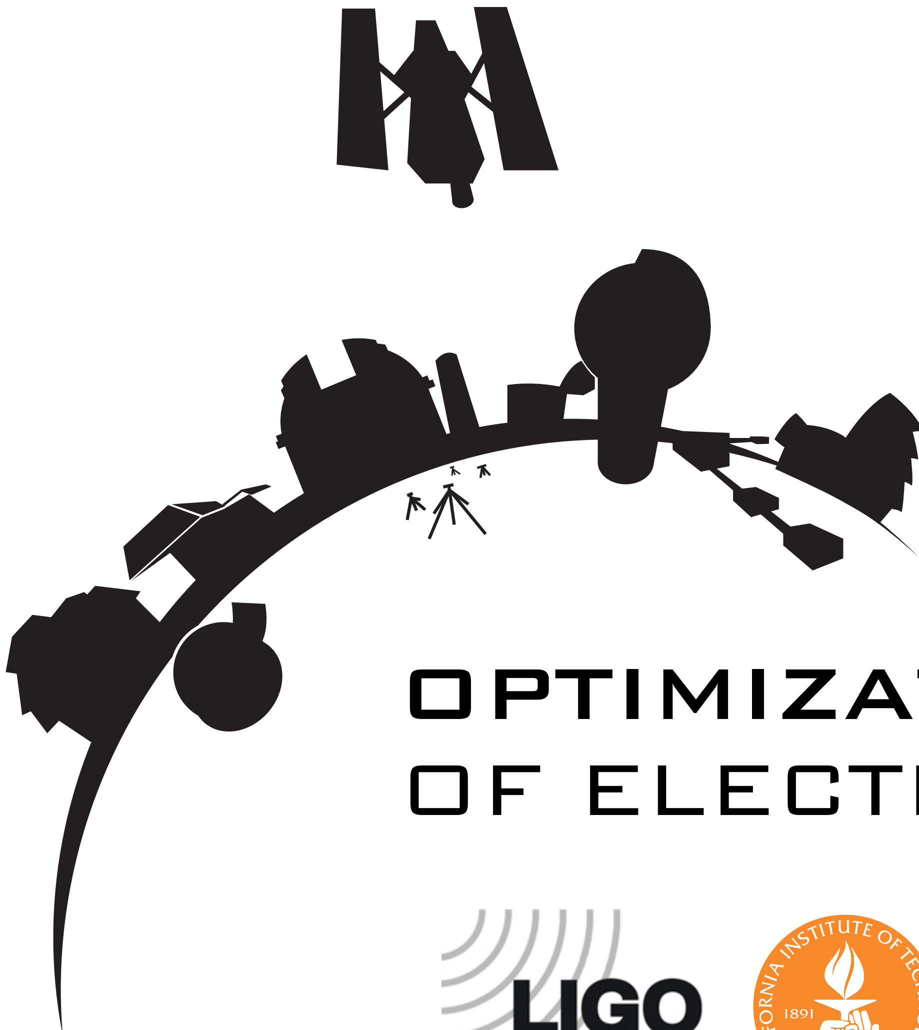
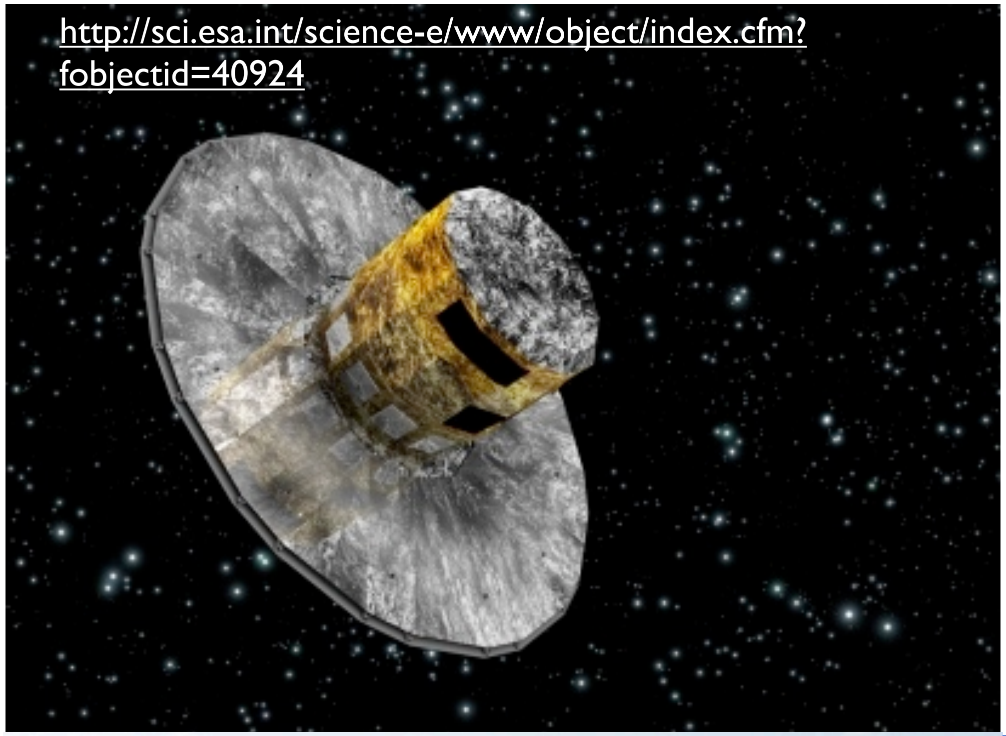


OPTIMIZATION & COORDINATION OF ELECTROMAGNETIC FOLLOWUP

Leo Singer & Larry Price
California Institute of Technology

Antony Speranza
Massachusetts Institute of Technology

Digging Faster and Deeper
13 December 2011
Caltech, Pasadena, CA



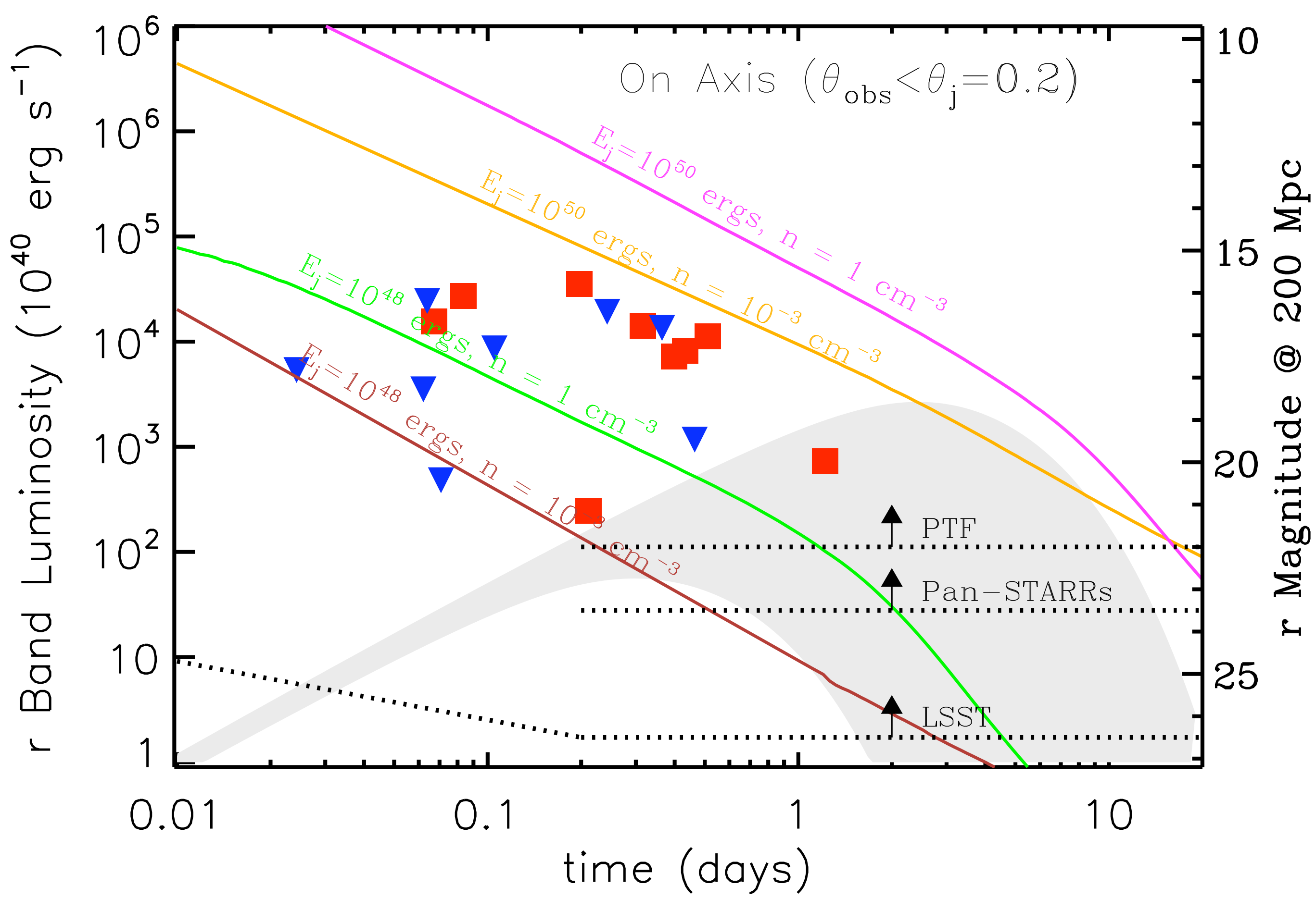
There is an growing need for ***coordinated*** optical followup of a deluge of transients in expanding field of ***time domain astronomy***.

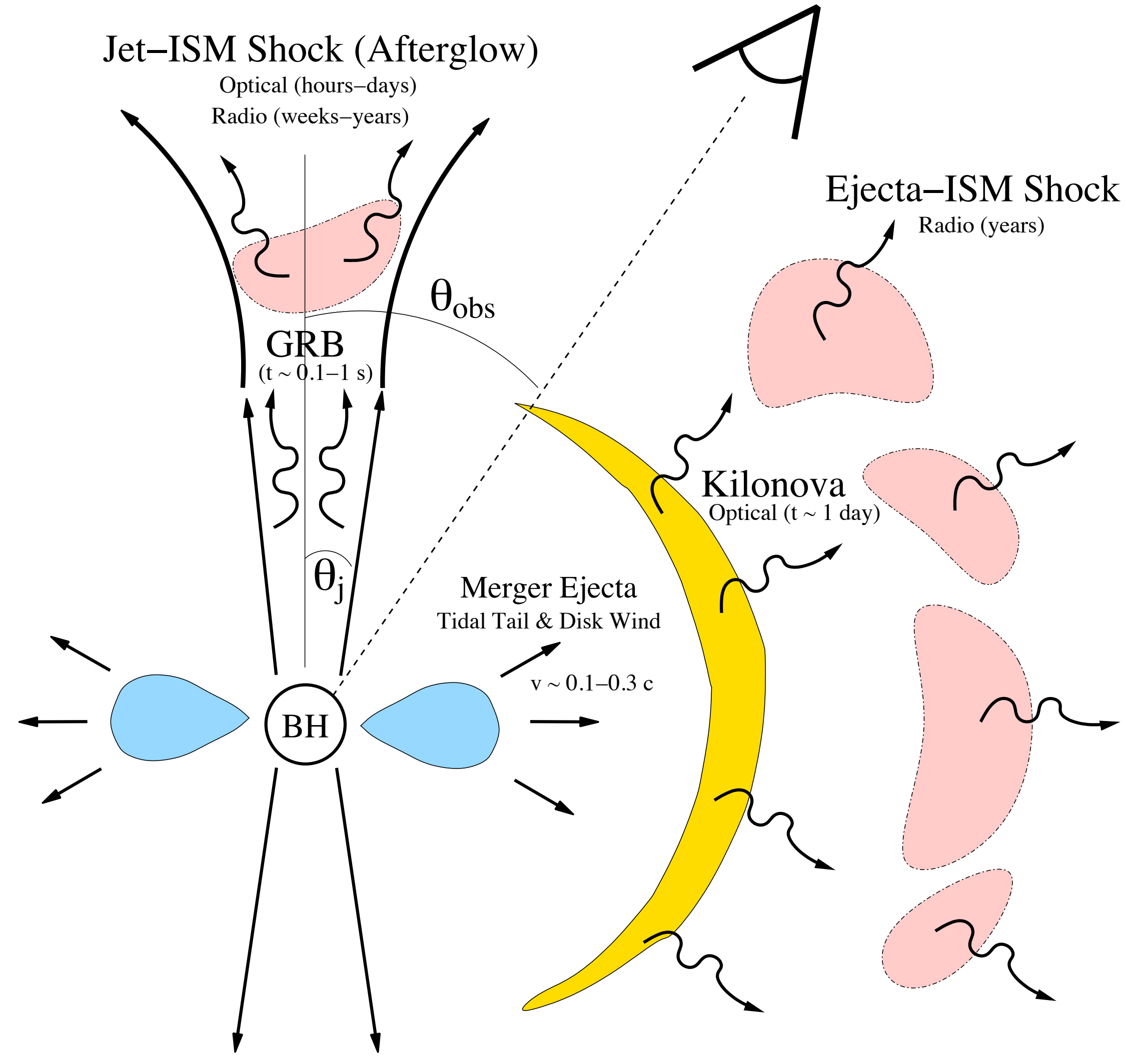

http://www.phys.ufl.edu/~bernard/IREU2008/images/largeimages/Virgo0.jpg

http://www.ligo.org/multimedia/gallery/llo-images/Aerial%201%20small.jpg

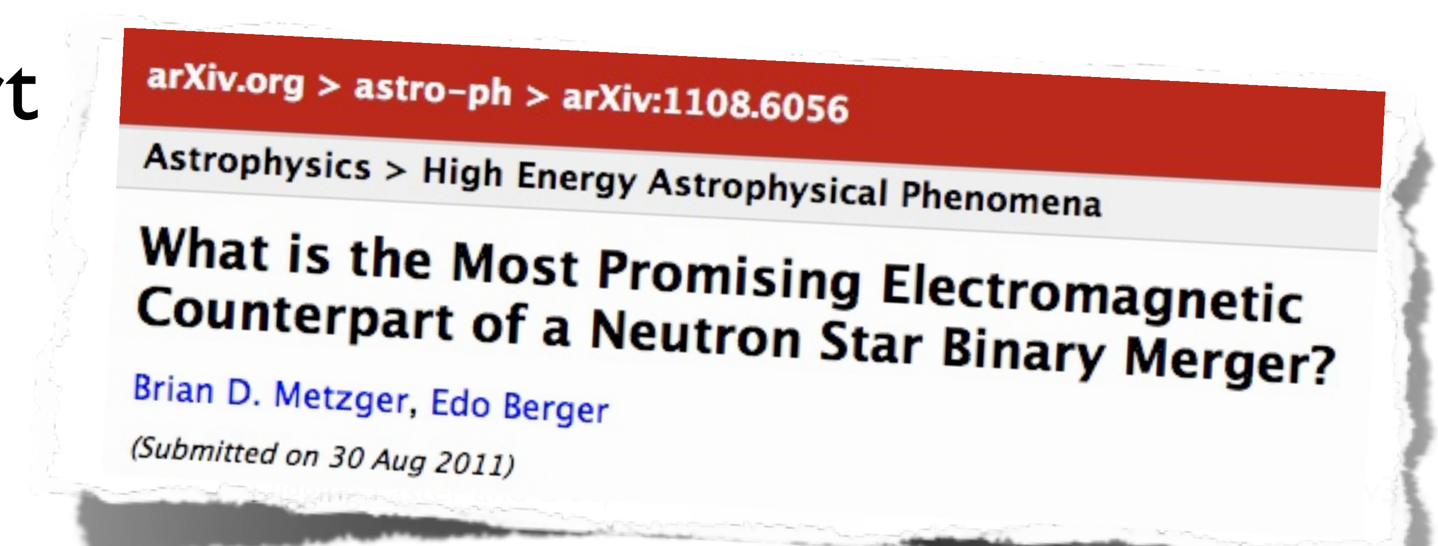
http://www18.i2u2.org/elab/ligo/home/project.jsp

Motivation: gravitational waves, GRBs, and compact binary coalescence





← Gravitational waves: start *before* γ ray burst


arXiv.org > astro-ph > arXiv:1108.6056

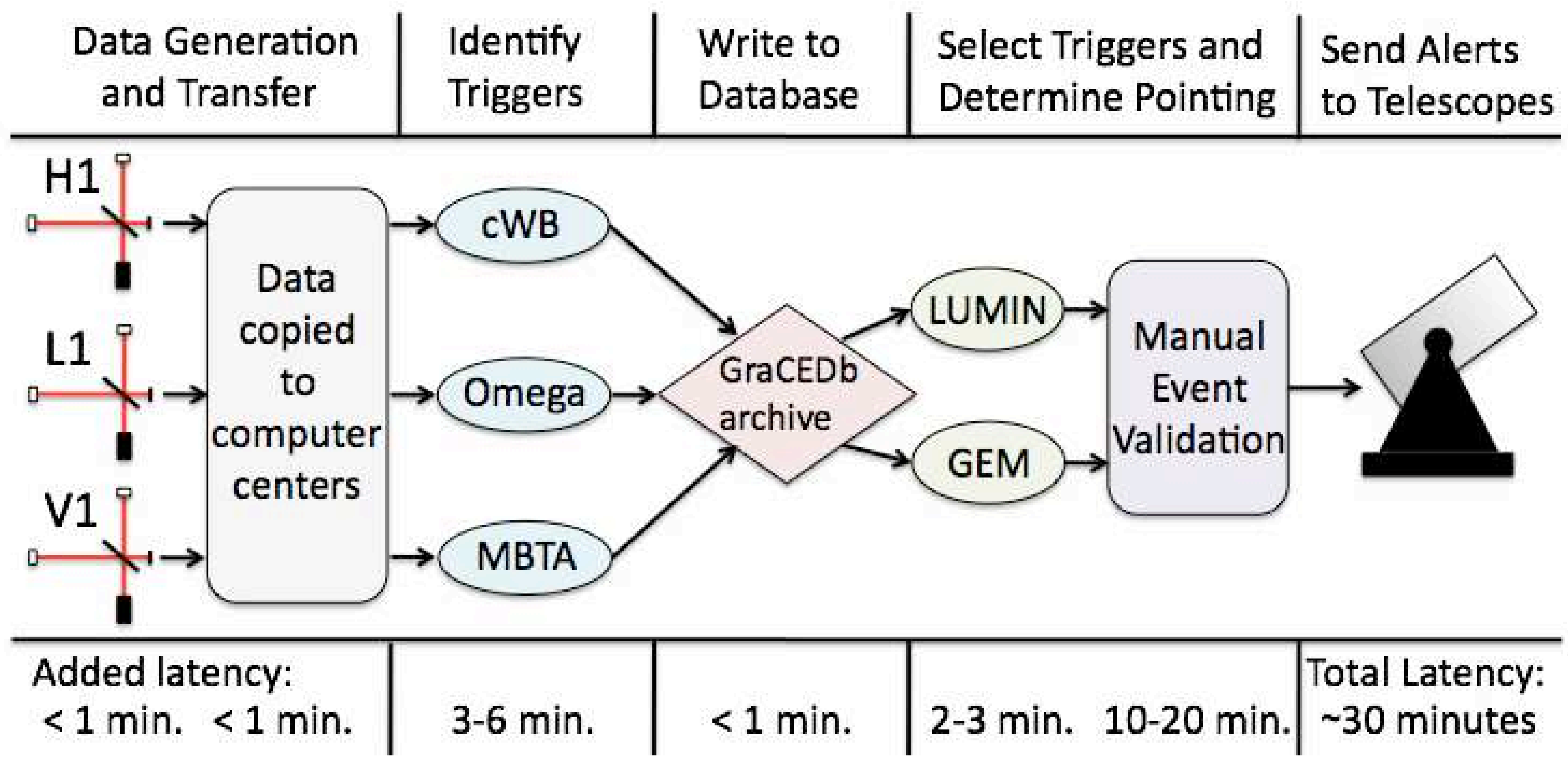
Astrophysics > High Energy Astrophysical Phenomena

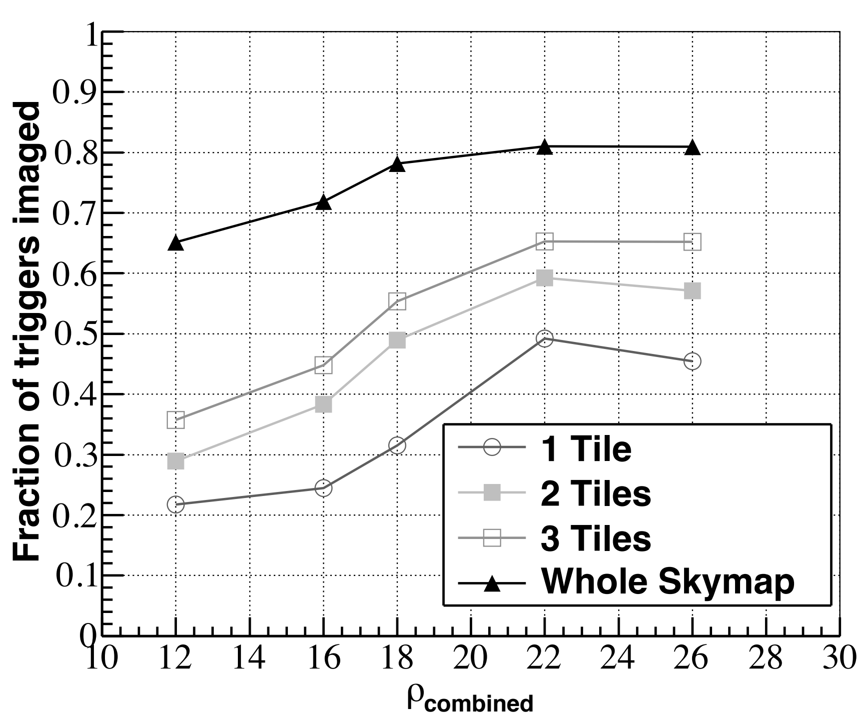
What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger?

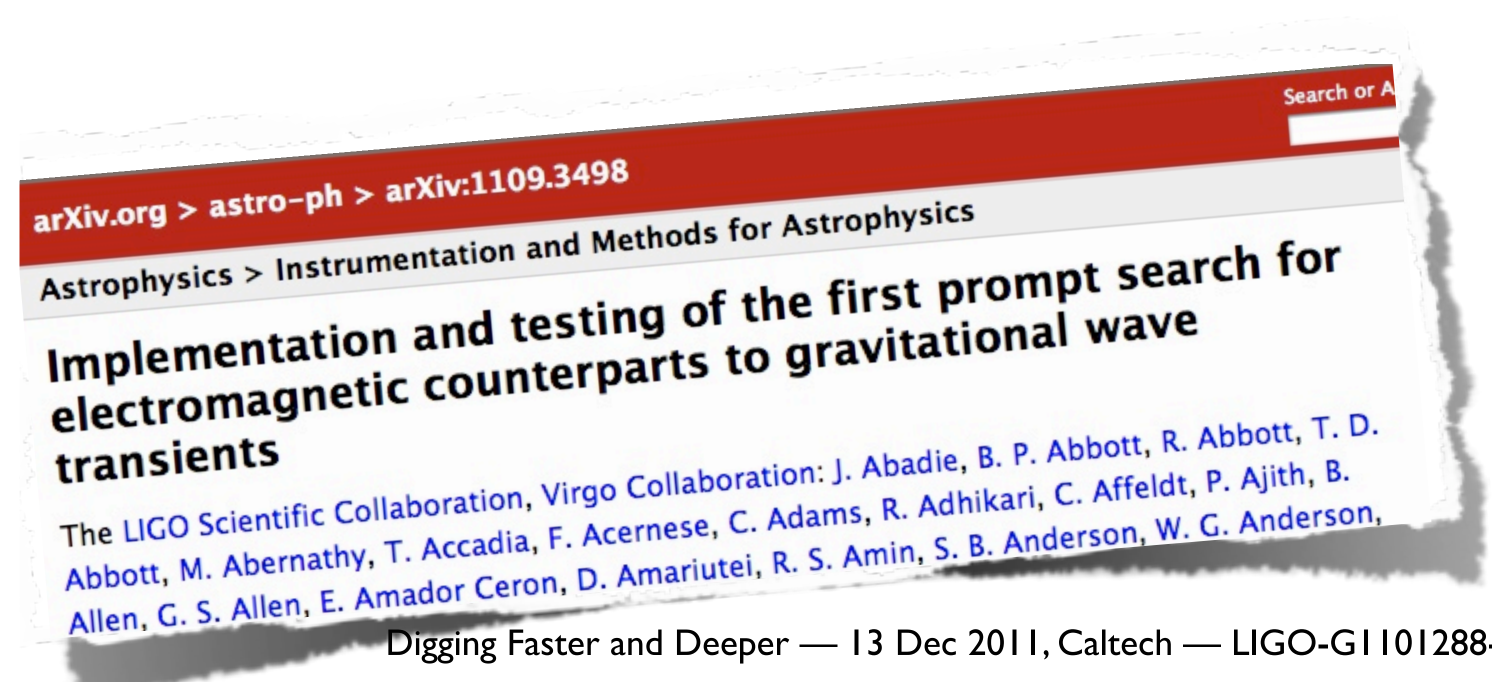
Brian D. Metzger, Edo Berger

(Submitted on 30 Aug 2011)

Multimessenger astronomy







arXiv.org > astro-ph > arXiv:1109.3498

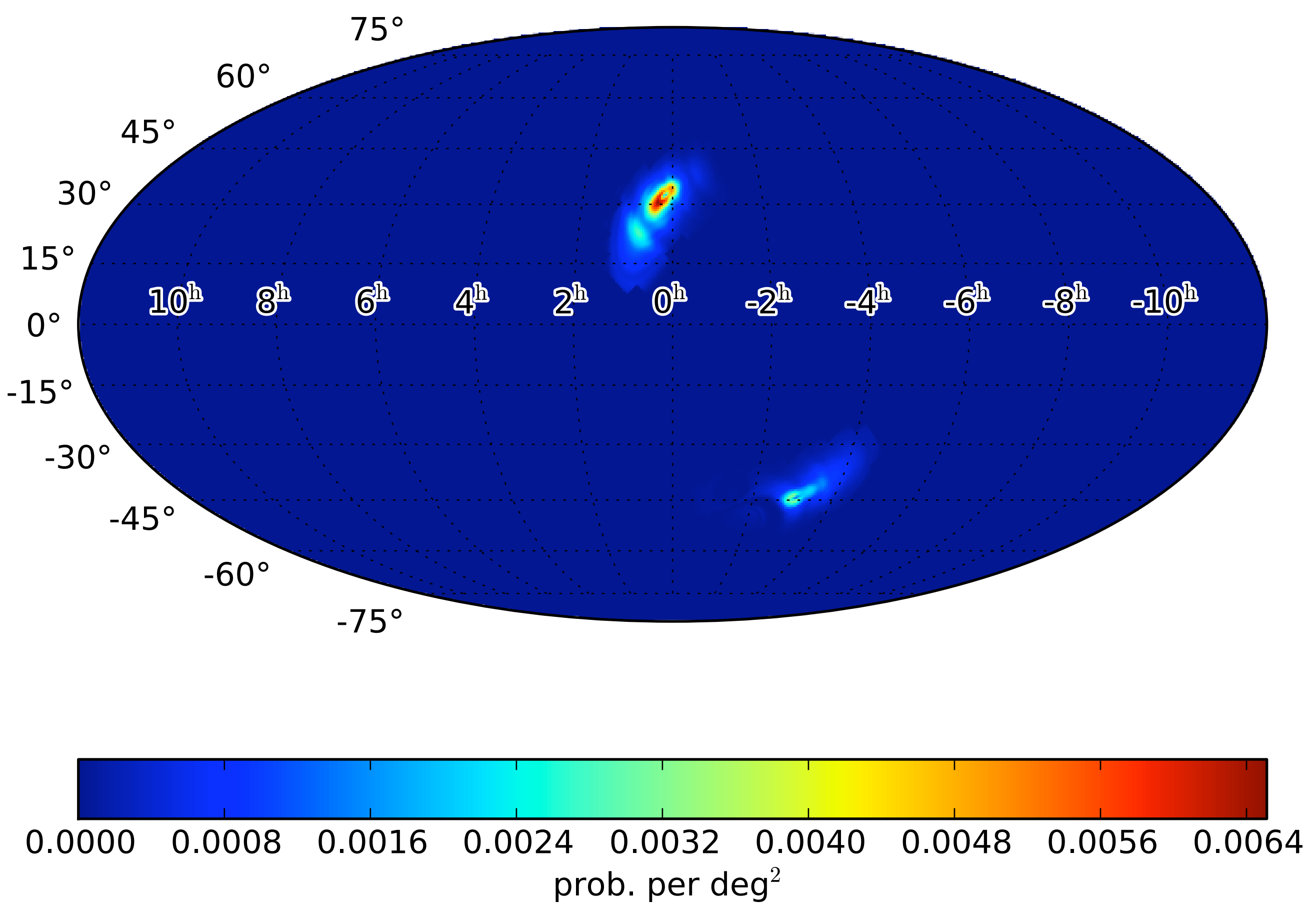
Search or A

Astrophysics > Instrumentation and Methods for Astrophysics

Implementation and testing of the first prompt search for electromagnetic counterparts to gravitational wave transients

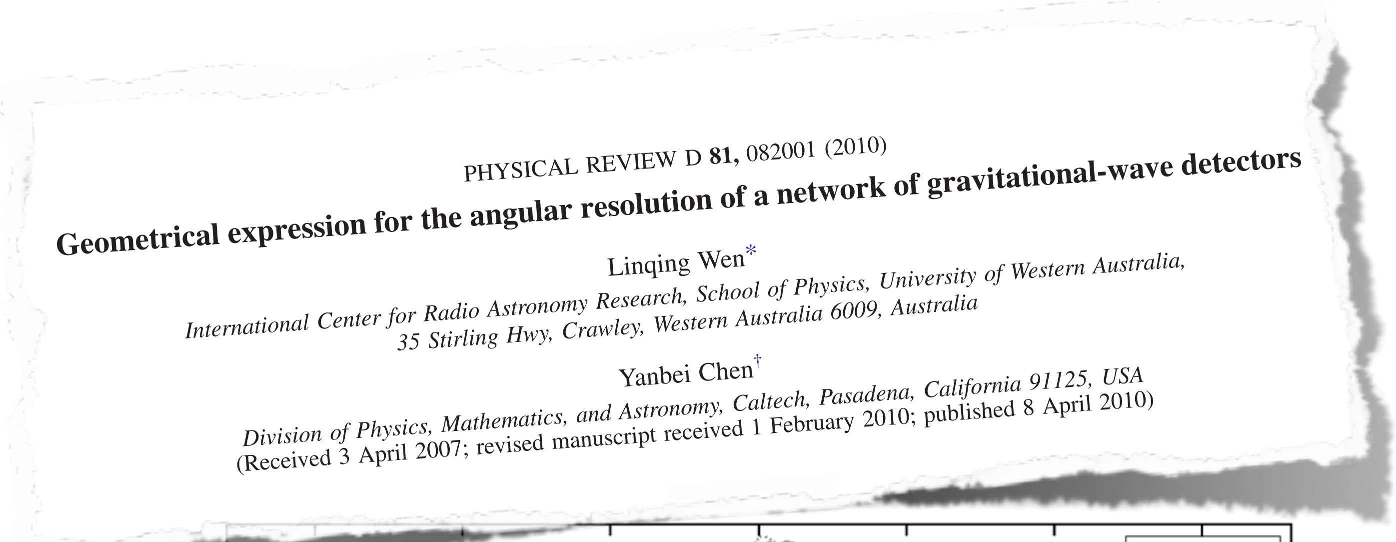
The LIGO Scientific Collaboration, Virgo Collaboration: J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams, R. Adhikari, C. Affeldt, P. Ajith, B. Allen, G. S. Allen, E. Amador Ceron, D. Amariutei, R. S. Amin, S. B. Anderson, W. G. Anderson,

GW skymaps



- multimodal
- dispersed over 4π
- spread over blobs or rings that are 10 — 100 deg^2 across

Triangulation from time delay on arrival with ≥2 detectors


PHYSICAL REVIEW D **81**, 082001 (2010)

Geometrical expression for the angular resolution of a network of gravitational-wave detectors

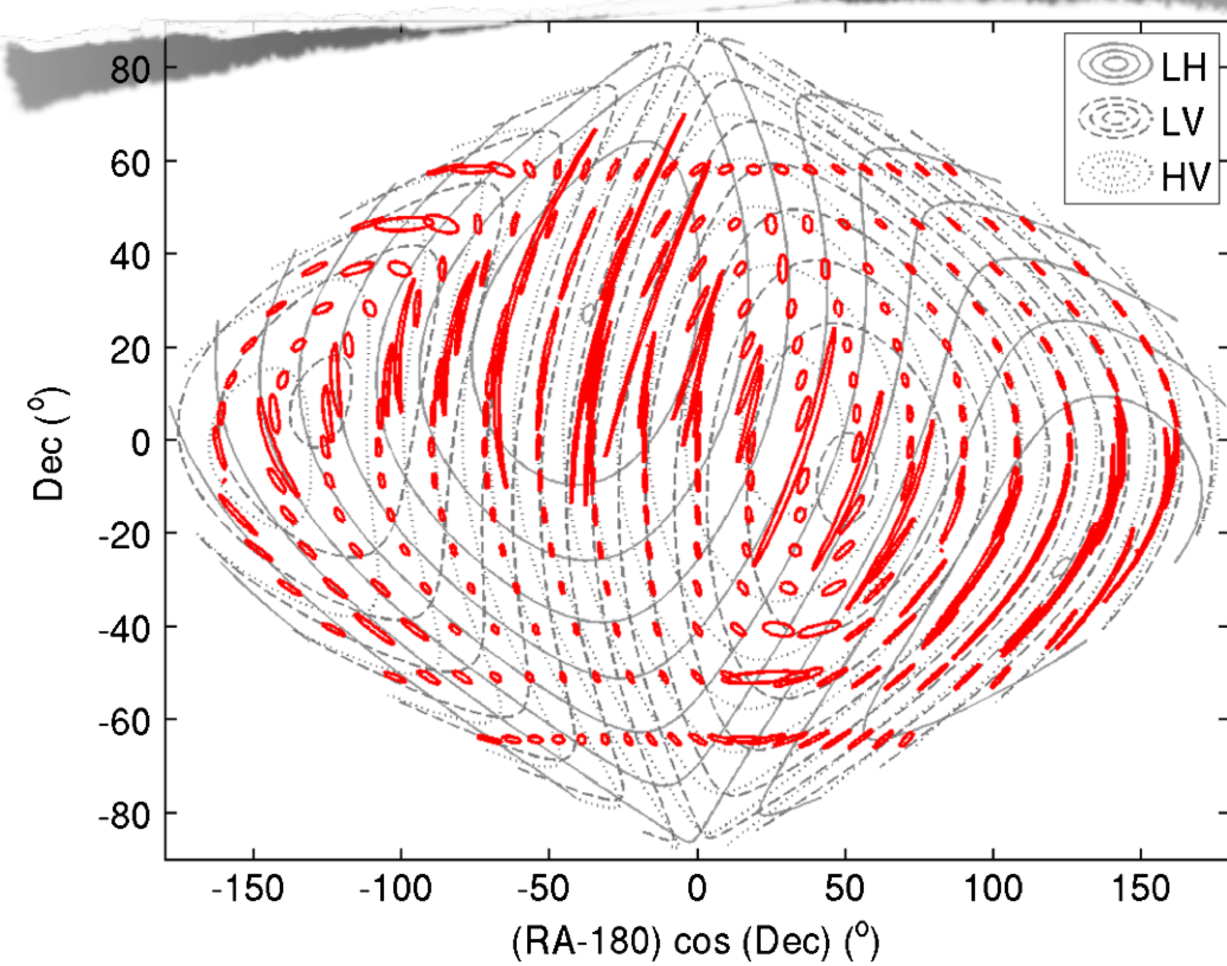
Linqing Wen*

International Center for Radio Astronomy Research, School of Physics, University of Western Australia, 35 Stirling Hwy, Crawley, Western Australia 6009, Australia

Yanbei Chen†

Division of Physics, Mathematics, and Astronomy, Caltech, Pasadena, California 91125, USA

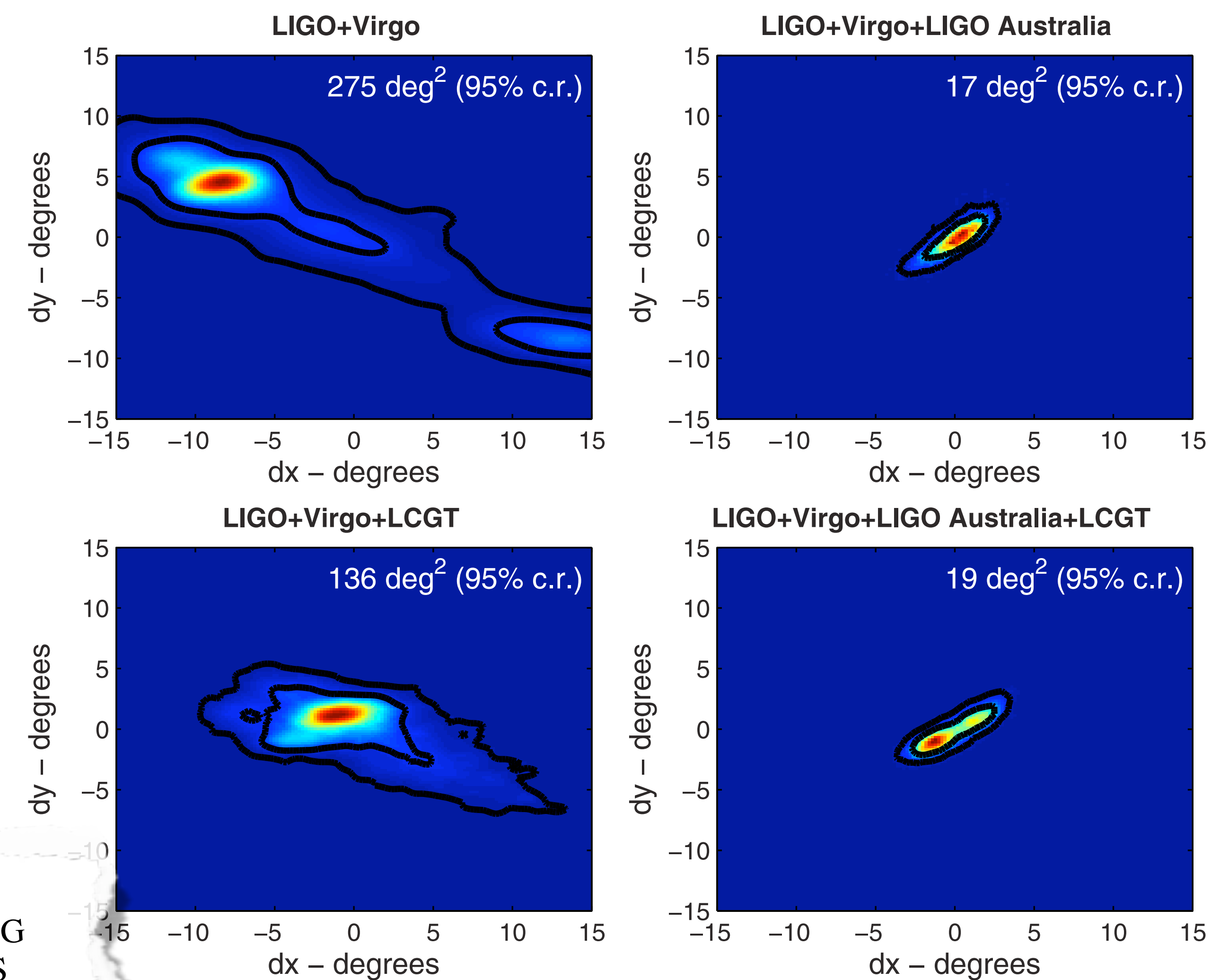
(Received 3 April 2007; revised manuscript received 1 February 2010; published 8 April 2010)

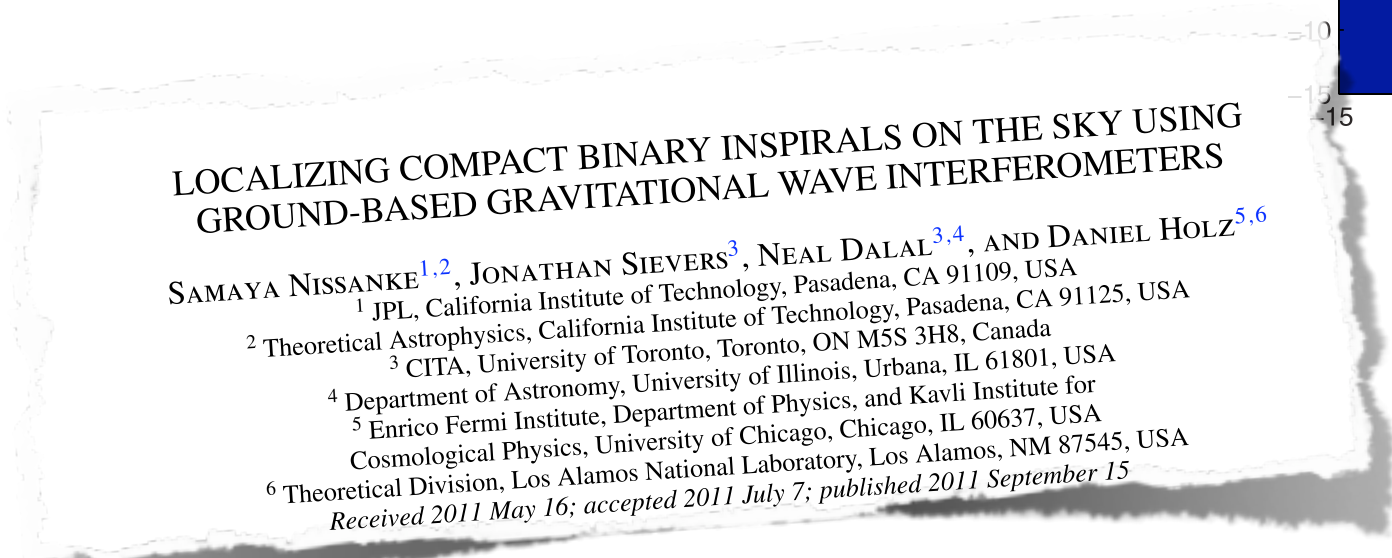


- 2 detectors: source location constrained to a ring on the sky
- With 3+ detectors, source location is constrained to two blobs in mirroring locations
- Accuracy highly dependent on elevation plane of detectors, antenna patterns

Area of 95% localization confidence: ≳10-100 deg²

- At high SNR, confidence level contours are ellipses
- At low SNR, confidence region is irregularly shaped, spans hundreds of deg²




LOCALIZING COMPACT BINARY INSPIRALS ON THE SKY USING GROUND-BASED GRAVITATIONAL WAVE INTERFEROMETERS

Samaya Nissanke[1,2], Jonathan Sievers[3], Neal Dalal[3,4], and Daniel Holz[5,6]

[1] JPL, California Institute of Technology, Pasadena, CA 91109, USA
[2] Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
[3] CITA, University of Toronto, Toronto, ON M5S 3H8, Canada
[4] Department of Astronomy, University of Illinois, Urbana, IL 61801, USA
[5] Enrico Fermi Institute, Department of Physics, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
[6] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Received 2011 May 16; accepted 2011 July 7; published 2011 September 15

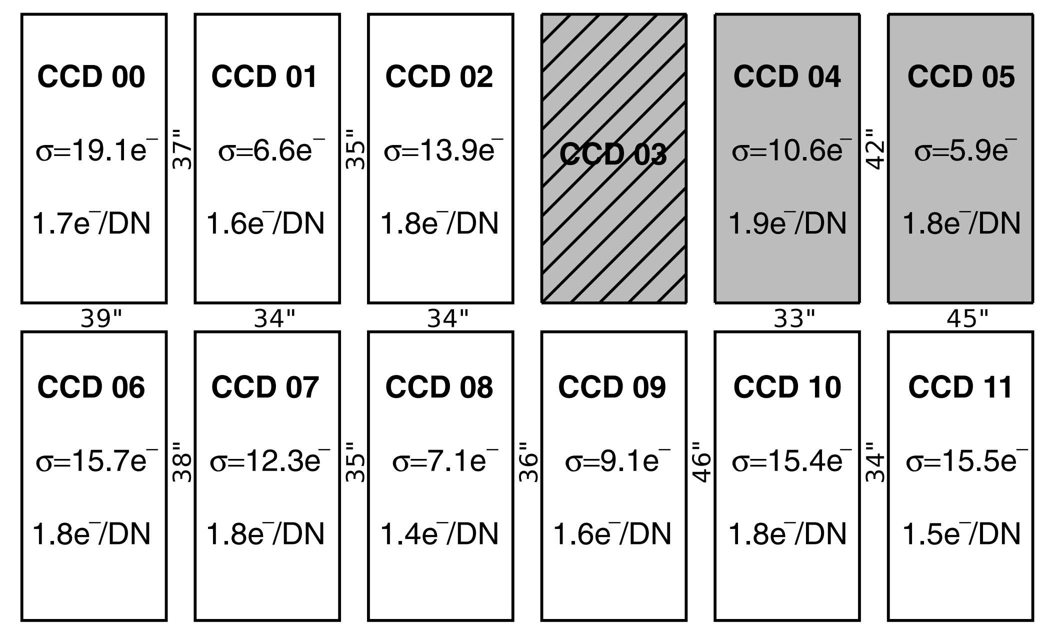
Telescopes: deep, or wide, but not* both

site	field of view	limiting magnitude	slew time (s)	geographic location
Liverpool[ab]	0.077°×0.077°	22 in 120 s	30	28°45′44.8″N, 17°52′45.2″W
Zadko[c]	1.4°×1.4°	21 in 180 s	20	31°21′24″S, 155°42′49″E
ROTSE III-a[d]	1.85°×1.85°	17.5 in 20 s	4	31°16′24.1″S, 149°3′40.3″E
ROTSE III-b[d]	1.85°×1.85°	17.5 in 20 s	4	23°16′18″S, 16°30′00″E
ROTSE III-c[d]	1.85°×1.85°	17.5 in 20 s	4	36°49′30″N, 30°20′0″E
ROTSE III-d[d]	1.85°×1.85°	17.5 in 20 s	4	30°40′17.7″N, 104°1′20.1″W
TAROT[e]	1.86°×1.86°	17 in 10 s	1.5	43.7522°N, 6.9238°E
TAROT-S[e]	1.86°×1.86°	17 in 10 s	1.5	29.2608°S, 70.7322°W
Skymapper[f]	2.373°×2.395°	21.6 in 110 s		31°16′24″S, 149°3′52″E
PTF[g]	3.5°×2.31°	20.6 in 60 s		33°21′21″N, 116°51′50″W
*LSST[h]	3.5°×3.5°	24.5 in 2×15 s		30°14′39″S, 70°44′57.8″W
QUEST[i]	3.6°×4.6°	20.0 in 60 s		33°21′21″N, 116°51′50″W
Pi of the Sky South[jk]	20°×20°	12.5 in 10 s	60	22°57′12″S, 68°10′48″W
Pi of the Sky North[jk]	40°×40°	12.5 in 10 s	40	37°6′14″N, 6°44′3″W

Telescopes: rich variety of instruments

Telescopes have:

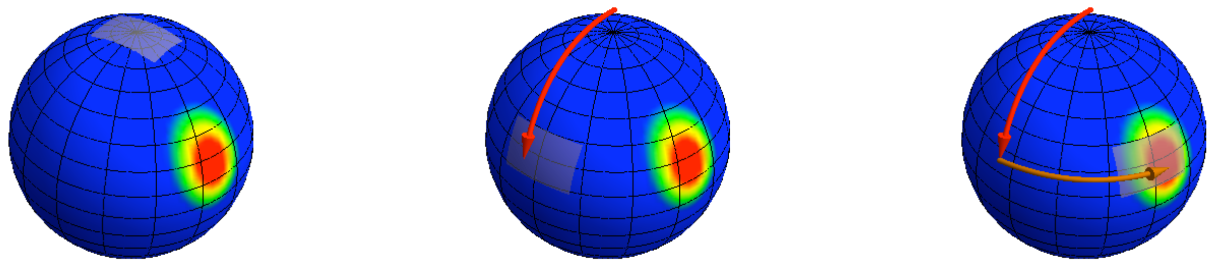
- different limiting magnitudes
- different slew times
- different filters
- gaps between CCDs
- dead CCDs
- vignetted or clipped image planes



from "The Palomar Transient Factory: system overview, performance, and first results," PASP 121:1395—1408, December 2009.

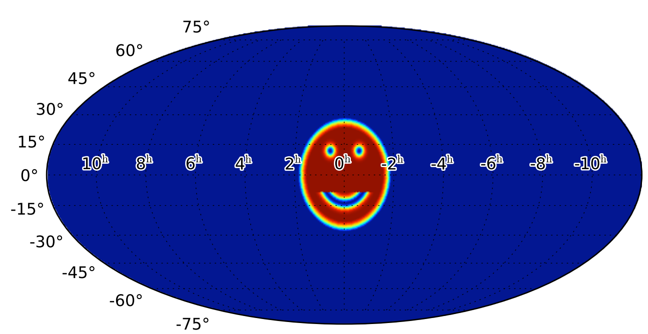
Single telescope problem

- Rotate FOV to γ_i, multiply by sky map, and integrate → probability of imaging source if telescope is pointed at γ_i



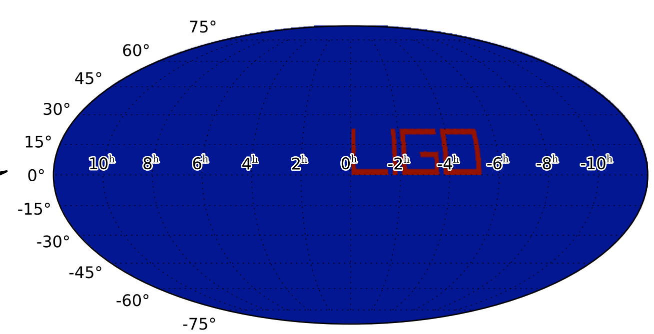
- Analogous to a convolution integral

Kernel/FOV



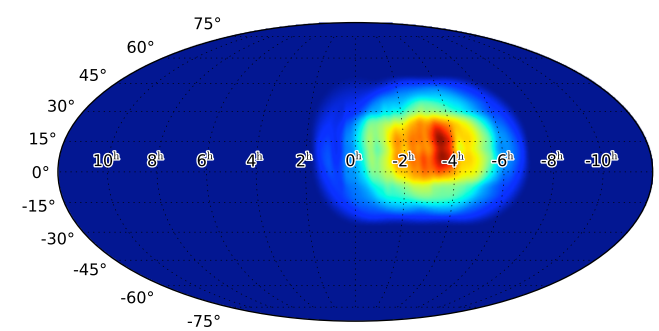
⋆

GW sky map



=

"Cross-correlation"



$b_i(\gamma_i^{-1}\omega) \triangleq p(\mathrm{EM}_i|\gamma_i, \omega)$

$s(\omega) \triangleq p(\omega|\mathrm{GW})$

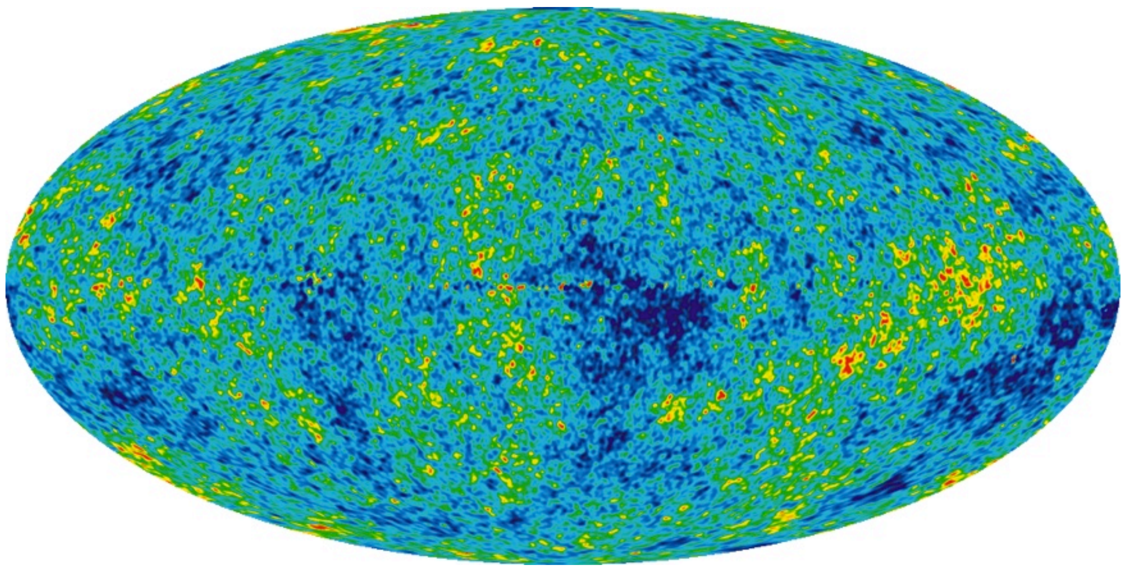
$p_i \triangleq p(\mathrm{EM}_i|\gamma_i, \mathrm{GW}) = \int s(\omega) b_i(\gamma_i^{-1}\omega)\, \mathrm{d}\Omega$

- Maximum of this integral is optimal pointing:

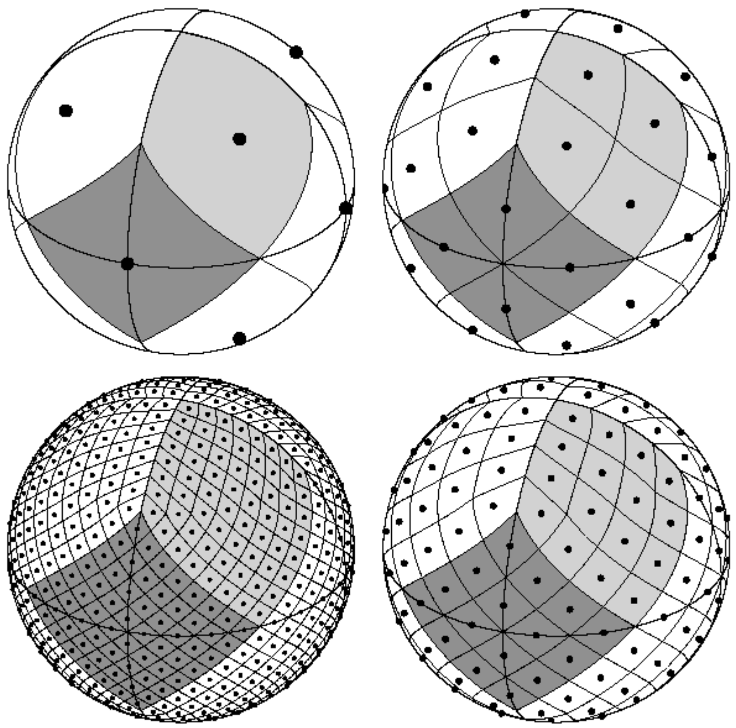
$$\gamma_i^* \triangleq \arg\max_{\gamma_i} p(\mathrm{EM}_i|\gamma_i, \mathrm{GW})$$

Fast convolution in HEALPix

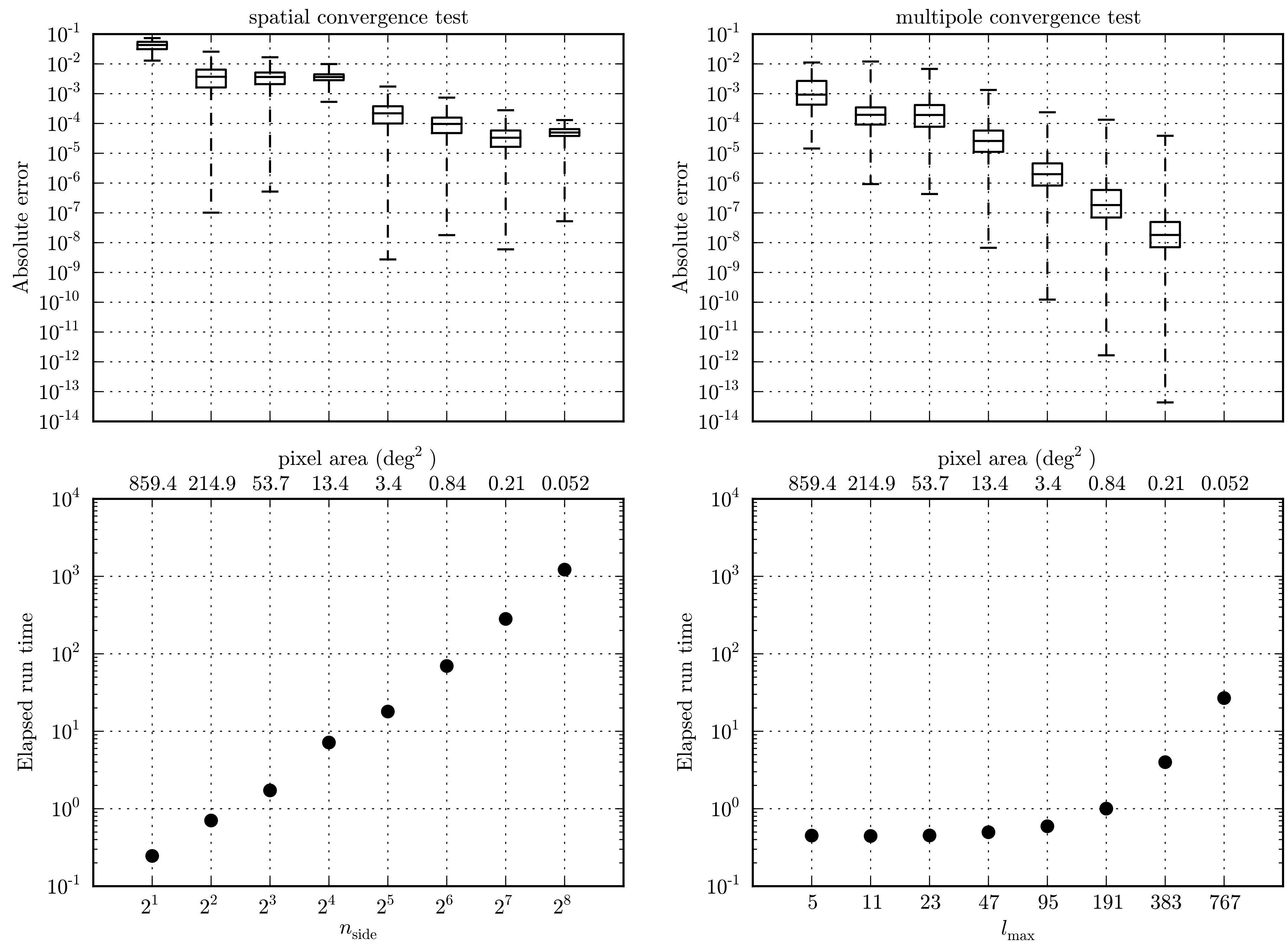
- Hierarchical Equal Area isoLatitude PIXelization
- Well-suited for harmonic analysis (isoLatitude)
- Existing tools for C/C++, Fortran, Python, IDL, MATLAB, Java, ...
- Part of the official FITS World Coordinate System (since 2006), so it's readable by many freely available astronomy software packages



WMAP 7-year survey from
http://map.gsfc.nasa.gov/media/101080/index.html



from Górski et al. ApJ, 622:759 – 771, 2005 April 1



Checked convergence and runtime of both ***spatial*** and ***multipole*** algorithms. On a single core machine, at a resolution of ≈0.05 deg^2, ***spatial*** took about ≈1000 s while ***multipole*** took only ≈25 s.

Parallelization with OpenMP

```
arr2<xcomplex<double> > Tmm(2 * lmax + 1,

#pragma omp parallel for
for (int l = 0; l <= lmax; l ++)
{
    for (int m = 0; m <= l; m++)
    {
        xcomplex<double> val(0., 0.);
        for (int M = -l; M <= l; M ++)
        {
```

Both implementations are accelerated with ***OpenMP***, the standard multiprocessing API that is built into modern C/C++/Fortran compilers.

Designed so that convolution calculation scales up to multi-core machines for very rapid, near real-time operation if needed.

On CIT cluster head node, ***multipole*** has achieved execution times as short as 5 s.

Multiple telescope problem

- With *N* telescopes, optimization problem in 2*N* dimensions.
- Exhaustive search is intractible: cost goes as
  $$(\text{pixel area})^{-N}$$
- Need efficient numerical approach

Noncooperative planner

Every astronomer for him/herself!

Each telescope points where it is most likely to image the source, regardless of what others are doing.

Not very efficient if there are many telescopes, but works reasonably well if coverage is poor.

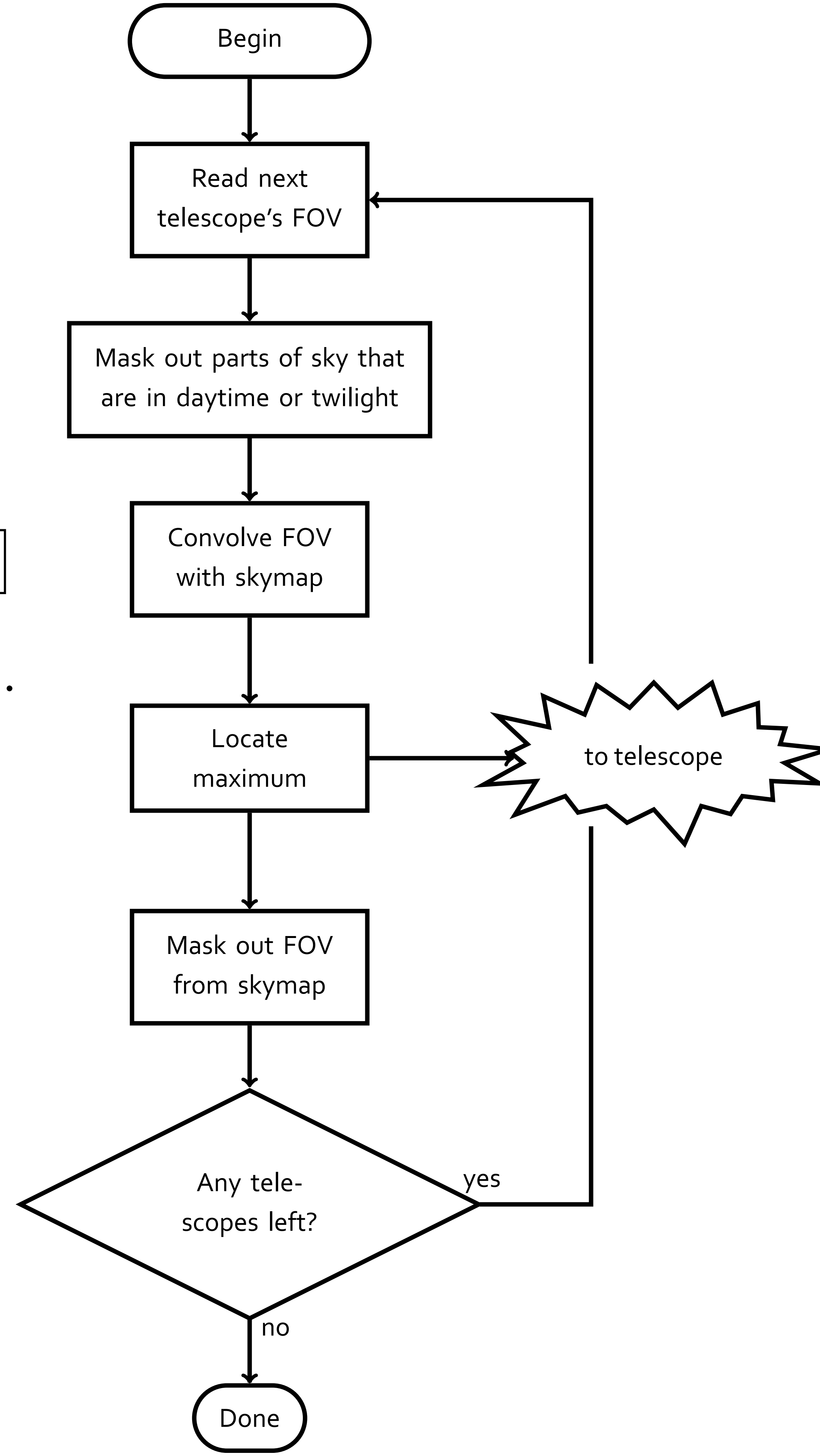
http://contentedlymaladaptive.com/2009/12/the-inmate-fightingmating-dance/

Greedy planner

Gobble up sky map one telescope at a time

$$p_{\geqslant 1} = 1 - \int \left[1 - b_1\left(\gamma_1^{-1}\omega\right)\right]\left[1 - b_2\left(\gamma_2^{-1}\omega\right)\right] \cdots \left[1 - b_N\left(\gamma_N^{-1}\omega\right)\right] s(\omega)\,\mathrm{d}\Omega.$$

http://dpinedoblog.blogspot.com/2010/06/focus-on-mission.html



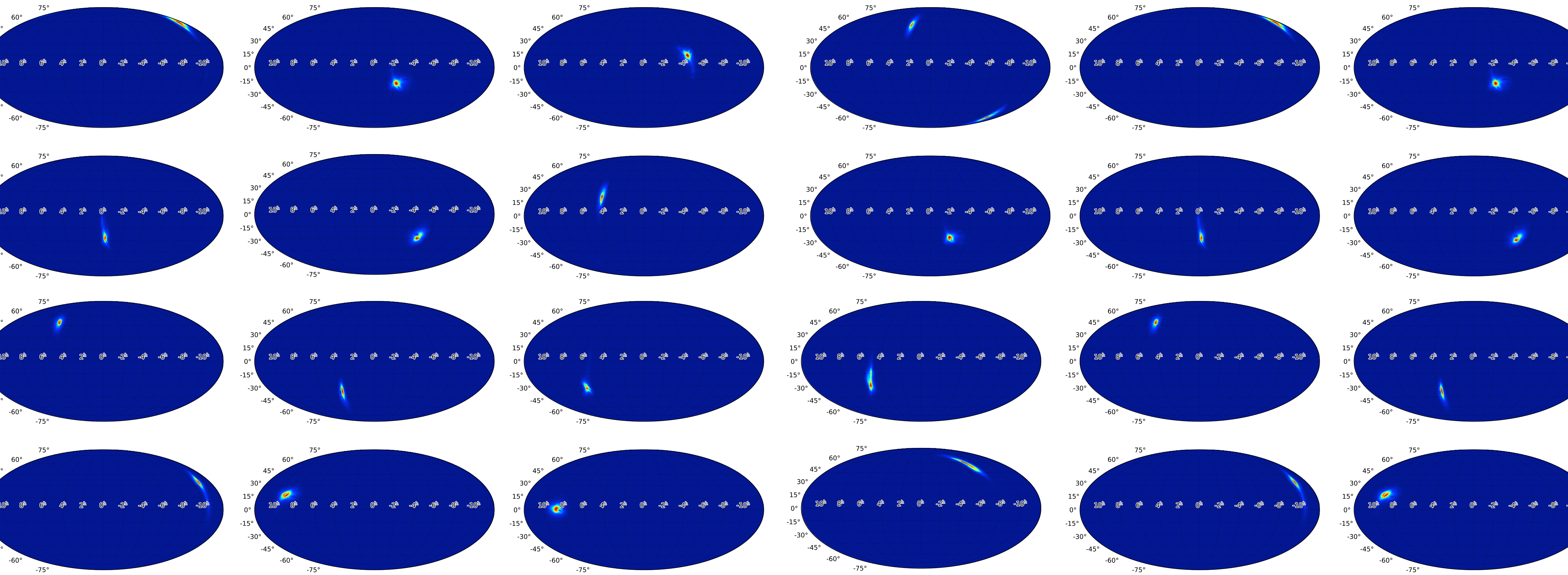
Anneal planner

Randomly perturb pointings of all telescope simultaneously

http://calexis.com/blog/2010/05/24/infinite-monkeys-spell-gazortenflap/

Plug prob. of imaging source into good old *scipy.optimize.anneal*!

Use modified "fast annealing" schedule of L. Ingber (1989).

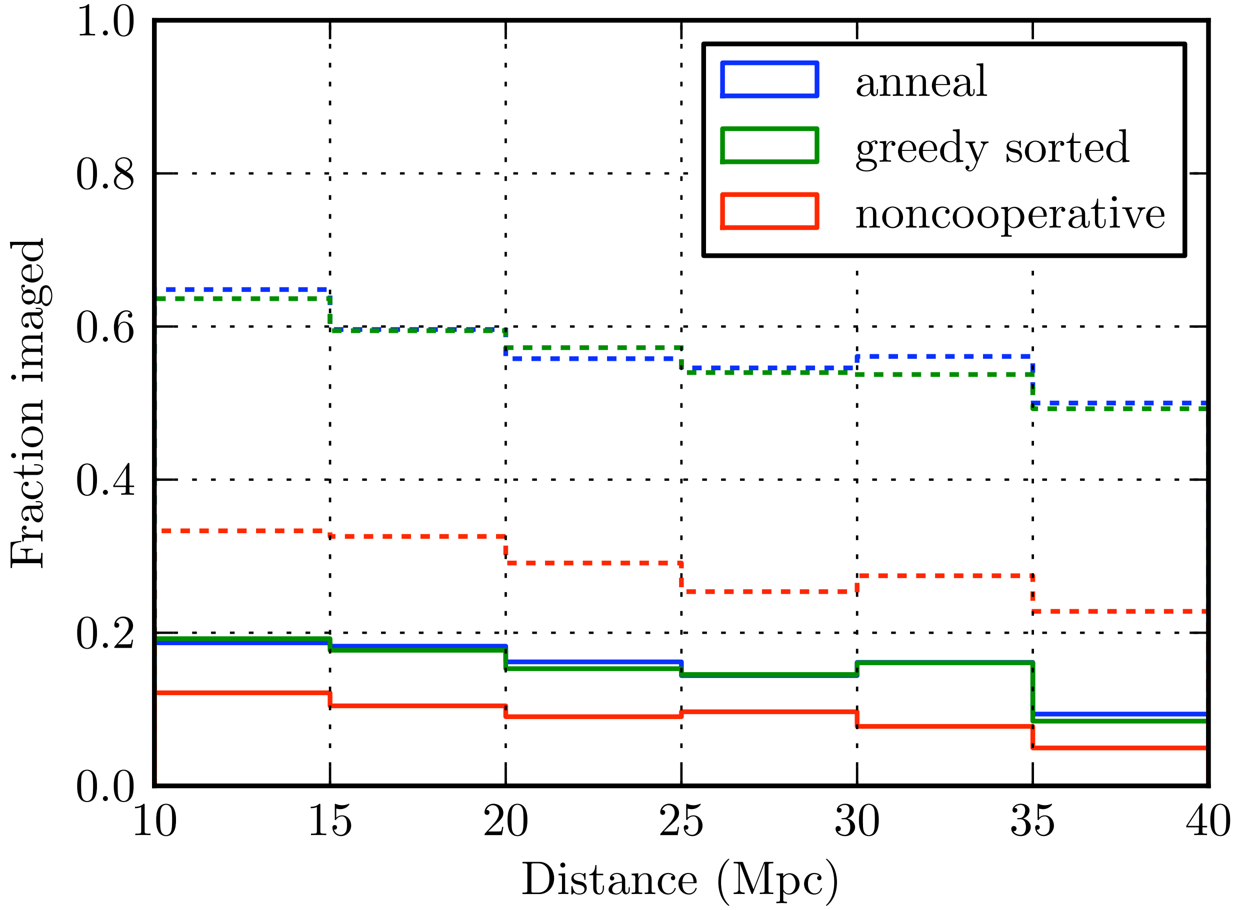


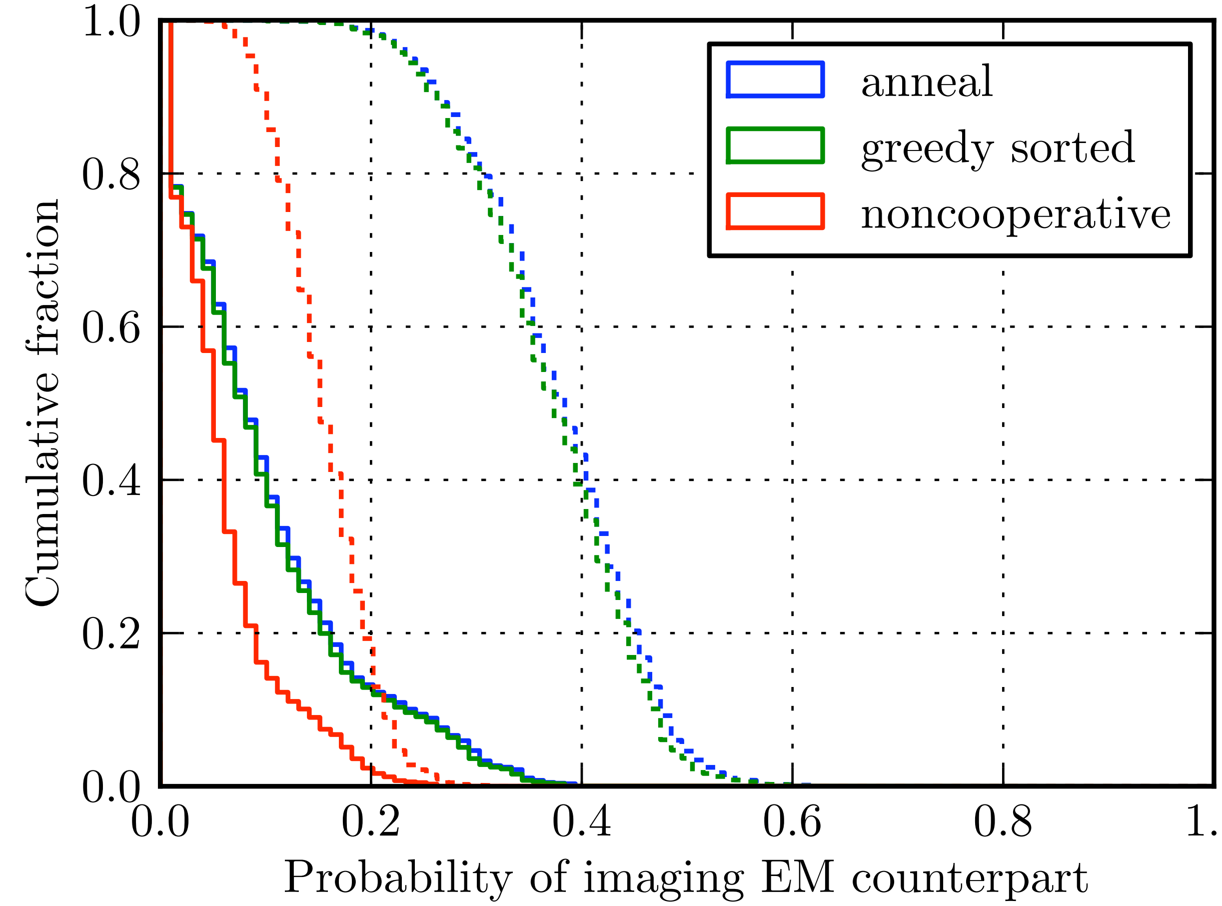
Case study

- Low mass inspiral injections into simulated initial LIGO noise
- Sky maps generated with Larry Price's localization code
- Generate observing plans using ***noncooperative***, ***greedy***, and ***anneal*** planners
- Use PyNOVAS for checking sun and horizon interference

Coordination may be important for EM followup!

plots from Singer, Price, and Speranza (in preparation)





If we want to image an EM counterpart ***as soon as possible*** after the GW trigger, ***coordinating*** observations by many telescopes ***drastically increases our odds*** as compared to deciding where to point each telescope independent of all of the others.

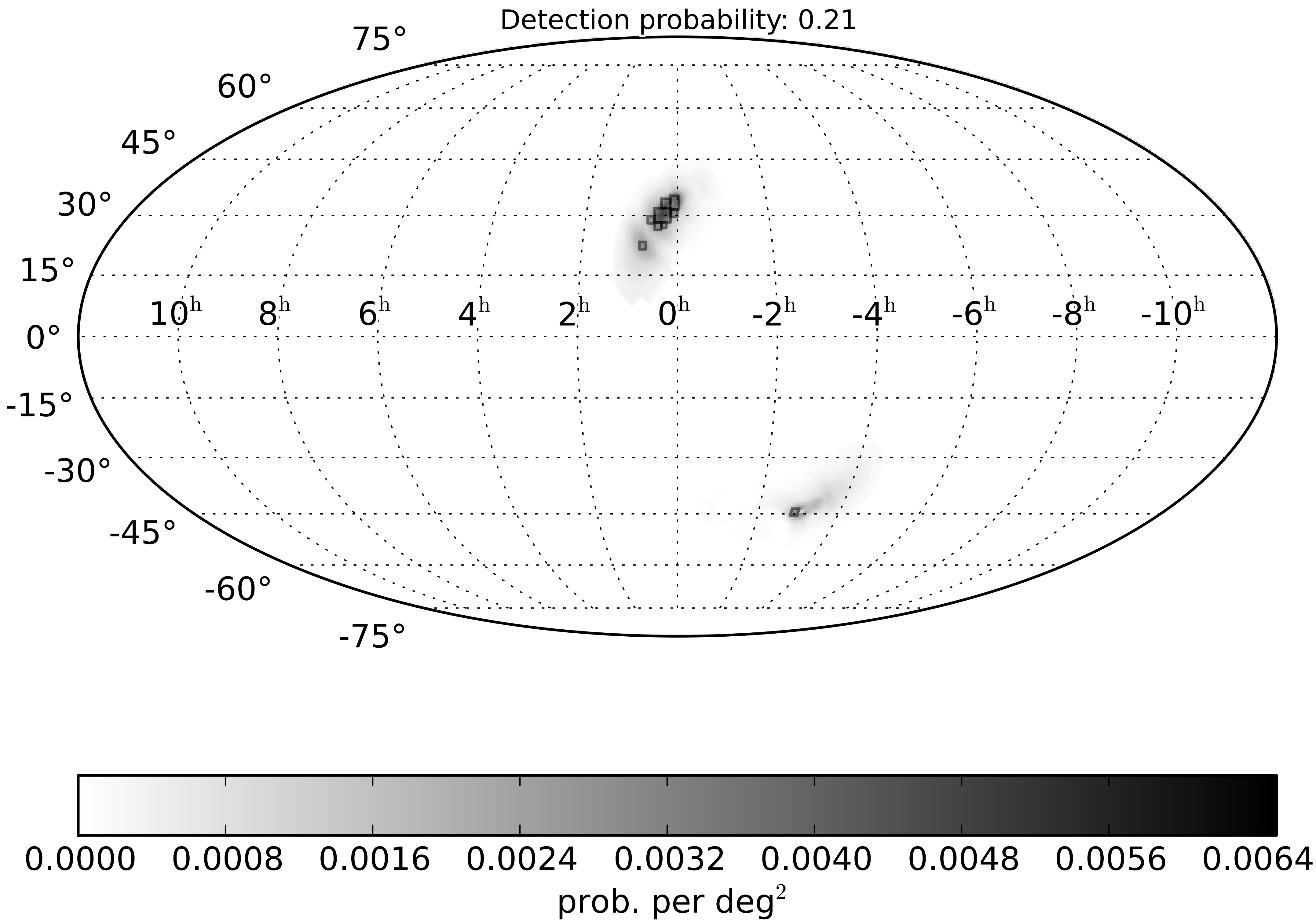
Conclusion

What we did:

- applied spherical harmonic analysis to planning EM followup
- developed code for planning observations that is:
  - ***fast*** enough to use for extensive injection campaigns
  - ***flexible*** enough to handle any telescope network
  - ***simple*** enough to add sophistication to telescope models
  - ***scalable*** so that it can be used for very low latency operation on multicore machines

Future work:

- incorporate light curve model, slew time, limiting magnitude
- handle multiple observations (mosaic) spread through time
- explore detectability of CBC+GRB+optical events in aLIGO with GW injections combined with light curves and telescope model


Detection probability: 0.21
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
10h
8h
6h
4h
2h
0h
-2h
-4h
-6h
-8h
-10h
0.0000
0.0008
0.0016
0.0024
0.0032
0.0040
0.0048
0.0056
0.0064
prob. per deg2

fin