(Some Additional) Multi-Messenger Astronomy Opportunities for the LSC and Virgo

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September 12, 2008

LIGO-G080438-00-Z

Outline

- Scientific motivation
- What we are already doing
- Additional things we want to do
- Details about the specific projects
- Actions needed

Scientific Motivation

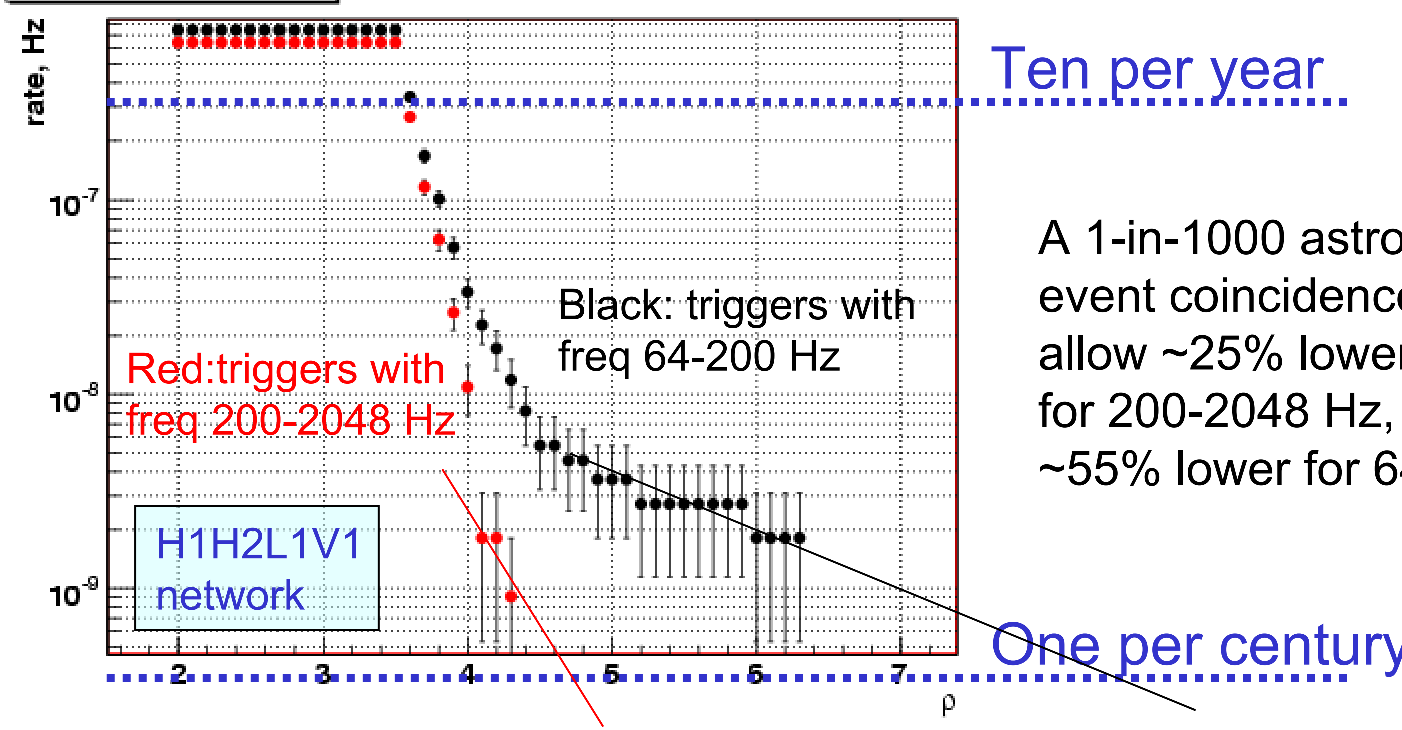
Many Eyes on the Sky

- **A GW source is reasonably likely to radiate in other ways too**
  - A *detectable* GW source must release a lot of energy and/or be relatively close
  - Specific GW, electromagnetic (EM) and particle emission mechanisms have been studied in many scenarios
- **Erg for erg, EM emissions are easier to detect than GW**
- **Taking advantage of this improves our ability to detect GW signals and understand sources**
- **“Multi-messenger astronomy”: connect different kinds of observations of the same astrophysical event or system**

Benefit: Improved Reach

- **Additional “coincidence” test enables us to confidently detect weaker GW signals**
- **How much weaker?**

Example based on S5/VSR1 Coherent WaveBurst background, using *only* time coincidence



A 1-in-1000 astronomical event coincidence would allow ~25% lower threshold for 200-2048 Hz, ~55% lower for 64-200 Hz

Benefit: Additional Info

- **EM or particle signal may provide more information about the GW source**
  - Sky position
  - Host galaxy type
  - Distance
  - Emission characteristics / astrophysical processes

What we are already doing

Gamma Ray Bursts

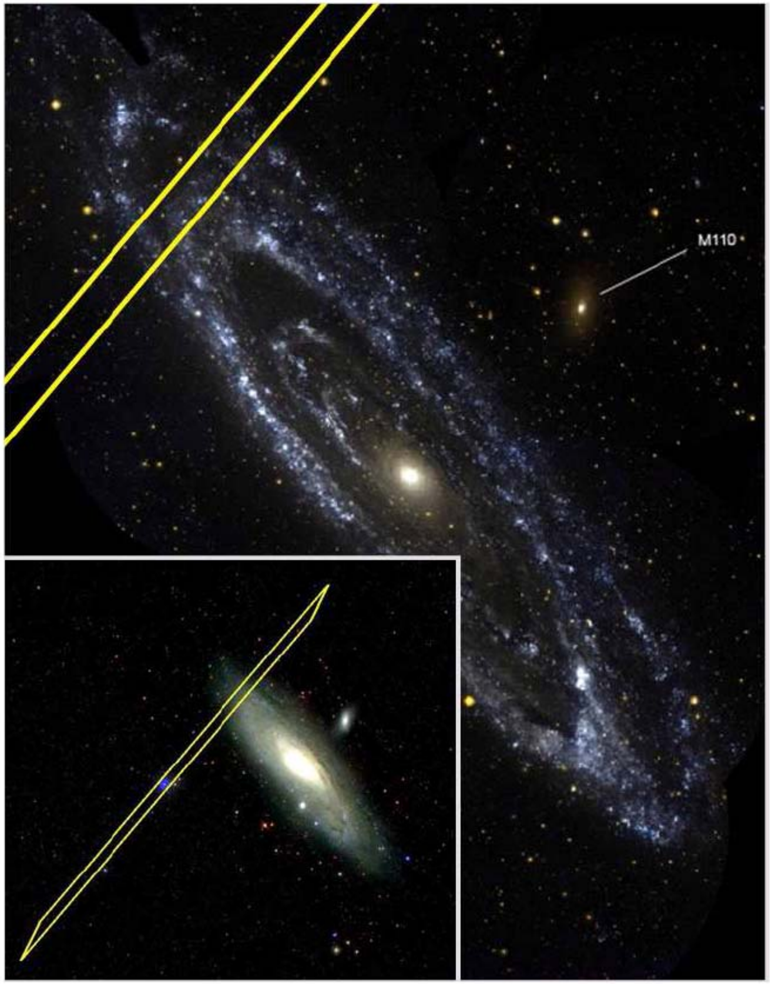


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main fi gure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

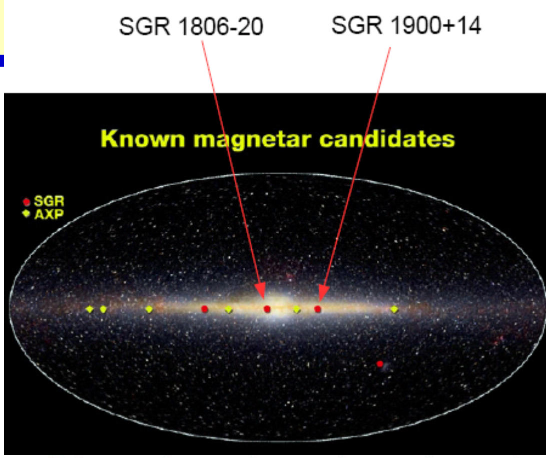
- **Have gotten GRB trigger info from GCN alerts and other sources**

Externally triggered searches:

- **GRB 030329**
- **39 GRBs during S2/S3/S4**
- **GRB 070201**
- **S5/VSR1 GRB inspiral and burst searches in progress**

Soft Gamma Repeaters

- **Publicly available info about SGR flares & expert advice**
- **SGR-burst (Flare) and SGR-QPO searches**
- **Results on giant flare of SGR1806-20 (pre-S4 Astrowatch data)**
  -QPO search: E_{GW} =7.7 x10^{46} erg (=4.3 x10^{-8} $M_{sun}c^2$), which is of the same order as the total (isotropic) energy emitted in the electromagnetic spectrum. (Phys. Rev. D 76, 062003 (2007)
  -Flare search: (arXiv:0808.2050v1 [astro-ph])
- **S5 first-year SGR burst search (Flare)**
  -Upper limits on E_{GW} overlap the range of EEM 10^{44}–10^{46} erg seen in SGR giant flares.
  -Most of the WNB limits, and some of the RD limits, are Below the 10^{49} erg maximum EGW predicted in some theoretical models [Ioka]. Sensitive to neutron star f-modes.
- **Other S5/VSR1 SGR analyses in progress**
  Improved QPO search
  Stack-a-flare multiple burst analysis
- **Ready for fast publication in case of another Giant Flare; quick results expected for S6**
- **Advanced LIGO promises 100x better limits, bringing really interesting science into scope**



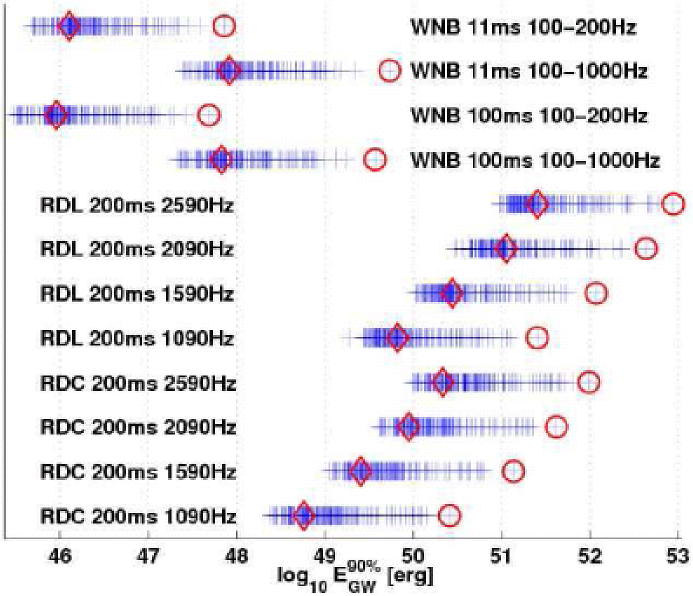


FIG. 1: $E^{90\%}_{GW}$ upper limits for the entire SGR burst sample for various circularly/linearly polarized RD (RDC/RDL) and white noise burst (WNB) signals. The limits shown in Table I, for the giant flare and GRB 060806, are indicated in the figure by circles and diamonds, respectively.

Supernovae Detected Optically

- **Using publicly available information**
- **Core collapse (CC) supernovae (SN) are exciting gravitational wave burst candidates [K. New, 2003].**
- **Various SN types known to be due to core collapse: II,Ib, Ic [K. New, 2003, A. Filippenko, 1997].**
- **Currently <10 CC SN are observed electromagnetically per year within ~40Mpc.**
  - This is an observational, not astrophysical, limitation (expect ~20 [N. Arnaud et. al., 2003])
  - Number of observations expected to increase significantly due to new large scale surveys coming on line soon.
- **Core collapse mechanisms are not well understood, so GW observations can tell us much about the physics of supernovae.**

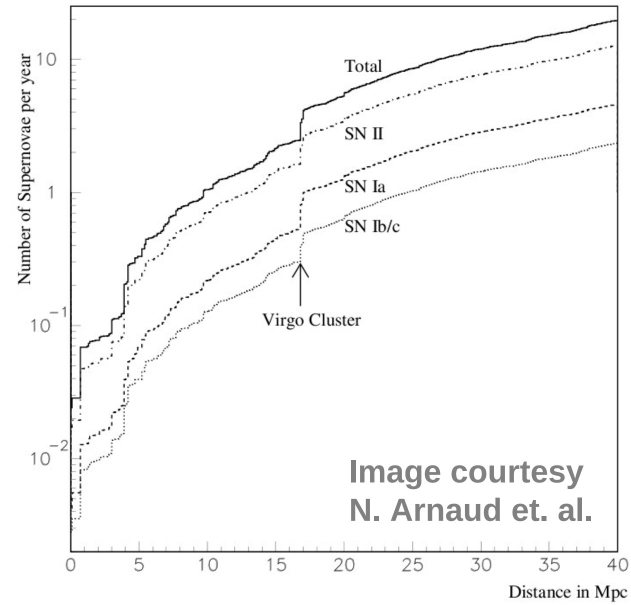
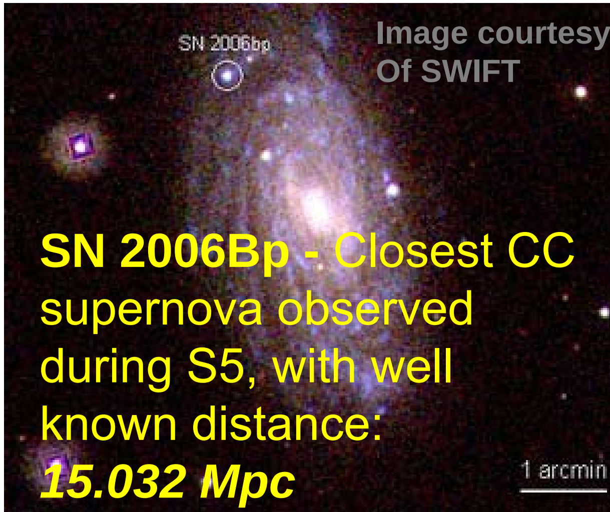


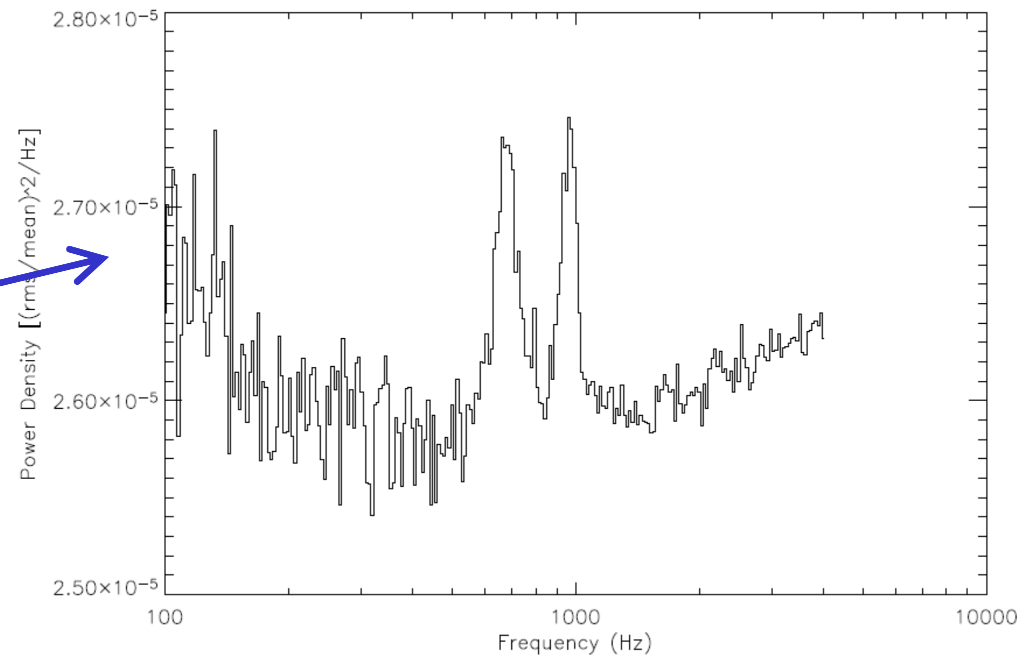
Figure 1: Number of supernova per year as function of the survey distance in Mpc, estimated from the Tully catalog [13]. The assumed Hubble constant value is $H_0 = 75$ km/sec/Mpc.



Joint Observation of Sco X-1

- **Look for connection between GW and X-ray emission from Sco X-1**
  - MOU between LSC and a team of RXTE scientists
  - Made special observations with RXTE during S5
  - Looking for correlation between X-ray variability and GW data

Power spectrum of X-ray data shows QPOs in the ~kHz region



Additional things we want to do

Development History

- **Externally triggered ("ExtTrig") searches have been part of the data analysis effort from the beginning**
  - Initial focus: GRBs
  - Expansion to other types of triggers over the past few years
- **Some experience working with "external" scientists on projects governed by MOUs**
  - HETE-II low-threshold GRB triggers during S2/S3
  - RXTE joint observations during S5
- **Strengthening connections with the astro community**

including:

gwdaw12@mit

Connecting Gravitational Waves with Observational Astrophysics

December 13-16, 2007, Royal Sonesta Hotel, Cambridge, MA, USA

The Role of External Collaborations

- **Recognized the need to *actively* engage the astronomy community**
  - Obtain proprietary trigger information for ExtTrig searches
  - Arrange for follow-up observations of GW event candidates using well-suited telescopes
  - Take advantage of “guest observer” programs to carry out target-of-opportunity (TOO) observations with premium telescopes, if/when needed
- **Requires protocols and MOUs with external scientists**
  - Data Analysis Council has been discussing this since Spring
- **Presented wide range of options at Orsay L-V meeting**
- **Since then: development of a coherent plan and identification of the most beneficial / well-supported projects**

Burst Group Plan for External Collaborations & Observations

- **The document: http://tinyurl.com/LVBurstExtCollabPlan**
- **Externally Triggered Searches**
  - GRBs (obtain non-public info)
  - High-energy neutrinos from extragalactic sources ★
  - Neutrinos from supernovae
  - Optical transients, including nearby supernovae
  - Radio transients (bursts, afterglows)
- **"LoocUp" Searches** (rapid follow-up observations of GW triggers)
  - Wide-field optical follow-ups ★
  - X-ray TOO observations ★
  - Deep optical TOO observations ★
  - Radio TOO observations

★ *We are seeking approval to proceed with these now*

Details about the specific projects

GW – HE-ν search ★

- Method development and impact study contributors: Columbia Experimental Gravity Group + Aso (LIGO), Finley (IceCube), Kouchner, Pradier, Van Elewyck,
- Di Palma (ANTARES), Chassande-Mottin, Barsuglia (VIRGO), Ando, Kotake (Theorists)

Potential sources of joint emitters of GWs and HEνs are highly energetic sources that feature bursting activity.

- *Long GRBs*: In the prompt and afterglow phases, high-energy neutrinos (10^5-10^{10} GeV) are expected to be produced by accelerated protons in relativistic shocks (e.g., Waxman & Bahcall 1997; Vietri 1998; Waxman 2000). Good prospects for detection out to cosmological distance. (A km^2-scale neutrino detector would observe at least several tens of events per year correlated with GRBs.)

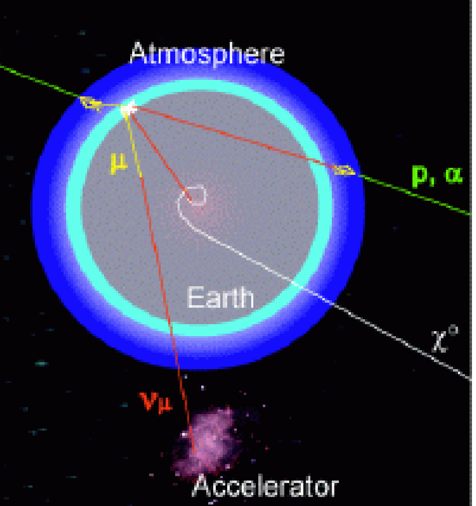
- *Short GRBs*: HEνs can also be emitted during binary mergers (Nakar 2007; Bloom et al. 2007; Lee & Ramirez-Ruiz 2007). The nu flux is expected to be large enough for the current generation of detectors, but reach is limited.

- *Low-Luminosity GRBs*: associated with particularly energetic population of core-collapse supernovae. Might also be a strong neutrino emitters (Murase et al. 2006; Gupta & Zhang 2007; Wang et al. 2007); although the luminosity is considered to be generally smaller, smaller distance would compensate it. Expected event rate in the local volume is more than an order of magnitude larger than that of conventional long GRBs (Liang et al. 2007; Soderberg et al. 2006).

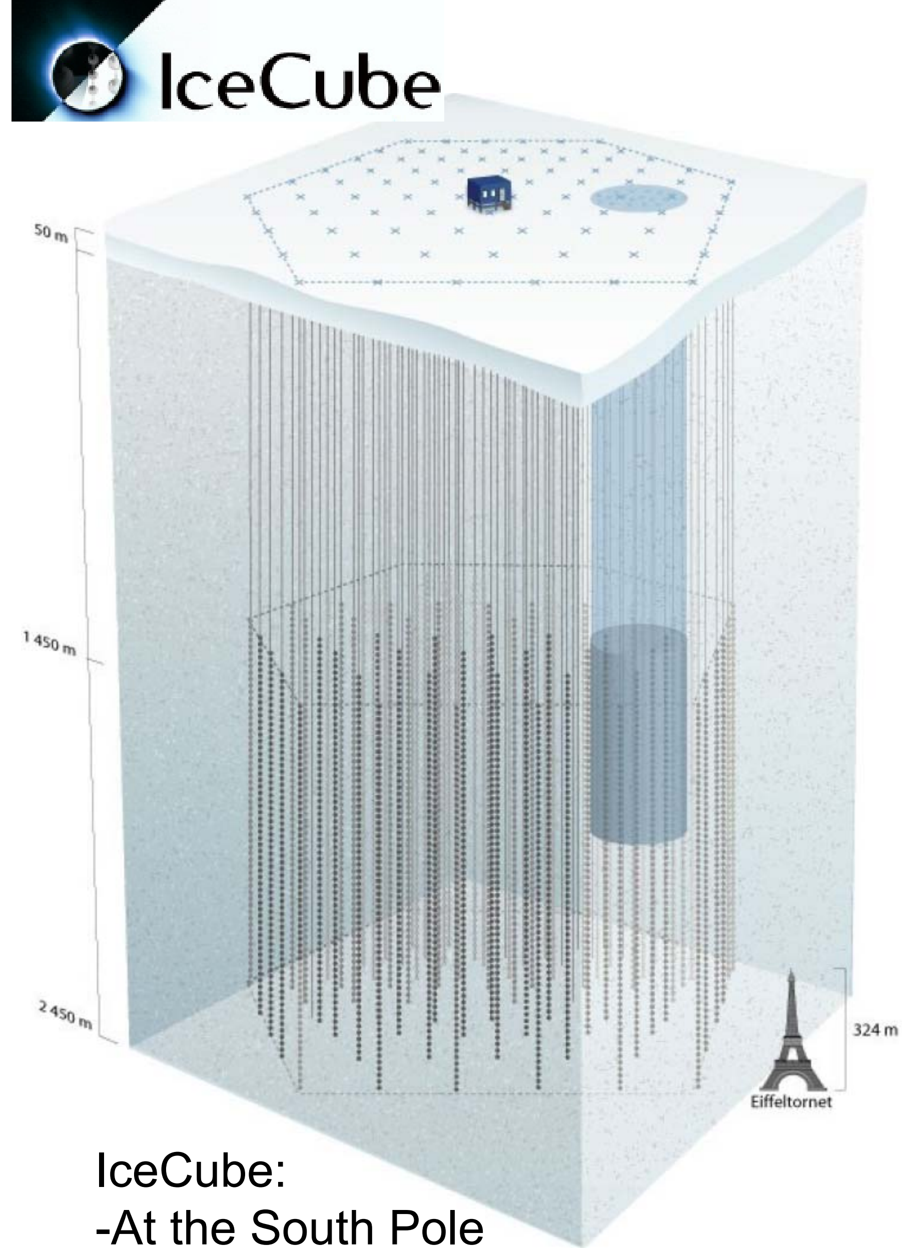
- *Failed GRBs*: Associated with plausible baryon-rich jets. Optically thick, completely hidden from any conventional astronomical telescopes, only neutrinos and GWs can reveal their properties. (Expect 30 neutrino events at a km^2 detector, Ando & Beacom (2005), Razzaque et al. 2004; Horiuchi & Ando 2008.) Rate of failed GRBs is estimated to be 1–10 yr^{-1} within 30 Mpc (Ando and Kotake, recent estimate).

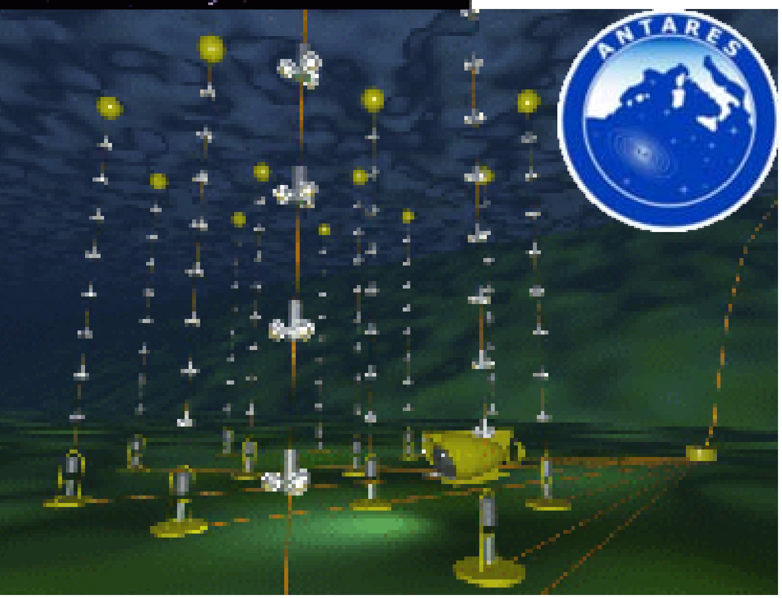
-*SGR giant flares*: Both neutrino and GW emission are estimated (Ioka et al. ,2005). At current sensitivities a joint study would at least limit existing SGR models.

- other known and possibly some *unexpected sources…*



A neutrino telescope uses the detection of upward-going muons (reconstructed from Cherenkov photons) as a signature of muon neutrino interactions in the matter below the detector.





ANTARES:
- In the Mediterranean sea
-detector surface area: 0.1 km^2
-1000 photomultiplier tubes in 12 vertical strings
- active height: about 350 meters

There are plans for a kilometer scale detector.

IceCube:
-At the South Pole
-10^{11}eV to about 10^{21} eV
- ~5000 Digital Optical Modules
- ~1 km^3 volume

Schedule

- 2007 May - Sept. offers ideal overlap of IceCube (22 strings) + LIGO (S5) + VIRGO (VSR1) for first joint analysis
- ANTARES started in May of 2008.
- Currently IceCube operates with 40 strings. Upgrades are ongoing during the Southern Summer season, now without much interruption. By the first half of S6 ~60 strings are likely, by 2010-11 IceCube 80-string configuration will be complete.
- A significant overlap in operation time for all detectors is expected during S6.
- Operation is expected to continue into Advanced LIGO era.

ANTARES – sees Southern hemisphere

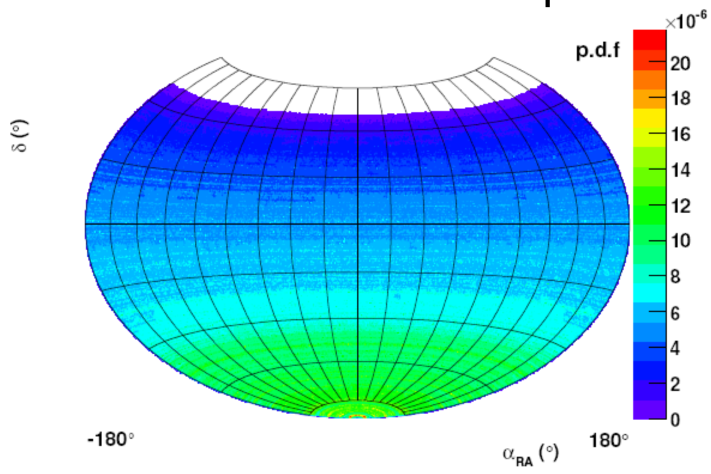
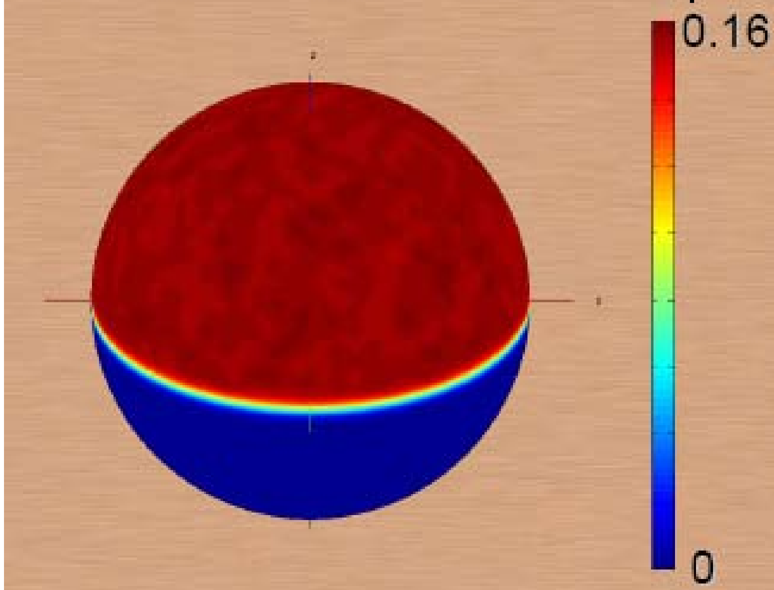


Figure 4.7: Normalized probability density (p.d.f) for the atmospheric neutrino background in equatorial coordinates.

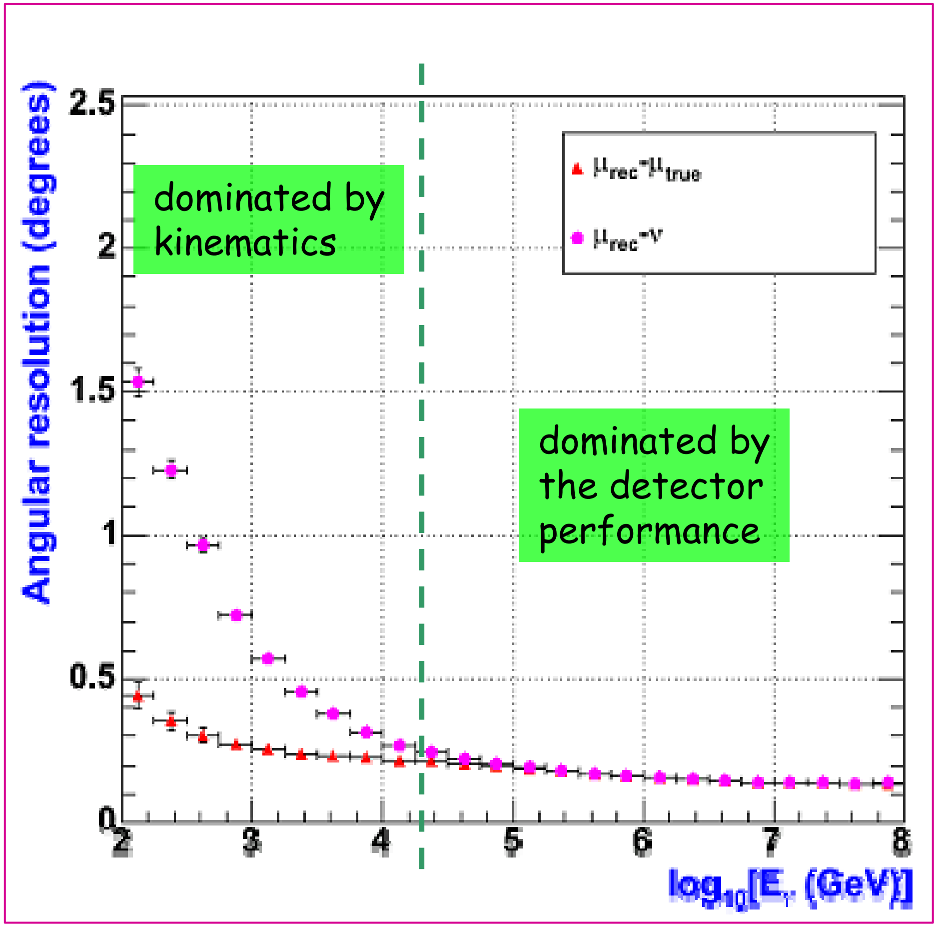
Notes: these are simulation results

IceCube – sees Northern hemisph.



Pointing precision

ANTARES (simulation)



IceCube:

- ~1.5º for 22 strings configuration, with some structure due to non uniform distribution of strings.

- For 40 strings the final results are not public (expected to be somewhat smaller and more uniform).

Joint Analysis Methodology

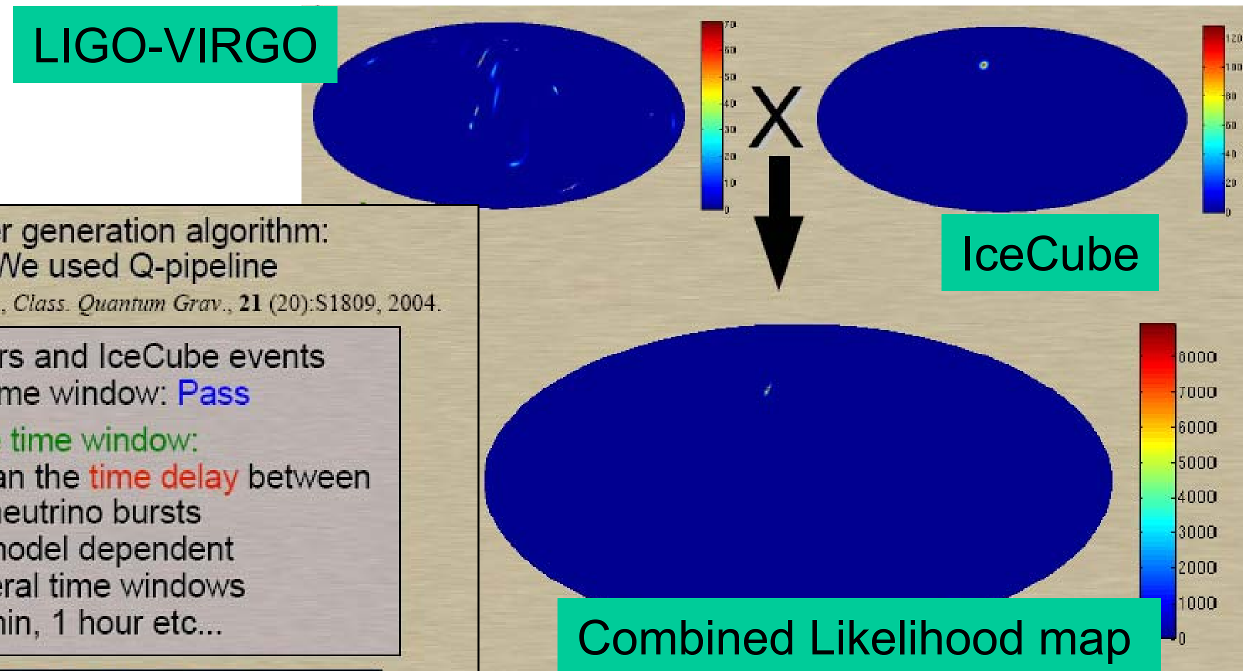
Performed offline (online is possible if really needed)**, using only internal event lists generated within each collaboration.**

2007 May - Sept. offers ideal overlap of IceCube + LIGO + Virgo for first joint analysis

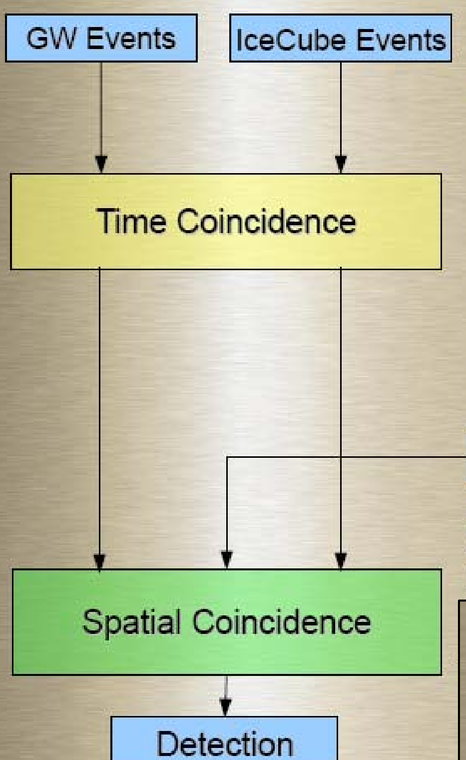
Will be possible to translate non-detection into upper limits **on bursts.**

Joint analysis allows search for bursts with lower threshold than possible with either experiment individually**.**

Simulation results exist: (LIGO-VIRGO-IceCube(22))



See Aso et al CQG (2008) and Aso 2008 APS talk



GW trigger generation algorithm:
We used Q-pipeline

S. Chatterji, et al., *Class. Quantum Grav.*, **21** (20):S1809, 2004.

GW triggers and IceCube events within a time window: Pass

Size of the time window:
- Larger than the time delay between GW and neutrino bursts
- Source/model dependent
- Use several time windows 1 sec, 1 min, 1 hour etc...

Background GW & IceCube Events

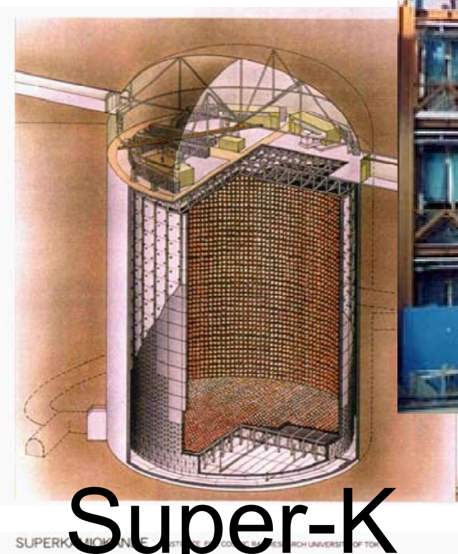
Background generation method
GW: Time shift data between interferometers
IceCube: Monte Carlo

$$\mathrm{FAR} = \frac{1}{1184}\left(\frac{p}{1\%}\right)\left(\frac{T_w}{1\,\mathrm{sec}}\right)\left(\frac{R_{GW}}{1/\mathrm{day}}\right)\left(\frac{R_\nu}{10/\mathrm{day}}\right)[\mathrm{events/year}]$$

p-value threshold time window GW BG event rate IceCube BG event rate

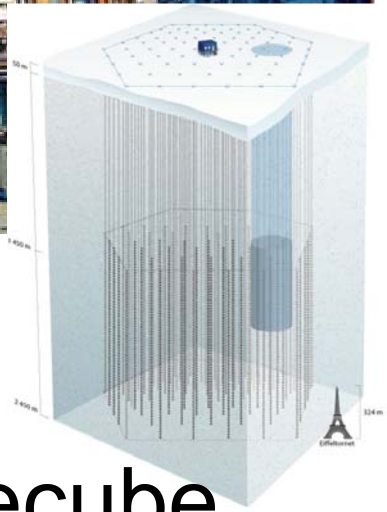
Neutrinos from core collapse

- Collapse of a massive star to a neutron star: ~3x10^{53}erg of gravitational energy released primarily (99%) in the form of neutrinos and over tens of seconds (about half in first 1-2 seconds)



Super-K

LVD



Icecube

- Several scintillator and water Cerenkov detectors provide sensitivity to core collapse within our Galaxy and the LMC/SMC primarily thru the inverse beta decay of their proton targets when they are struck by electron antineutrinos emitted during core collapse

Neutrino detector status and capabilities

- Super-K, LVD and Icecube are the three main detectors that operated during S5/VSR1 and plan to continue taking data throughout S6/VSR2 (and possibly beyond)
  - other detectors with much reduced sensitivities and past/future data overlaps exist
- SNO, a heavy water Cerenkov detector with sensitivity to core collapse neutrinos overlapped with S5/VSR1 for O(1) year in 2005-2006. Plans for future detector exist but data taking is unclear.
- The three main detectors is expected to detect core collapse supernovae in our Galaxy and the nearby LMC/SMC with high efficiency
- Reaching to M31 at 700kpc (where the expected rate of SN is approximately doubled) is practically impossible for neutrino detectors alone. For a supernova in M31 the expected neutrino events in Super-K is of O(1).
- The best pointing they can provide is by the neutrino-electron scattering channel of detection (<5% of the neutrino events in Super-K) and it has an estimated 1-sigma angular width of $\sim 5^{o}$

Science case for GW-ν joint analyses

- **Improve chance of detection via lowering individual detector thresholds and increasing the time coverage of a global GW-ν detector network.**
  - If detections are made, present a far more complete picture of the collapse mechanism and the high-density regime of the star
  - Use relative timing to probe neutrino mass
- **A coincident GWs -ν's search can allow an O(2) improvement in the GW sensitivity w/r/t an all-sky search. Given the significant uncertainties and open questions surrounding the strength of GW emission from core-collapse SN, such improvement is highly valuable.**
  - Analysis mode: use existing GW transient events in a time-coincidence analysis with existing neutrino events
  - If no detections made, present UL result with twice the sensitivity of an all-sky search
- **Ability to explore "distant" SN searches (in M31) unable to be seen reliably by neutrino detectors alone. This is on the assumption the GW signature as currently estimated is overly conservative.**
  - Analysis mode: "few" event ν-clusters triggering a search in GW sector; use existing GW transient event, or fine tune search
  - If no detections made, present UL which under certain assumptions for the GW emission may reflect uncharted territories for the neutrino detectors

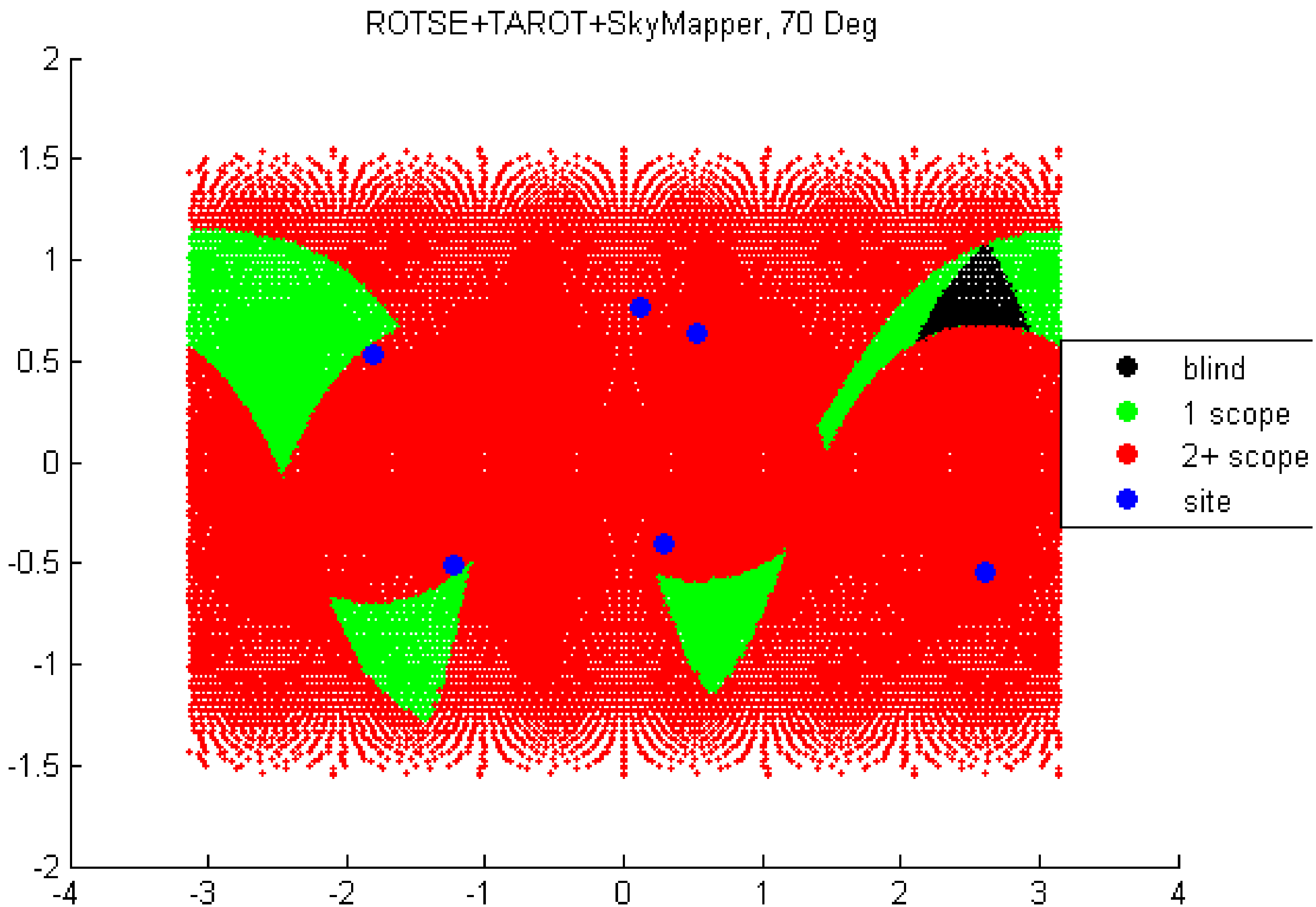
Position Reconstruction for LoocUp Follow-Ups

- **How well can the GW data analysis localize the source?**
- **Some studies have been done; not very systematic**
  - Klimenko et al. (PRD 72, 122002 (2005)) —
    BBH mergers, Mtotal = 100 Msun, H1-L1-G1 network.
    Pointing resolution ~8 degrees, depending on network SNR.
  - Cavalier et al. (PRD 74, 082004 (2006)) —
    position reconstruction using timing only. For a certain timing uncertainty model, pointing resolution ~2–3 degrees.
  - Markowitz et al. (P080003) —
    use antenna factors to resolve ambiguity, remove angular biases; *loud* signals are almost always reconstructed within a few degrees
- **A team has been formed and is working on the issue of position reconstruction**

Wide-Field Optical Follow-Ups ★

- **Requirements**
  - Wide-field telescopes
  - Robotic, with reasonably fast response
  - Good sky coverage
- **Available telescopes include:**
  - ROTSE – 4 telescopes around the globe, 3.4 sq deg FOV
  - TAROT – 2 telescopes, also 3.4 sq deg FOV
  - SkyMapper – 1.3-meter telescope in Australia, 5.7 sq deg FOV
  - LONEOS – 0.6-meter telescope, 9 sq deg FOV
- **Notes**
  - ROTSE and TAROT regularly used for GRB follow-ups
  - SkyMapper will be systematically surveying the southern sky; will inform us of any interesting optical transients it detects

Sky Coverage



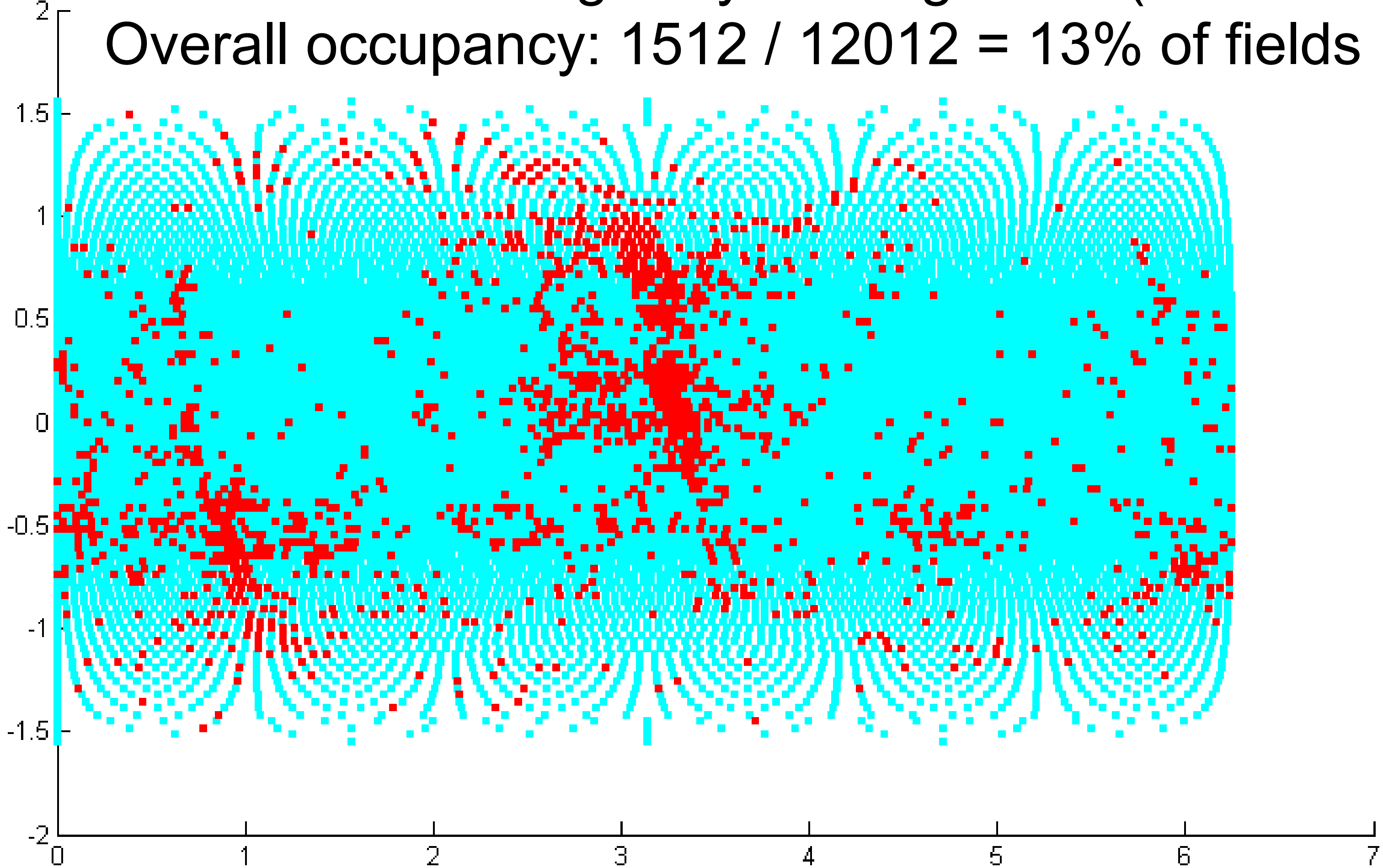
Galaxy Targeting

- **Can reduce the amount of sky to be imaged if we assume that a detectable GW source is *probably* located in a nearby galaxy, a Milky Way globular cluster, or the Galactic Center**
  - There are ~1500 such objects within a distance of 20 Mpc

i.e. “Look under the lamppost” !

Effectiveness of Galaxy Targeting

Dots: centers of ROTSE/TAROT size image fields
Red: one or more galaxy-catalog items (within 20 Mpc)
Overall occupancy: 1512 / 12012 = 13% of fields



General Notes on TOO Observations

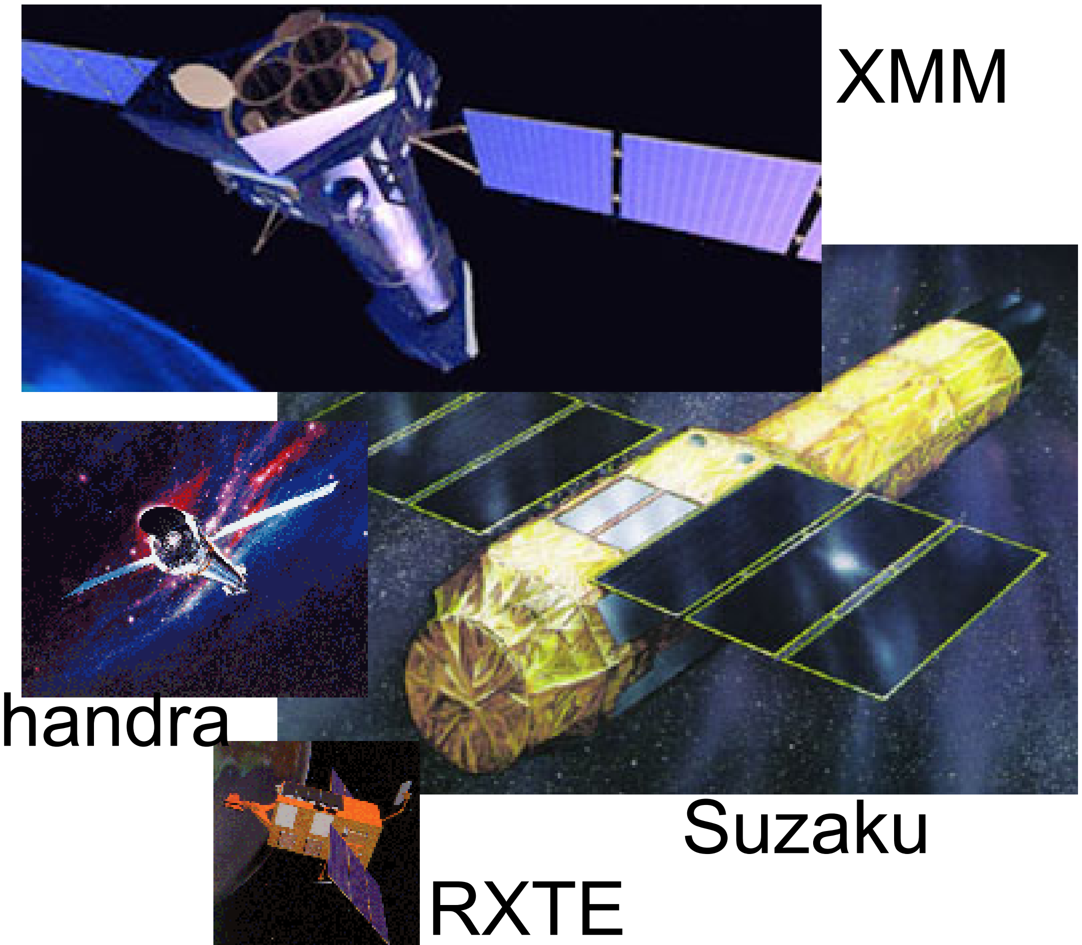
- **Premium telescopes have fairly small fields of view, so event candidate needs to be localized well**
  - From an exceptionally loud event ??
  - From an optical transient captured by wide-field imaging
  - From galaxy targeting
- **Asking for time does not mean we have to use it**
  - We want it to be available if we need it
  - The opportunistic nature of the project is understood
  - We are not required to use all the time we're allocated
  - If we're unable to use the time for reasons beyond our control, that should not reflect poorly on us

X-ray Signatures from GW Sources

- Prompt X-ray outbursts as well as bright X-ray afterglows have been observed in connection with core-collapse supernovae as well as GRBs. Prompt emission has been interpreted as shock breakout emission; X-ray flares are thought to be produced by late time activity of the GRB central engine
- Coincidence observations may reinforce GW detection, provide position of the source with much reduced error circle that may be subsequently used for observations by other instruments/wavelengths

X-ray Satellites

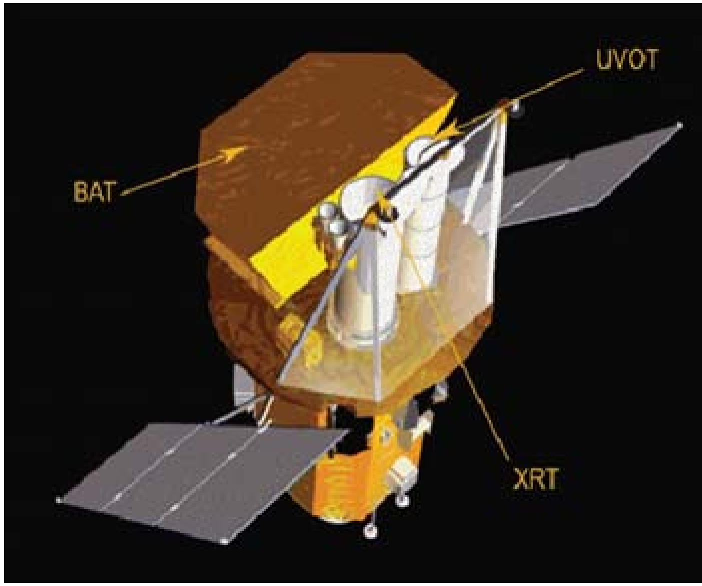
- **Work-horses of X-ray astronomy:**



- XMM-Newton (ESA) FOV 5-34’ sq depending on X-ray energy/instrument
- Chandra (NASA) FOV ~10-50’ sq depending on X-ray energy/instrument
- RXTE (NASA) ASM
- Suzaku (J-ISAS) FOV 2-34’ sq depending on X-ray energy/instrument

The Swift Satellite ★

- **Swift is capable of performing multi-wavelength observations of GRBs and their aftermath. Three different telescopes record gamma-ray, X-ray, ultra-violet, and optical light.**
- **<u>Unique feature</u>: it can "swiftly" turn its telescopes in order to detect GRB afterglows, or any other source upon demand**
- **UV/optical telescope: 0.4 degrees FOV**
- **X-ray telescope: 0.3 degrees FOV**
- **We have submitted a Notice of Intent**
  - Non-binding, but we do want to propose !
  - Stage 1 proposal due **October 15**



Deep Optical TOO Observations ★

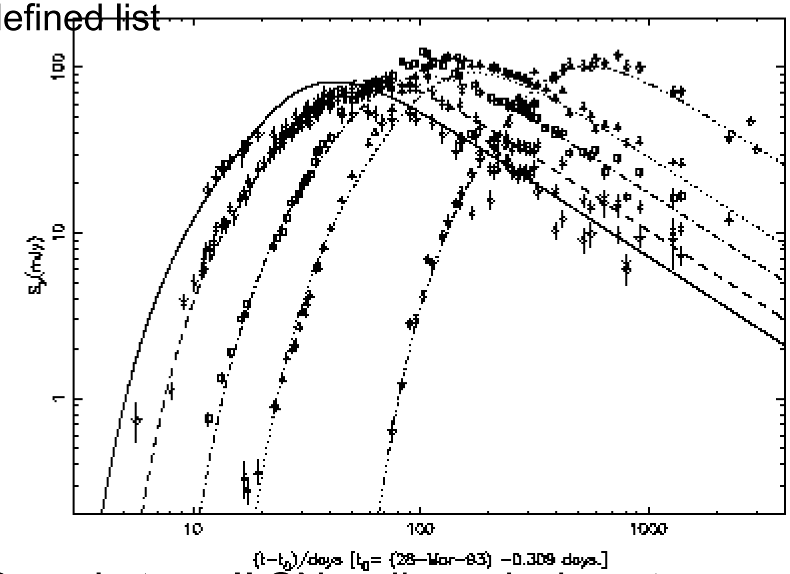
- **For southern hemisphere sources, SkyMapper's 1.3-meter aperture allows fairly deep imaging**
  - Also could get access to 2.3-meter telescope at Siding Spring if necessary
- **Want to line up at least one larger-aperture ground-based telescope in the northern hemisphere**
  - Needs to support TOO / rapid-response observing
  - Highly desirable: fast camera, automated image processing
- **Astronomer Vik Dhillon (Sheffield) can help with this**
- **Near term: Liverpool Telescope**
  - Proposal due in late March
- **Longer term: New Technology Telescope with UltraCam**

Radio Frequency Follow-ups with VLA

Radio frequency afterglows from supernovae/GRBs occur in timespans of days to years, depending on frequency and properties of system.
Usually detected in radio bands at frequencies of 1 GHz and above.

NRAO indicates ToO response time on the order of days.

Effective beamwidth of VLA is ~32 arcminutes at 1.4 GHz, varies inversely with freq.
- For high SNR GW signal, could map out ~1 degree diameter circle using 5 sightings
- For any signals, would point at likely radio sources in error circle based on previously defined list



Sample type II SN radio emission at Various frequencies (astro-ph0703411v1)

The Very Large Array

http://www.vla.nrao.edu/

Actions needed

What We Need to Do This Science

- Precise documentation (ideally peer-reviewed publication) of methods, performance and possible outcomes
- MOUs with a number of groups
- TOO proposals authorized by the collaborations
- Data from our GW detectors !
- For LoocUp / TOO, need online analysis with position reconstruction
- Infrastructure for communicating with telescopes

What We Intend to Ask For in Amsterdam

- **Approval from the LSC and Virgo to negotiate MOUs:**
  - With IceCube and ANTARES — for joint ExtTrig analysis using their high-energy neutrino triggers
  - With ROTSE, TAROT and SkyMapper — for rapid follow-up observations of the sky locations of our GW triggers (for SkyMapper, also info about interesting optical transients)
  - With Vik Dhillon, to collaborate on getting TOO telescope time on suitable large ground-based telescopes
- **Approval to prepare and submit TOO proposals:**
  - Swift
  - Liverpool Telescope

(We'll come back to the rest of the items in our plan at a later time)

Possible Approval Sequence

- Presentation and discussion in Tuesday plenary session in Amsterdam
- Vote by the LSC Council on Tuesday evening
- Vote by the EGO/Virgo Council
- We negotiate MOUs over the next 2-3 months
- MOUs are presented to the LSC and Virgo in December or January for final approval and signing