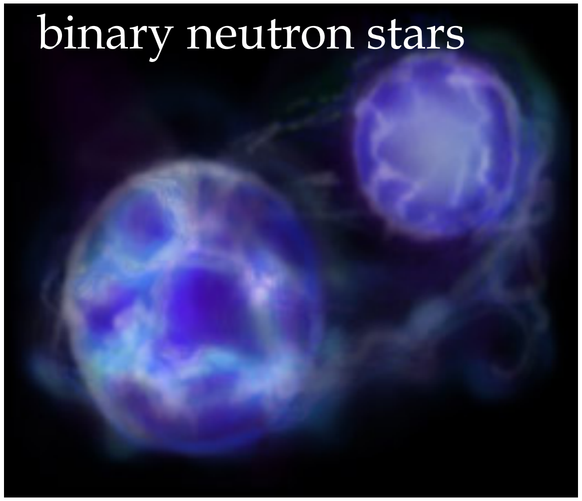
- NS-NS, NS-BH, BH-BH: the most efficient emitters among expected GW sources: up to 10 % of total mass → GWs
  - rare – need to search vast space volume

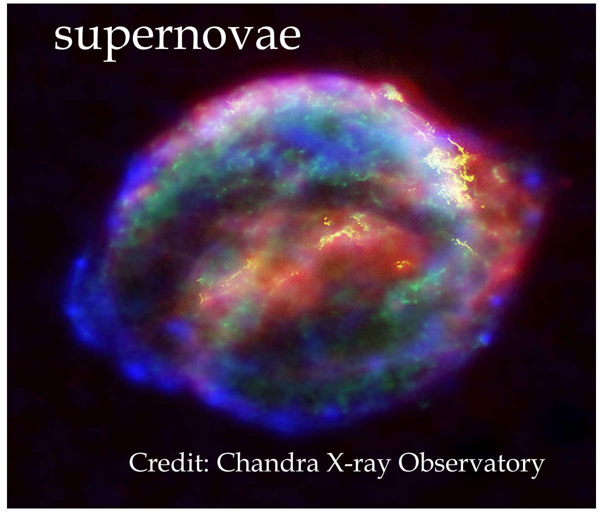
detectors with sensitivity better than

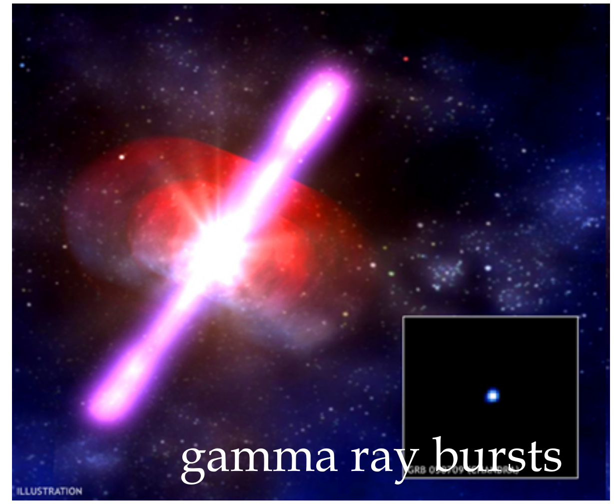
$$\frac{\Delta L}{L} \sim 10^{-21}$$

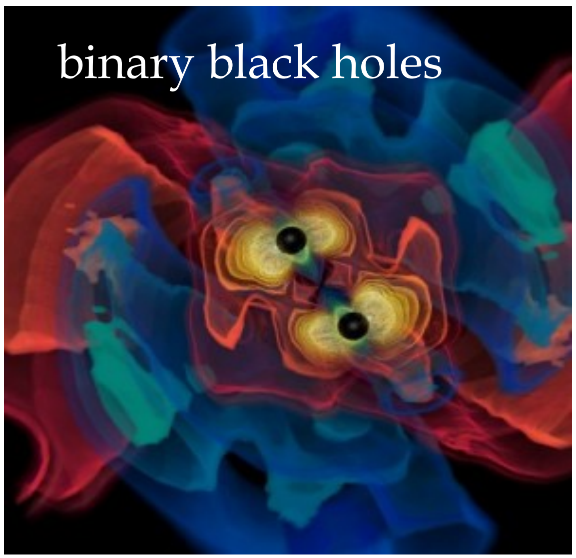


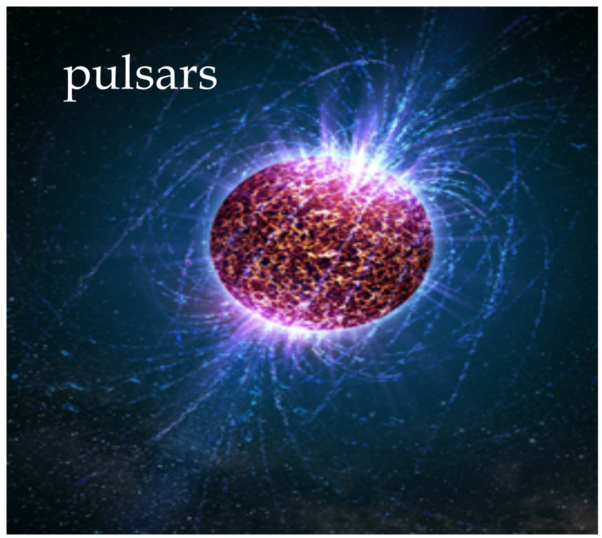
Sources

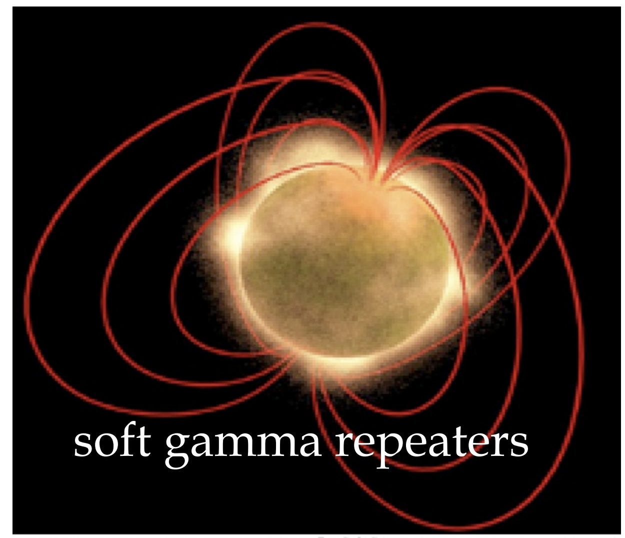












Artists concept: magnetic field lines NASA

and other violent astrophysical sources..

GW Interferometers: the concept

- 1962, Gertsenshtain & Pustovoit – interferometers is a way to get much better sensitivity than Weber's bar
- 1972, R.Weiss – Michelson interferometer as GW detector
- 1978, R.Forward – first prototype
- ……., R.Drever et al. - Fabry-Perots cavities, power/signal recycling, locking scheme

R.Weiss, 1972

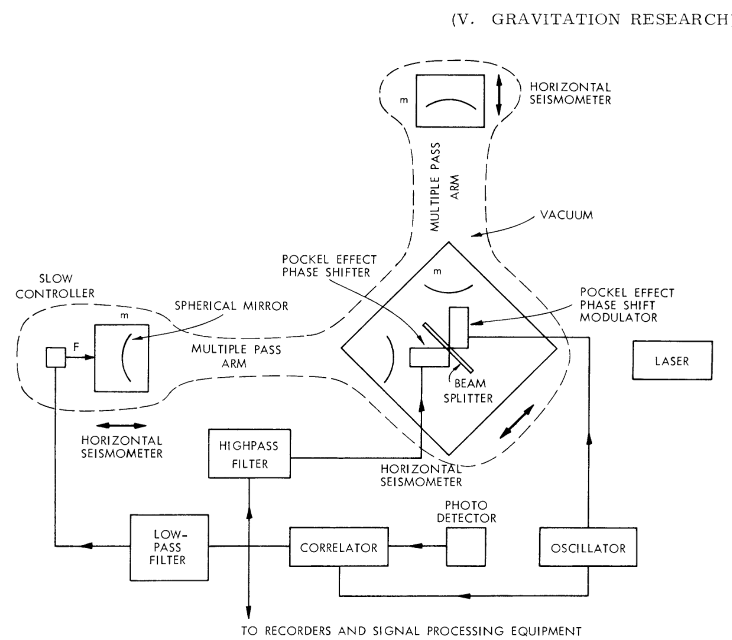
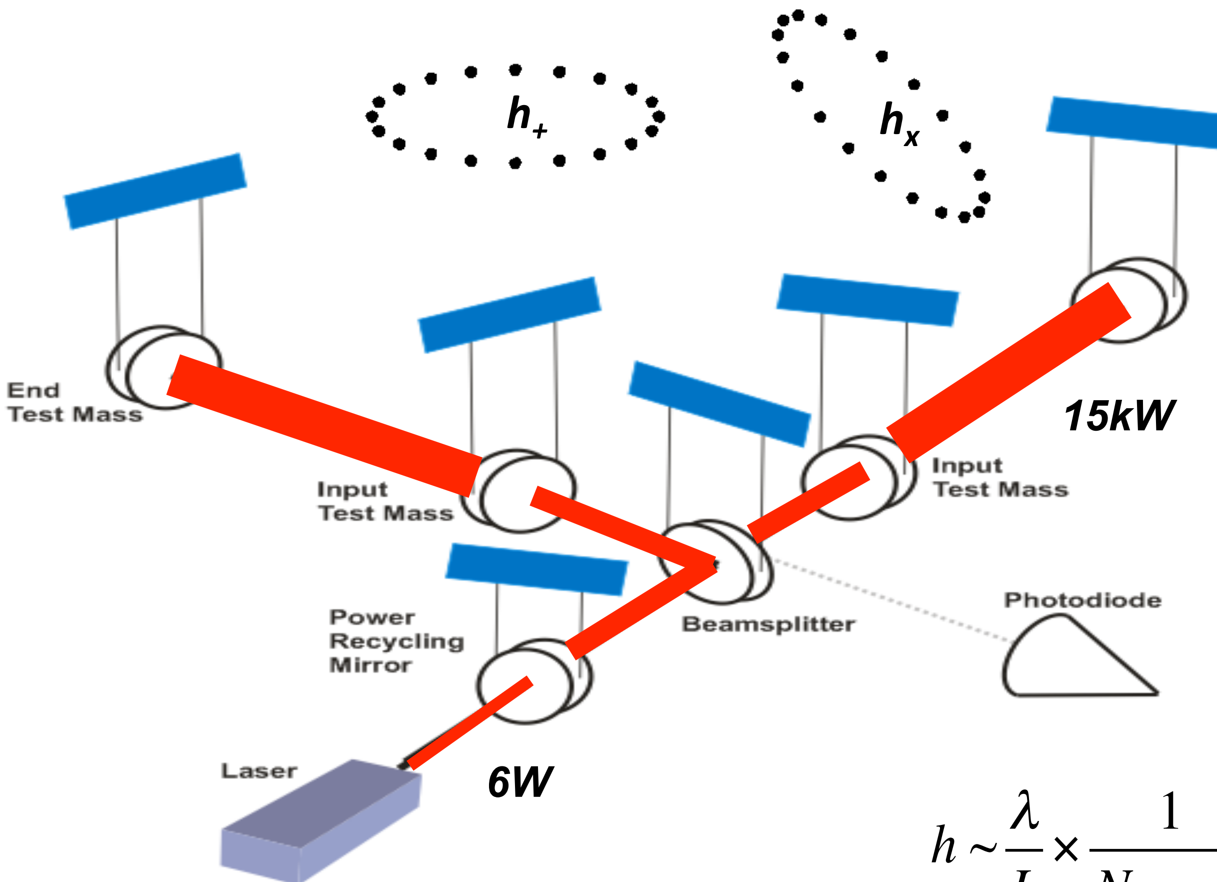


Fig. V-20. Proposed antenna.

LIGO

- Laser Interferometer Gravitational wave Observatory
  - ✓ proposal to NSF in 1989



L=4km

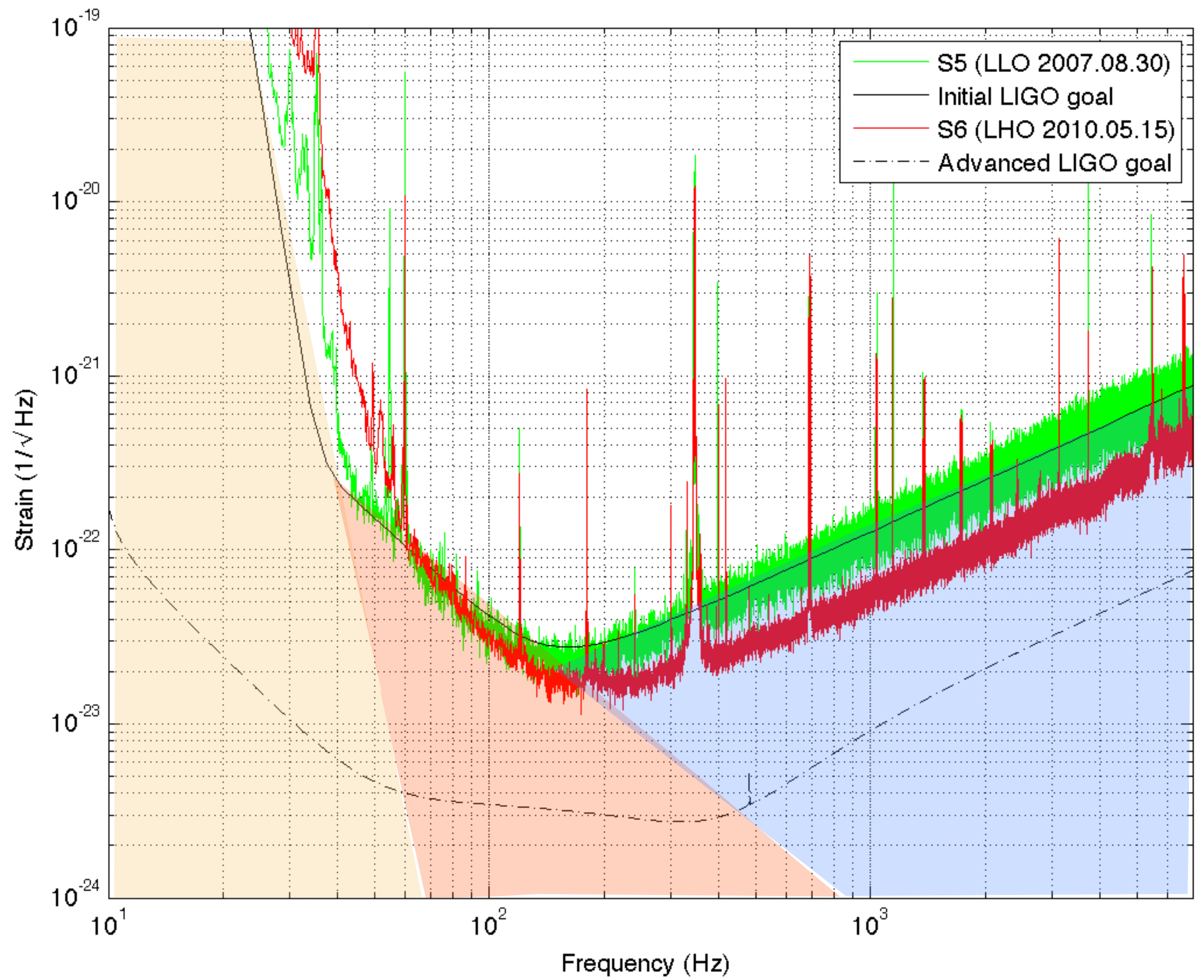
λ=1μm

$$h \sim \frac{\lambda}{L} \times \frac{1}{N_{\text{roundtrip}}} \times \sqrt{\frac{h\nu}{P \cdot \tau_{\text{storage}}}} \sim 10^{-22}$$

LIGO sensitivity

arXiv:1203.2674

- **Seismic**
- **Newtonian**
- **Thermal**
  - **suspension**
  - **mirrors**
- **Quantum**
  - **shot noise**
  - **radiation pressure**



Detector Antenna Sensitivity

- **Detector response**

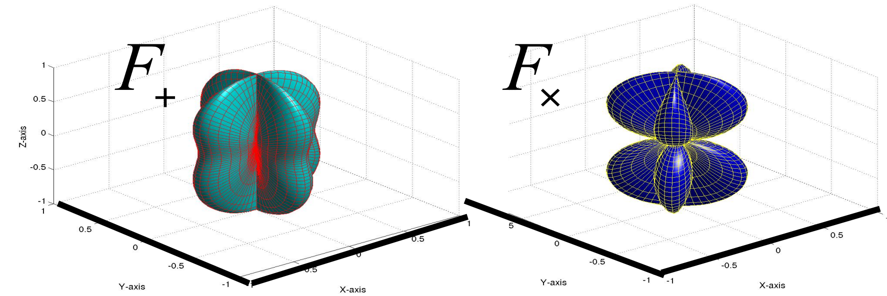
$$\xi(t) = F_+ h_+(t) + F_\times h_\times(t)$$

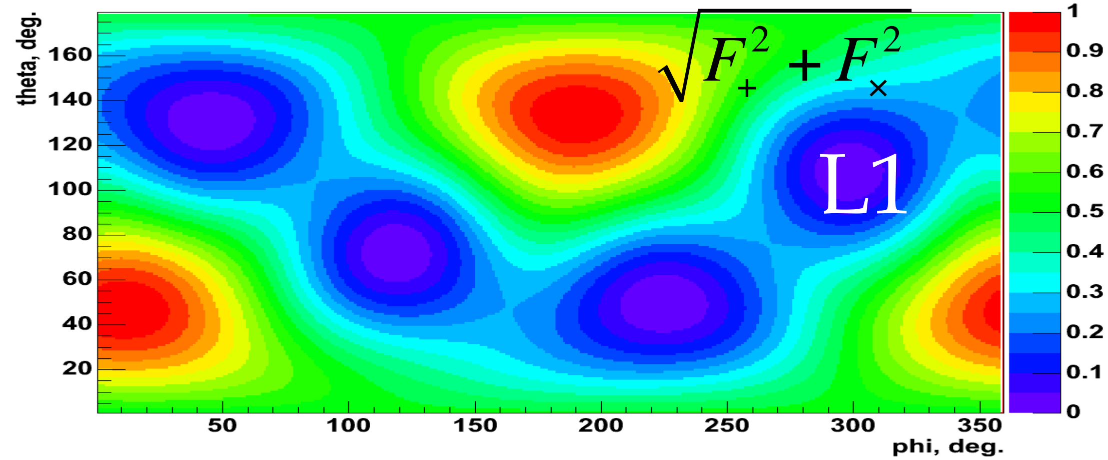
- **Detector data**

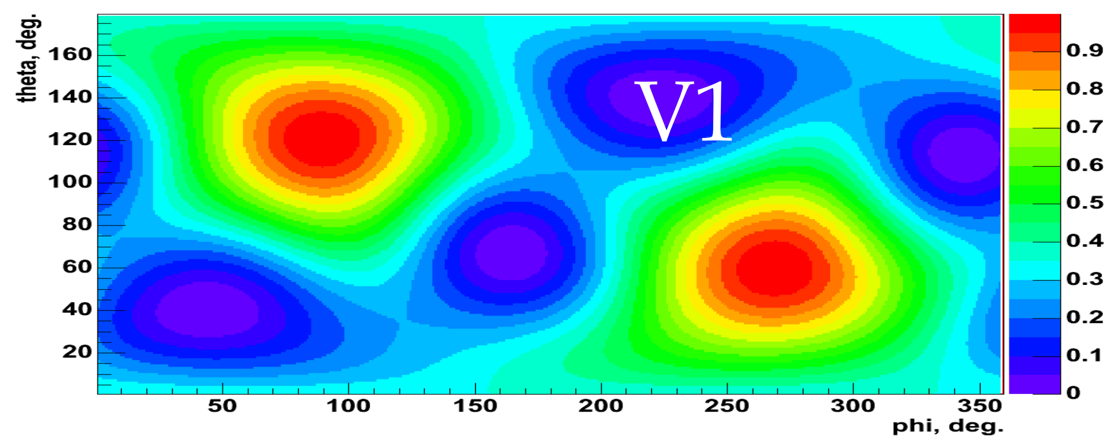
$$x(t) = \xi(t) + n(t)$$

noisy time-series

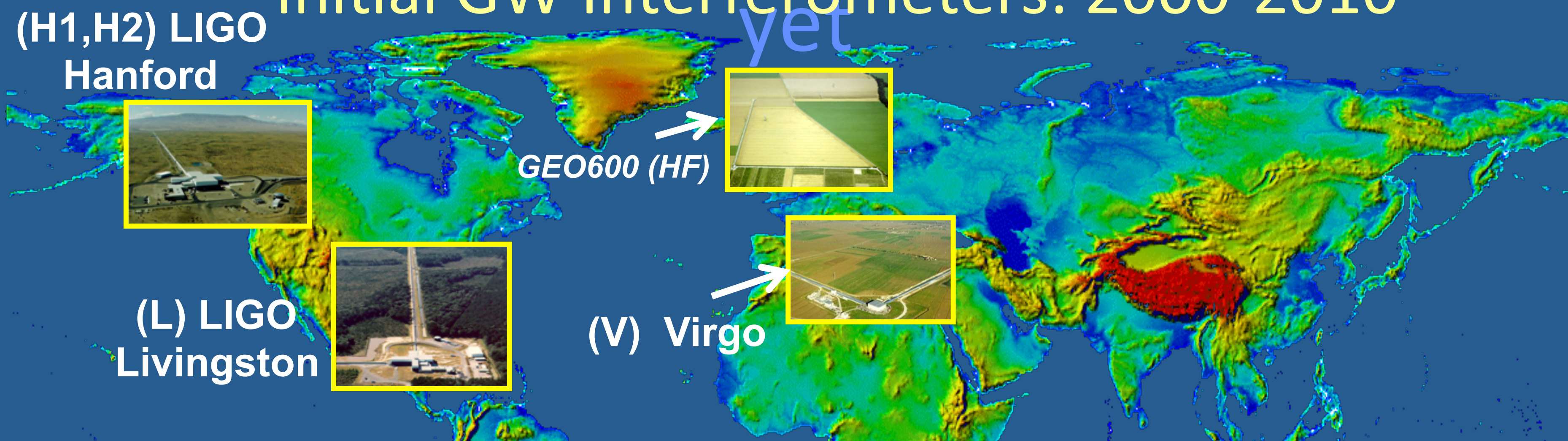
- **FOV: almost entire sky**
- **Several detectors increase coverage of the sky and detection confidence**







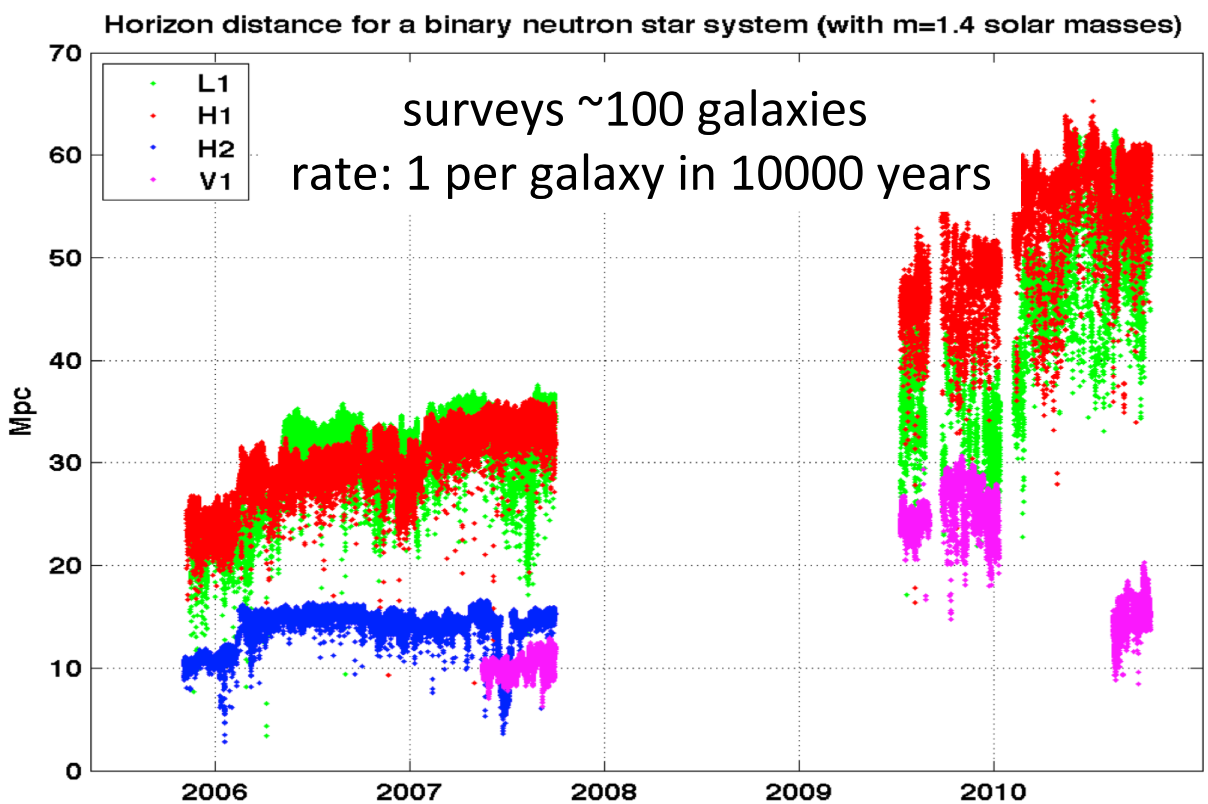
Initial GW Interferometers: 2000-2010



- Initial LIGO detectors (1G) operated for a decade
  - 6 data taking runs (~1.5 years of 2D live time)
  - reached its design sensitivity during the S5 run: 2005-2007
  - run enhanced configuration during the s6 run: 2009 – 2010
  - decommissioned in October 2010
- Virgo detector joined in May 2007
- started to constrain source models
- paved road for advanced (2G) detectors
- established conceptually new GW data analysis
- began integration of GW experiment and astronomy

Binary Neutron Stars (BNS) range

- **BNS horizon distance to a 1.4-1.4 M binary detected at SNR of 8 and optimal source location/orientation**
- **BNS range (averaged over sky and inclination angles) ~horizon distance / 2**



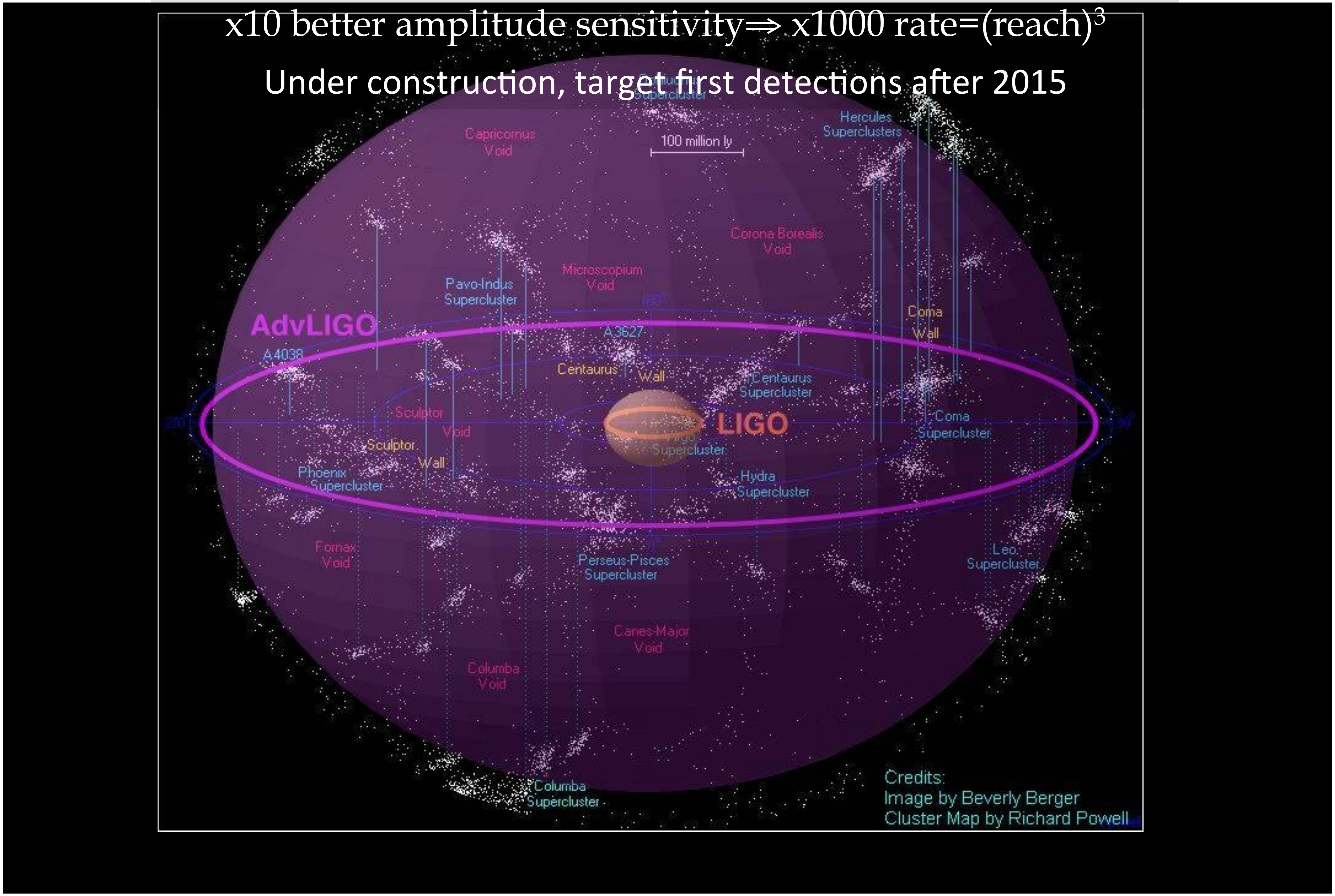
$$SNR = 2\sqrt{\int_0^\infty \frac{|\xi(f)|^2}{S(f)} df}$$

1 pc = 30.8×10^{12} km = 3.26 light years

Advanced LIGO

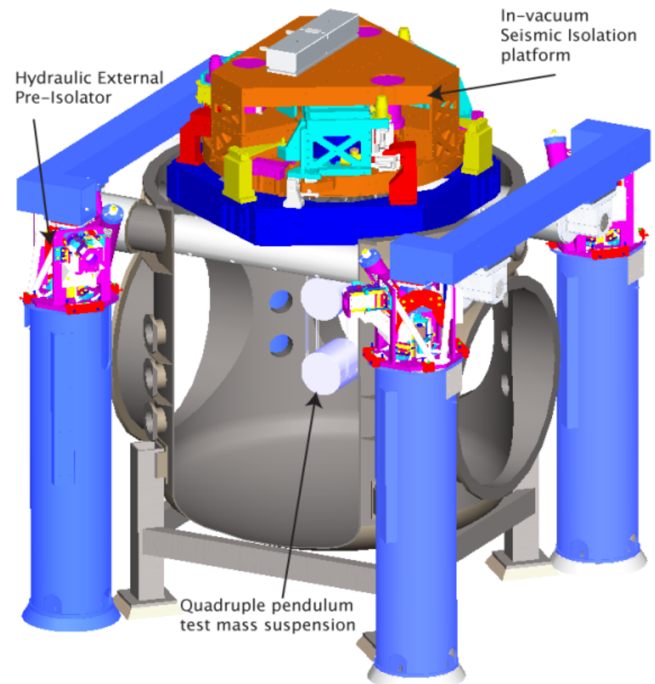
x10 better amplitude sensitivity⇒ x1000 rate=(reach)^3

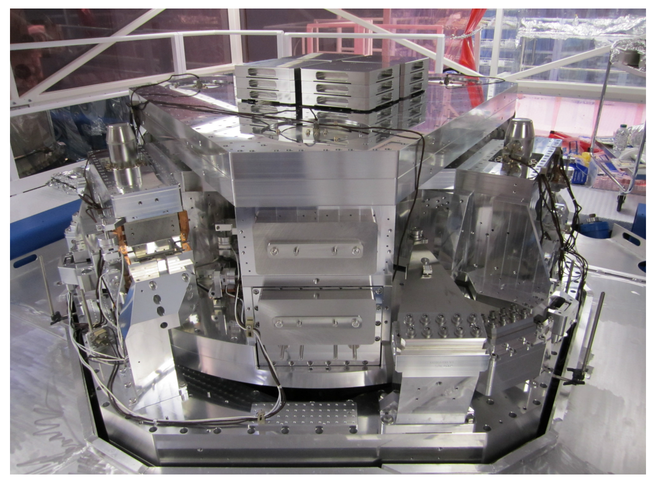
Under construction, target first detections after 2015



Multi-stage Seismic Isolation

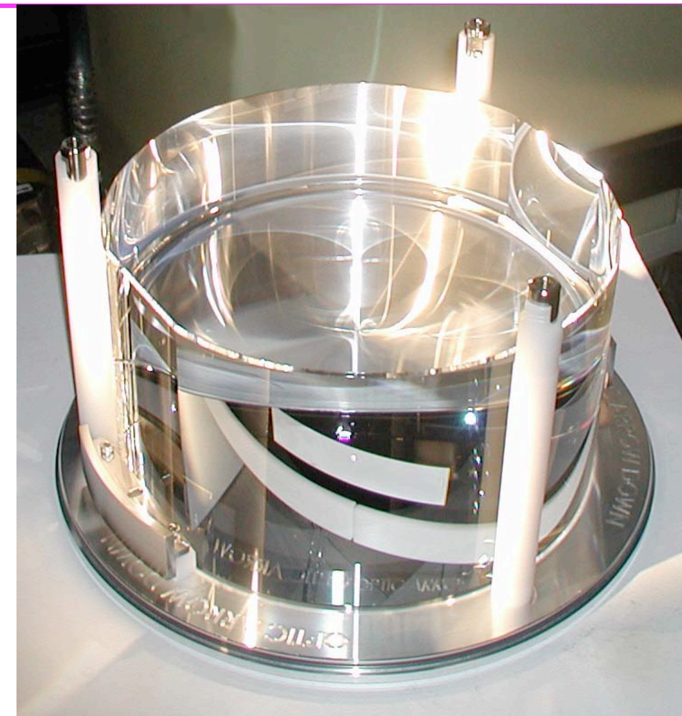
- **Multi-stage**
  - **Hydraulic External Pre-Isolation**
  - **In-vacuum Isolation platform**
  - **Quadruple pendulum test mass suspension**
- **Active**
  - **Feedback sensor signals (position, velocity, acceleration) through active control loop to hold platforms still**

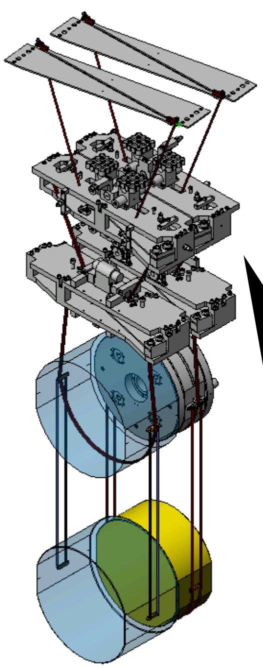




State of art optics & suspension

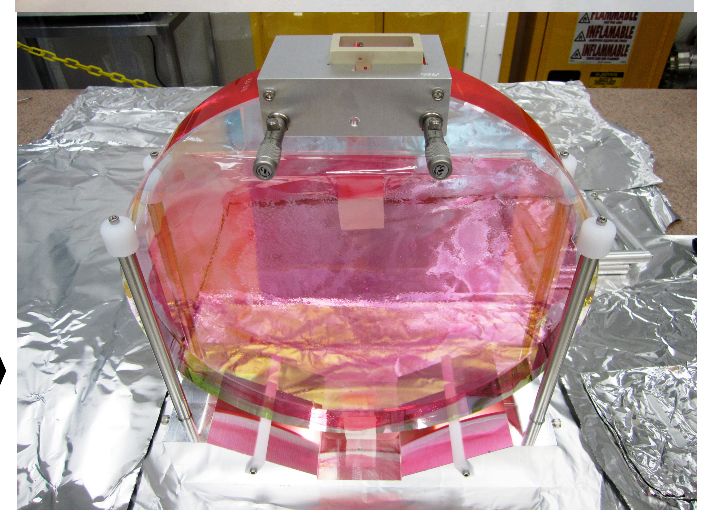
- **Test masses**
  - **40kg fused silica**
  - **75ppm round trip optical loss**
  - **sub-nm precision over 30 cm**





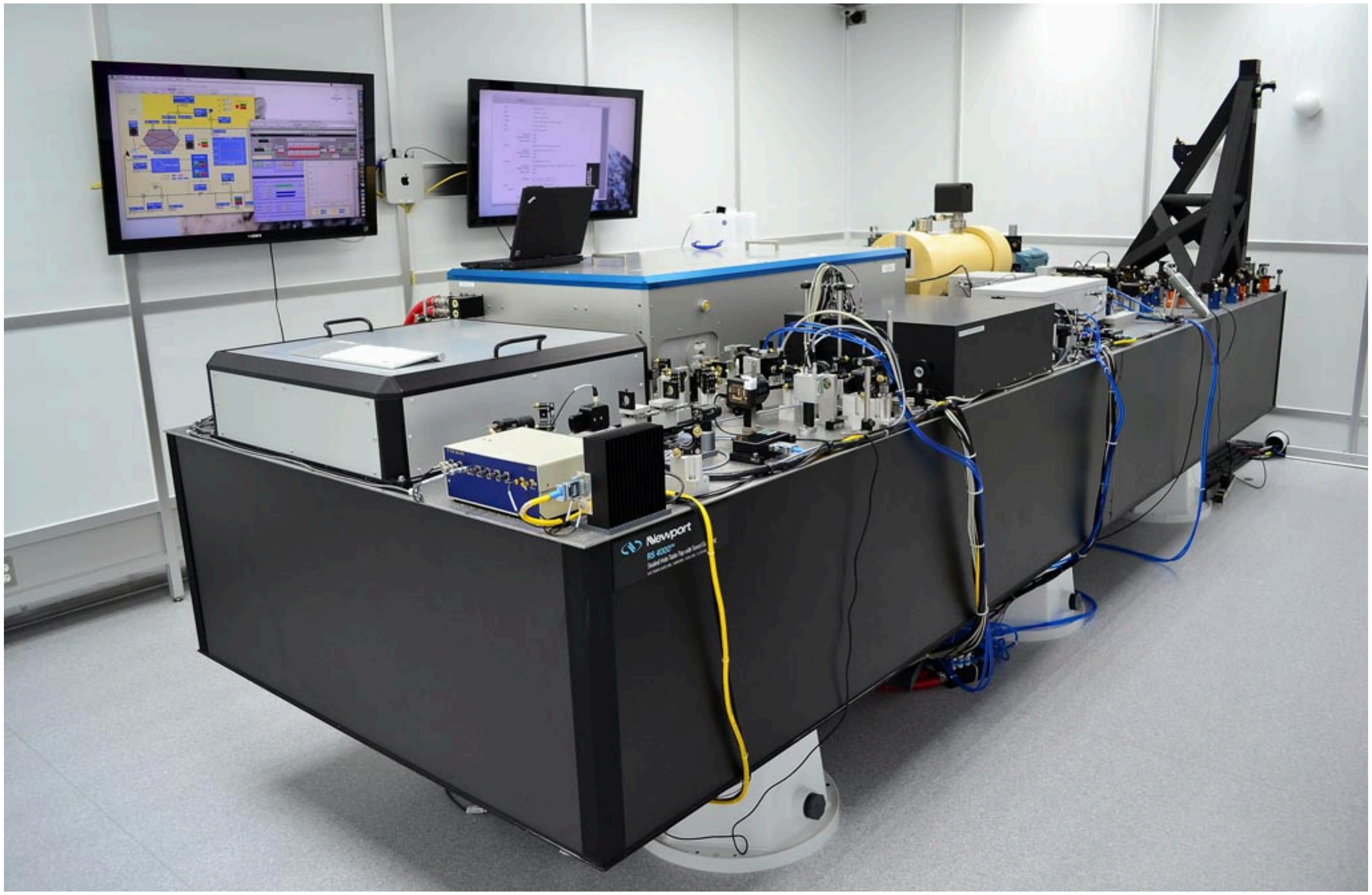
quasi-monolithic pendulums - 400μm fused silica fibers

aLIGO beam-splitter

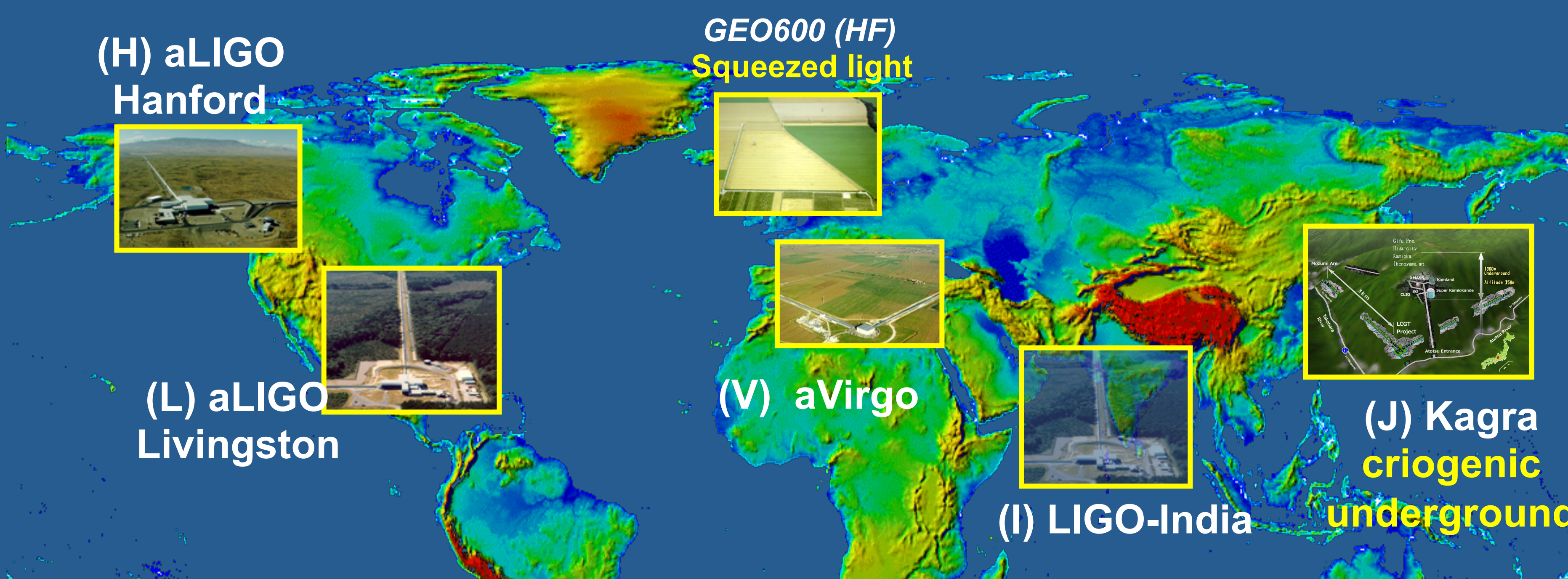


More Power

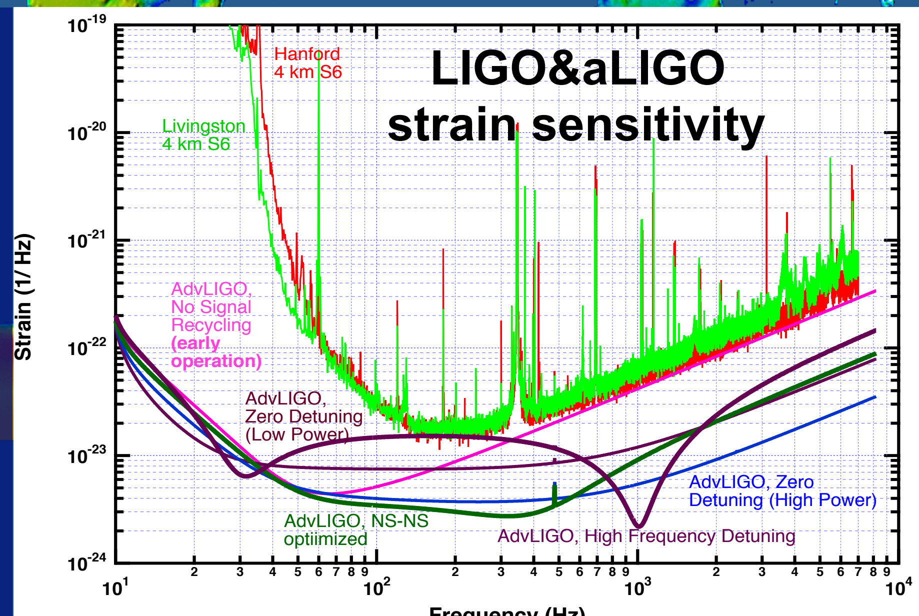
- **200W Nd:YAG laser**
  - **built by Max Plank AEI, Germany**
  - **pushes power in the FP arms up to 800kW**



Advanced GW Interferometers: 2015-2025



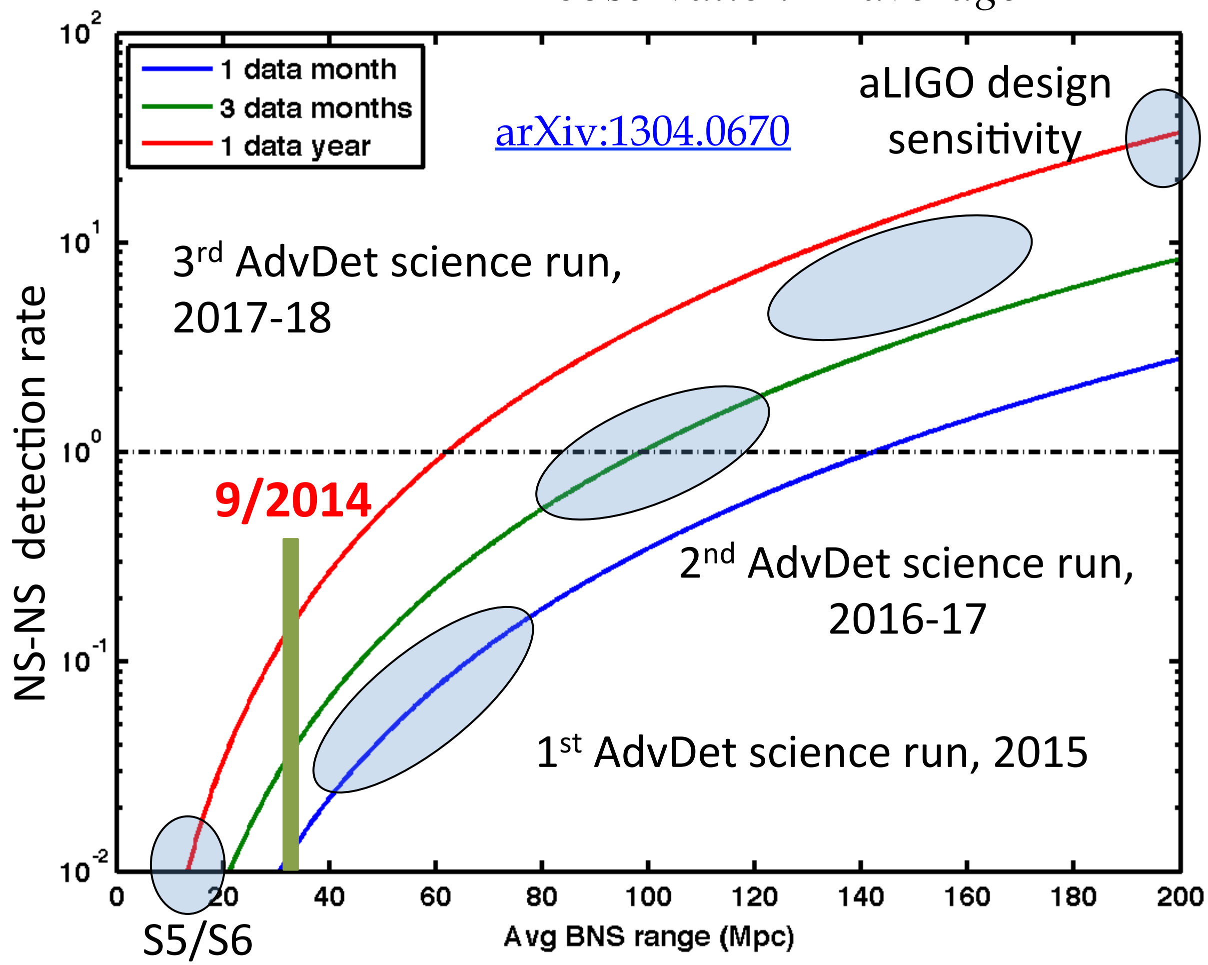
- **Target first detection after 2015**
- **Tuning aLIGO configurations to accommodate new physics**
- **Significant improvement of GW reconstruction as LIGO-India and Kagra join the network**



Projected aLIGO sensitivity & detection rates

$$\text{rates} \propto T_{observation} D^3_{average}$$

- All dates are very preliminary
- Actual rates can be lower (/100) or higher (x10)
- NS-BH and BH-BH can be seen much further away
- Rate may increase as $K^{1/2}$ as more detectors join advanced detector runs



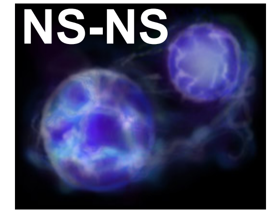
more on estimation of astrophysical rates

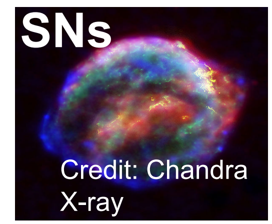
PRD **85** (2012) 082002

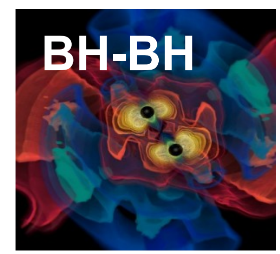
CQG, 27 (2010) 173001

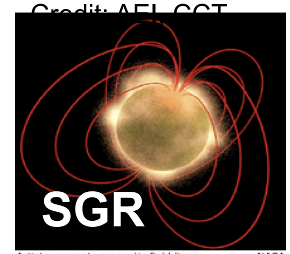
aLIGO sources & astrophysics

- GW are produced by relativistic motion of dense masses at strong field regime, not absorbed or scattered
- ultimate test of GR (non-linear effects, polarizations, speed of gravity, BH hairs, ..)
- formation of black holes and neutron stars, distribution and rate of compact binary mergers → stellar population synthesis
- existence of intermediate mass black holes (BH mass gap)
- new standard candle (NS-NS) → cosmology, Hubble constant
- NS physics (equations of state, mass distribution, are there mountains on the NS surface?,…)
- understanding GRB progenitors
- gravitational core collapse and accompanying supernovae
- nature of pulsar glitches and magnetars
- possibly entirely new sources and phenomena









How to find signal in noisy data?

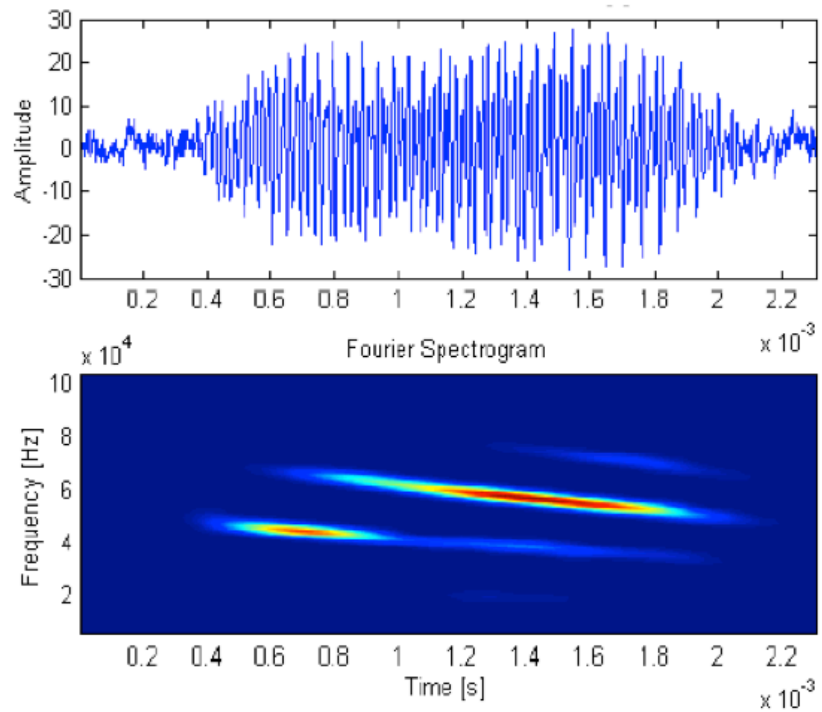
Template Search

Templates:
require exact
source model

find template
that fits data best

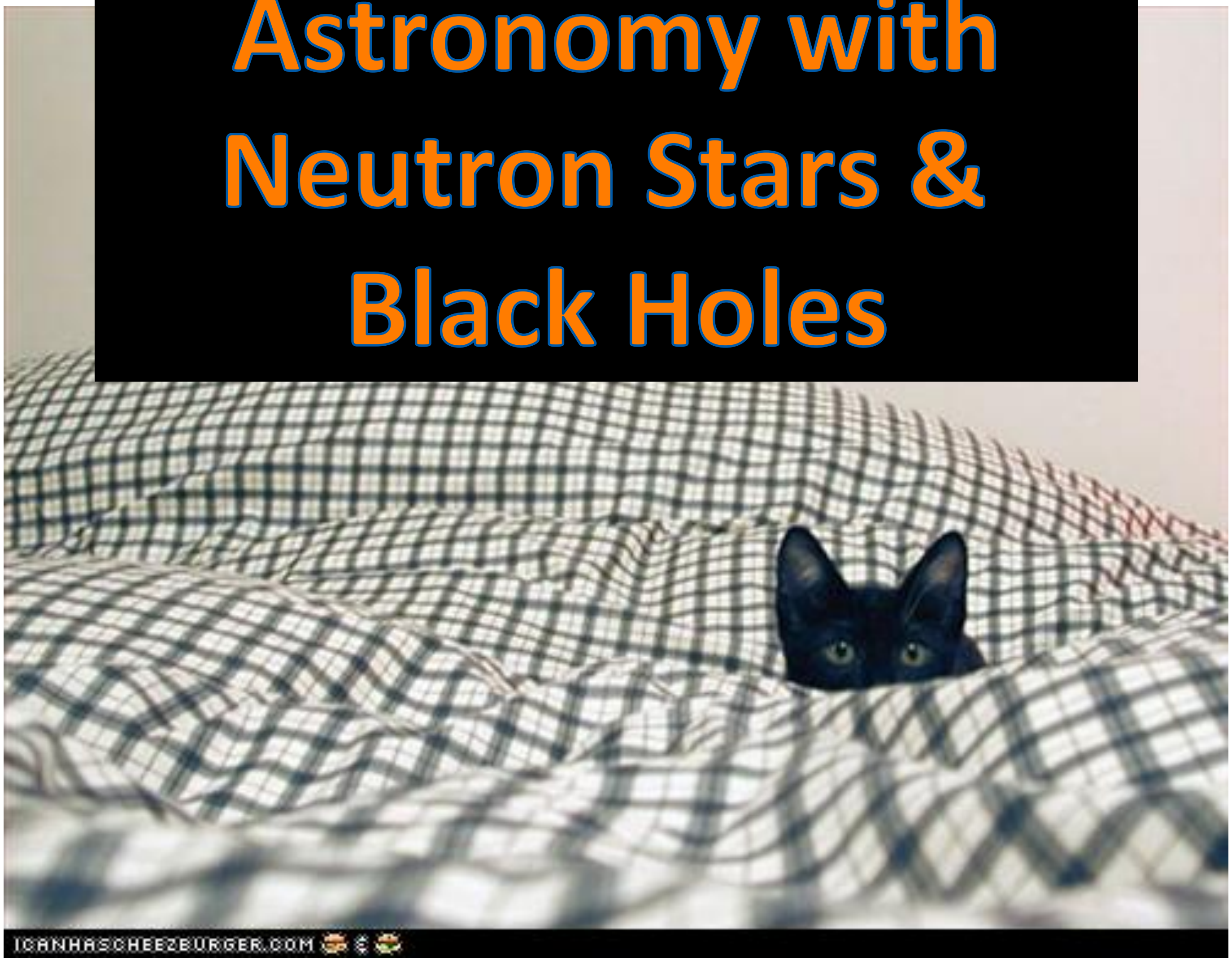
- confident detection & parameter estimation
- need exact source model, may fail, if theory does not match Nature

Burst Search



- Look for excess power time – frequency patterns consistent in different detectors
- can search for un-modeled & un-expected sources

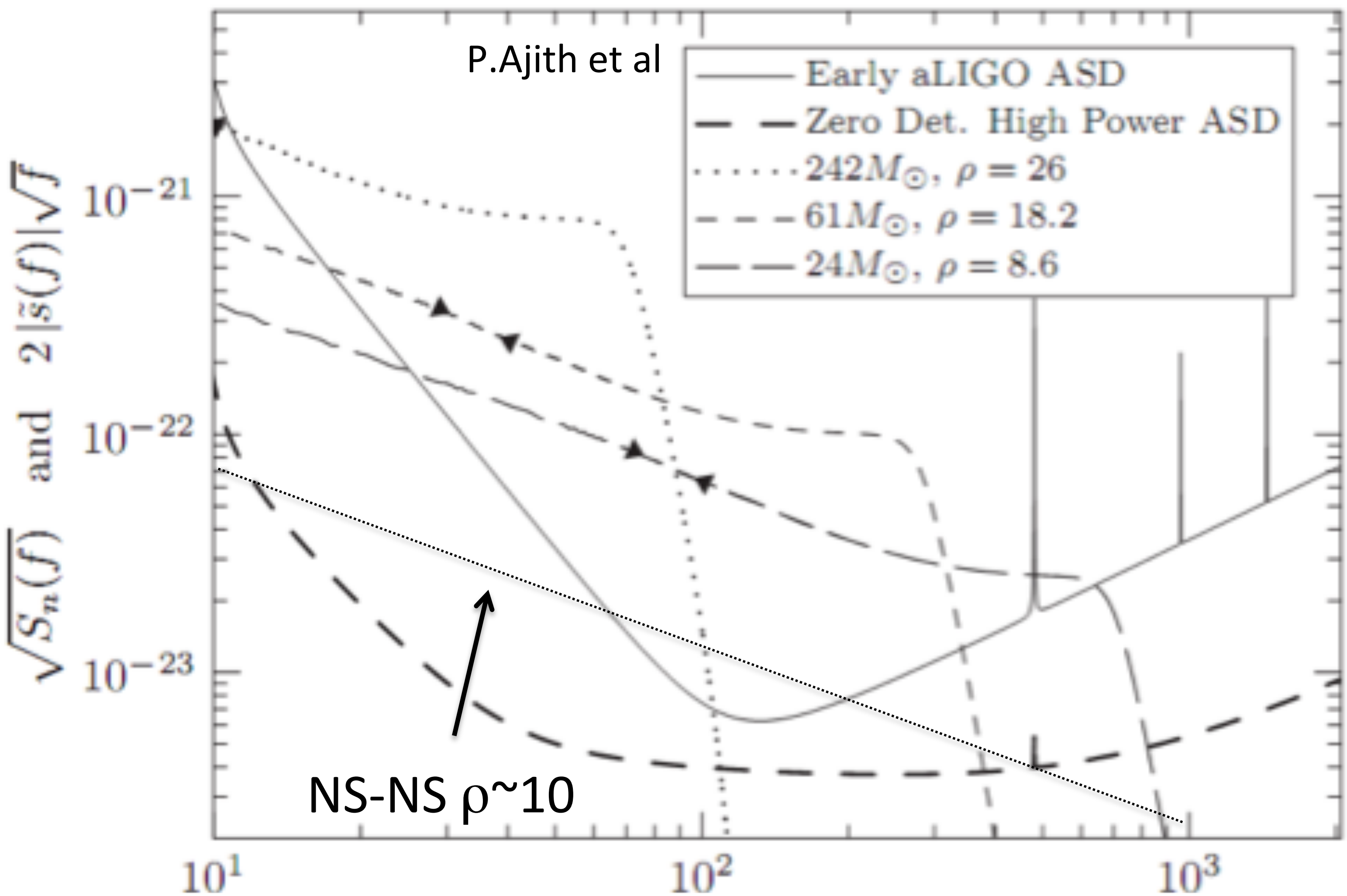
Astronomy with Neutron Stars & Black Holes



BH/NS Astrophysical Sources

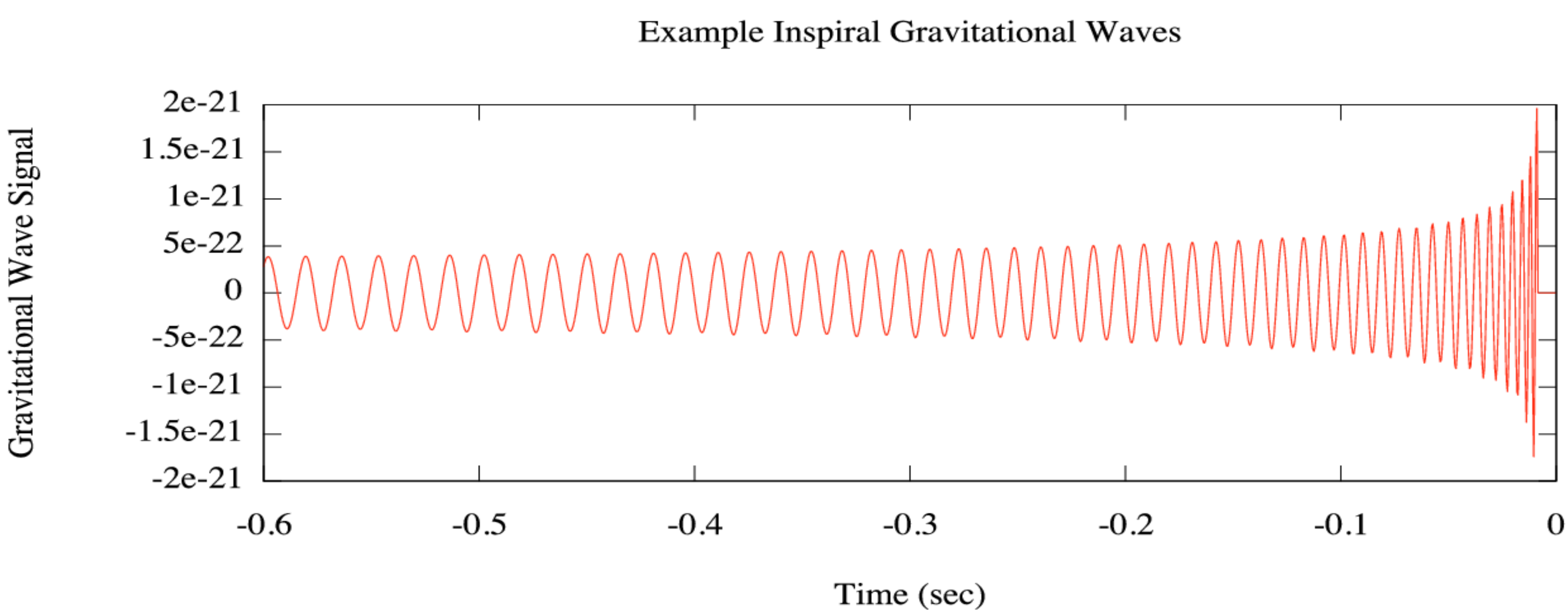
- **Binary neutron stars (NSNS)**
  - **9 NS-NS in our Galaxy**
- **Binary black holes (BHBH, BH-NS)**
  - **~20 stellar mass BHs known (e.g Cyg X-1, no BHBH yet)**
- **Intermediate mass black hole binaries (IMBBH)**
  - **10^2Mo<M<10^4Mo – do they exist?**
- **Intermediate mass ratio inspirals (IMRI)**
  - **NS-BH/IMBH, BH-IMBH – tests of GR**
- **Eccentric binary black holes (eBBH)**
  - **dynamic formation in GNs**

aLIGO Detection Band



GW waveforms

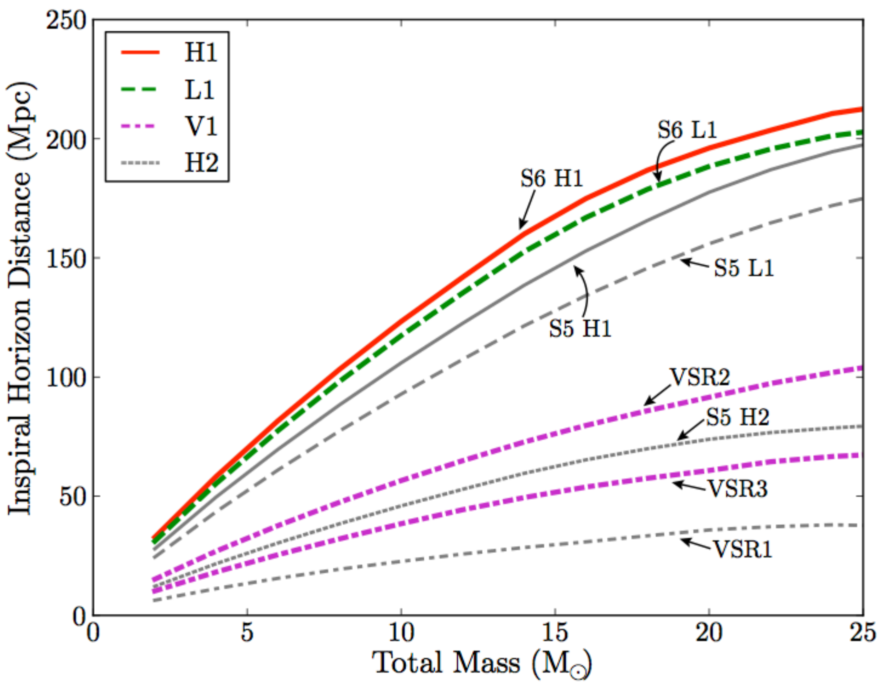
- Binary waveforms (chirps) can be calculated by using PN (analytical) and NR (numerical) methods
- Source parameters are encoded in detected waveforms
  - Chirp mass, component masses, spins, eccentricity, inclination angle, distance, sky location,..
- Very challenging to find waveforms for complex systems or when source model is uncertain

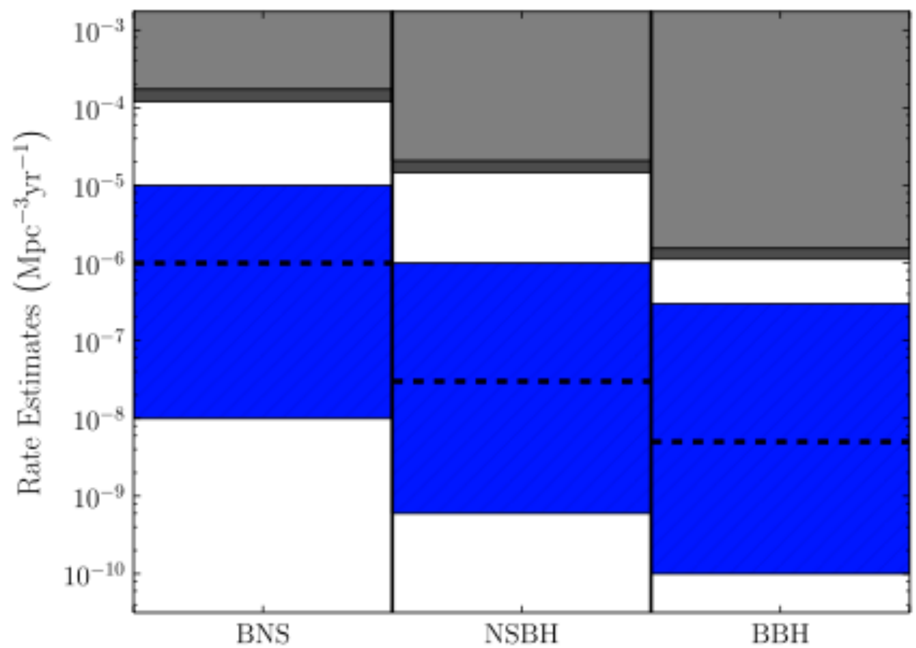


Low mass CBC (<25Mo)

horizon distance vs mass

NS-NS, NS-BH, BH-BH PRD 85, (2012)





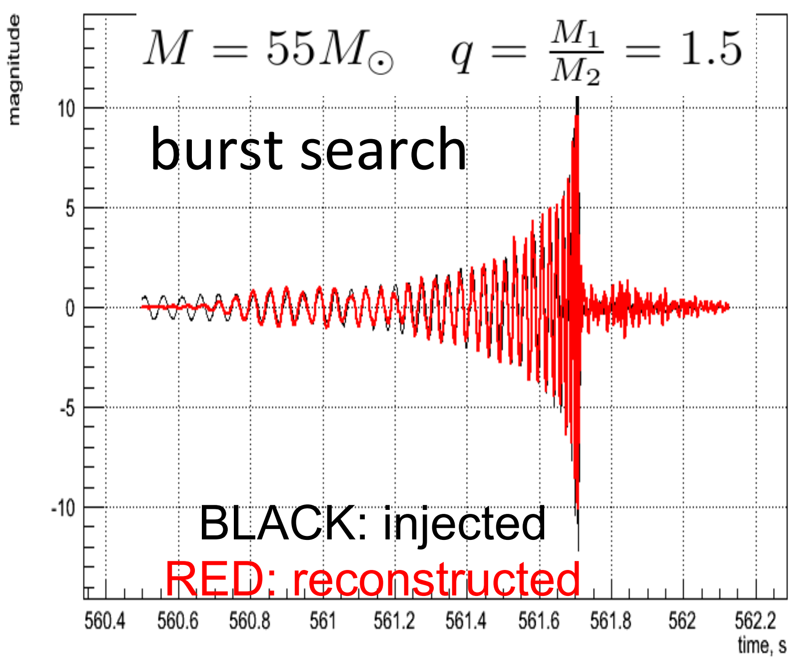
System	Masses (M_{sun})	Range (Mpc)	expected detection rates for aLIGO low (yr^{-1})	Realistic (yr^{-1})	High (yr^{-1}) CQG 27 (2010)
NS-NS	1.4/1.4	200	0.4	40	400
NS-BH	1.4/10	410	0.2	10	300
BH-BH	10/10	970	0.4	20	1000

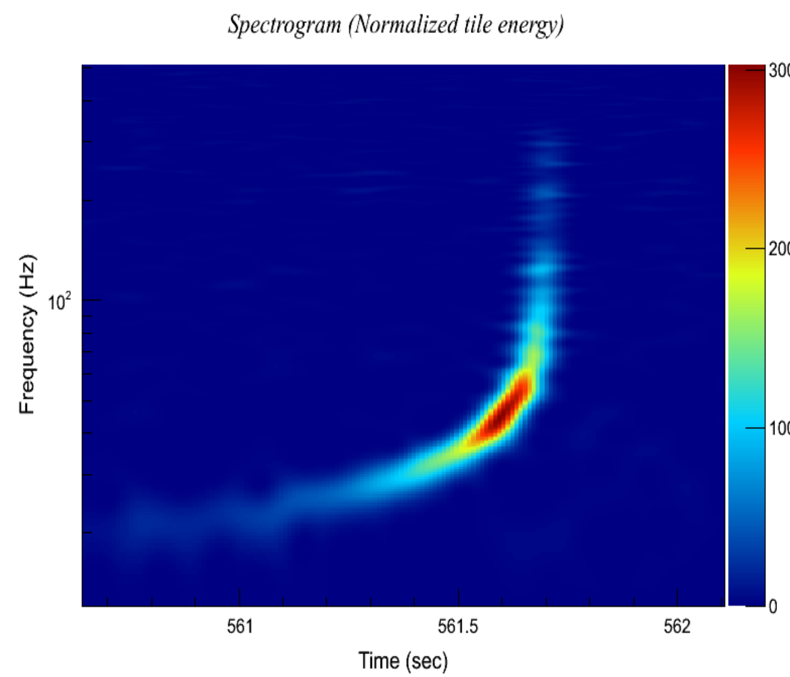
IMBH Sources & Science

- Intermediate Mass Binary Black Holes (IMBBH) - – missing link between stellar mass BHs (<100Mo) and supermassive BHs (>10^4 Mo)
- growing but still ambiguous evidence for IMBH existence, including observations of ultra-luminous X-ray binaries
- number of formation mechanisms which may lead to the existence of IMBHs in globular clusters.
- A single detection of a 100+ Mo system would be first unambiguous confirmation of the existence of IMBHs. This alone is a major discovery.
- Further detections could allow us to investigate the prevalence of IMBHs in globular clusters and cluster dynamics.
- IMBHs could provide particularly exciting ways of testing GR
  - probe the IMBH spacetime structure.
  - test whether IMBHs are really Kerr black holes

IMBBH Waveforms

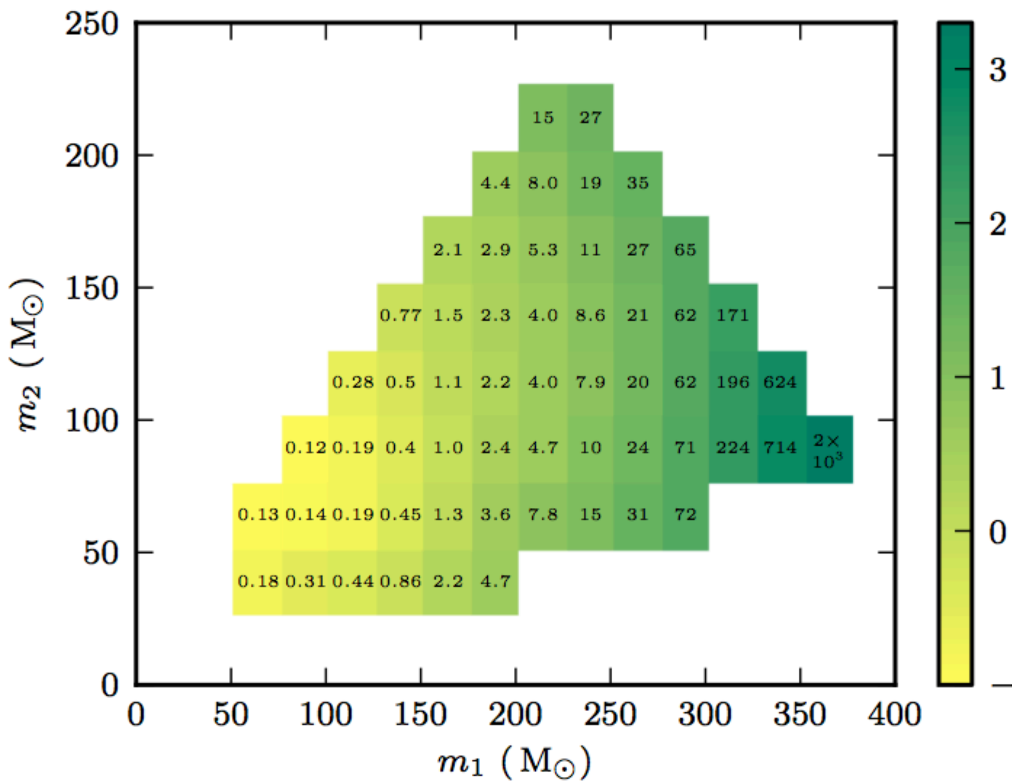
- Large mass → ranges of few Gpc for aLIGO detectors
- GW signal in the band is dominated by merger and ring-down
  - search just by looking for excess power (burst) pattern in the TF domain



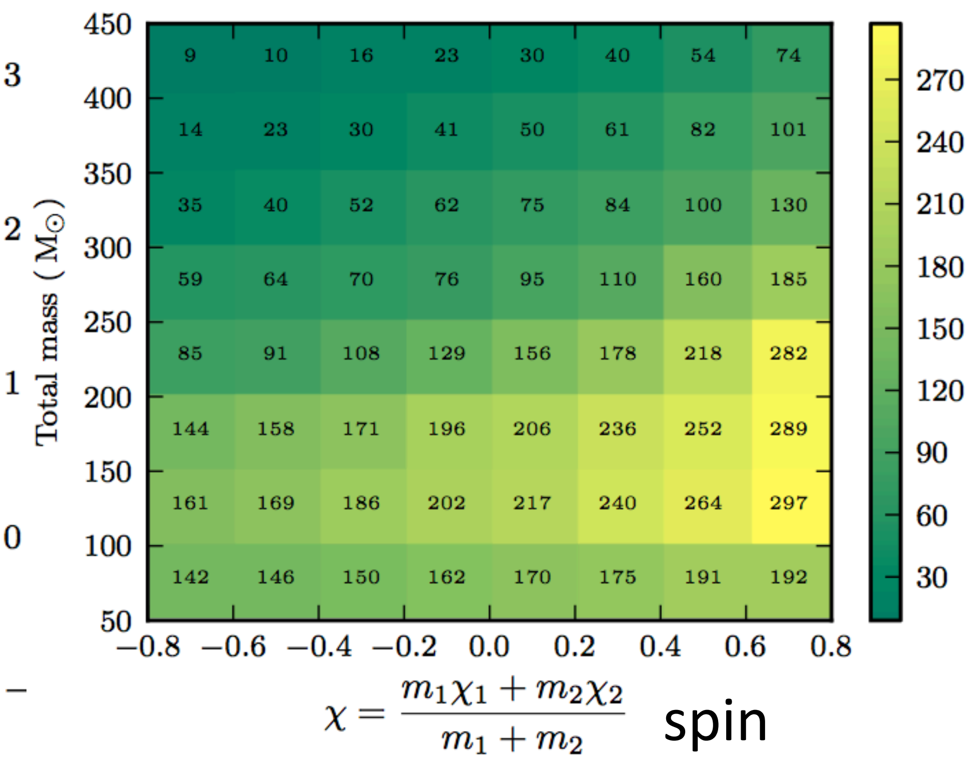


S5/S6 IMBH Burst Searches

rate density limits: Mpc^{-3} Myr^{-1}



Search range: Mpc



spin

- Search range depends on spin configuration: $R_{antialigned} < R_{aligned}$
  - significant for large masses

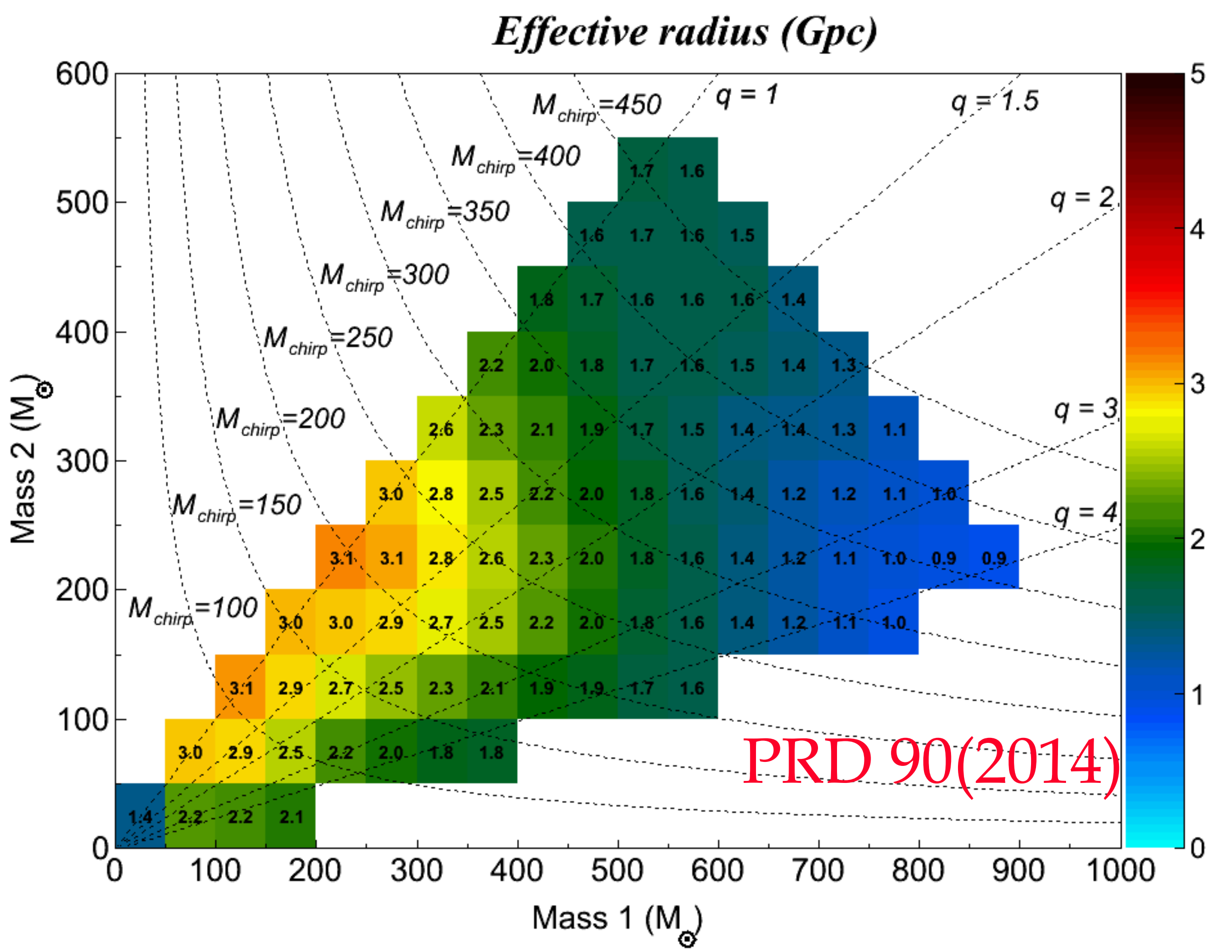
PRD **85** (2012), PRD **89** (2014)

Best $R_{90\%}$ limit: 0.12 Mpc^{-3} Myr^{-1}

anticipated rates: < 3 10^{-4} Mpc^{-3} Myr^{-1}

Prospects for advanced detectors

burst IMBBH analysis with simulated aLIGO/aVirgo noise



- **Range**
  - **Max: 3. Gpc**
  - **Avr: 2. Gpc**
- **Rate ULs**

$$\mathcal{R} \sim 3 \times 10^{-3} \left(\frac{1\ \mathrm{yr}}{T_{\mathrm{obs}}}\right) \ \mathrm{GC}^{-1}\ \mathrm{Gyr}^{-1}$$

$$\langle\mathcal{R}\rangle \sim 10^{-2} \left(\frac{1\ \mathrm{yr}}{T_{\mathrm{obs}}}\right) \ \mathrm{GC}^{-1}\ \mathrm{Gyr}^{-1}$$

Expected rates

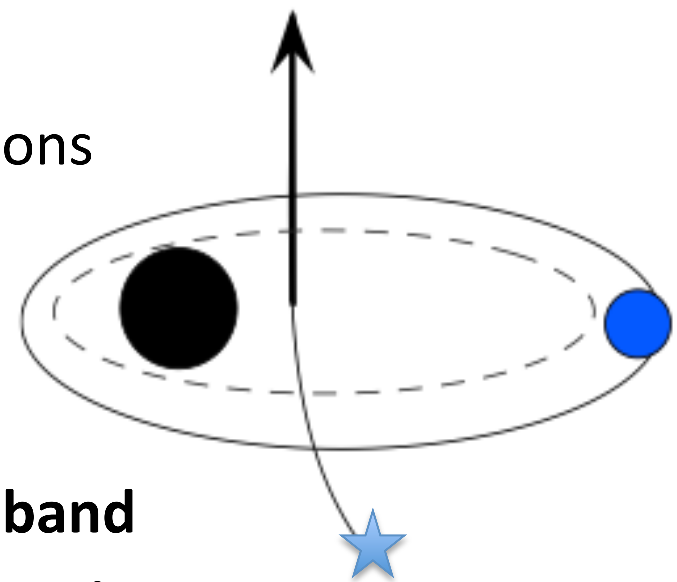
$< 0.1 GC^{-1} Gyr^{-1}$

Expect detection or interesting astrophysical limits

Intermediate Mass Ratio Binaries

- **Intermediate-mass-ratio inspirals of compact objects (1.4 solar-mass NSs or few solar-mass BHs) into massive black holes**
- **Excellent tool for testing GR: many deep-field cycles**
- **Formation mechanism:**

  IMBH swaps into binaries, 3-body interactions tighten IMBH-CO binary, merger via GW radiation reaction [Mandel +, 2008 ApJ 681 1431]



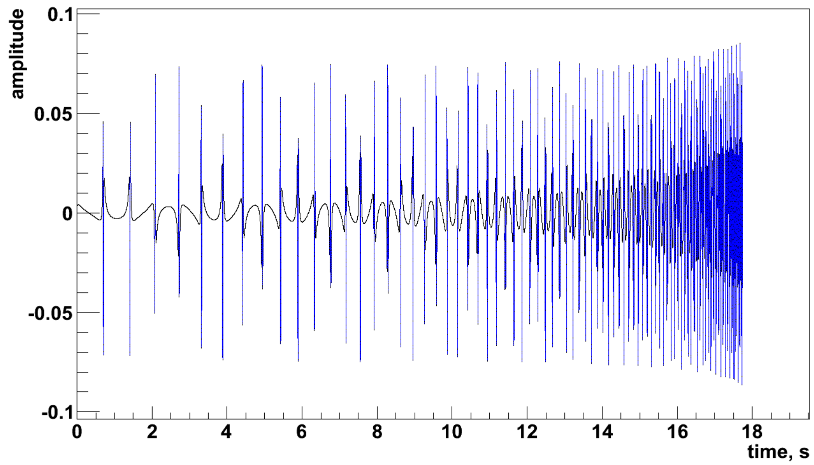
- **Low expected eccentricity in the detector band however, accretion into BH may change this (Melvin et al,** MNRAS. 356 (2005)**)**
- **Rate per globular cluster: few x 10^{-9} yr^{-1}**
- **Predicted Advanced LIGO event rates between 0 : 30 / year**

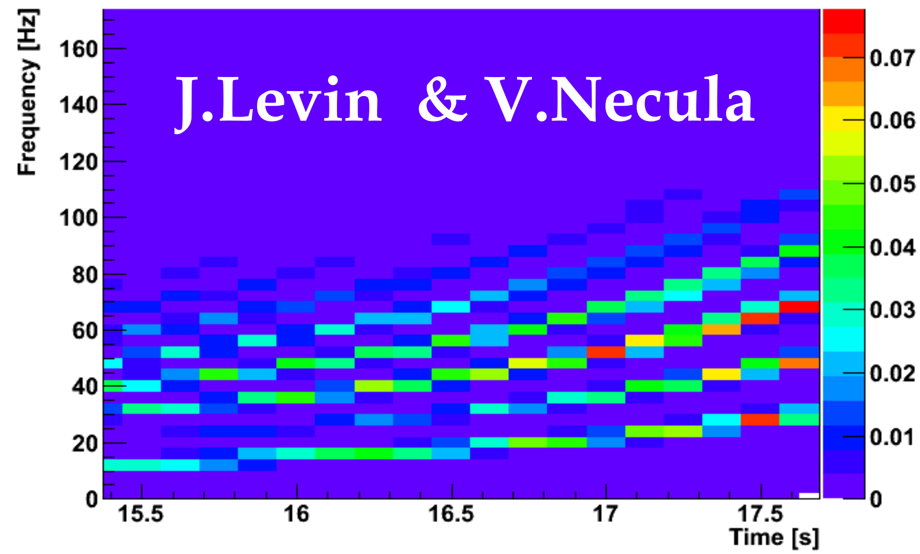
Eccentric BBH

- Form dynamically by BH-BH scattering in dense stellar environments by GW energy loss in a close encounter
  - density cusps around SMBH – Bahcall&Wolf, 1976
  - mass segregation – Morris, 1993
  - ~10^4 of ~10Mo BHs within 1pc of Sgr. A* - Miralda-Escude&Gould
  - BH mass distribution ~$M^{-\beta}$ - O'Leary, Kocsis and Loeb, 2009
  - merge within minutes-hours – retain significant eccentricity
- Expected aLIGO rates: comparable to circular BBH (Kocsis et al. 2006), but very debatable – can be 0.
- Unique GW source to study galactic nuclei

Eccentric Waveforms

10+10 Mo eBBH





- PN models - “faithful” waveforms
  - Princeton code (S.McWilliams et al PRD 87 2013)
  - Columbia eBBH tool (J.Levin et al, CQG 28 (2011) 175001)
  - Cbwaves, 3.5PN, spins (I. Rasz et al CQG 29 (2012) 245002)
- NR simulations (costly)
  - Georgia Tech (J. Healy, L. Pekowski, D. Shoemaker)
- Use burst searches to detect and identify a characteristic eBBH signature

Binaries as Standard Sirens

- What do we need to know to find the luminosity distance D_L?

Red-shifted chirp mass: analysis of binary's TF evolution

Direction to the binary: source localization with networks of GW detectors

$$\mathcal{M} = m_1^{3/5} m_2^{3/5}/(m_1 + m_2)^{1/5}$$

$$h_+ = \frac{2[(1+z)\mathcal{M}]^{5/3}}{D_L}[\pi f(t)]^{2/3}\left[1 + (\hat{L}\cdot\hat{n})^2\right]\cos[\Phi(t)]$$

$$h_\times = \frac{4[(1+z)\mathcal{M}]^{5/3}}{D_L}[\pi f(t)]^{2/3}\left[\hat{L}\cdot\hat{n}\right]\sin[\Phi(t)] \ .$$

$D_L(z)$ degeneracy: find electro-magnetic counterpart with telescopes

source orientation: reconstruction of the wave's polarization state

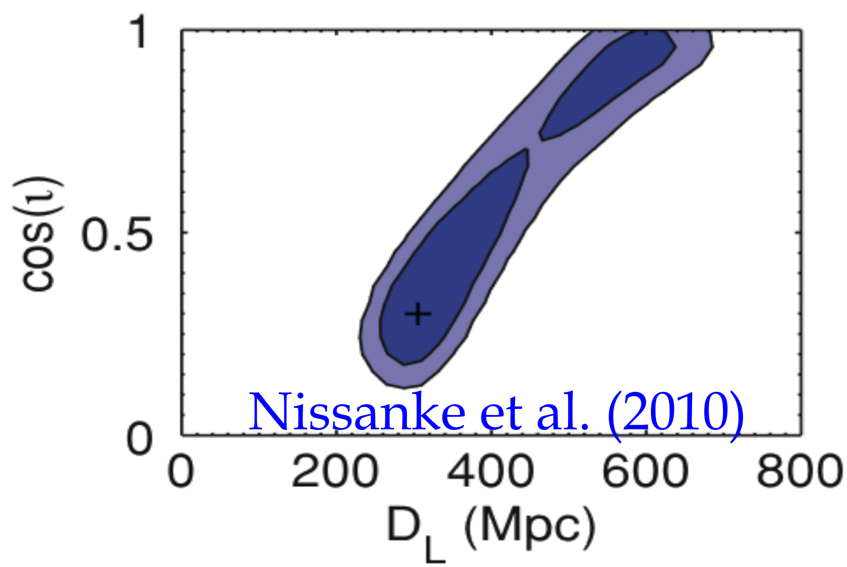
CQG, 20 (2003)
ApJ.725,2010

Inclination – distance degeneracy

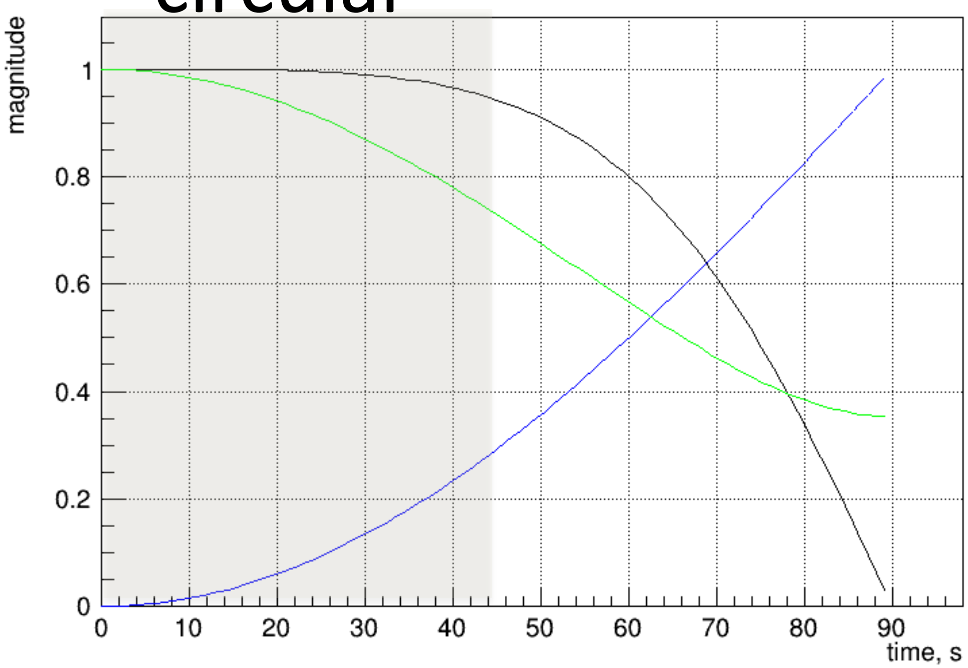
- measured parameter: ellipticity

$$e = 1 - \frac{2\cos(\iota)}{1+\cos^2(\iota)}$$

- ellipticity-distance correction is degenerate for ι<45°



circular



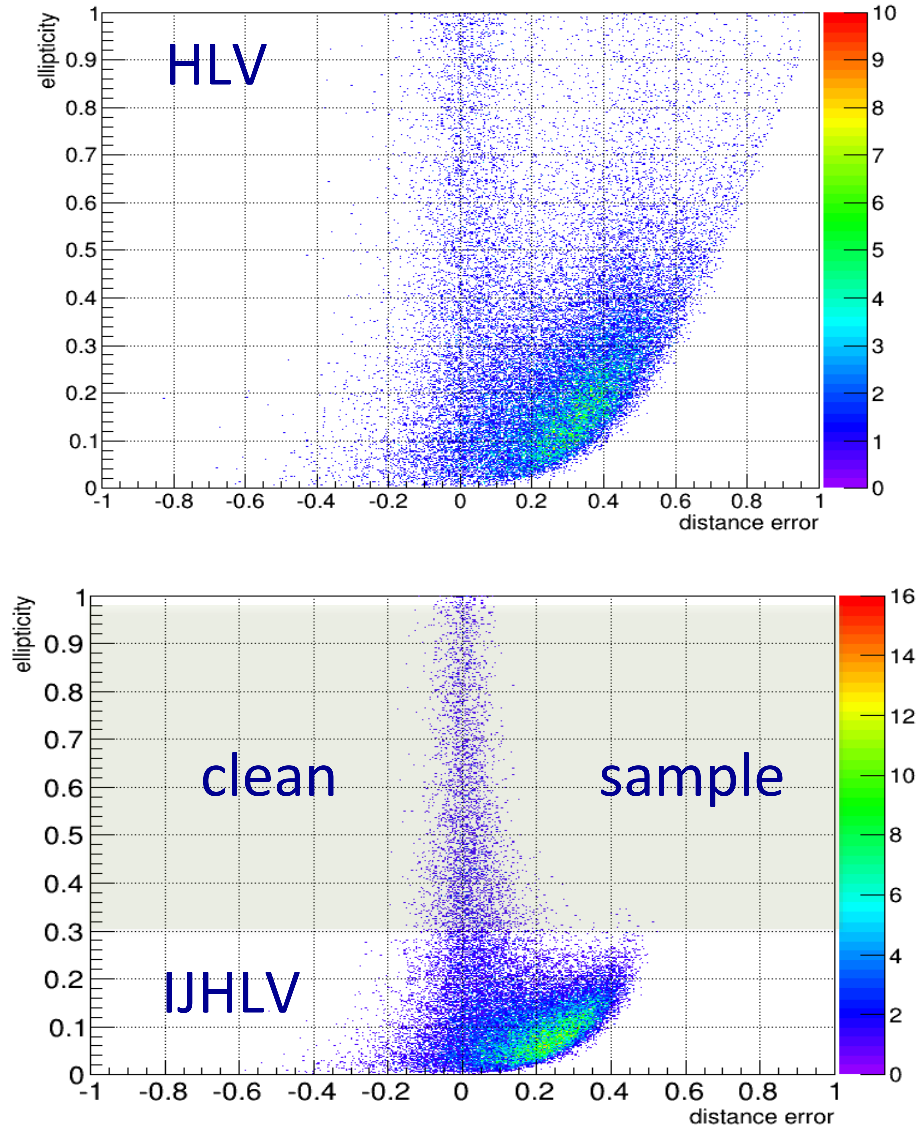
black: 1-e

green: signal amplitude

Blue: fraction of sources

Clean Samples

- "face-on binaries"→ GRBs pointing at us: assuming that a significant fraction of short GRBs are NS-NS, NS-BH mergers
- "edge-on binaries": measure and apply ellipticity correction
  - polluted by miss-reconstructed events due to poor polarization coverage
  - increase polarization coverage with more detectors in the network



Hubble with advanced detectors

$\text{Plank}: 67.4 \pm 1.4 \text{ km s}^{-1}\text{Mpc}^{-1}, \text{ HST}: 73.8 \pm 2.4 \text{ km s}^{-1}\text{Mpc}^{-1}, \text{ SST/CHP}: 74.3 \pm 1.5 \text{ km s}^{-1}\text{Mpc}^{-1}$

arXiv:1307.2638v1

MEASUREMENT ERRORS IN H_0 FOR A SAMPLE OF GW-EM EVENTS. RESULTS ARE PRESENTED FOR UNBEAMED AND BEAMED SOURCES, FOR BOTH NS-NS AND NS-BH MERGERS, AND FOR A RANGE OF DETECTOR NETWORKS. THE % VALUES ARE THE 68% C.L. FRACTIONAL ERRORS, AND THE NUMBER OF BINARIES DETECTED BY EACH NETWORK IS GIVEN IN PARENTHESES.

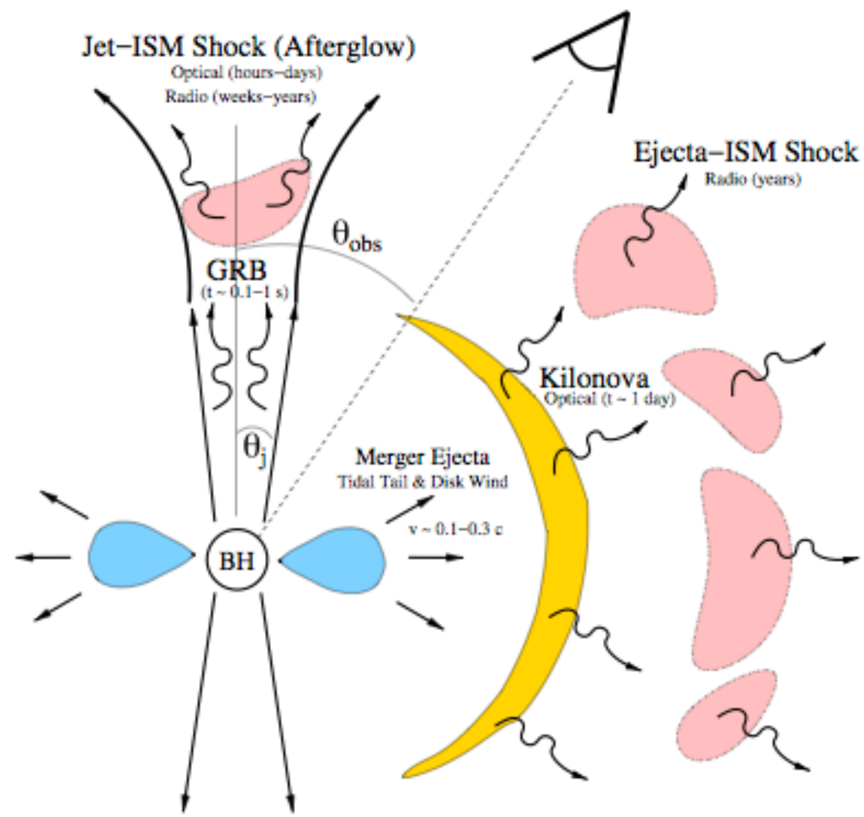
Network	LIGO+Virgo (LLV)	LLV+LIGO India	LLV+KAGRA	LLV+LIGO India+KAGRA
NS-NS Isotropic	5.0% (15)	3.3% (20)	3.2% (20)	2.1% (30)
NS-NS Beamed	1.1% (19)	1.0% (26)	1.0% (25)	0.9% (30)
NS-BH Isotropic	4.9% (16)	3.5% (21)	3.6% (19)	2.0% (30)
NS-BH Beamed	1.2% (18)	1.0% (25)	1.1% (24)	0.9% (30)

- Caveats
  - Beamed (GRB): expected # of GRB-GW associated events <1/y
  - Isotropic: need prompt detection of GRB afterglow, kilonova,..

Anticipated EM signatures of NS mergers

- γ rays
  - GRB (may be pointing away) - seconds
  - Ejecta from magnetar - minites
  - GRB afterglow - hours
- UV, optical, IR
  - GRB afterglow - hours
  - kilonova - days
- Radio
  - GRB afterglow – weeks-months
  - Prompt emission - seconds

Metzger & Berger, 2012



GW-EM association

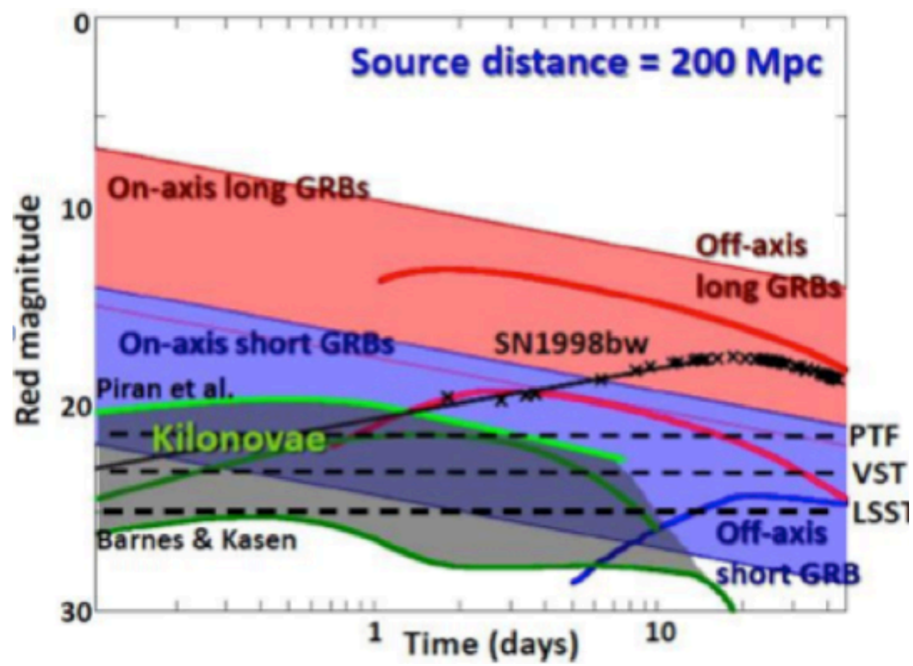
guide EM instruments

Inform GW searches

LSST.org

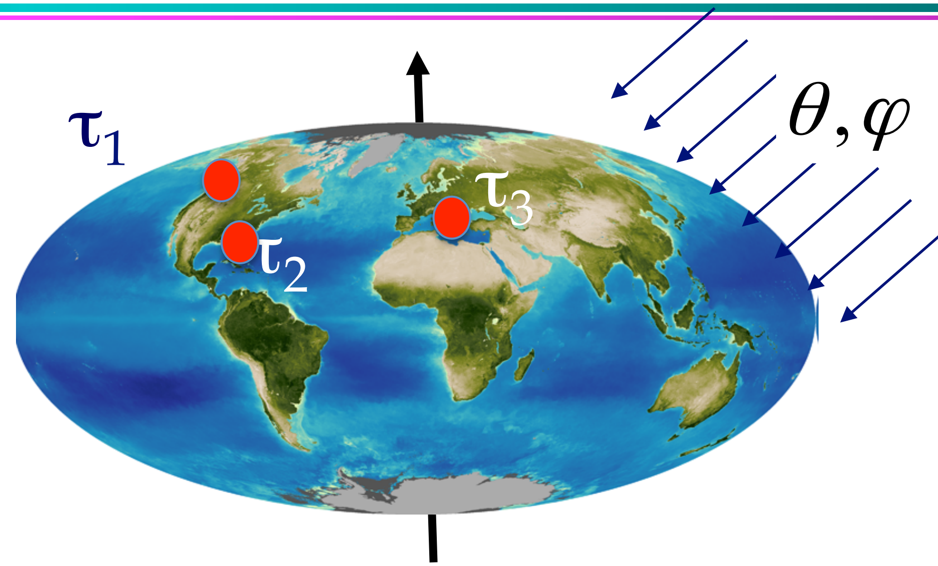
- **Other than NS-NS/BH progenitors**
  - Soft gamma repeaters: star-quakes
  - Galactic (& nearby) supernovae
  - BH-BH(?), unexpected sources

For confident EM-GW association & to identify NS mergers among other transients need low latency sky localization of GW events



GW Source Localization

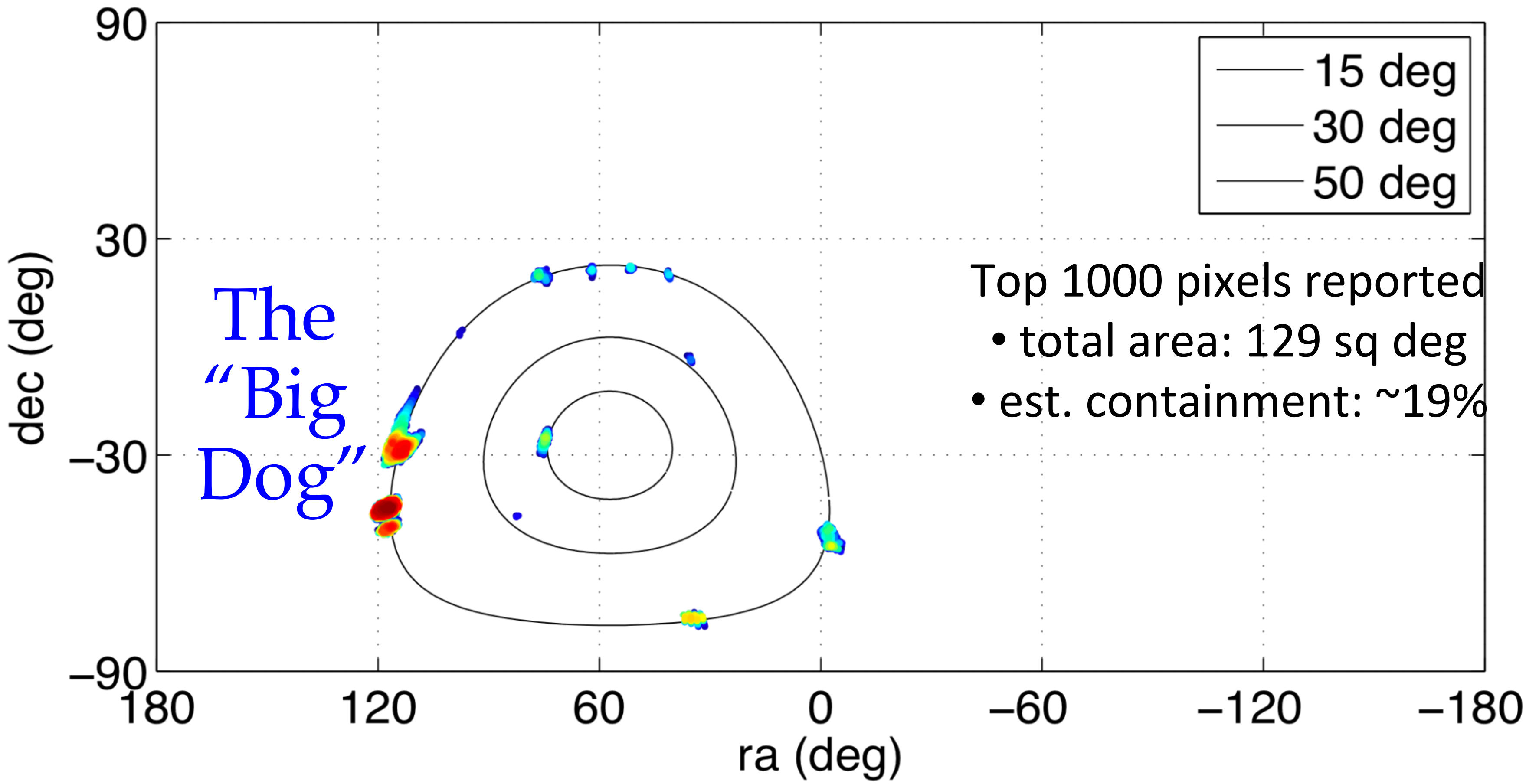
- Two basic methods
  - triangulation (t_1,t_2,t_3,..)
  - antenna patterns
- at least 2 detectors (annulus), preferably >3 detectors



- Latency: not a problem (~1 minute for existing searches)
- Resolution: not nearly as sharp as for telescopes, particularly at low GW frequency

How GW event looks in the sky

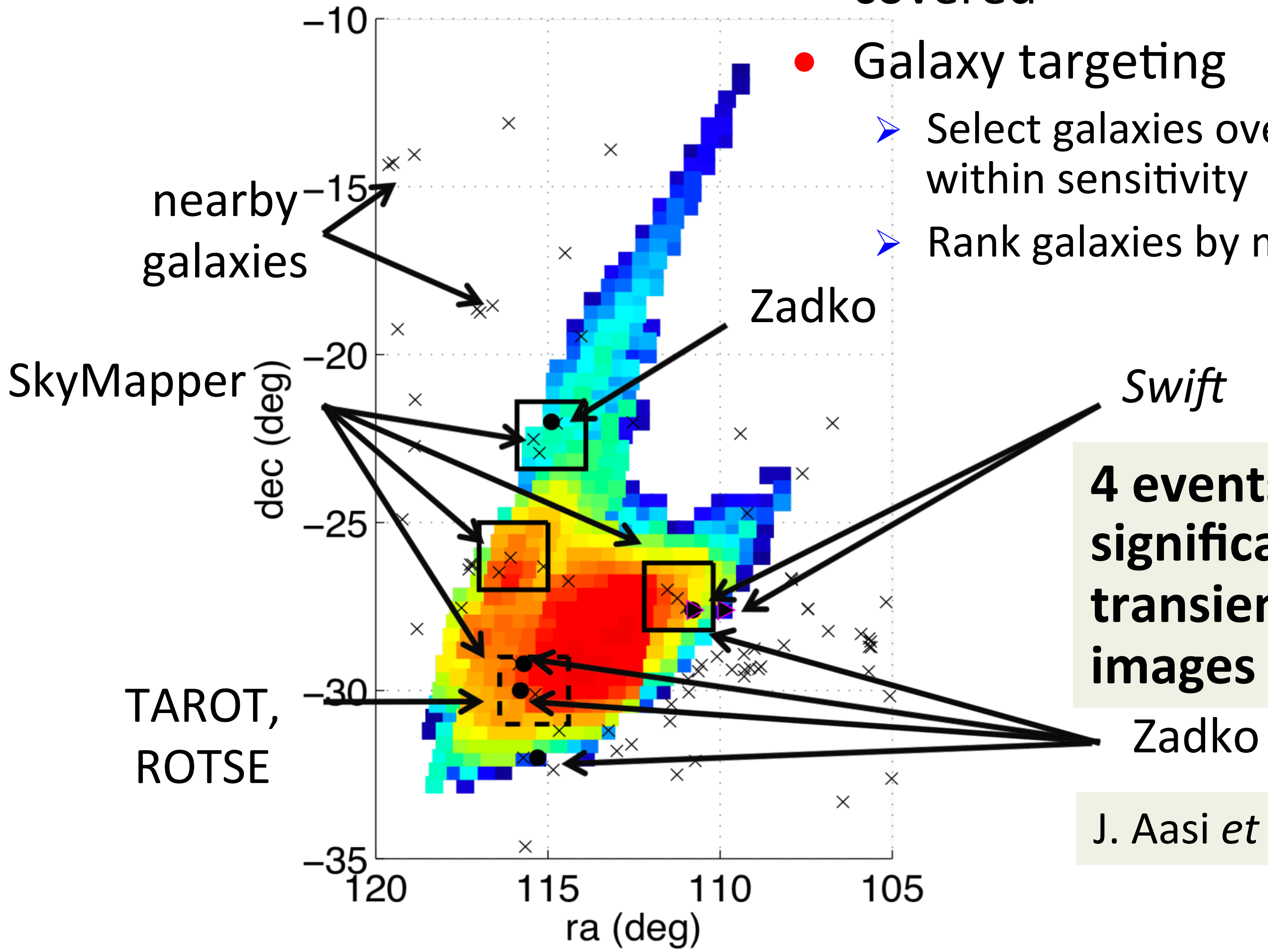
- Event reported for EM follow-up during S6 run
  - large error regions, fragmented



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

Follow-up with Telescopes

- Only fraction of GW error regions covered
- Galaxy targeting
  - Select galaxies overlapping with ER and within sensitivity range of GW network
  - Rank galaxies by mass, luminosity

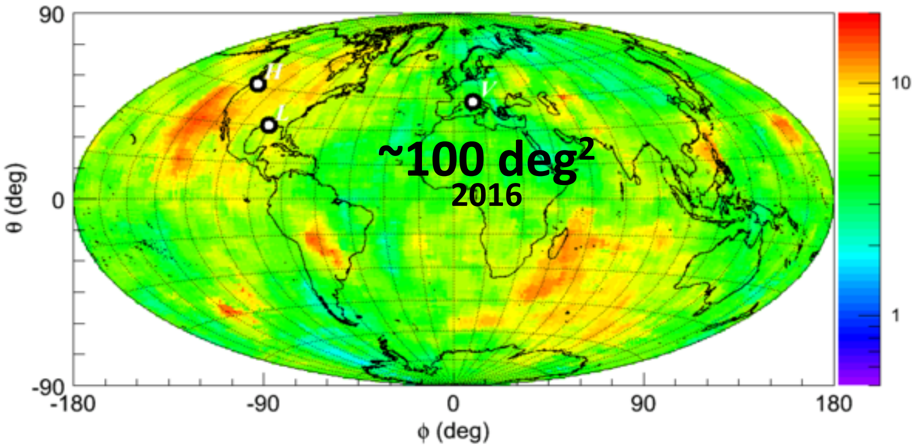


4 events during S6 - no significant optical transients found in the images

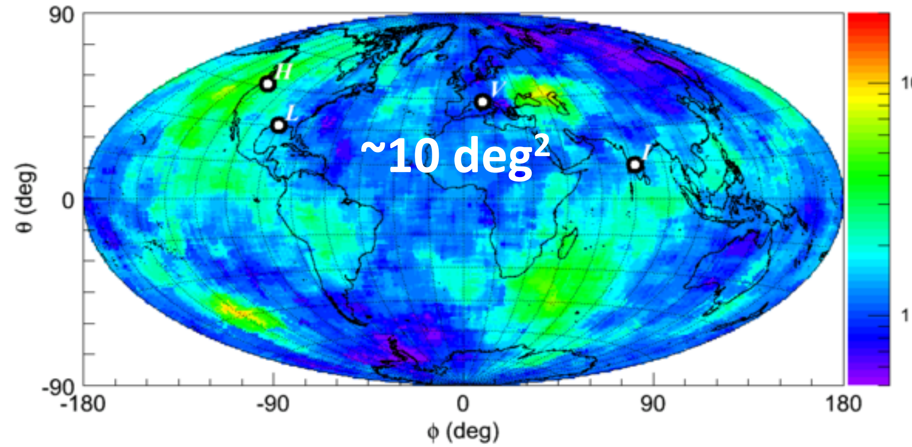
J. Aasi *et al.* 2014 *ApJS* **211** 7

Evolution of GW Sky Localization

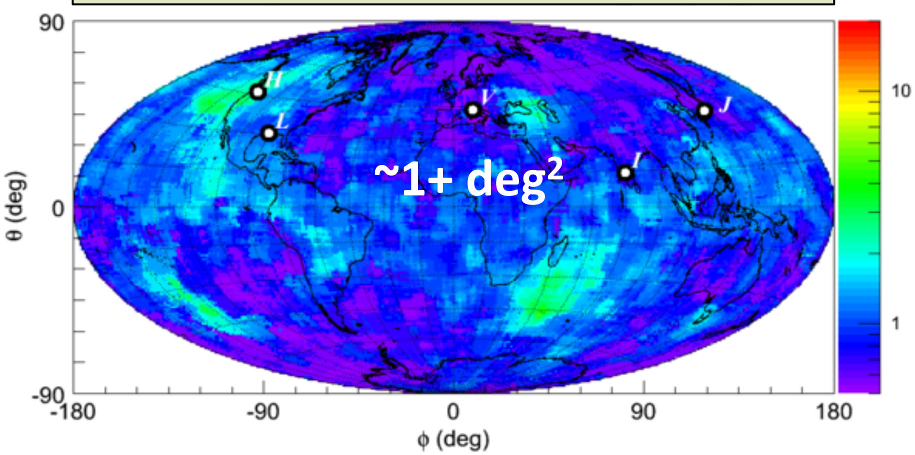
3 sites – HLV



4 sites - IHLV



5 sites – IJHLV



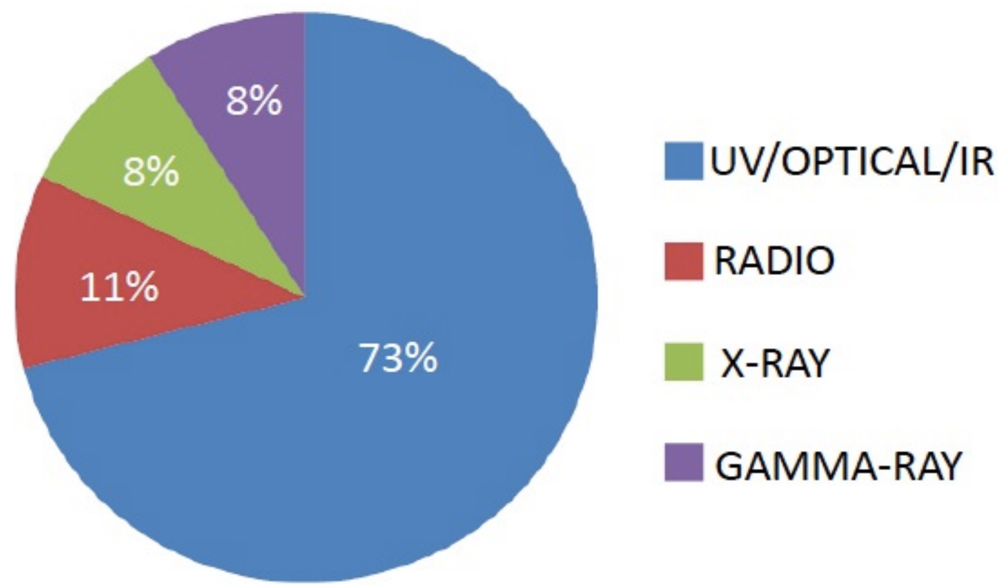
- more sites is better
- large FOV telescopes required
- joint observations of NS mergers (afterglow/optical/UV & GW) and other sources will require a significant commitment of observing telescope time

- Median error angle (50% CL, SNRnet<30) for "worse case scenario" - reconstruction of ad-hoc (un-modeled) signals

Call for EM-GW follow-ups

- "Starting with the first observation run in 2015 and until first 4 GW events have been published, LVC will share triggers promptly with astronomy partners who have signed MOU"

About 60 MOUs signed, from 19 countries including 150 instruments covering full EM spectrum from radio to gamma-rays

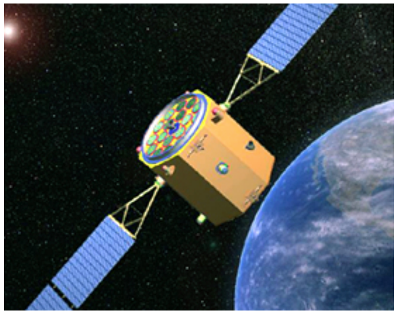


- After the first four published GW events, LSC and Virgo will promptly release triggers to public.

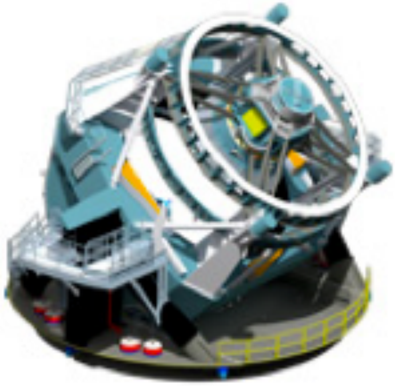
Celestial Cinematography

- Astronomers are now exploring all regions of the electromagnetic spectrum, from gamma-rays through UV, optical, IR to radio waves.
- Astronomical instruments also look wider and deeper, and develop more capabilities to capture a detailed time evolution of sources (celestial cinematography) uncovering a complex structure of the transient Universe.
- With inception of new telescopes, the data-intensive time domain astronomy is on the horizon

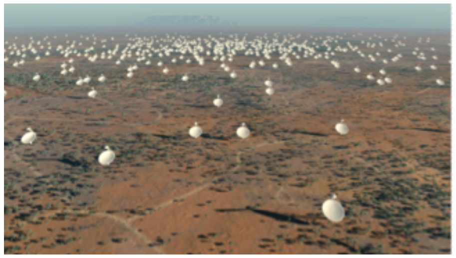
hxmt.ch



LSST.org

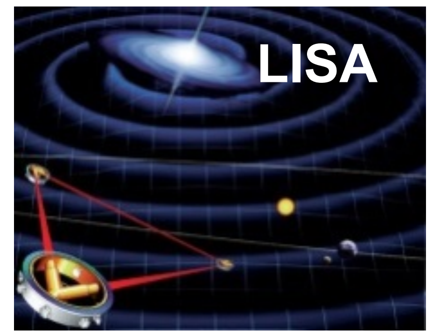


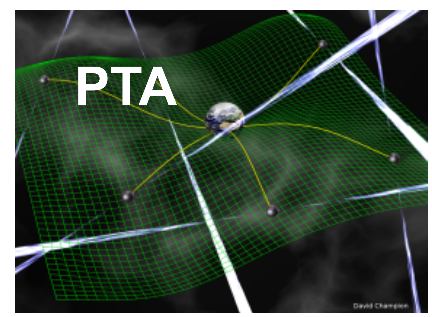
skatelescope.org



Multi-Messenger Astronomy

- With the advent of advanced gravitational wave detectors, unexplored domains in gravitational-wave spectrum (Celestial Soundtrack) will soon be available
- This all-sky multi-messenger astronomy will enable quantitatively and qualitatively new science, from studies of our Galaxy, understanding of black holes to the discoveries of rare, unusual, or even completely new types of astronomical objects and phenomena.





Summary

- Starting in 2015 advanced detectors target first direct observation of gravitational waves from astrophysical objects.
  - Advanced network will evolve with time improving GW network capabilities to capture science
  - as astrophysical GW landscape is revealed, expect rapid development of GW instrumentation and network configurations beyond advanced detectors.
- Science-rich data-intensive time domain astronomy is on the horizon
- Coordinated effort is required to realize full potential of multi-messenger observations