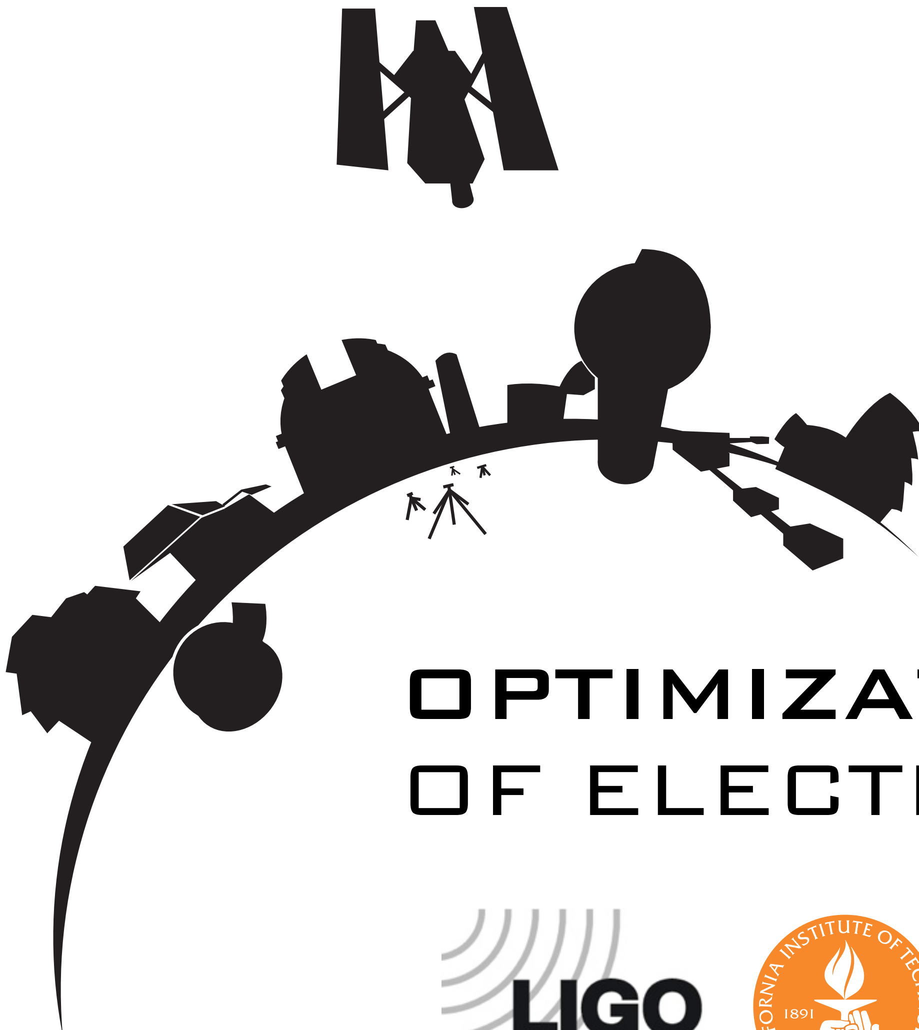
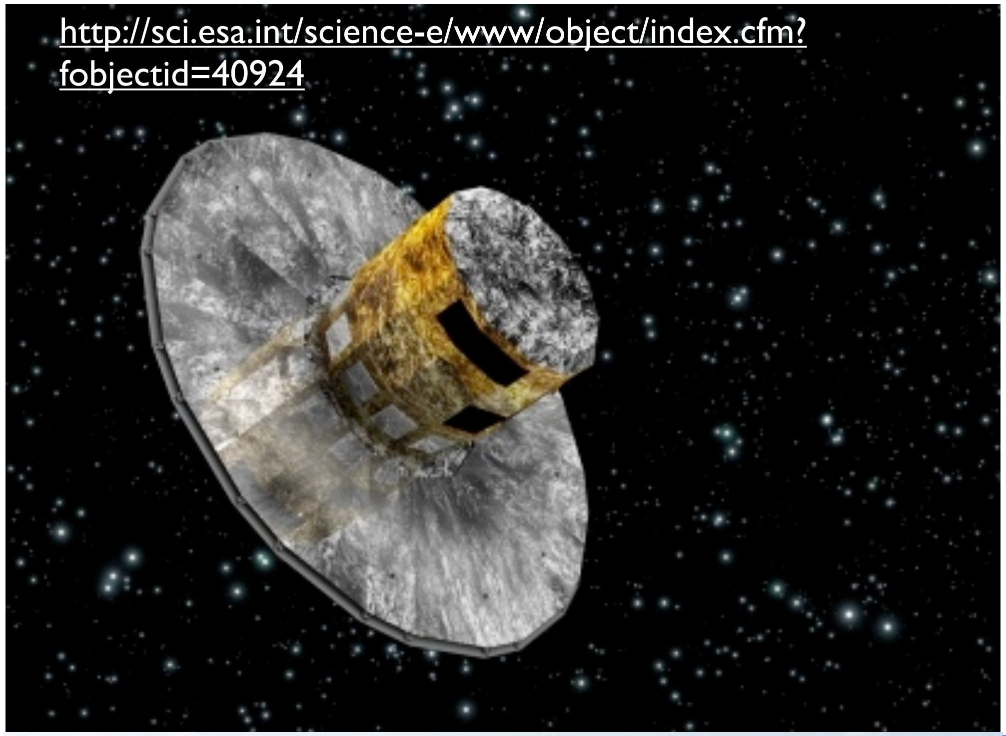


OPTIMIZATION & COORDINATION OF ELECTROMAGNETIC FOLLOWUP

Leo Singer & Larry Price
California Institute of Technology

Antony Speranza
Massachusetts Institute of Technology

28th Pacific Coast Gravity Meeting
24 March 2012
UCSB, Santa Barbara, CA



http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=40924

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

http://www.jb.man.ac.uk/news/2011/LOFAR-pulsars/

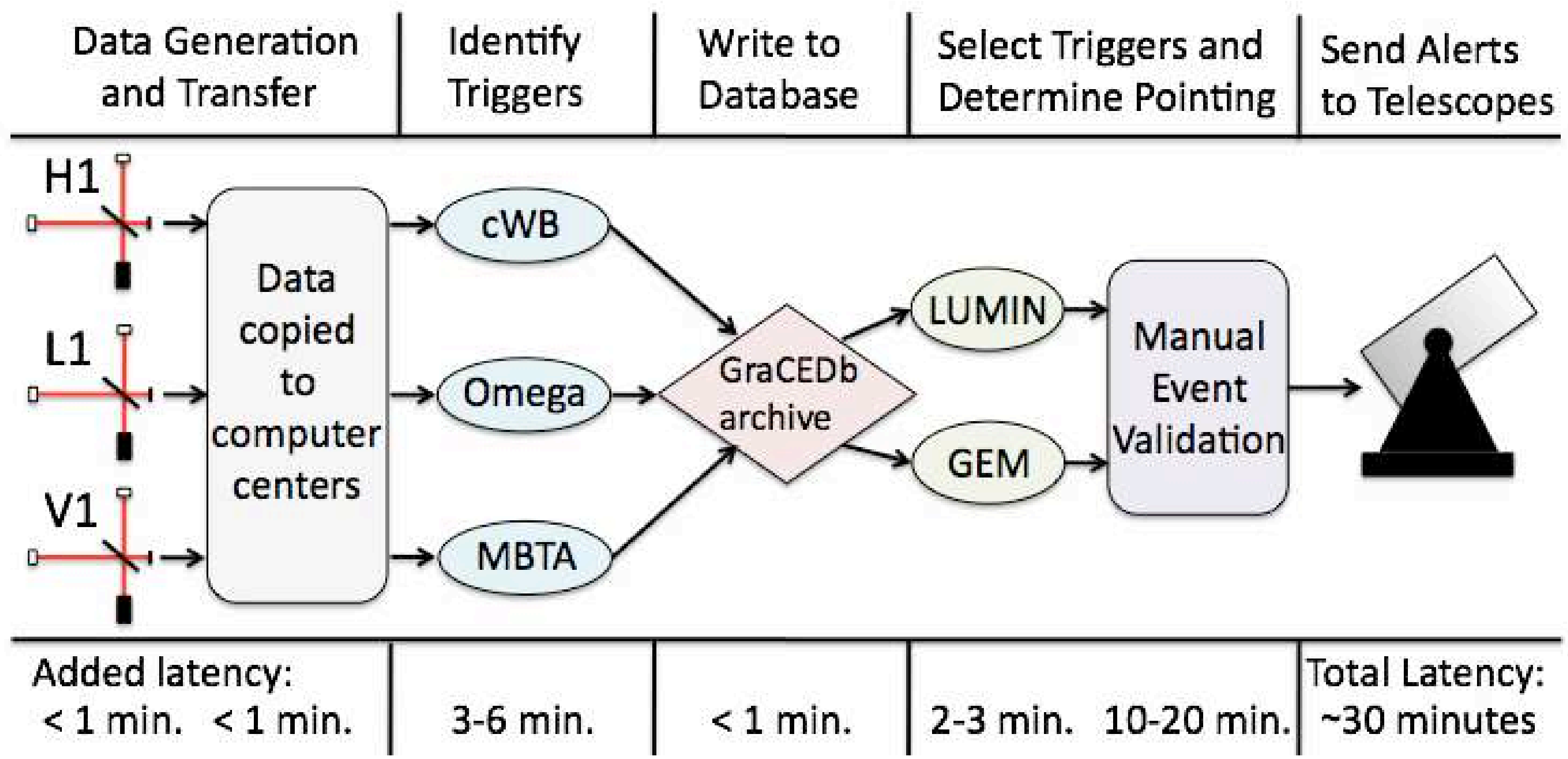
http://touro.ligo-la.caltech.edu/%7Ebonnie/publish/aerials/aerials-Pages/Image5.html

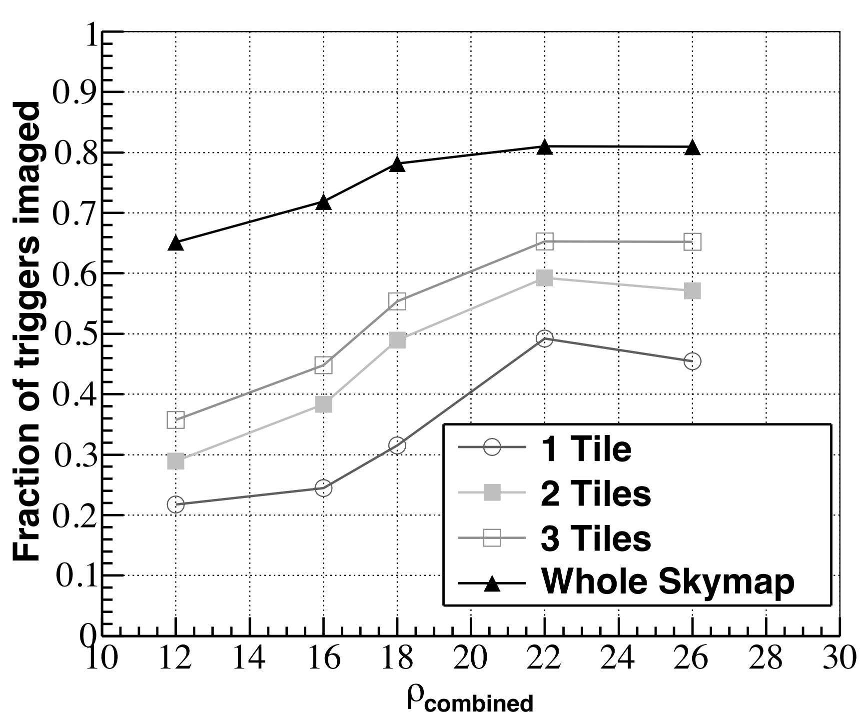

http://www.phys.ufl.edu/~bernard/IREU2008/images/largeimages/Virgo0.jpg


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


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

Multimessenger astronomy





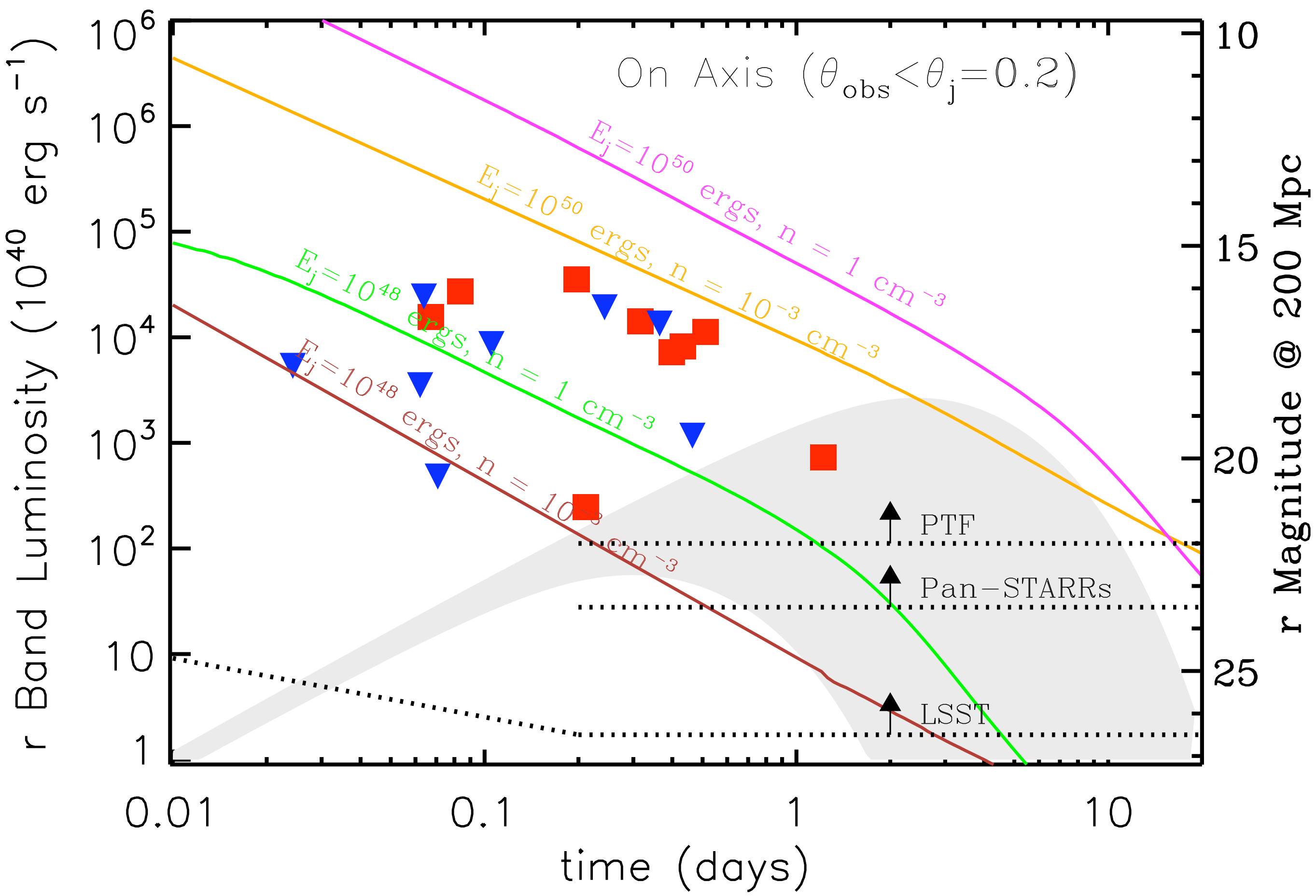
arXiv.org > astro-ph > arXiv:1109.3498

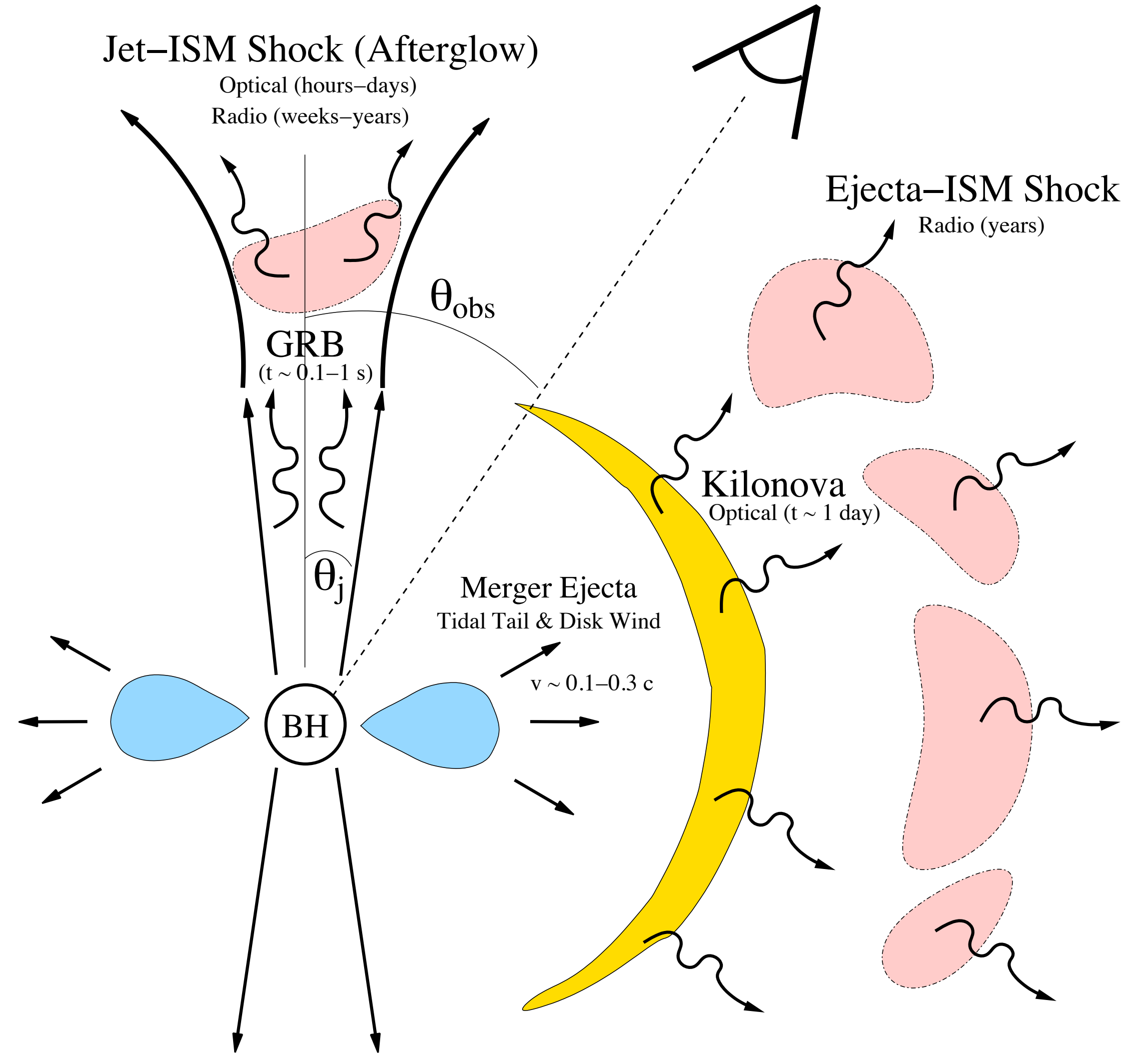
Astrophysics > Instrumentation and Methods for Astrophysics

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,

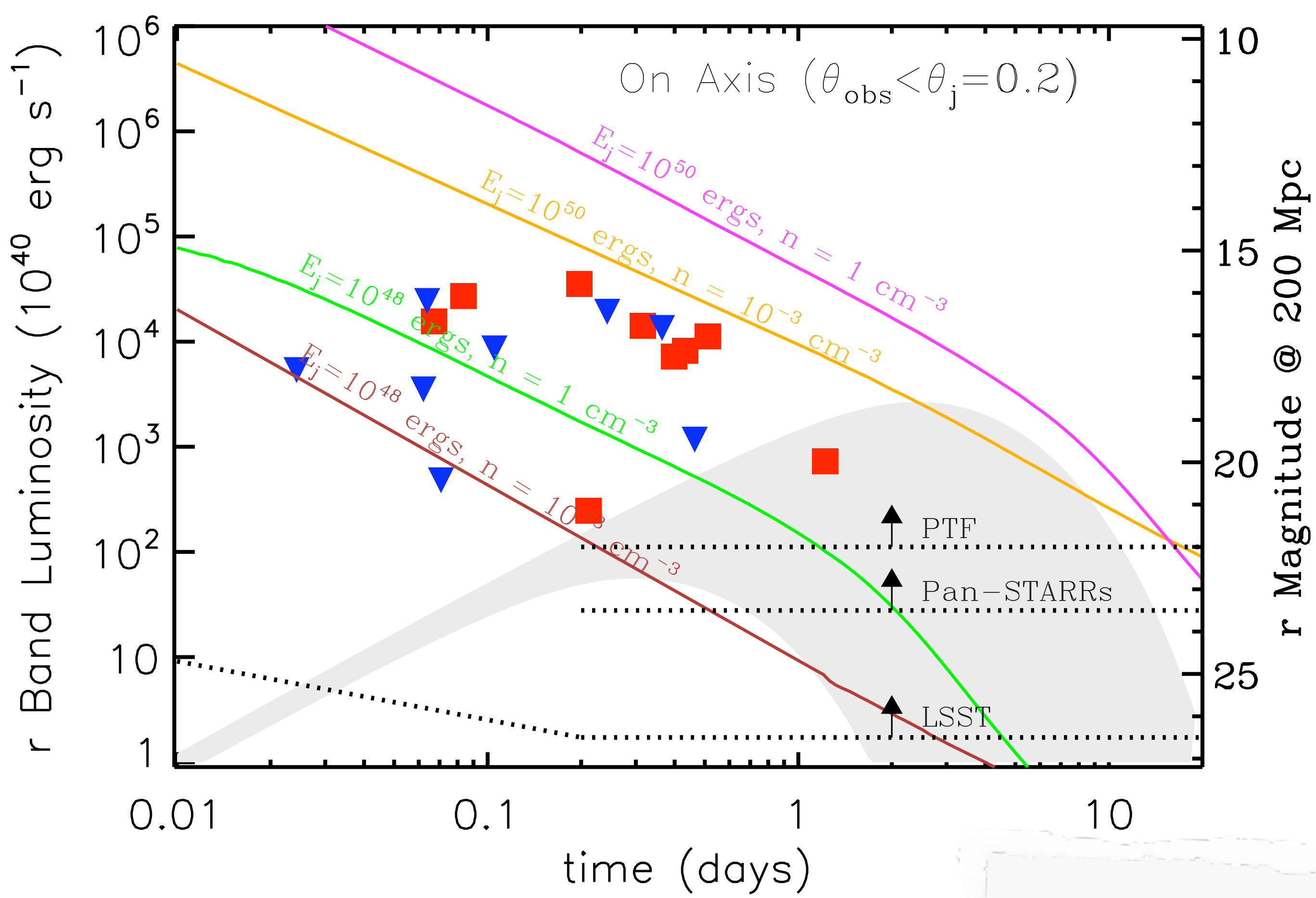
Motivation: gravitational waves, GRBs, and compact binary coalescence

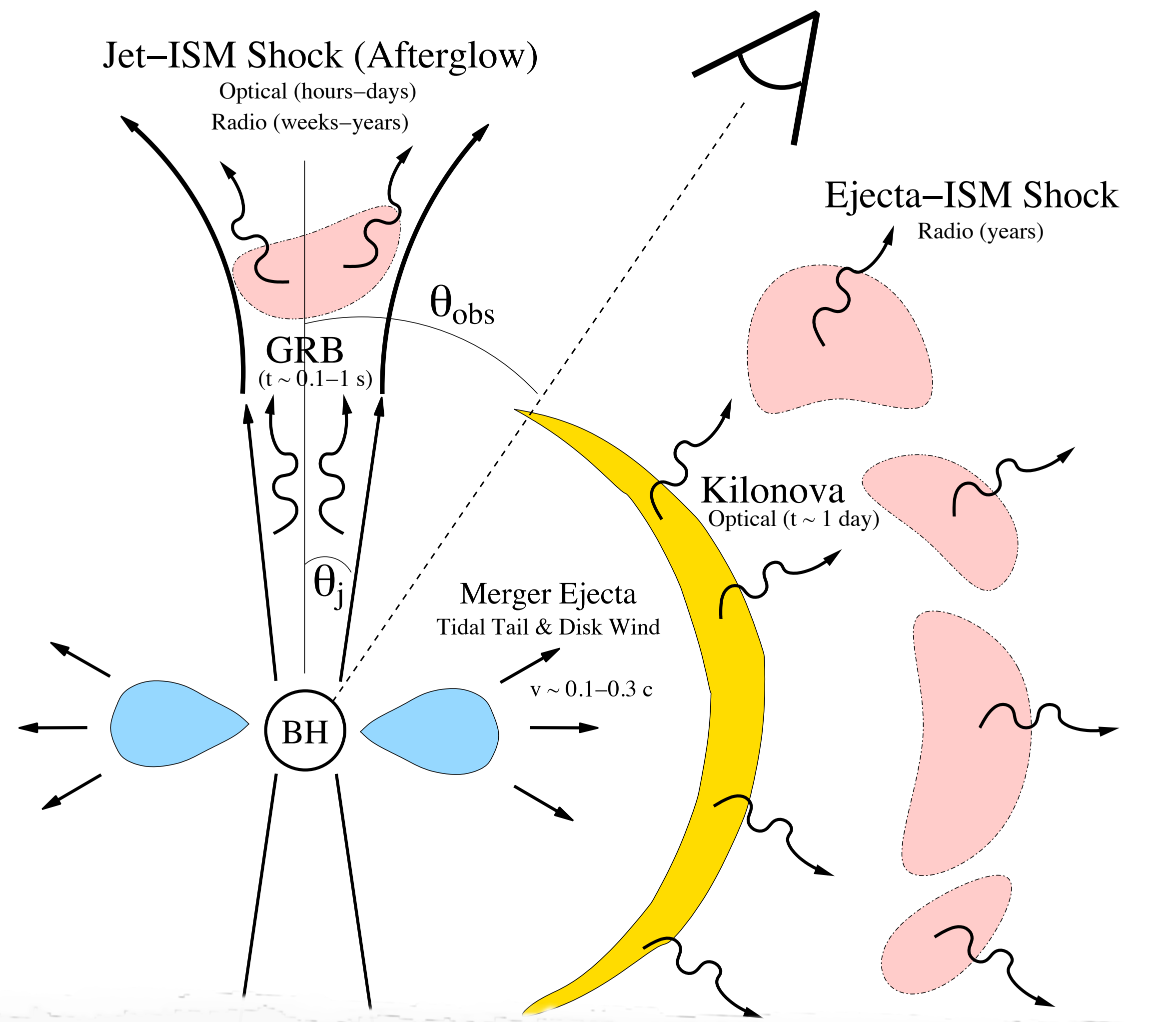




← Gravitational waves: start *before* γ ray burst

Motivation: gravitational waves, GRBs, and compact binary coalescence





← Gravitational waves: start *before* γ ray burst

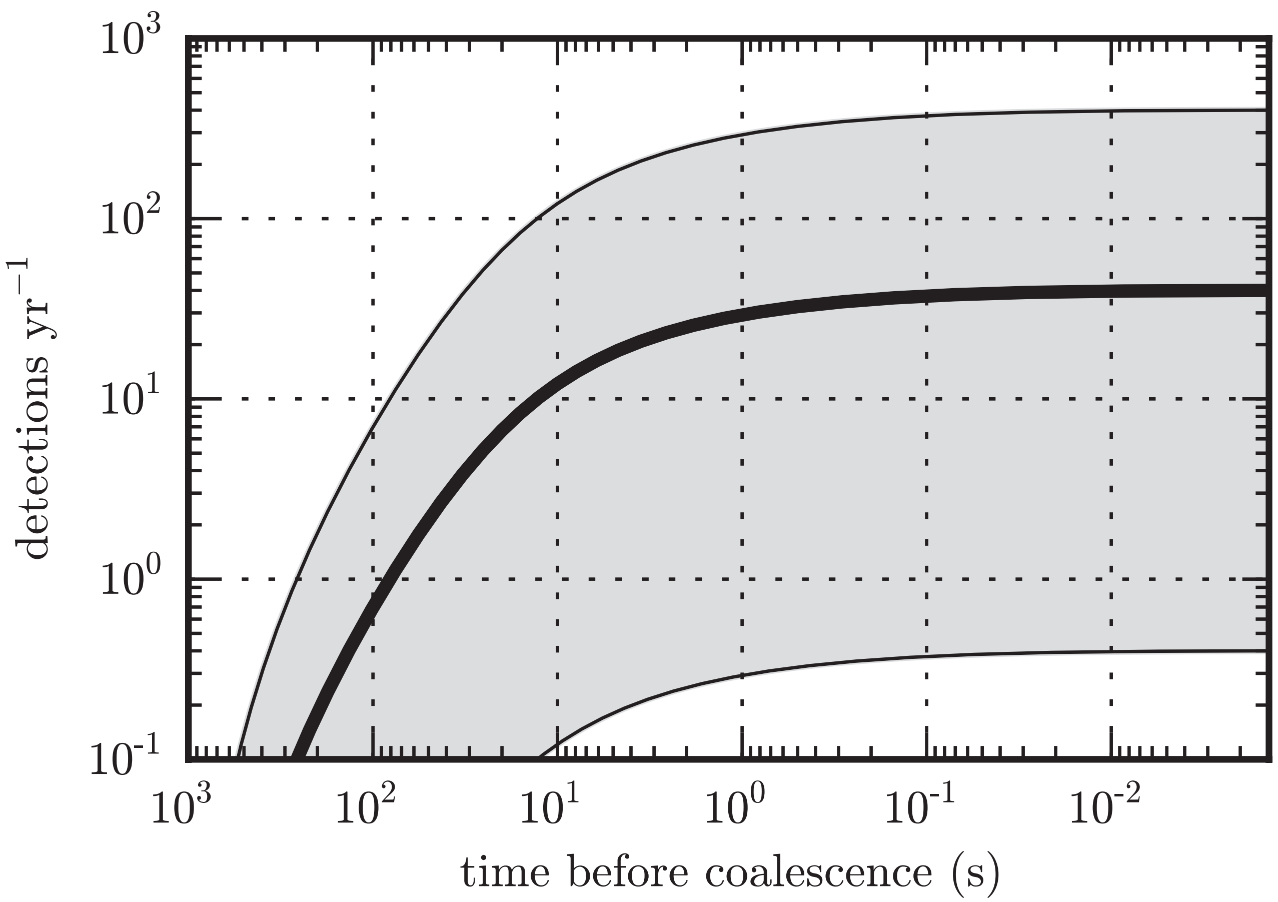
The Astrophysical Journal, 746:48 (15pp), 2012 February 10

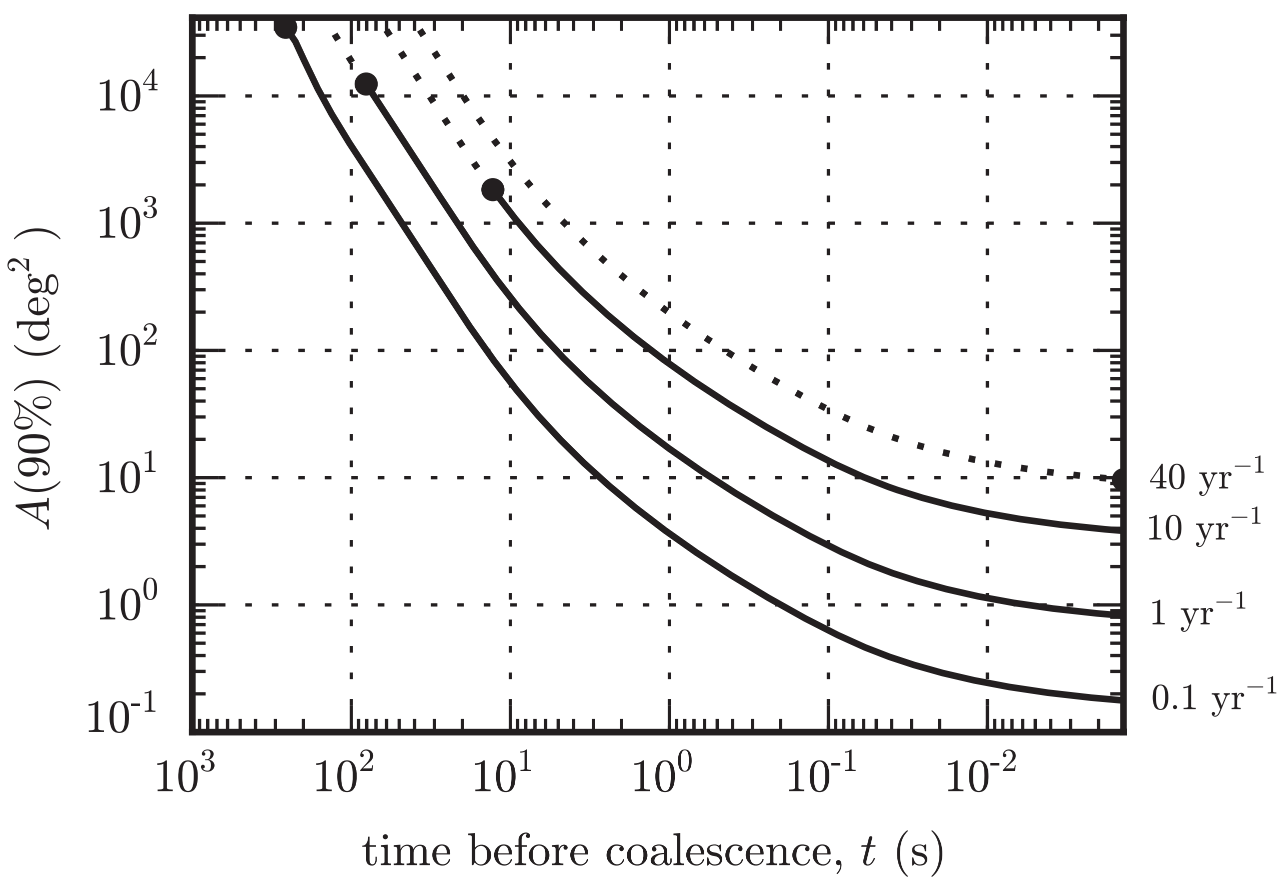
doi:10.1088/0

WHAT IS THE MOST PROMISING ELECTROMAGNETIC COUNTERPART OF A NEUTRON STAR BINARY MERGER?

B. D. Metzger[1,3] and E. Berger[2]
[1] Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2011 August 30; accepted 2011 November 10; published 2012 January 24



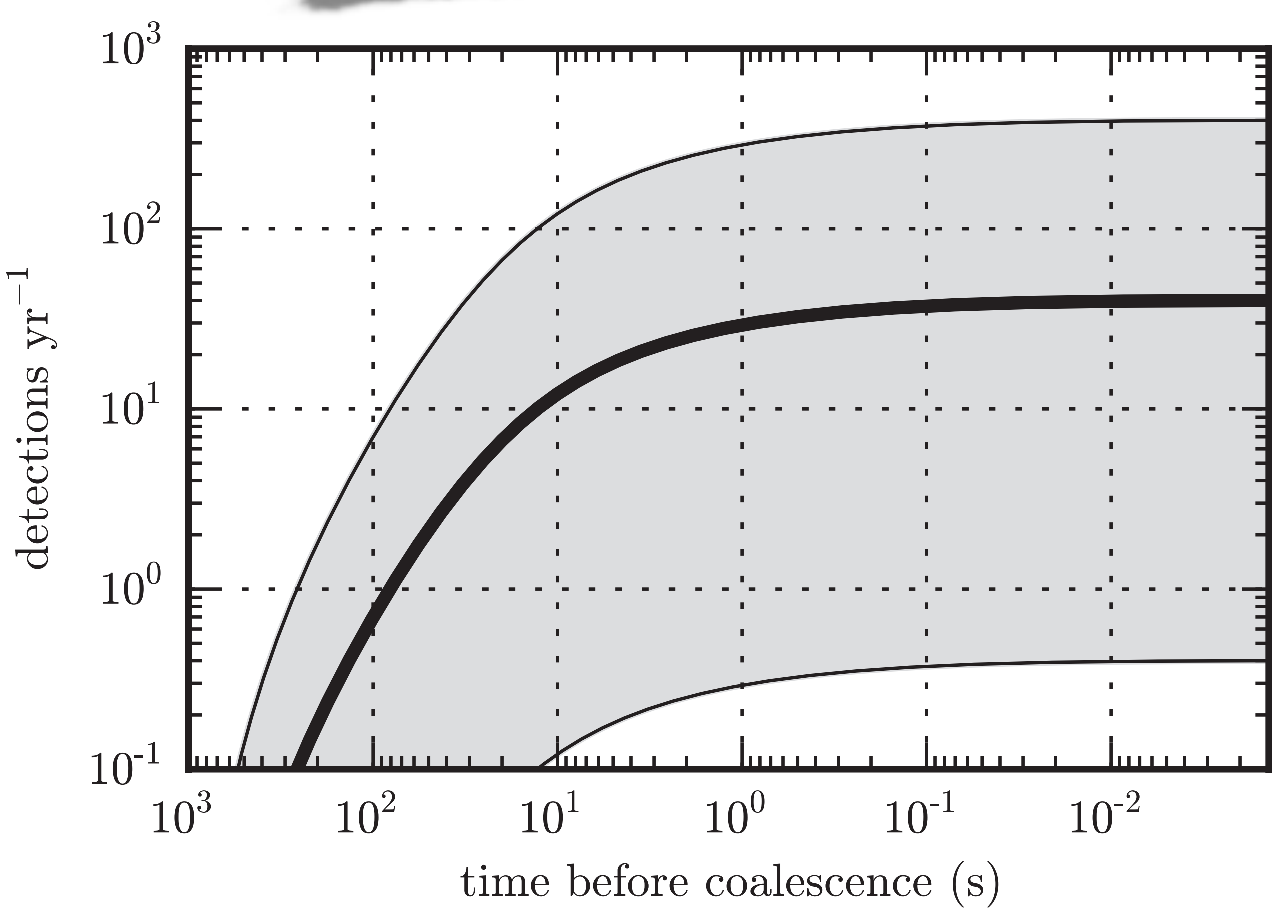


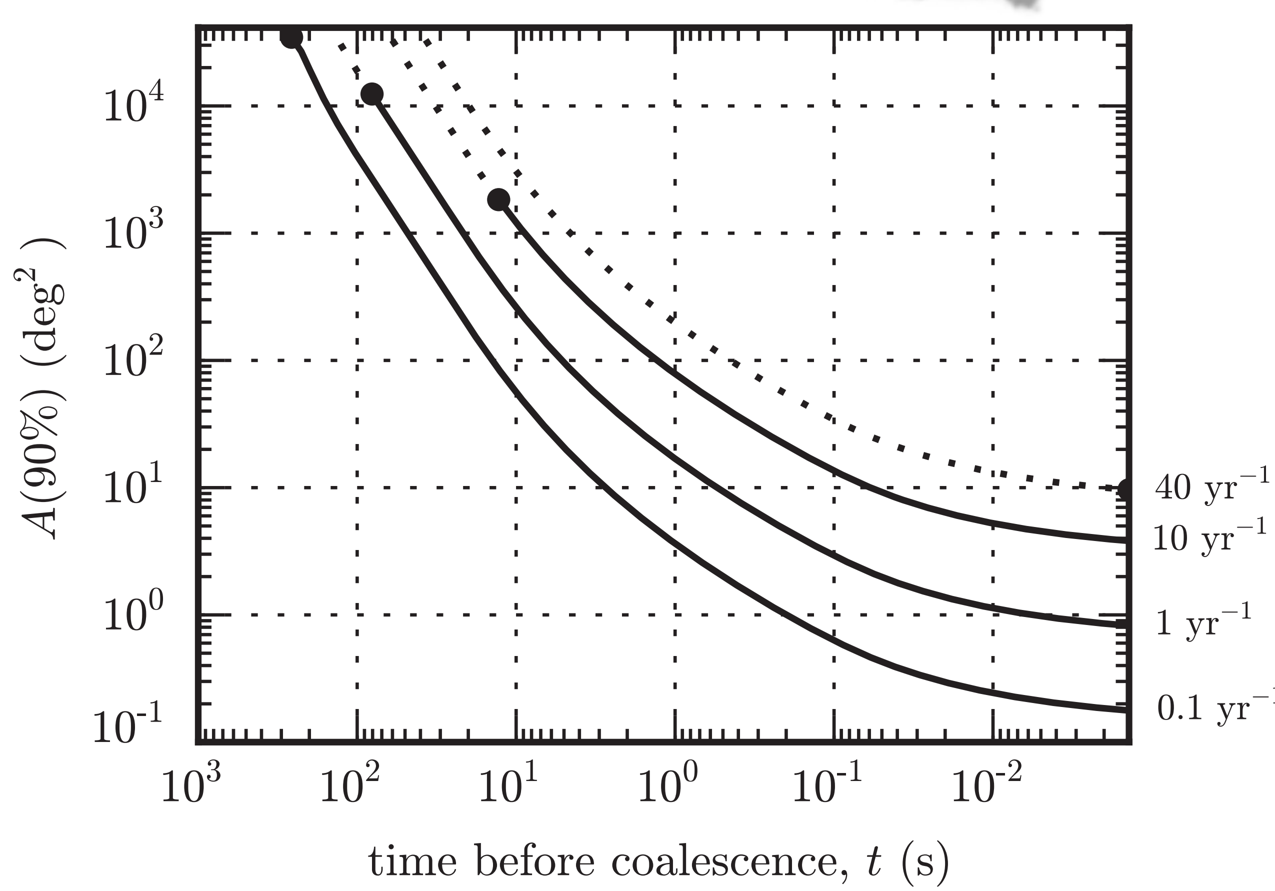
← Gravitational waves: start *before* γ ray burst ... detect GW signal a few seconds before or after merger?

THE ASTROPHYSICAL JOURNAL, 748:136 (14pp), 2012 April 1
doi:10.1088/0004-637X/748/2/136

TOWARD EARLY-WARNING DETECTION OF GRAVITATIONAL WAVES FROM COMPACT BINARY COALESCENCE

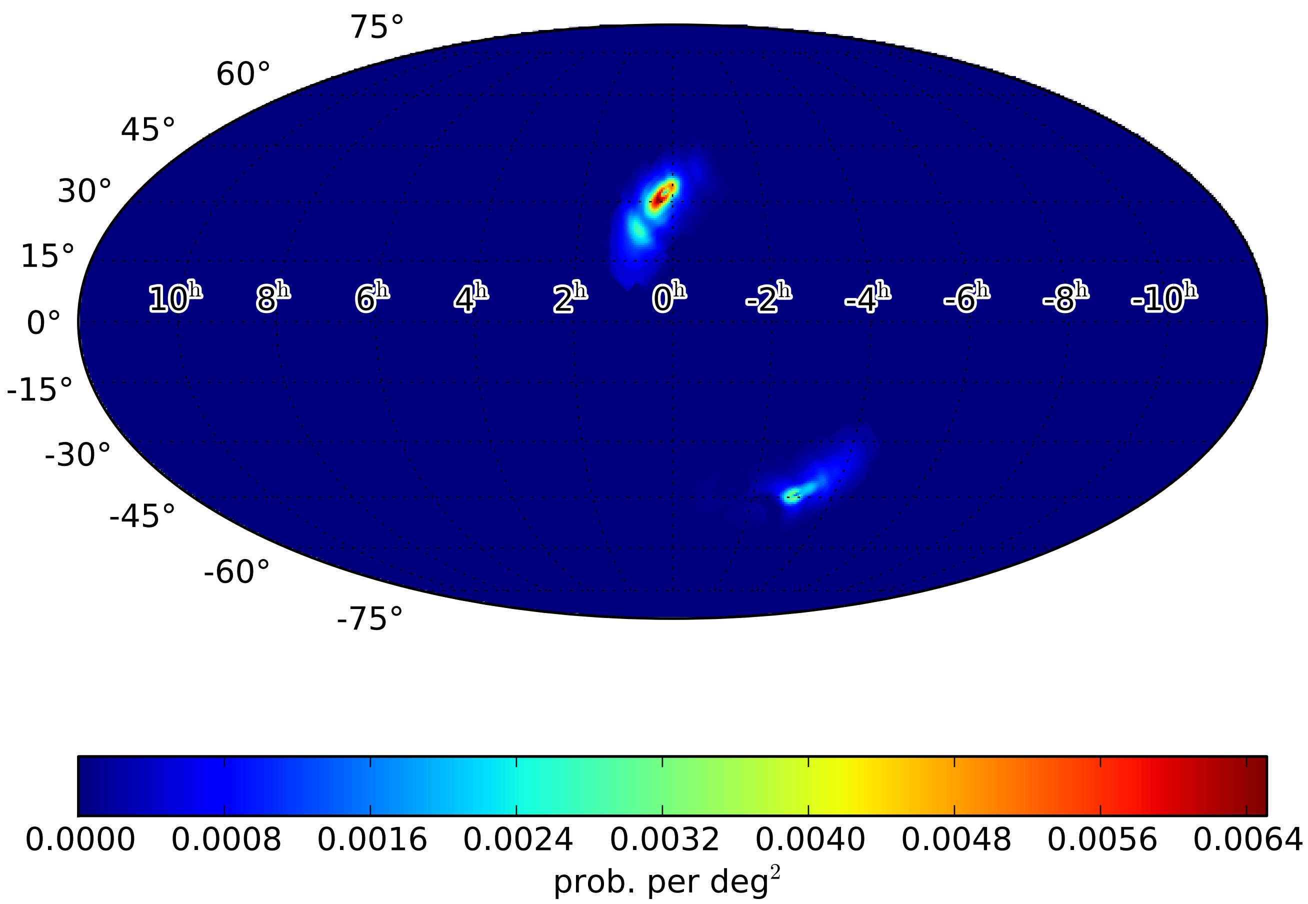
KIPP CANNON[1], ROMAIN CARIOU[2], ADRIAN CHAPMAN[3], MIREIA CRISPIN-ORTUZAR[4], NICKOLAS FOTOPOULOS[3], MELISSA FREI[5,6], CHAD HANNA[7], ERIN KARA[8], DREW KEPPEL[9,10], LAURA LIAO[11], STEPHEN PRIVITERA[3], ANTONY SEARLE[3], LEO SINGER[3], AND ALAN WEINSTEIN[3]





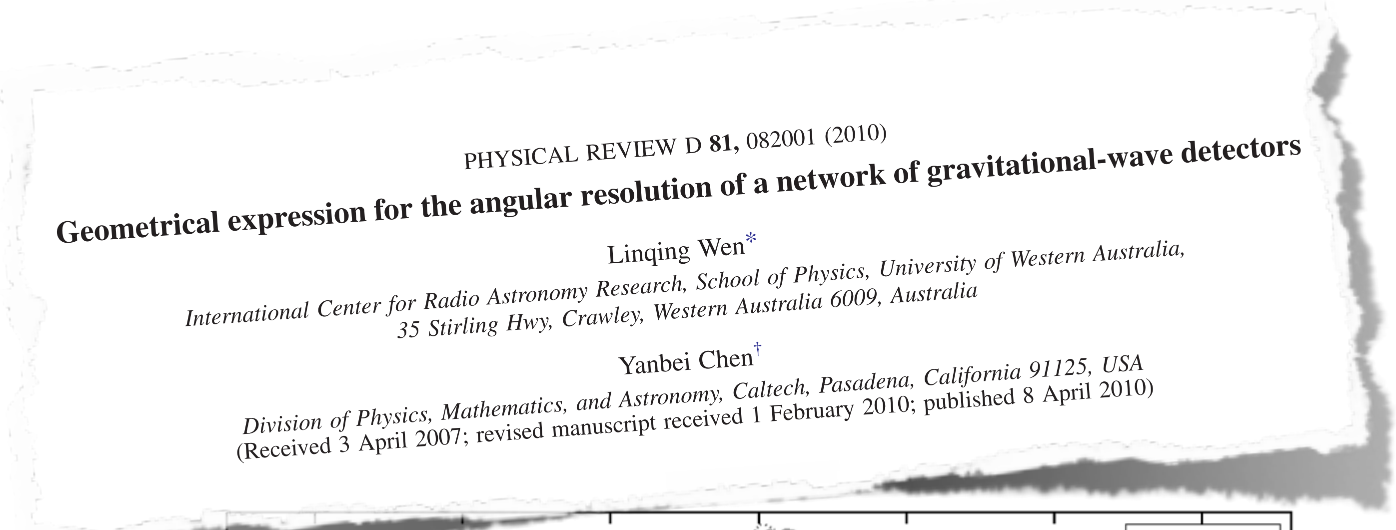
← Gravitational waves: start *before* γ ray burst ... detect GW signal a few seconds before or after merger?

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

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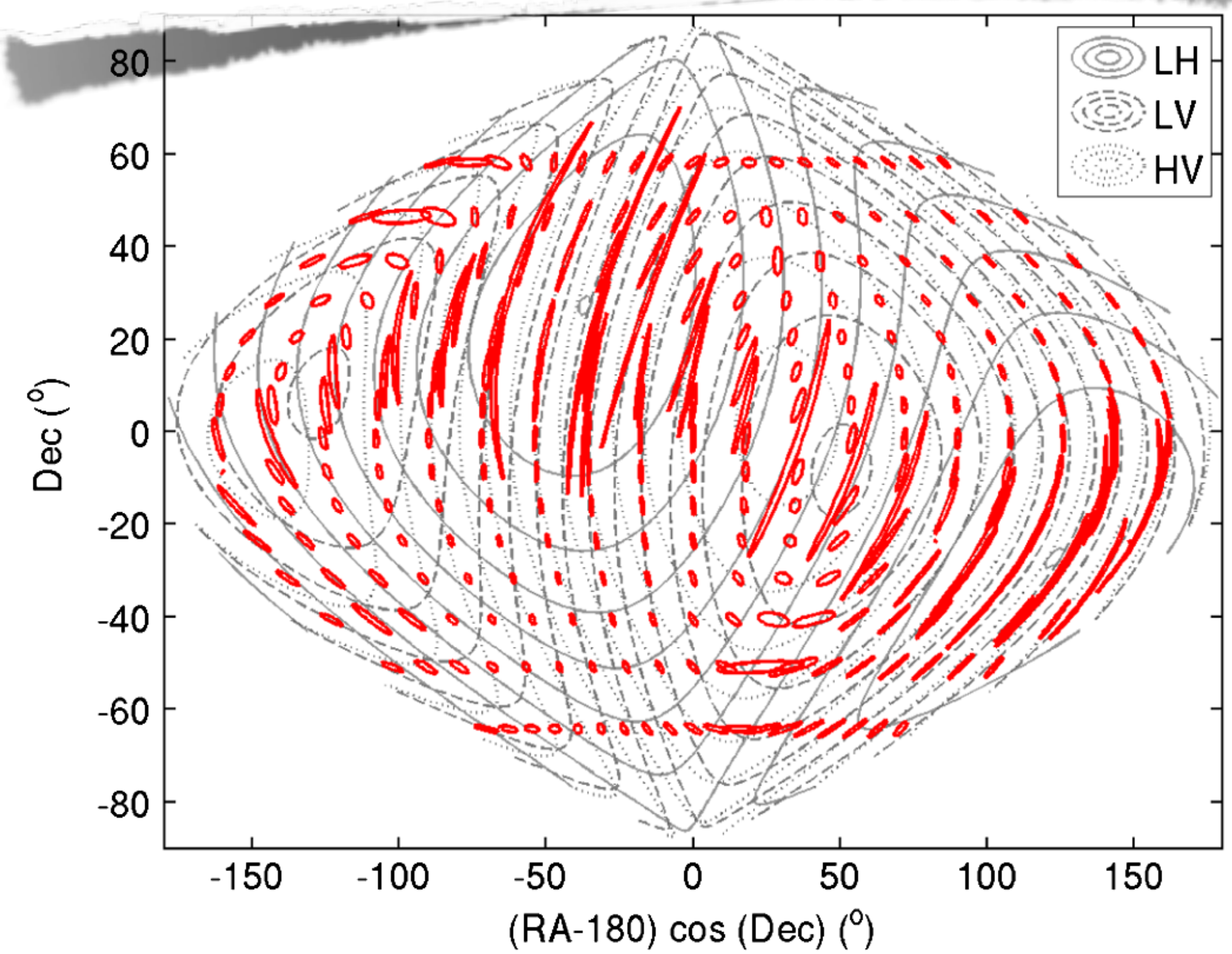
International Center for Radio Astronomy Research, School of Physics, University of Western Australia, 35 Stirling Hwy, Crawley, Western Australia 6009, Australia

Yanbei Chen†

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

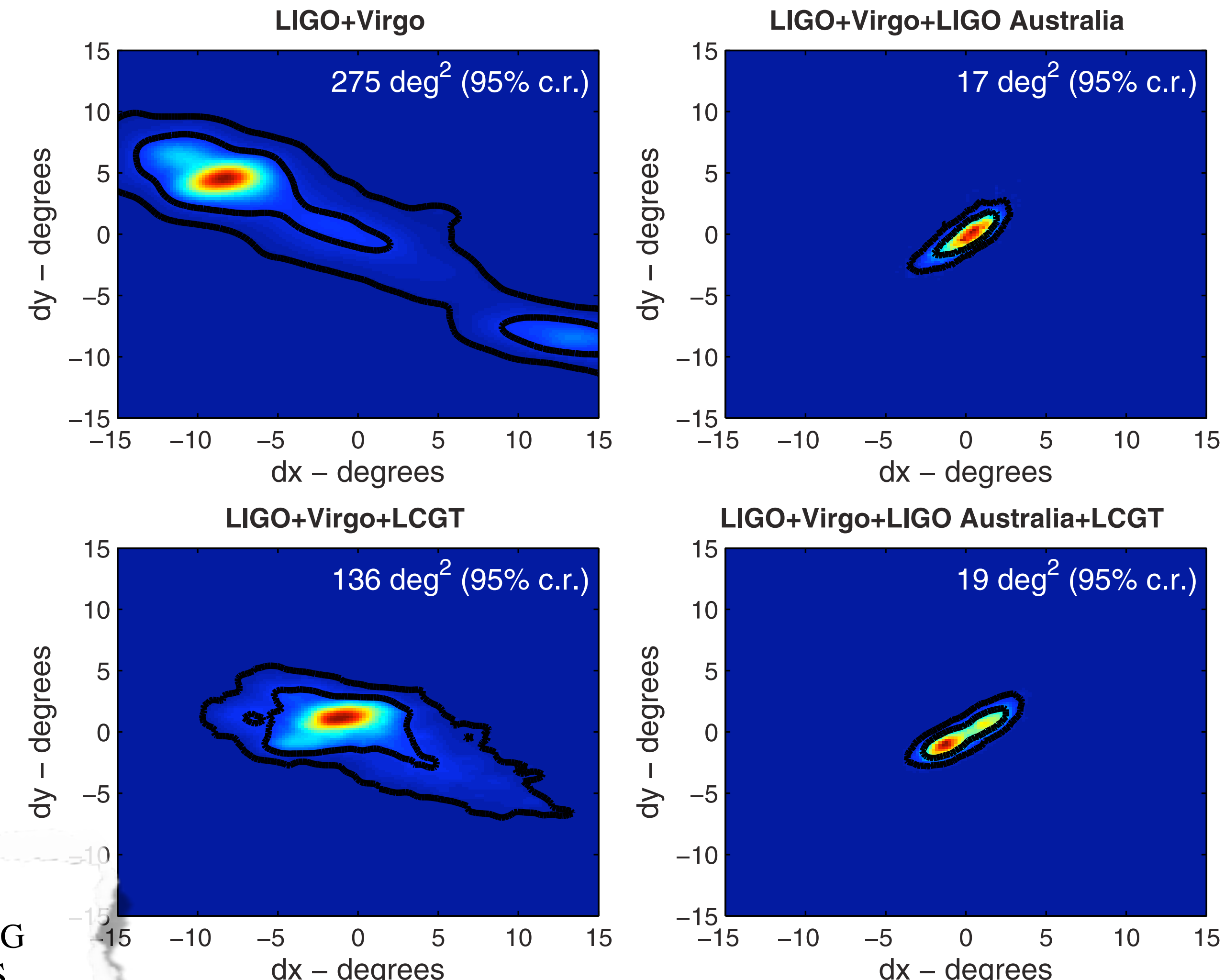
(Received 3 April 2007; revised manuscript received 1 February 2010; published 8 April 2010)

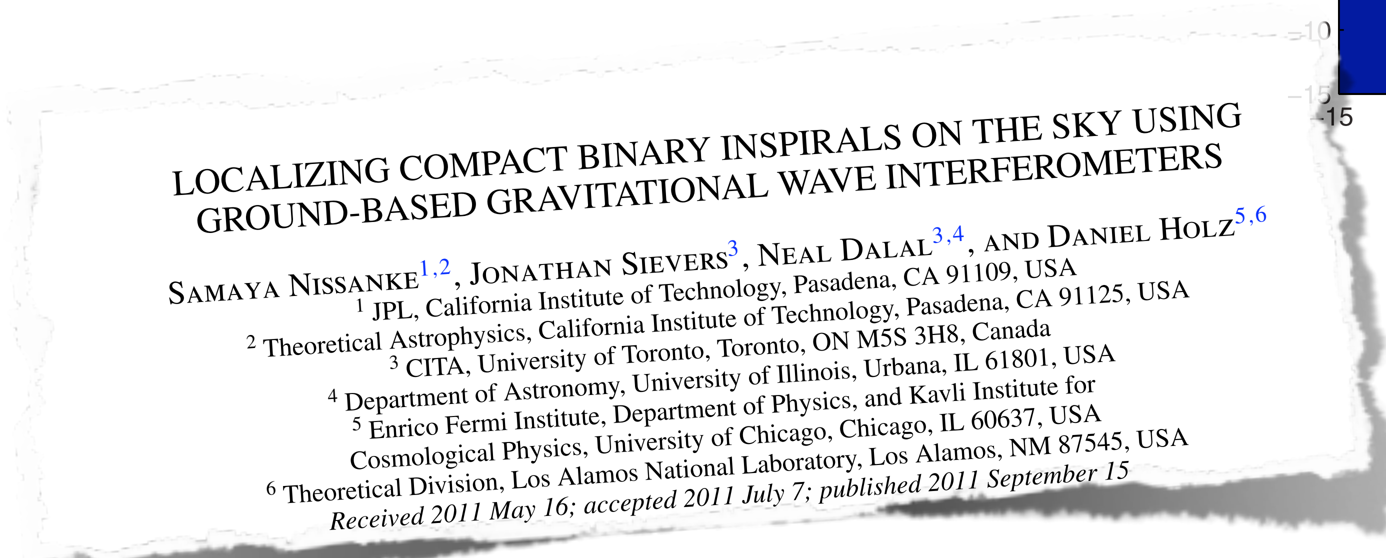


- 2 detectors: source location constrained to a ring on the sky
- With 3+ detectors, source location is constrained to two blobs in mirroring locations
- Accuracy highly dependent on elevation plane of detectors, antenna patterns

Area of 95% localization confidence: ≳10-100 deg^2

- At high SNR, confidence level contours are ellipses
- At low SNR, confidence region is irregularly shaped, spans hundreds of deg^2





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

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

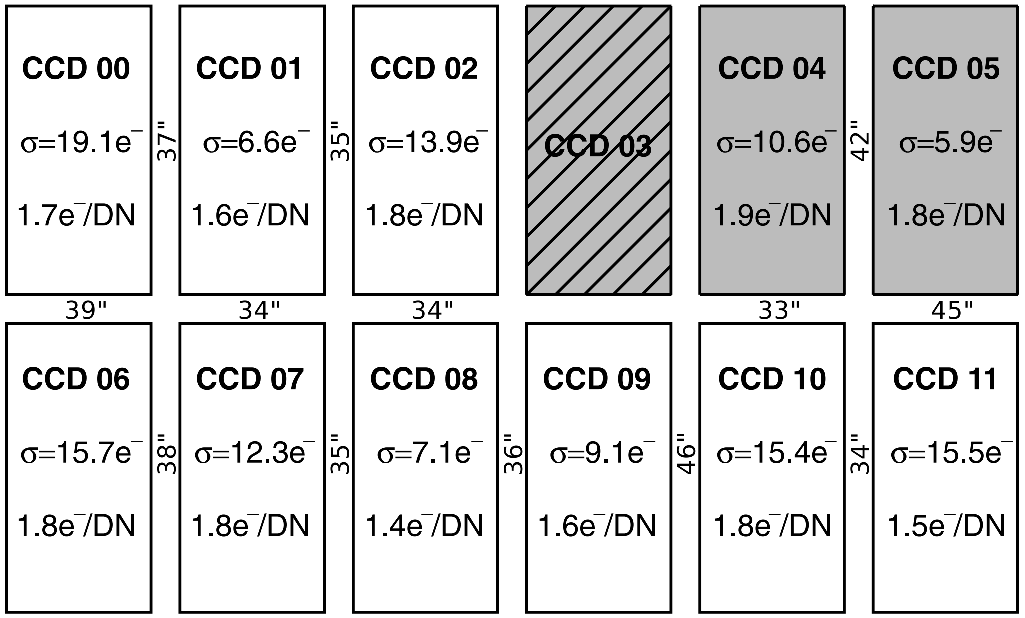
Telescopes: deep, or wide, but not* both

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:

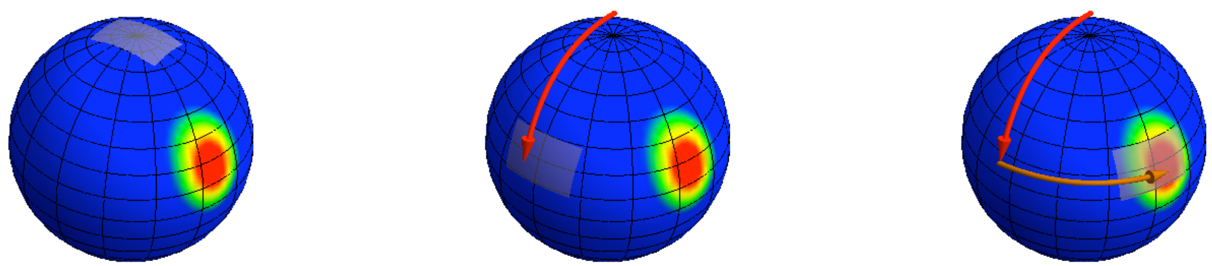
- different limiting magnitudes
- different slew times
- different filters
- gaps between CCDs
- dead CCDs
- vignetted or clipped image planes



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

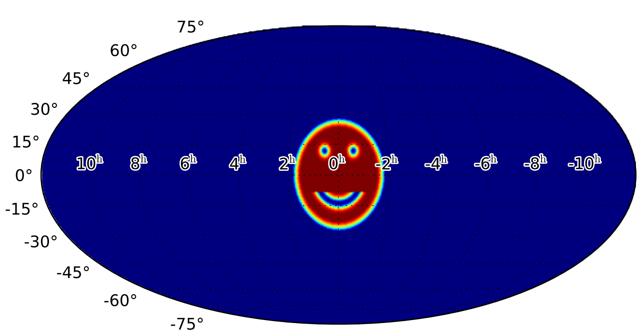
Single telescope problem

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



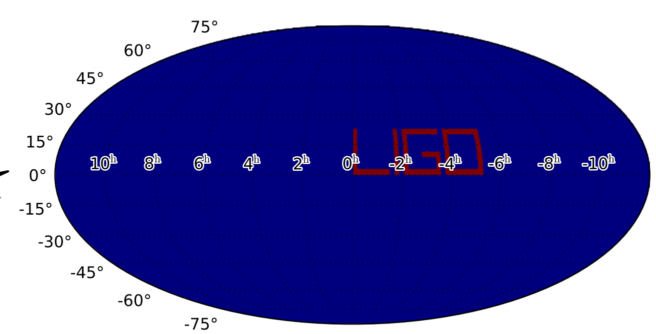
- Analogous to a convolution integral

Kernel/FOV



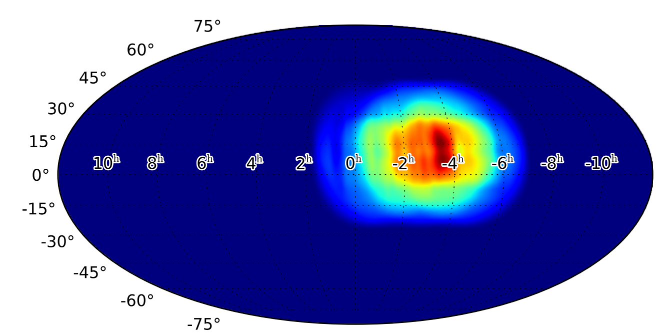
$\star$

GW sky map



$=$

"Cross-correlation"



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

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

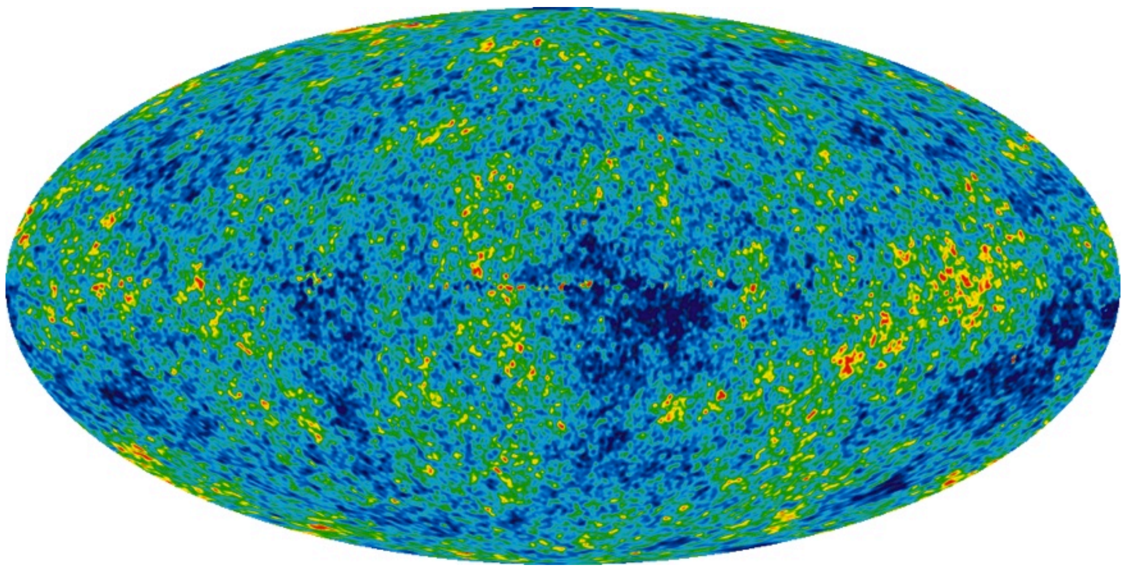
$p_i \triangleq p(\mathrm{EM}_i|\gamma_i,\mathrm{GW}) = \int s(\omega) b_i(\gamma_i^{-1}\omega)\,\mathrm{d}\Omega$

- Maximum of this integral is optimal pointing:

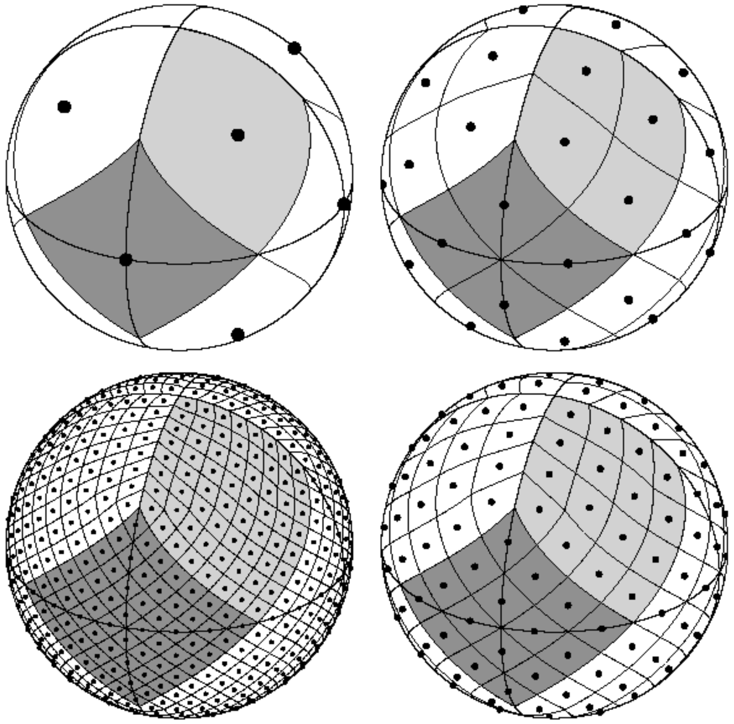
$$\gamma_i^* \triangleq \arg\max_{\gamma_i} p(\mathrm{EM}_i|\gamma_i,\mathrm{GW})$$

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

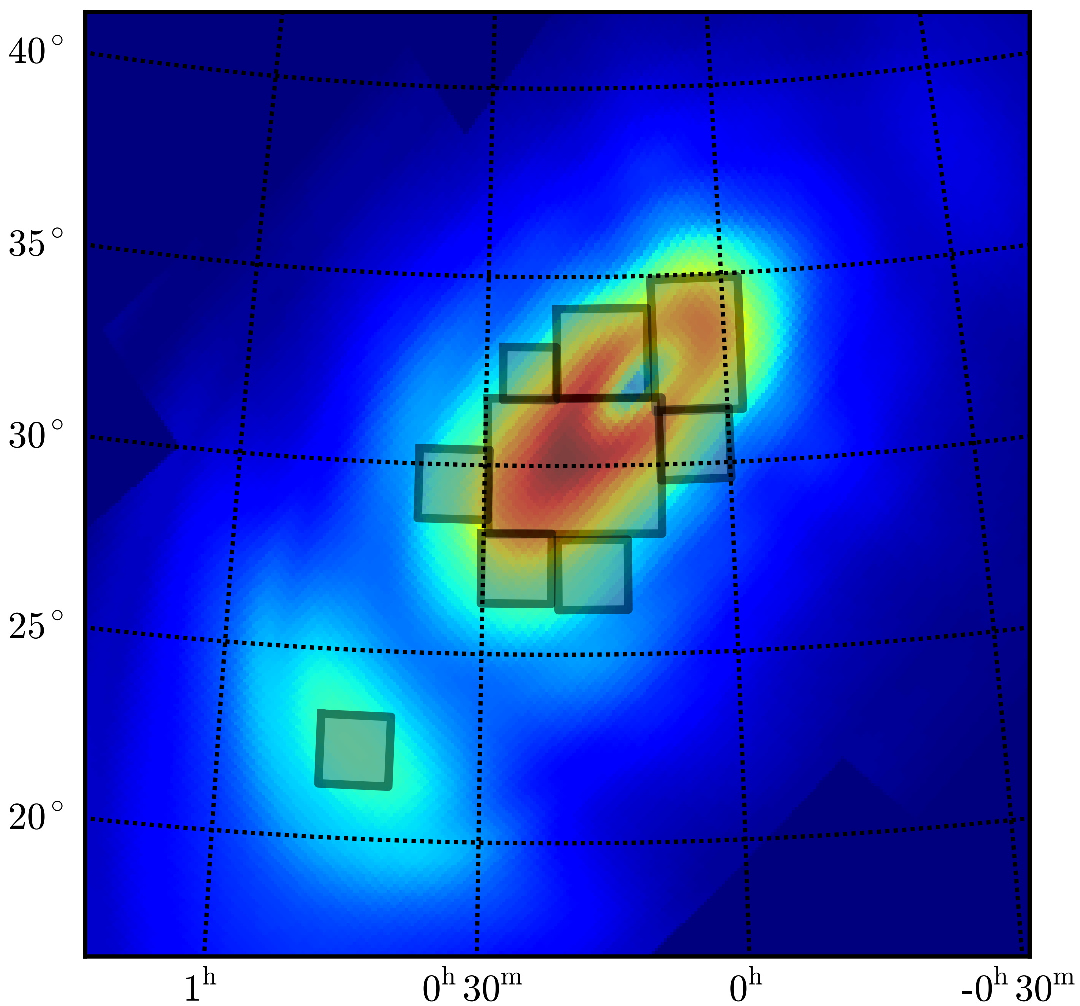


WMAP 7-year survey from
http://map.gsfc.nasa.gov/media/101080/index.html



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

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.

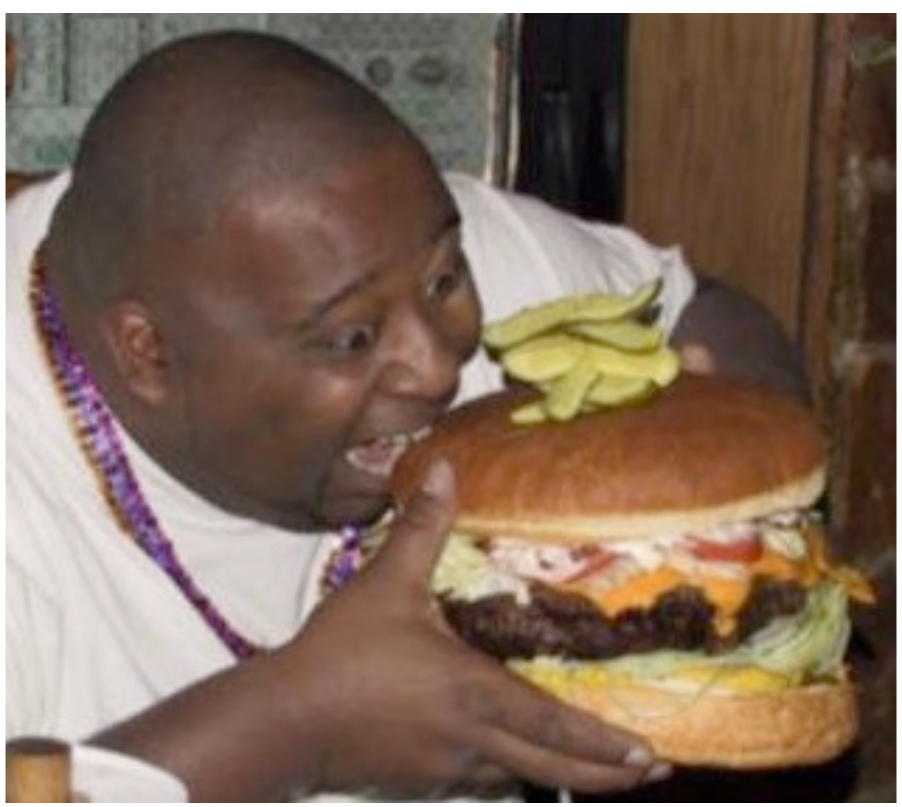
Not very efficient if there are many telescopes, but works reasonably well if coverage is poor.

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

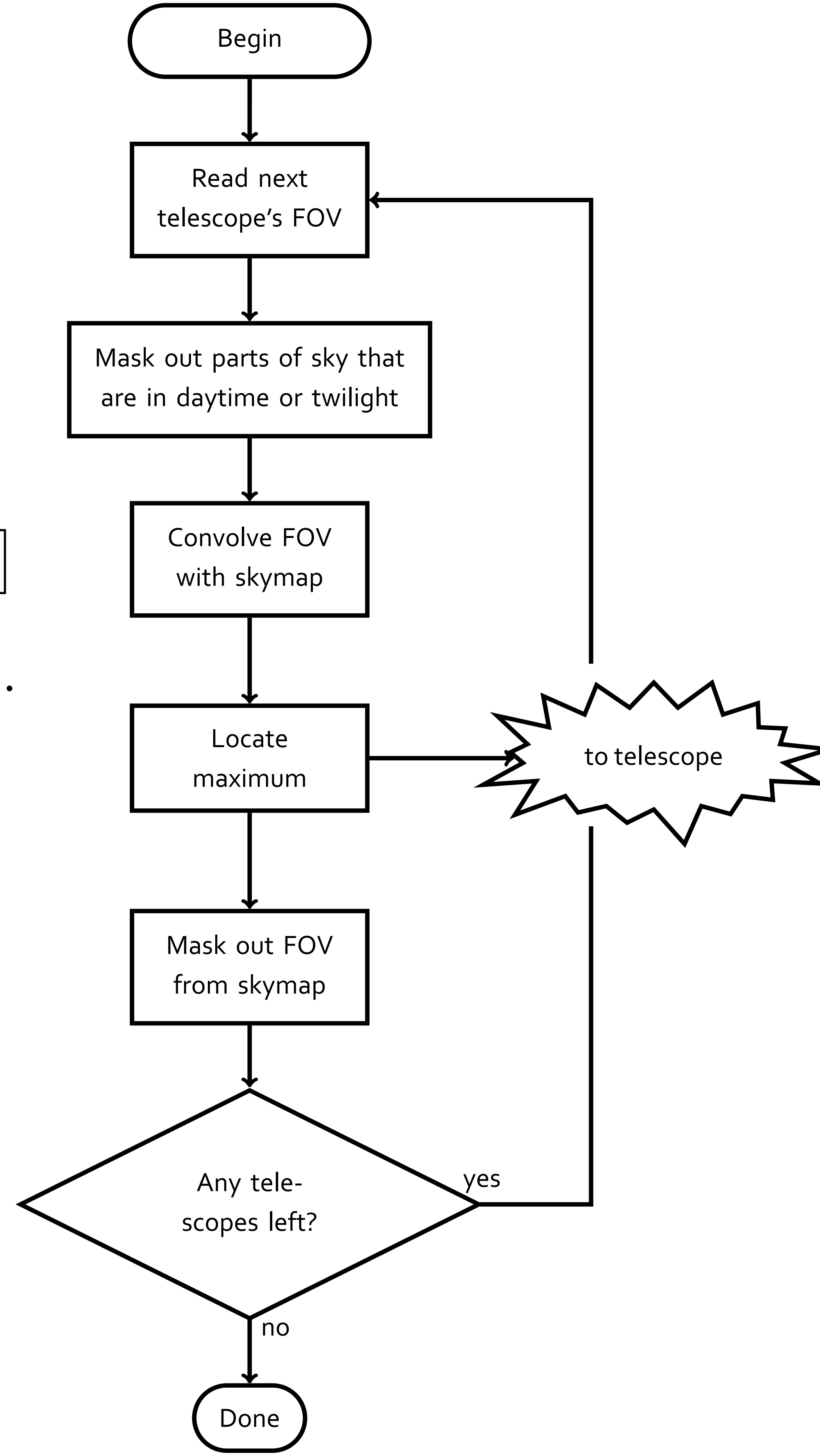
Greedy planner

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/

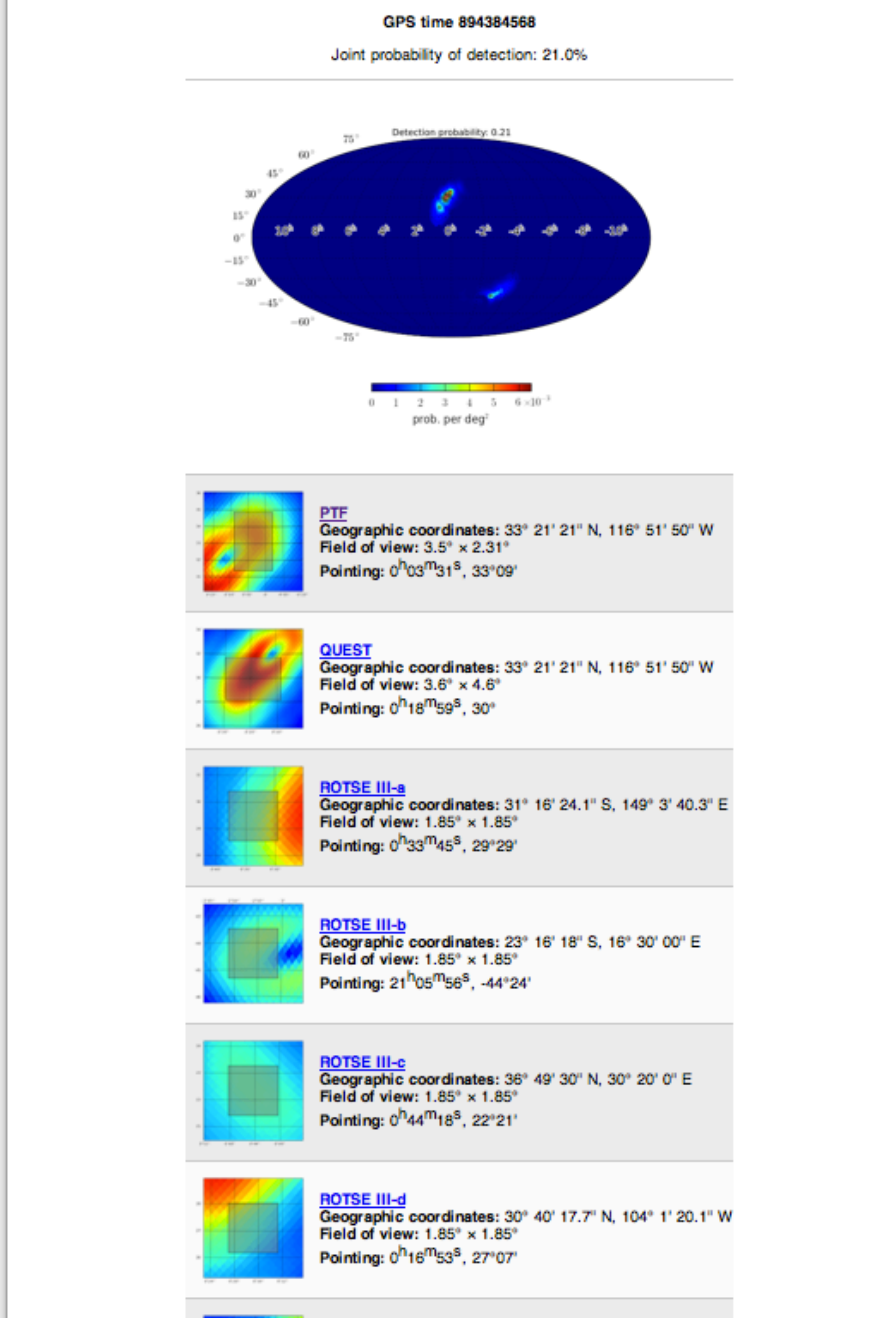
Plug prob. of imaging source into good old *scipy.optimize.anneal*!

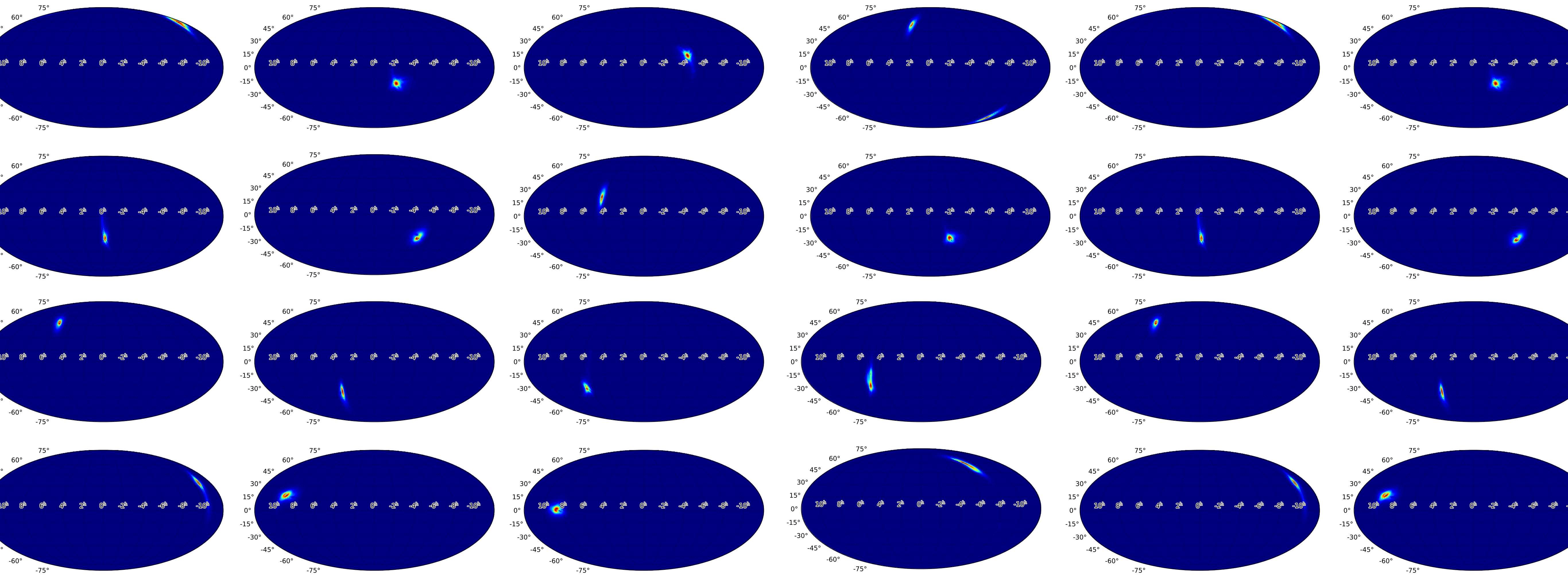
Use modified "fast annealing" schedule of L. Ingber (1989).

BAYESTAR

BAYEsian optimal **S**earch for **T**ransients with **A**utonomous and **R**obotic telescopes

Parallelized, C/C++/Python code for generating ***optimal*** tilings of the sky for ***coordinated***, ***simultaneous*** optical followup of GW candidates.

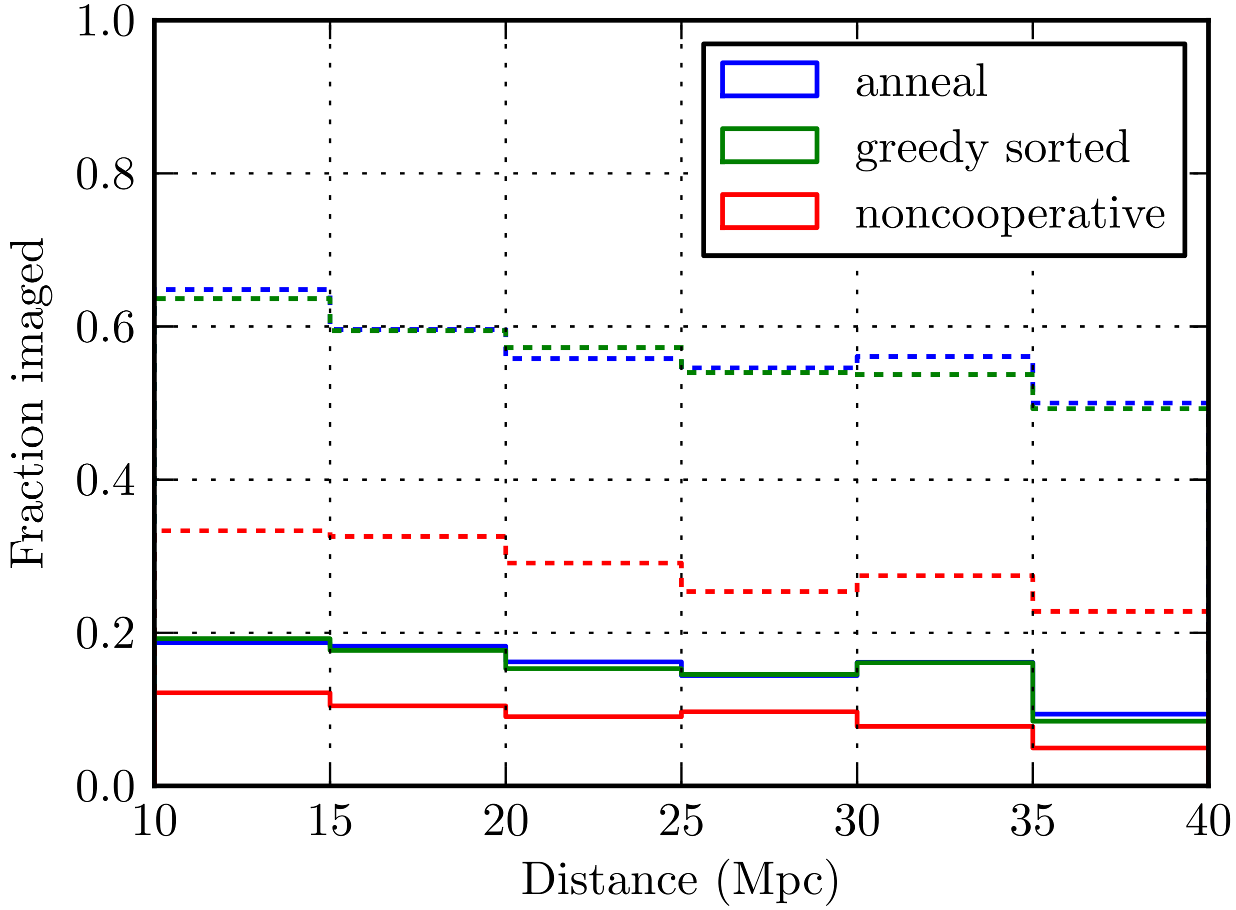




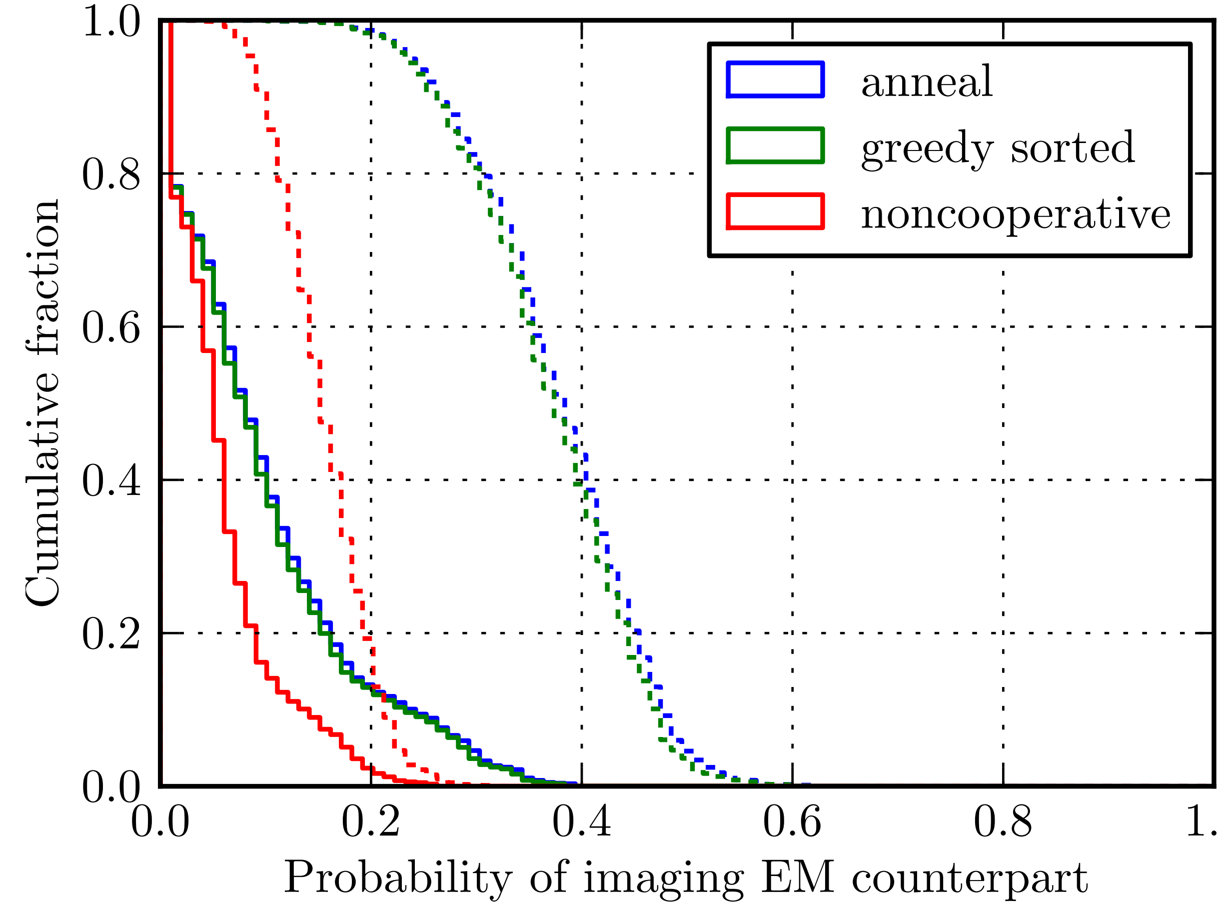
Case study

- 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!



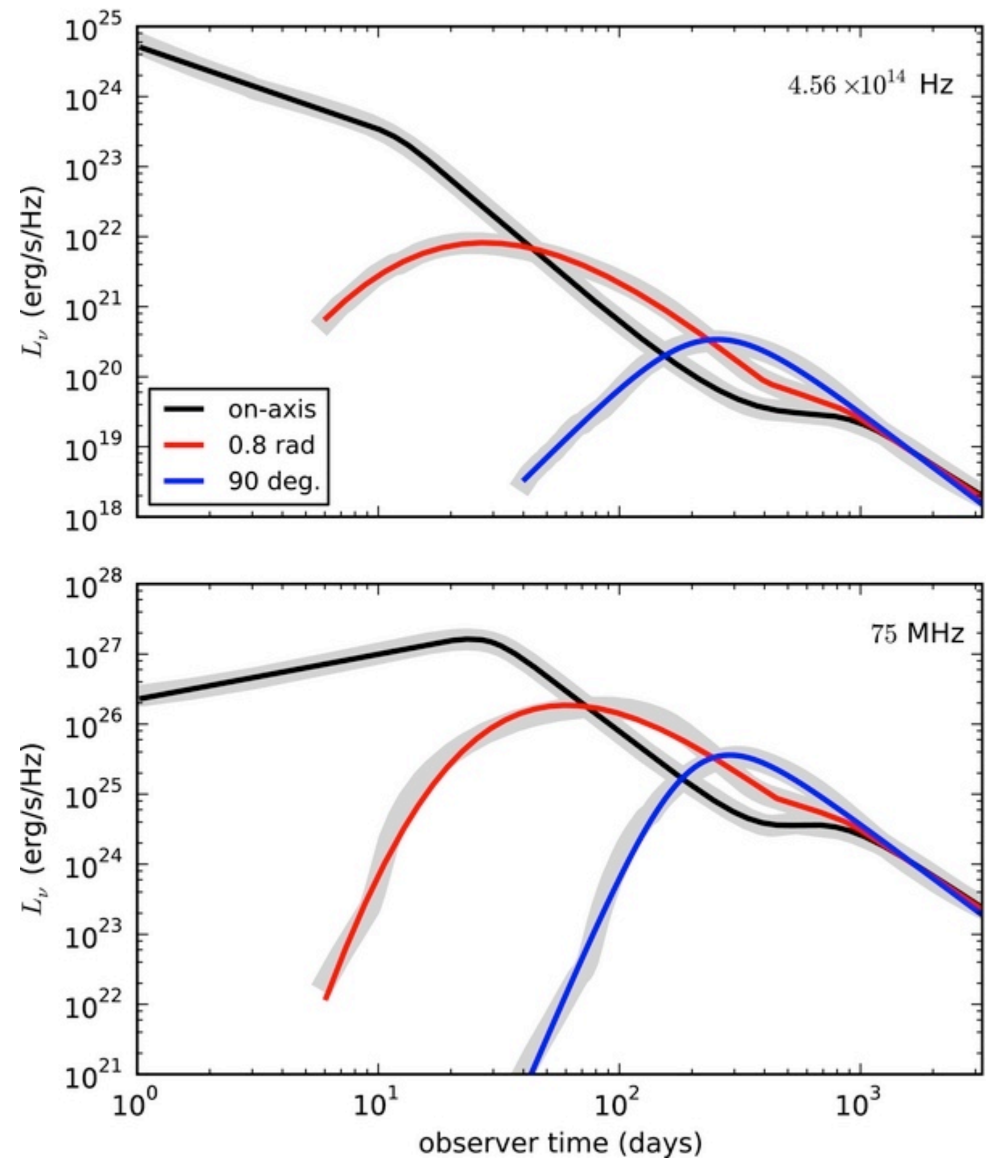
plots from Singer, Price, and Speranza (in preparation)



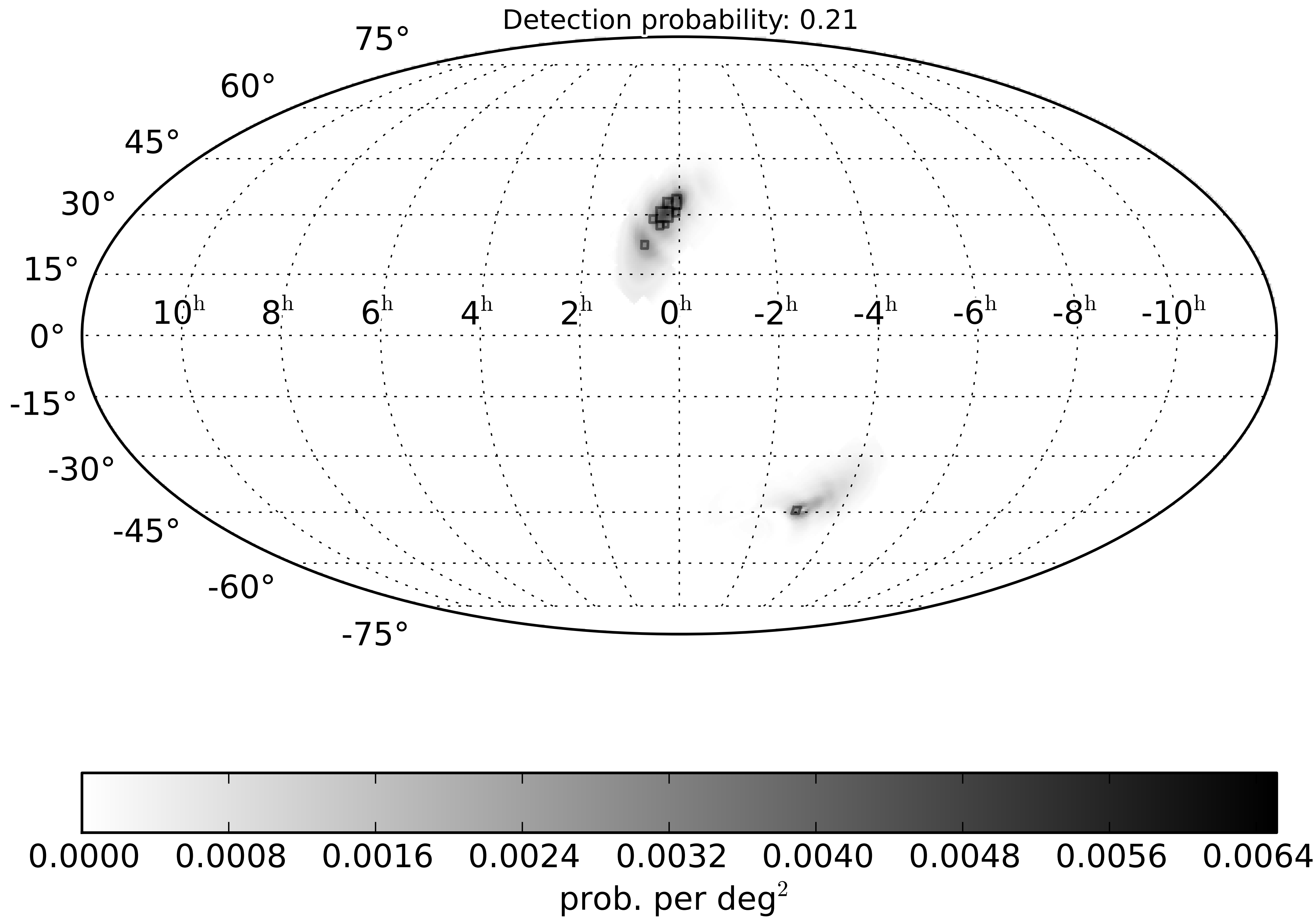
If we want to image an EM counterpart ***as soon as possible*** after the GW trigger, ***coordinating*** observations by many telescopes ***drastically increases our odds*** as compared to deciding where to point each telescope independent of all of the others.

What's next?

- Efficient use of ***limited observational resources***: cannot follow up everything, ***not even all GW candidates***
- We have answered ***where*** to point, but now we want to know ***when*** to use ***what*** telescopes
- For ***faint*** counterparts (kilonovas and slightly off axis afterglows), can any gain in efficiency be had by ***distributing*** followup over ***multiple survey telescopes***?
- ***What*** optical counterparts are we likely to see in the ***advanced GW detector era***?

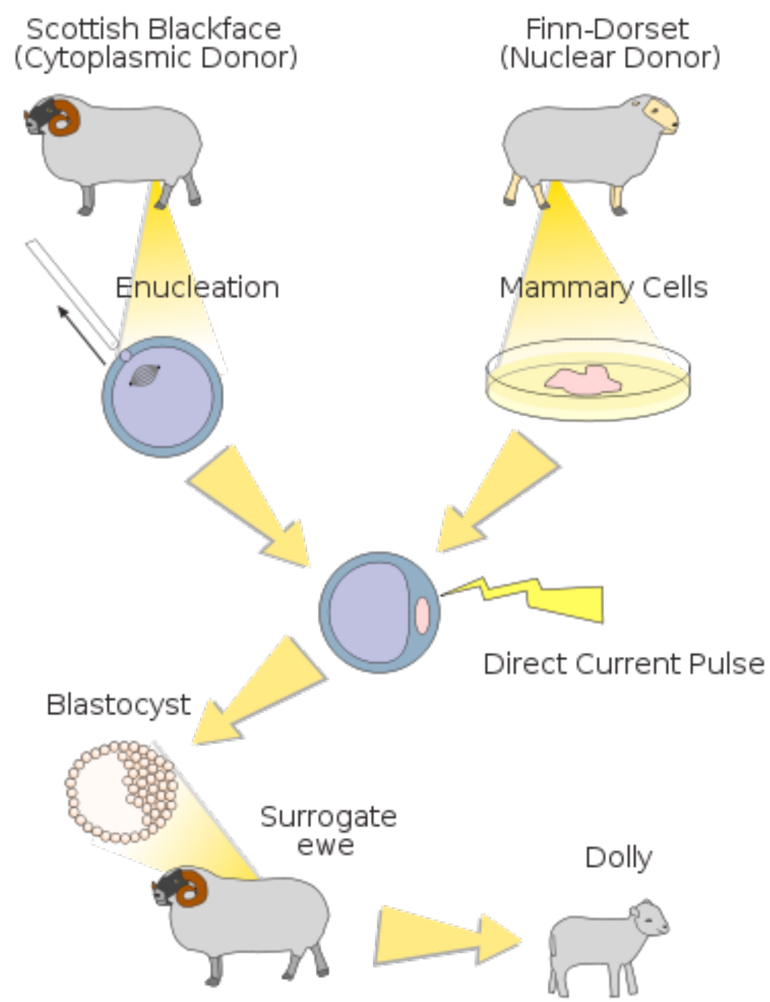


Hendrik J. van Eerten and Andrew I. MacFadyen 2011 ApJ 733 L37 doi:10.1088/2041-8205/733/2/L37
SYNTHETIC OFF-AXIS LIGHT CURVES FOR LOW-ENERGY GAMMA-RAY BURSTS


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

CLONE ME



project web page

`http://www.lsc-group.phys.uwm.edu/daswg/projects/bayestar.html`

git repository

`git clone git://ligo-vcs.phys.uwm.edu/bayestar`

web repository browser

`http://www.lsc-group.phys.uwm.edu/cgit/bayestar/`

image from http://en.wikipedia.org/wiki/Cloning