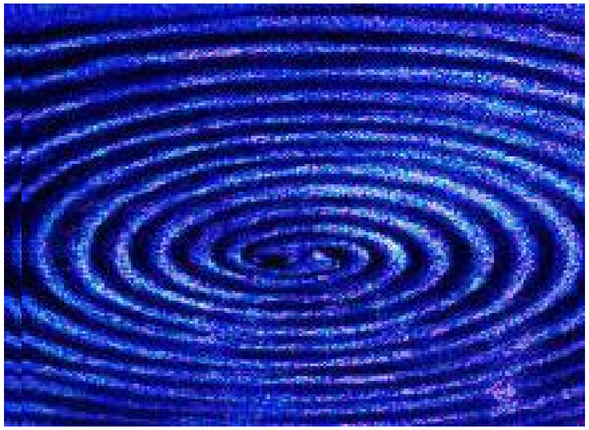


Gravitational-wave transient detection and multi-messenger astrophysics

Ray Frey, University of Oregon

for the

LIGO Scientific Collaboration

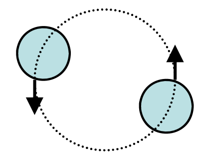
and the Virgo Collaboration

LIGO-G1000515

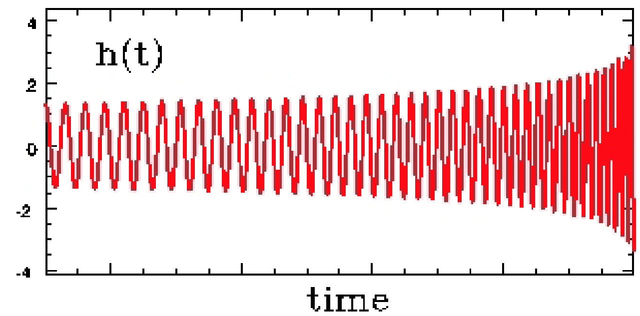
- Introduction – overview and status of LIGO and Virgo
- Observational results
- A new astronomy with advanced GW detectors

Required GW Sensitivity for Detection

- GW emission requires time varying quadrupole moment of mass distribution, $\ddot{Q}_{ij}$ → gravitational-wave strain, h = δL/ L, is the analog of the radiation field E in E&M
- Strain estimate:



$$h \sim \left(\frac{GM}{c^2}\right)\left(\frac{v^2}{c^2}\right)\frac{1}{r}$$



For $1M_\odot \Rightarrow R_s = 2GM_\odot/c^2 = 3$ km

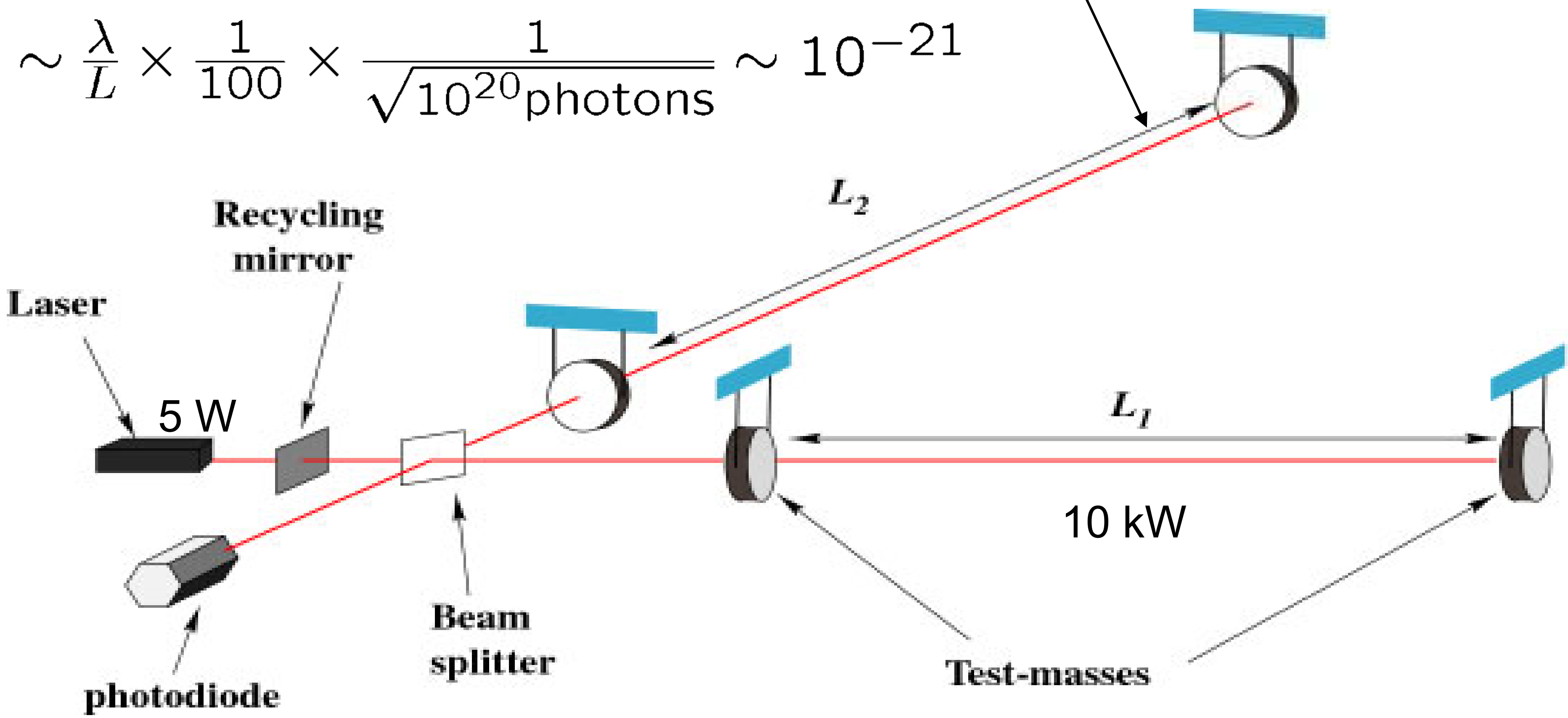
If $v \approx c$, then at $r = 15$ Mpc:

$$h \sim 3 \times 10^{-21}$$

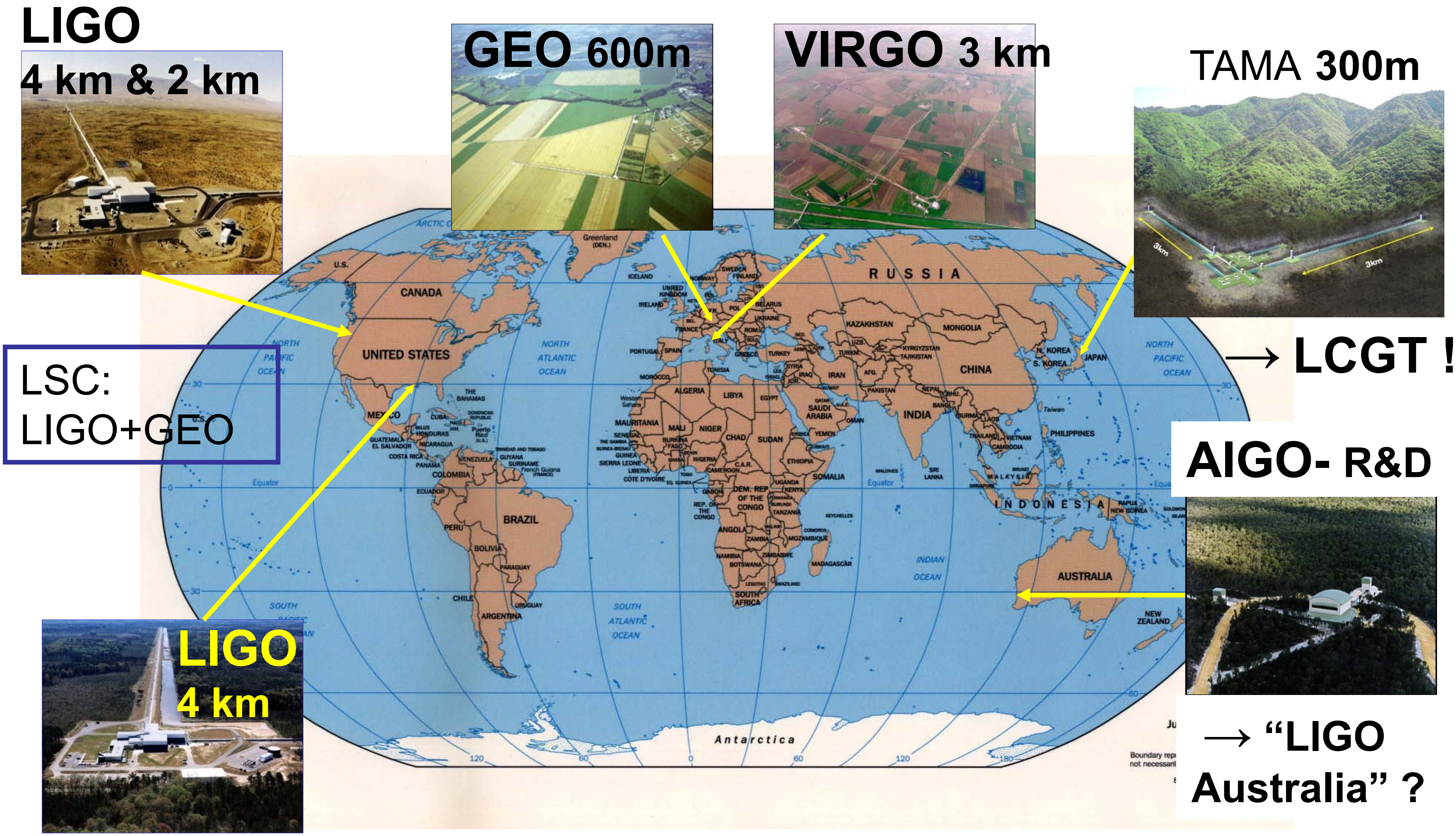
GW Interferometer principle

- Michelson interferometer with Fabry-Perot cavity arms.
- Long baseline: 4 km (h = δL/ L) - **For h ≈10^{-21}, L ≈ 1 km, then δL ≈ 10^{-18} m**
- Fabry-Perot Cavity storage time ~1 ms (~100 bounces)
- Power recycling (x30)
- Noise estimate:

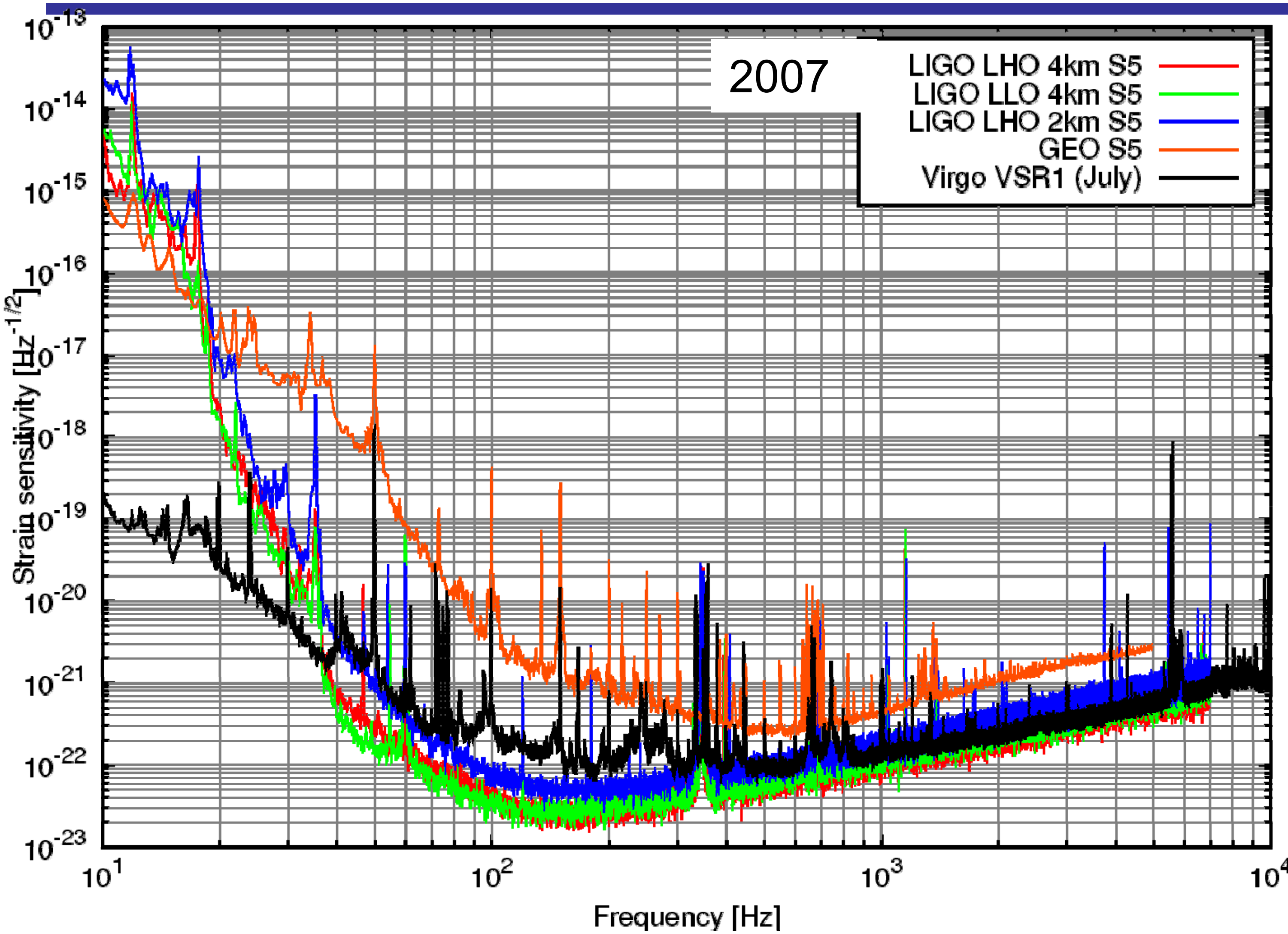
$$h \sim \frac{\lambda}{L} \times \frac{1}{100} \times \frac{1}{\sqrt{10^{20}\text{photons}}} \sim 10^{-21}$$



Global network of interferometers

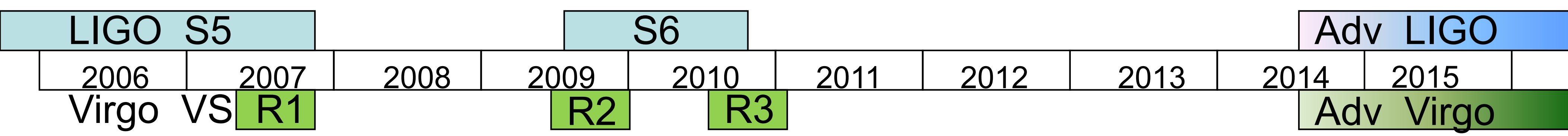


S5/VSR1 sensitivity

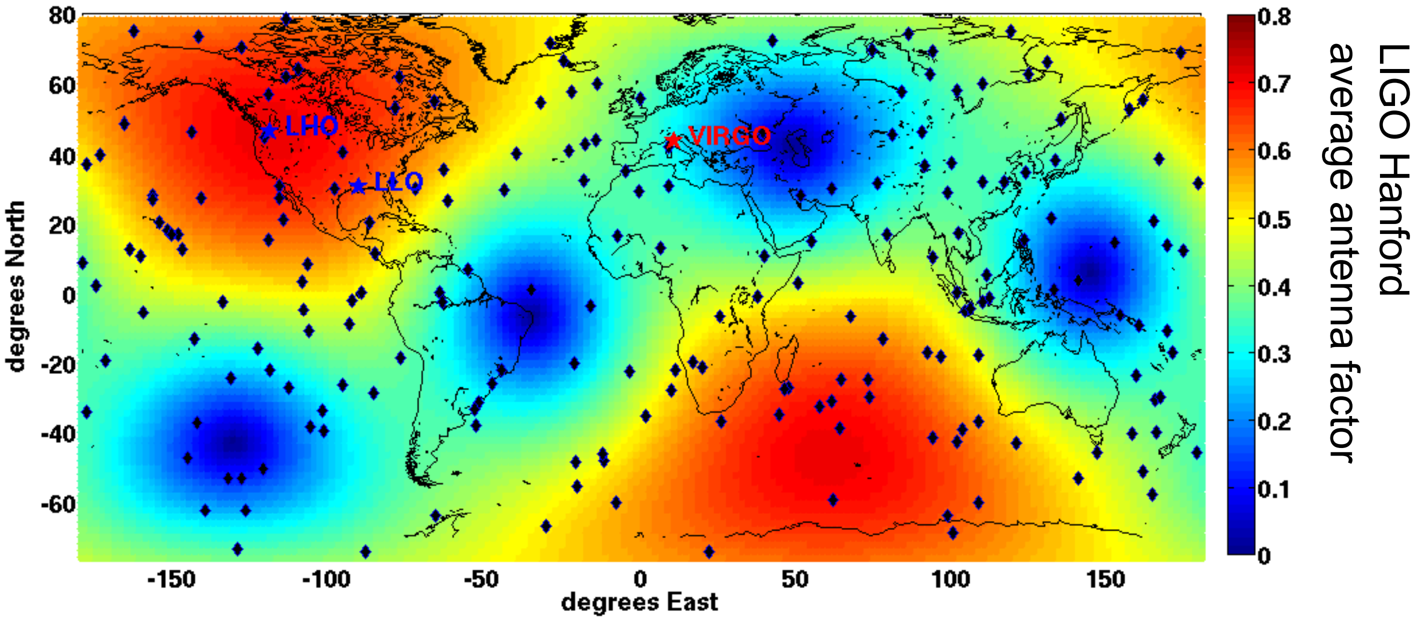


LIGO Run S5:
2005-07
Ran at design sensitivity for initial LIGO

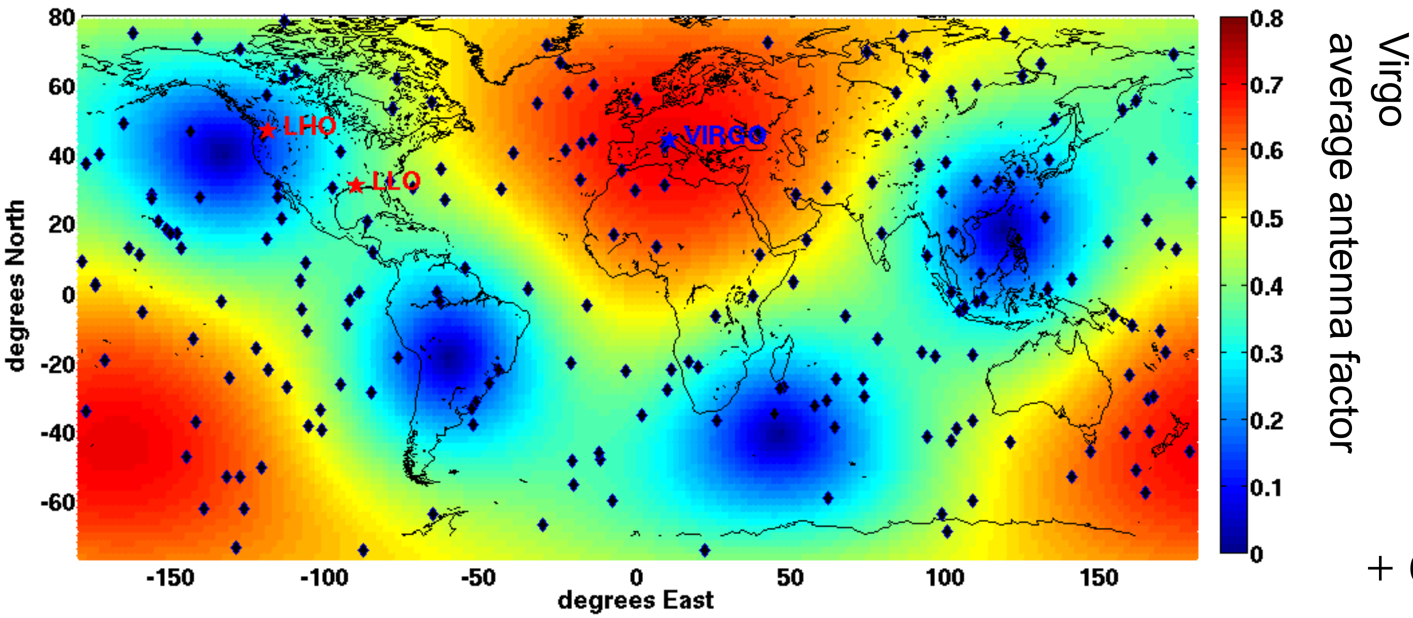
Virgo Run VSR1:
2007
Data sharing with LIGO/GEO



The LIGO-Virgo network: sky coverage



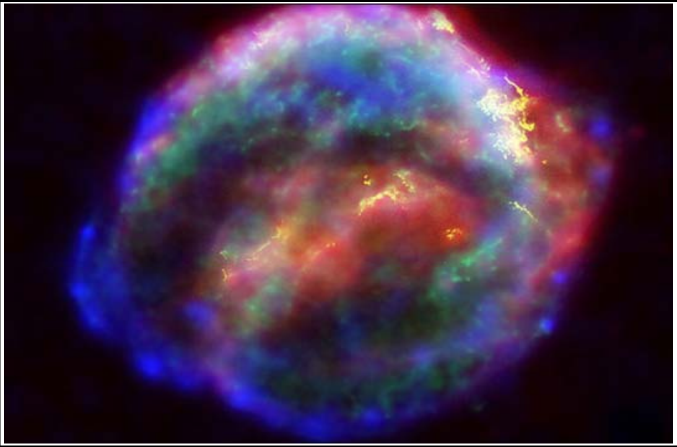
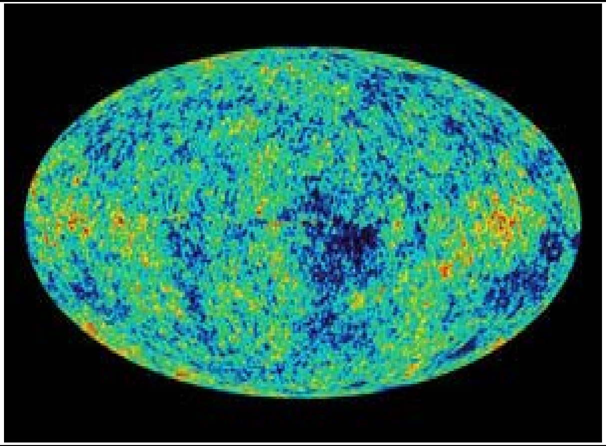
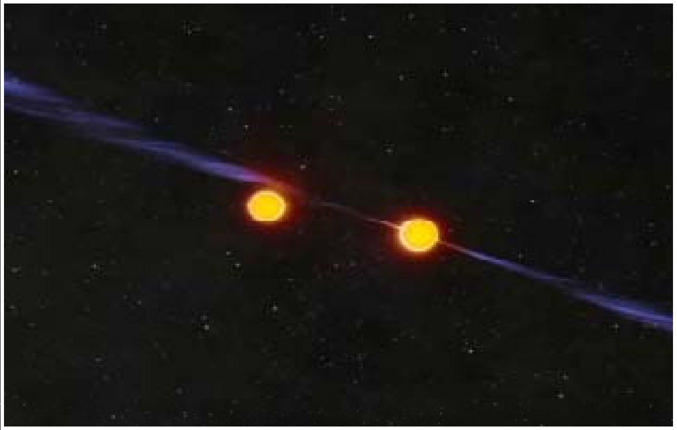
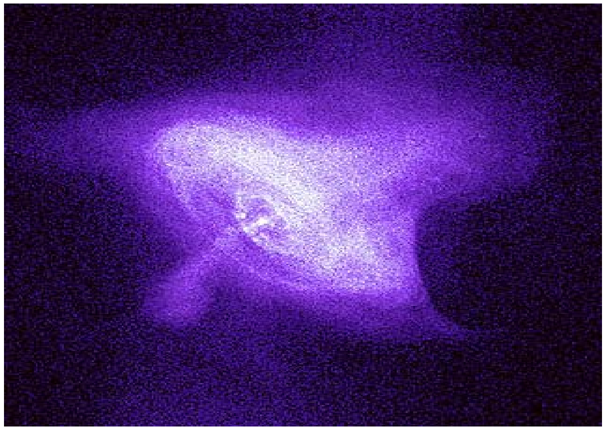
$$h(t) = F_x\, h_x(t) \;+\; F_+\, h_+(t)$$



$$F_+ \oplus F_x$$

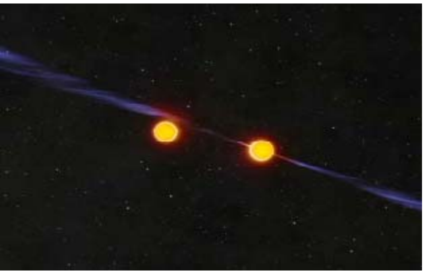
+ GRBs in S5/VSR1

GW signals classification

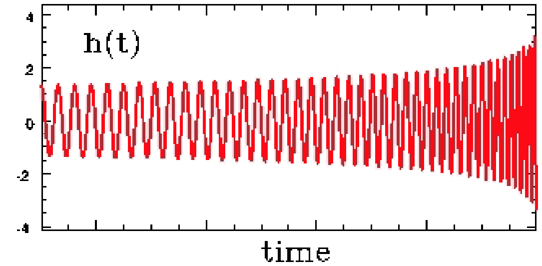
	Short duration	Long duration
un-modeled		
matched filter		

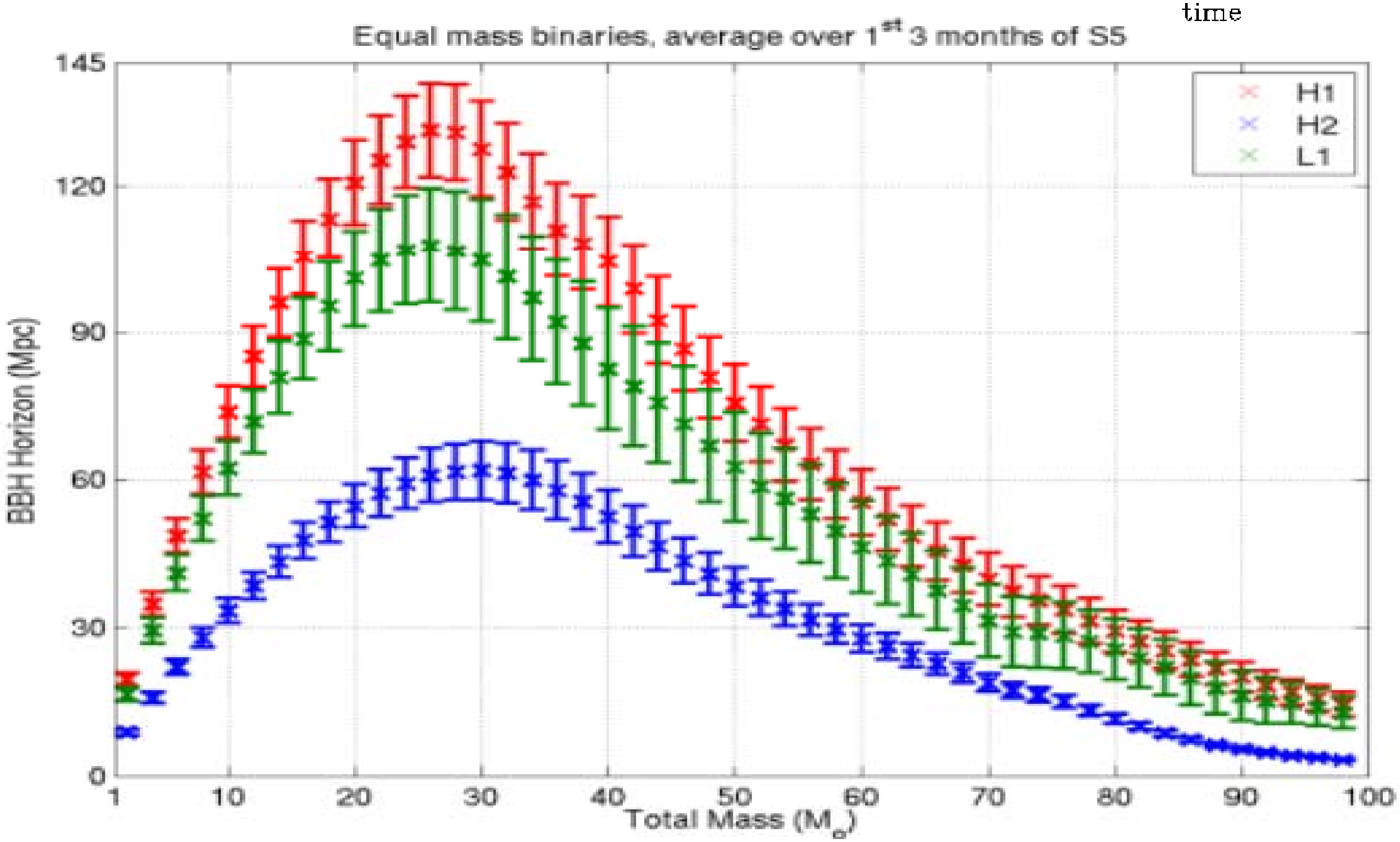
Credit: NASA/CXC/ASU/J. Hester et al.

S5/VSR1 sensitivity to compact binary coalescence



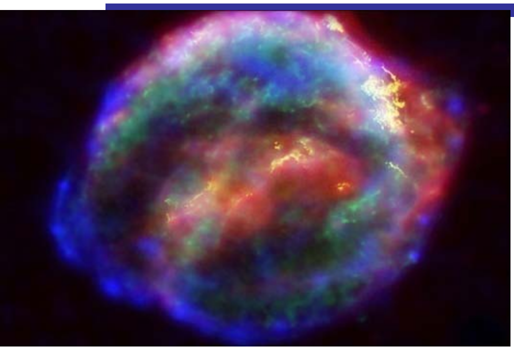
- NS-NS, NS-BH, BH-BH
- Efficient GW radiators: ~10^{-2} Mc^2
- Matched filter analysis for low-mass inspirals



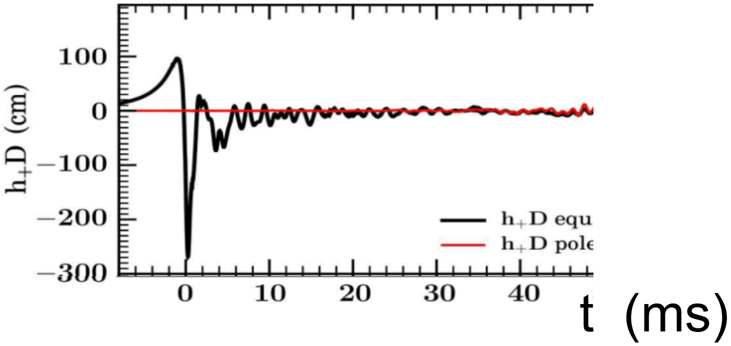


(horizon= distance to optimally oriented and located binary which gives SNR=8 in one detector)

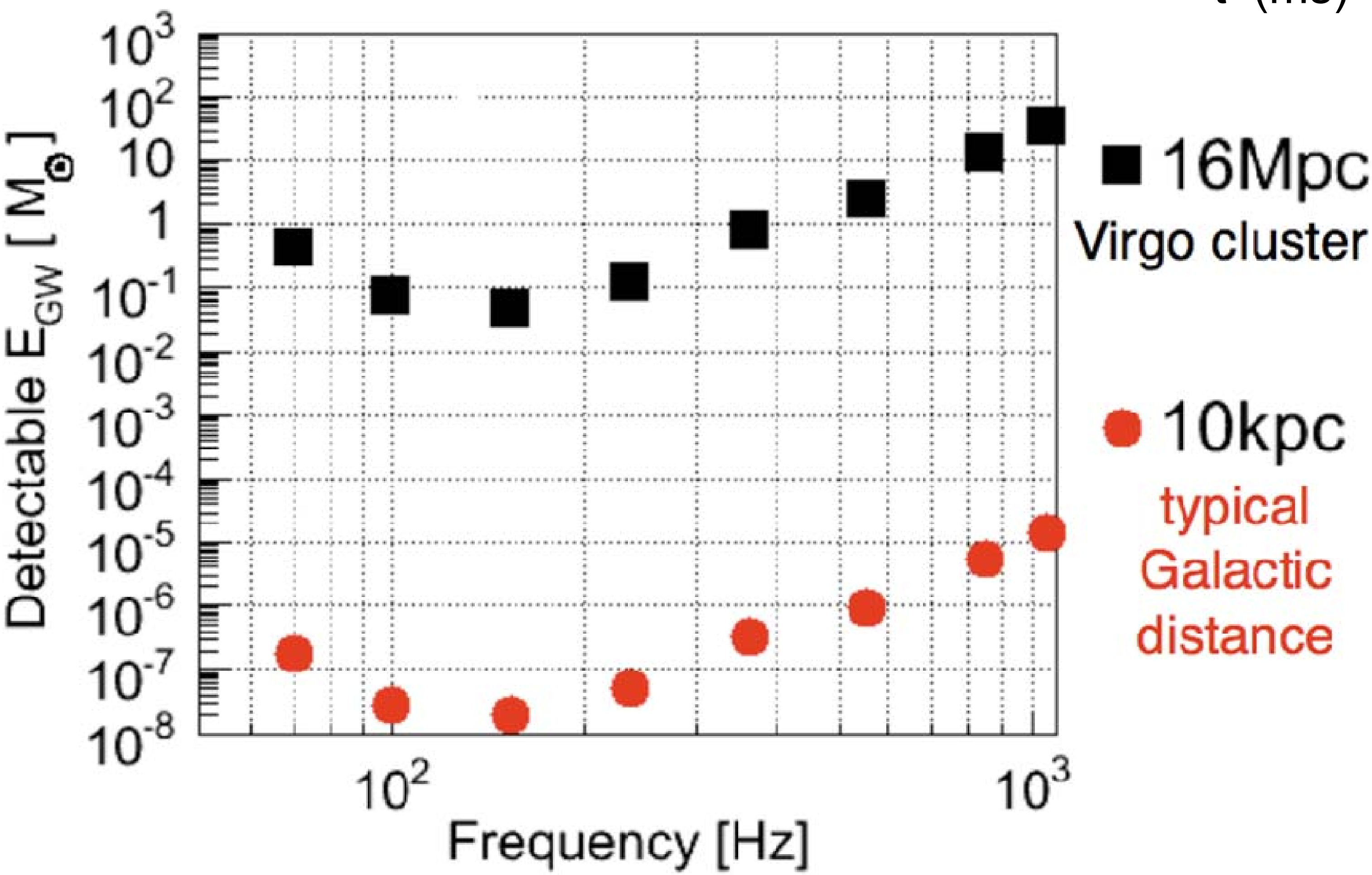
S5/VSR1 sensitivity to GW Bursts



- short (< 1s) transients
- unmodeled waveforms
- CCSNe, GRBs, SGRs, …



$$E_{GW} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{rss}^2$$

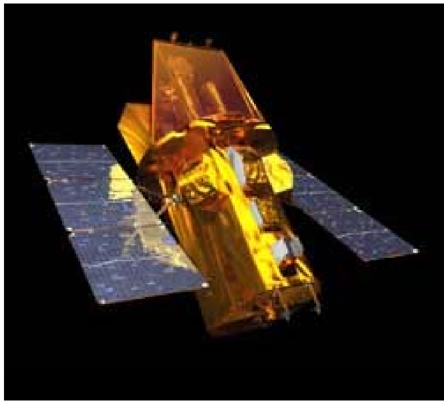
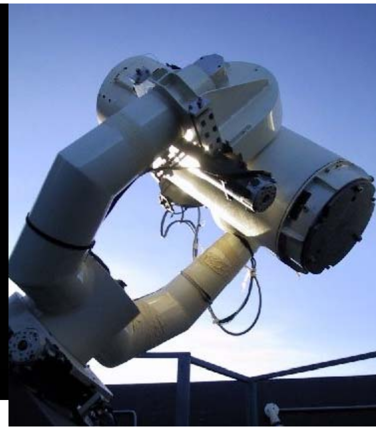


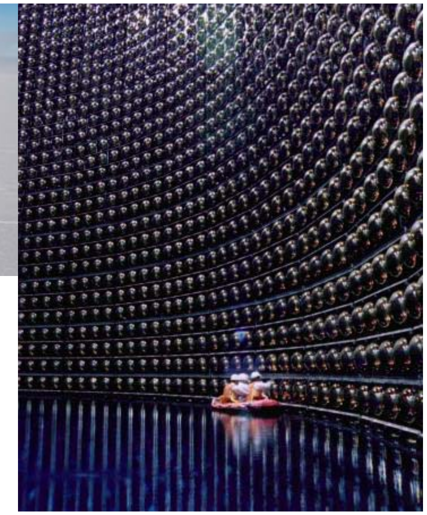
LIGO-Virgo Search Results

- No GW detections yet
- However, beginning to make astrophysically interesting limits
  - This talk: Astrophysically targeted transient searches (GRBs, SGRs)
  - Others:
    - Crab pulsar spindown limit (ApJ 683 (2008) 45)
    - cosmic GW background limit < BBN (Nature 460 (2009) 990)

- Era of advanced GW detectors is approaching (>2014) in which we expect GW detections will become frequent (more on this later)
- To take advantage of this opportunity, we have developed a suite of *multi-messenger* pathways to fully explore the science (this talk)

Multi-messenger astronomy with GWs

EM , neutrinos

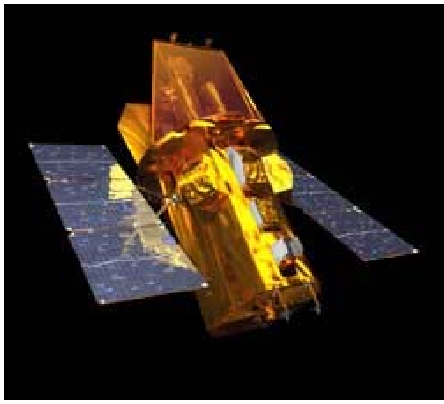
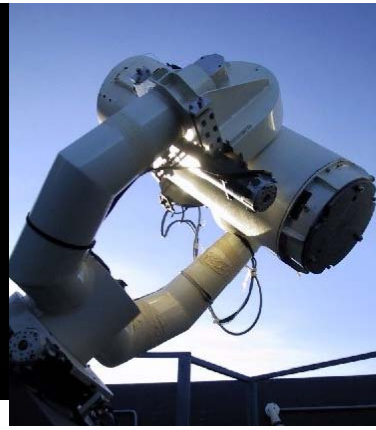
External Triggers

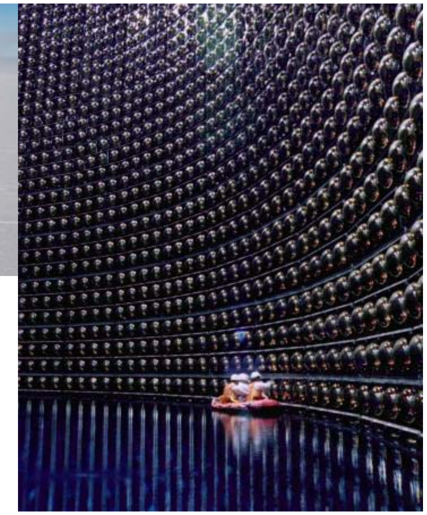
Follow Ups

GW




Multi-messenger astronomy with GWs

- Detection confidence
- Event time
- Sky position
- Improved search sensitivity
- Redshift
- Progenitor information



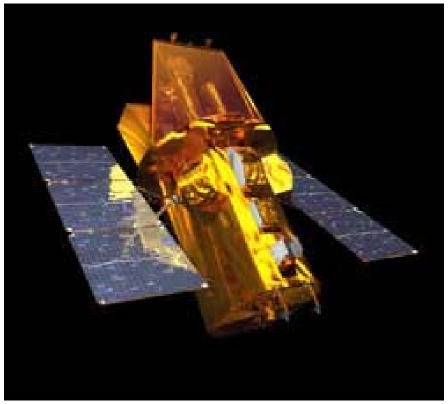

Multi-messenger astronomy with GWs – Status

- Externally triggered searches – gamma, X-rays (Swift, Fermi, IPN)
  - GRBs
  - SGRs
- Externally triggered searches – neutrinos
  - High-energy neutrinos (Ice Cube, ANTARES, …)
    - GRBs, ?
  - Low-energy neutrinos (Super-K, LVD, Borexino,…)
    - Core-collapse supernovae
- Electromagnetic follow-ups of GW triggers
  - Requires fast (~10 min) id and distribution of LIGO-Virgo trigger (for S6)
    - ~few degree resolution with LIGO-Virgo network
  - Swift ToO – XRT
  - Wide-angle optical telescopes (SkyMapper, TAROT, Quest, …)
  - Radio

Multi-messenger astronomy with GWs – Status

- Externally triggered searches – gamma, X-rays (Swift, Fermi, IPN)
  - GRBs
  - SGRs

Past and ongoing searches



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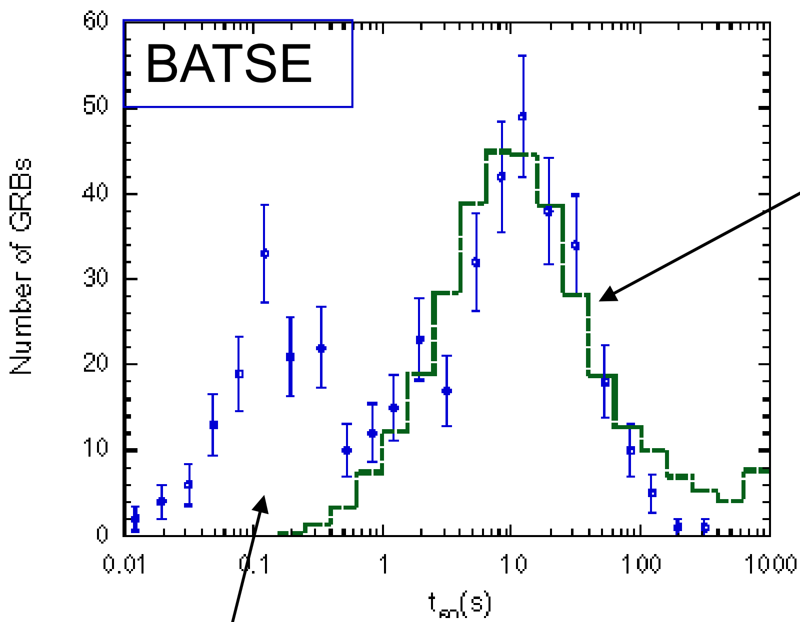
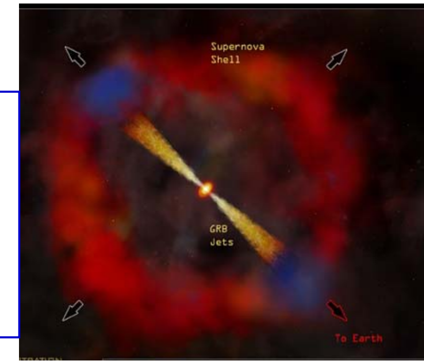
Gamma-ray Bursts and GWs





<u>Long-duration GRBs</u>

- Associated with core-collapse of massive stars (“hypernovae”)

<u>Short-duration GRBs</u>

- Associated with binary mergers (NS-NS, NS-BH)

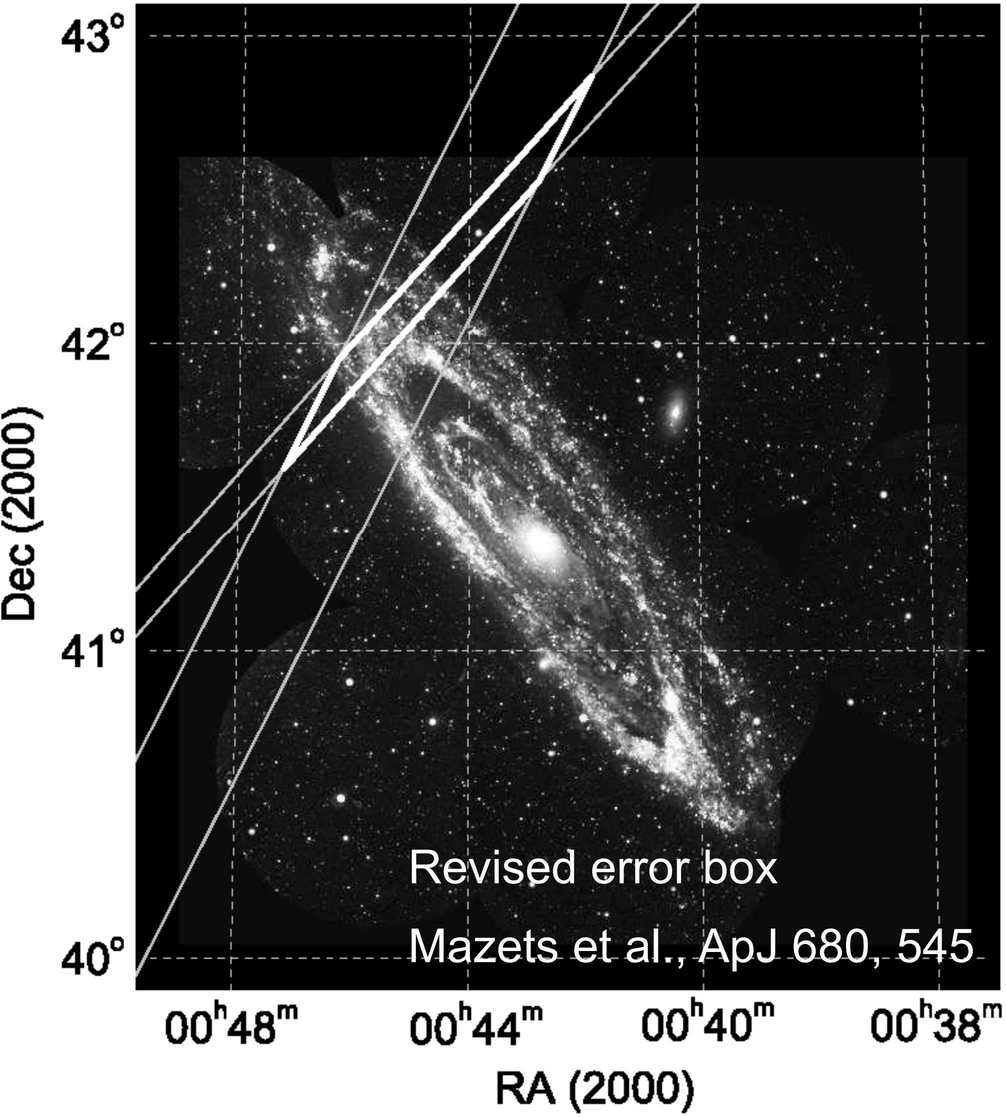
Both progenitor models would also give GW emission

- Mergers are efficient GW radiators

$$E_{GW} \sim 10^{-2}\ Mc^2$$

- Massive core collapse – unknown, but expected to be less efficient

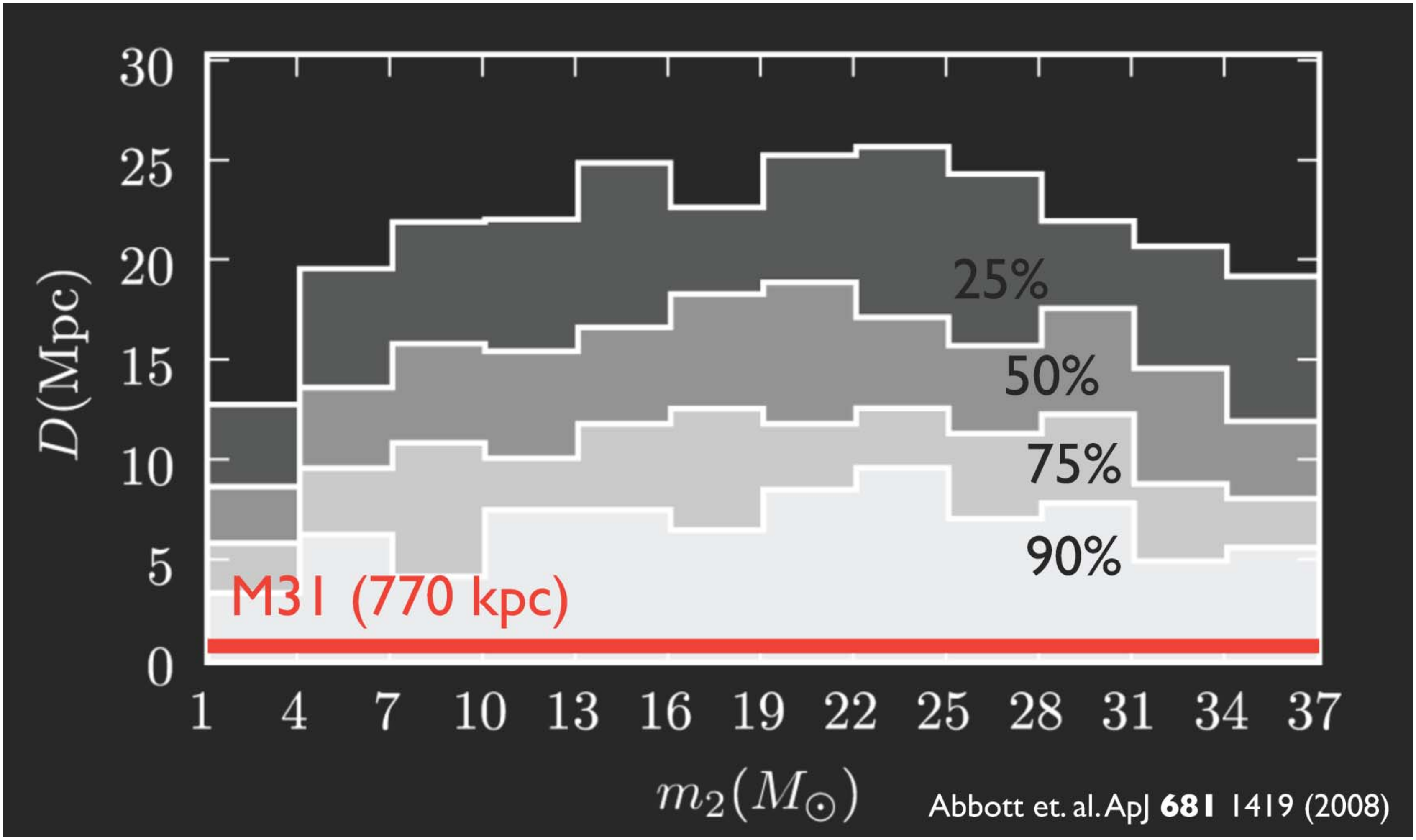
GRB 070201



- GRB 070201 – a short-duration gamma-ray burst with position consistent with M31 (Andromeda), 0.8 Mpc away.
- Such a nearby GRB would have easily been observed by LIGO if due to a binary merger
- This hypothesis ruled out at ~99% CL
- Most likely: SGR in M31 (E_{iso}~10^{45} erg)
- Astrophys. J. 681 (2008) 1419

GRB 070201 (contd)

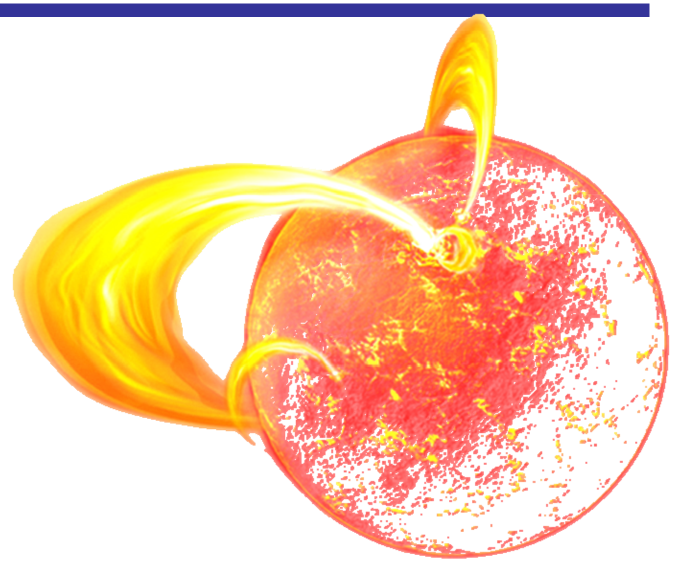
Binary coalescence exclusion:

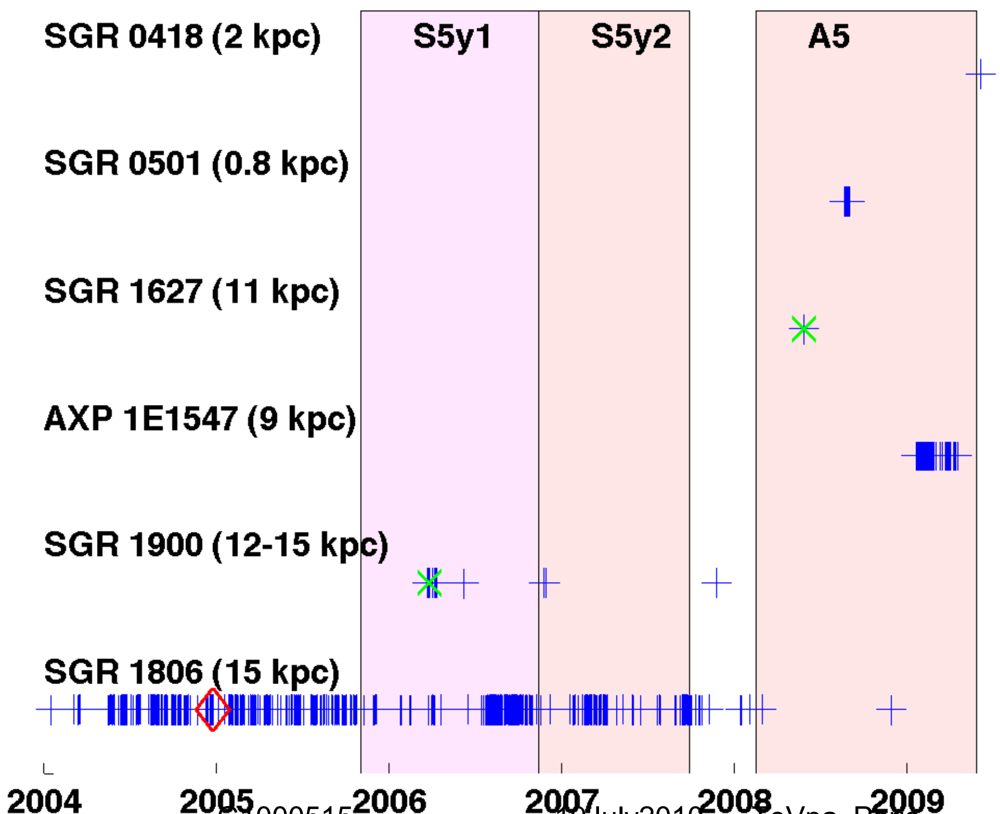


Also searched for unmodeled bursts:
Unable to exclude SGR from M31

Search for GWs from SGRs

- Soft Gamma Repeaters are thought to be magnetars – highly magnetized neutron stars
- Can emit occasional EM flares (~10^{42} erg), giant flares (~10^{46} erg), or flare "storms"
- Flare mechanism (crust cracking) would excite vibrational modes → GWs



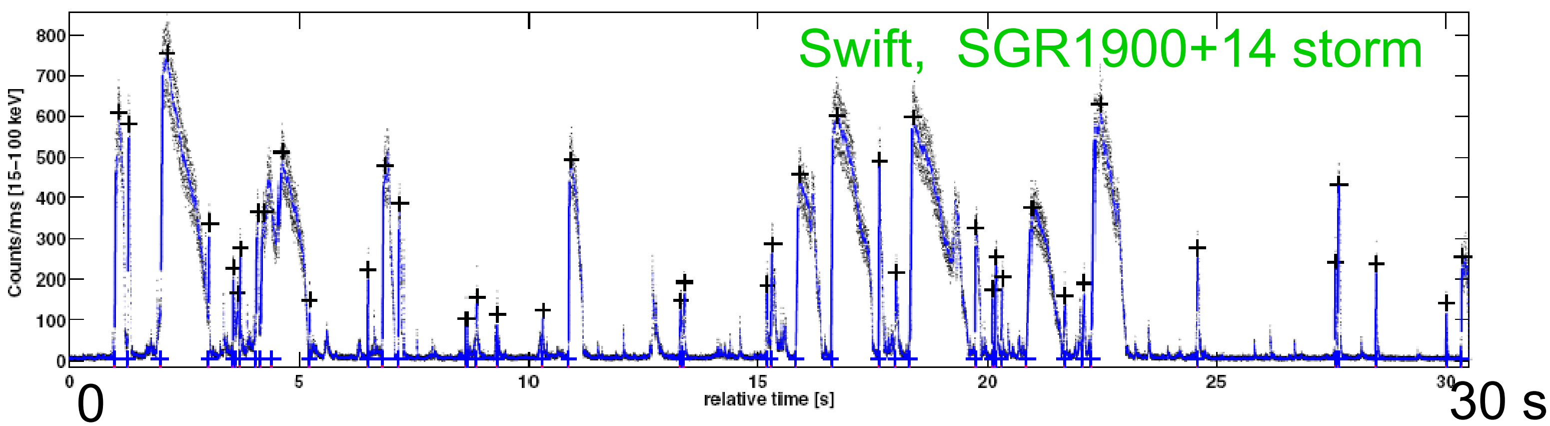


General idea: Look for GW in coincidence with flares

+ flare
◊ giant flare
* storm

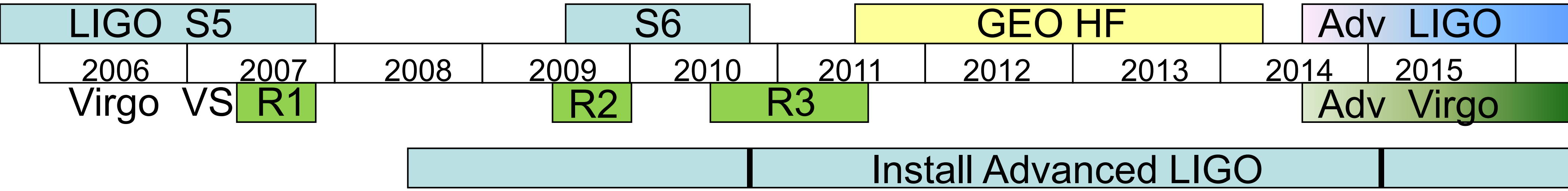
SGRs (contd)

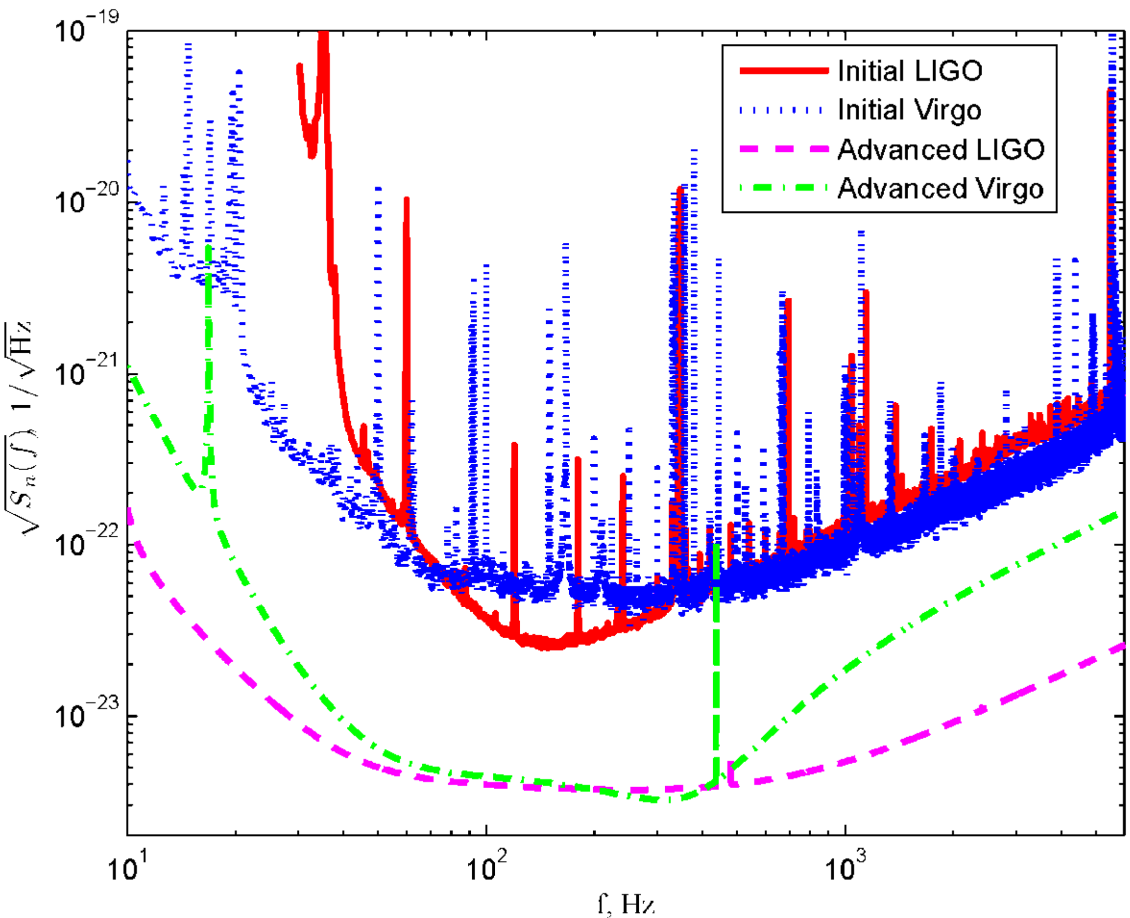
- Search for long-lived quasiperiodic GWs after giant flare SGR 1806-20
  - GW energy limits are comparable to total EM energy emission
  - **PRD 76 (2007) 062003 (LSC)**
- Search for GW bursts at times of 190 flares from 1806-20, 1900+14
  - Excess power search for neutron star *f*-modes (~1.5–3 kHz) and arbitrary lower-frequency bursts
  - GW energy limits as low as *few* × 10^{45} erg; **PRL 101 (2008) 21110**
- Stack GW signal power from each flare in 2006 SGR 1900+14 "storm":



  - GW energy limit *few* × 10^{45} erg; **ApJ 701 (2009) L68**.

Advanced GW detectors





Advanced LIGO and Virgo

- Major upgrades
  - Lasers, optics, suspensions
  - Limited by Quantum noise
- 10x better sensitivity
- 1000x bigger search volume

Some elements of advanced detectors implemented already in S6 and VSR3

Multi-messenger astronomy with GWs – current developments

- Externally triggered searches – gamma, X-rays (Swift, Fermi, IPN)
  - GRBs
  - SGRs
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  - High-energy neutrinos (IceCube, ANTARES, …)
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    - Core-collapse supernovae
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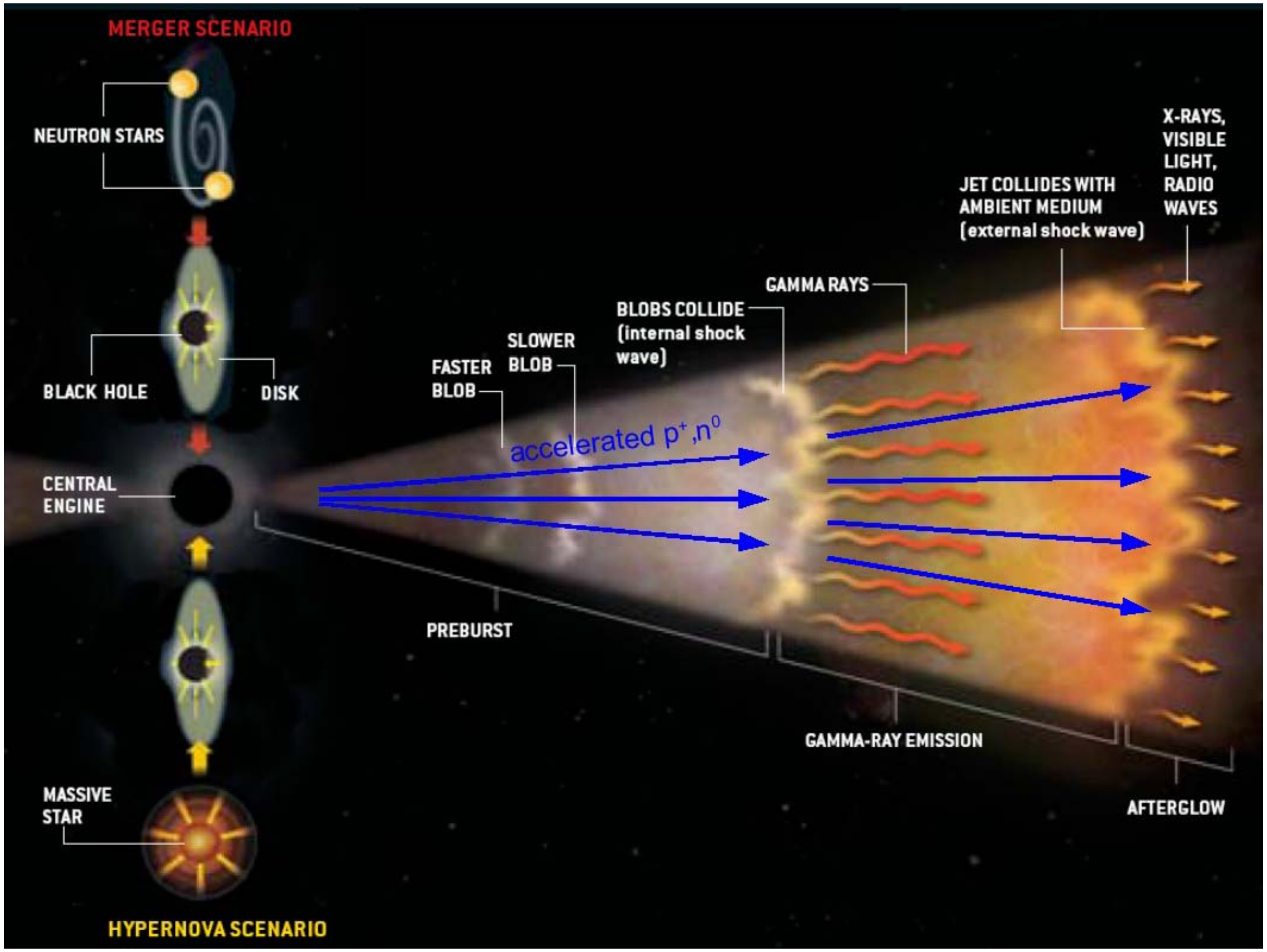
High-energy neutrinos + GW



- High-energy neutrinos possible from GRBs: baryons accelerated in relativistic shocks
  - Long GRBs
  - Short GRBs
  - Failed GRBs
  - Low-L GRBs
- Joint data analysis planned: LIGO-Virgo + IceCube, ANTARES

(e.g. Y. Aso, et al CQG 25 (2008) 114039)

See Poster by B. Bouhou

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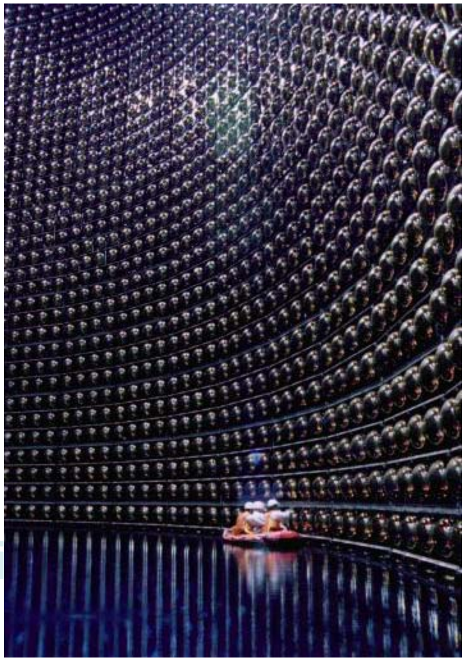
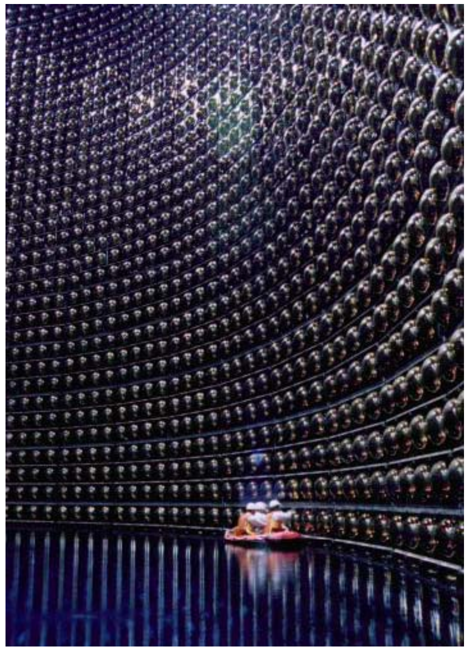
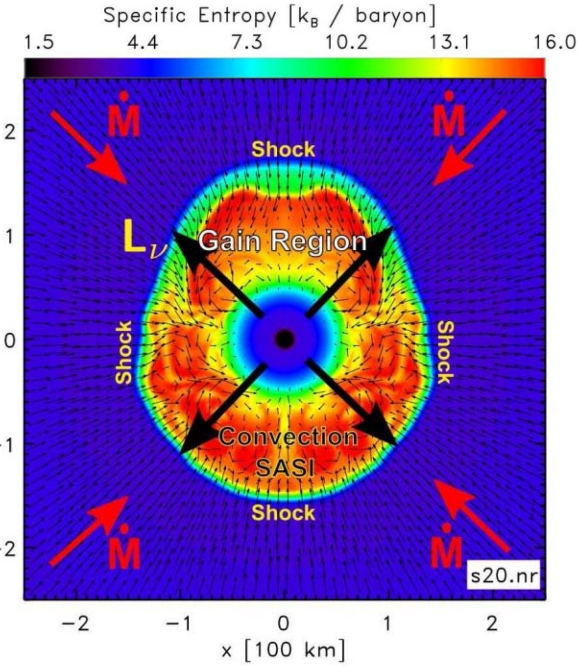


Core-collapse supernovae

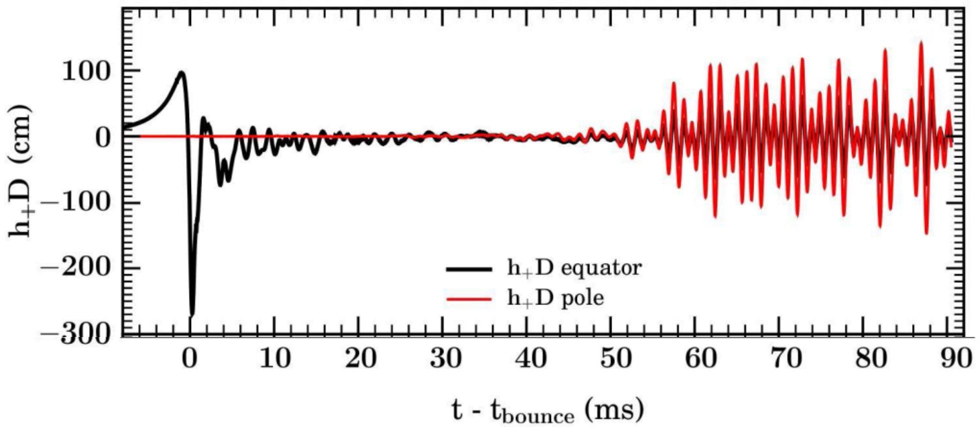
- Classic multi-messenger astronomical events:
  - Gravitational Waves (prompt)
  - Neutrinos (prompt, 10s of MeV, 3 flavors)
  - Electromagnetic (delayed)
- Optical (EM) signature:
  - may be obscured (eg SN 2008iz in M82 missed in optical)
  - unable to determine time of bounce to better than ~ day
- Neutrinos and GWs directly probe physics of core collapse
  - Signatures separated by < seconds
  - A tight coincidence window can be used to establish a correlation
  - Sensitivity range of current GW and neutrino detectors similar



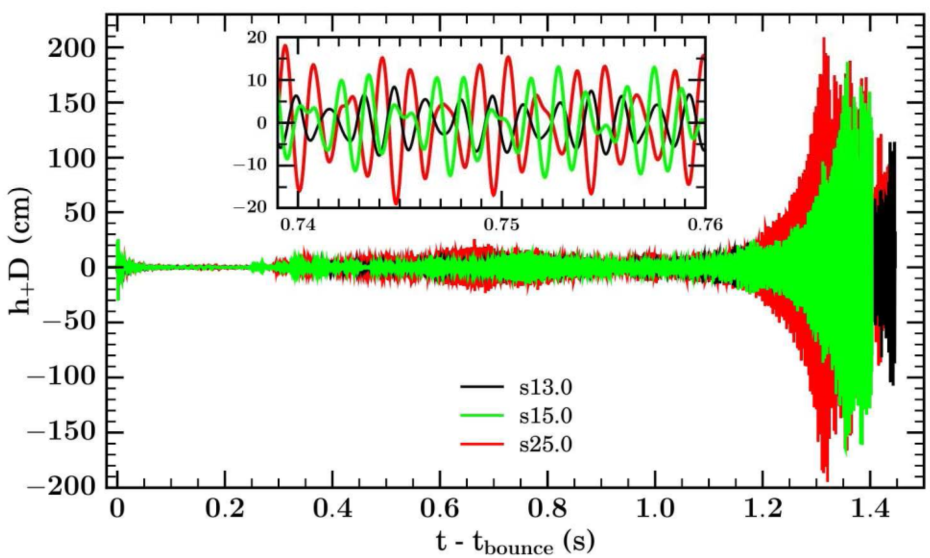


C. D. Ott, A. Burrows, L. Dessart, and E. Livne. Astrophys. J., 685, 1069, 2008.

Core-collapse SNe (contd)



- Classic core bounce GW burst



- Perhaps: acoustic pulsations of proto-neutron star

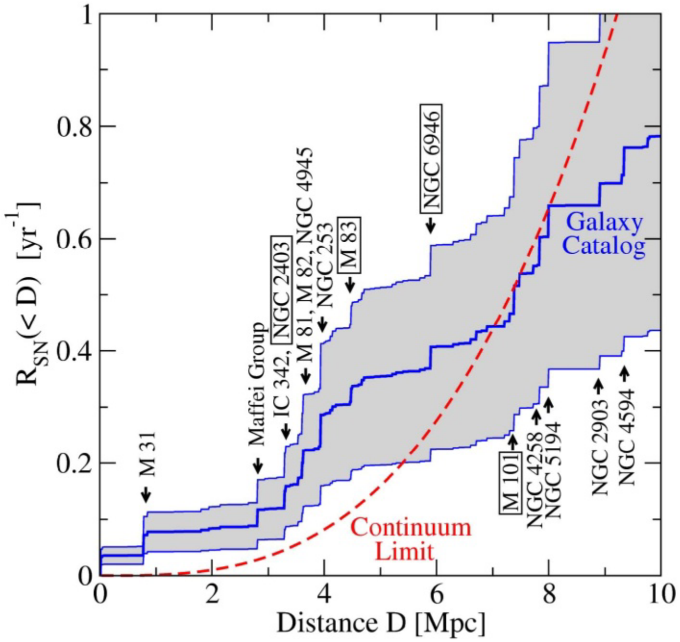
A. Burrows, E. Livne, L. Dessart, C. D. Ott, and J. Murphy. Astrophys. J., 655, 416, 2007.

CCSNe (contd)

- Neutrinos:
  - Super-K: ~10^4 detected neutrinos for galactic SN
  - ~1 for M31
  - Next generation (larger) detectors proposed
- Currently pursuing agreements for joint GW-neutrino searches
- GW range very uncertain (need detections to understand the physics!)
- Comparable range for aLIGO/AdV and Super-K (local group) with weak signals for extragalactic SNe – coincidence helpful

(I. Leonor et al CQG 27 (2009) 084019)

- Rate: 5 Mpc sensitive range gives ~1 CCSN / 2 y (Ando 2005)



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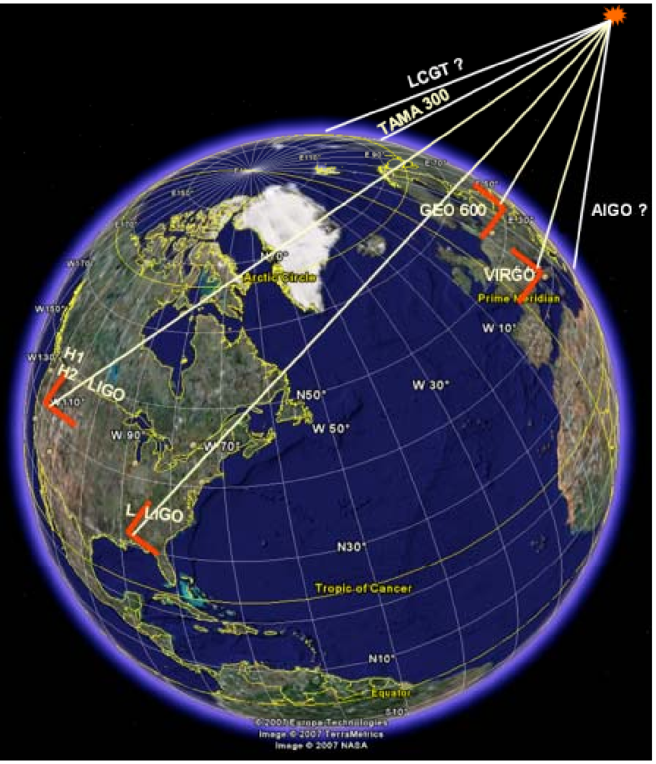
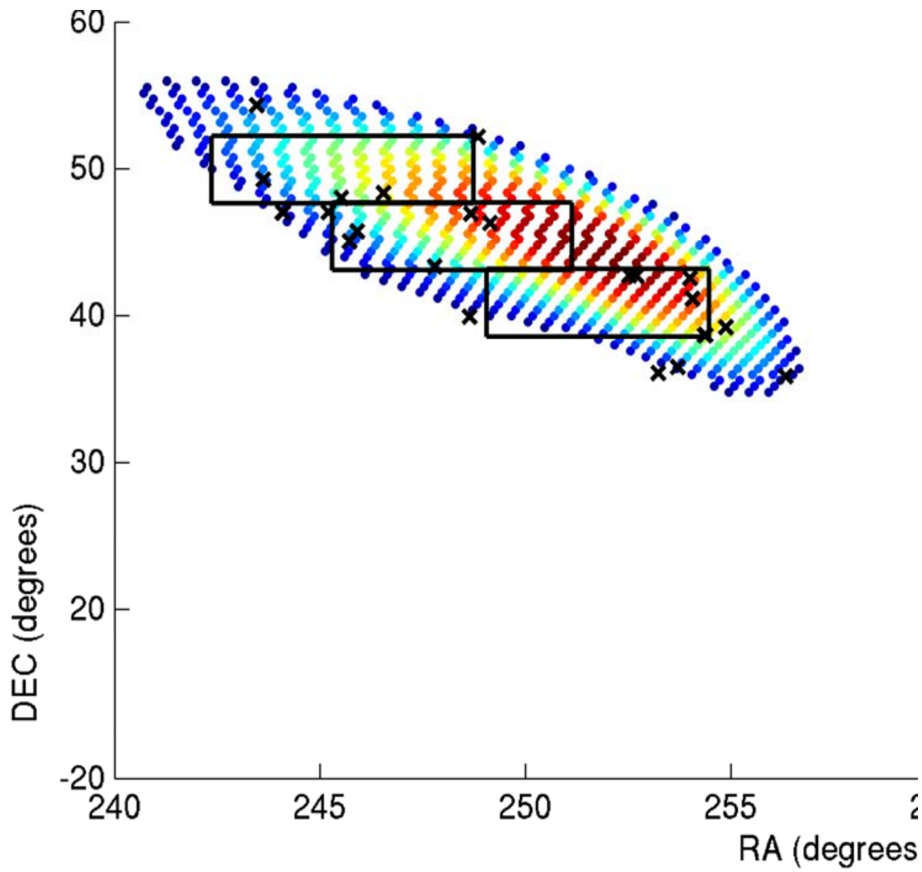
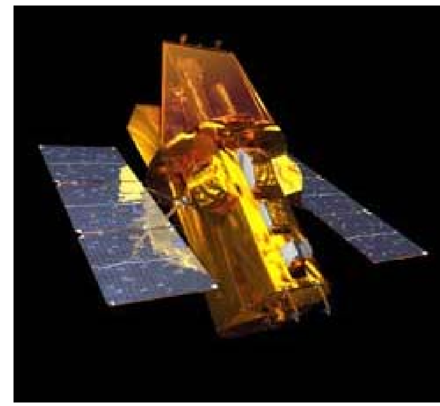
EM Followups







- First attempts with LIGO-Virgo network Dec, 2009
- More expected Aug-Sept 2010

Advanced LIGO/Virgo reach (example)

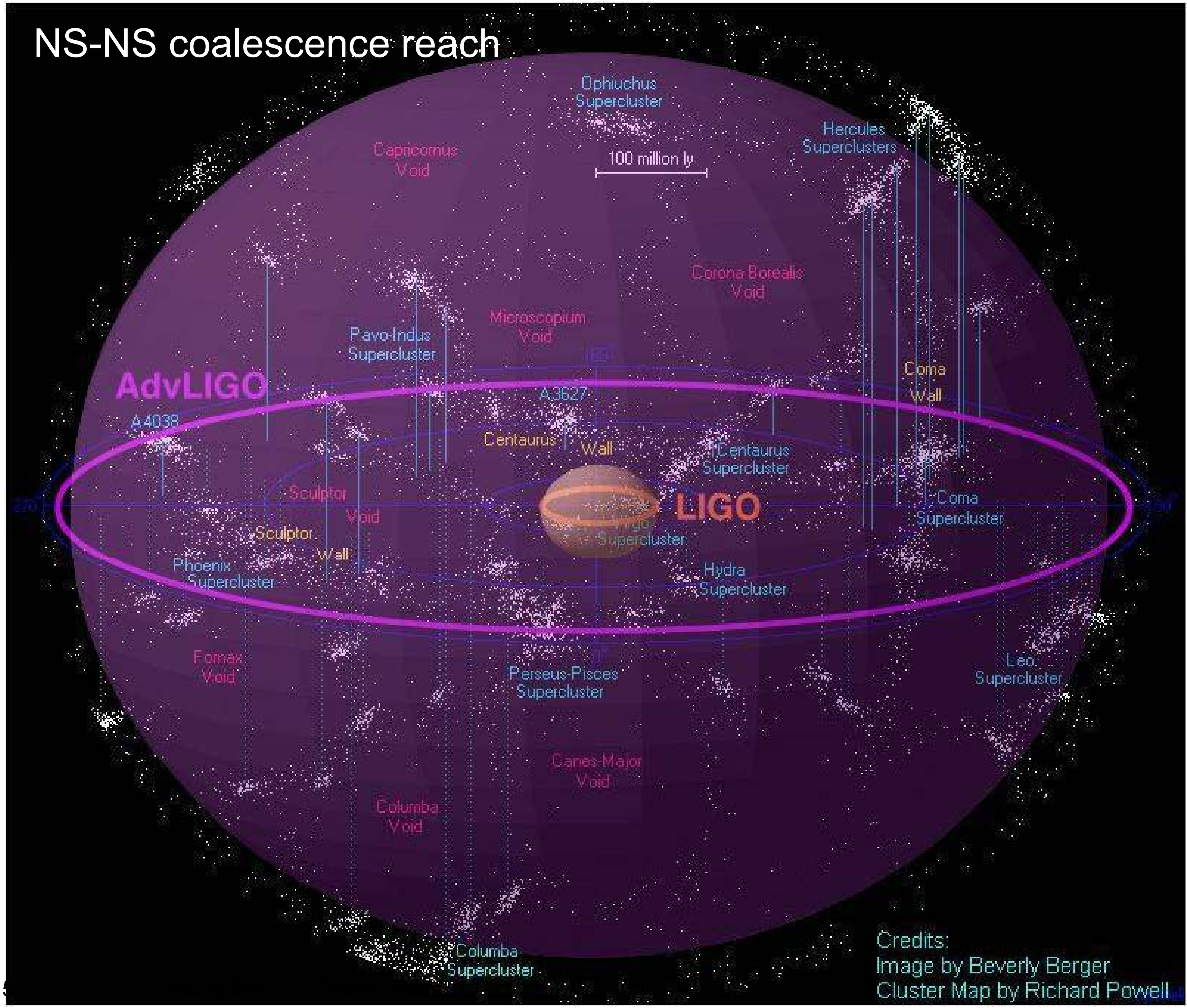
BNS sources ~ D^n

n = 2.7 → 3

D ~ 50 Mpc, initial LIGO/Virgo

~ 500 Mpc, Adv LIGO/Virgo

Advanced detectors reach includes millions of large galaxies and hundreds of super-clusters



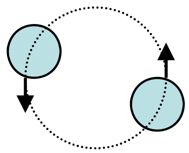
Binary coalescence expected rates

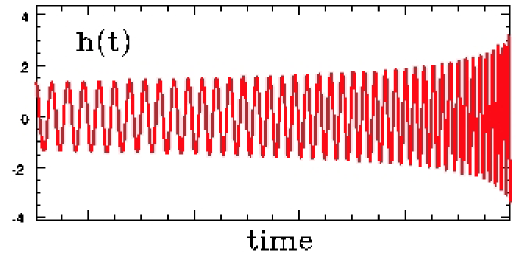
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm re}$ $\rm yr^{-1}$	$\dot{N}_{\rm high}$ $\rm yr^{-1}$	$\dot{N}_{\rm max}$ $\rm yr^{-1}$
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

arXiv: 1003.2480 (LSC, Virgo)

- Advanced LIGO/Virgo is sensitive to coalescing NS and/or BH binaries to distances which are cosmologically relevant.

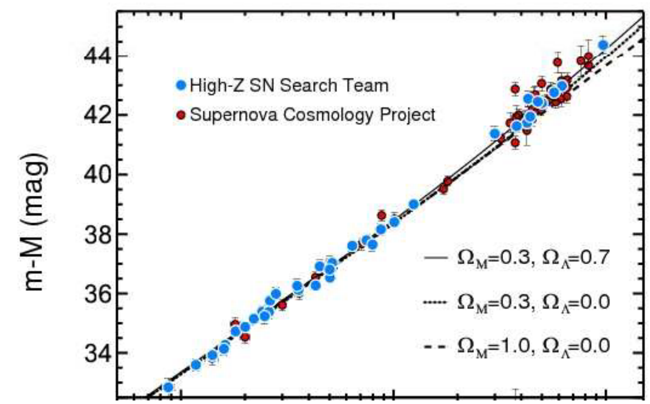




- The detected waveform is a function of many quantities, including:

$$(1+z)\mathcal{M}, D_L, \iota, \theta, \phi, \psi \qquad \mathcal{M} = m_1^{3/5} m_2^{3/5} / (m_1+m_2)^{1/5}$$

- A sample of short GRBs with measured redshifts allow extraction of Distance (D_L) *independent of EM distance ladder* (based only on GR)
  - e.g. Dalal et al, PRD 74 (2006) 063006: measure Ho to 2% in a year of Advanced LIGO data (too optimistic?)
- Sky position (θ, ϕ) and beaming constraint (ι) improve measurement of D_L
  - Nissanke et al, arXiv:0904:1017



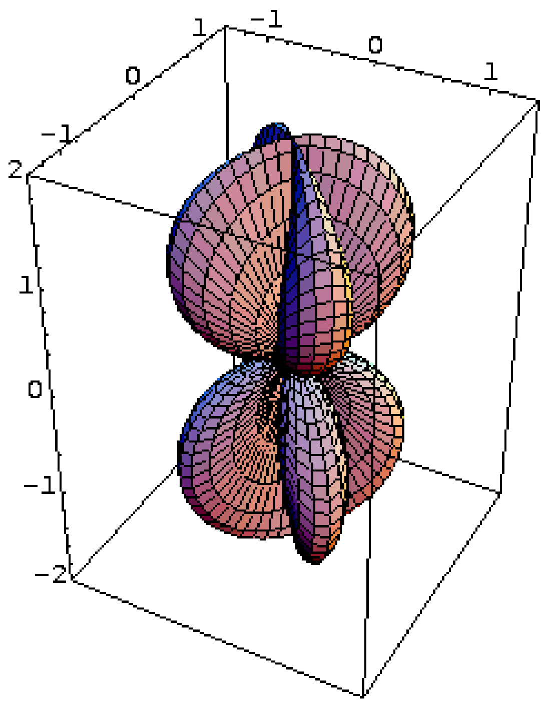
Summary

- LIGO and Virgo have accumulated substantial data sets at the design sensitivity of the initial detectors (runs S5 and VSR1)
  - No detections yet, but starting to make interesting statements:
    - GRBs, SGRs (and others)
- Current data taking and analysis: Runs S6/VSR2
- Advanced LIGO and Virgo are being constructed
  - x10 better sensitivity; x1000 larger volume for sources
  - Science turn on ~2015
- Expect detections to become "routine" → GW science & astronomy
  - GWs can provide unique information toward understanding the astrophysics underlying transient sources
- To fully exploit this science, a suite of multi-messenger techniques have been developed (EM external triggers), while others are now being developed and tried (neutrinos, EM follow-ups)

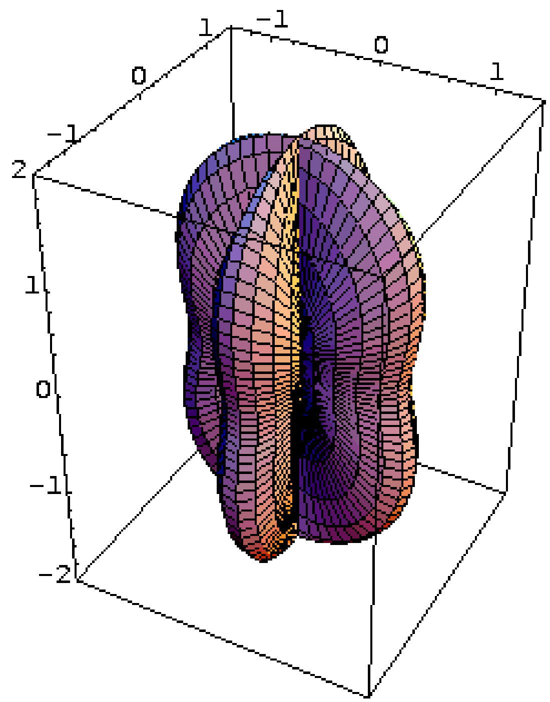
Antenna Pattern

GWs are transverse, with x and + polarizations: $h_x(t)$, $h_+(t)$

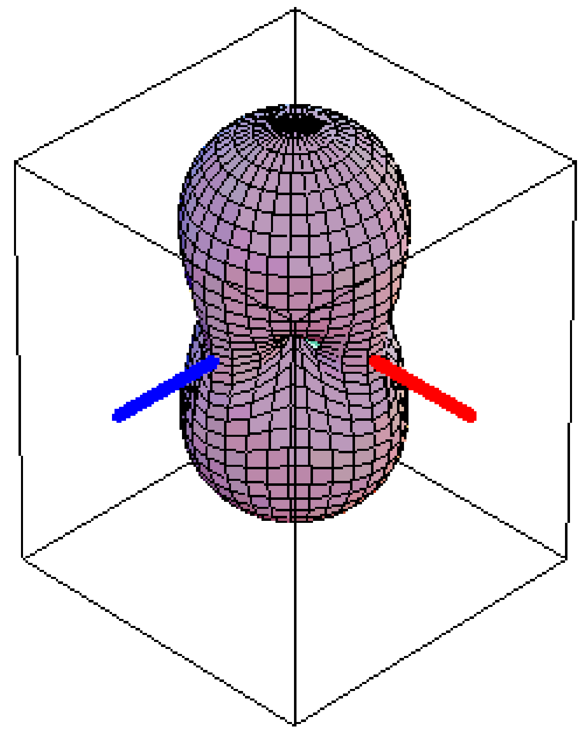
"×" polarization



"+" polarization



RMS sensitivity

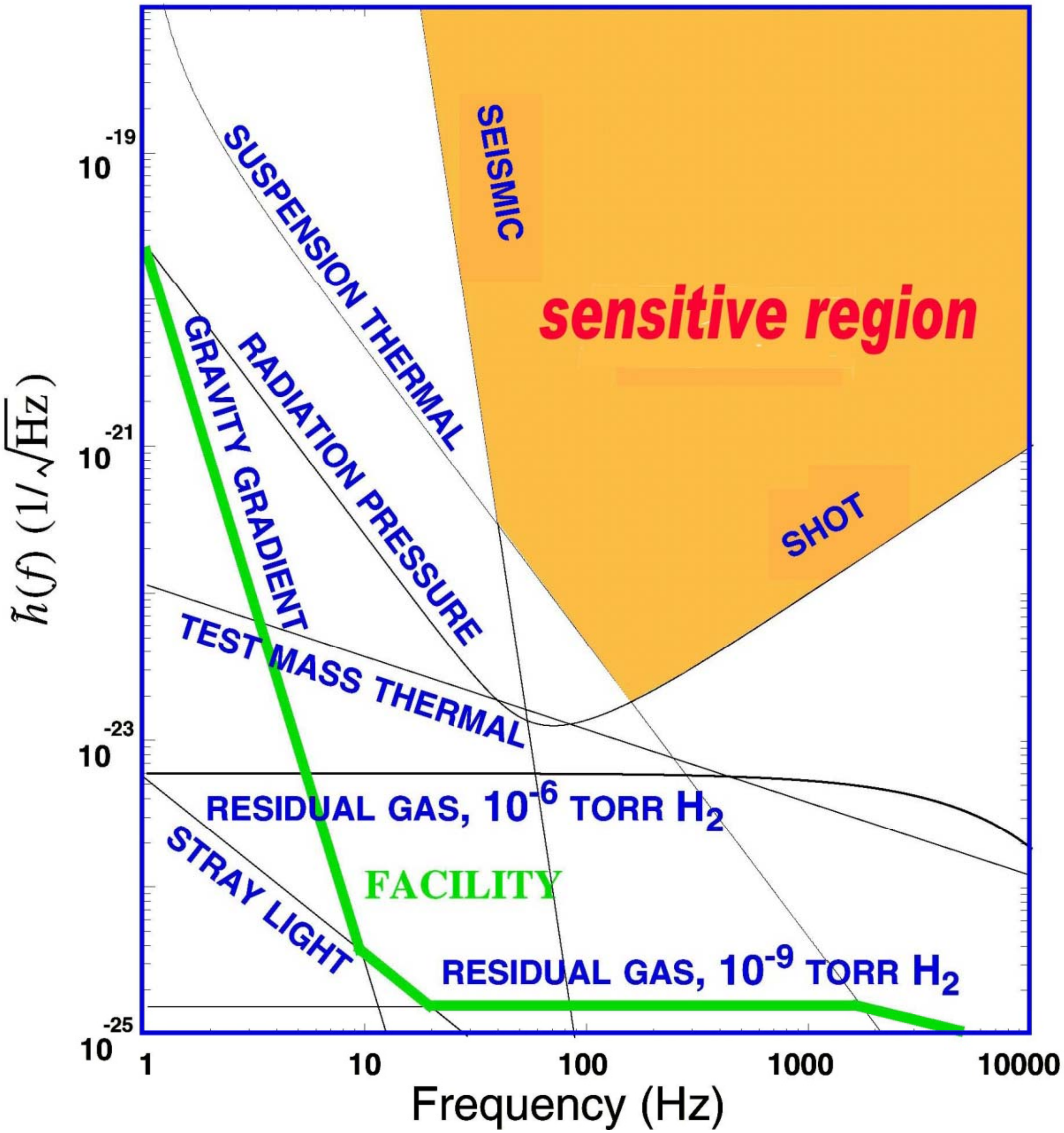


Detector response

$$h(t) = F_x\, h_x(t) + F_+\, h_+(t)$$

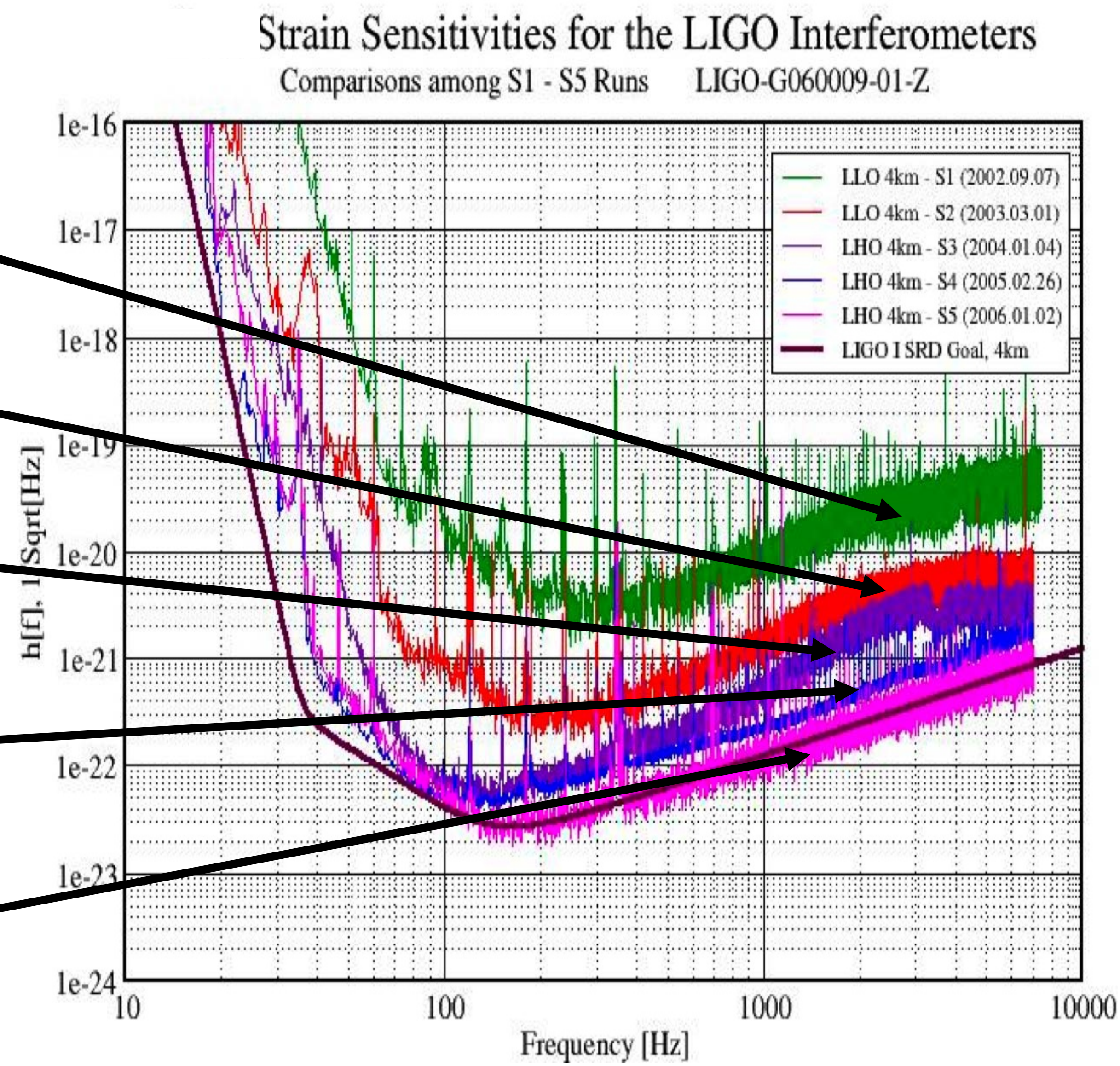
What Limits Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses
- Quantum nature of light (Shot Noise) limits at high frequencies
- Limitations of facilities much lower

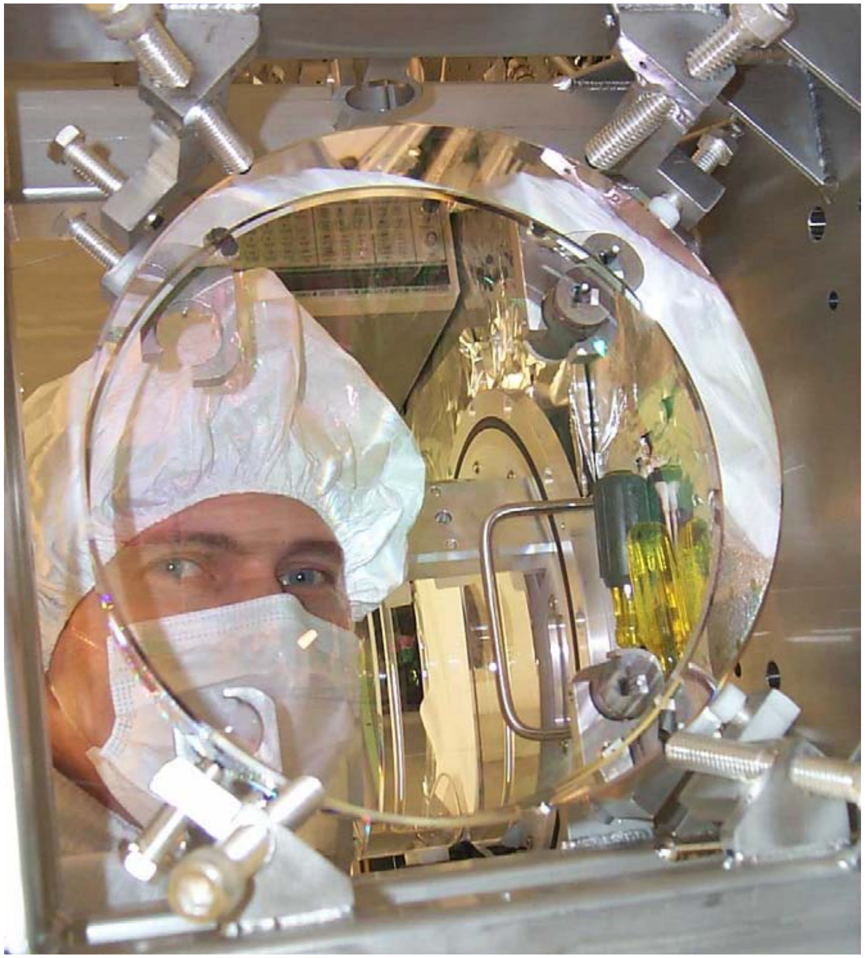


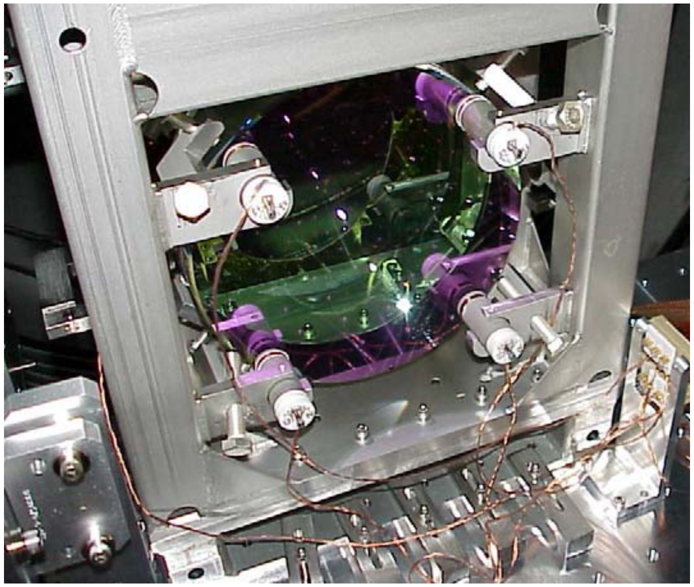
Science runs and sensitivity

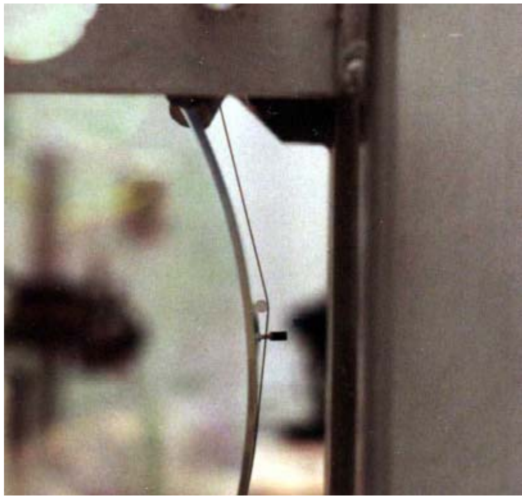
Run	# days
S1 Sept '02	17
S2 Feb 03-Apr 03	59
S3 Nov 03-Jan 04	70
S4 Feb- March 05	30
S5 Nov 05 – Sep 07	2 y (1y coincident)



Test Masses

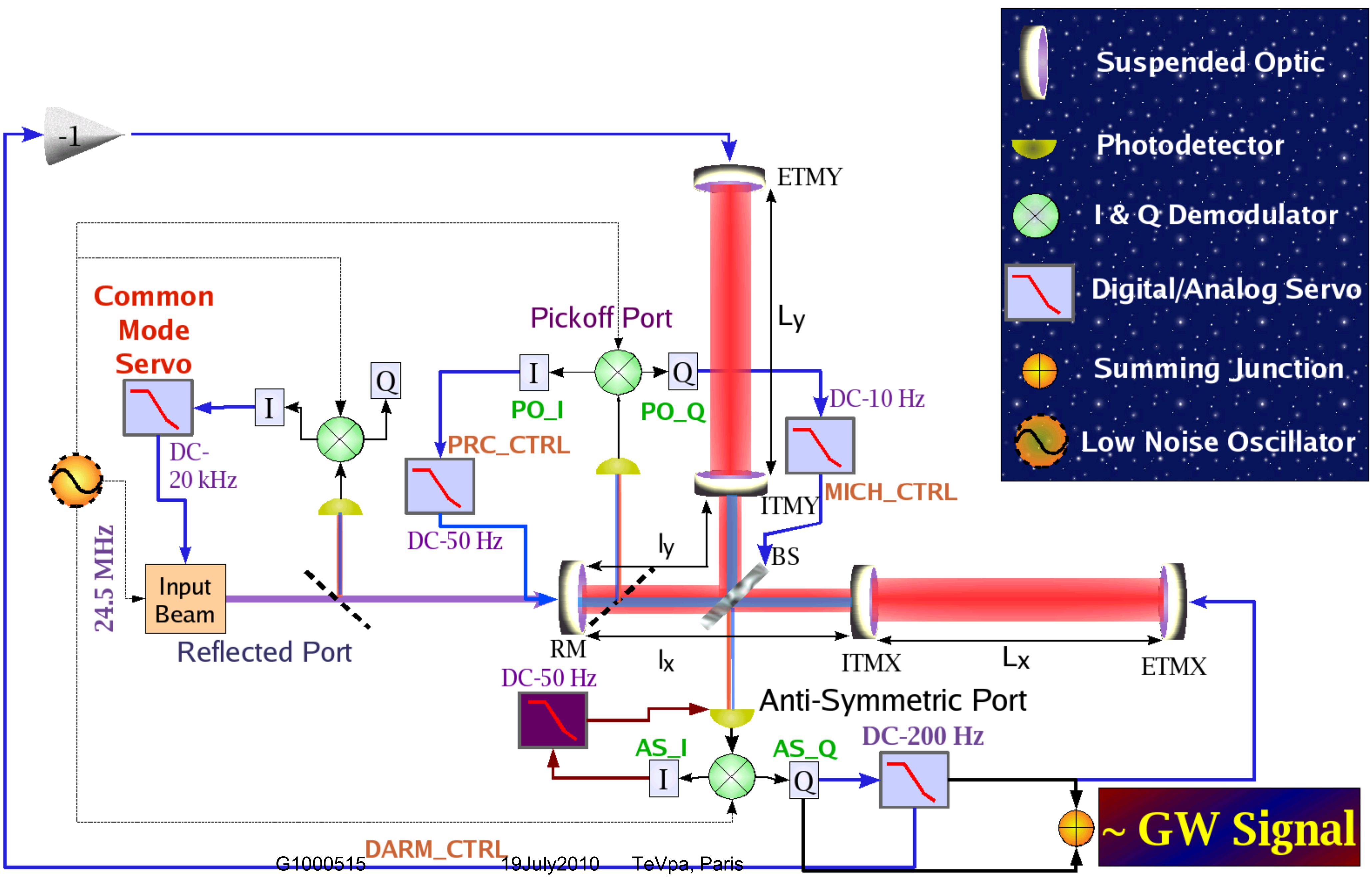






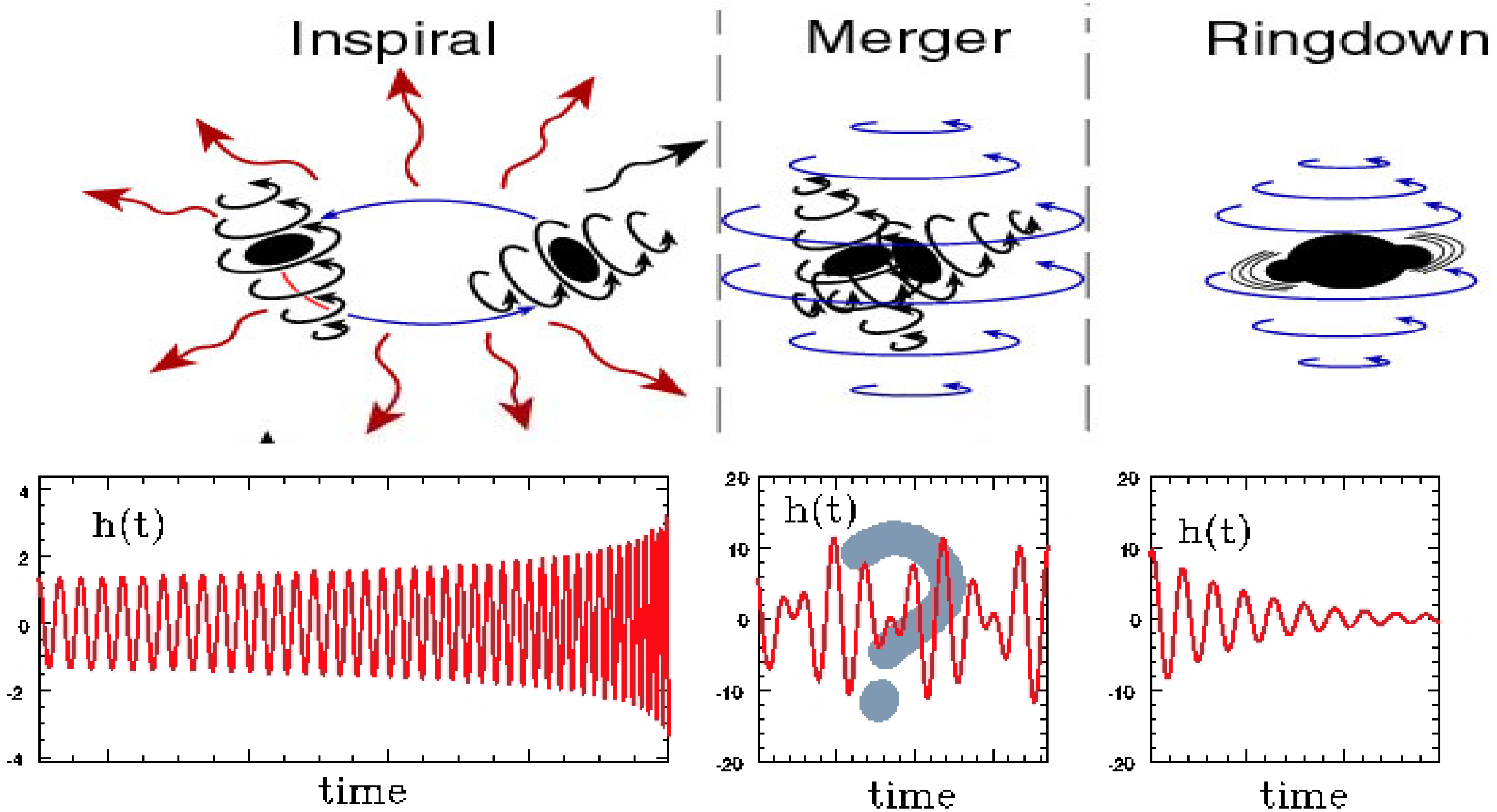
Fused Silica, 10 kg, 25 cm diameter
and 10 cm thick
Polished to λ/1000 (1 nm)

Length readout and control



Coalescing Compact Binaries

NS-NS, BH-BH, (BH-NS) binary systems

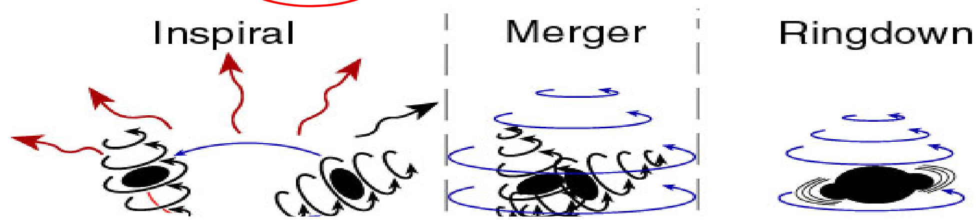


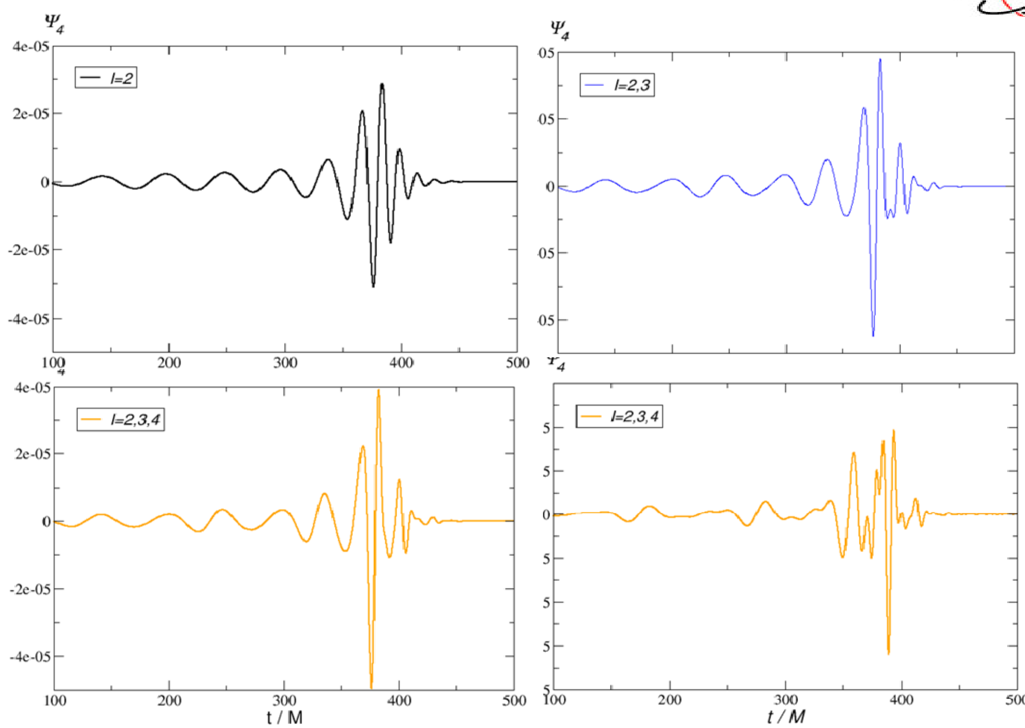
Matched filter | Template-less | Matched filter

Numerical relativity

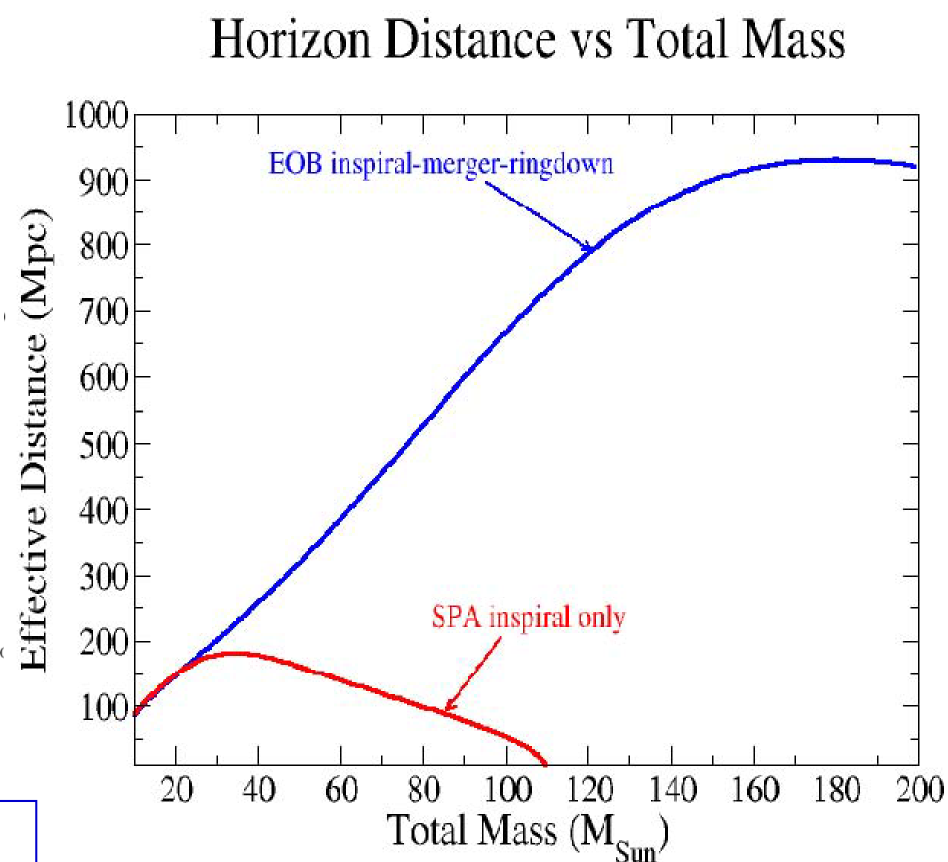
Development of a numerically stable formalism…
F. Pretorius, PRL 95 (2005)

NS-NS, BH-BH, (BH-NS) binary systems



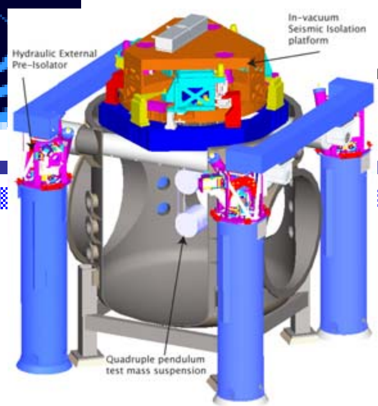


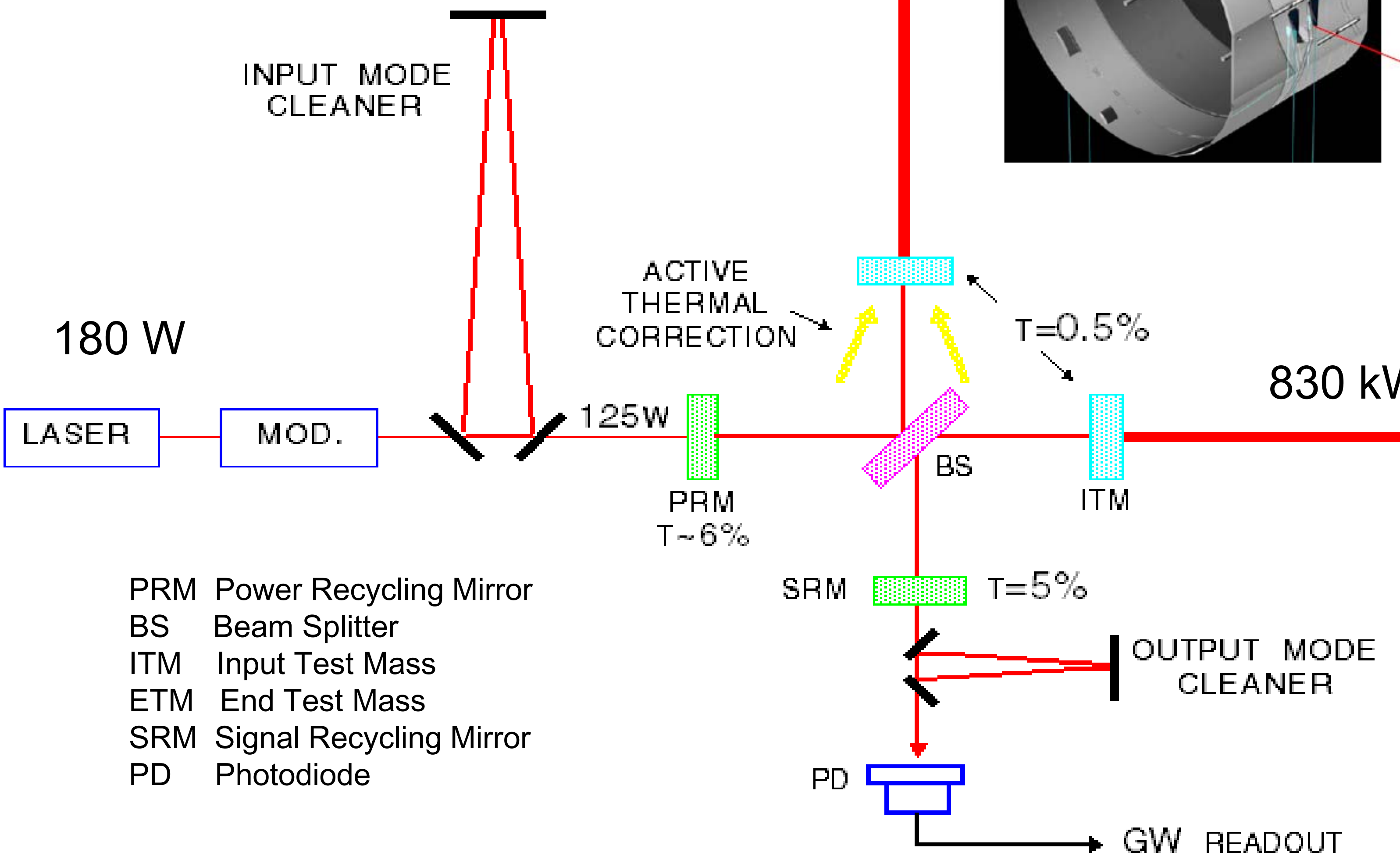
BH-BH, 10:1 mass ratio, arXiv:0811.3952

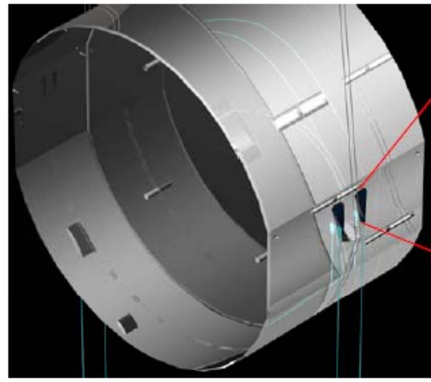


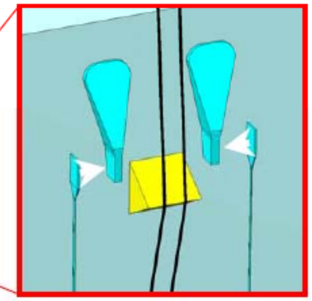
LSC+theory "NINJA": arXiv:0901.4399

Advanced LIGO









Ribbons welded to silica ears bonded to mass

PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode