Listening to the Universe with gravitational-wave interferometers: Recent observational results from LIGO and Virgo

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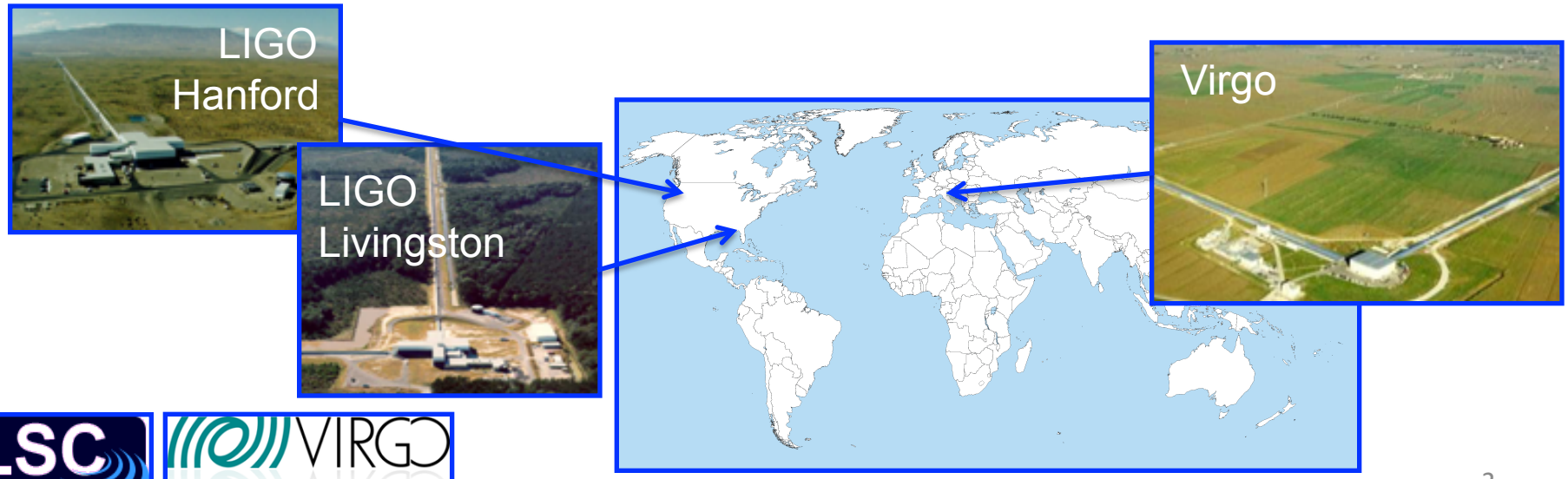
Introduction

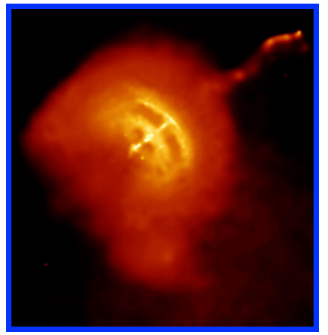
- We've been looking at the universe via astronomy for several centuries

- With the global network of gravitational wave (GW) interferometers
we are trying to listen to the universe
  - measuring differential strain $\Delta L/L < 10^{-21}$ in the arms of the interferometers

- Goals of this talk:
  - Summarize analysis to come out in the last year or so, using data from 2007-2010
  - Focus on multi-messenger astronomy, especially our recent low-latency EM follow-up program (trying to see and hear the same thing at the same time)
  - Touch on detection prospects in the Advanced detector era



Continuous Waves



Vela in X-ray

Searches for periodic long-term gravitational waves from pulsars

- All-sky search for periodic signals
  - factor of 2 below previous results
  - expands parameter space

Phys. Rev. D85 (2012) 022001

- Search for GWs from Vela pulsar with Virgo
  - 3 methods well below limit derived from "spin down"

Astrophys. J. 737:93, 2011

- Spin-off science (non-LIGO/Virgo paper):
  - 9 Gamma-ray pulsars discovered with Fermi-LAT data
  - Using analysis methods developed for continuous GW searches

Astrophys. J. 744:105, 2012

Stochastic

Search for unresolved sources from cosmological background or composite of astrophysical sources

➢ Whole-sky stochastic analysis

ArXiv: 1112.5004

- 600-1000 Hz frequency band
- First to include Virgo in stochastic cross-correlation analysis
- Factor of 7 improvement over previous limits

➢ Directional searches:

Phys. Rev. Lett. 107 (2011) 271102

- First spherical harmonic decomposition search: sensitive to extended sources
- Radiometer search for point-like sources: factor of 30 improvement over previous
- Factor of 5 improvement for individual point sources like Sco X-1, SN1987A and Galactic center

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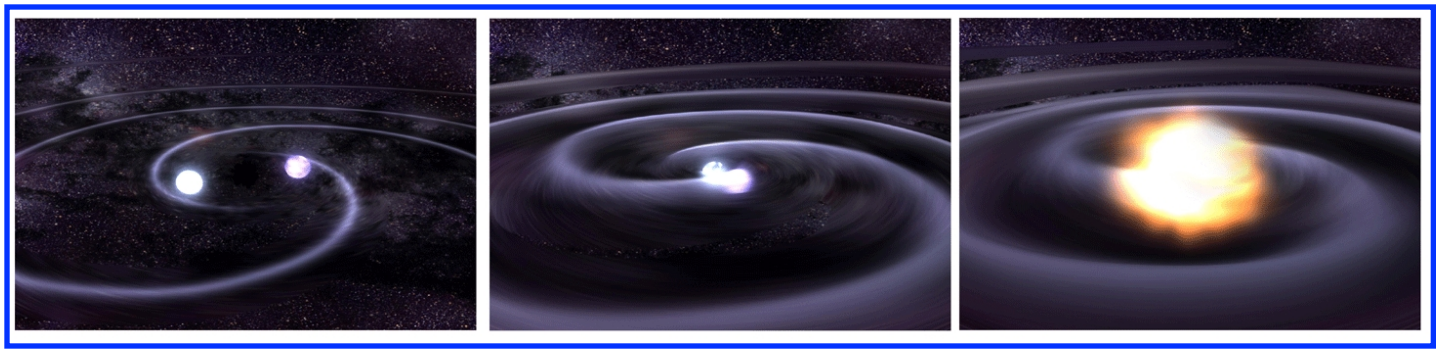
Compact Binary Coalescence

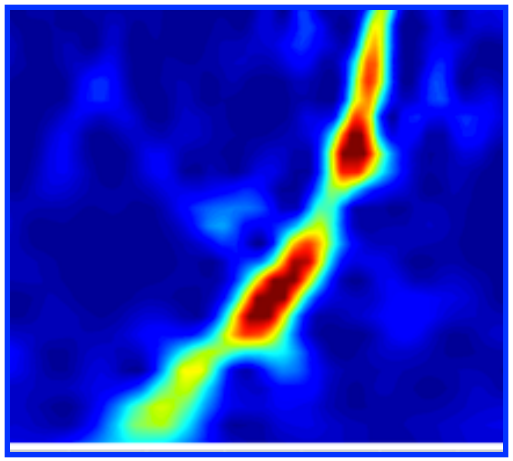


Transient GWs from coalescing binary systems of neutron stars and black holes

- First search to use complete numerical relativity waveforms for entire inspiral-merger-ringdown process

Phys. Rev. D83 (2011) 122005

- Inspiral search in S6/VSR2-3 data for systems with mass 2-25 $M_{\odot}$
  Includes results of blind injection challenge: GW100916 or "the Big Dog"



- End to end hardware injection test of LIGO-Virgo detection
- Simulated neutron star binary coalescence
- Full test of process - not revealed as injection for months
- Facilitated much work on parameter estimation
- False alarm rate estimate 1 per 7000 years

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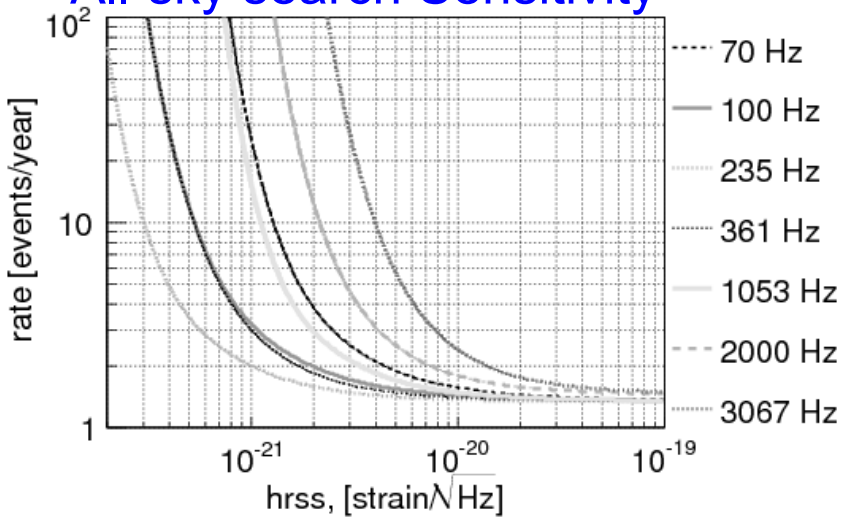
Phys. Rev. D85 (2012) 082002

All-Sky Burst Search

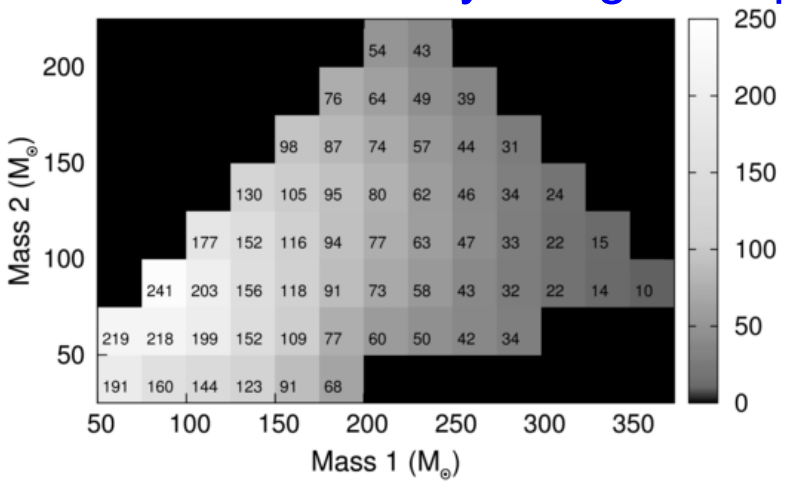
ArXiv: 1202.2788

- All-sky, all-times search for signals which do not assume specific morphology (GW 'bursts') is least constrained transient search – open to many source models and unexpected signals

All-sky search Sensitivity



IMBH Sensitivity Range in Mpc



- Intermediate Mass Black Hole search uses same algorithm to target black hole binaries at larger masses than CBC searches

ArXiv: 1201.5999

Multi-messenger Transient GW-EM Astronomy

Gravitational waves (GWs) tell us different things than electromagnetic (EM) signals
You learn different things by hearing than you do by seeing

Gravitational Wave Signal

- Bulk motion dynamics
- Luminosity distance
- Progenitor mass
- Direct probe of central engine

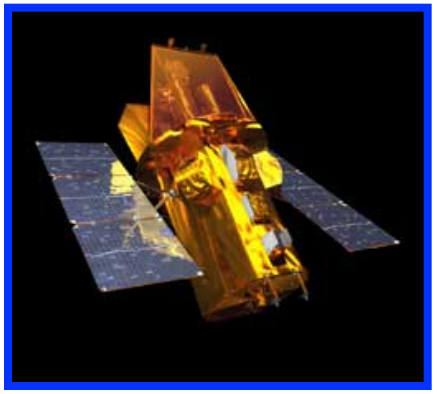
Light curve and spectrum

- Host galaxy
- Gas environment
- Red shift distance
- Precise Sky Localization

Full picture of progenitor physics

Plus: coincident observation of EM signal can dramatically increase detection confidence of a gravitational wave candidate event

Externally Triggered Searches

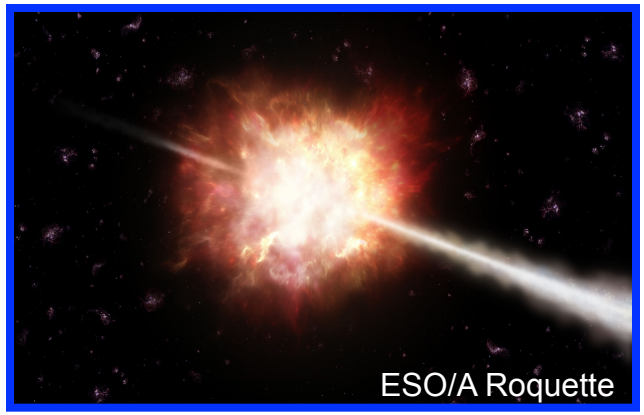


- Offline searches in which external electromagnetic triggers are used to dig into GW data

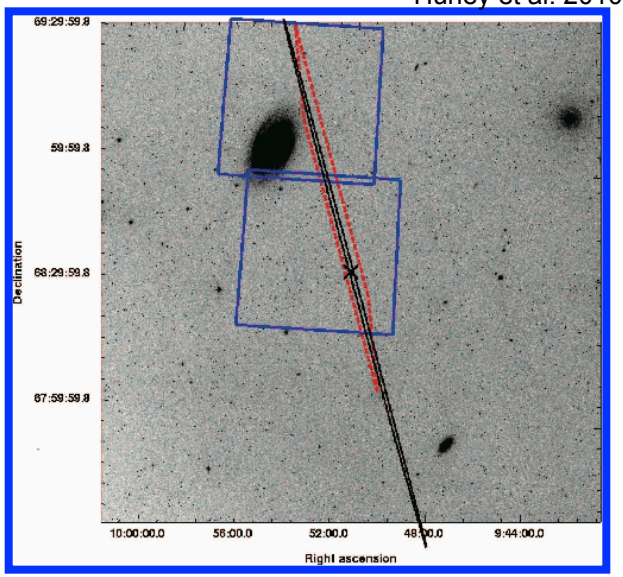
Coincidence with GRBs

ArXiv: 1205.2216

- Search for GWs in coincidence with 154 GRBs during recent science runs
- Both “burst” search and compact binary coalescence search (for short GRBs)
- GRBs from Fermi, Swift and other contributors to GCN network



Hurley et al. 2010



- Special analysis devoted to a possibly nearby short GRB051103 (in M81, 3.6 Mpc distant) lookings for CBCs, star-quakes or generic bursts
- Compact binary merger in M81 excluded to good confidence, Supports case that it was a distant SGR if event was in M81

ArXiv: 1201.4413

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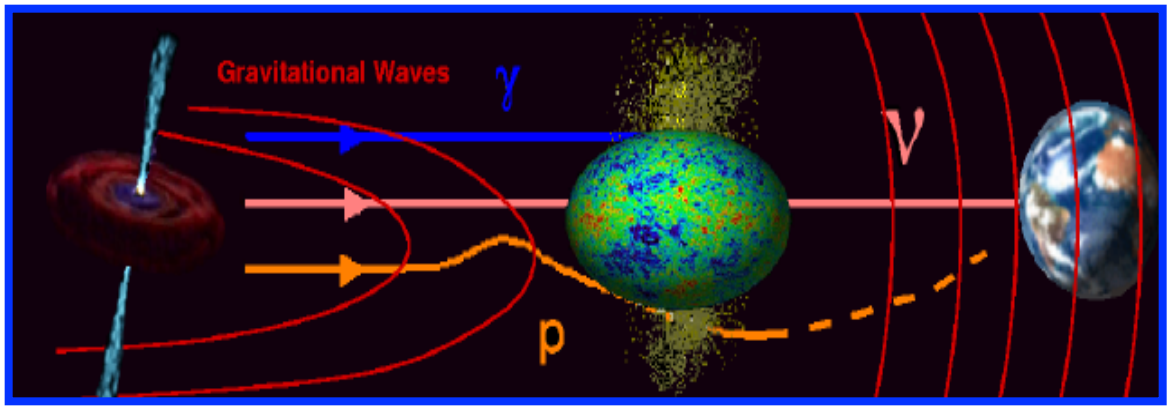
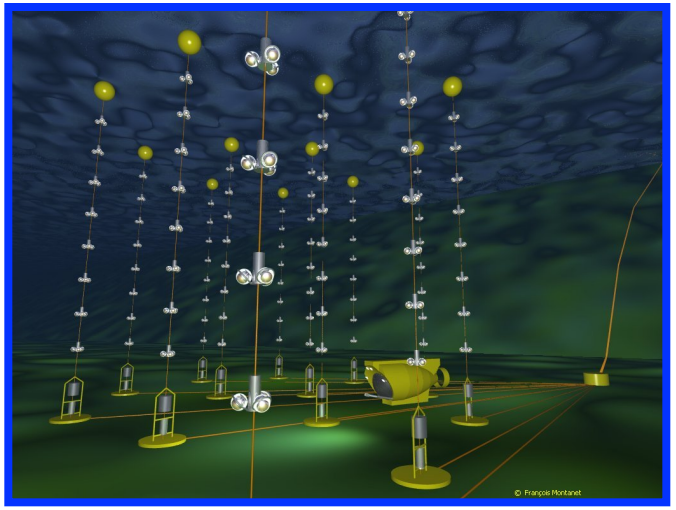
Search for Coincidence with Neutrinos from ANTARES

ArXiv: 1205.3018

- Search for GWs in coincidence with 158 neutrino events from 5-line ANTARES
- Events identified in 2-lines have 2 possible locations; both analyzed
- Possible joints sources: GRBs (including “choked” GRBs), SGRs or cosmic strings
- More joint ANTARES/LIGO/Virgo analysis on the horizon, plus IceCube…..





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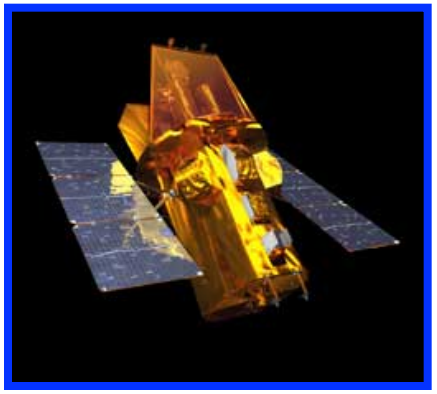
Multimessenger Astronomy with Gravitational Waves



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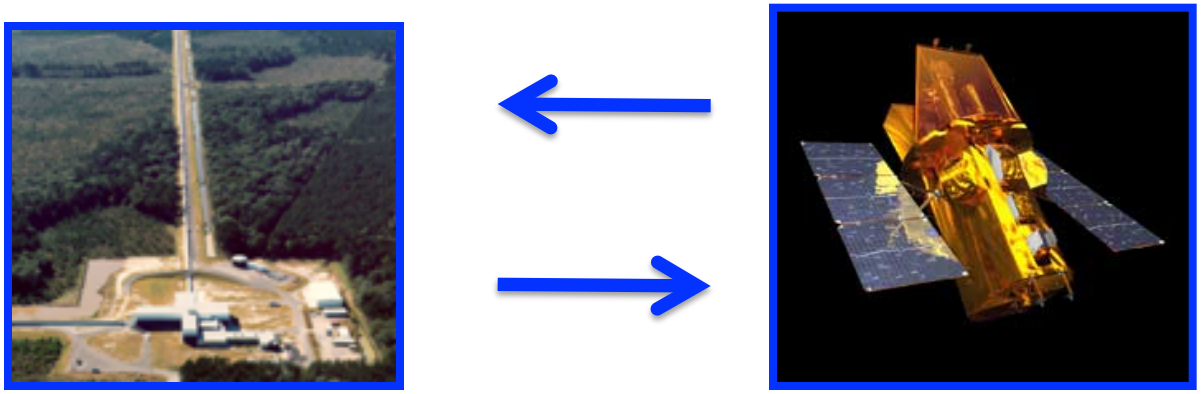
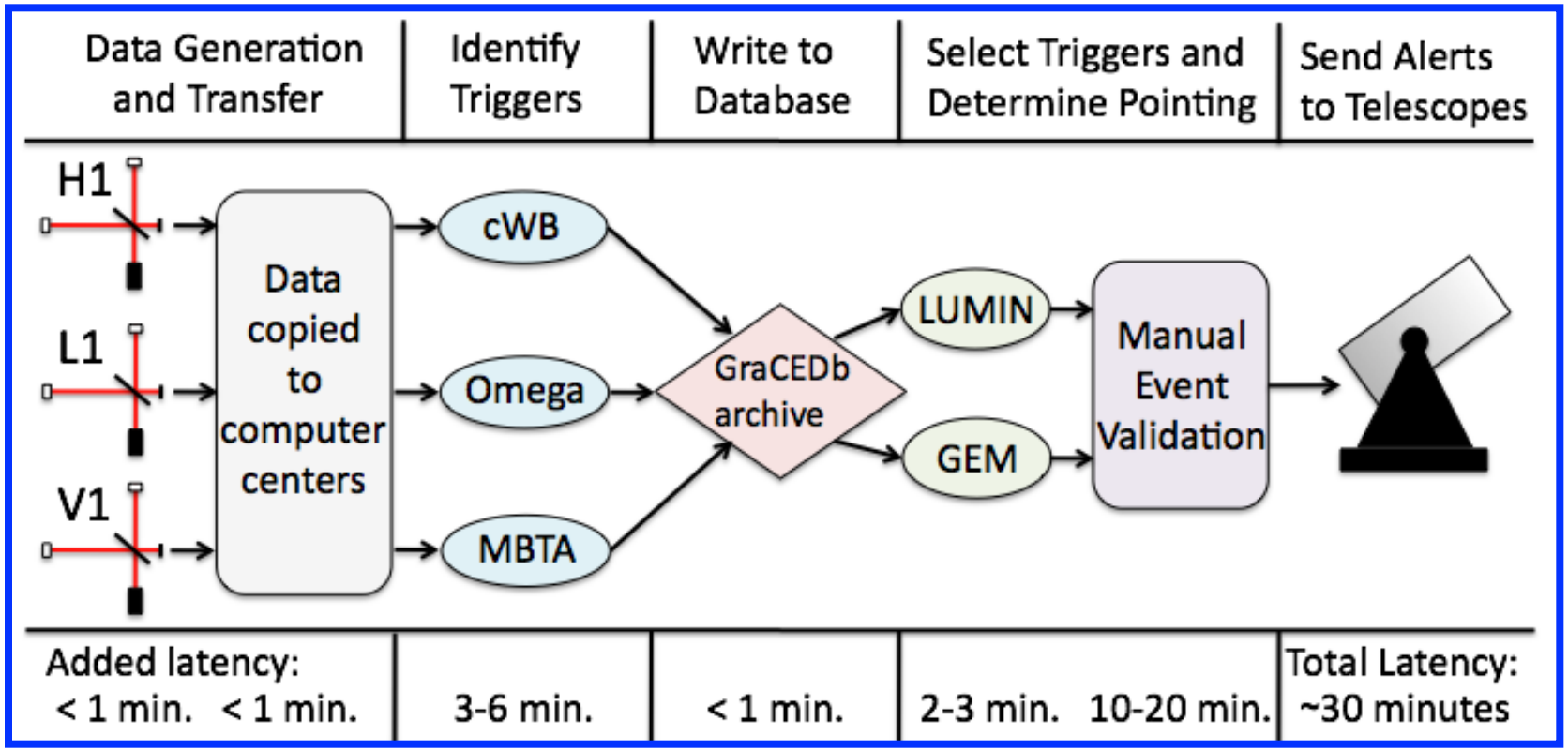
Multimessenger Astronomy with Gravitational Waves



- Offline searches in which external electromagnetic triggers are used to dig into GW data
- Low-latency electromagnetic follow-up of GW triggers

Low Latency EM Follow-Up Program



- Subthreshold candidate GW events sent to partner ~meter class telescopes network
- Target alert rate of 1 per week
- Ran during parts of most recent science runs Dec 2009-Jan 2010 and Sep to Oct 2010
- Images obtained for 8 different events

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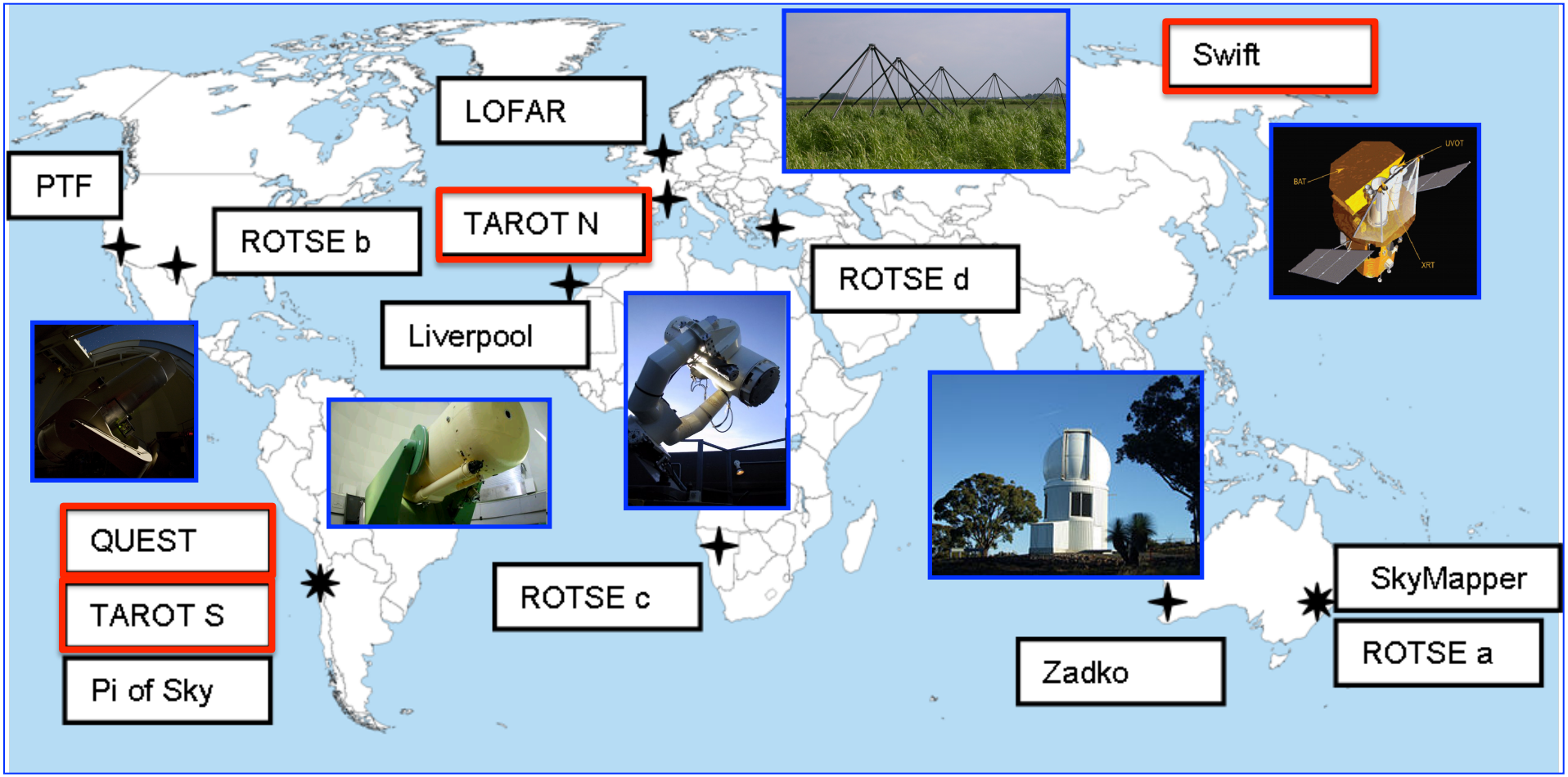
Astronomy & Astrophysics 539 (2012)A124

Astronomy & Astrophysics 541 (2012)A155

Telescope Network

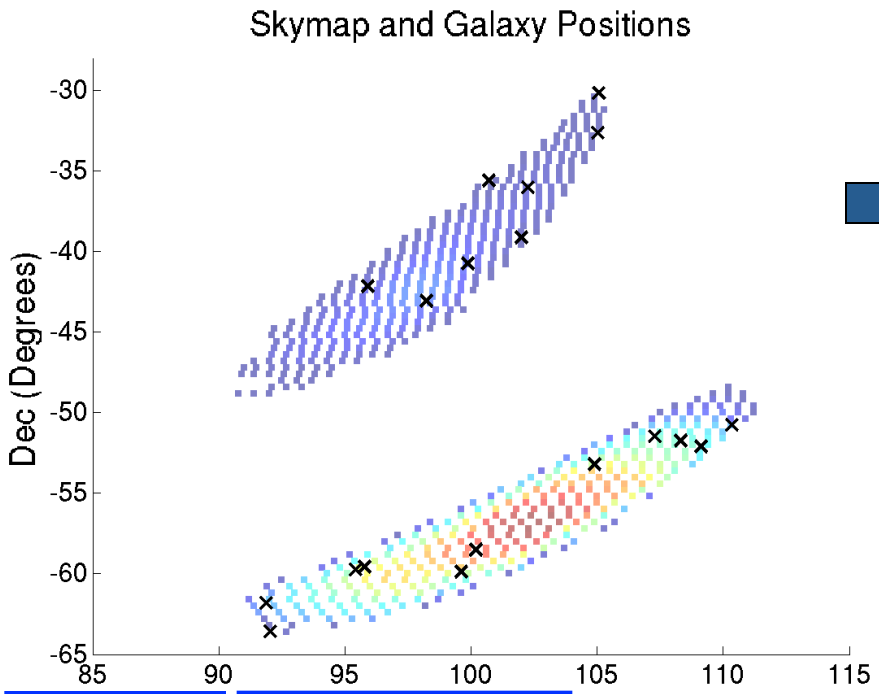
Used in winter and autumn run autumn run only

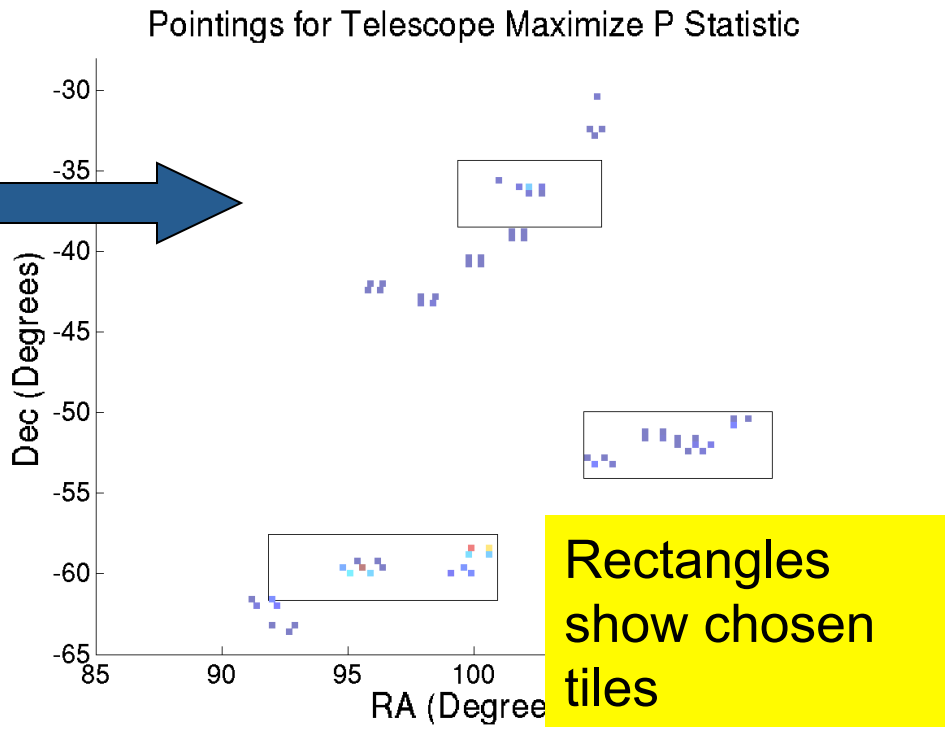


Probability Skymap and Pointing

Catalog used to find locations of nearby galaxies D < 50 Mpc Marked in black

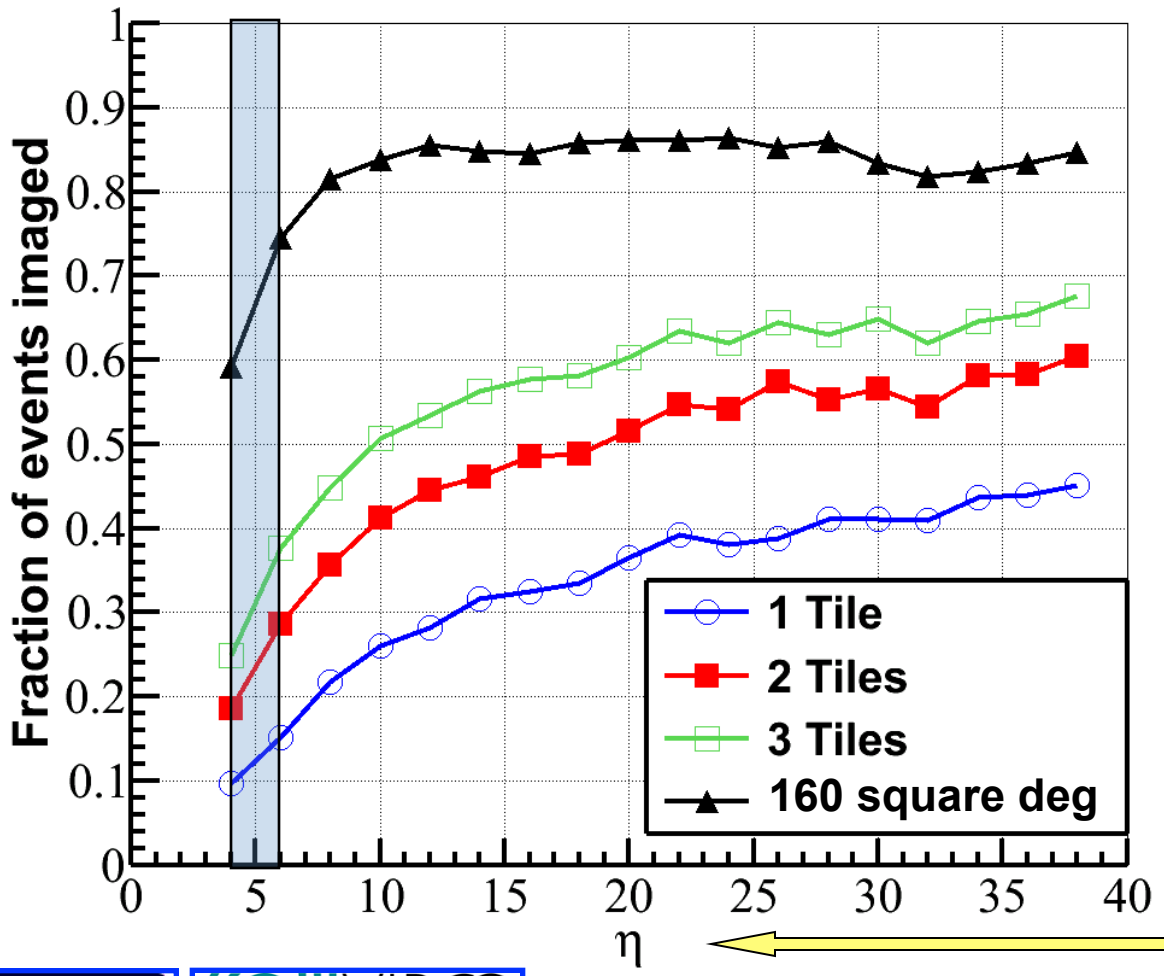
Blue Light Luminosity used as proxy for stellar mass, and so prior for each galaxy





Rectangles show chosen tiles

Sample of Pointing Success Rates



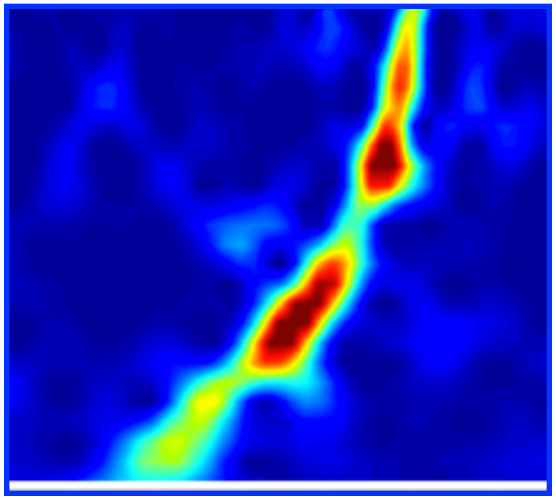
Coherent Wave Burst
ROTSE size FOV

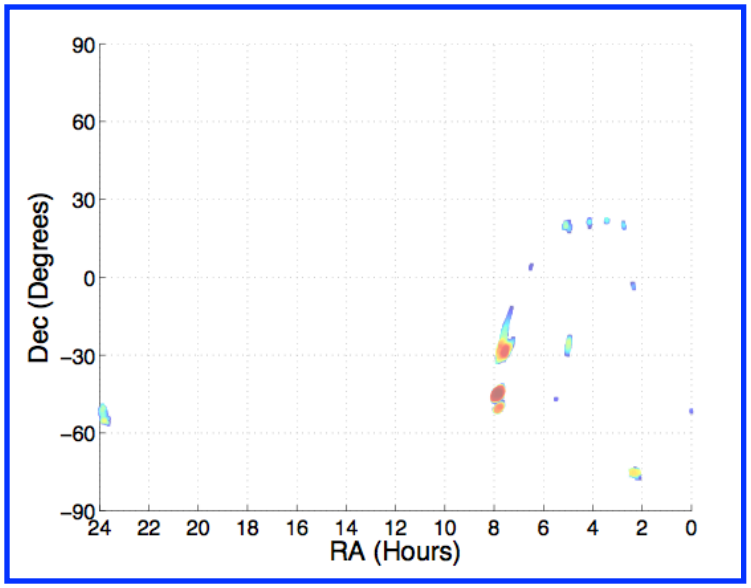
Shaded box shows range of nominal detection thresholds in S5/VSR1 search

η is "coherent SNR" measured by cWB; roughly proportional to network SNR

Big Dog Revisited

- Received alert 8 minutes after event (in middle of night)
- Sent to telescopes 45 minutes after event
- Visually identified as inspiral shortly after trigger generated
- Demonstrates that we're identifying "signal" with very low latency

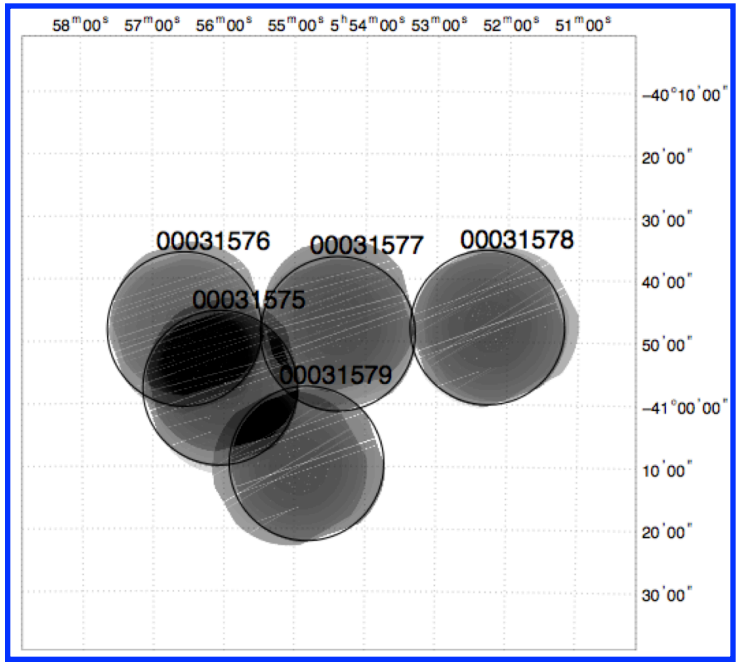


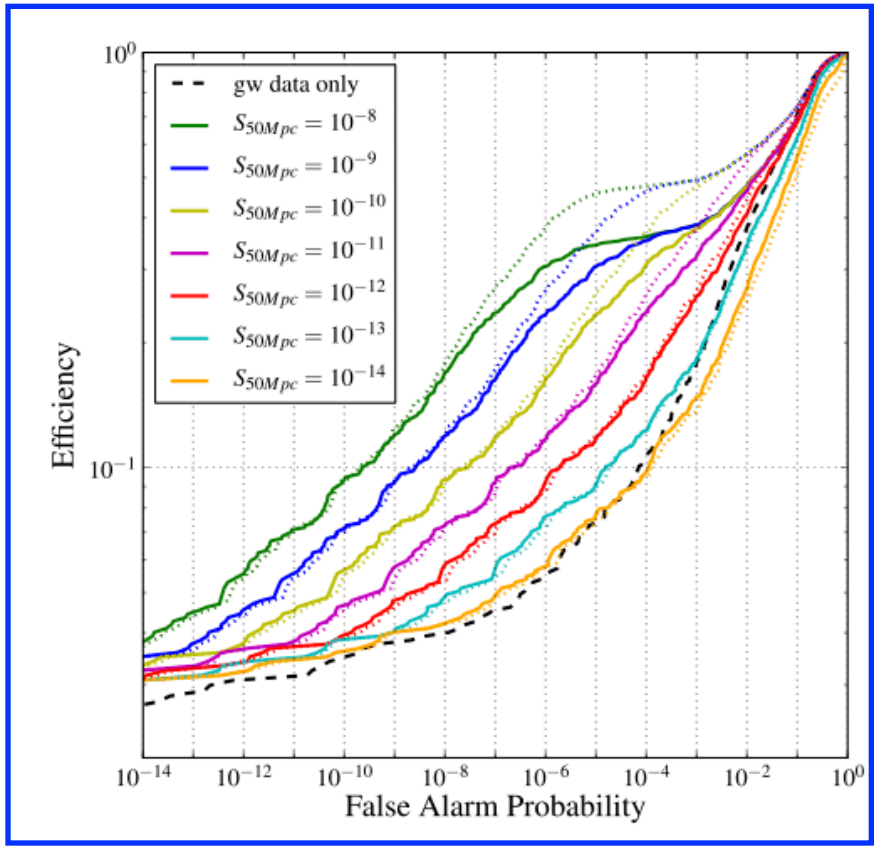


EM Follow-up with Swift

ArXiv: 1205.1124

- Swift satellite followed up 2 triggers
- Paper written jointly with Swift scientists describes X-ray and UV/optical search
- Includes monte carlo study of combined X-ray and GW significances





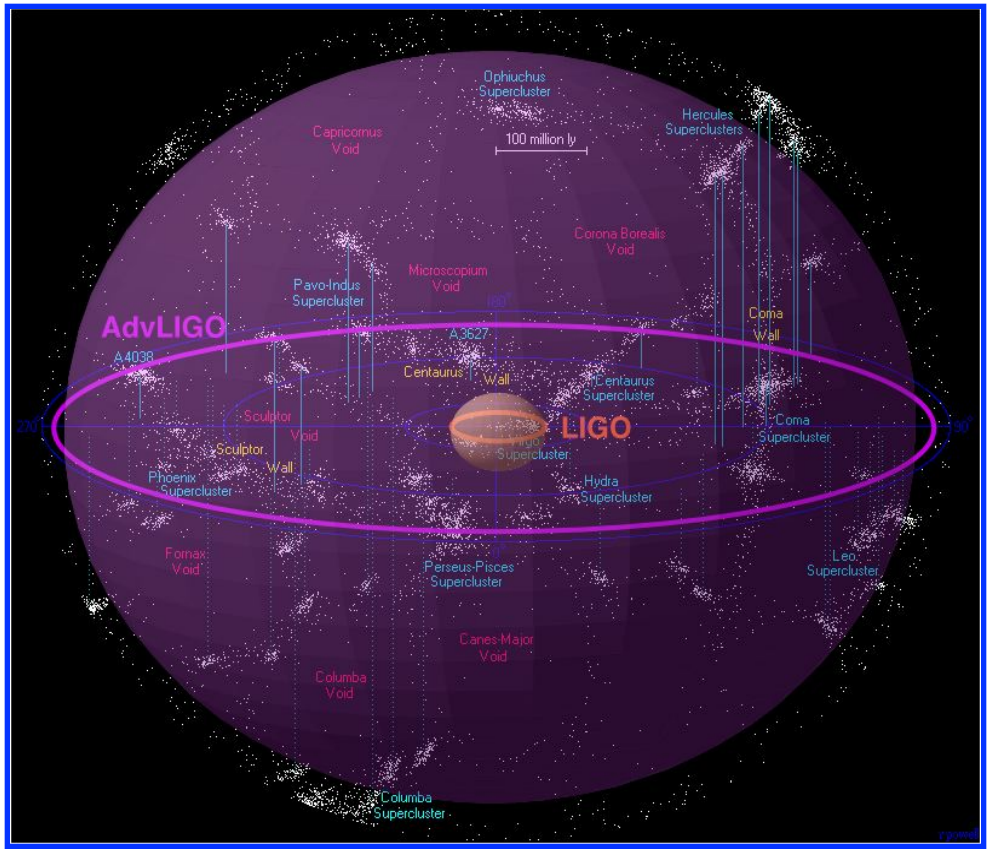
Prospects for Detection in Advanced Era

Predicted Advanced Detector CBC detection rates per year *at design sensitivity*

	Low	Realistic	High
NS-NS	0.4	40	400
NS-BH	0.2	10	300
BH-BH	0.4	20	1000

Compared to initial detectors

	Low	Realistic	High
NS-NS	2X10-4	0.02	0.2
NS-BH	7X10-5	0.004	0.1
BH-BH	2X10-4	0.007	0.5



Order of magnitude improvement in sensitivity →
Order of magnitude improvement in range →
3 orders of magnitude more volume

Class. Quant. Grav. 27: 173001 (2010)

Multi-messenger GW Astronomy in Advanced Era

- Joint transient detection rate likely to be much less than GW-only rate
- Beaming of EM emission means most GRBs not pointing at us
- Sky coverage in EM remains a critical issue, LSST should help
- Work underway to optimize pointing strategy, statistical treatment etc.
- Metzger & Berger* suggest kilonova as most promising source
- Even one or few joint detections will enable a lot of additional science: e.g. measure Hubble constant, confirm GRB progenitor

*arXiv:1108.6056