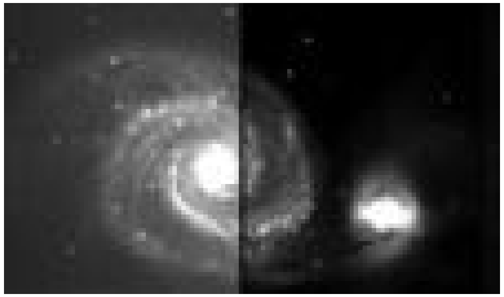
Locating and Observing Optical Counterparts to Unmodeled Pulses in Gravitational Waves



Targeted transient searches with GW data

Jonah Kanner University of Maryland

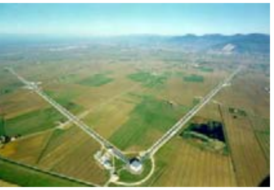
Who is LOOC UP?

- Columbia
  - Szabolcs Marka, Jennifer Piscionere
- UMD
  - Peter Shawhan, Jonah Kanner, Molly Reed
- Harvard-Smithsonian Center for Astrophysics
  - Tracy Huard
- Carnegie Institute of Washington
  - David Murphy
- http://geco.phys.columbia.edu/~jap2117/

Talk Outline

- Proposed Search Overview
- Motivation
- Pilot study
- Opportunity in S6/VSR2
- Challenges for S6/VSR2
- Conclusions

What is LOOC UP?



- 1) Analyze GW data in near real-time to find **low-threshold** “event candidates” (H-L-V)

- 2) Estimate the source location of “candidates”
  - Time of flight and/or “coherent” approach

- 3) Image the source location with an optical, radio, and/or x-ray telescope
  – A GW producing astrophysical event could produce an EM transient, thus **confirming the event** and **gaining extra astronomical information**

Search Skeleton

H1 Trigger Generator

L1 Trigger Generator

V1 Trigger Generator

Coincidence and Position

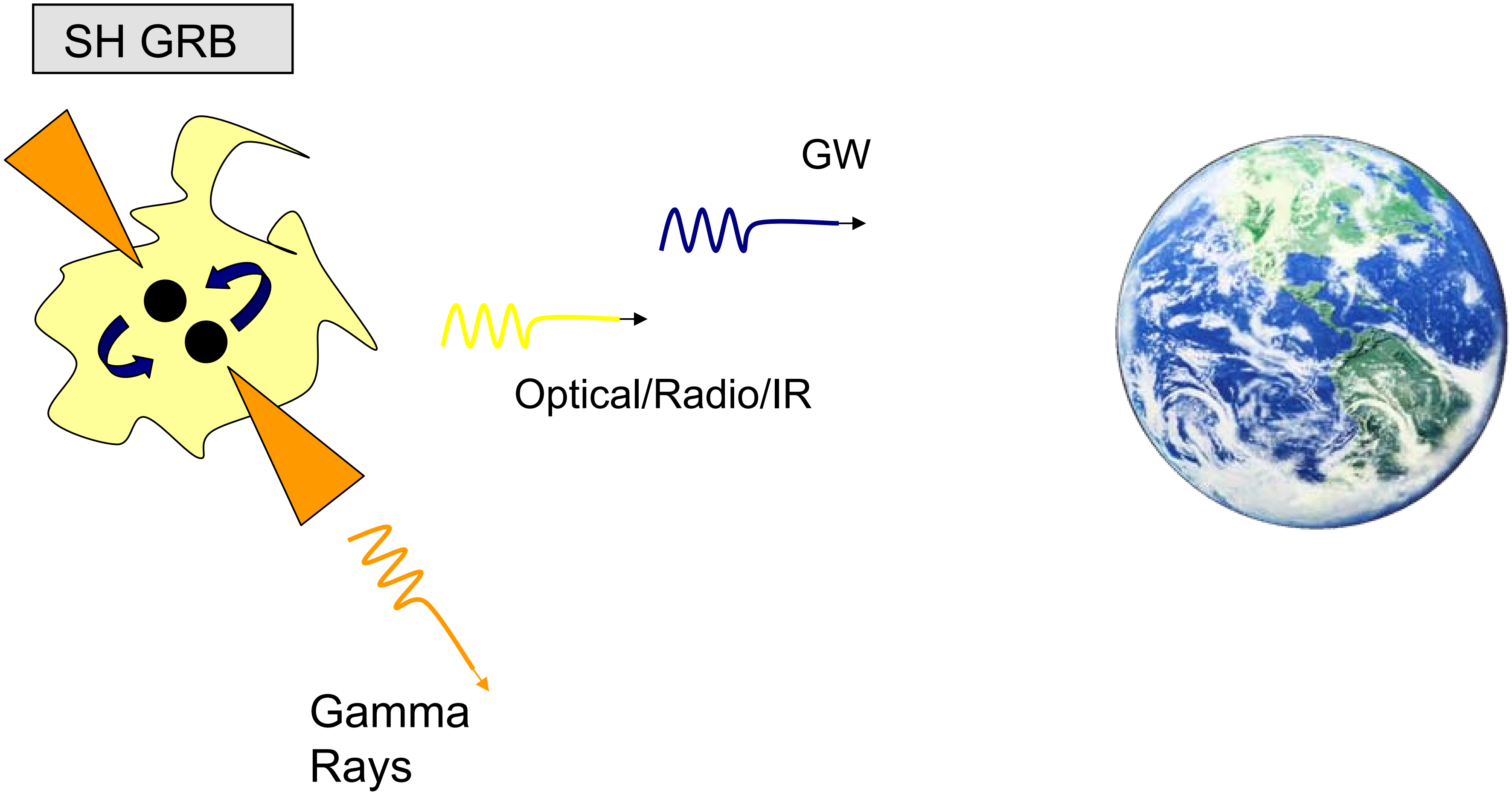
Take Optical Images

Image Processing

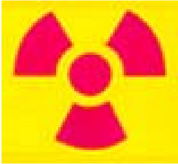
Motivation

- Increased GW sensitivity
  - Low-threshold search
- Even at high SNR, would like to confirm first GW detection in independent channel
- Rapid astronomical response to transients
    - “Natural” approach for EM-GW network
- Prepare for Advanced LIGO era
- Important step toward integrating GW astronomy into greater astronomical community
    - Education/Research opportunity at forefront of GW and EM astronomy

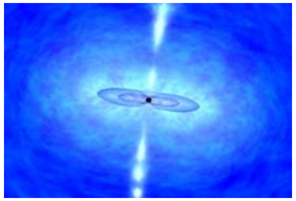
Orphan Afterglow Model



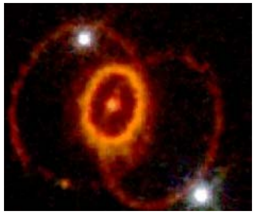
Sample Source Models



- Nuclear fireball of Li and Paczynski
  - Simplified theoretical model
  - NS matter ejected during merger decays
  - Tau ~ 1 day, R ~ 13 at 20 Mpc

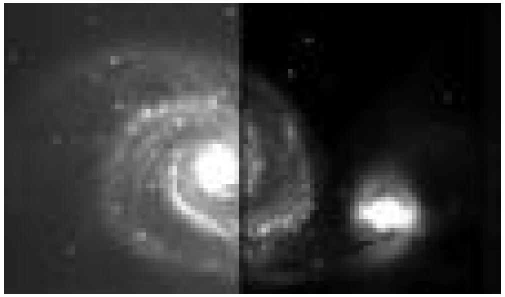


- Optical afterglow of short GRB's
  - Empirical
  - Beaming means we may not see gammas
  - Tau ~ 1 hour, bright at 20 Mpc



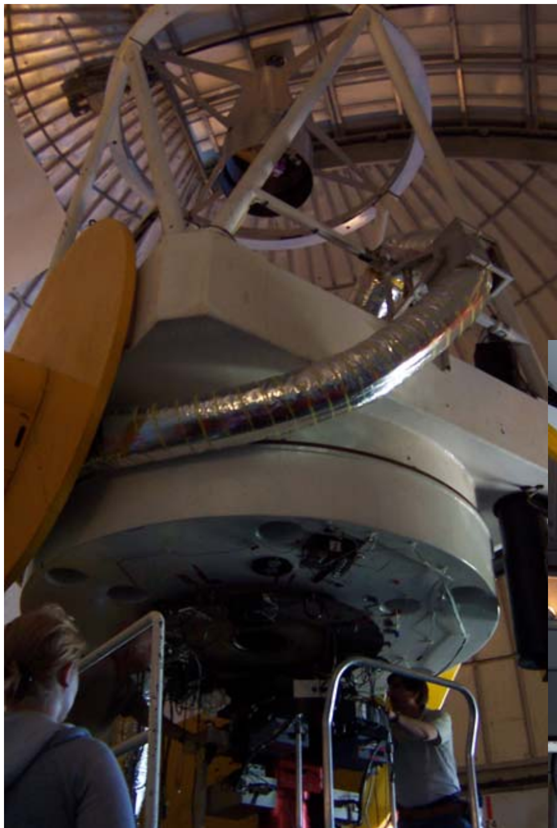
- Supernovas
  - Tau ~1 week, R~14 at 20 Mpc

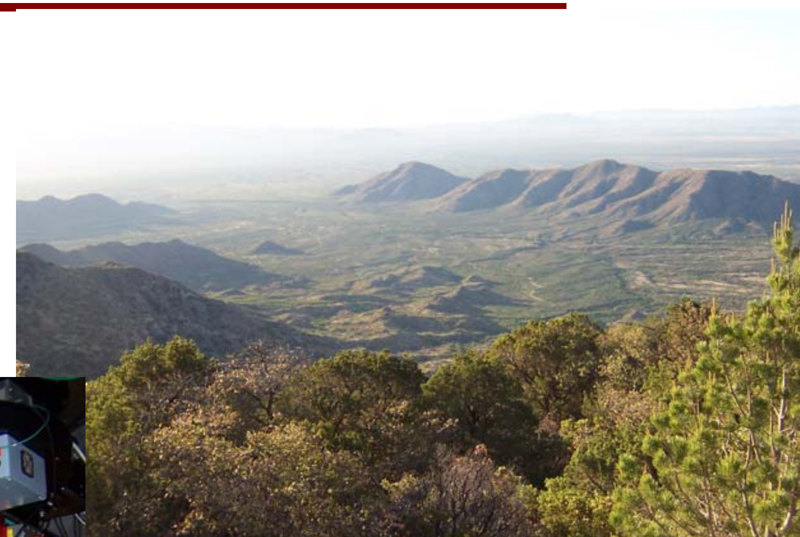
LOOC UP



Pilot Study

Pilot Study: Summer '07



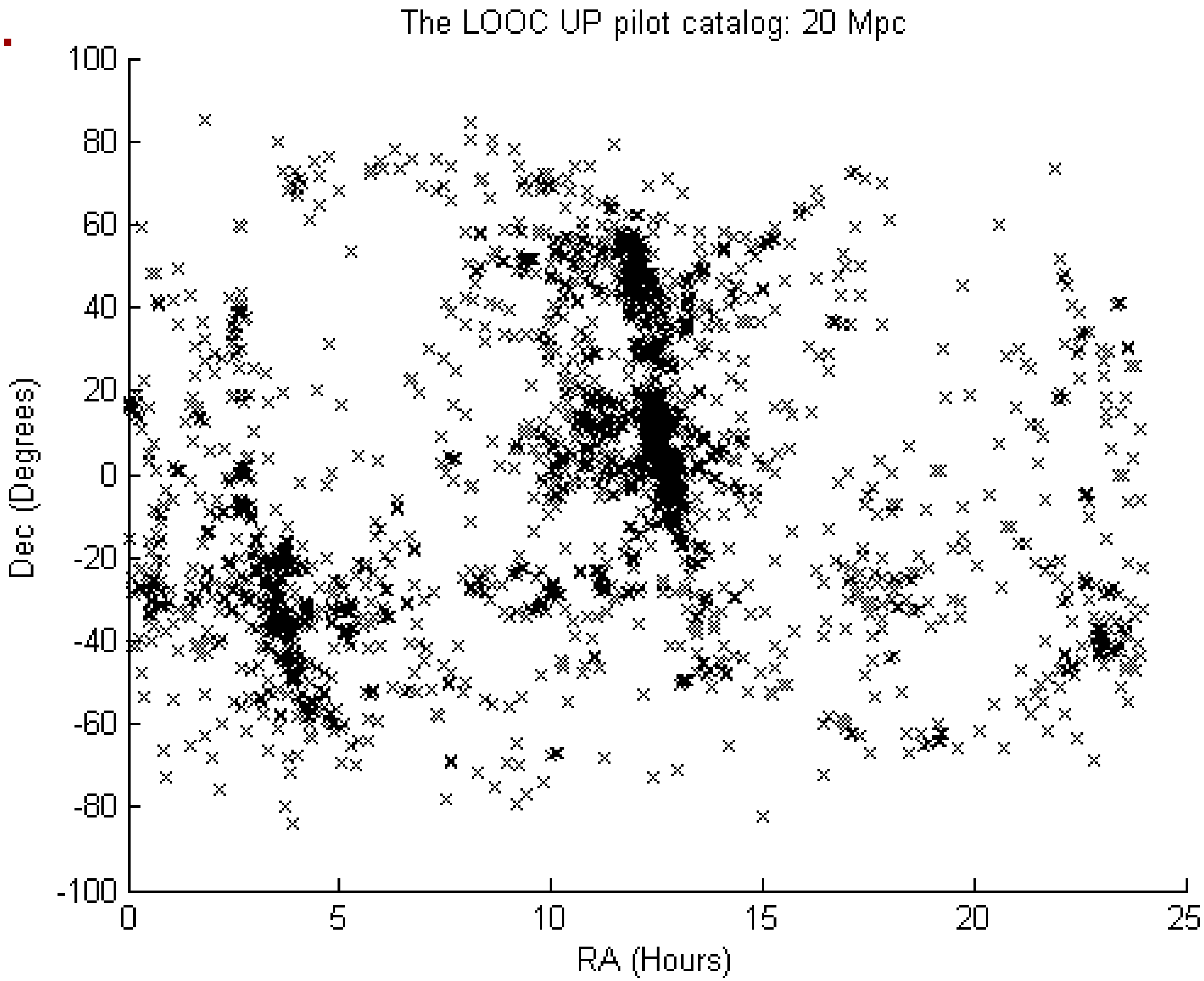


Pilot Study: Summer ‘07

- 3 Runs on 3 different telescopes:
  - MDM 2.4 m June 4-6
  - Swope Telescope July 22 – Aug 1
  - MDM 1.3 m Sept. 4-9
- Timing only source reconstruction
- H-L-V and H-L networks
- I and R-Harris filters

Pilot Study

LIGO S5 DNS Pos-avg. range ~15 Mpc



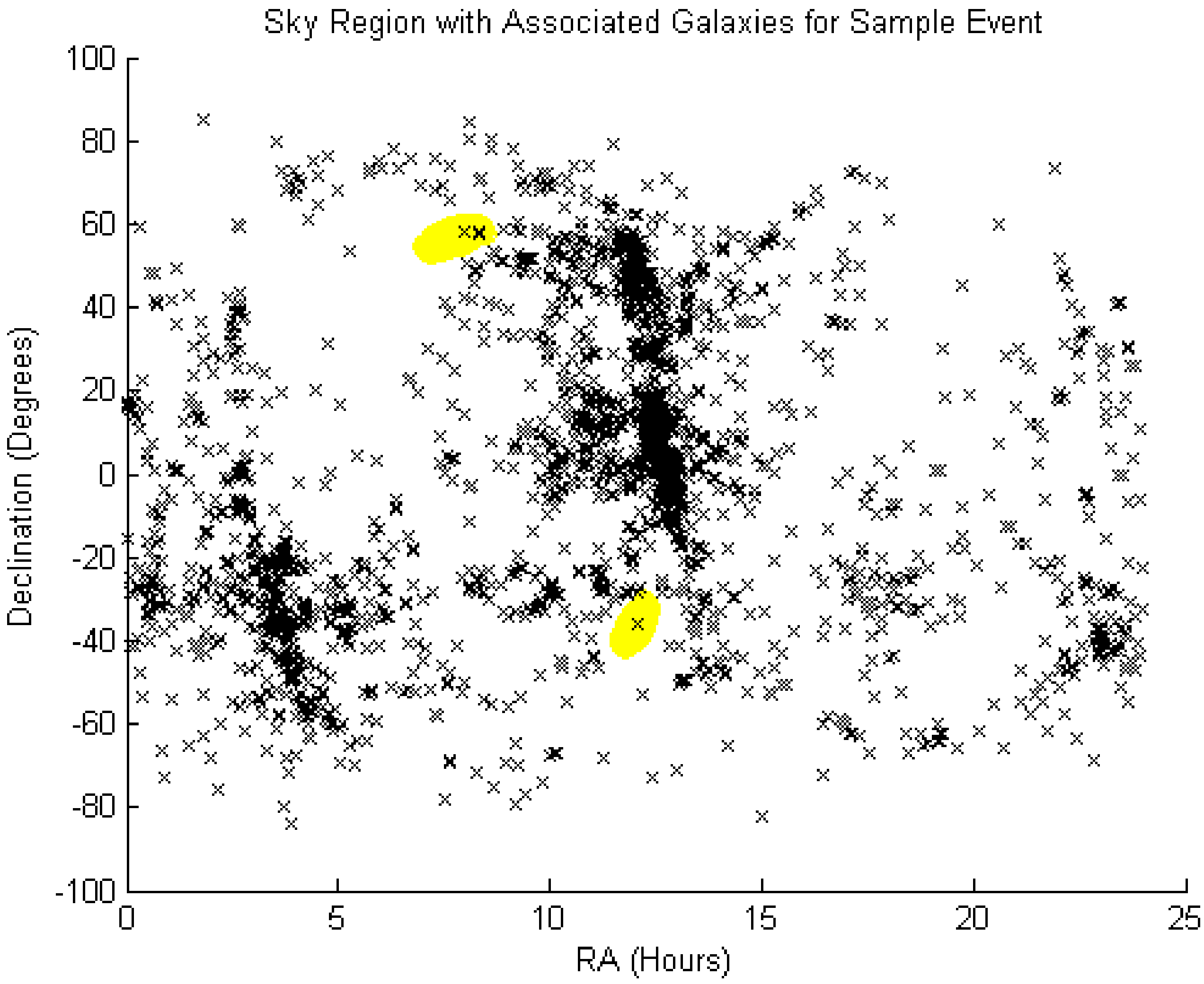
Catalog:

- Globular clusters & galaxies
- 20 Mpc cut-off
- Modified version of CBC catalog
- 2766 Objects

Pilot Study

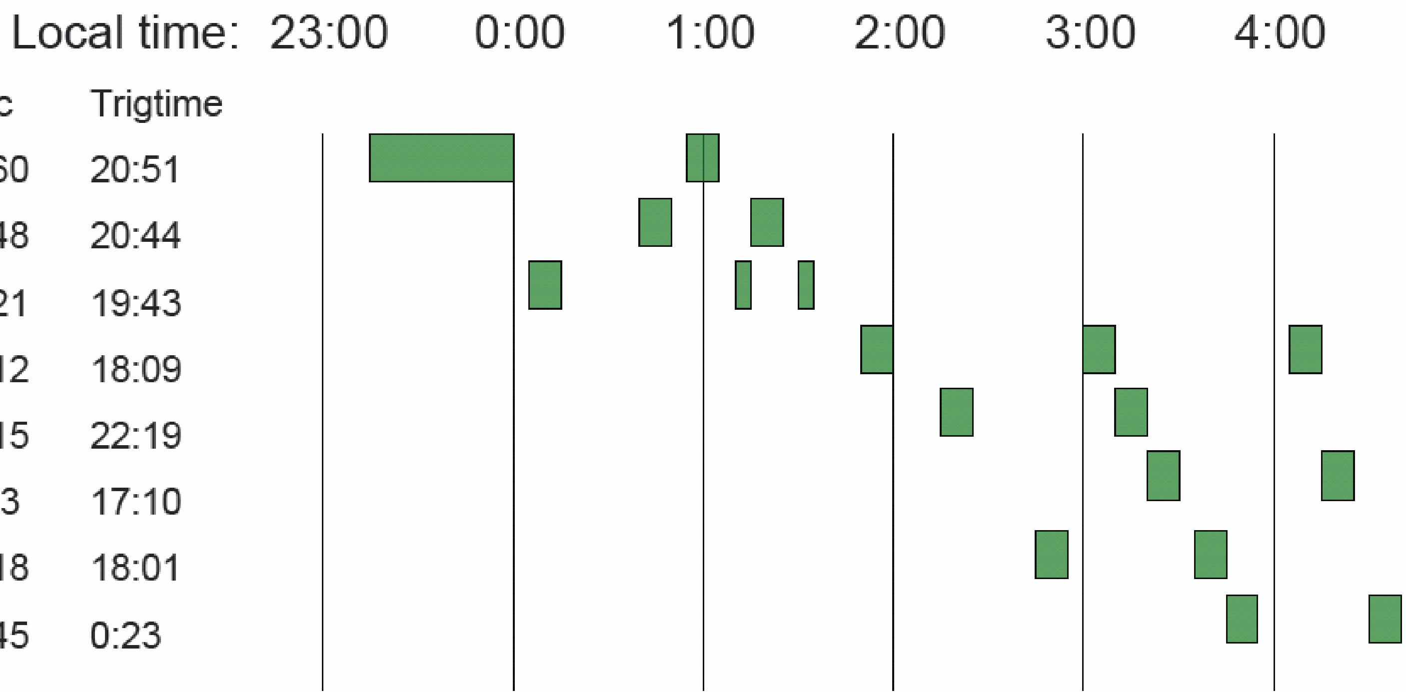
For each candidate event, we seek galaxies within the error box of the estimated source location.

These galaxies are then imaged for transients.



Sample Observing Schedule

Name	RA, Dec	Trigtime
NGC6946	20.6, +60	20:51
NGC6229	16.8, +48	20:44
NGC5904	15.3, +21	19:43
NGC7078	21.5, +12	18:09
PAL 14	16.2, +15	22:19
NGC6717	18.9, -23	17:10
NGC7177	22.0, +18	18:01
UGC11466	19.7, +45	0:23

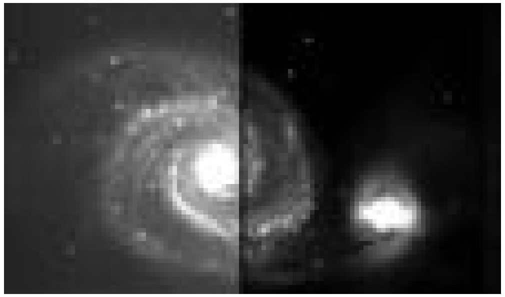


Each target is observed several times to trace time domain light curves of imaged objects.

Pilot Study Accomplishments

- Automated software to:
  - download trigger lists
  - estimate position
  - cross-reference with catalog
  - post observing targets to
- Observed 90 targets
- Lag times of 1 to several hours
- Demonstrated the feasibility of such a search

LOOC UP



Next Steps

Proposal: LOOC UP in S6/VSR2

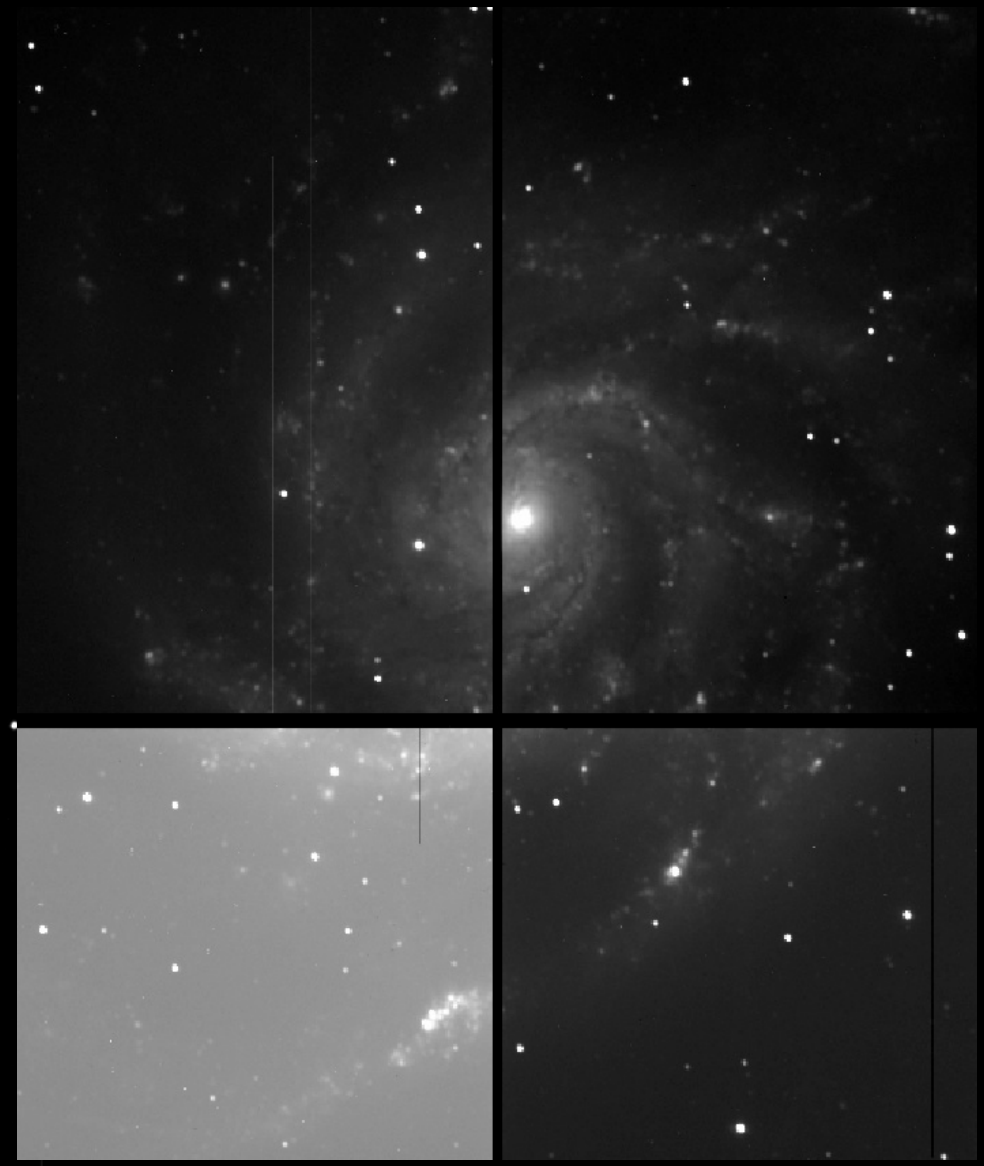
- During Enhanced LIGO/Virgo+ era
  - About 1 target galaxy per square degree
  - Could meet demands of source models imaging to modest depth (R ~ 15)
  - Basic technique has been demonstrated in pilot studies
  - *With a dedicated or semi-dedicated network of robotic telescopes, we could perform a GW search with FAR of a few per day instead of a few per year*
- The S6 run is an opportunity to develop real-time analysis
- Opportunity to perform a rapid response, targeted transient search for SHGRB afterglows, etc.
- LC/HR/HP – certainly good science

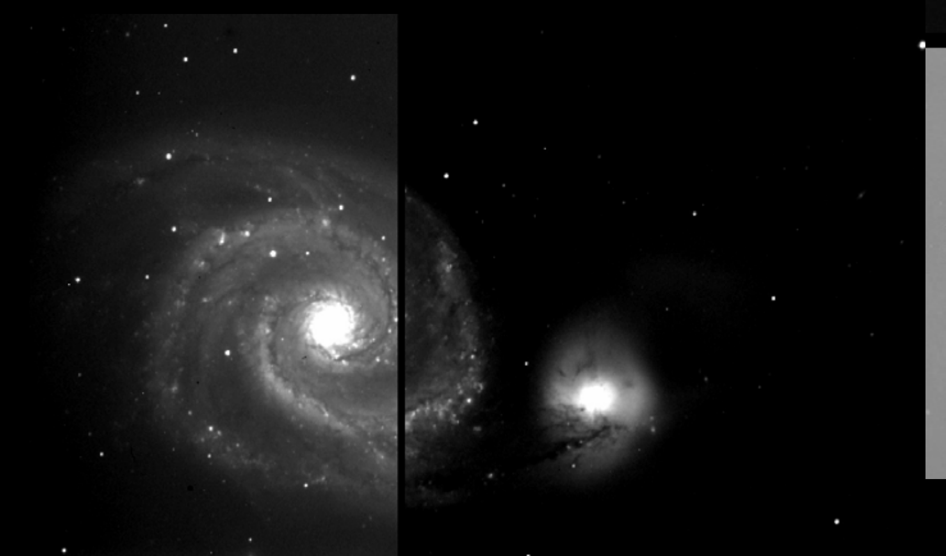
Open Issues: Observational Resources

- We need to identify the observational resources to use for this search.
  - Small robotic telescopes
  - ~2 m telescopes
  - Radio telescopes such as LOFAR
  - Public Alerts, such as VoEvent
  - ToO (Chandra, etc.)
- Survey style telescopes, such as ROTSE and RAPTOR may be ideal
  - Modest time commitment??
- Sociological worries exist…
  - Data privacy
  - Non-traditional requests for time

Open Issues: Image Processing

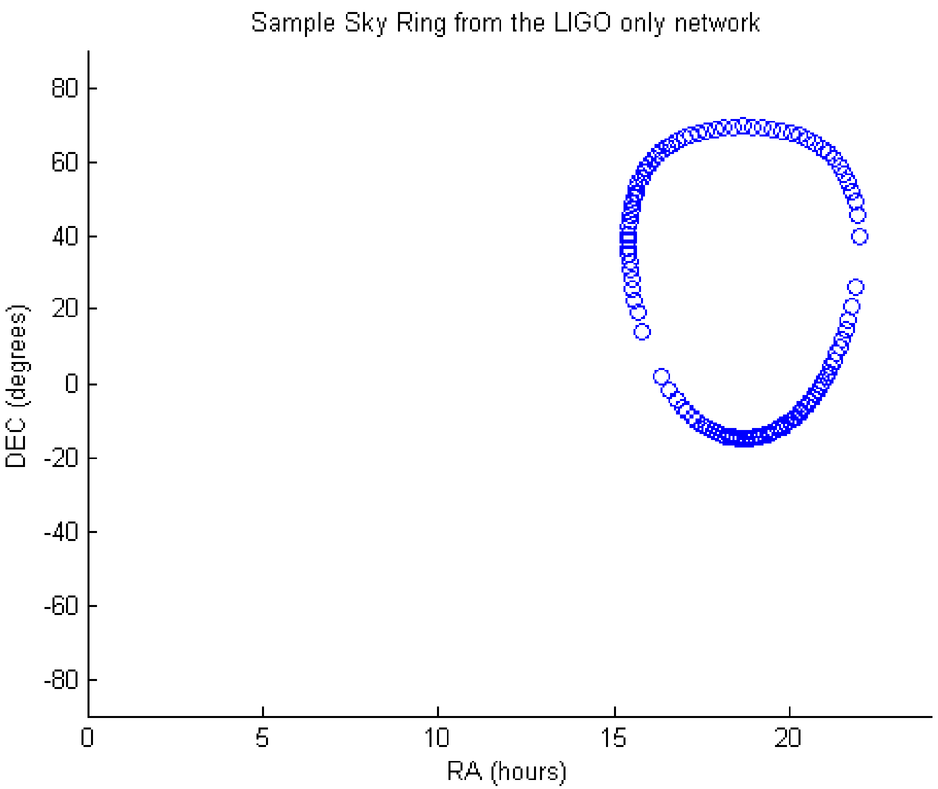
Need a data analysis pipeline, including image reduction, transient recognition, and categorization.





Open Issues: Source reconstruction

- Algorithm
  - Coherent or Incoherent??
  - Estimate the uncertainty
- Data transfer
- Need prompt vetoes and data quality

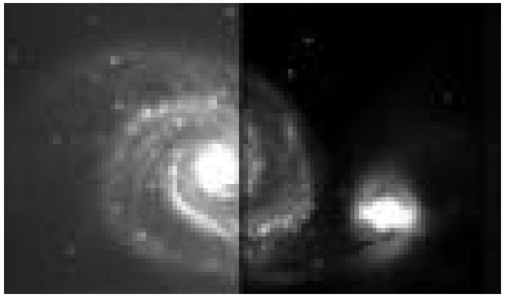


Concluding Remarks

- GW-first searches promise to eventually offer nearly all-sky coverage for exciting astrophysical events

- Performing low-threshold optical follow-ups during S6/VSR2:
  - Pushes the limits of interferometer sensitivity
  - Develops important Adv. LIGO technologies
  - Encourages EM/GW astronomy cooperation
  - Rapidly responds to potential EM transients

LOOC UP



Thank you!

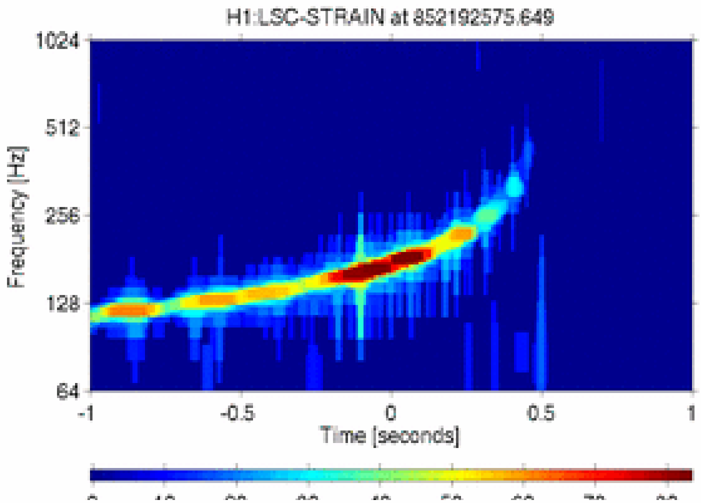
Extra Slides

Search Skeleton (cont.)

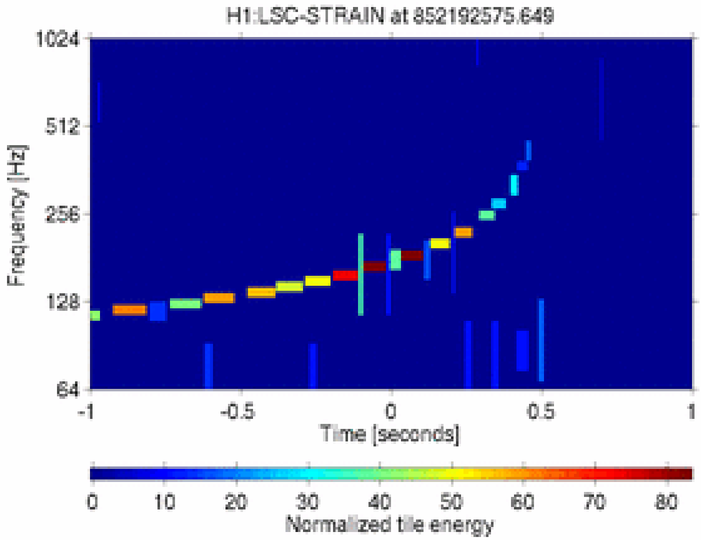
- First Image About 1 Hour after IFO event
  - Catch light curve on way up for considered models
- Follow-up images of same target hours/days later
  - Compare for reference – Look for objects with changing flux
  - Trace light curve as a function of time
- Sensitive “enough”
  - R ~ 15 for Enhanced LIGO era (~2009)
  - R ~ 20 for Advanced LIGO era (~2013)

http://ldas-jobs.ligo-la.caltech.edu/~qonline/L1/index.html?about.html

Trigger Generation



- IFOs produce sampled time series strain signal
- Data is conditioned and Fourier Transformed to produce time-frequency plane
- "Trigger" is a time-freq pixel with excess power



Reduction and Analysis Steps

Construct set of dark images for a night.

Construct the flats

Construct a bad pixel map

Dark-subtract, flat-field, bad-pixel mask, and sky-subtract images from each night

Refine the astrometry in the images

Extract the positions of sources detected in the image.

Compare the photometry of repeat observations of a source in order to identify sources that exhibit significant variability.

Slide Courtesy Jennifer Piscionere

"Phrase Book" for first time observers

If a physicist wants to say:	He should tell the astronomer:
Flux	Magnitude
Luminosity	Magnitude
Mass	Blue Light Luminosity
Distance	Redshift
Please, No Decaf!!!	What's decaf?
Let's turn off the computers, have a sandwich, and take a nap.	"Emergency Lightning Shutdown Procedure!!"
The picture's kinda fuzzy	"The seeing is 3.2"
Why are these pictures so dark?	"I think I forgot to open the dome again."

Current Issues: Arranging Telescope Time

- Oliver Twist Scenario: Request for Time
  - Used for S5 pilot studies
  - Great for trying things out, but may not be practical for an extended science run

Current Issues: Arranging Telescope Time

- The Bat Phone Scenario: Target of Opportunity
  - Accepted practice in astronomical community
  - Arrange in advance to call in a small number of observations when needed
  - Potentially get "low-cost" follow-ups with a high-performance instrument
  - Probably a sensible option for Adv. LIGO era

Current Issues: Arranging Telescope Time

- The Private Eye Scenario: Dedicated Instrument
  - Robotic telescopes, perhaps a network
  - In an S6 era scenario, checking down many events could lead to an earlier first detection
  - Modest technology requirements
  - Could perform other studies in “down time”

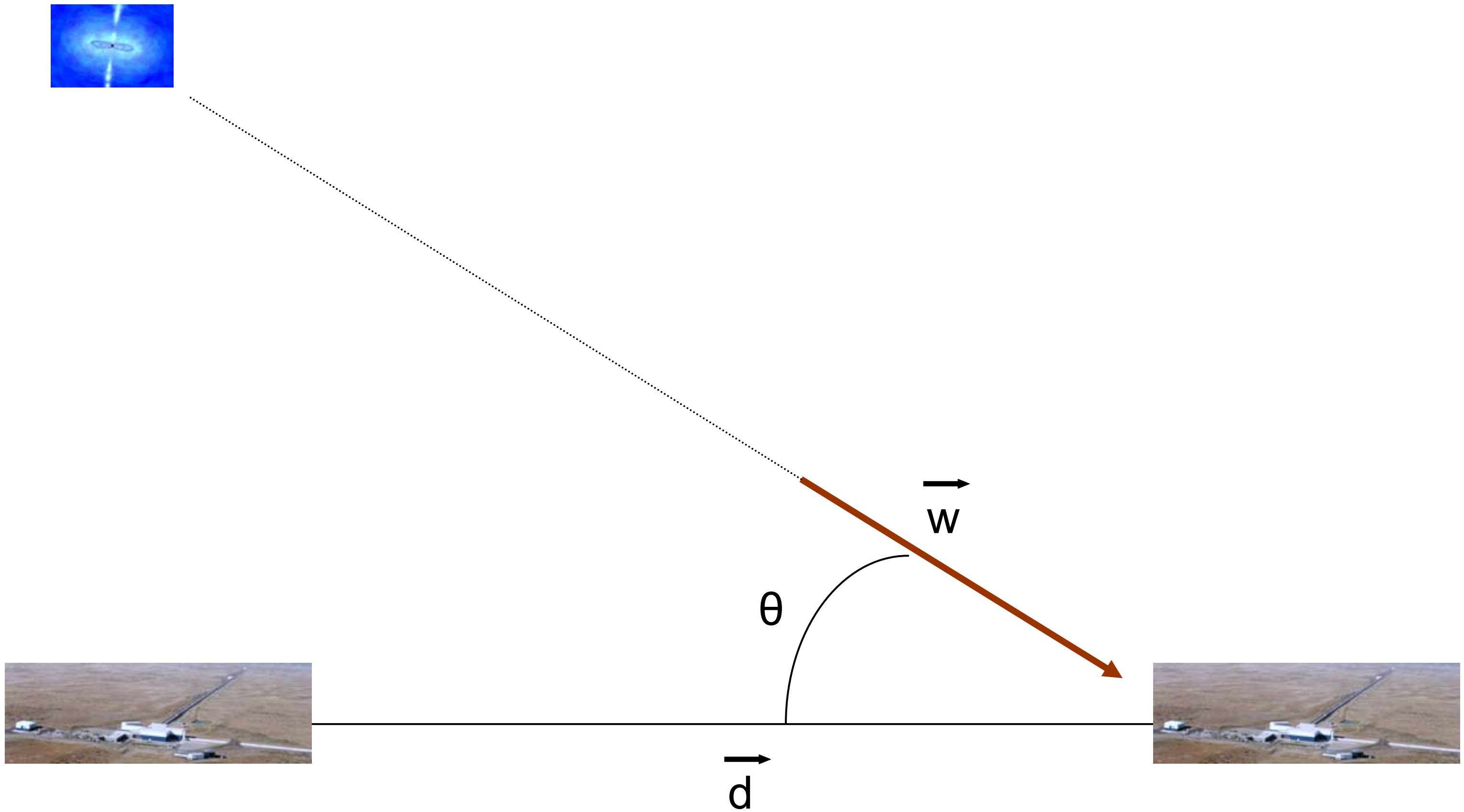
Current Issues: Arranging Telescope Time

- The Most Wanted Scenario: Public Notices
  - E-mail notices or internet postings available to general astronomical community
  - Many telescopes => full sky coverage
  - Low cost, may be willing to speculate
  - Forums for both amateurs and professionals
  - Sky and Telescope, SNEWS, etc.

“Incoherent” Method

Timing Only Solution

- Single IFO pair gives a ring on the sky
- 3 IFOs => 2 pairs => 2 sky rings which intersect at 2 points



$$\frac{\vec{w} \bullet \vec{d}}{|\vec{w}|\ |\vec{d}|} = \cos\theta \qquad |\vec{d}|\cos\theta = ct$$

The Galaxy Catalog

- For our pilot:
  - Modified CBC galaxy catalog
  - Added globular clusters
  - Cut on M/d
  - Cut at 20 Mpc
  - Favored galaxies with higher M/d
  - 2766 objects

- Generally:
  - Great method to beat limitations of source precision
  - May need refining for Adv LIGO ~50 gal / (deg^2)
  - Gal ranking? Refined positions? Wide field of view?

Position Reconstruction: Incoherent or Coherent?

Each trigger represented by ~1 number (peak time)	Each trigger represented by ~60,000 numbers (sampled time series)
Straightforward calculation	Uses “likelihood statistics”, reliable method TBD
Trigger peak times => central sky position	Tests each point in a grid of ~10^4 sky positions
Uses detector locations, ignores antenna patterns	Folds in antenna patterns

A "Likelihood statistic"

$$E_{\mathrm{null}}(\hat{\Omega}) = \sum_{k=0}^{N-1} \sum_{\alpha=1}^{D} \sum_{\beta=1}^{D} \tilde{d}^{*}_{\mathrm{w}\alpha}[k] Q_{\alpha\beta}[k, \hat{\Omega}] \tilde{d}_{\mathrm{w}\beta}[k] \quad (27)$$

Sum over frequencies

$$= \sum_{k=0}^{N-1} \begin{bmatrix} \tilde{d}^{*}_{\mathrm{w}1} & \cdots & \tilde{d}^{*}_{\mathrm{w}D} \end{bmatrix} \begin{bmatrix} Q_{11} & Q_{12} & \cdots & Q_{1D} \\ Q_{21} & Q_{22} & & Q_{2D} \\ \vdots & & & \vdots \\ Q_{D1} & Q_{D2} & \cdots & Q_{DD} \end{bmatrix} \begin{bmatrix} \tilde{d}_{\mathrm{w}1} \\ \tilde{d}_{\mathrm{w}2} \\ \vdots \\ \tilde{d}_{\mathrm{w}D} \end{bmatrix}.$$

Detector Data

Some Crazy Matrix
that is a function of:
*Sky Position
*Frequency
*Antenna Patterns

Detector Data

Coherent Method calculates various "likelihood statistics" from sampled detector data. The statistics are functions of sky position. Best estimate of source location is found by optimizing some statistic over a grid of trial sky positions.

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