Multi-Messenger Astronomy and Astrophysics with Gravitational-Wave Transients

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LSC VIRGO

Virtual Institute of Astroparticle physics lecture
May 14, 2010

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Multi-Messenger Astr

Things That Go Boom

avitational-Wave Transients

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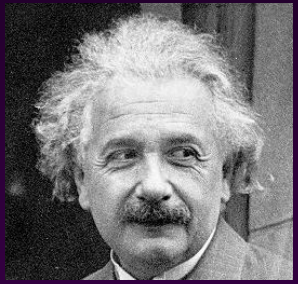
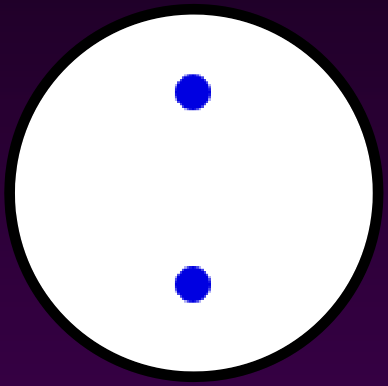
What Kinds of Events Emit Gravitational Waves?

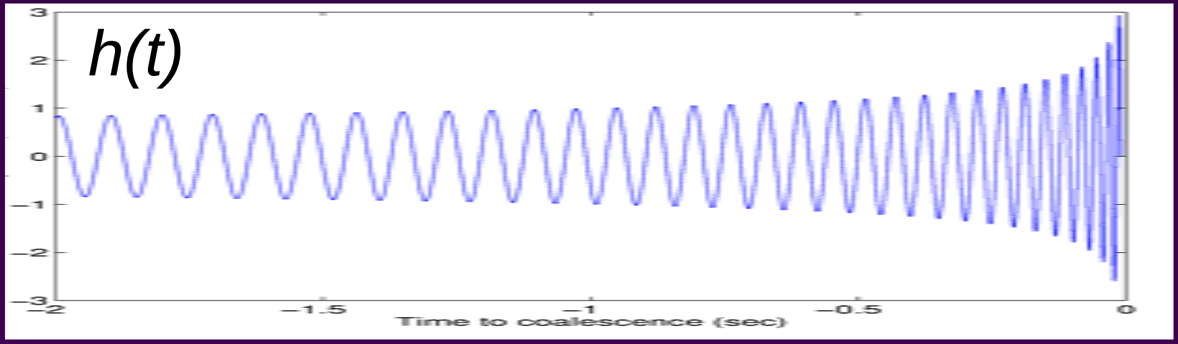
➔ Anything involving rapid motion of mass with a time-varying quadrupole (or higher-order) moment

Example: a compact binary system (e.g., two neutron stars) produces a time-varying strain





Gravitational radiation causes the binary system to “inspiral”...



The final stage of this process can be heard by ground-based GW detectors

Gravitational Wave Sources...

and LSC – VIRGO data analysis working groups

	Short duration	Long duration
Waveform known	Cosmic string cusp / kink; NS / BH ringdown; Low-mass inspiral; High-mass inspiral *Compact binary inspirals & modeled bursts*	Asymmetric spinning NS *Continuous wave*
Waveform unknown	Binary merger; Rotation-driven instability; Stellar core collapse; ???; ???; ??? *Unmodeled bursts*	Cosmological stochastic background; Astrophysical stochastic background *Stochastic*

The Promise of Gravitational-Wave Astronomy

Gravitational waves are a unique messenger

- Direct information about an energetic event or compact object
- Not scattered or attenuated by matter
- Emission is only weakly anisotropic

(Some) Sources are known to exist

Science goals for ground-based GW detectors:

- Detect gravitational waves directly
- Test the correctness of GR vs. other theories of gravity
- Reveal the dynamical mechanisms of energetic astrophysical events
- Survey source populations
- Determine the properties of neutron stars, etc.
- Search for cosmological GW signals

The Challenge of Gravitational-Wave Astronomy

Strain amplitude is inversely proportional to distance from source

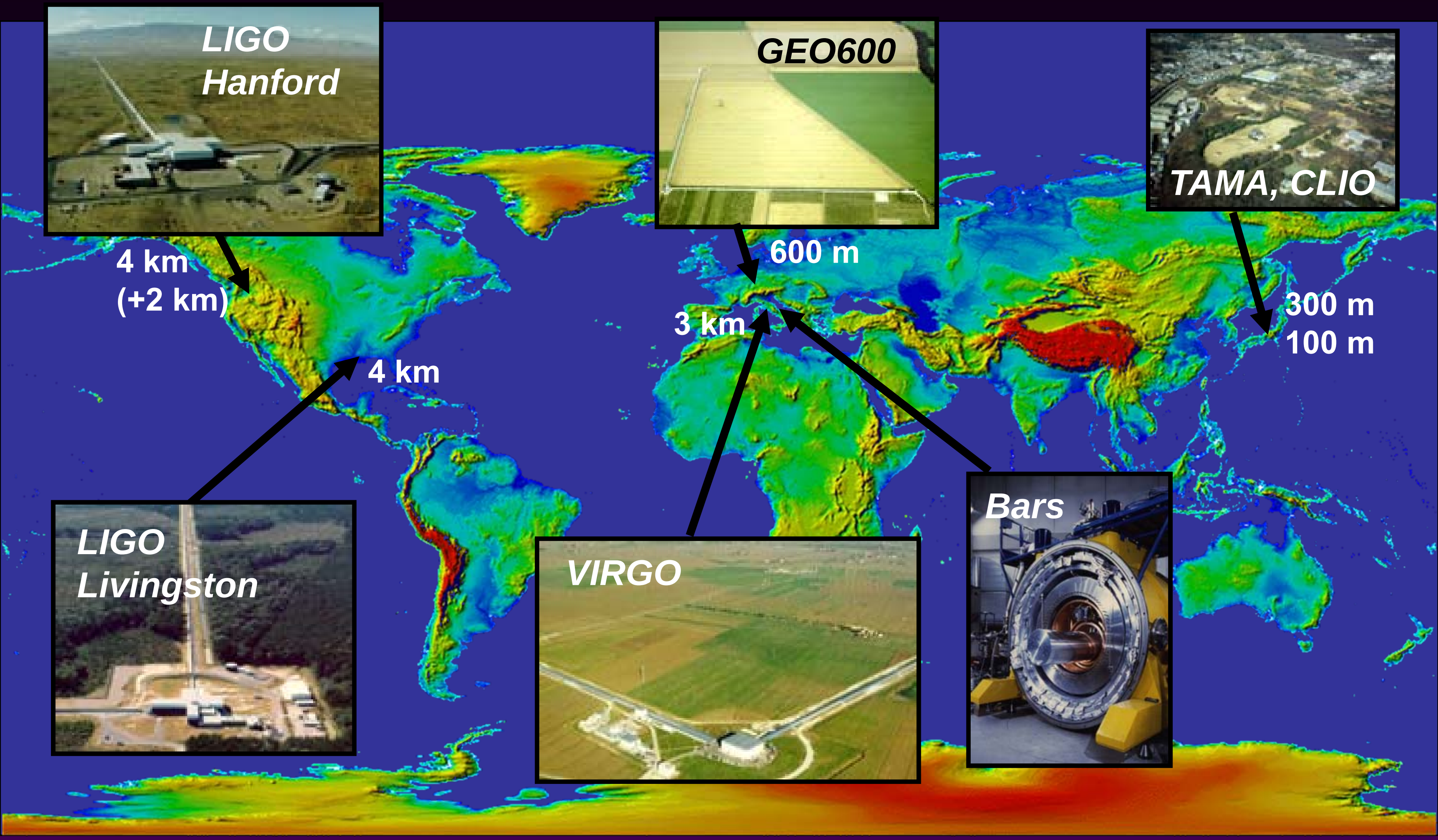
- ➔ Have to be able to search a large volume of space
- ➔ Have to be able to detect very weak signals
- ➔ GW searches fight against “background” from instrumental noise fluctuations

What We Have Detected So Far :

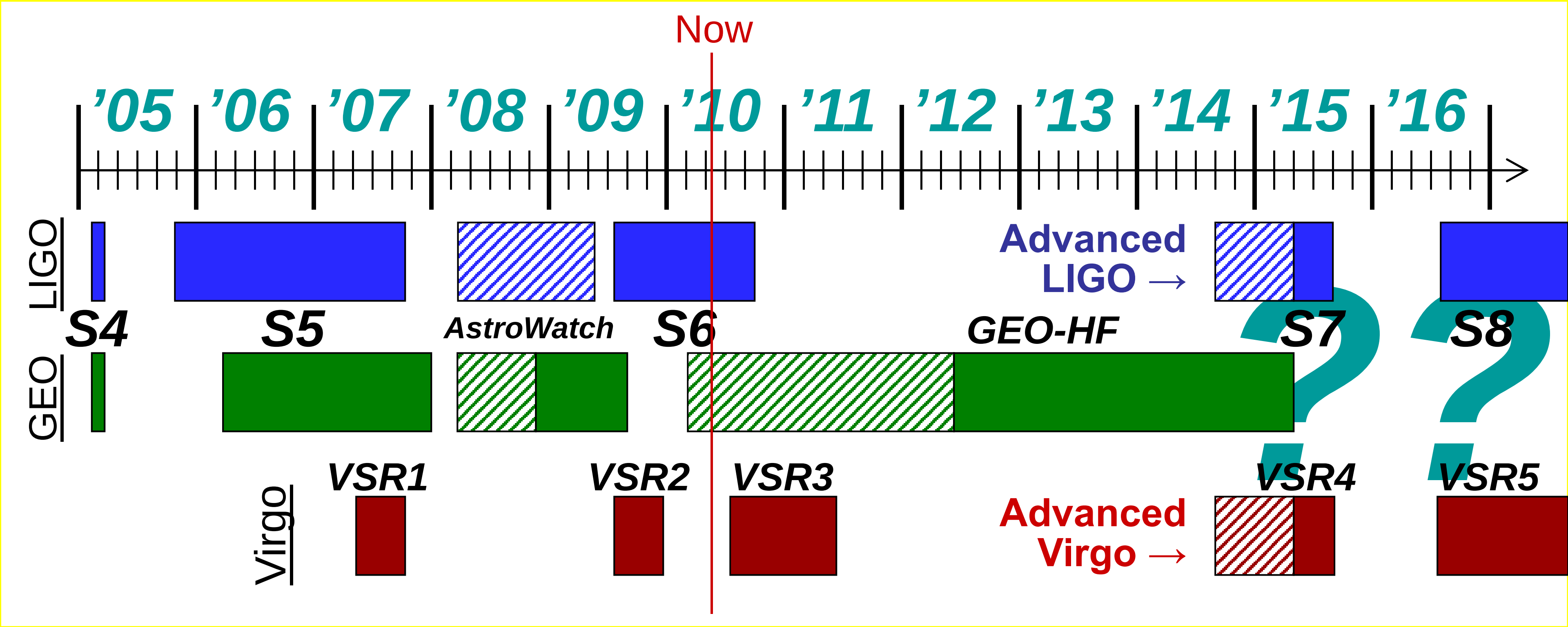
Nothing.

But even non-detections are starting to get interesting...

Worldwide Network of Gravitational Wave Detectors



Science Runs— Past, Present, and Future



Advanced LIGO & Advanced Virgo:
An order of magnitude more sensitive than initial detectors
⇒ Sensitive to sources in ~1000 times more volume of space !

Known Things That Go Boom

Multi-Messenger Advantages

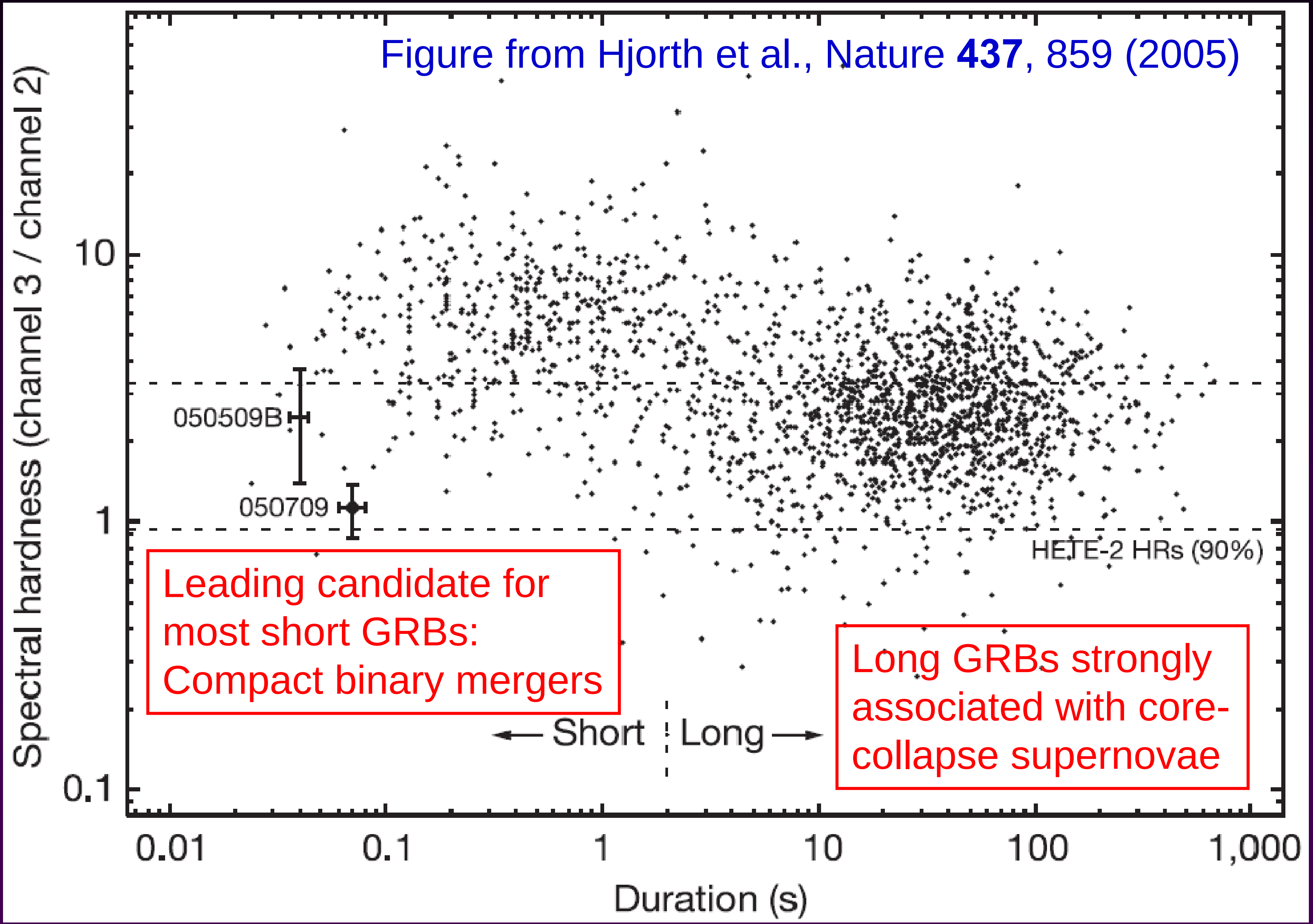
If an event has already been detected, then GW searches:

- know *when* to look at the data
- know *where* in the sky to look
- may know *what kind* of GW signal to search for
- may know the distance to the source

As a result,

- Background is suppressed, so a weaker GW signal can be confidently detected
- The extra information from the combined observations will reveal more about the astrophysics of the source
- *Non*-detection of a GW signal can still provide useful information

Gamma-Ray Bursts



Multi-Messenger Bursts: Emission Mechanisms

Gamma rays

- From "internal" or "external" shocks

X-ray afterglow

- "Fireball model" – expands into local medium
- Typically stronger for long GRBs than for short

Optical afterglow

- Supernova or supernova-like emission
- Reprocessing of energy by local medium

Radio afterglow

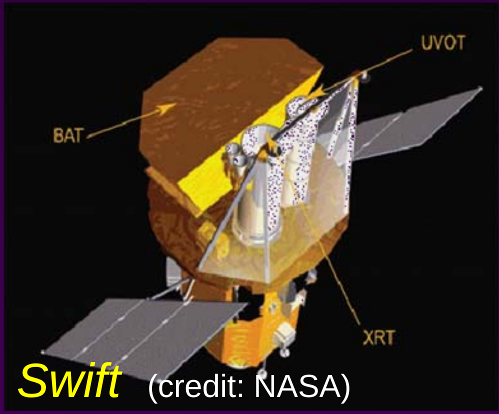
High-energy neutrinos

- Expected from accelerated protons in shocks

Gravitational waves

- Should be detectable ***if*** source is close enough, especially for short GRBs

Can indicate host galaxy !



Reveal central engine !

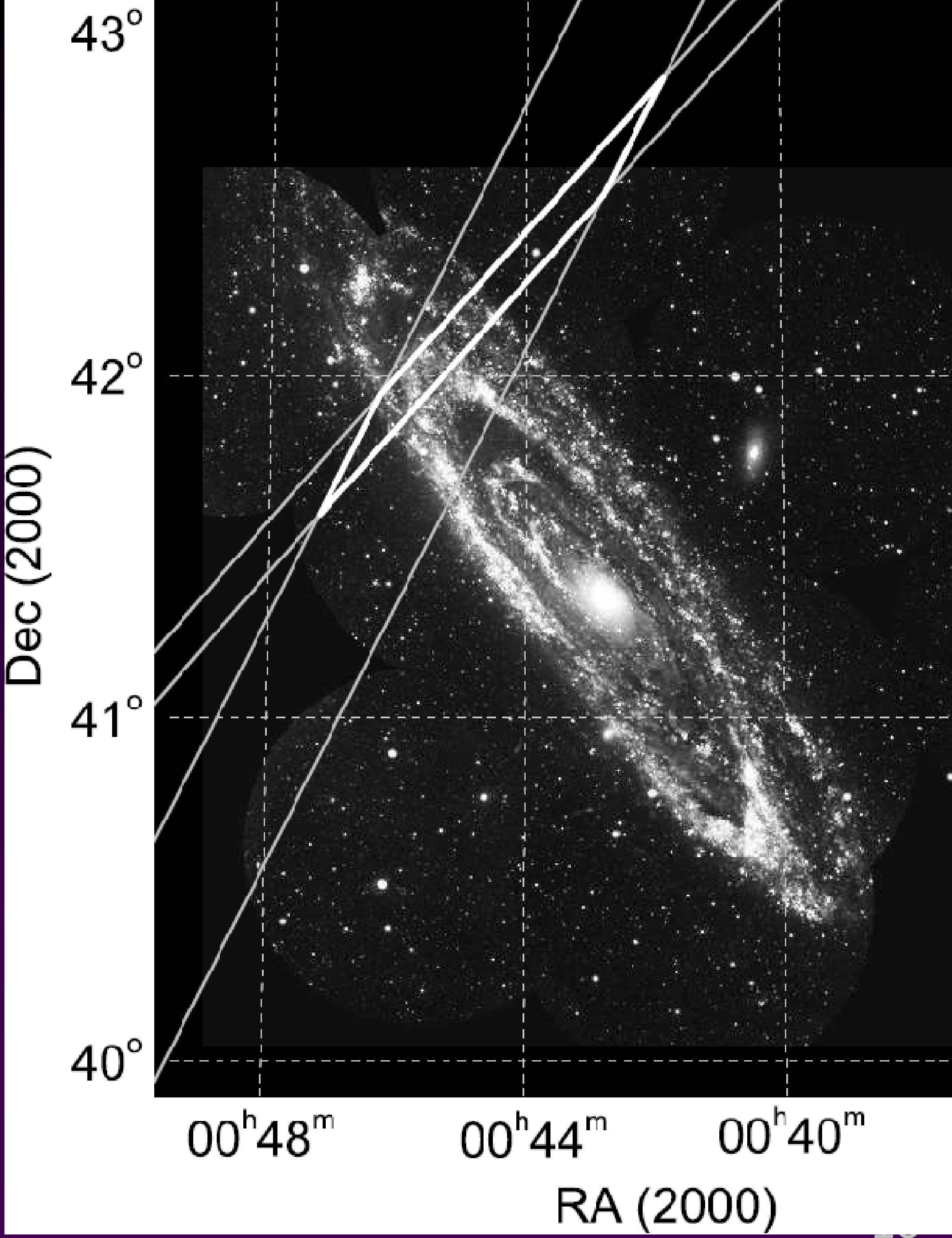
GRB 070201

Very bright short GRB
detected by Konus-Wind, INTEGRAL, MESSENGER, and *Swift*

Consistent with being in M31, at a distance of ~770 kpc

Both LIGO Hanford detectors were on !

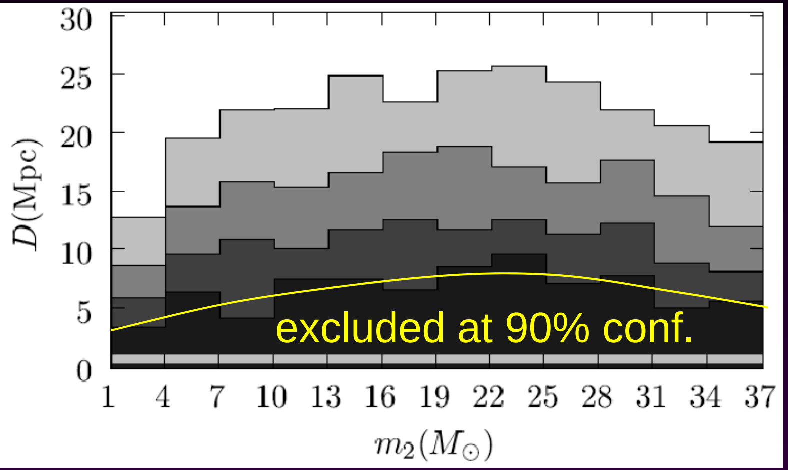
Inter-Planetary Network
3-sigma error region from
Mazets et al., ApJ 680, 545



Searches for a GW Signal from GRB 070201

Searched for an inspiral signal

- Matched filtering with templates for m_1 in [1,3] $M_\odot$, m_2 in [1,40] $M_\odot$
- No GW inspiral signal found
- Hypothesis of a binary merger in M31 excluded with >99% conf.



Also searched for an arbitrary GW burst signal

- Cross-correlated data streams with time windows of 25 and 100 ms
- Compared to background estimated from off-source times
- No GW burst signal found
- Model-dependent limits on GW energy emission as low as 5×10^{-4} $M_\odot$

Both searches described in *Abbott et al., ApJ 681, 1419 (2008)*

➔ Conclusion: most likely an SGR giant flare in M31

- Mazets et al., ApJ 680, 545 ; Ofek et al., ApJ 681, 1464

Searches for GWs Associated with Other GRBs

There were 137 GRBs (35 with redshifts) during the S5/VSR1 run with data from two or more LIGO+Virgo detectors

Inspiral search

- Sub-sample of 22 short GRBs
- [–5,+1] second time window around time of GRB
- Matched filtering followed by coincidence test based on time and mass parameters
- "Loudest event" analysis

Abadie et al., ApJ 715, 1453 (2010)

Burst search

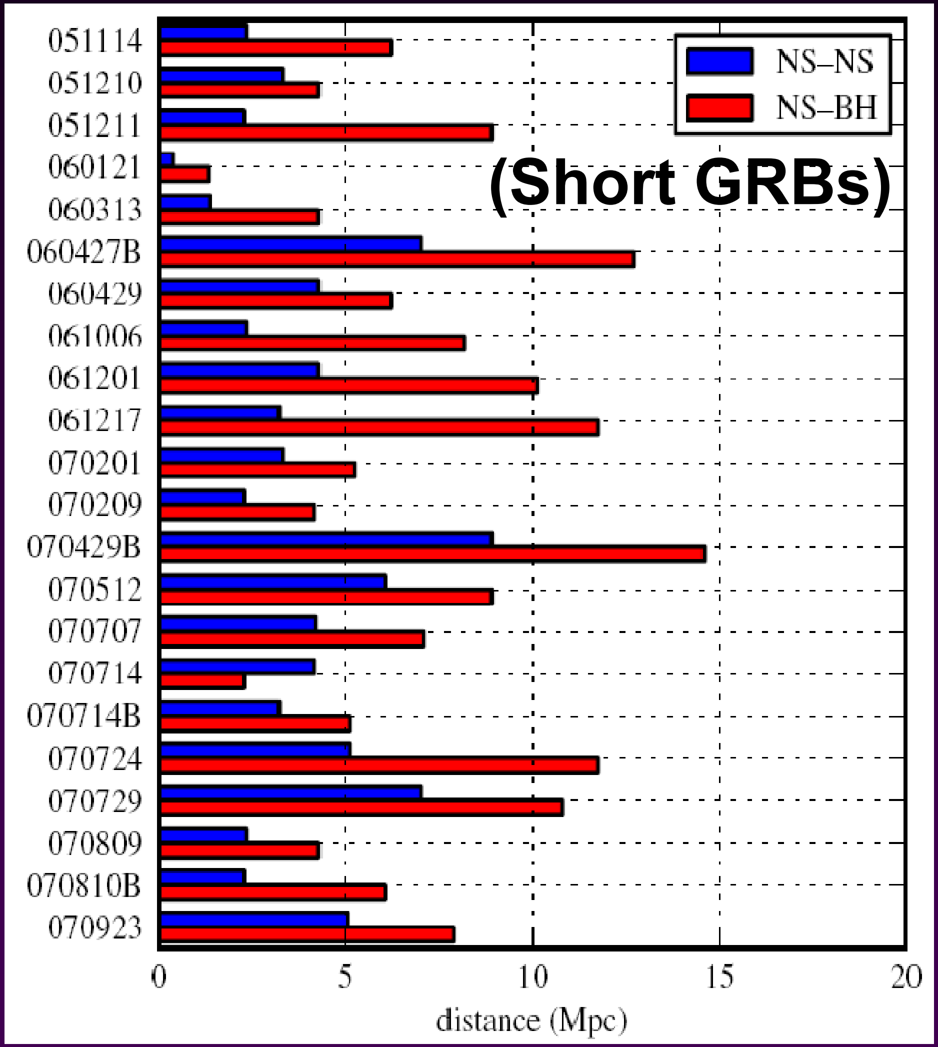
- All 137 GRBs
- [–120,+60] second time window around time of GRB
- Coherent multi-detector burst search with 2, 3, or 4 detectors
- "Loudest event" analysis

Abbott et al., ApJ 715, 1438 (2010)

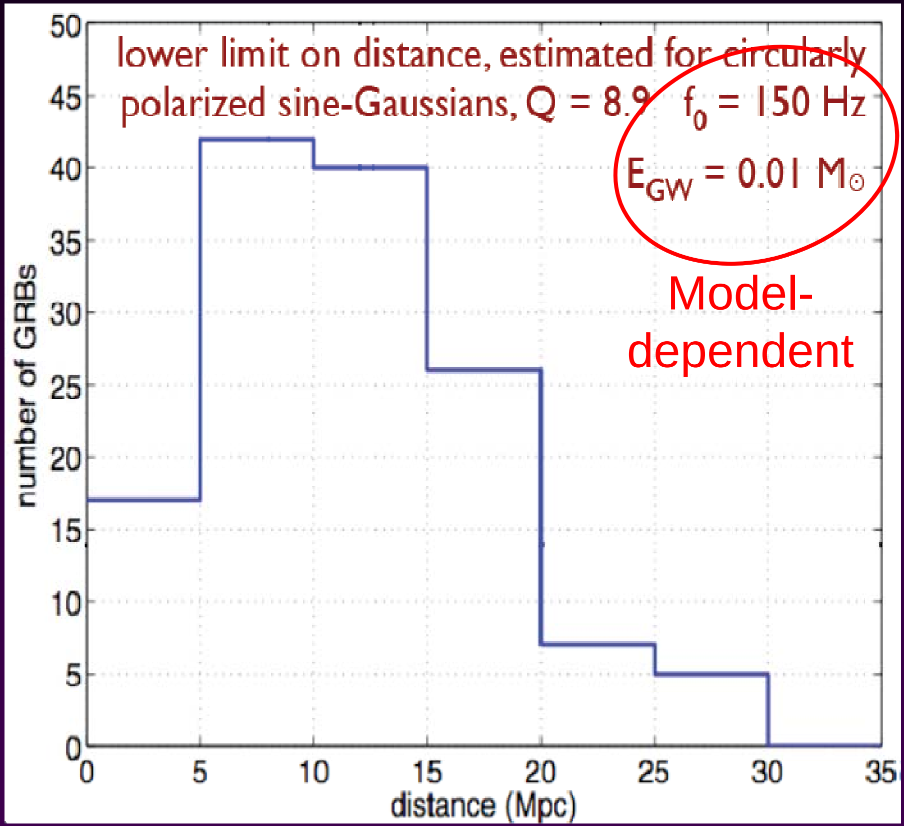
➔ No significant signal found for any individual GRB, and no statistical excess for any subset

Lower Limits on Distance to Each S5/VSR1 GRB

For GW inspiral signals:



For hypothetical GW bursts:

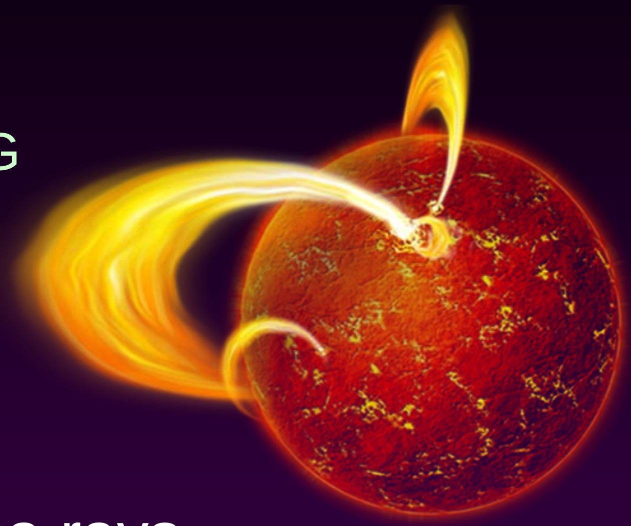


➔ We didn't get lucky with a close-enough event

Soft Gamma Repeater (SGR) Flares

SGRs are believed to be magnetars

- Neutron stars with magnetic field ~10^{15} G interacting with crust
- Anomalous X-ray pulsars (AXPs) are essentially the same thing



Occasionally emit flares of soft gamma rays

- Ordinary flares E_{EM} ~ 10^{42} erg
- Some SGRs have produced a ***giant flare*** with energy ~10^{46} erg

Thought to be associated with cracking of the crust

- Probably excite vibrational modes of the neutron star
- Quasiperiodic oscillations seen in X-ray emission after giant flares

Some vibrational modes couple to gravitational waves !

- Can probe what is going on with the star

Searches for GW Signals from SGRs

Long-lived quasiperiodic GWs after giant flare ?

- December 2004 giant flare of SGR 1806–20
- Searched for GW signals associated with X-ray QPOs
- GW energy limits are comparable to total EM energy emission

Abbott et al., PRD 76, 062003 (2007)

GW bursts at times of flares ?

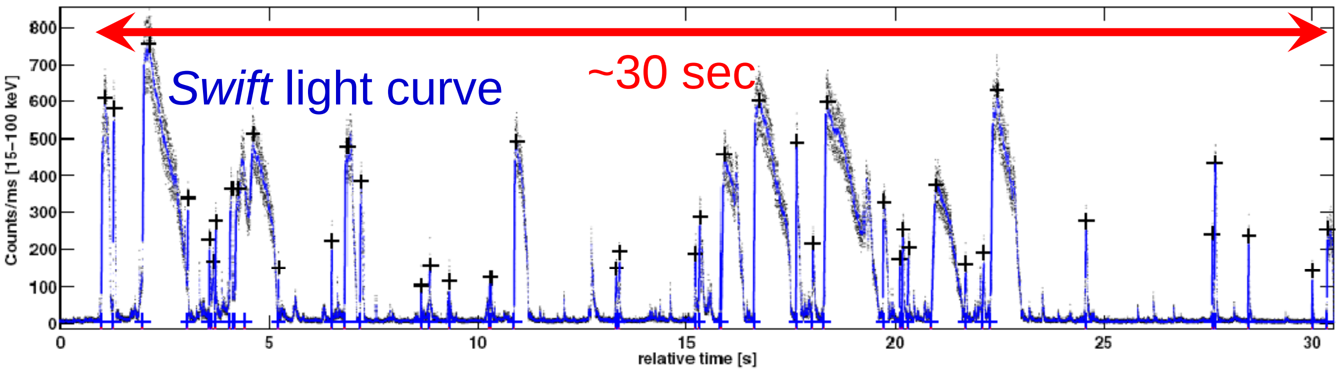
- 2004 giant flare plus 190 other flares from SGR 1806–20 and SGR 1900+14 during first calendar year of LIGO S5 run
- Excess-power search for neutron star *f*-modes ringing down (~1.5–3 kHz), also for arbitrary lower-frequency bursts
- For certain assumed waveforms, GW energy limits are as low as few × 10^{45} erg, comparable to EM energy emitted in giant flares

Abbott et al., PRL 101, 211102 (2008)

Searches for GW Signals from SGRs

Repeated GW bursts associated with multiple flares ?

- “Storm” of flares from SGR 1900+14 on 29 March 2006

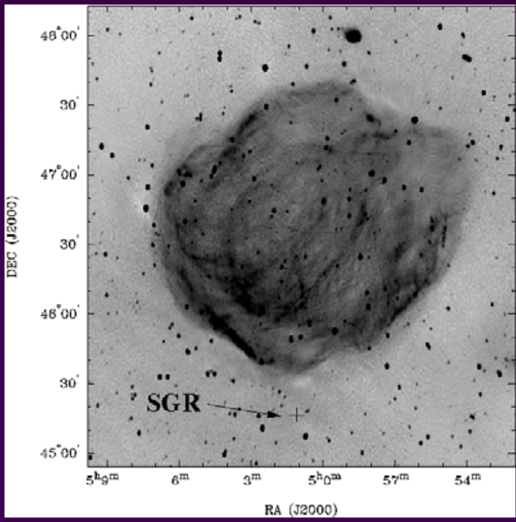


- “Stack” GW signal power around each EM flare
- Gives per-burst energy limits an order of magnitude lower than the loudest-event analysis —as low as few × 10^{45} erg

Abbott et al., ApJ 701, L68 (2009)

In progress: More flares, new SGRs

- Including SGR 0501+4516 at ~1–2 kpc →
- Closer source gives sensitivity to lower energies !
- Hoping for a giant flare from a nearby SGR



Supernovae

Several possible GW emission mechanisms

- Rotating collapse and bounce
- Rotational instabilities
- Convection
- Standing accretion shock instability
- Protoneutron star g-modes
- ...

Review: C. D. Ott, Classical & Quantum Gravity 26, 063001 (2009)

Relative strength of GW emission mechanisms depends on what drives the supernova explosion

- Leading possibilities: MHD with rotation, neutrinos, acoustic waves

➔ Detection or non-detection of GWs can distinguish !

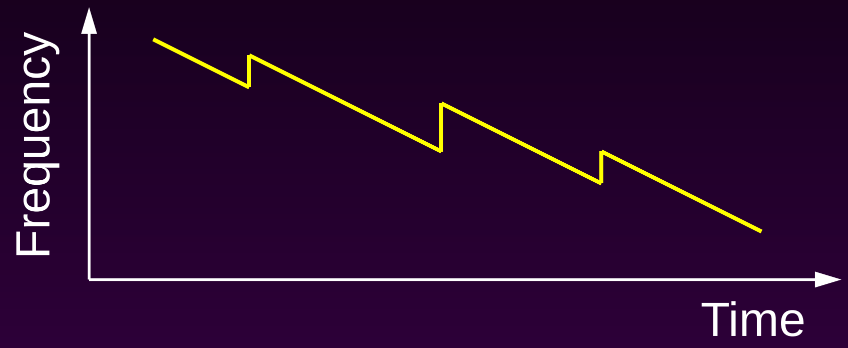
- Especially in conjunction with neutrino signal

Current detectors can probably only see SNe in our galaxy

- Advanced detectors may go out to a few Mpc – non-negligible rate

Pulsar Glitches

Some pulsars exhibit “glitches” in pulse frequency



Mechanism for glitches is unclear

- Crust cracking?
- Coupling of differentially rotating crust and core?
- Rearrangement of superfluid vortices?

May excite quasinormal vibrational modes

- Some modes couple to GW emission !

Searches are in progress

- e.g. Vela pulsar glitch in August 2006 : $\otimes\nu/\nu = 2.6 \times 10^{-6}$

Unknown Things That Go Boom

Single-Messenger Events ?

Not all energetic events will be seen by other means, even for GRB progenitors

- Gamma-rays are strongly beamed
- X-ray flashes / “Orphan afterglows” outnumber regular GRBs by 1–2 orders of magnitude
- Limited surveys for X-rays and optical transients
- “Failed GRBs” – optically thick
- Some GW sources may be totally dark – e.g. binary black hole mergers

All-Sky Inspiral Search

Search for GW inspirals arriving from any direction

Latest published search: first 18 months of LIGO S5 data

- Matched filtering for binaries with total mass up to 35 $M_\odot$
- No event candidates in excess of background distribution
- Set upper limits on event rates, using a population model
  - Binary neutron star: < 0.014 per year per L_{10}
  - Black hole – neutron star: < 0.0036 per year per L_{10}
  - Binary black hole: < 0.00073 per year per L_{10}

  where L_{10} is 10^{10} times the blue-light luminosity of the sun
  and black holes are assumed to have mass ~ 5 $M_\odot$

  Abbott et al., PRD 80, 047101 (2009)

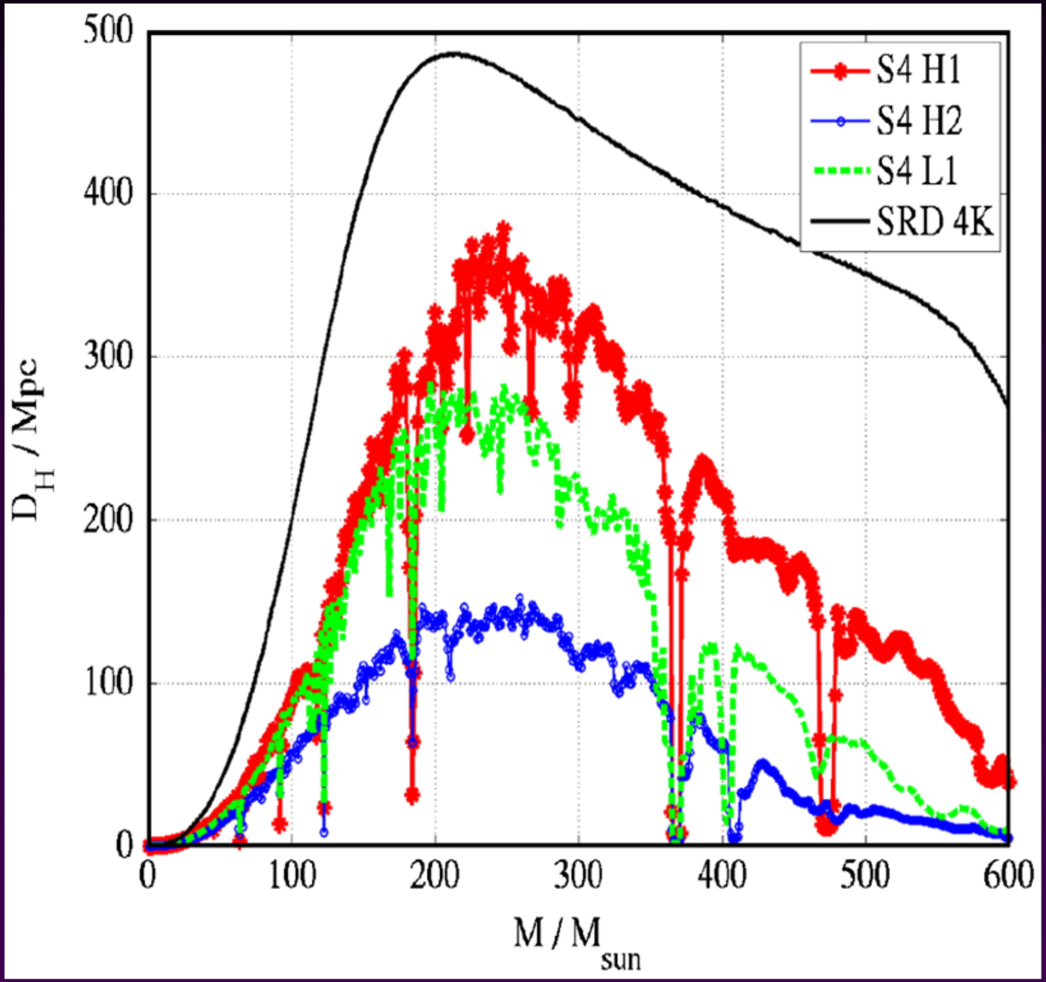
- Still 2–3 orders of magnitude away from likely rates
  "Realistic" rates compiled in *Abadie et al., arXiv:1003.2480* :
  BNS 6×10^{-5}, BH-NS 2×10^{-6}, BBH 2×10^{-7} per year per L_{10} –
  but with large uncertainties

Black Hole Ringdown Search

Search for ringdown of perturbed black hole resulting from a merger

- Sensitive to mergers of intermediate mass black holes
- Characteristic frequency & damping time depending on mass and spin
- S4 search published:

  Abbott et al., PRD 80, 062001 (2009)

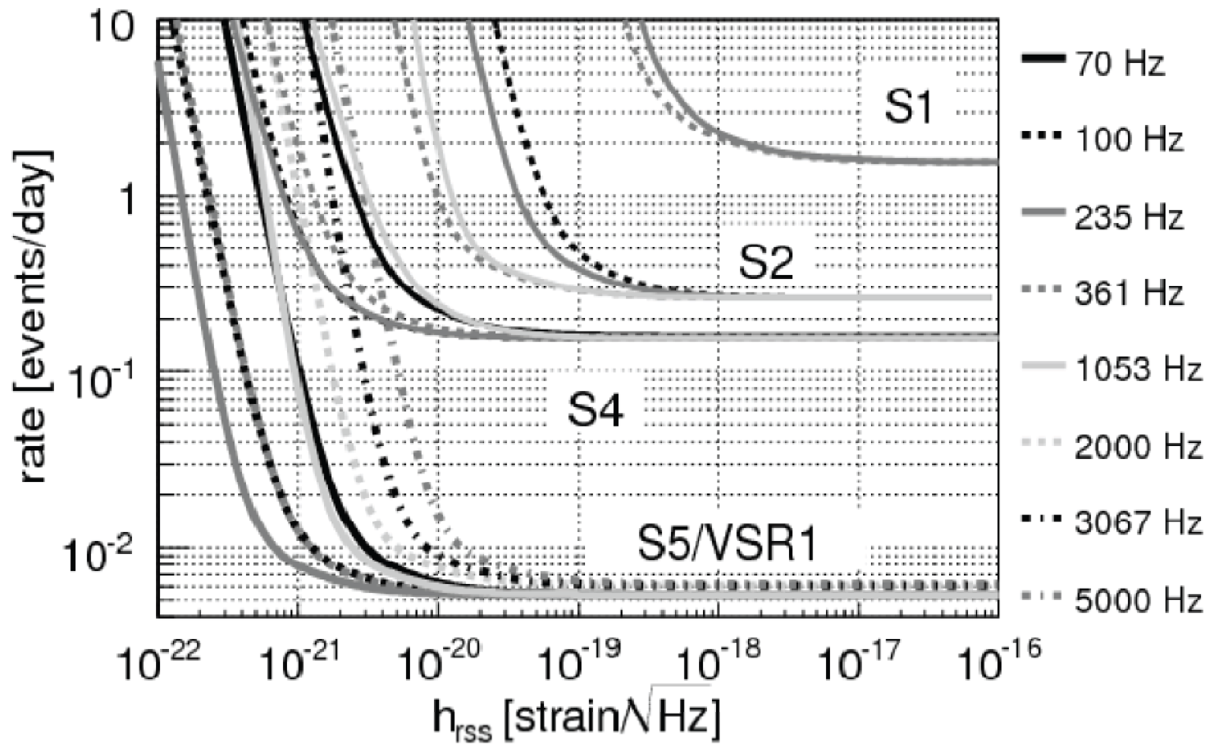


All-Sky Burst Search

Most general search for transient GW signals

- Coherent search methods using data from 2+ LIGO/Virgo detectors
- Effective observation time of 429 days during S5 / VSR1
- Sensitive to arbitrary GW signals in the range 50–6000 Hz
- No events detected; set upper limits on burst rate vs. amplitude for representative waveforms:

Abadie et al., PRD 81, 102001 (2010)



GW energy sensitivity for a 153 Hz burst:

~2×10^{-8} $M_{\odot}c^2$ at 10 kpc

~0.05 $M_{\odot}c^2$ at 16 Mpc

Further Steps Toward Multi-Messenger Astronomy

Additional Messengers

Neutrinos

- Models for emission from GRBs – and “failed GRBs”
- Joint searches planned with neutrino telescopes

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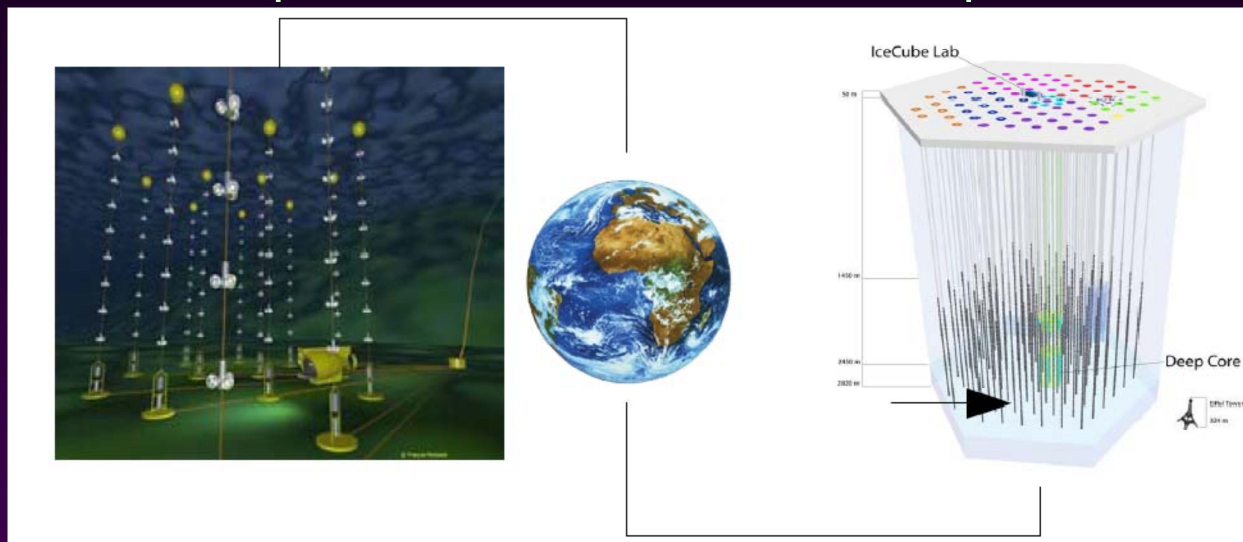


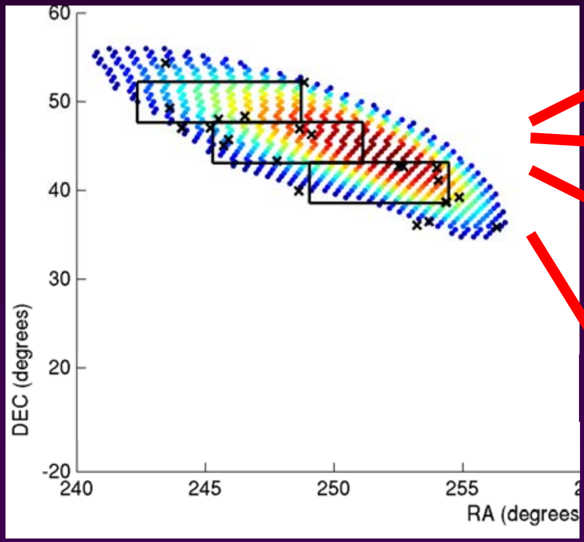
IceCube

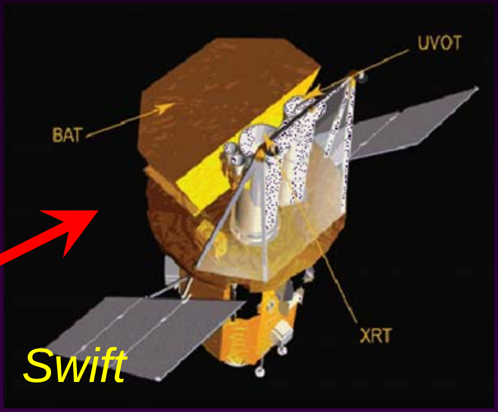
Radio transients

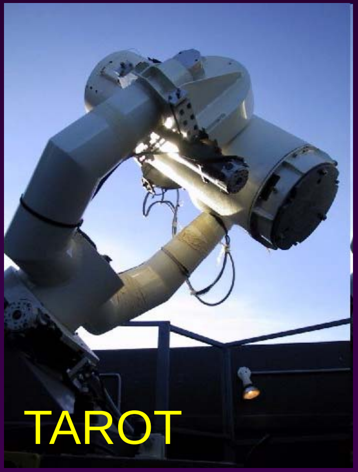
Electromagnetic Follow-Ups to GW Triggers

Analyze GW data promptly to identify possible event candidates and reconstruct their apparent sky positions; alert telescopes

- Try to capture an EM transient that would otherwise have been missed !
- First attempts underway







Other telescopes...

Summary

Gravitational waves can provide unique information about astrophysical events

- Direct probe of the central engine of the event

We are pursuing many modes of multi-messenger astronomy

- GW searches triggered by GRBs, SGR flares, supernovae, ...
- Joint searches with neutrinos, radio telescopes
- Electromagnetic follow-up observations of GW event triggers

Prepared to detect a signal – but no luck yet

Even non-detection of a GW signal can be relevant

- Constraints on astrophysical event types and emission mechanisms

Building capabilities for the advanced GW detector era

- Advanced LIGO, Advanced Virgo, others?
- GW signals will be detected – let’s do as much as we can with them!