Finding Electromagnetic Counterparts of Gravitational Wave Signals in the Transient Universe

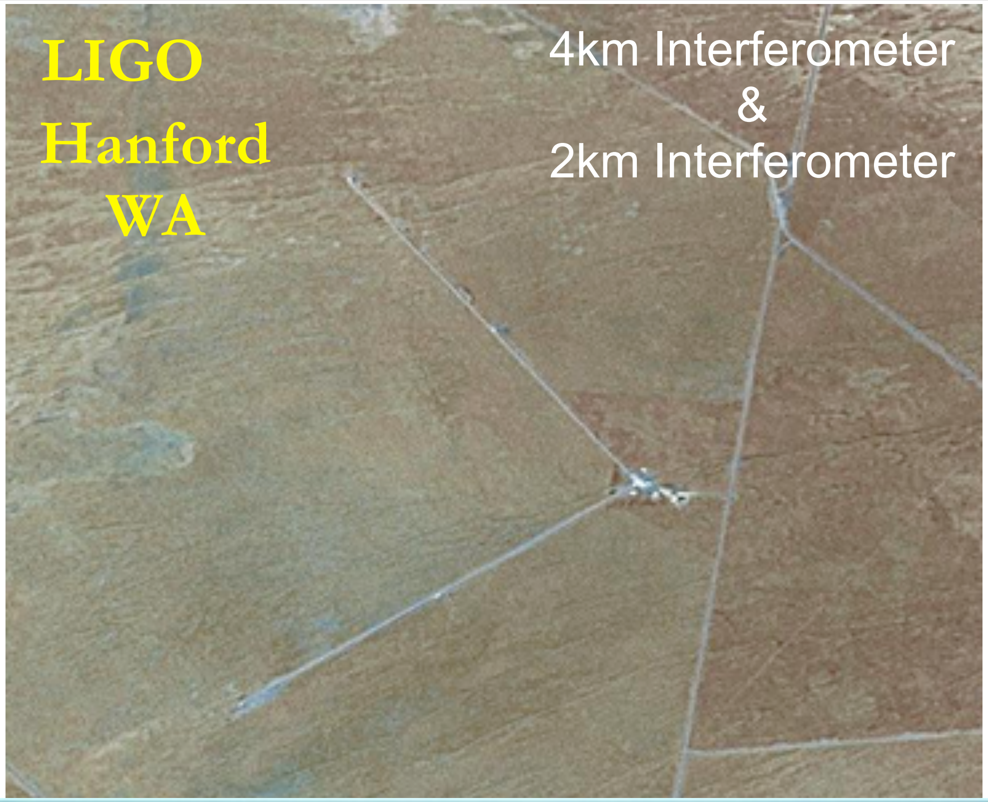
Larry Price

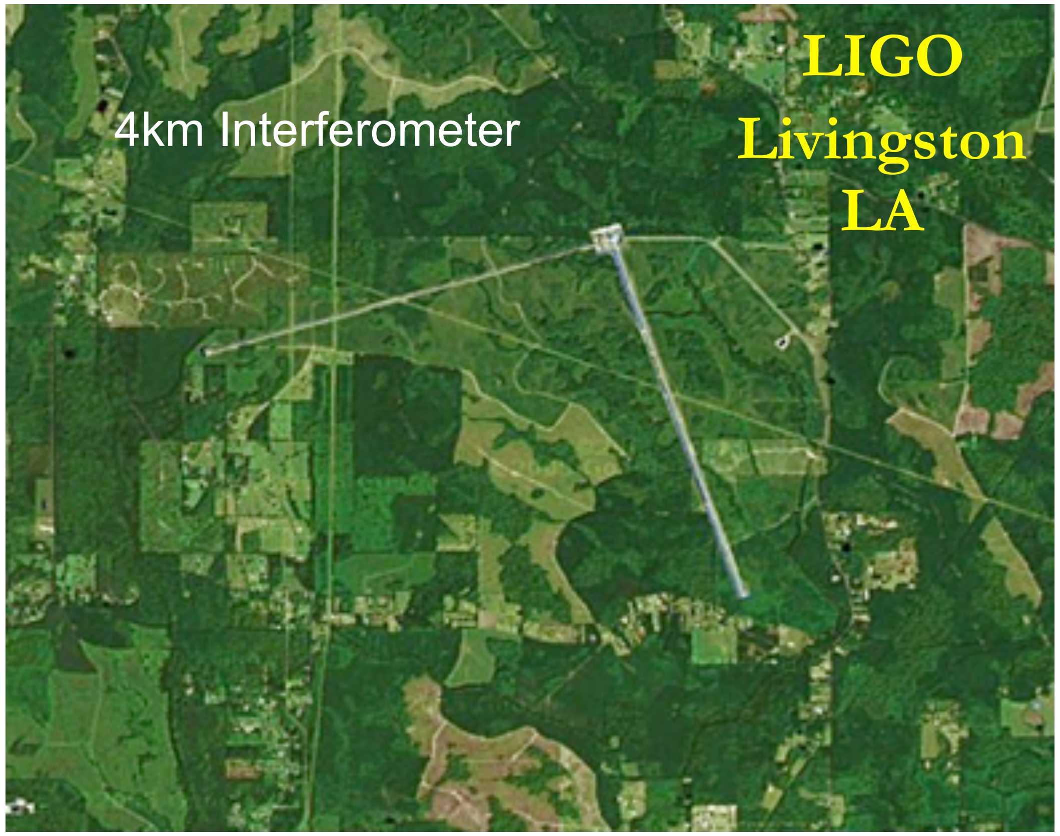
Caltech 11.1.11

The Plan

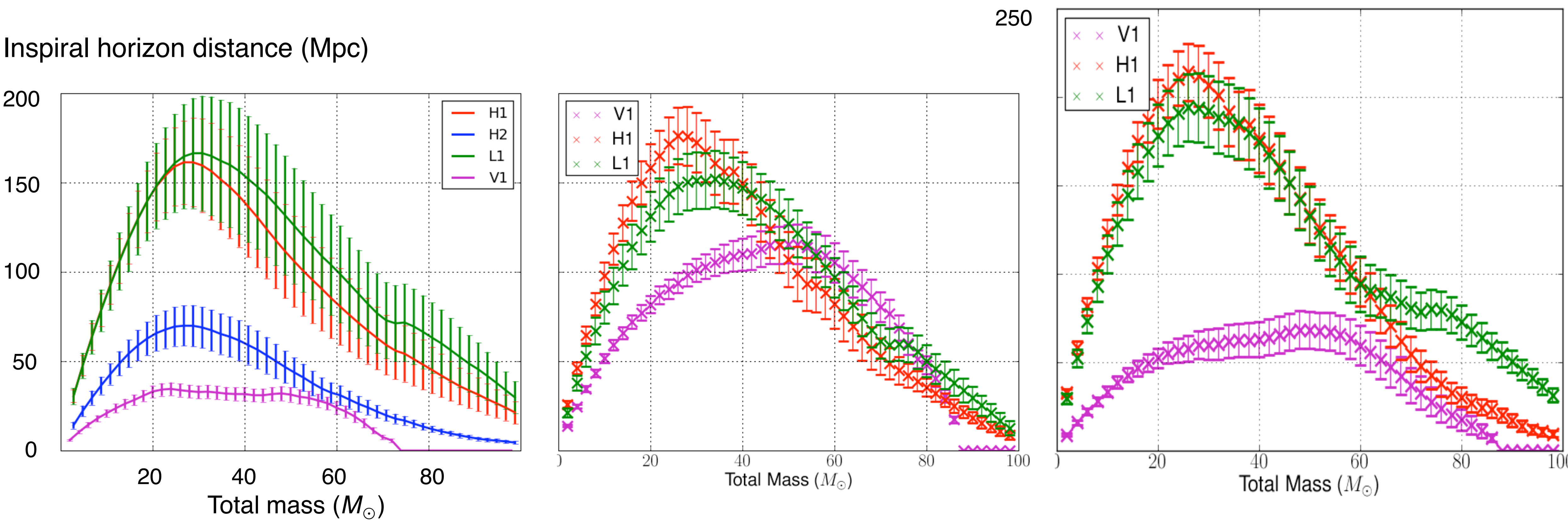
- Introduction
- Past and present multimessenger efforts with LIGO & Virgo
    - ExtTrig
    - LOOCUP
- Looking towards aLIGO

I got IFOs in different area codes





Sensitivity gains over time



S5/VSR1 Start of S6/VSR2 End of S6/VSR3

Multimessenger Astronomy: An overview

Gravitational wave and electromagnetic signals provide complimentary information about an event.

- GW
  - Progenitor properties, e.g. mass
  - Luminosity distance
  - Bulk motion dynamics
  - Direct probe of the central engine
- EM
  - Sky location
  - Host galaxy
  - Redshift
  - Gas environment

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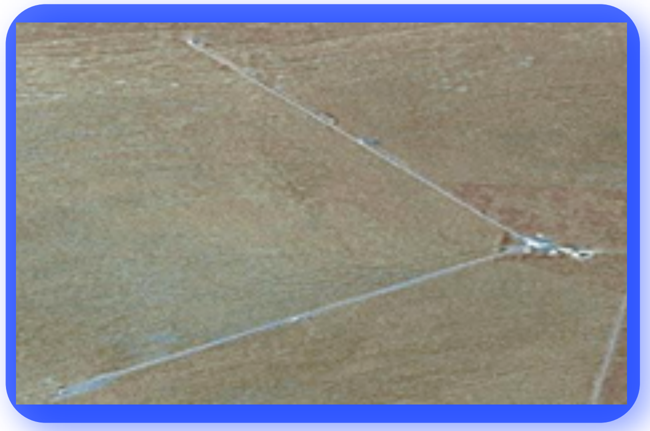
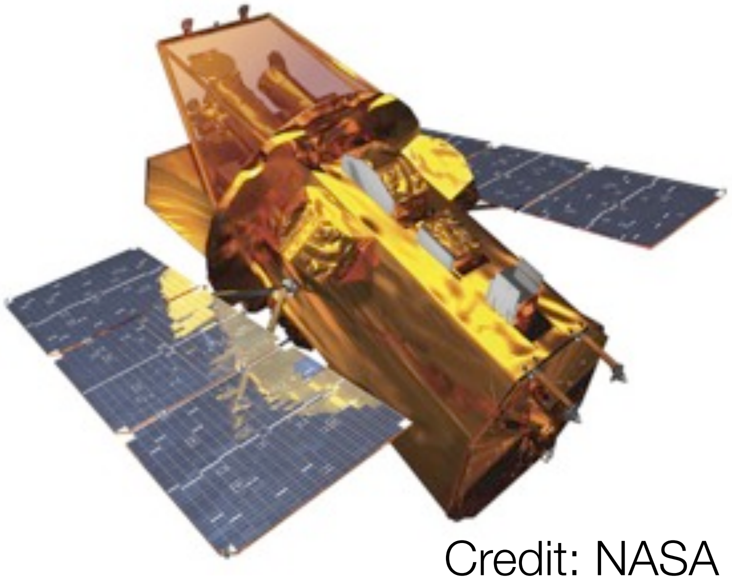
Information from both gives us a more complete picture of the event

Two types of GW+EM searches





Credit: NASA

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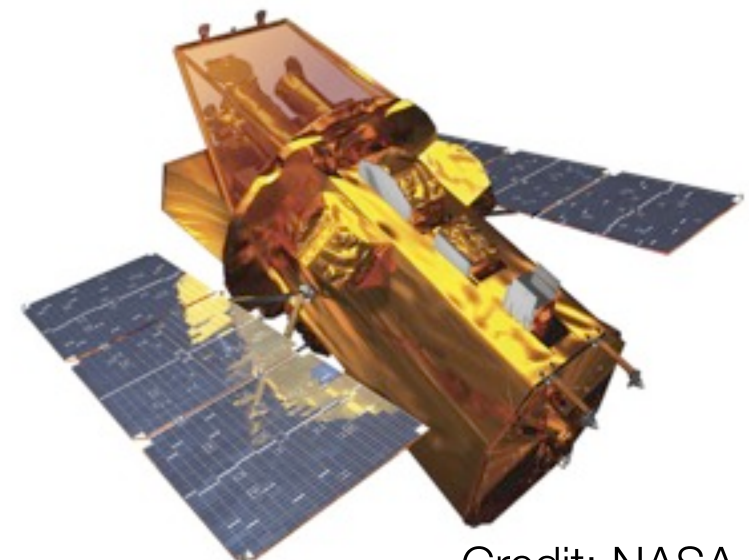
Credit: ROTSE

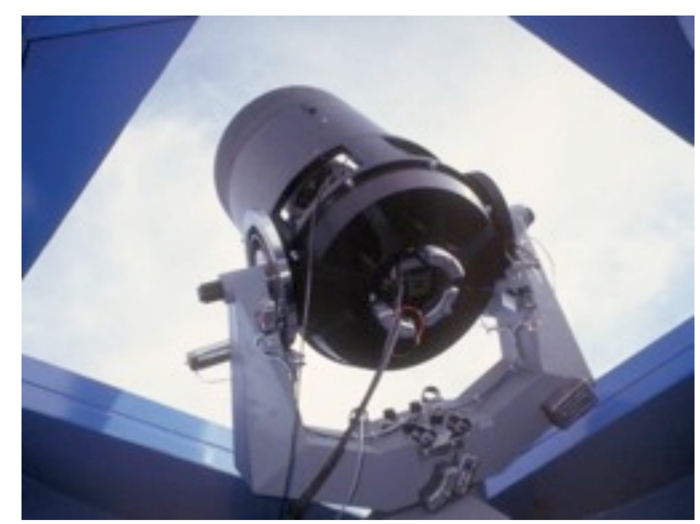
Two types of GW+EM searches

ExtTrig

Allows for a more sensitive search by focusing on a short period of data and a single sky location.

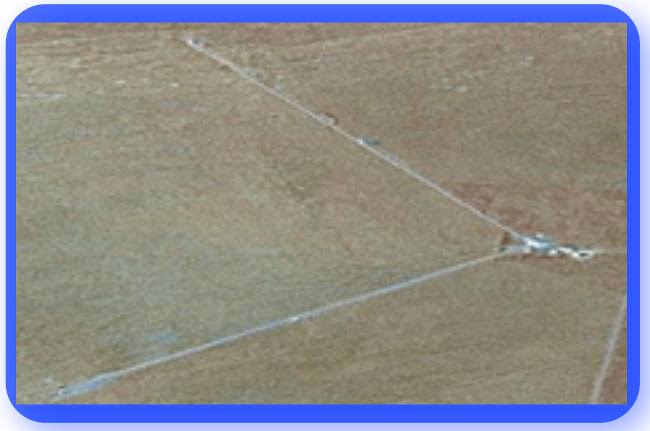


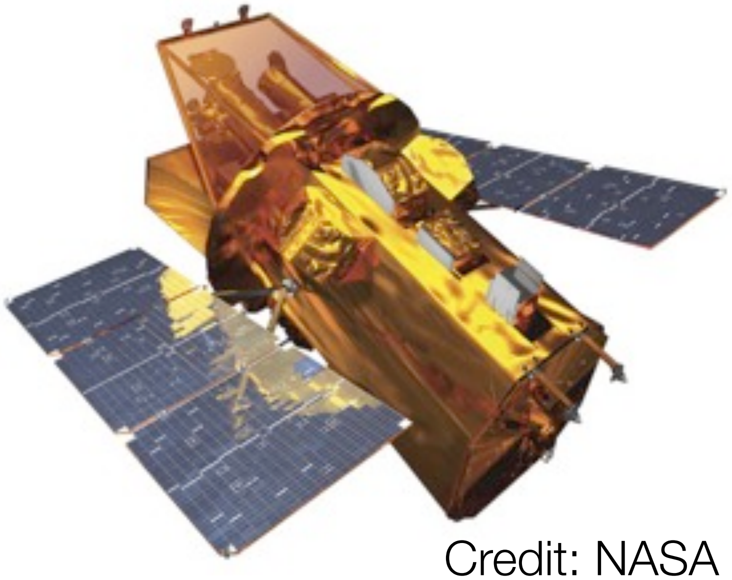
Credit: NASA



Credit: ROTSE

Two types of GW+EM searches





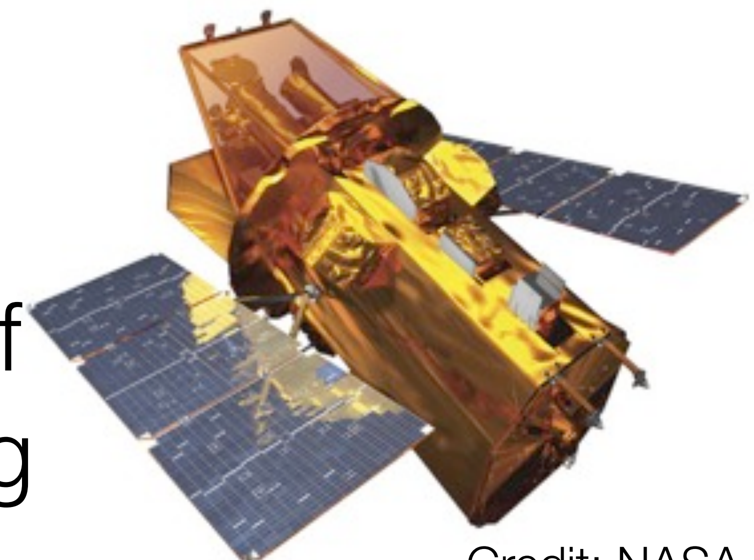
Credit: NASA

Credit: ROTSE

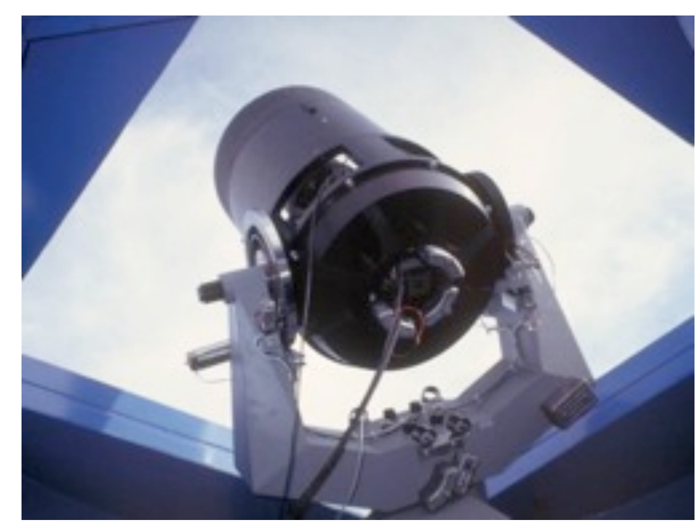
Two types of GW+EM searches

Allows for possibility of imaging corresponding EM signals as they occur.

LOOCUP



Credit: NASA



Credit: ROTSE

GRB 070201: A success story

LIGO observations ruled out an inspiral progenitor in M31 at >99% confidence.* They allow a soft gamma repeater (SGR) progenitor.†

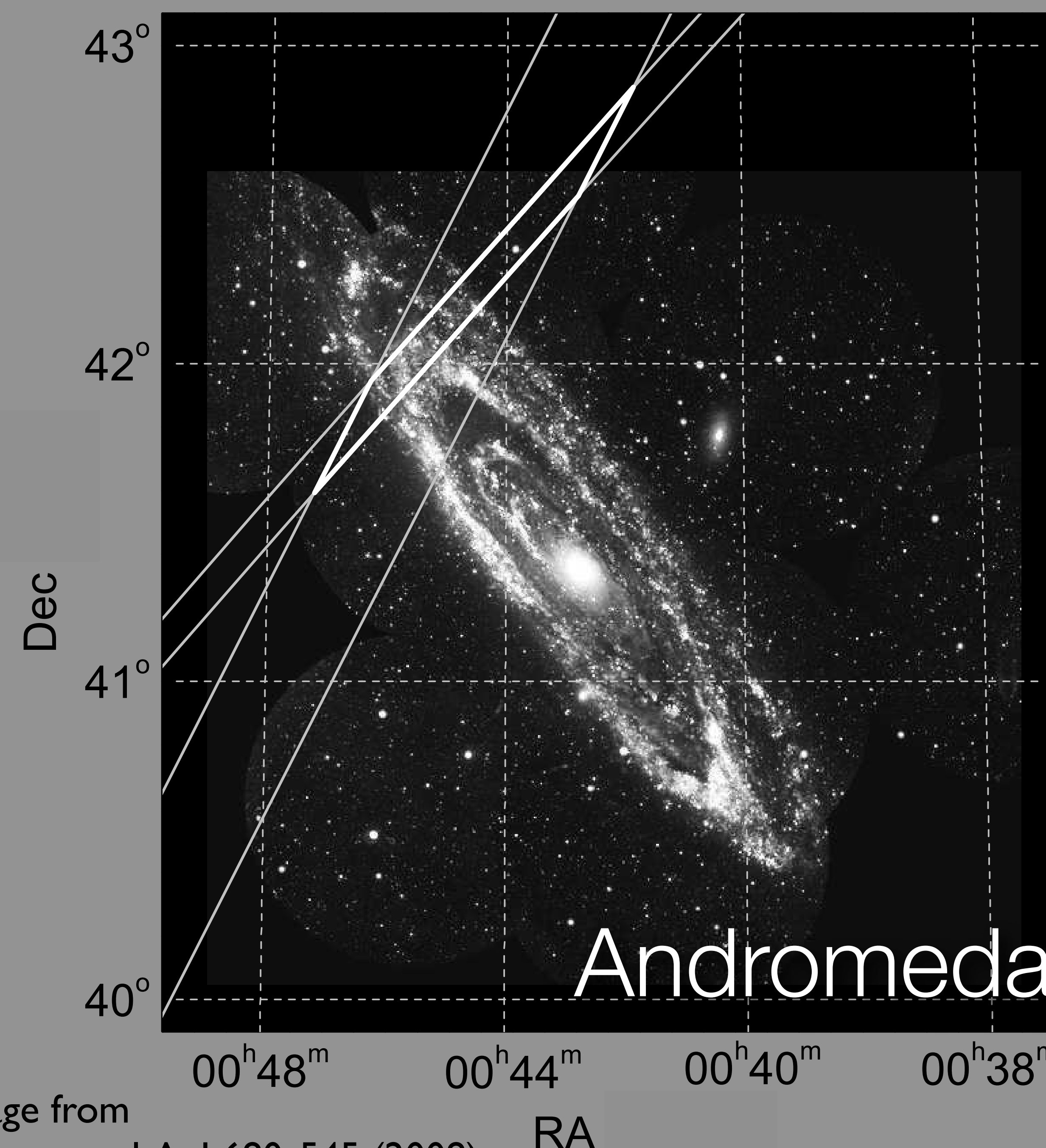


Image from
Mazets et al, ApJ 680, 545 (2008)

* Abbott et al, ApJ 681, 1419 (2008)

† Ofek et al, ApJ 681, 1464 (2008);
Mazets et al, ApJ 680, 545 (2008)

GRB 070201: A success story

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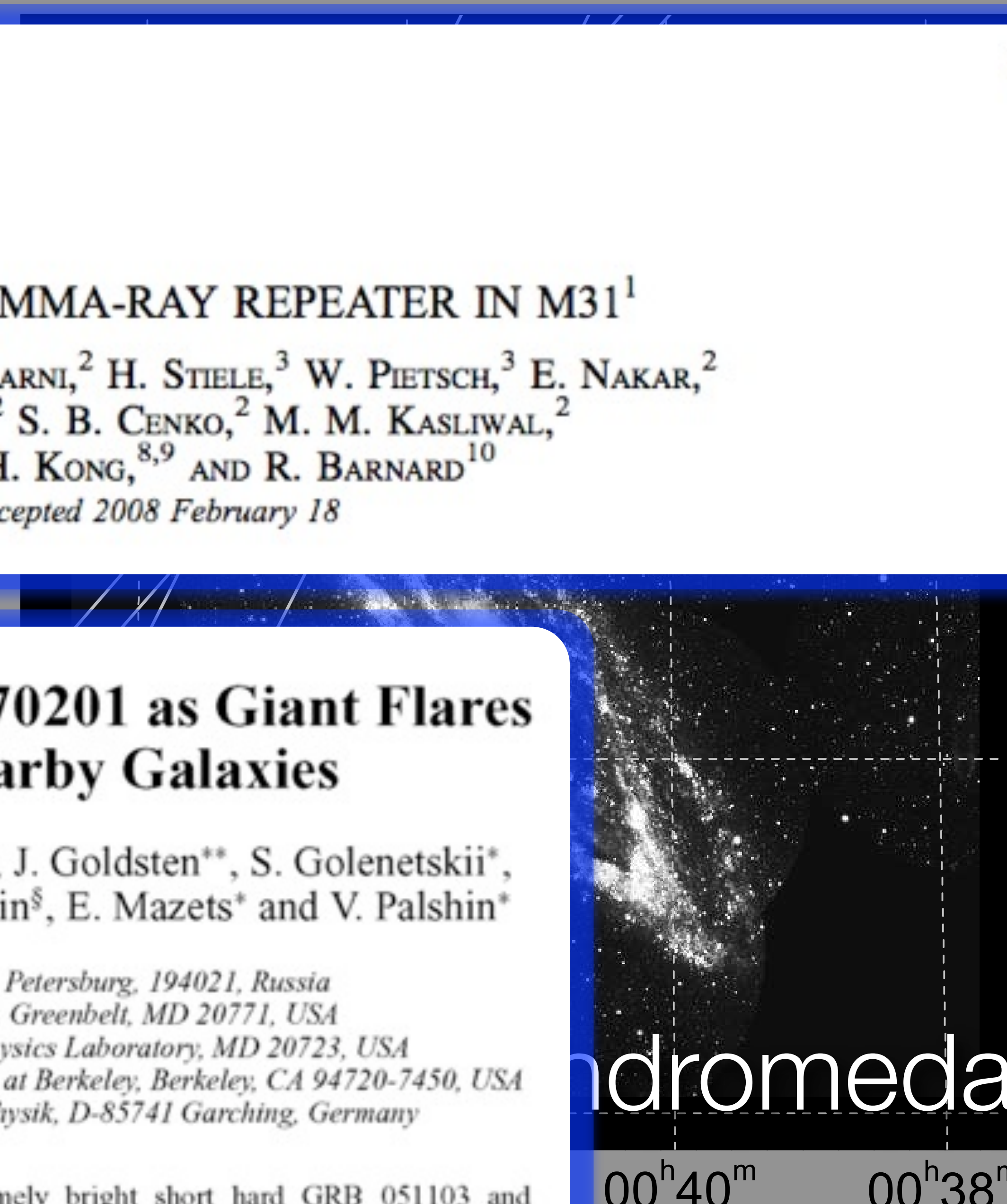
THE ASTROPHYSICAL JOURNAL, 681:1464–1469, 2008 July 10

GRB 070201: A POSSIBLE SOFT GAMMA-RAY REPEATER IN M31[1]

E. O. OFEK,[2] M. MUNO,[2] R. QUIMBY,[2] S. R. KULKARNI,[2] H. STIELE,[3] W. PIETSCH,[3] E. NAKAR,[2]
A. GAL-YAM,[4] A. RAU,[2] P. B. CAMERON,[2] S. B. CENKO,[2] M. M. KASLIWAL,[2]
D. B. FOX,[5] P. CHANDRA,[6,7] A. K. H. KONG,[8,9] AND R. BARNARD[10]
Received 2007 December 13; accepted 2008 February 18



GRB 051103 and GRB 070201 as Giant Flares from SGRs in Nearby Galaxies

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Abstract. The Konus-Wind observations of extremely bright short hard GRB 051103 and GRB 070201 are presented. Results of gamma-ray data temporal and spectral analysis together with IPN sources localization are bringing evidences of the bursts being initial pulses of Giant Flares from Soft Gamma-ray Repeaters in the nearby galaxies M81/M82 and M31.

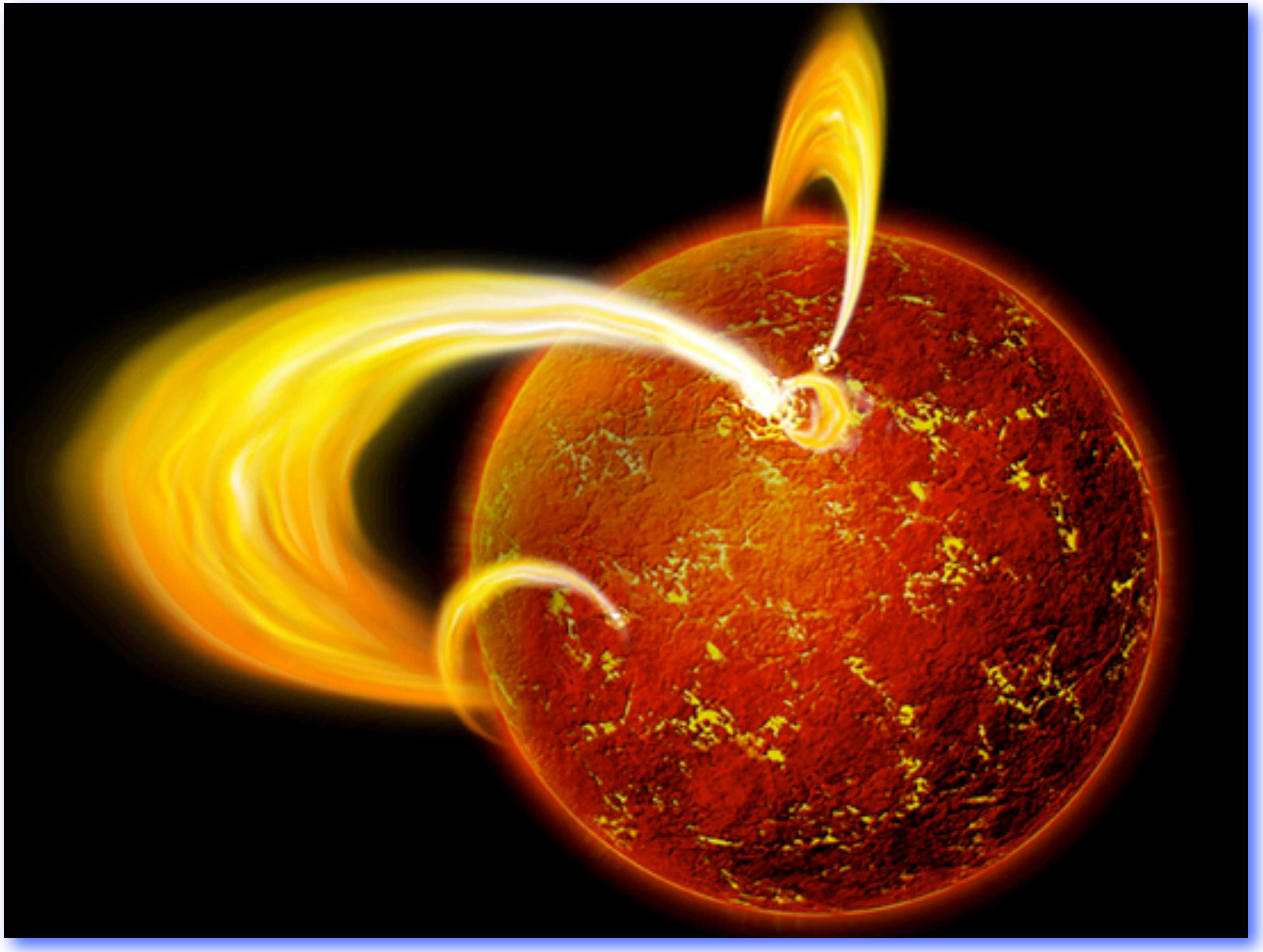
Keywords: gamma-ray bursts, soft gamma-ray repeaters, M31, M81/M82 group
PACS: 95.85.Pw, 98.70.Rz, 98.56.Ne, 97.60.Jd

* Abbott et al, ApJ 68

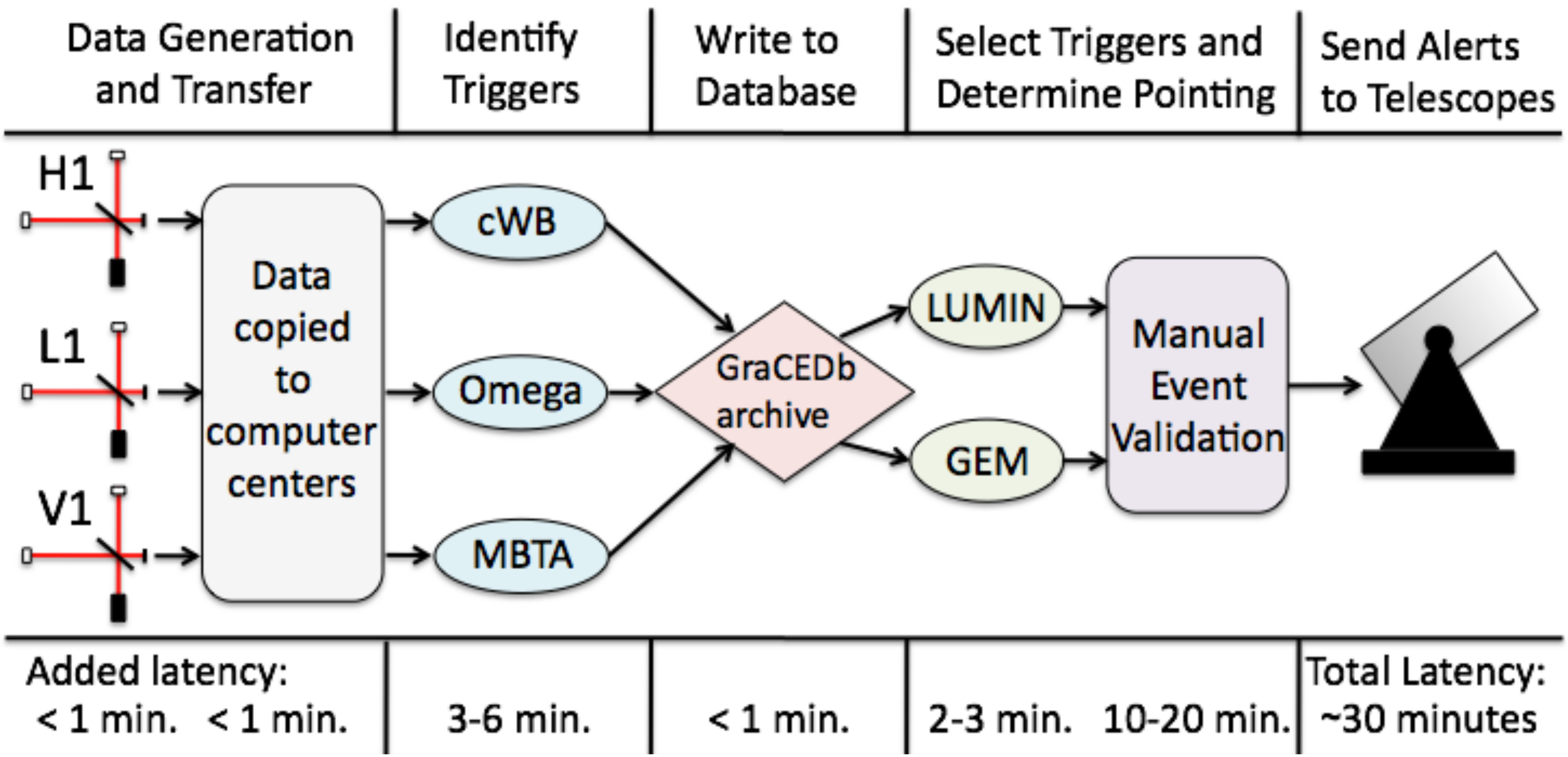
† Ofek et al, ApJ 681,
Mazets et al, ApJ 68

Other ExtTrig efforts

- SGRs
- Supernovae
- Neutrinos
- Radio bursts



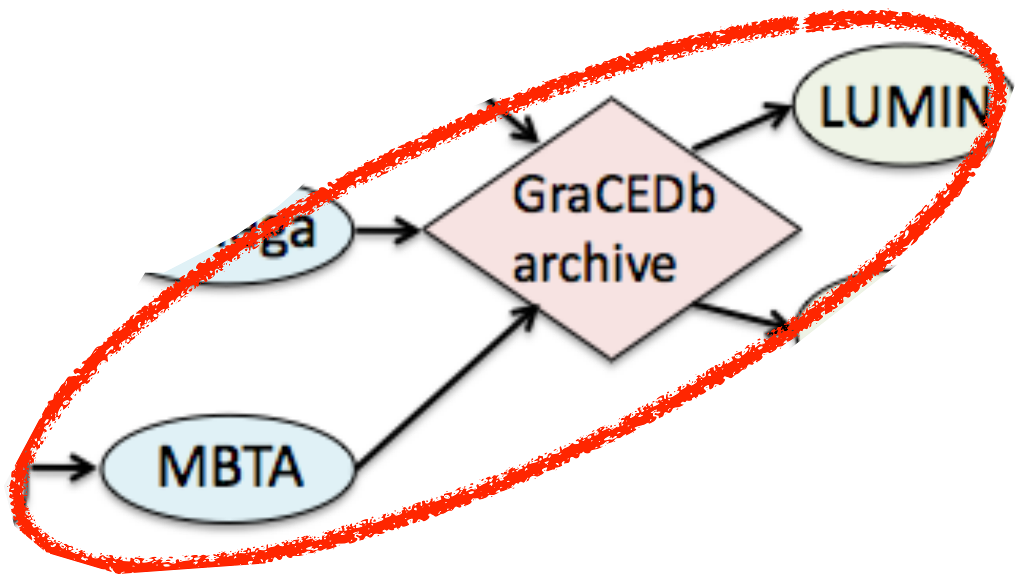
LOOCUP: A work in progress*



Credit: Brennan Hughey and Jameson Rollins

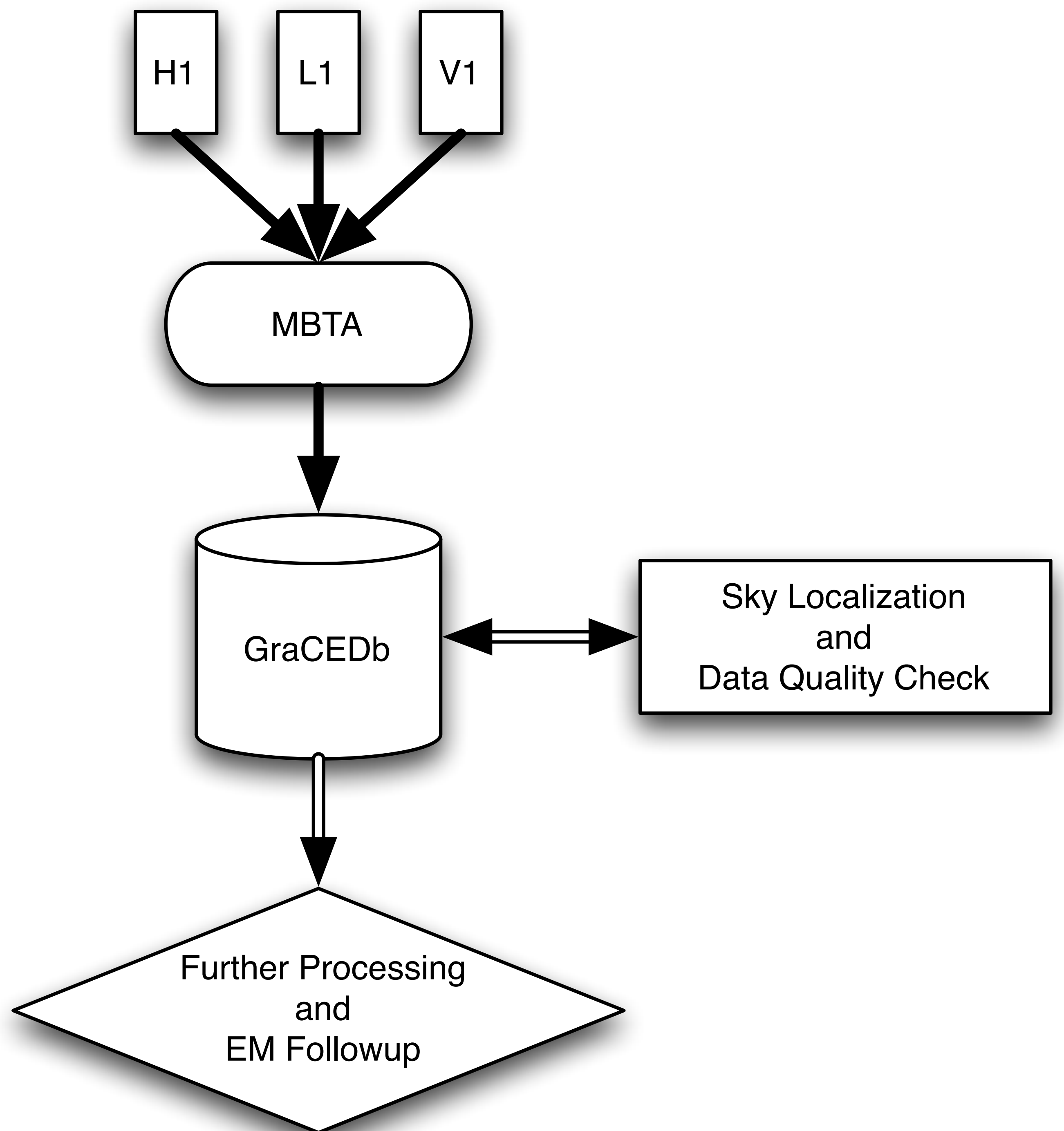
*Final analysis results pending

LOOCUP: A work in progress*



*Final analysis results pending

Overview of the pipeline



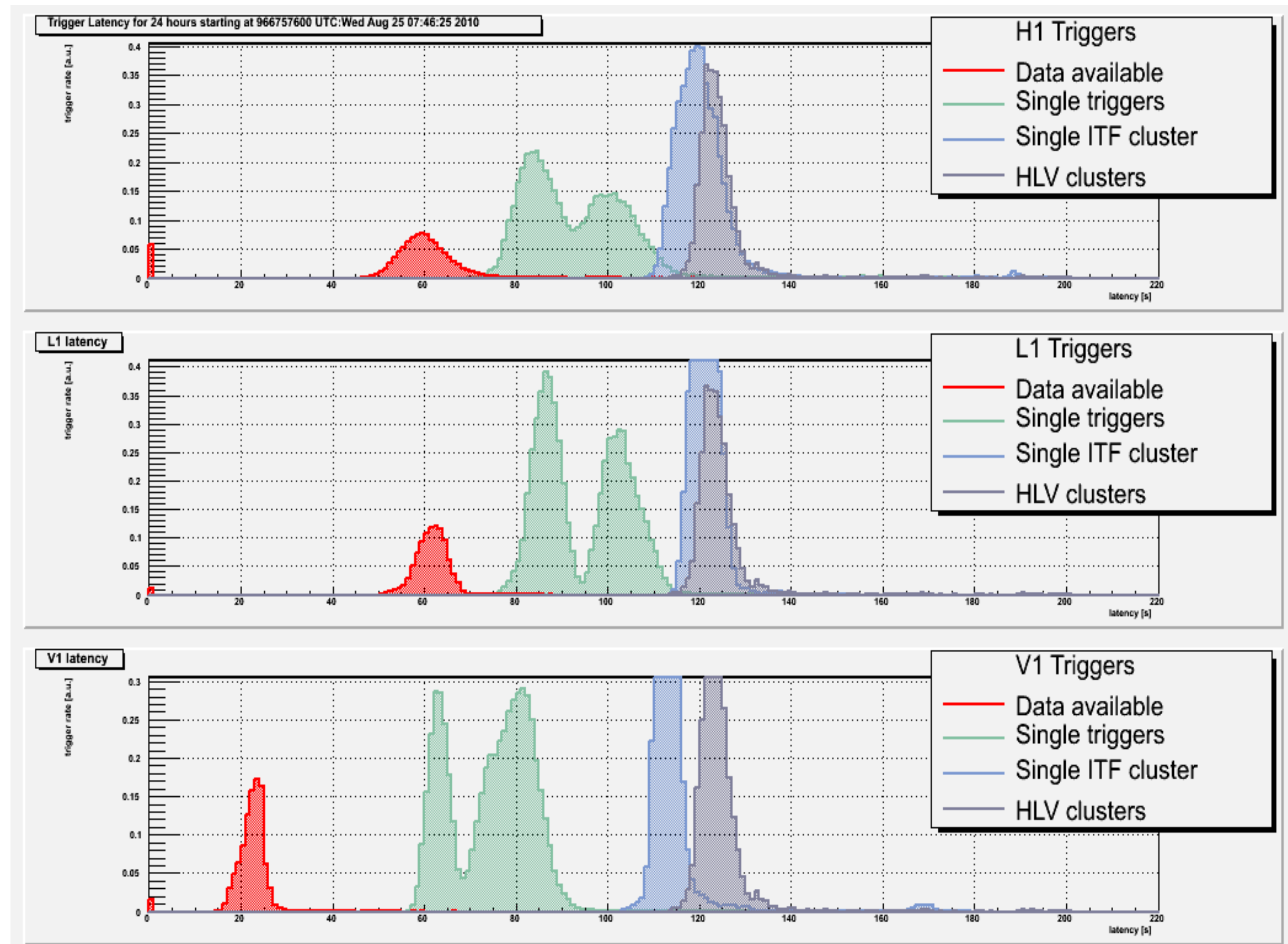
MBTA

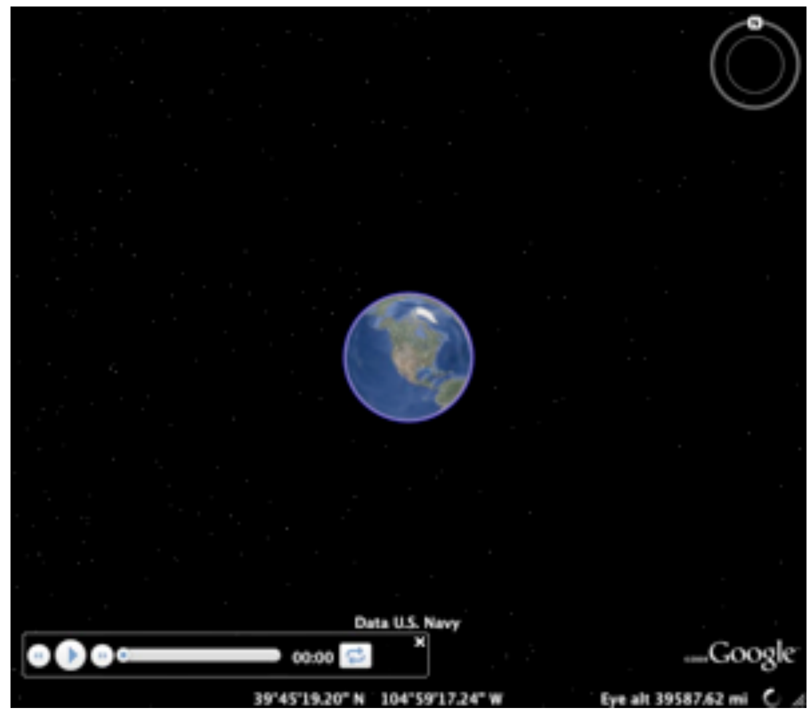
> **M**ulti **B**and **T**emplate **A**nalysis

> Matched filter search (2PN)

> Typical latencies ~ a few minutes, including 1 minute to get h(t)!

> Only triple coincident events sent out for followup



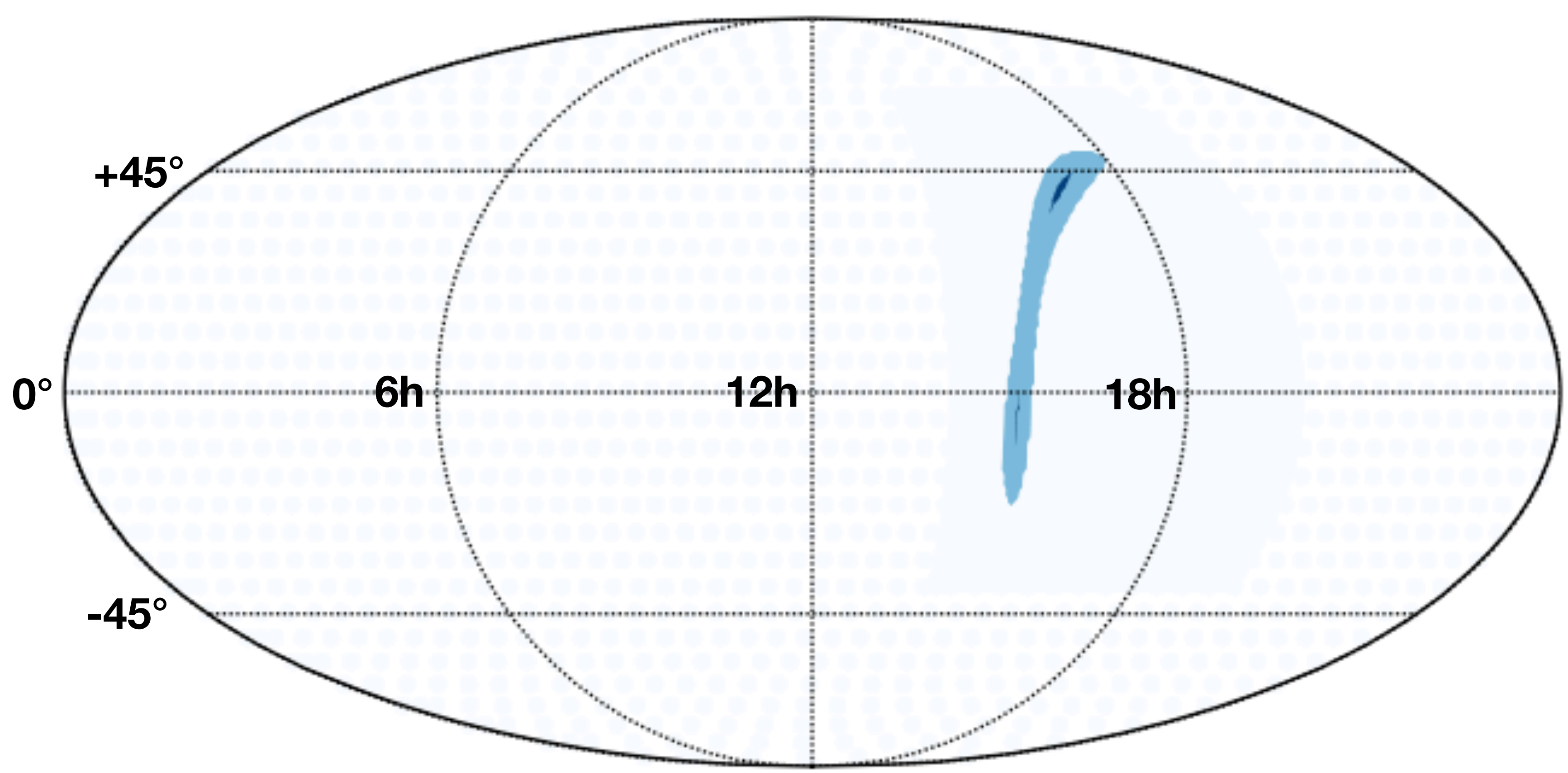


Sky localization

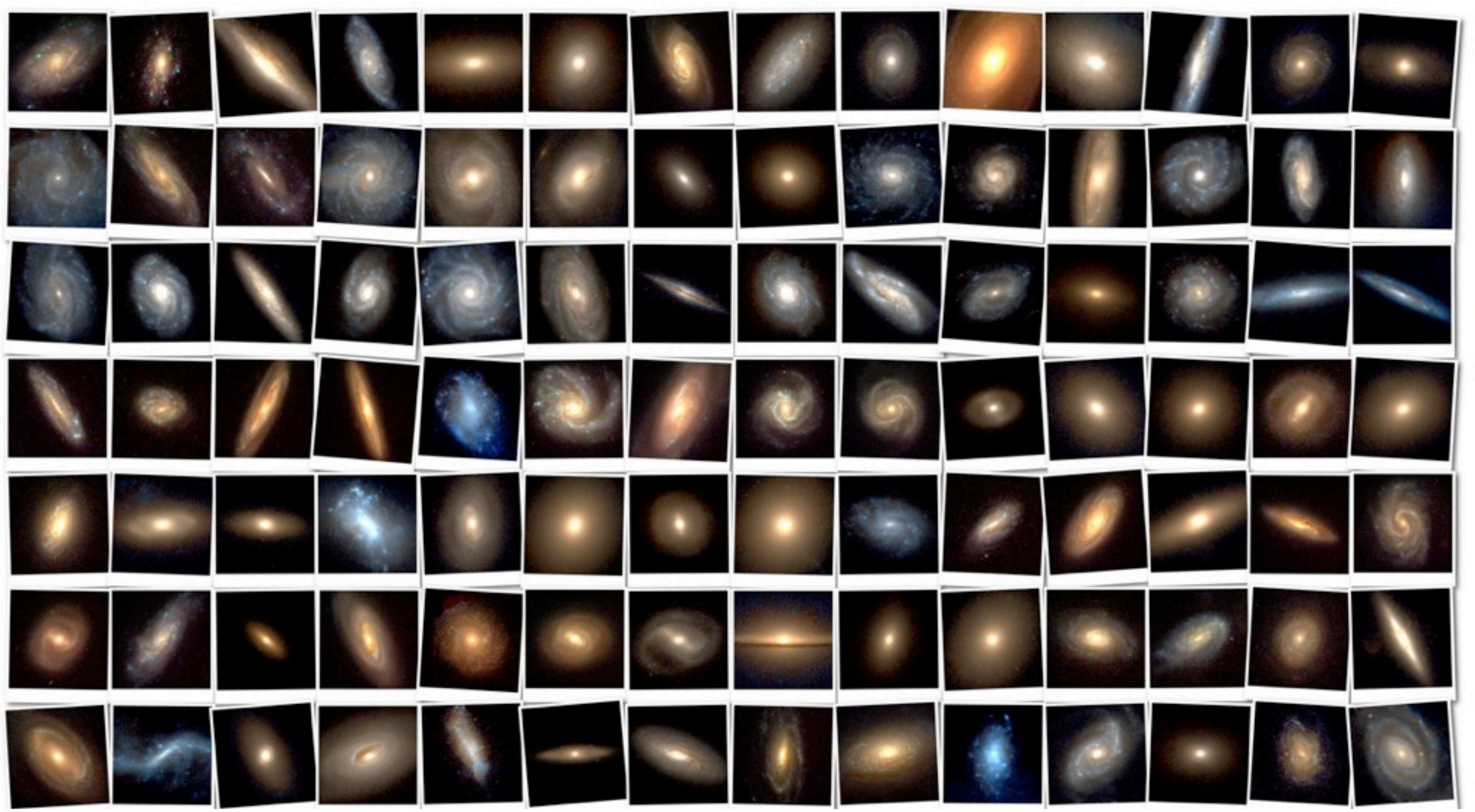
Use the time-delay between detector sites and the amplitude measured at each site to localize sources on the sky.

One big problem

Poor sky localization. Optimistically **tens** of square degrees, even for advanced detectors*.



*Fairhurst (2009)

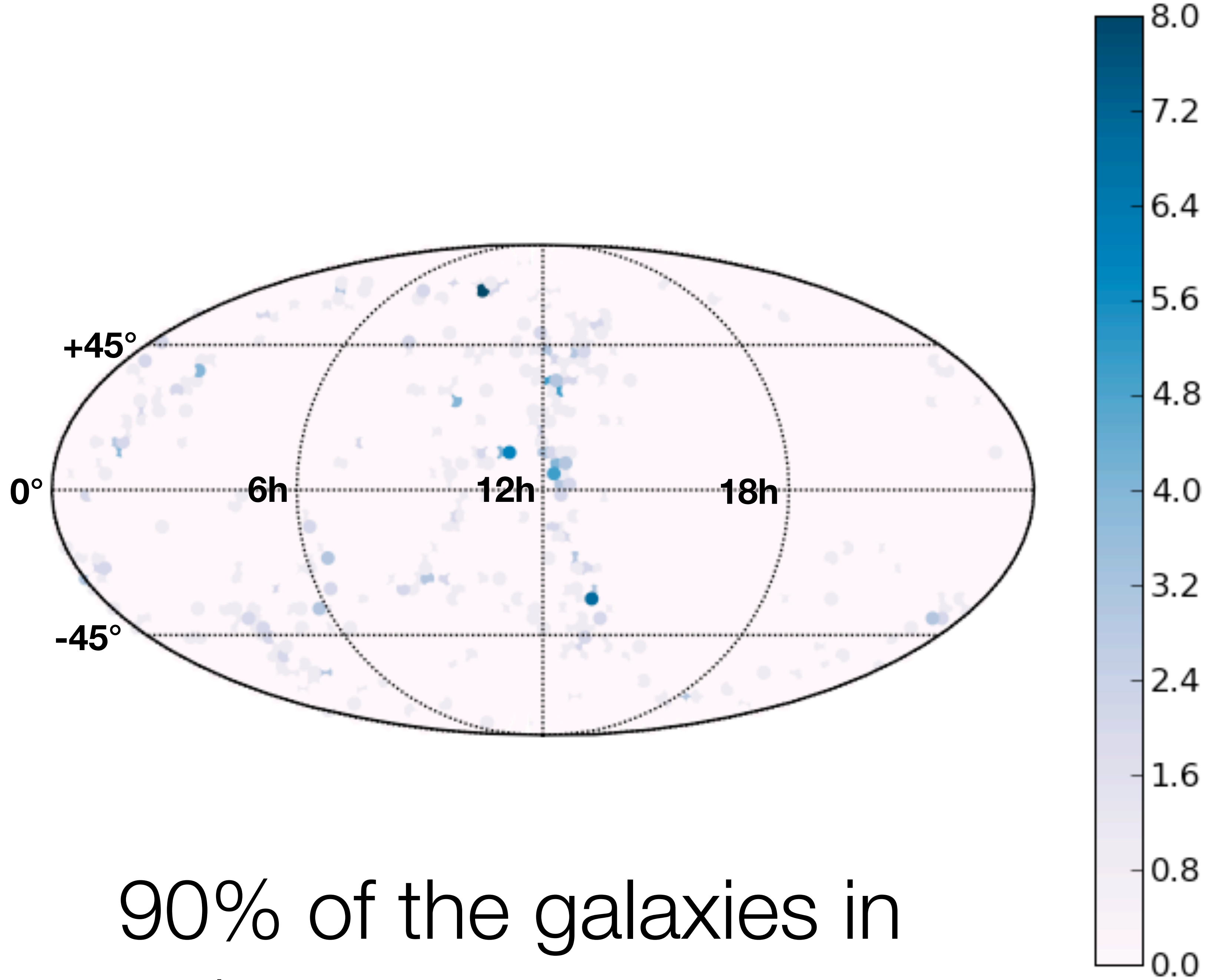


Credit: Zsolt Frei et al (1995)

Incorporating Astrophysical Priors

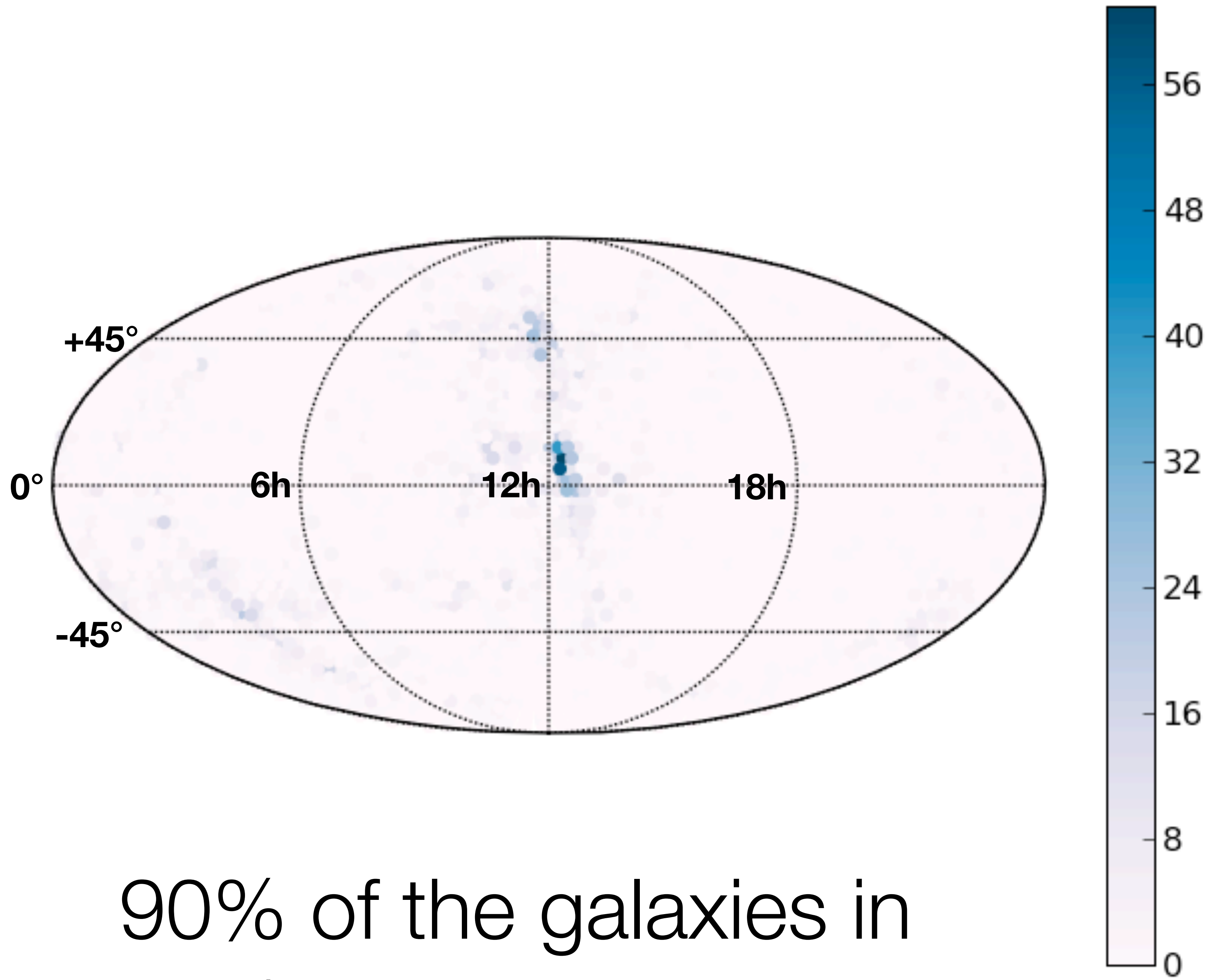
Kopparapu, Hanna, Kalogera, O'Shaughnessy, González, Brady & Fairhurst (2008)

Number of galaxies at 10Mpc



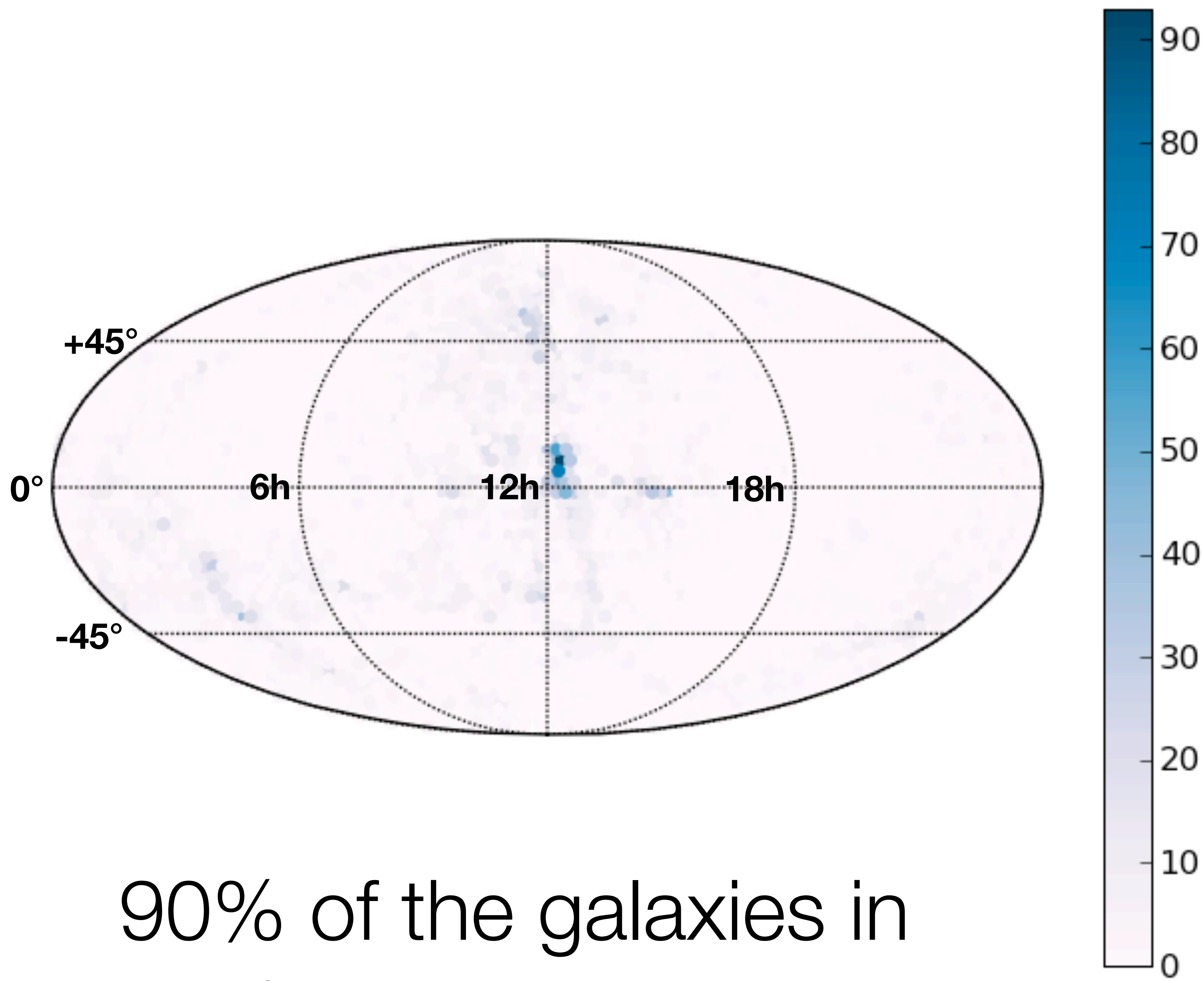
90% of the galaxies in
7% of the total sky area

Number of galaxies at 20Mpc



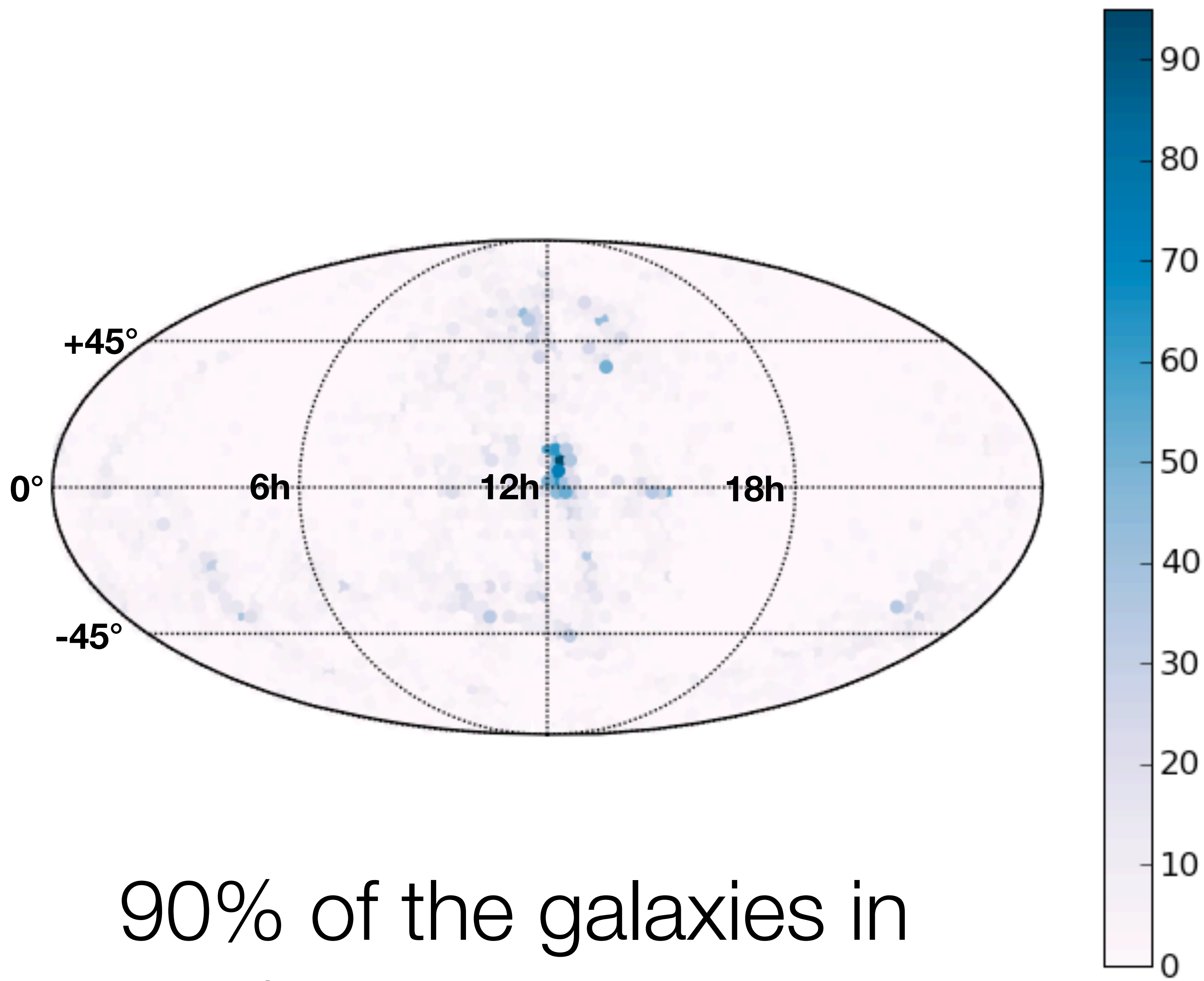
90% of the galaxies in
20% of the total sky area

Number of galaxies at 30Mpc



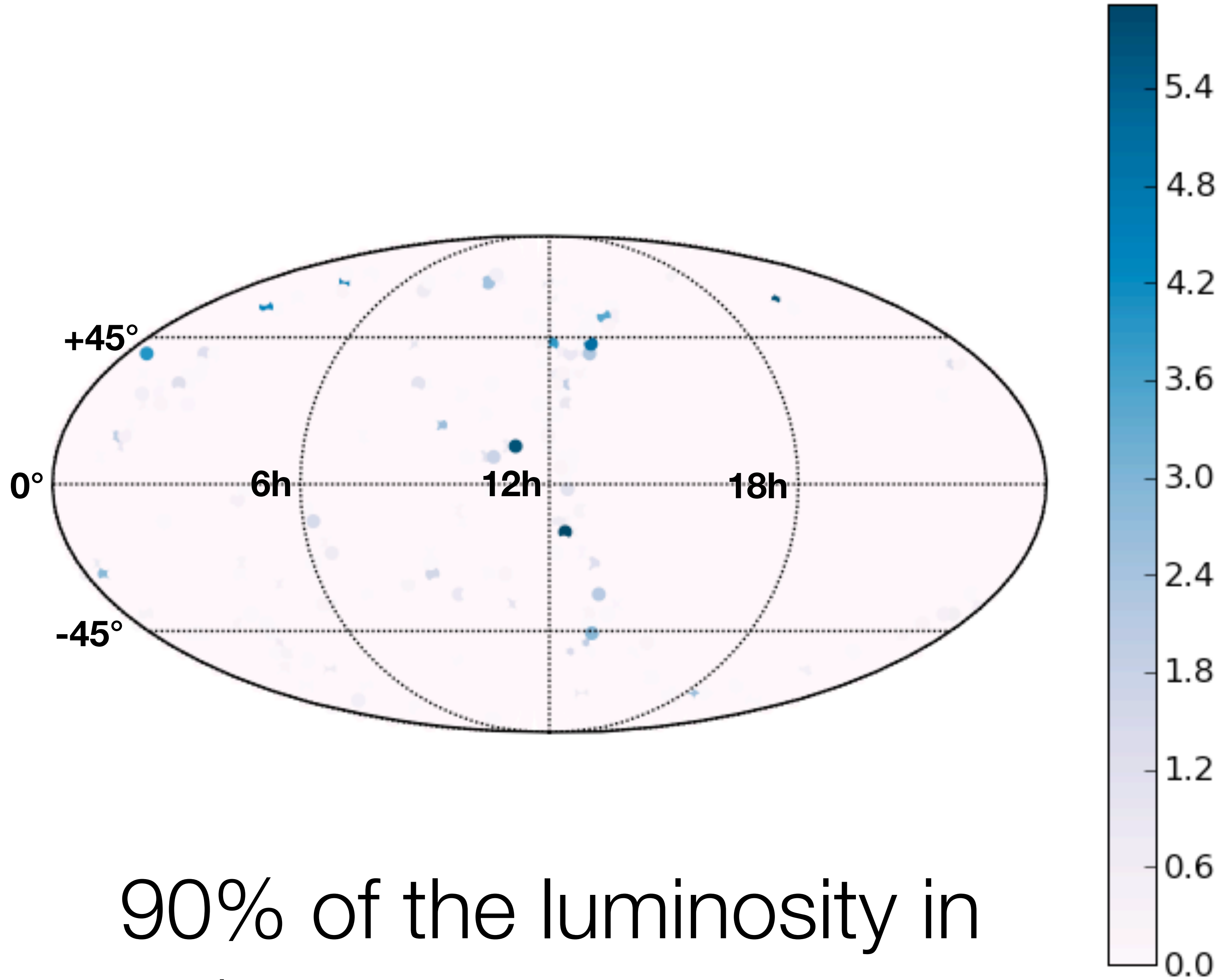
90% of the galaxies in
27% of the total sky area

Number of galaxies at 40Mpc



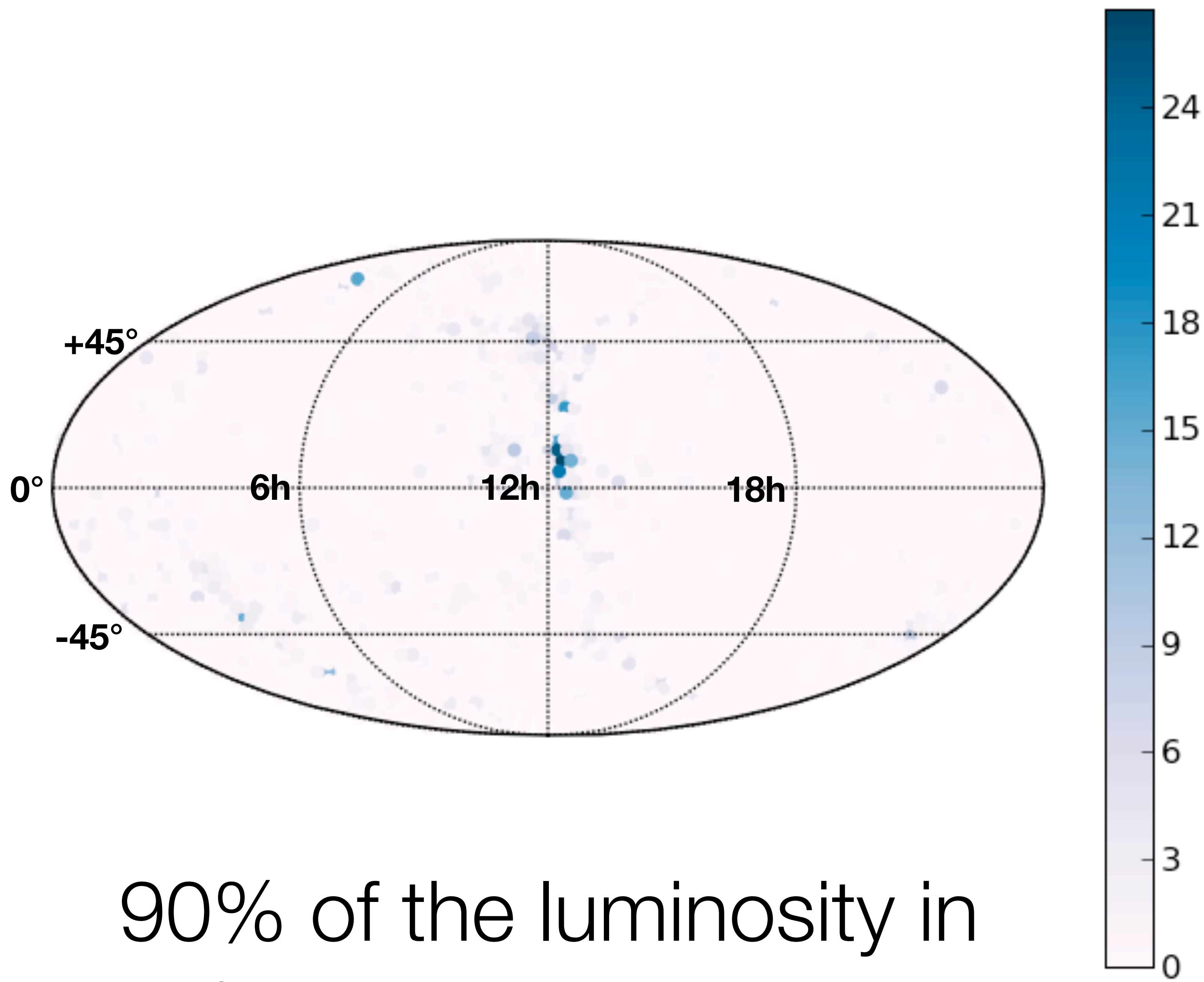
90% of the galaxies in
31% of the total sky area

Blue luminosity at 10Mpc



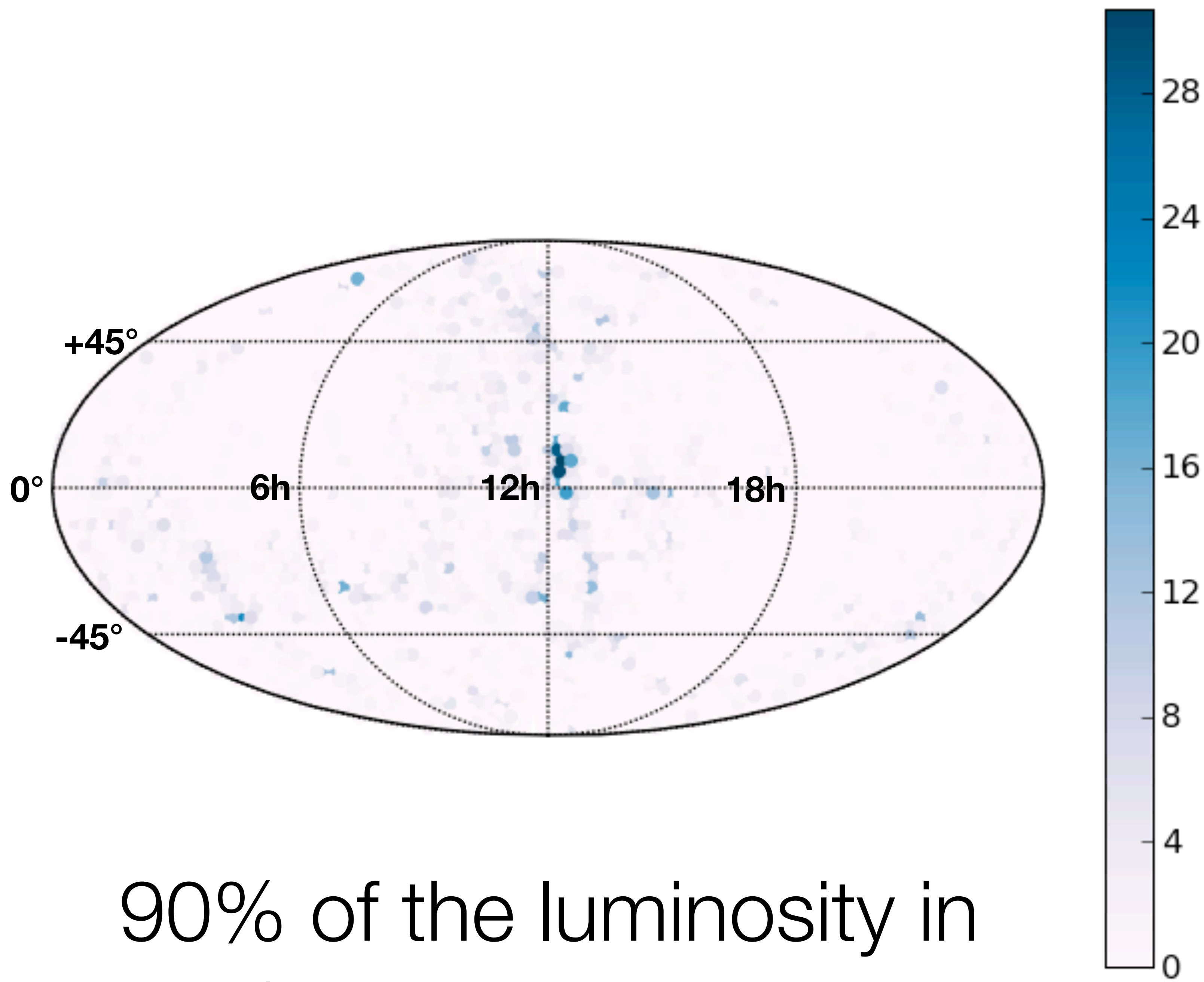
90% of the luminosity in
2% of the total sky area

Blue luminosity at 20Mpc



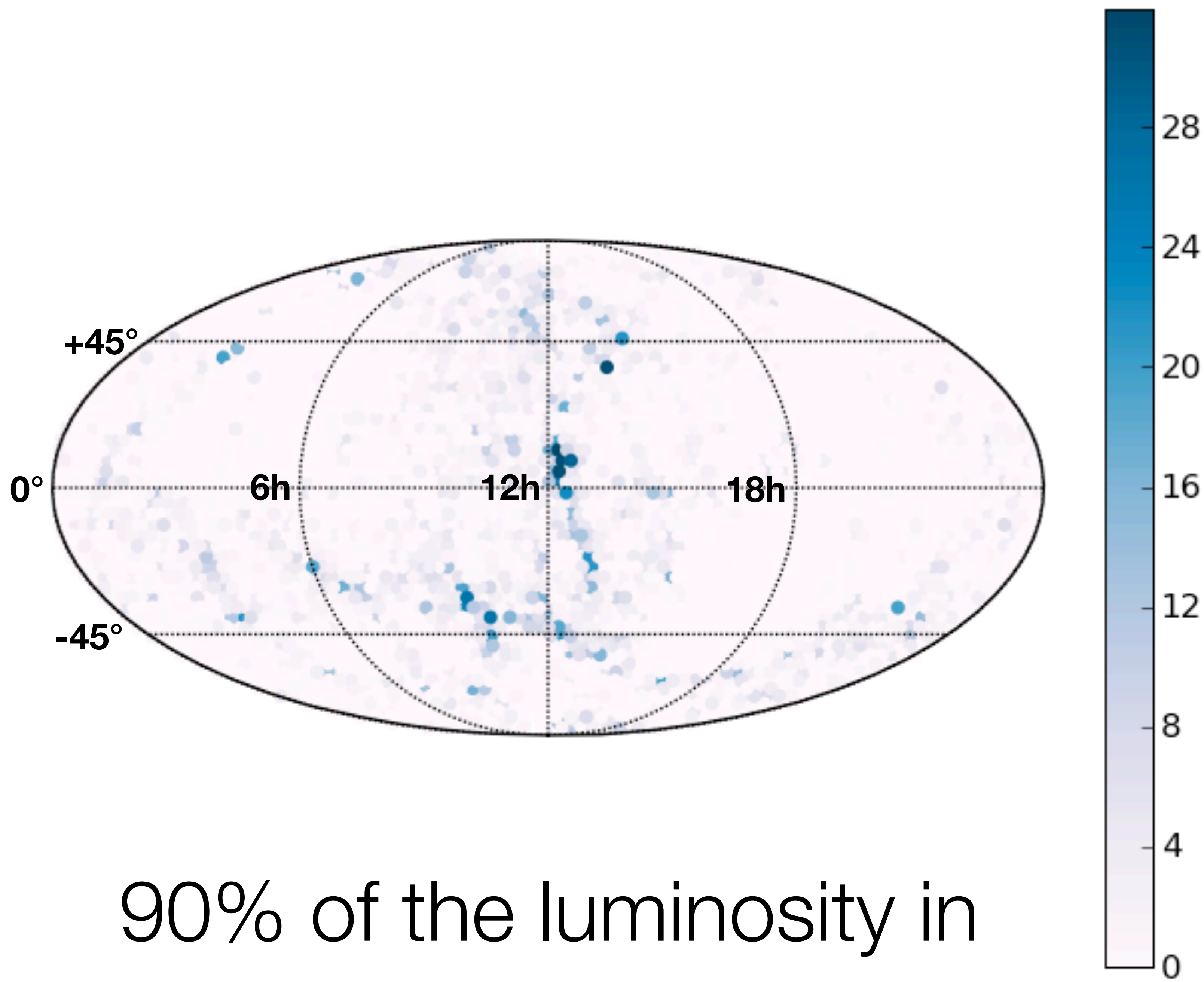
90% of the luminosity in
9% of the total sky area

Blue luminosity at 30Mpc



90% of the luminosity in
16% of the total sky area

Blue luminosity at 40Mpc



90% of the luminosity in
21% of the total sky area

Sky localization performance

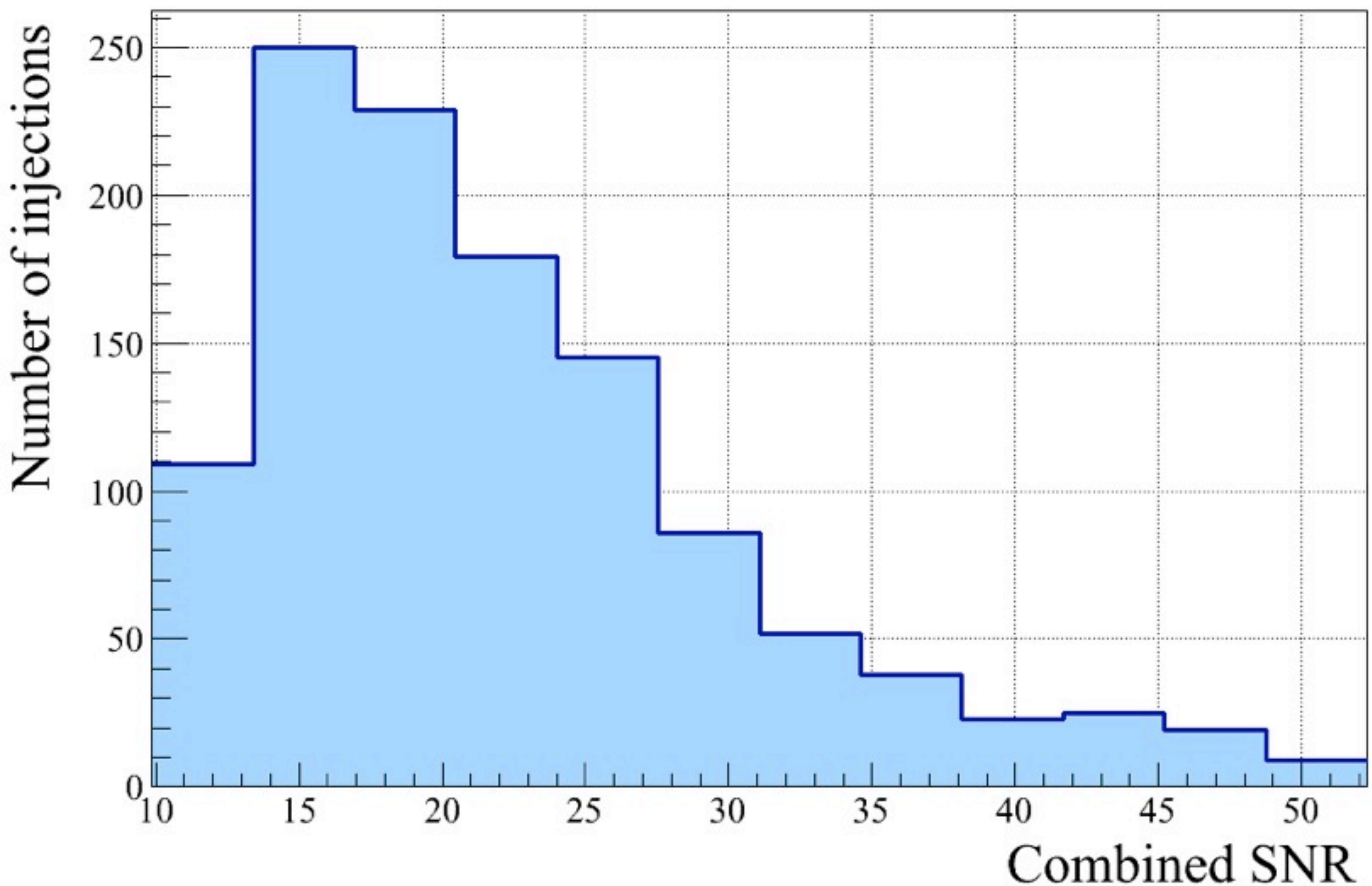
> Simulated signals (injections) put into real detector noise from week 6 of S6/VSR2

> Injection parameters taken from the low mass region of parameter space (systems more likely to contain a neutron star)

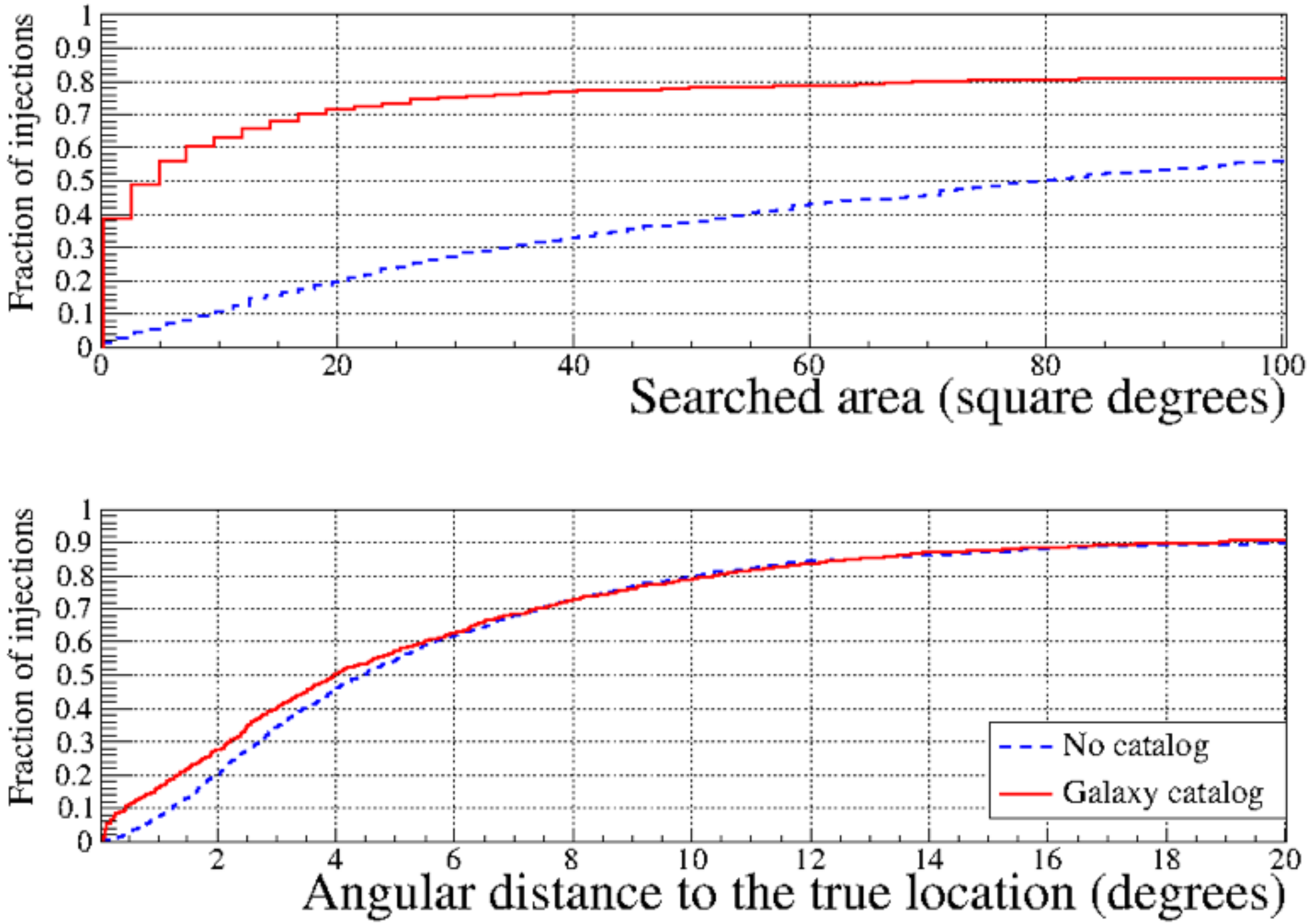
> Emphasis on low signal-to-noise ratio (SNR) injections

> Characterize performance by the area contained in the pixels ranked above the true location ("Searched Area")

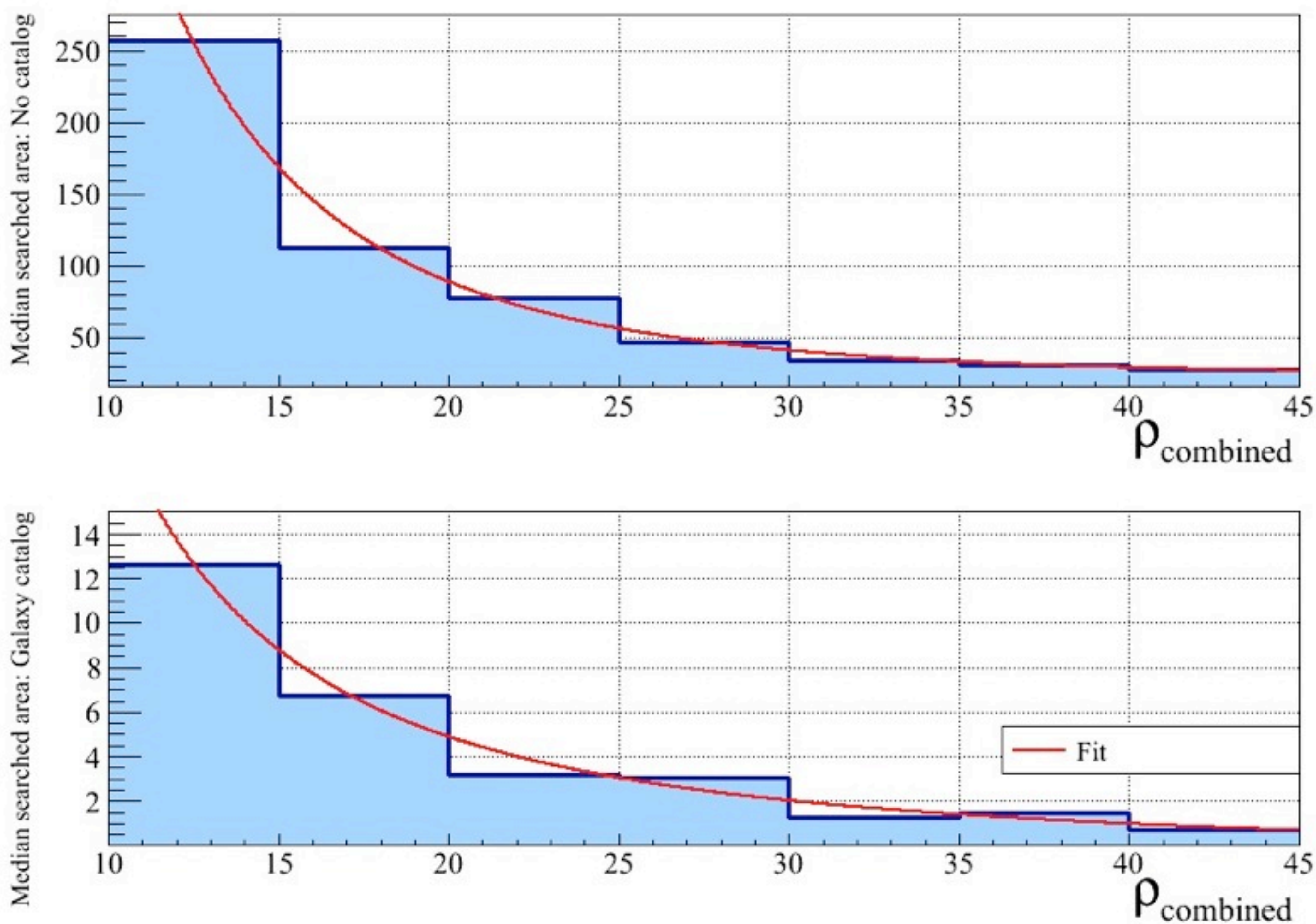
Sky localization performance



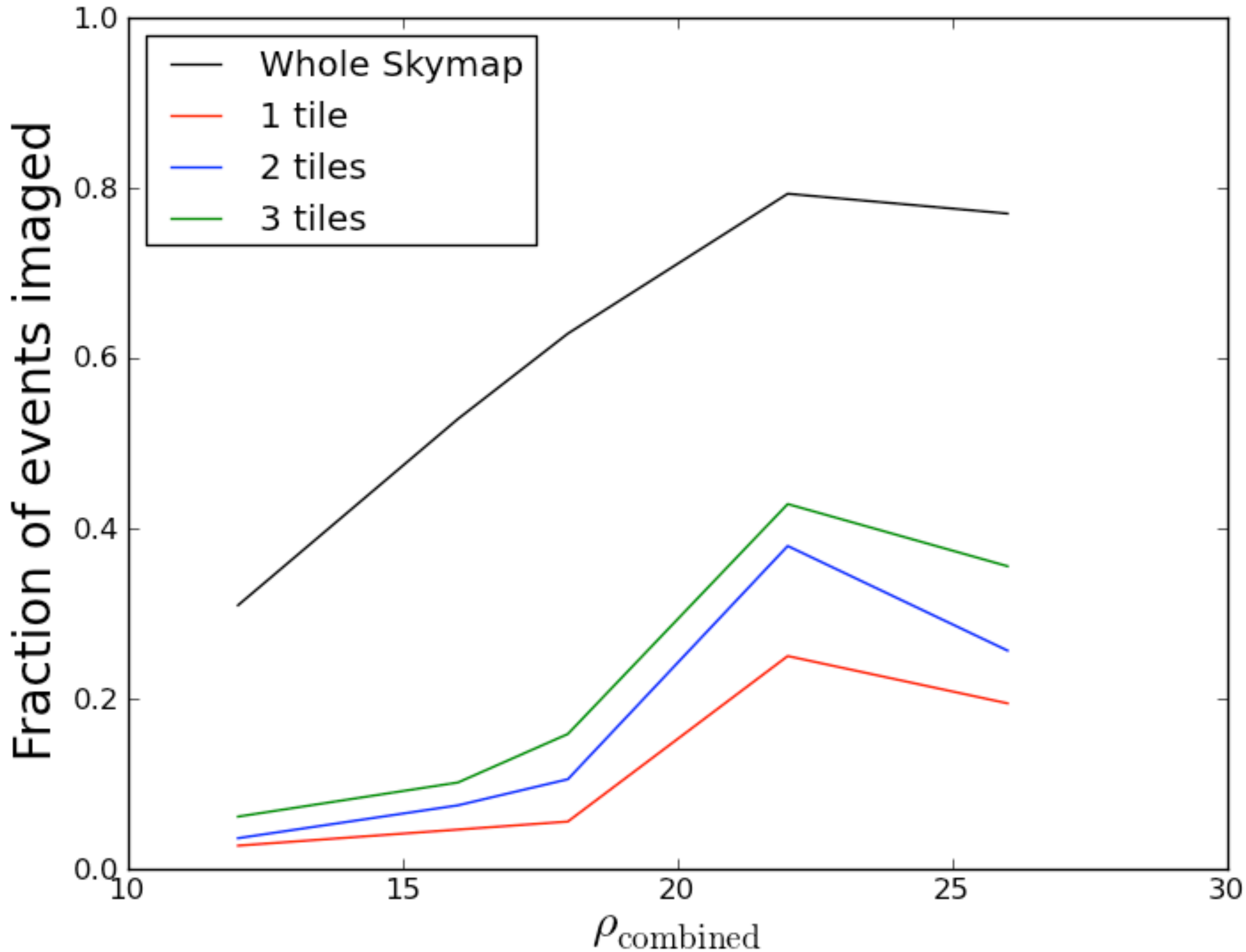
Sky localization performance



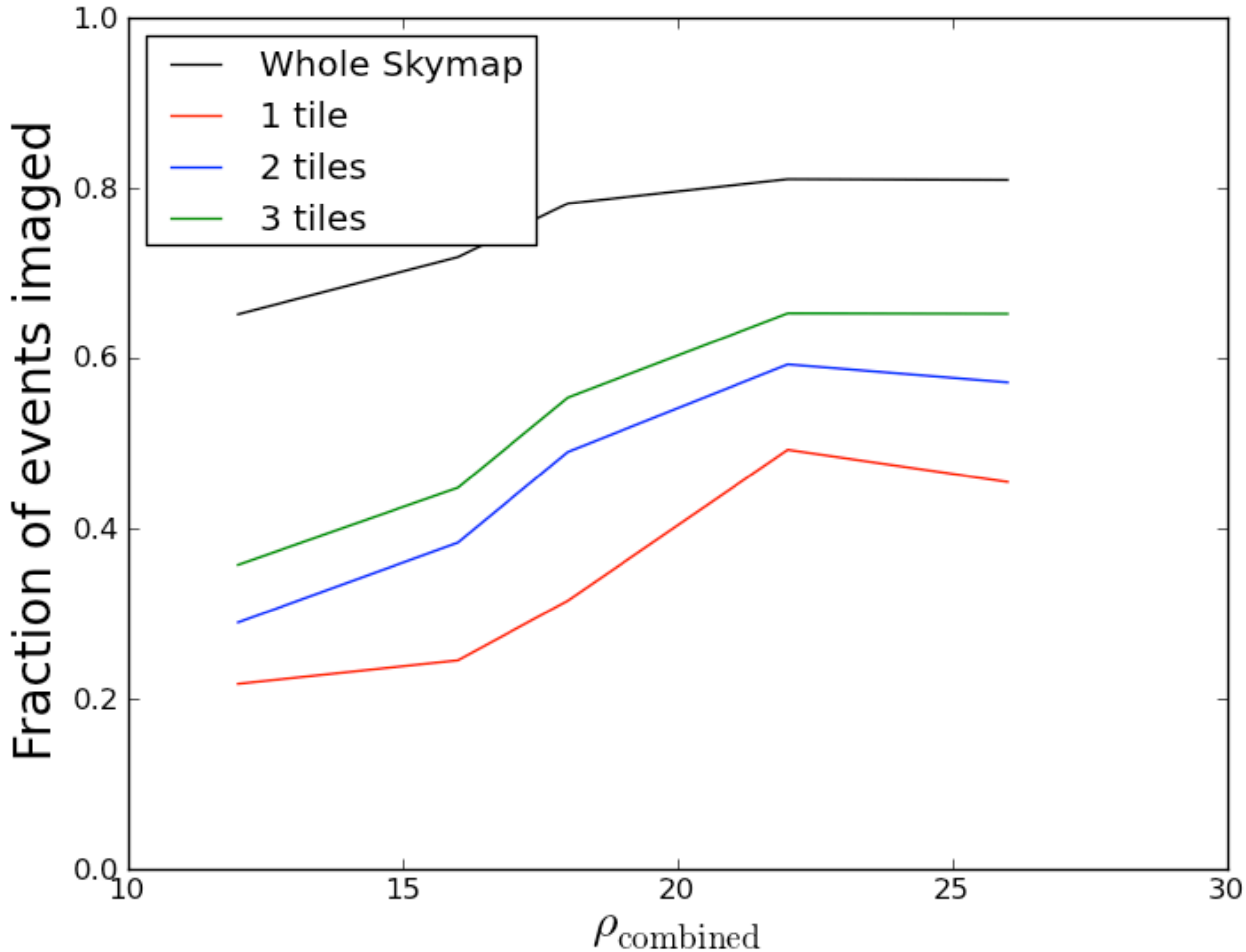
Sky localization performance: SNR dependence

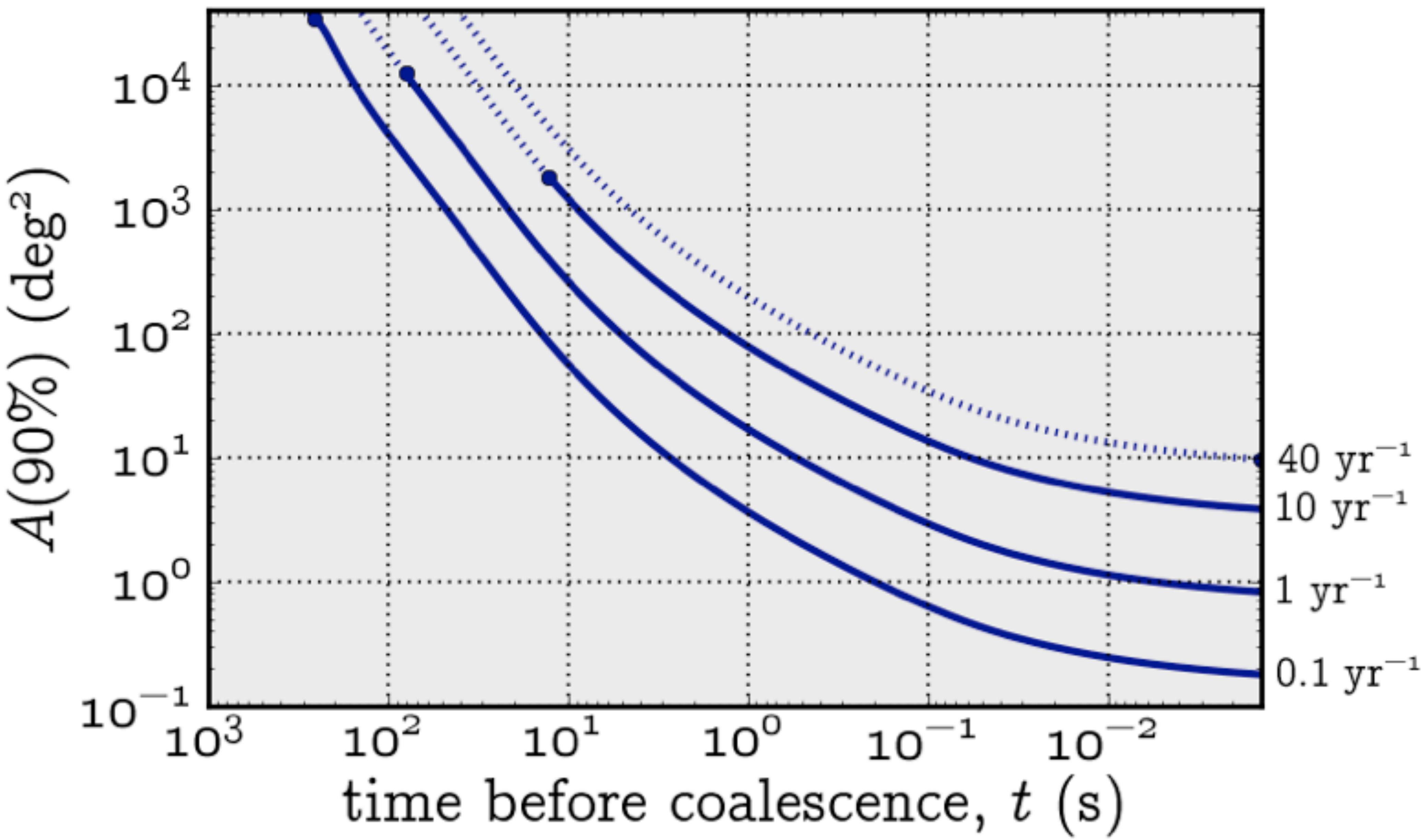


Sky localization performance: Telescope tilings I



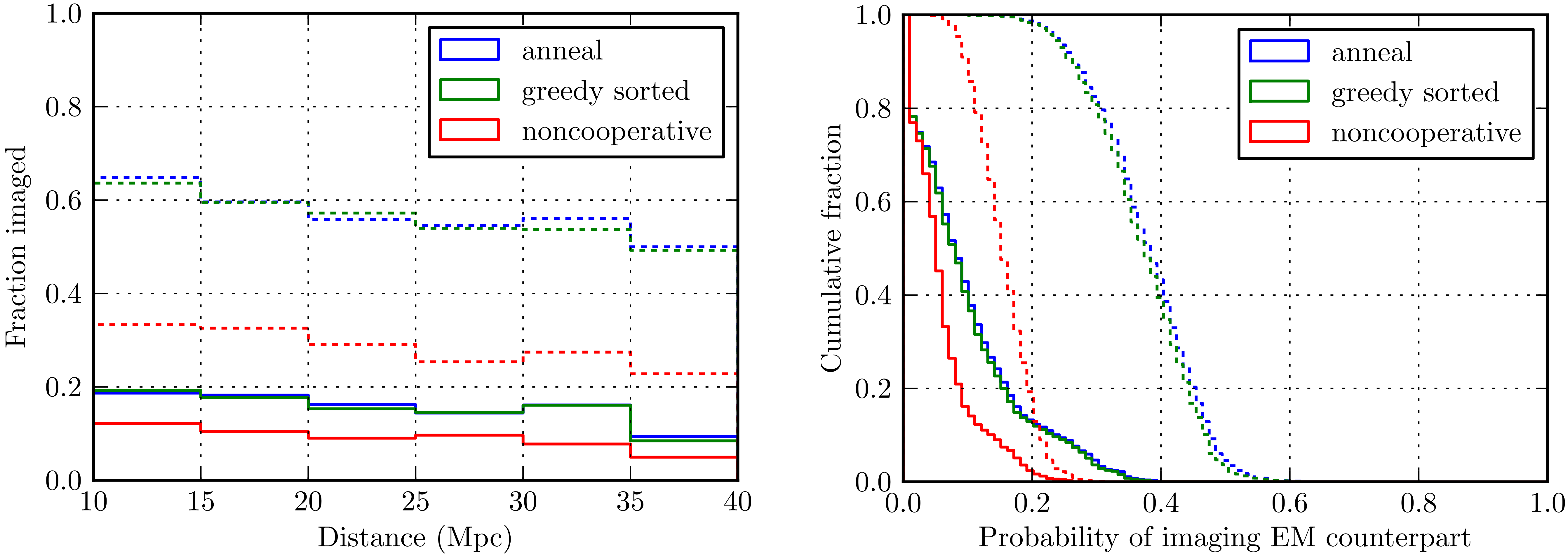
Sky localization performance: Telescope tilings II





Prospects for aLIGO

Cannon *et al* (2011)

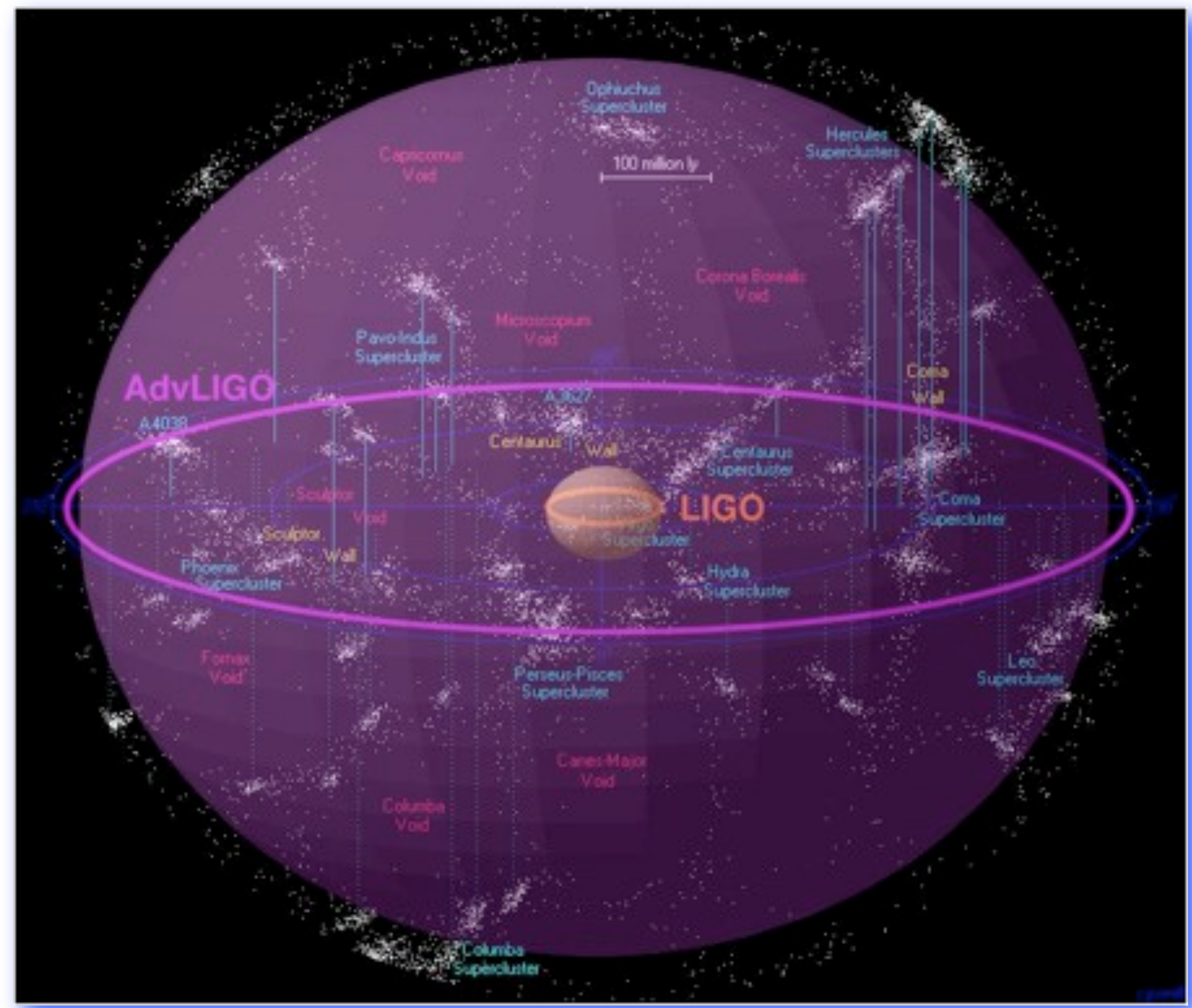


Coordination could be the key to success!

Singer, **LP**, Speranza (in prep)

Looking towards Advanced LIGO

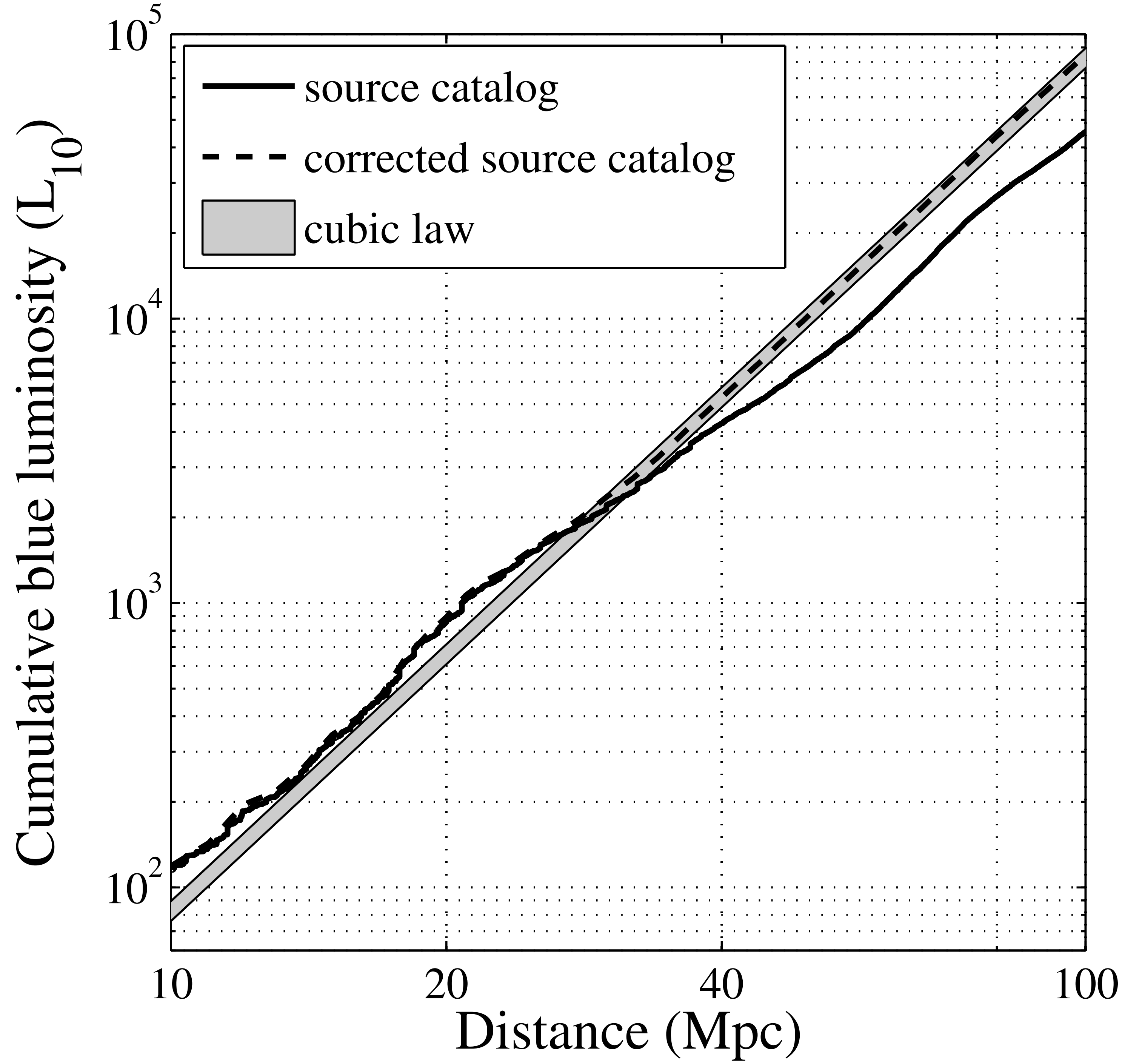
- Better galaxy catalogs?
  (Do they even help?)
  Kulkarni & Kasliwal (2009)
- Improved astrophysical priors, e.g. to account for kicks
- EM expectations?
  Metzger et al (2010)
  Nakar & Piran(2011)
- Better coordination with EM astronomers, e.g. observing and analysis strategies
- GW latency expectations
- Better EM coverage/More EM partners



The Completeness Problem

Catalog is roughly 80% complete to 40Mpc and only about 50% complete at 100Mpc.

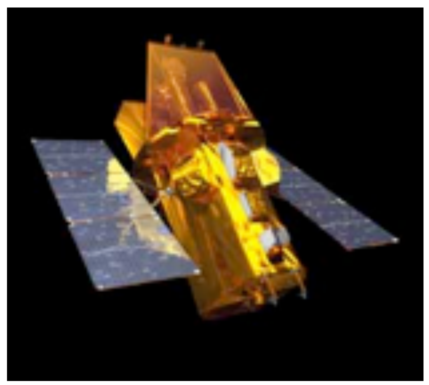
Advanced LIGO can see BNSs to ~400Mpc



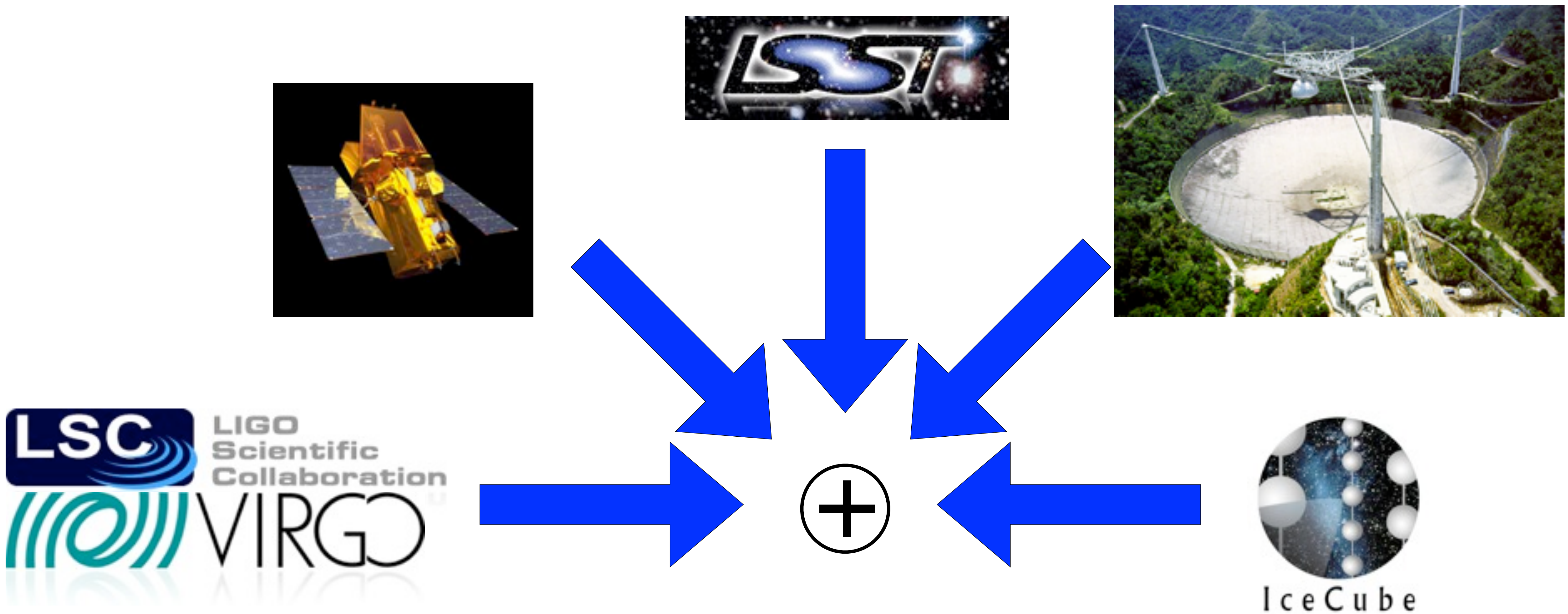
Kopparapu et al (2008)

The era of multi-messenger astronomy

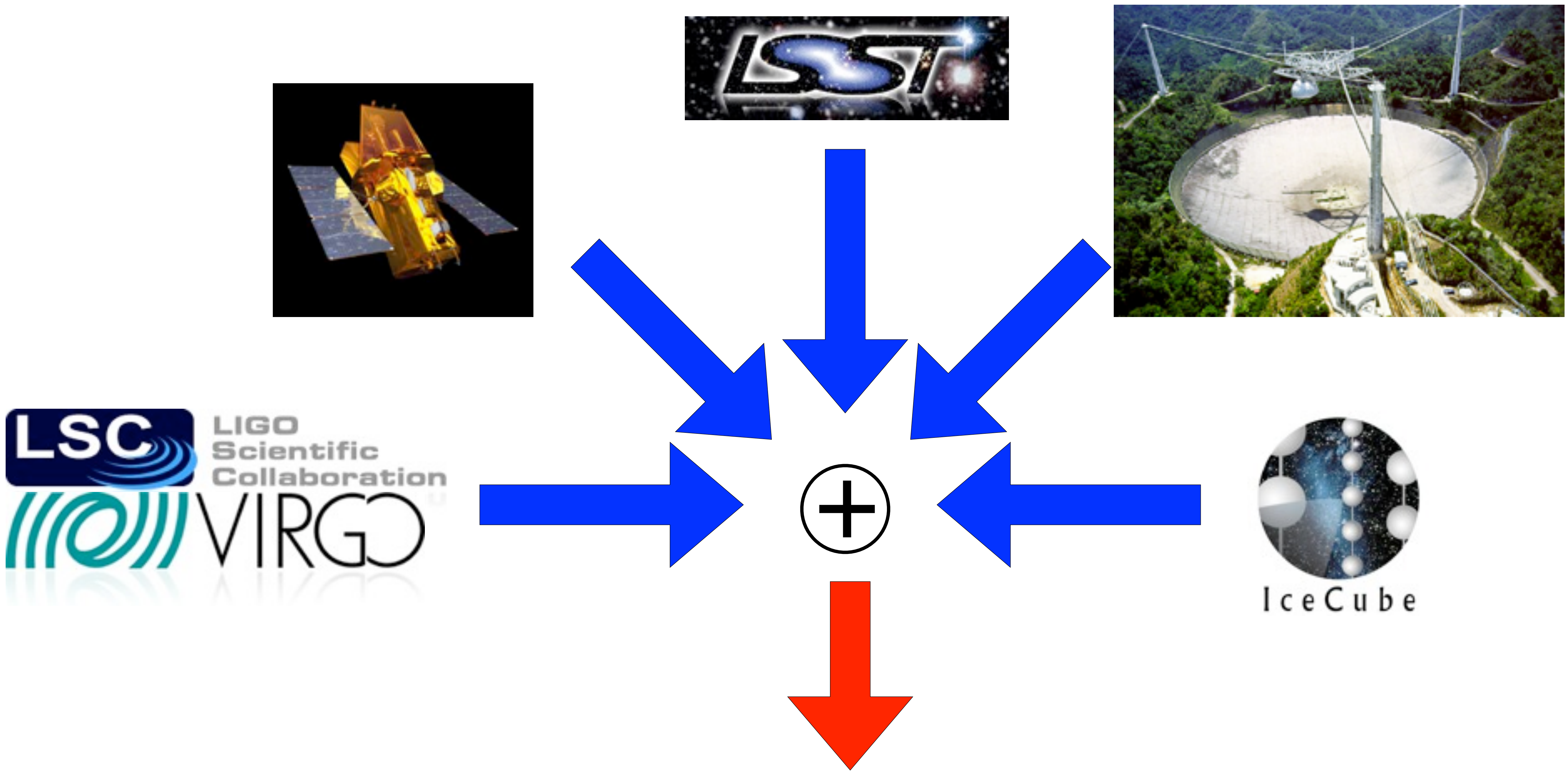
The era of multi-messenger astronomy



The era of multi-messenger astronomy

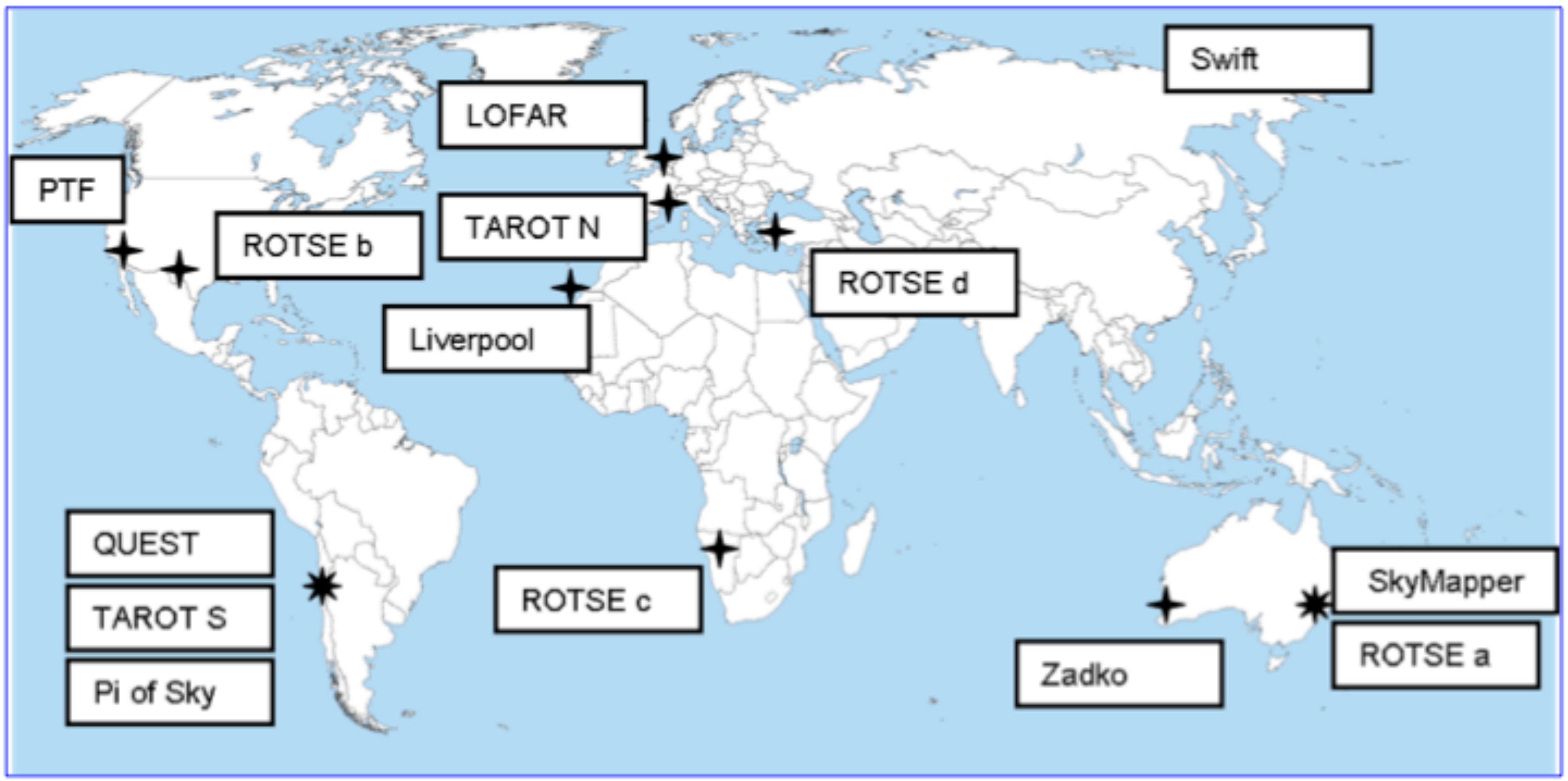


The era of multi-messenger astronomy



- understanding GRBs
- precision cosmology
- ...

The telescope network

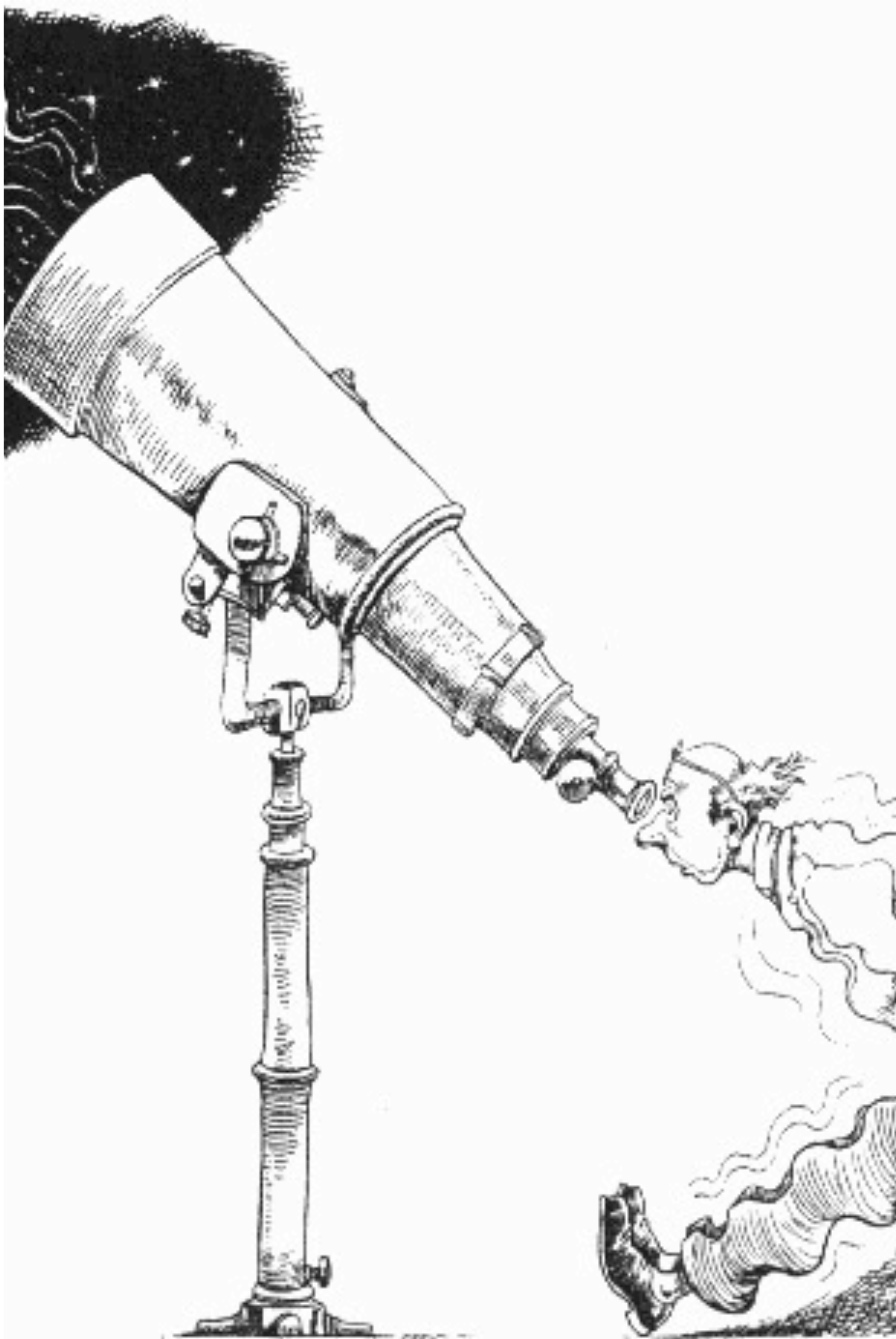


Possibilities for the advanced detector era

Credit: Lucia Santamaria

The immediate future

- Incorporate signal amplitude information for better sky localization.
- Get CBCs into the wide field followup effort.
- Determine feasibility of pointing at double coincident triggers.



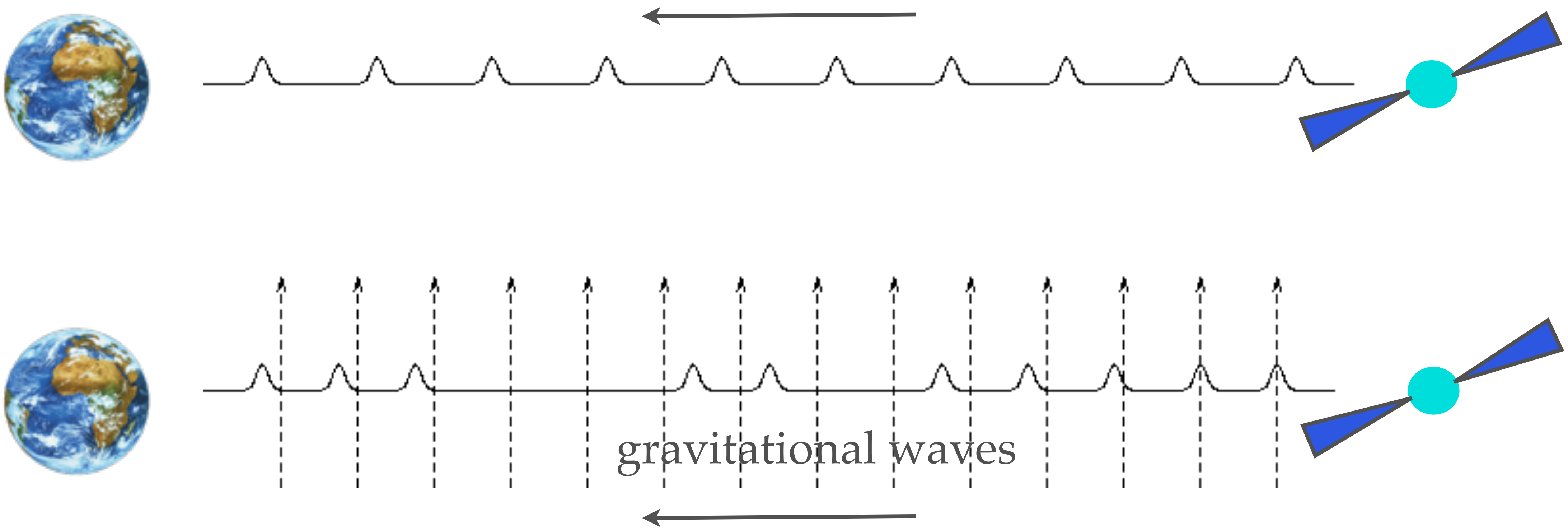
Part II: Looking for GWs in pulsar timing data

or

Another way to bridge the EM-GW astronomy gap

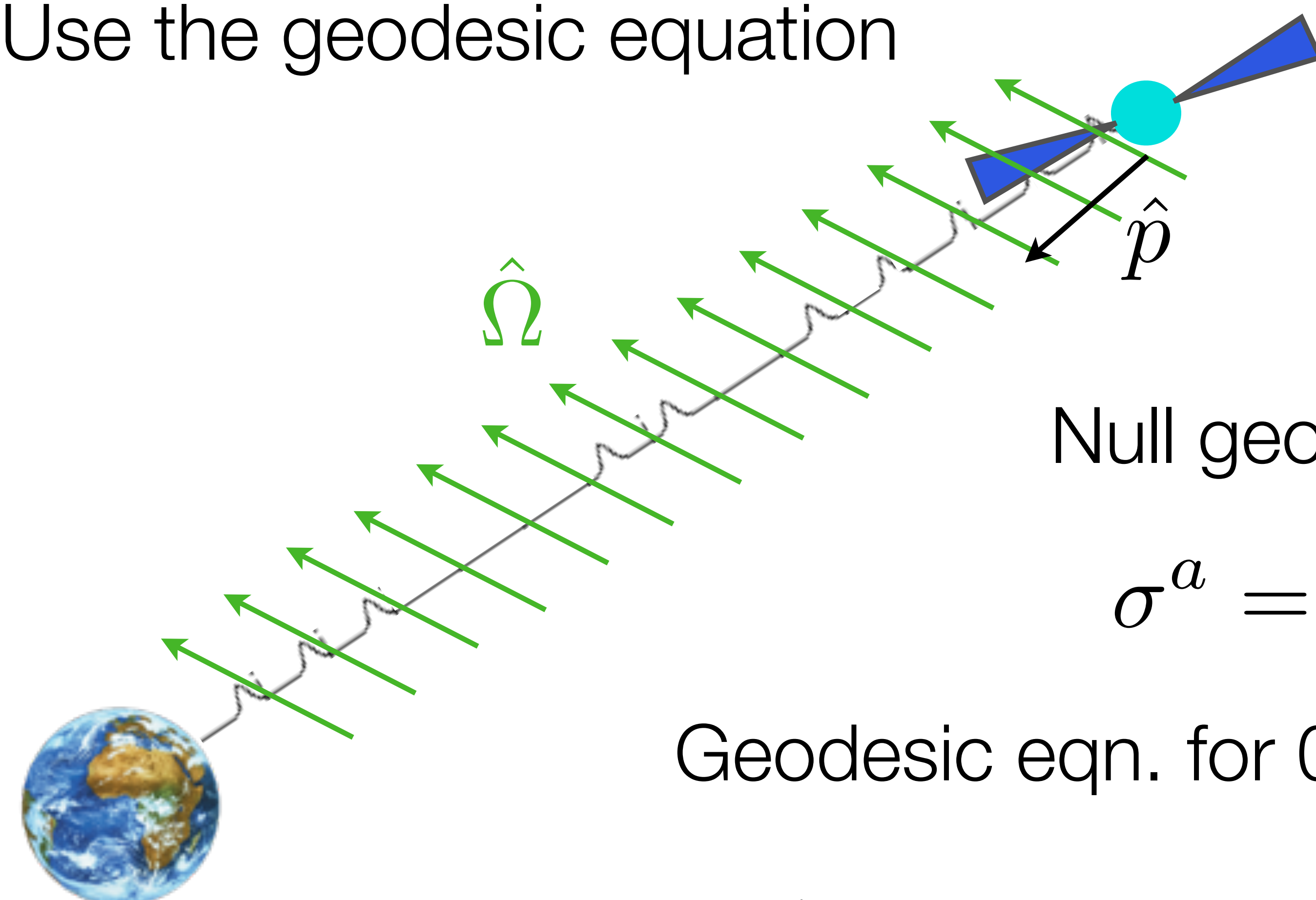
Pulsar Timing: A Nano-Hertz GW detector

- Pulsars are stable rotators that emit a steady train of EM pulses.
- GWs affect the pulse times of arrival.



Effect of a gravitational wave on pulsar radio pulses

Use the geodesic equation



$$h_{ab} = h_{ab}(t - \hat{\Omega} \cdot \vec{x}),$$

$$s^a = dx^a/d\lambda \equiv \nu(1, -\hat{p})$$

Null geodesic is perturbed by GW to:

$$\sigma^a = s^a + \delta s^a$$

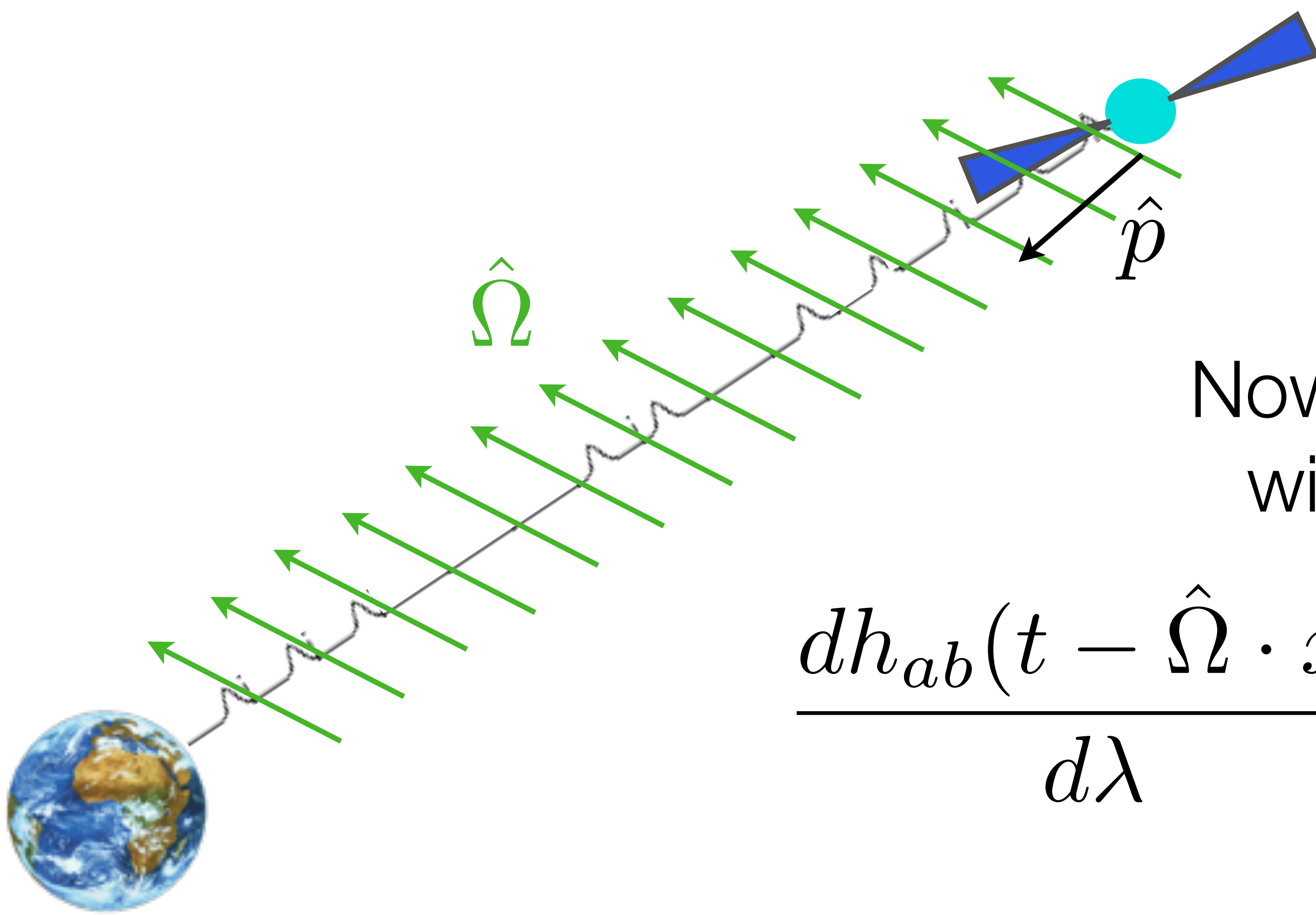
Geodesic eqn. for 0th component is:

$$\frac{d\sigma^t}{d\lambda} = -\Gamma^t_{ab}\sigma^a\sigma^b = -\frac{1}{2}\dot{h}_{ab}\sigma^a\sigma^b$$

$$\frac{d\sigma^t}{d\lambda} = -\frac{1}{2}\dot{h}_{ab}(s^a + \delta s^a)(s^b + \delta s^b) = -\frac{1}{2}\dot{h}_{ab}s^a s^b = -\frac{1}{2}\dot{h}_{ij}(\nu^2 p^i p^j)$$

b/c GW metric is purely spatial

Effect of a gravitational wave on pulsar radio pulses



$$\frac{d\sigma^t}{d\lambda} = -\frac{1}{2}\nu^2 p^i p^j \dot{h}_{ij}$$

Now need to connect time derivatives with derivates wrt affine parameter

$$\frac{dh_{ab}(t-\hat{\Omega}\cdot\vec{x})}{d\lambda} = \nu(1+\hat{\Omega}\cdot\hat{p})\frac{\partial h_{ab}(t-\hat{\Omega}\cdot\vec{x})}{\partial t}$$

Therefore: $$-\frac{1}{\nu}\frac{d\nu}{d\lambda} = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\frac{dh_{ij}(t-\hat{\Omega}\cdot\vec{x})}{d\lambda}$$

$$\frac{\nu_{\mathrm{P}}-\nu_{\mathrm{E}}}{\nu_{\mathrm{P}}} = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\left[h^{\mathrm{P}}_{ij}-h^{\mathrm{E}}_{ij}\right]$$

Timing residuals just an integral of redshift

Anholm, Ballmer, Creighton, **LP**, Siemens (2008)

The optimal statistic

Consider the statistic:

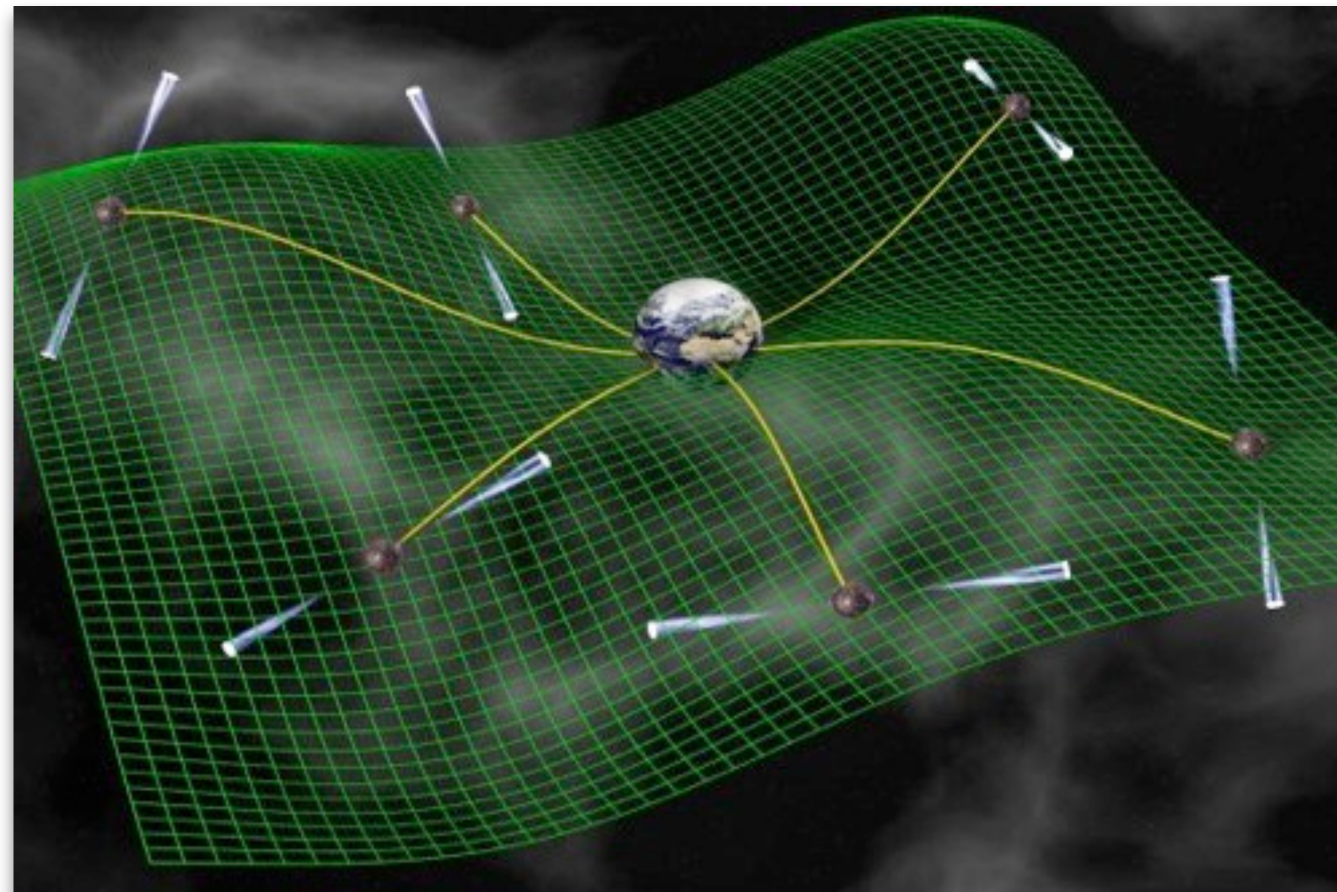
$$Y = \int dt \int dt' \, s_1(t) s_2(t') Q(t - t')$$

Maximize the SNR:

$$\tilde{Q}(f) = \chi \frac{\Omega_{\rm gw}(|f|)\gamma(|f|)}{|f|^3 P_1(|f|) P_2(|f|)}$$

Multiple detectors

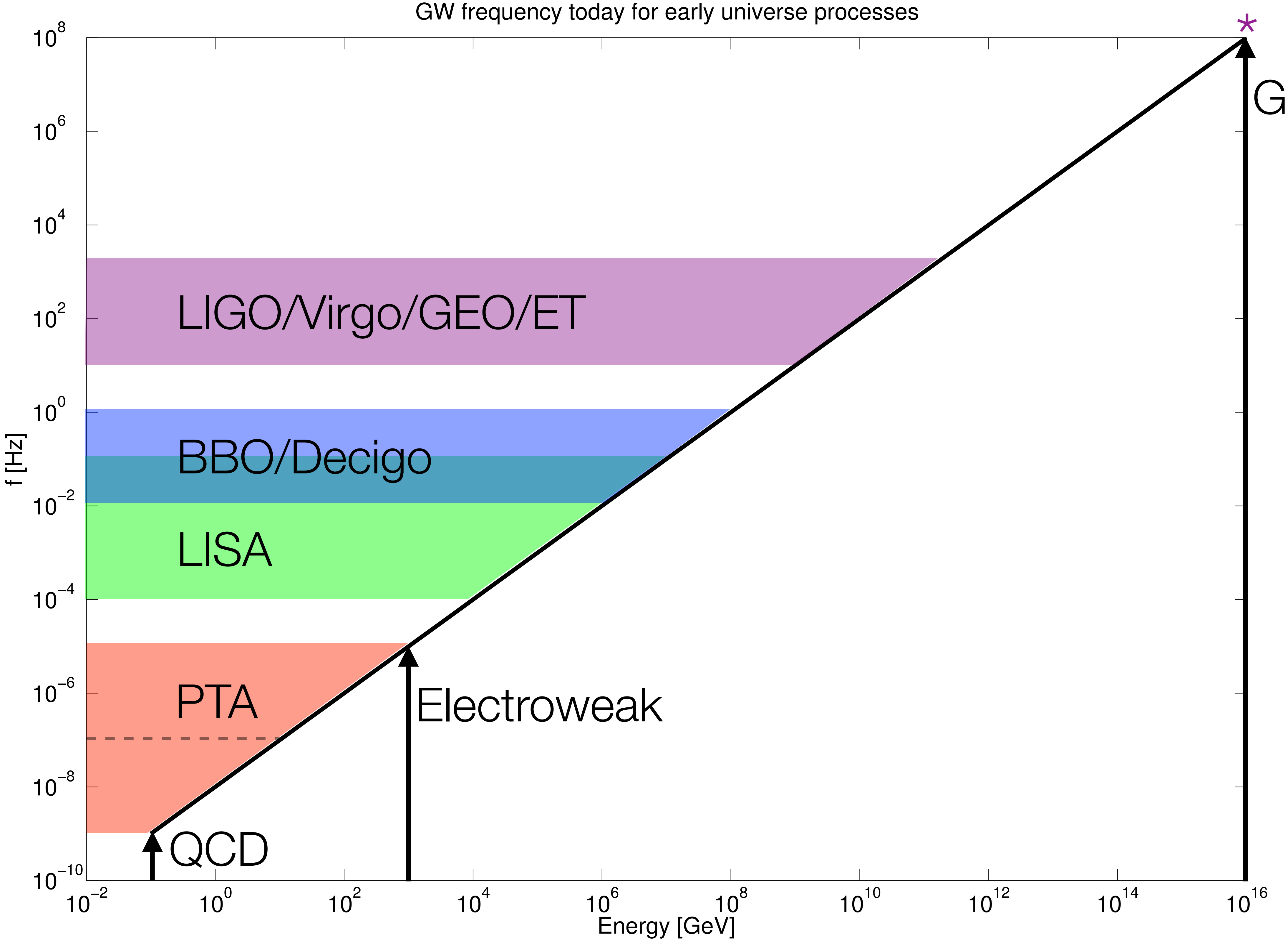
$$Y_{\mathrm{opt}} = \frac{\sum_{i,j}^{N} \sigma_{\mathrm{Y}_{ij}}^{-2} Y_{ij}}{\sum_{i,j}^{N} \sigma_{\mathrm{Y}_{ij}}^{-2}}$$



Credit: David Champion

Smaller variance => less noisy

Cosmological sources



* **LP**, Siemens (2008)
Giblin, **LP**, Siemens (in prep)

The BNS of pulsar timing

The MBHB background is expected at $A \sim 10^{-15}$

The current upper limit is at $A = 1.1 \times 10^{-14}$

Where $\Omega_{\rm gw} = \frac{2\pi^2}{3H_0^2} f^2 A^2 \left(\frac{f}{\rm yr^{-1}}\right)^{2\alpha}$

And $\alpha = -2/3$ (Phinney 2001)

Sensitivity estimate

For a flat spectrum in Ω

timing residual variance

$$\Omega_{\rm UL} = \frac{48\pi^2}{H_0^2}\frac{\sigma_t^2}{NT^4}\left(\sum_p \gamma_p^2\right)^{-1/2}{\rm erfc}^{-1}(2(1-c))$$

Total no. of data points/pulsar

Obs. time

sum over pulsar pairs (Hellings-Downs values) $\propto N_p^{-1}$

$$\Omega_{\rm UL} \propto \frac{\sigma_t^2}{N_p N T^4}$$

$$\left[h_c^2(f) = \frac{3H_0^2}{32\pi^3}\frac{1}{f^2}\Omega(f)\right]$$

Sensitivity estimate

timing residual variance

$$\Omega_{\rm UL} = \frac{48\pi^2}{H_0^2}\frac{\sigma_t^2}{NT^4}\Big(\sum_p \gamma_p^2\Big)^{-1/2}{\rm erfc}^{-1}(2(1-c))$$

Total no. of data points/pulsar

Obs. time

sum over pulsar pairs (Hellings-Downs values)

$$\sigma_t = 100{\rm ns}$$
$$T = 3\times 10^8{\rm s}$$
$$N = 500$$
$$N_p = 20$$

$\Omega_{\rm UL} \sim 10^{-11}$

Phase transitions!

$$\sigma_t = 10{\rm ns}$$
$$T = 6\times 10^8{\rm s}$$
$$N = 1000$$
$$N_p = 100$$

$\Omega_{\rm UL} \sim 10^{-15}$

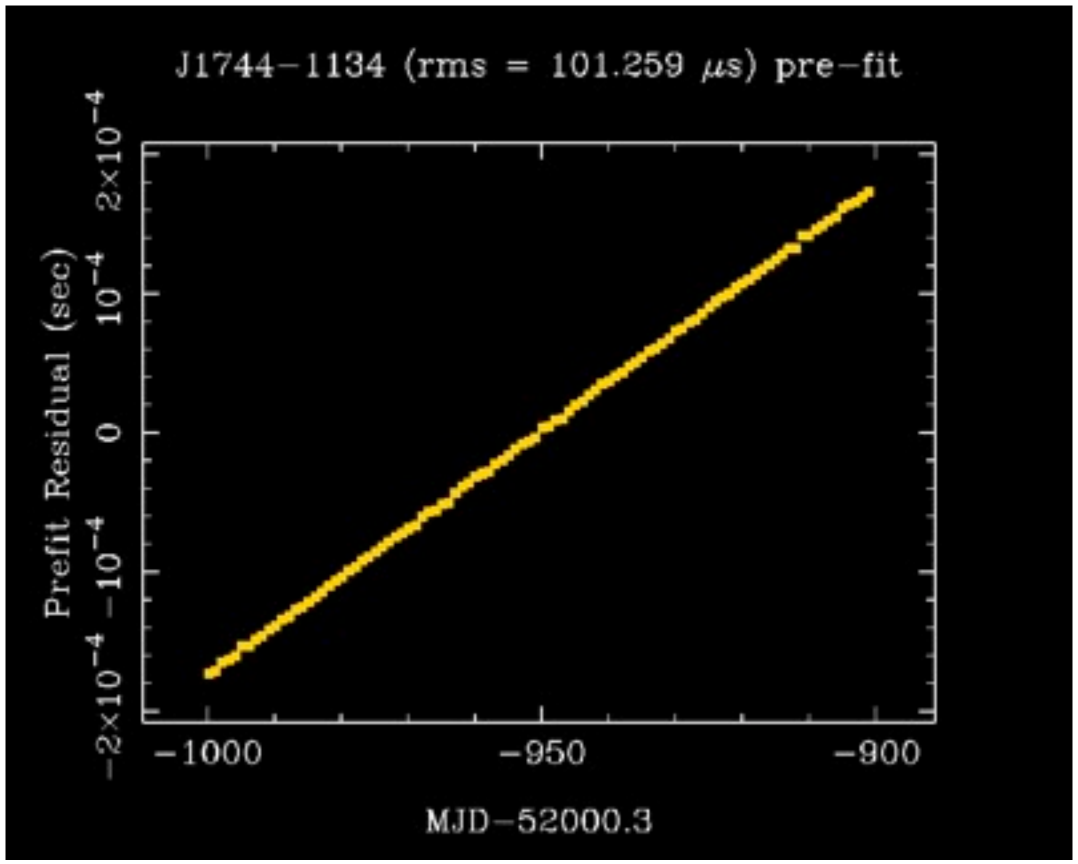
Inflation!

The reality

- Reported timing residuals are usually weighted, not rms.

- This kind of upper limit does not consider the effects of the timing procedure.

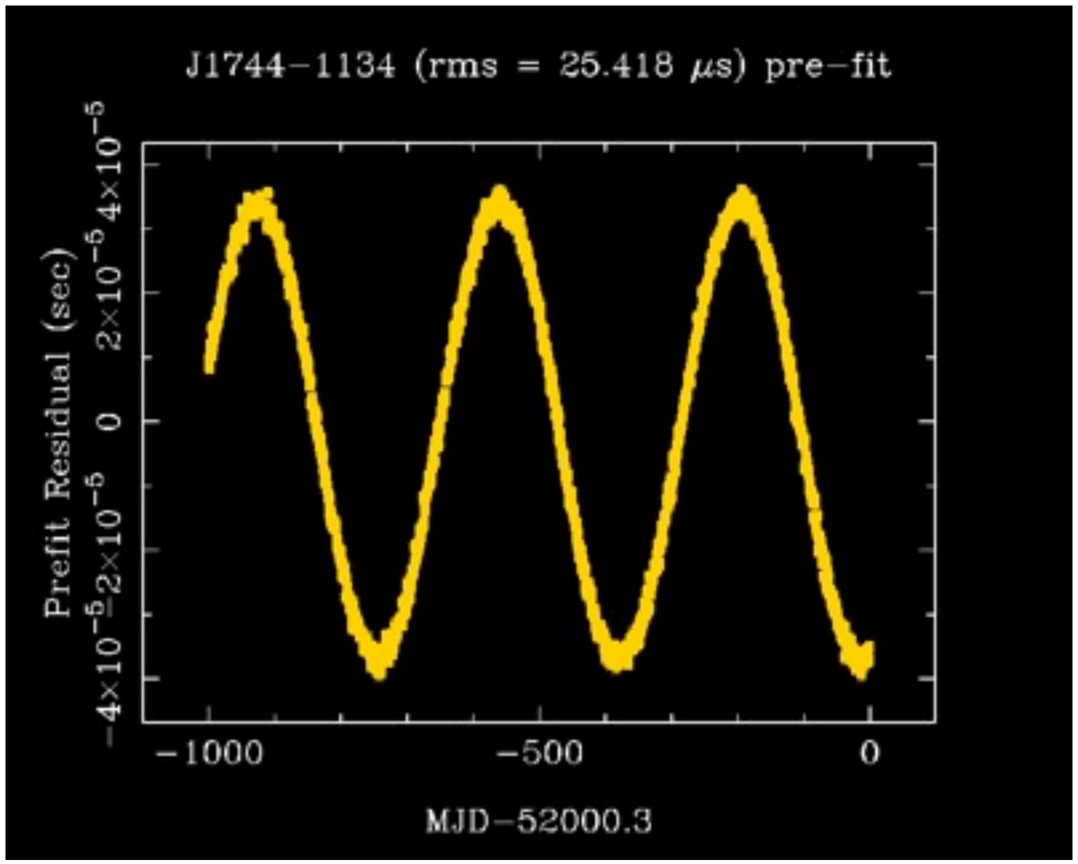
Pulsar timing in a nutshell (adapted from slides by George Hobbs)



- Start with something like this
- Correct for clock errors

Edwards, Hobbs, Manchester (2006)

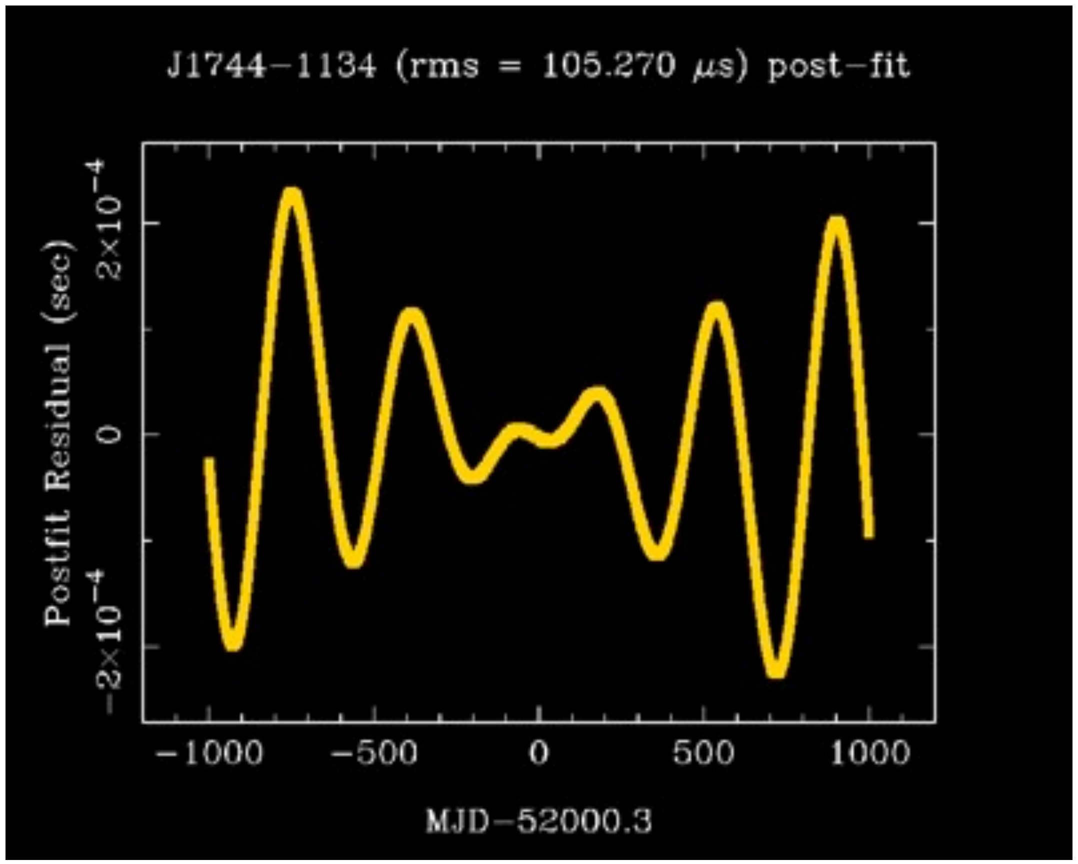
Pulsar timing in a nutshell (adapted from slides by George Hobbs)



- Now move to barycentric reference frame and correct for atmospheric delays, solar system dispersion, Shapiro delay...

Edwards, Hobbs, Manchester (2006)

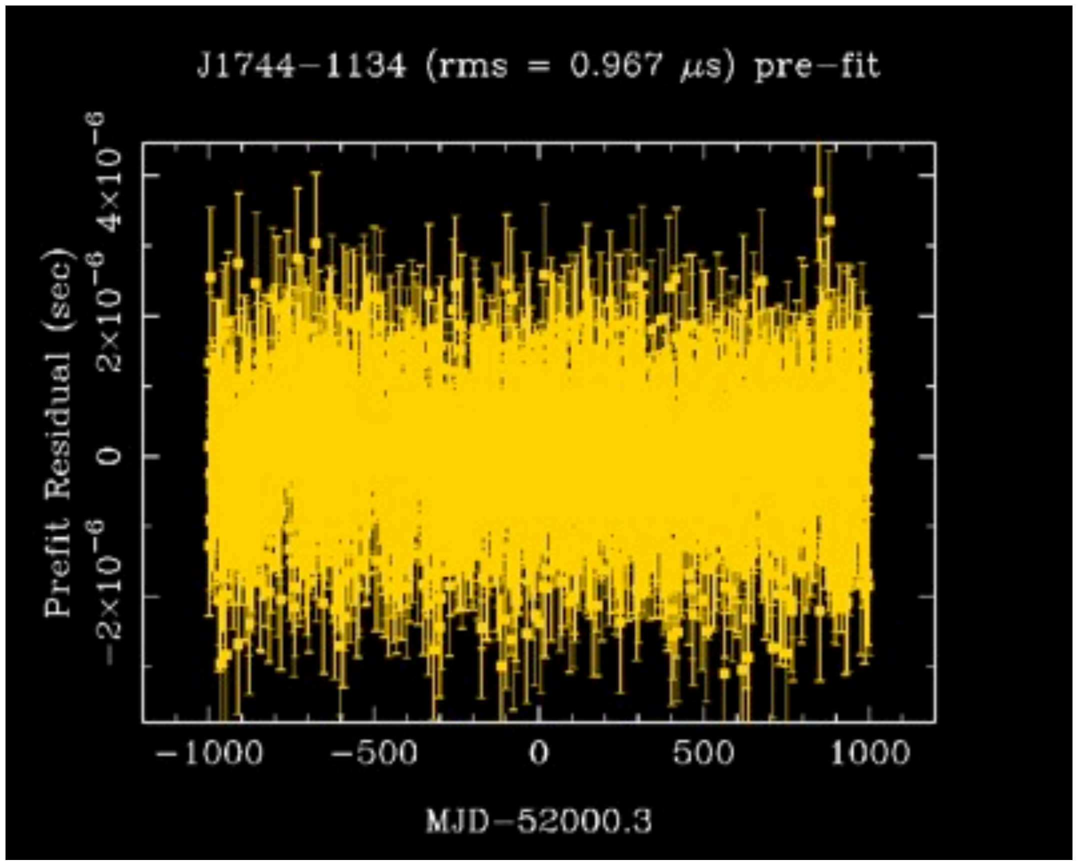
Pulsar timing in a nutshell (adapted from slides by George Hobbs)



- Then fit out ISM effects, spin down, possible binary parameters...

Edwards, Hobbs, Manchester (2006)

Pulsar timing in a nutshell (adapted from slides by George Hobbs)



- Iterate until you get something like this.

Edwards, Hobbs, Manchester (2006)

The reality

- Reported timing residuals are usually weighted, not rms.
- This kind of upper limit does not consider the effects of the timing procedure.
- Reliable upper limits must account for the effects of the timing procedure.
- In progress*...

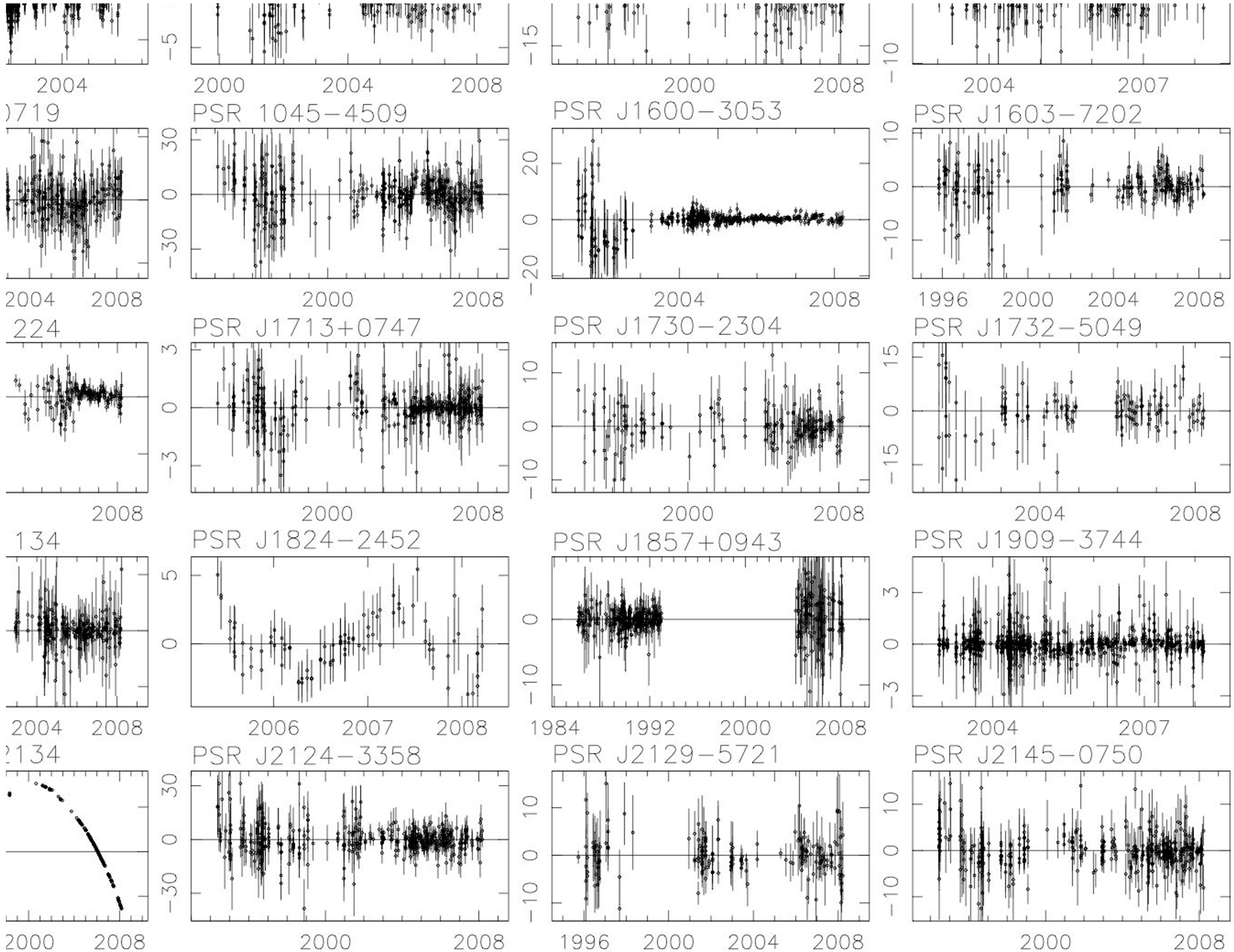
*Hobbs, Jenet, Manchester, **LP**, Siemens, Yardley and others (in prep)

Future work

- Publish the best upper limit to date on the stochastic background in the nano-Hertz region.

Future work

- Publish the best upper limit to date on the stochastic background in the nano-Hertz region.
- Make a detection?



Verbiest et al MNRAS (2009)

Future work

- Publish the best upper limit to date on the stochastic background in the nano-Hertz region.
- Make a detection?
- Develop methods for detecting other types of signals: Burst*, continuous...
- Make GW detection part of the timing process.

*Yu, Siemens, Creighton, **LP** (in prep)

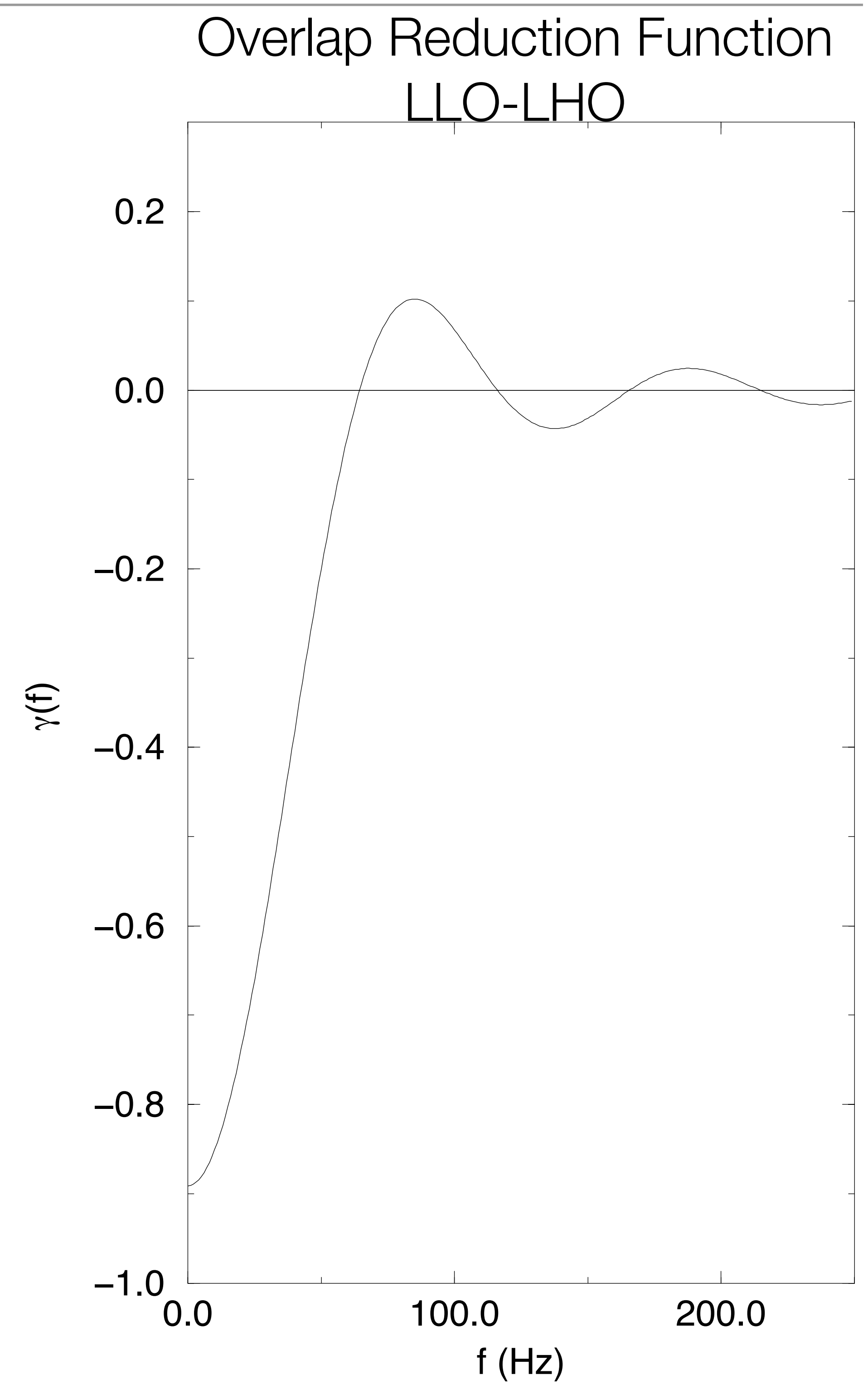
Summary

- The next 5-10 years is an exciting time for GW physics.
- Measurements across spectral bands will force new interactions between GW and EM astronomers.
- LIGO, Virgo and pulsar timing all have a role to play in GW astronomy.

The Overlap Reduction Function

The ORF describes the reduction in sensitivity due to the fact that the detectors are neither coincident nor coaligned.

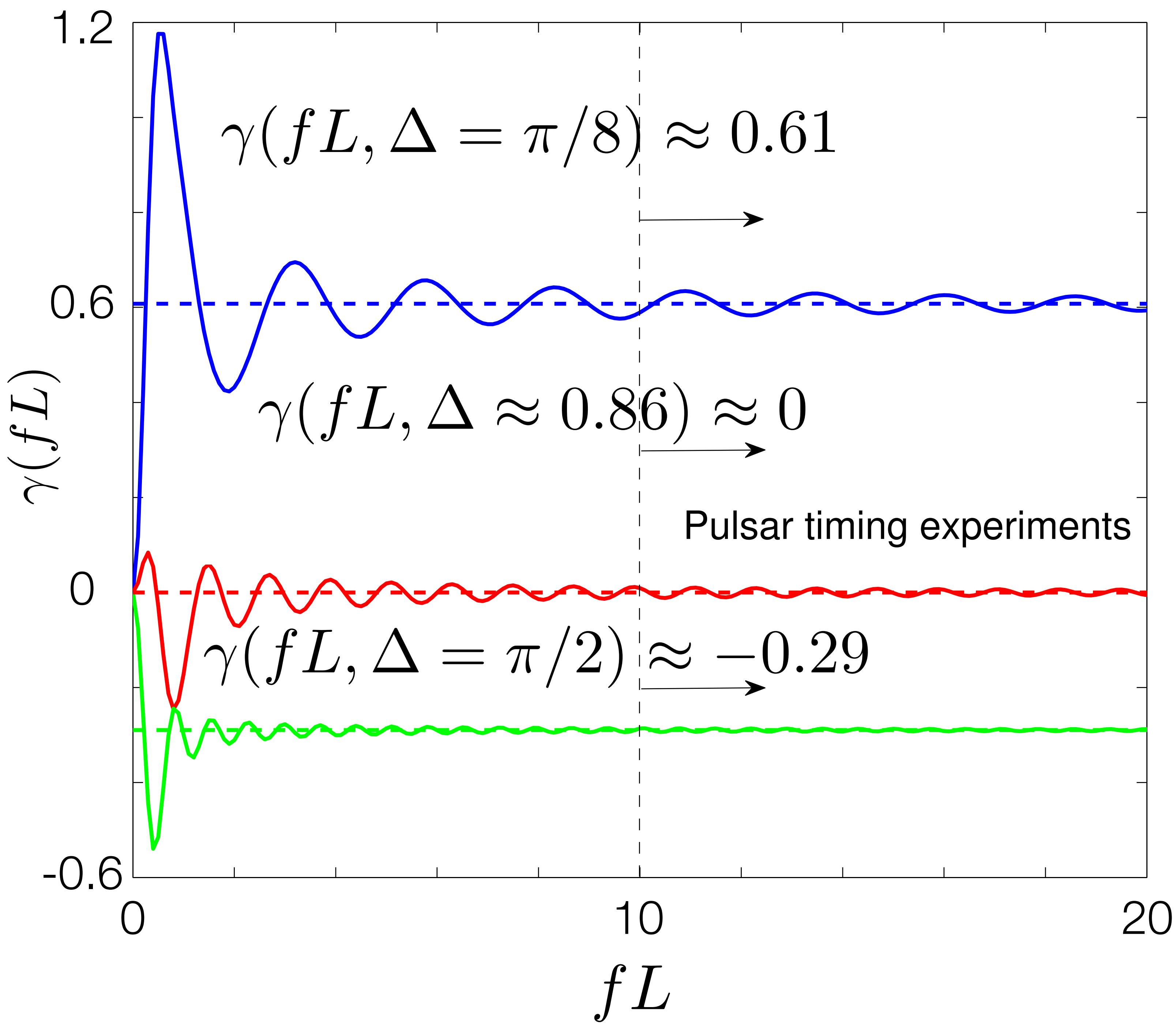
For ground-based interferometers it is known analytically [Flannagan (1993)]



From Allen & Romano (1999)

The Overlap Reduction Function

UNIVERSITY of WISCONSIN UWMILWAUKEE



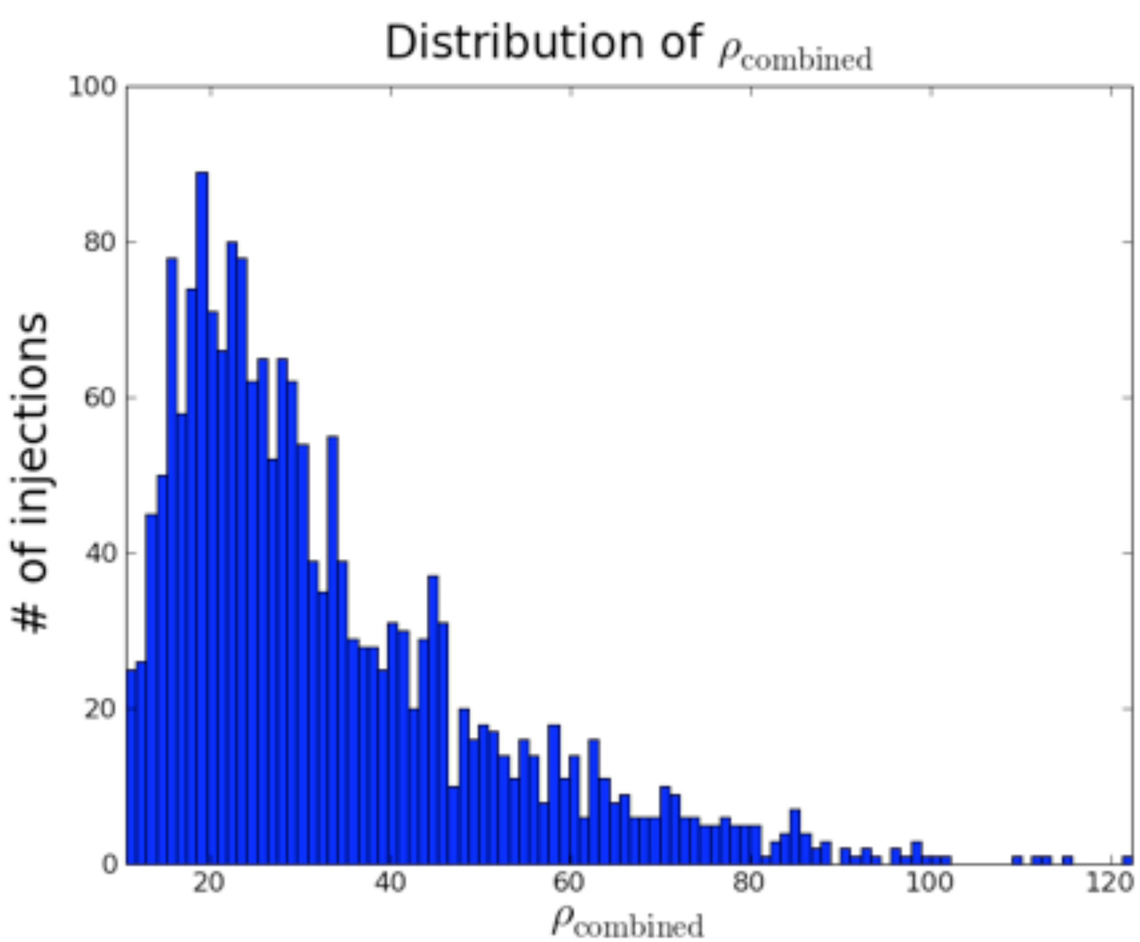
From Anholm, Ballmer, Creighton, LP, Siemens (2009)

For pulsars the ORF is more complicated, but is well approximated by the Hellings-Downs curve. So ignoring frequency dependence is near optimal

Specifics

- Simple threshold-based approach.

- Thresholds set by the percentage of injections recovered with a particular accuracy.



Simulation parameters*:

- Only consider triple coincidence
- Individual masses uniformly distributed between 1-15 Msun
- Maximum total mass of 20 Msun
- Logarithmically distributed in distance between 10-40 Mpc

***LP** and others (in prep)

Enhancement

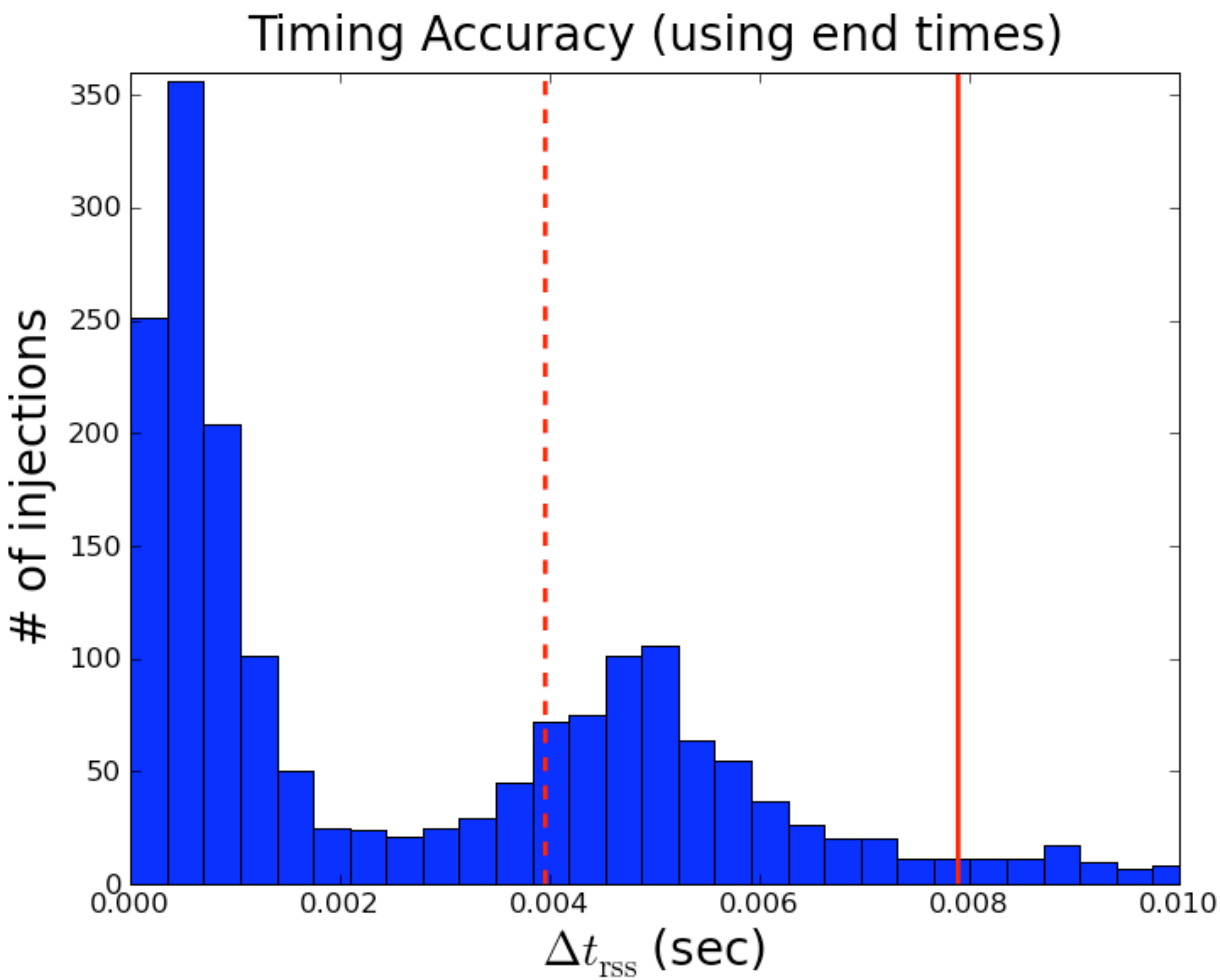
Problem:

- SNR does not accumulate uniformly across the frequency band of the detector.
- Phase difference does accumulate uniformly across the frequency band.

Solution:

Measure the time the signal crosses some reference frequency in the high SNR region of the frequency band, NOT the end time.
(F Acernese et al 2007)

Comparison of Timing Accuracy



Comparison of Timing Accuracy