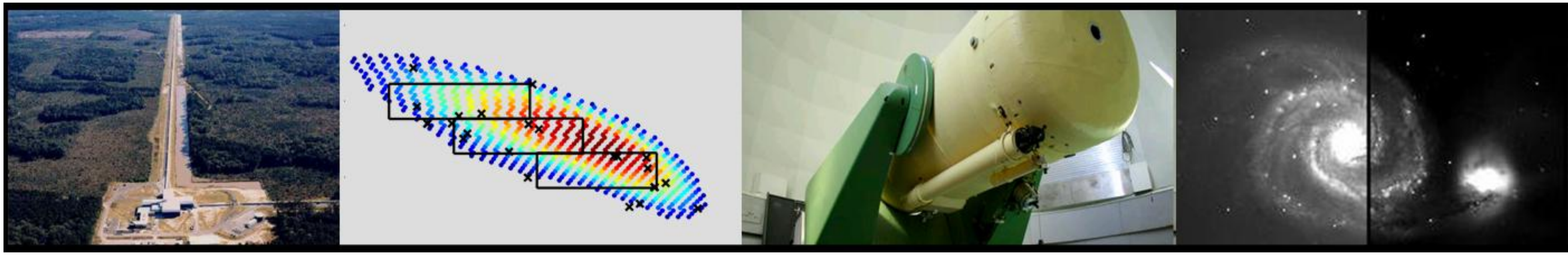
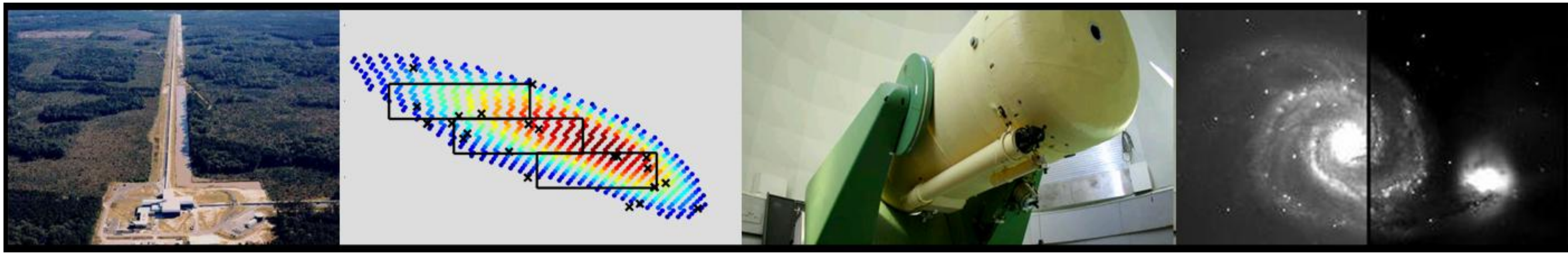


Low-latency GW searches and EM follow-ups

Jonah Kanner
NASA Goddard
for the LIGO Scientific Collaboration and the Virgo Collaboration

Hannover, Germany -- June 4, 2012

LIGO-G1200440-v7



Low-latency GW searches and EM follow-ups

3 publications describing this work:

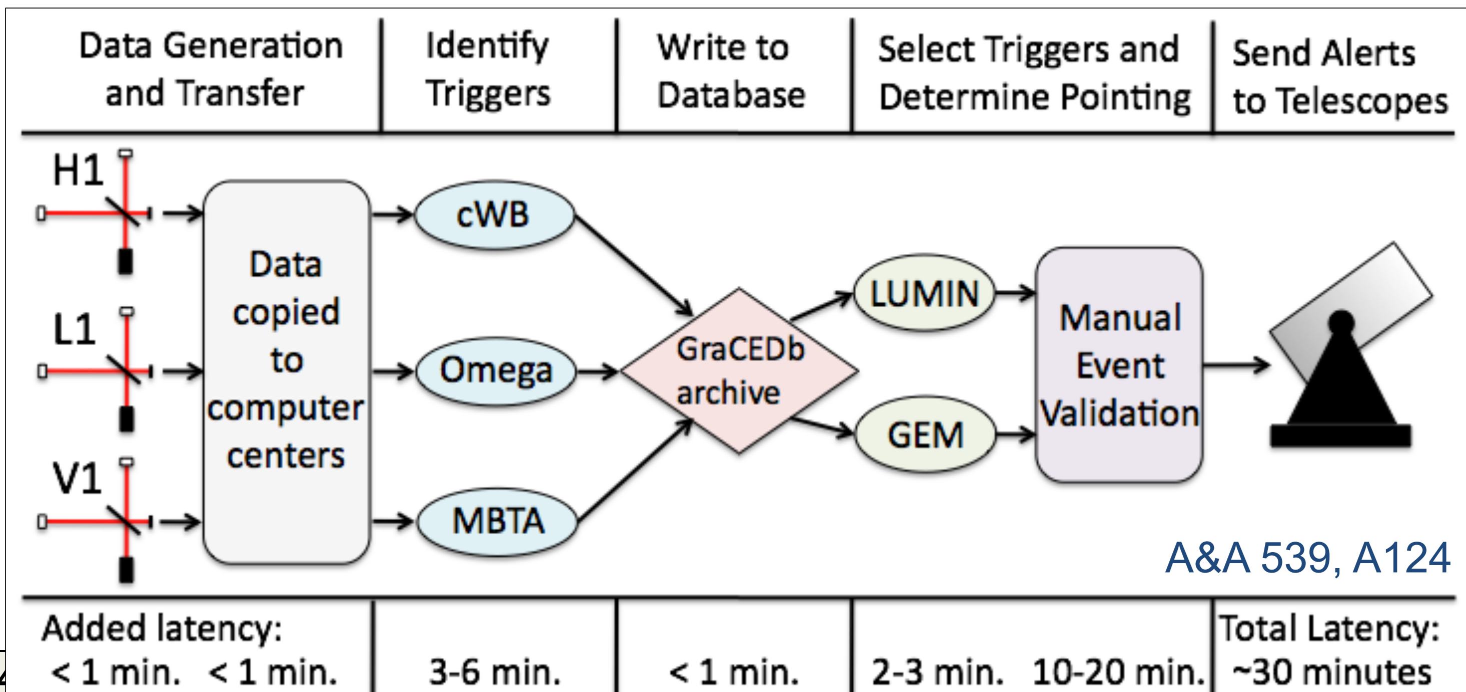
A&A 539, A124 (2012) *Implementation and testing of the first prompt search…*
A&A 541, A155 (2012) *First Low-Latency LIGO+Virgo Search….*
arXiv:1205.1124 (2012) *Swift Follow-Up Observations of Candidate GW…*

LSC VIRGO

LIGO-G1200440

First EM follow-up observations to low-latency GW signals in last LIGO/Virgo science run (2009/2010)

- Identify GW triggers in low-latency
- Online data quality & manual validation
- Sky localization & observation scheduling
- EM transient identification and classification

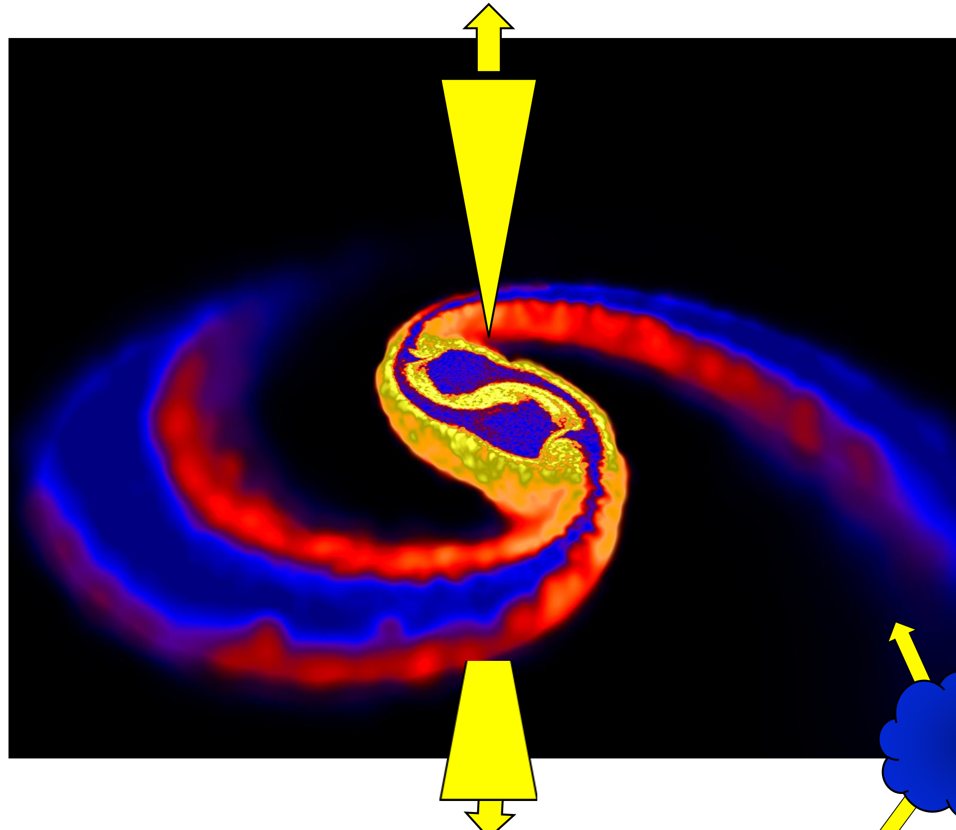


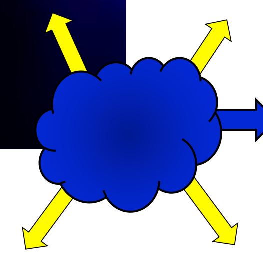
Sources

1) Merging Compact objects (CBC)

Binary neutron stars or black hole/neutron star

Expected EM emission:
Short GRB afterglow
"Kilonova"





2) Collapsing massive star (Burst GW signal)

– Expected EM emission: Long GRB or Supernovae

Image Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen).

Sources

1) Merging Compact objects (CBC)

Binary neutron stars or black hole/neutron star

Expected EM emission:
Short GRB afterglow

"Kilonova"

Estimates for Advanced Detectors
Warning: *Rates have large uncertainties!*

Binary NS
Detection to ~200 Mpc
~0.4-400 events per year
Best guess: 40

~1 per year, based on observed GRB rate

Kilonova may accompany all BNS events

2) Collapsing massive star

Long GRB or Supernovae

Optimistic range of ~20 Mpc
Rates < 0.1 per year

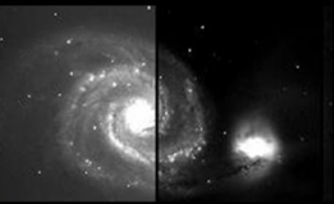
Choosing GW Triggers

Automated Pipeline

- 2009/2010 with LIGO-H, LIGO-L, & Virgo
- Both "CBC" and "Burst" searches
  - CBC looks for compact object mergers (BH/NS)
  - Burst looks broadly for excess power events
  - Ran **four** GW transient searches
- GW Triggers evaluated based on **false positive rate**
  - Time-slides done on-the-fly
  - Evaluate rate of chance coincidences between detectors
- Online "data quality" checked for detector problems
- Automated pipeline completed in ~5-10 minutes

Manual Trigger Validation

- Enthusiastic on-call team to ensure against spurious GW triggers
  - 24/7 coverage
- GW trigger alerts over text message, e-mail, control room alarms
- Conference call to discuss each GW trigger
  - Linked 3 control rooms, plus data analysts
  - Triggers approved or rejected in 30-45 minutes
- Team checked for unusual detector states, software bugs, seismic/traffic/train events, etc.



Manual Validation: Web Interface

Age (Hr:Min)	Id	GPS	DQ	Energy	Event Rate	Frequency	Status	Scopes	View Times	Trigger Details	ETG
6923:37	G19377	968654557.950	Clear	ρ = 4.338	0.00 Events/day	176.3 Hz	alert	Text: Plot:	plot	Details	cwb classic

Trigger Information

You should only request observations after performing the following checks:

- Confirm the event ID starts with "G" , not "T", in the table immediately above this checklist.
- Confirm there are no undefined CAT 1, CAT 2 or INJECTION flags by clicking the link in the DQ colu
- Get a "GO" message from the sanity check script by using the button below. The script will chec low KW glitch rate in H1 and L1.
- Discuss via the permanent EVO session with all 3 control rooms and confirm there are no work with the operator to classify recent data as normal or unacceptable.
- If the ETG column says cbc, check the lower mass is less than 3.5 for all 3 sites. Click on less than 3.5.
- Check the event time on the 1 hour Omega-grams for a glitch rate that is not dramatically elevated compared wi and report on the EVO session if there is a problem.
- Check that the View Times plot exists by clicking on the link View Times column above. This plot should be genera

Checklist to validate trigger

Sanity Checks <---- Click here to run the sanity checks script and view the output.

What would you like to do with this event?

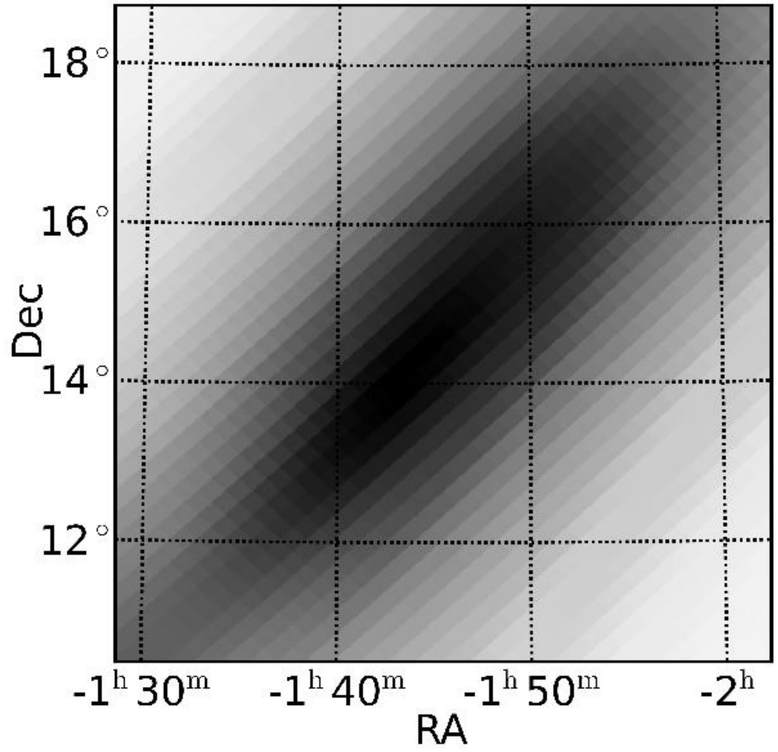
SCIENCE G19377 Request observations of this event.

Button to alert robotic telescopes

Source Localization

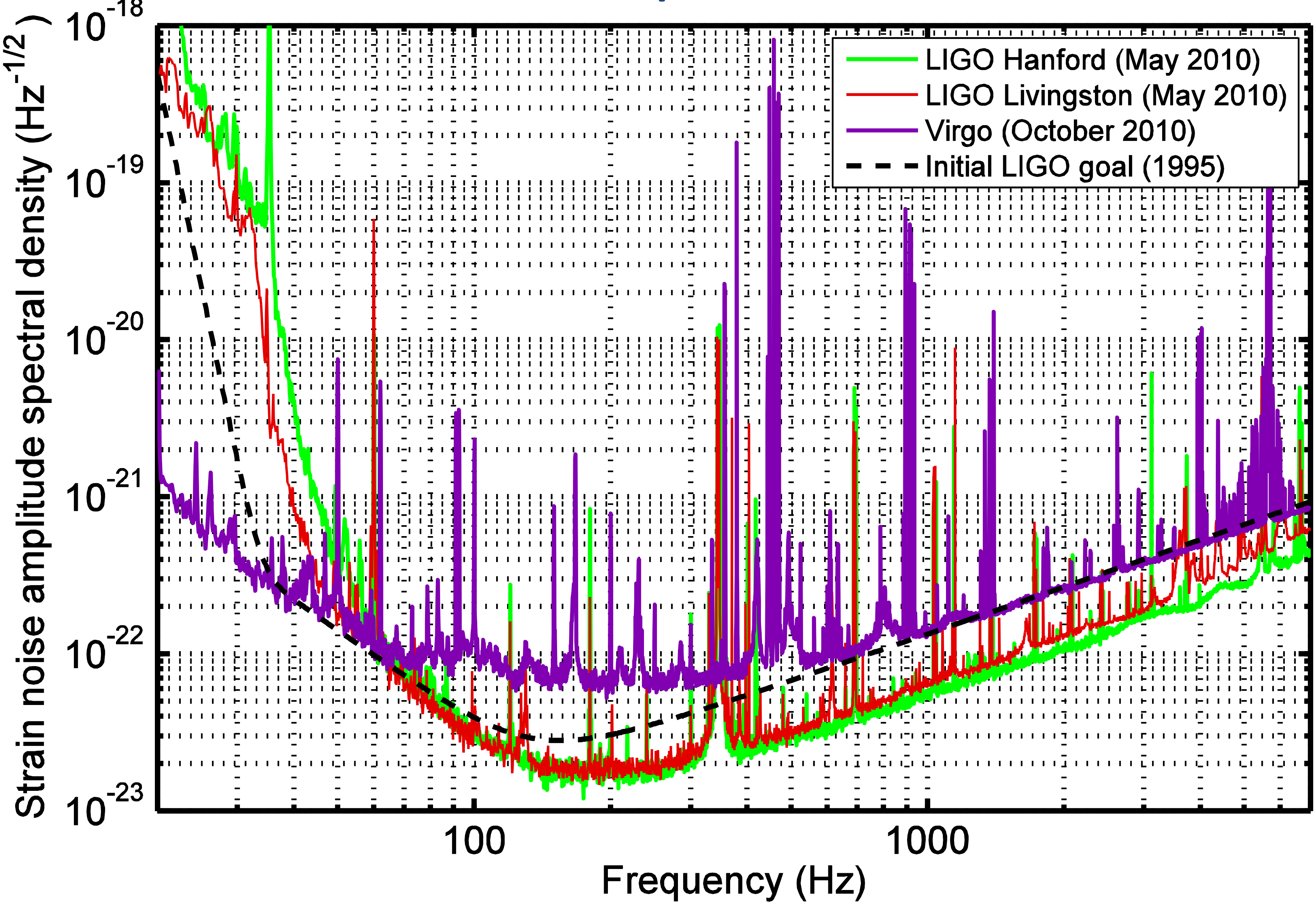
Source Localization: Triangulation

- In last run, used for NS/NS NS/BH search (CBC)
- Uses time delays between detectors to calculate source position
- Results in error ellipse on the sky
- Localization works best with equally sensitive detectors

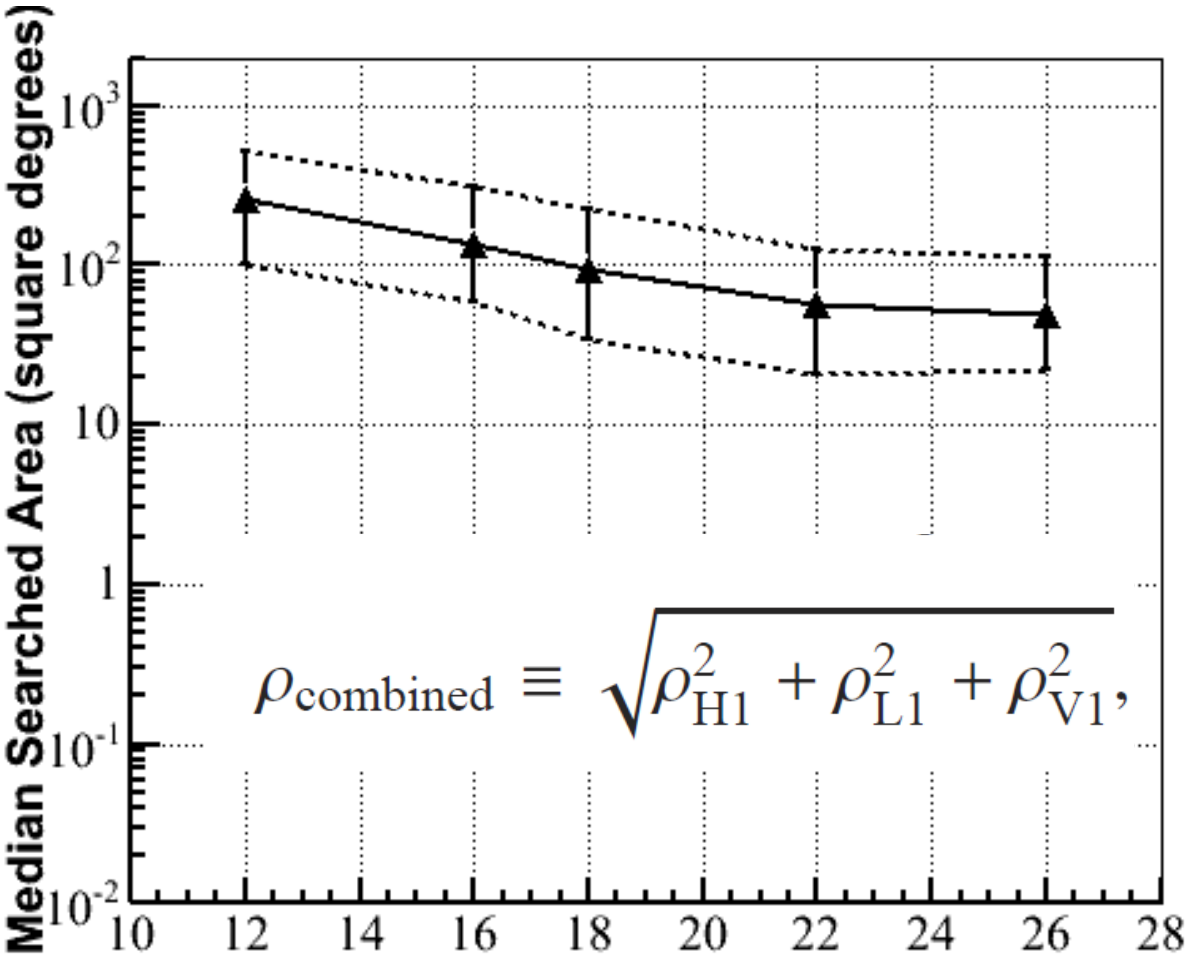


A&A 541, A155 (2012)

Similar, but not equal, noise curves



Triangulation in last science run



$$\rho_{\text{combined}} \equiv \sqrt{\rho_{\text{H1}}^2 + \rho_{\text{L1}}^2 + \rho_{\text{V1}}^2},$$

Network SNR ρ_{combined}

Low threshold, inspiral signals localized to ~200 square degrees

Larger area than for equally sensitive detectors

Strong SNR dependence
Area ~ $1/(\text{SNR})^2$

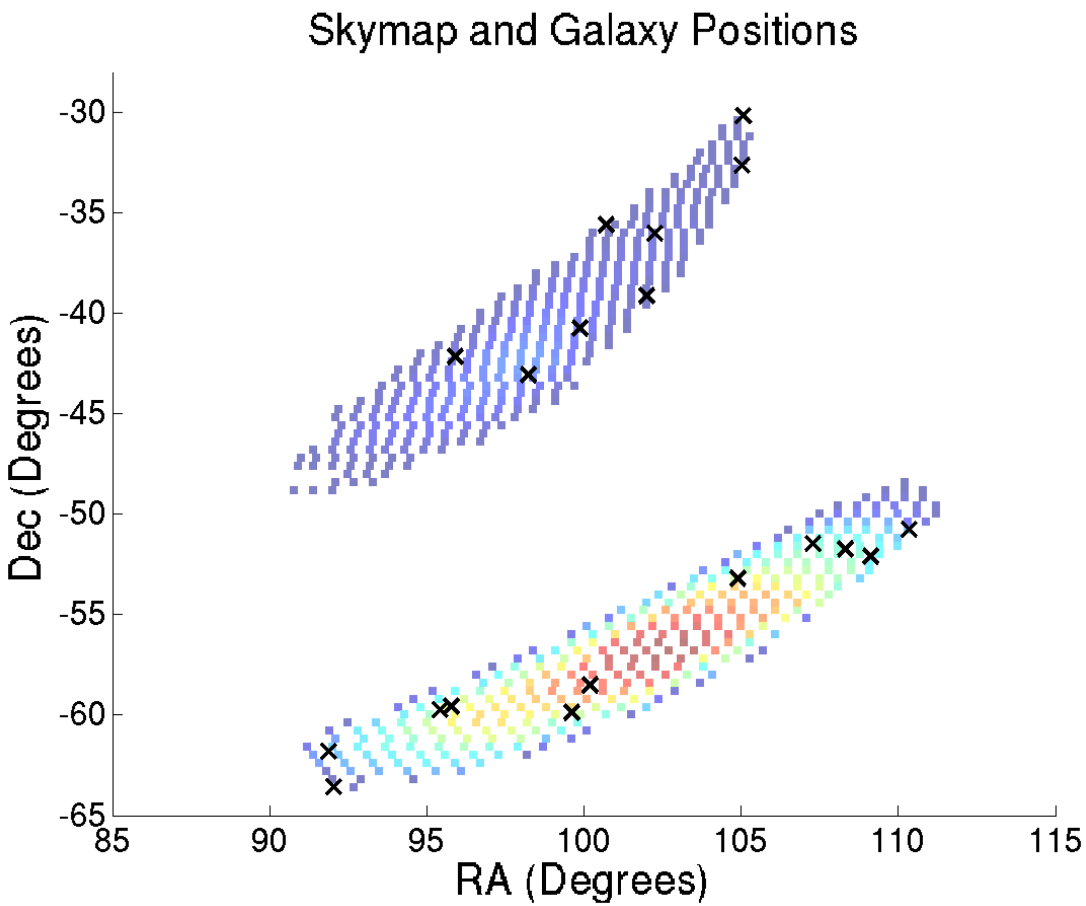
A&A 539, A124

Guessing the right galaxies

Finite detection horizon limits potential host galaxies

Look for nearby galaxies that overlap error region

Galaxies can be ranked by their mass and other properties

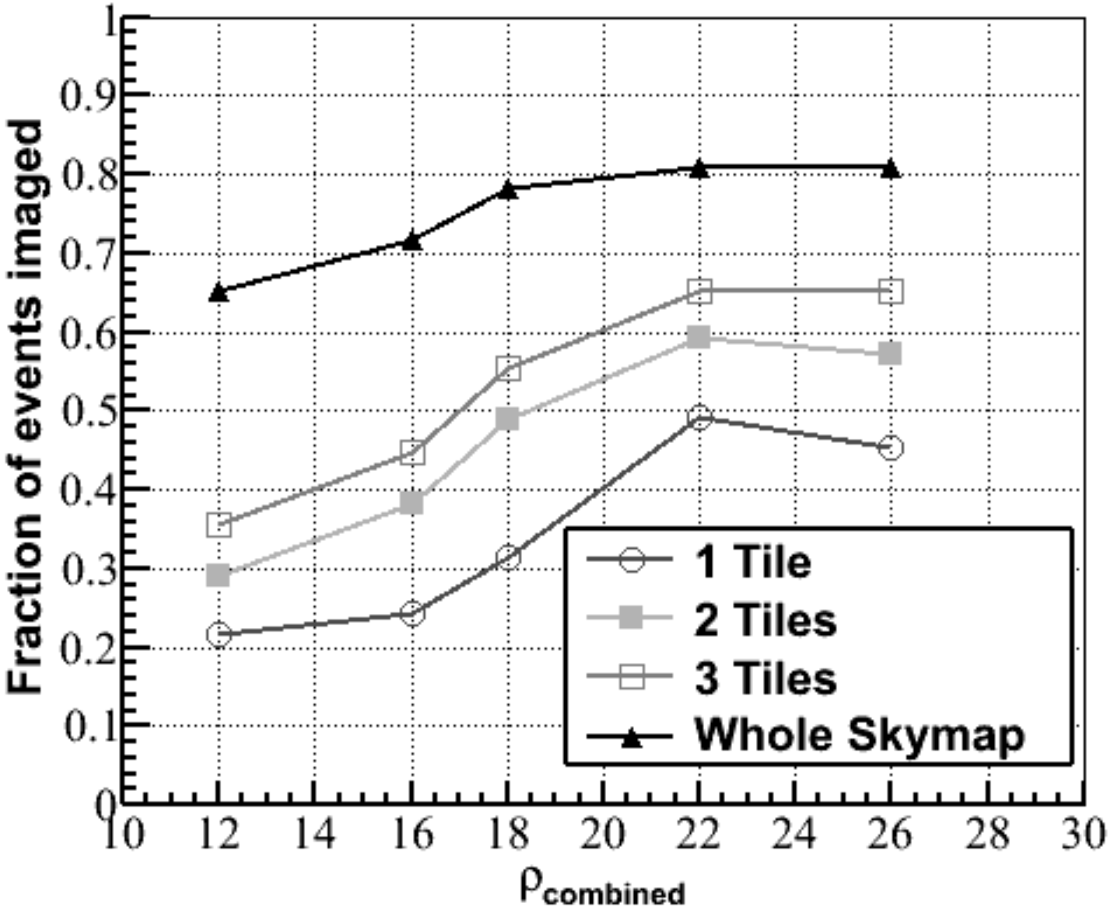


Galaxy targeting in last science run

Simulations show galaxy targeting very effective for initial LIGO/Virgo

Selecting a few (~5) galaxies is enough for moderate SNR (initial LIGO/Virgo)

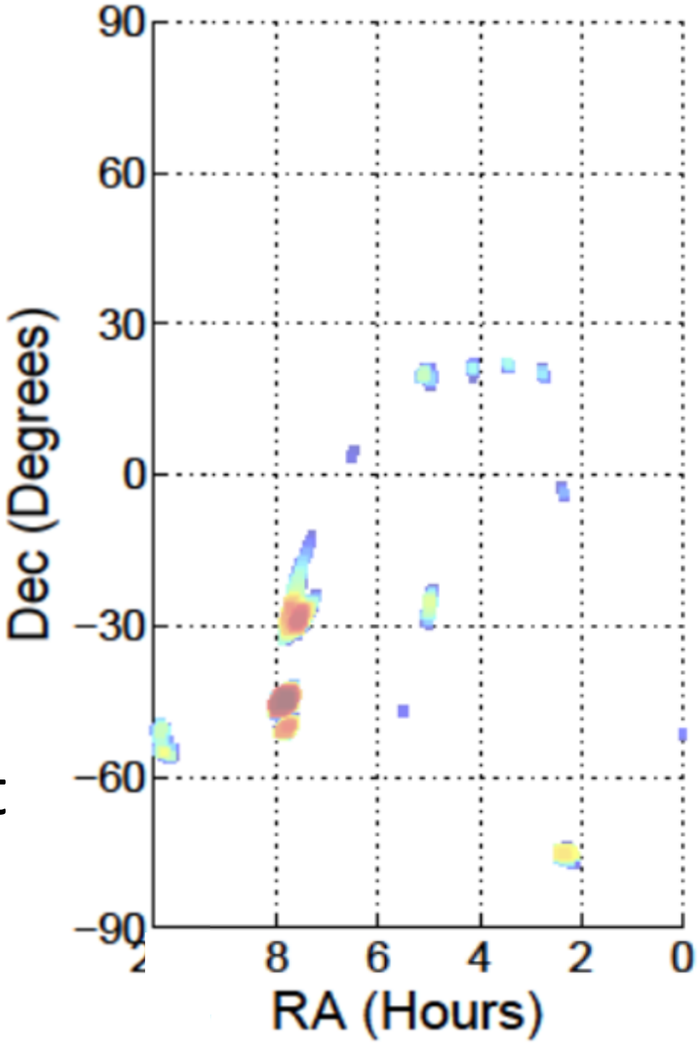
Number of galaxies will increase as horizon expands



A&A 539, A124

Coherent Parameter Estimation

- Attempts to find "best fit" signal parameters
- Seeks consistency between detectors
- Produces a "skymap" of likely source locations
  - May not be a simple ellipse!
- In last science run, used coherent parameter estimation for low-latency Burst searches



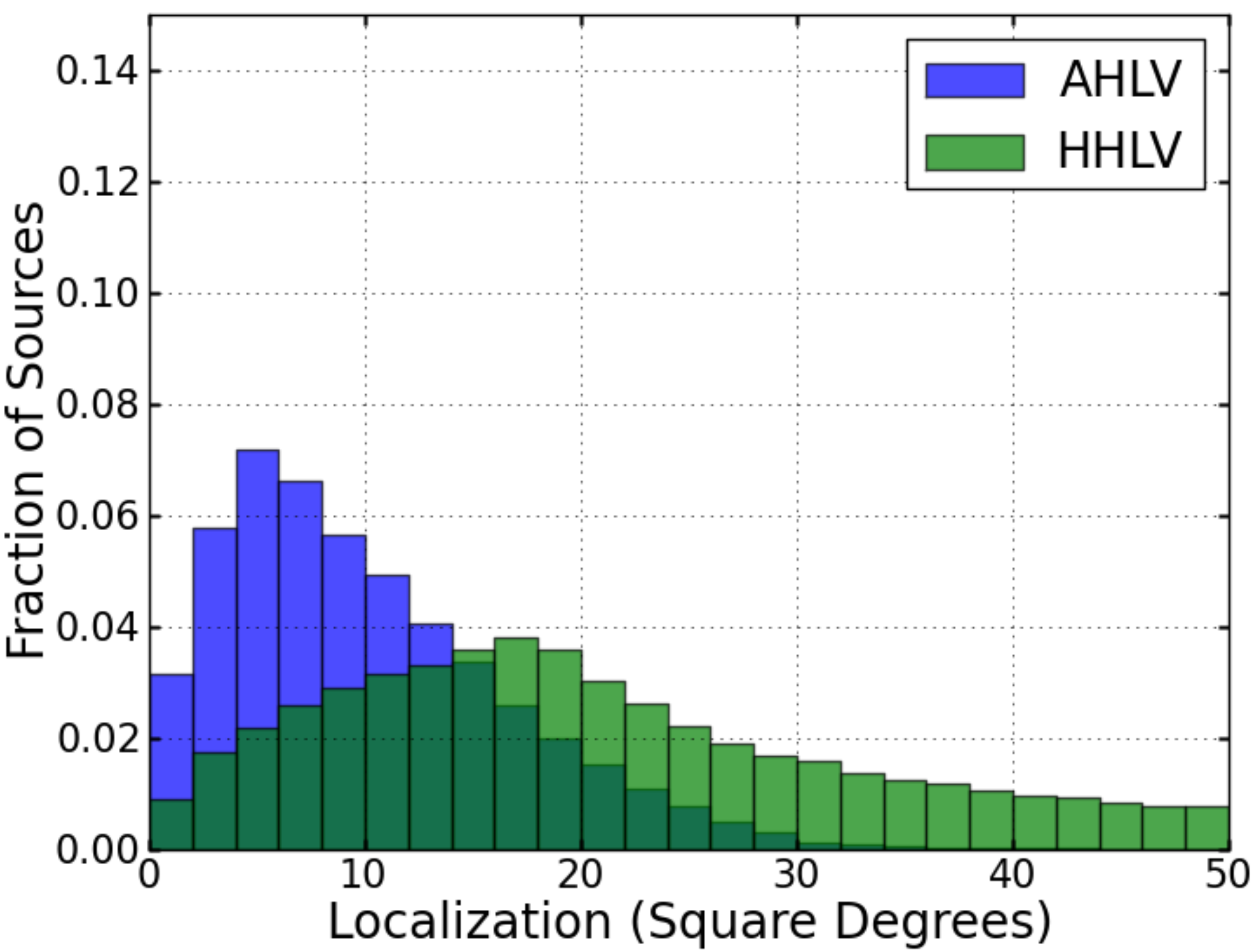
Localization with Advanced Detectors

Advanced GW Networks

- Advanced LIGO (H,L) & Advanced Virgo (V) operational 2015-2016
- LIGO India: Science data beginning ~2020
- KAGRA (Japan): Observation run planned ~2018
- Increasing number of detector sites dramatically improves source localization
- History shows that detector sensitivity improves with time – expect (H,L,V) to have varying and different sensitivity in early years

Localization ability w/ Advanced Detectors

Fairhurst, 2011 CQG 28, 105021



3 site / 4 detector network (green) LIGO-H, LIGO-L, Virgo

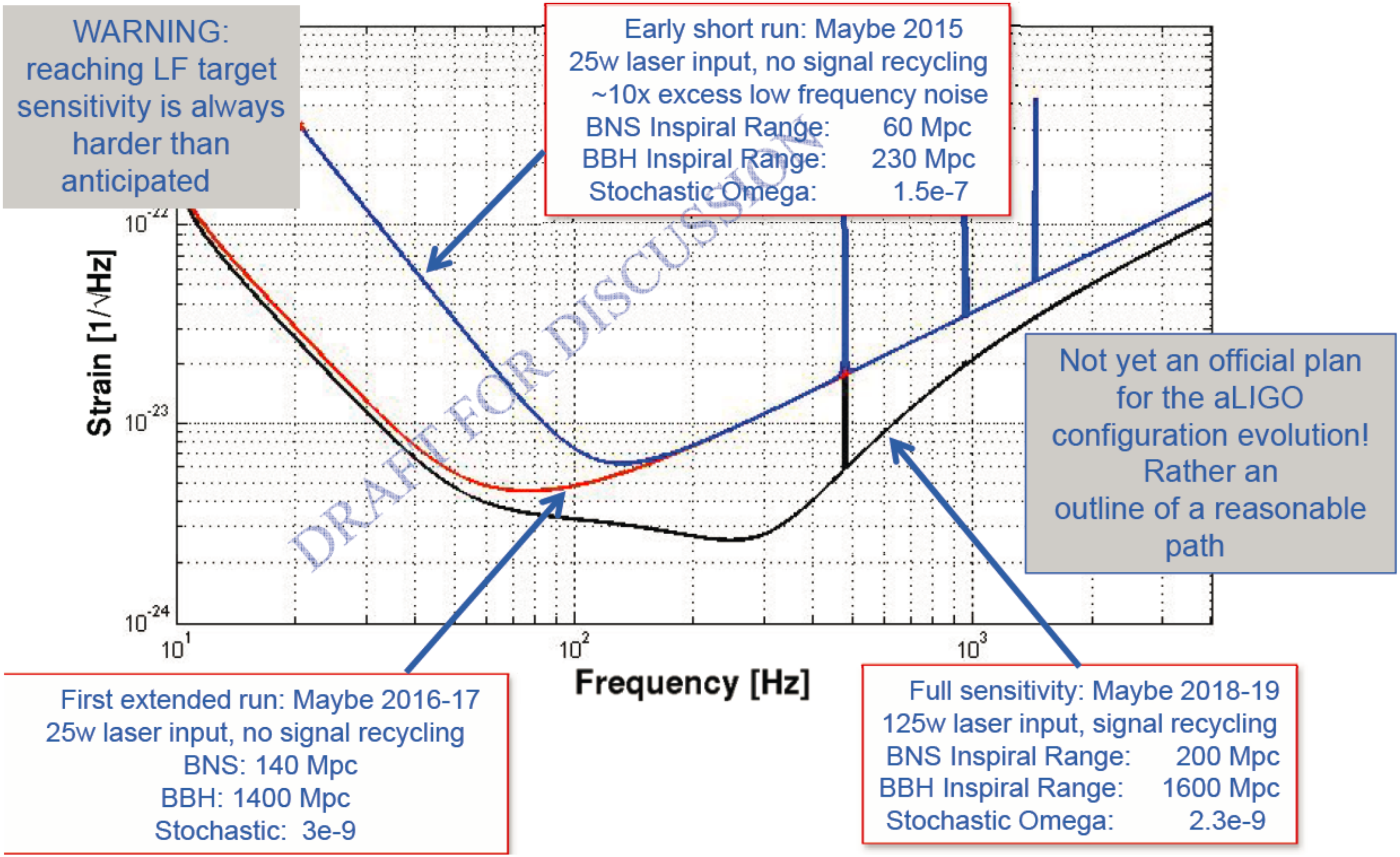
Assumes equally sensitive detectors

~10-40 square degrees

Simulation of NS-NS mergers

Possible Advanced LIGO Noise Curves (UNOFFICAL)

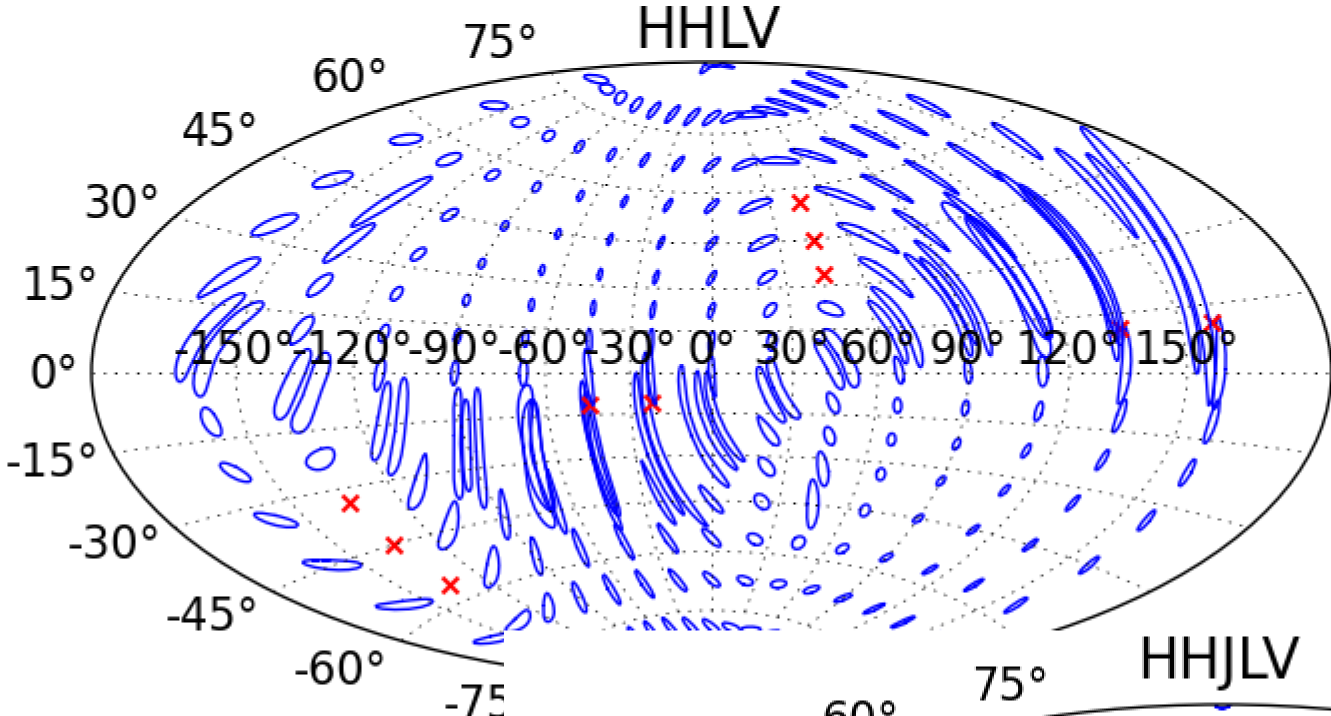
Sensitivity will evolve over time



Evolving Detectors

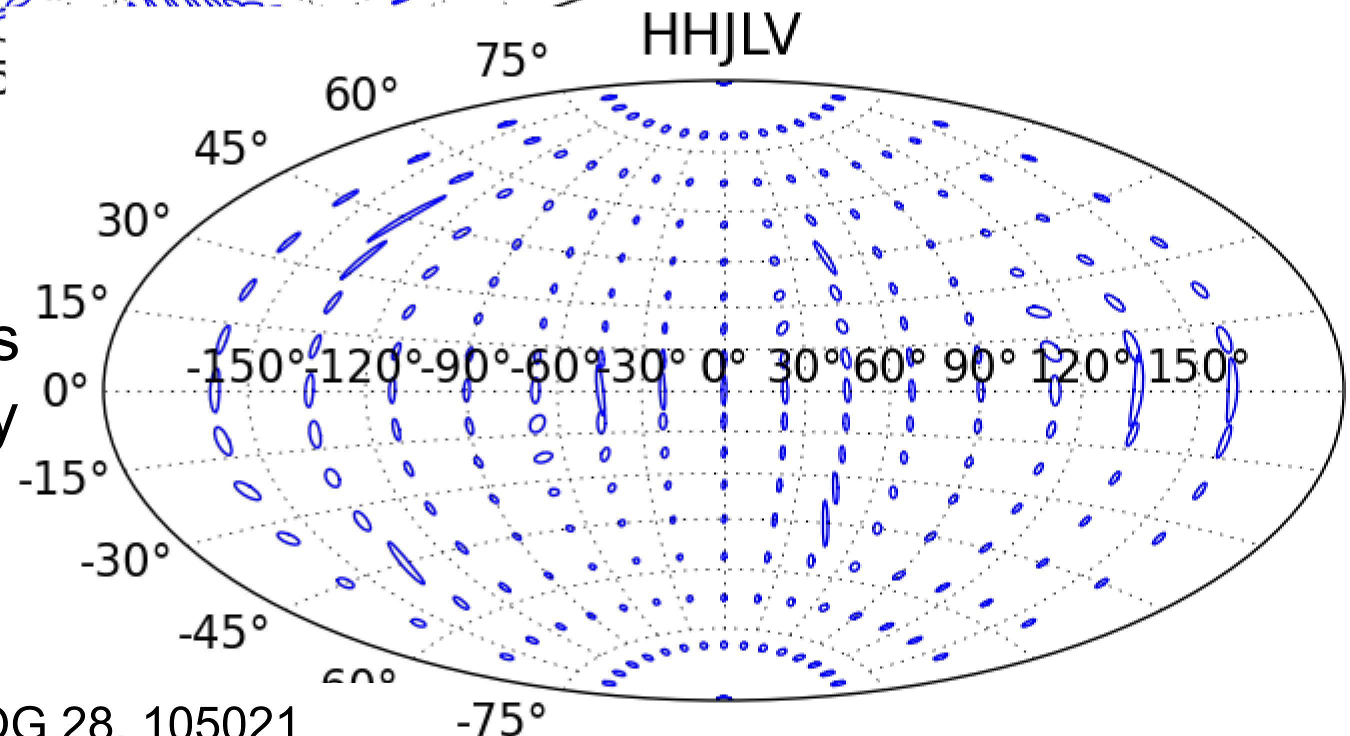
- 2015 – 2018 will be the very early years of GW astronomy
- Detector noise curves will evolve at different paces → evolving localization ability
- Some early detections may be with only 2 site network

  → ~Thousand square degrees
- More mature detectors and additional sites will improve localization ability



NS/NS signals
160 Mpc

Equally sensitive advanced detectors



Adding fourth detector site to network improves localization ability

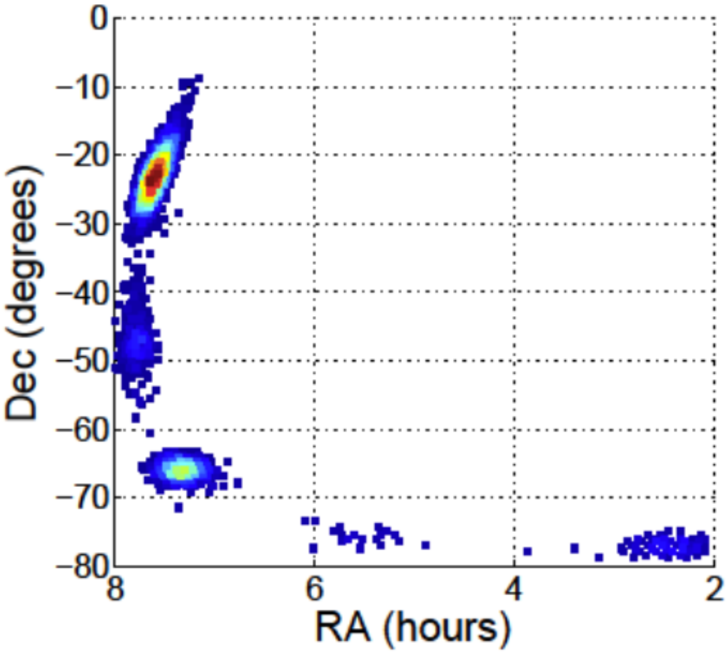
Fairhurst, 2011 CQG 28, 105021

Coping with the error "box"

Strategy I: Tile the whole thing

- Excitement of early detections may motivate large dedication of observing time
- Modern, large etendue optical surveys (PTF, Pan-STARRS, SkyMapper….) can observe error box in a night

  Not IF saw you it,
  but WHAT you saw!
- Low frequency, dipole radio arrays use aperture synthesis, and so can construct large FOV
- Other instruments may aggressively tile to cover region much larger than FOV



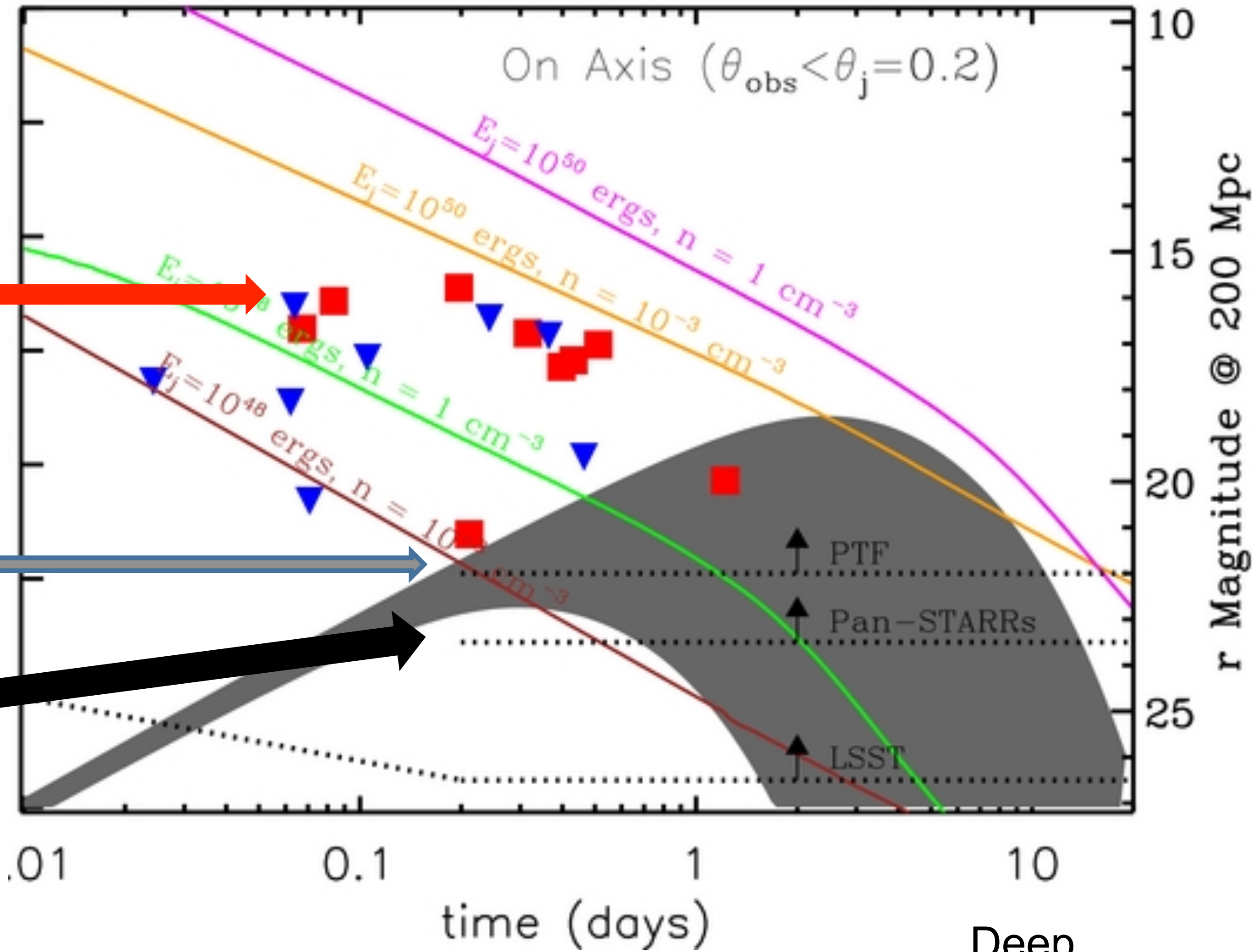
Try it yourself!
Tiling software available:
Singer, Price & Speranza (2012)
arXiv:1204.4510

Deep and Wide: Survey Optical Telescopes

Observed SGRB afterglows are bright

Kilonova peaks 19-22 magnitude

PTF
Pan-STARRS
SkyMapper
LSST
etc…

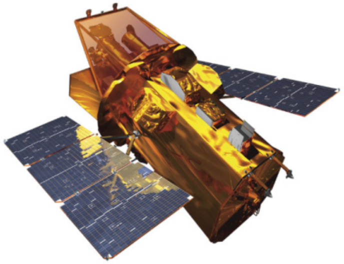


Deep

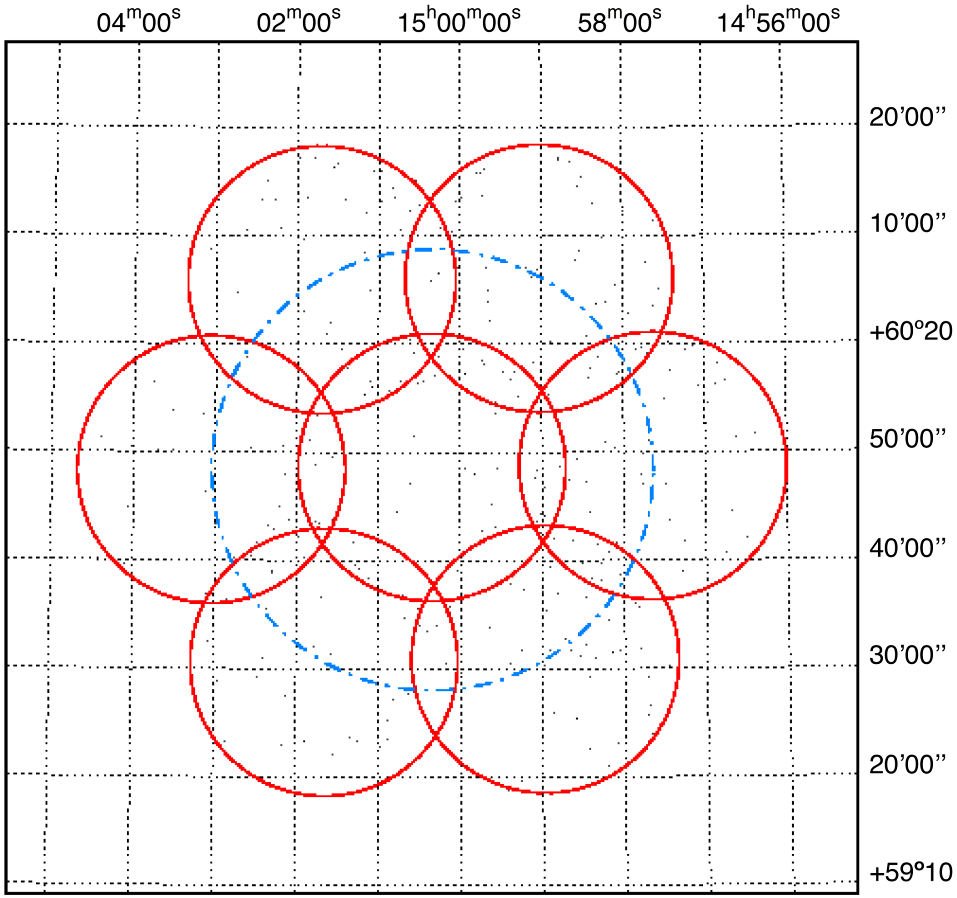
Pann-STARRS photo by Rob Ratkowski

Metzger & Berger, 2012

Swift X-ray Telescope Auto Tiling



Swift has recently added a feature to observe multiple tiles in one orbit

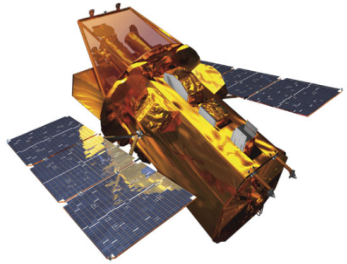


Multiple configurations:

- 2x2
- 7 …. See graphic →
- 19 (~0.7 degree radius)
- 37 (~1 degree radius)

Each configuration can observe all tiles in one ~90 minute orbit

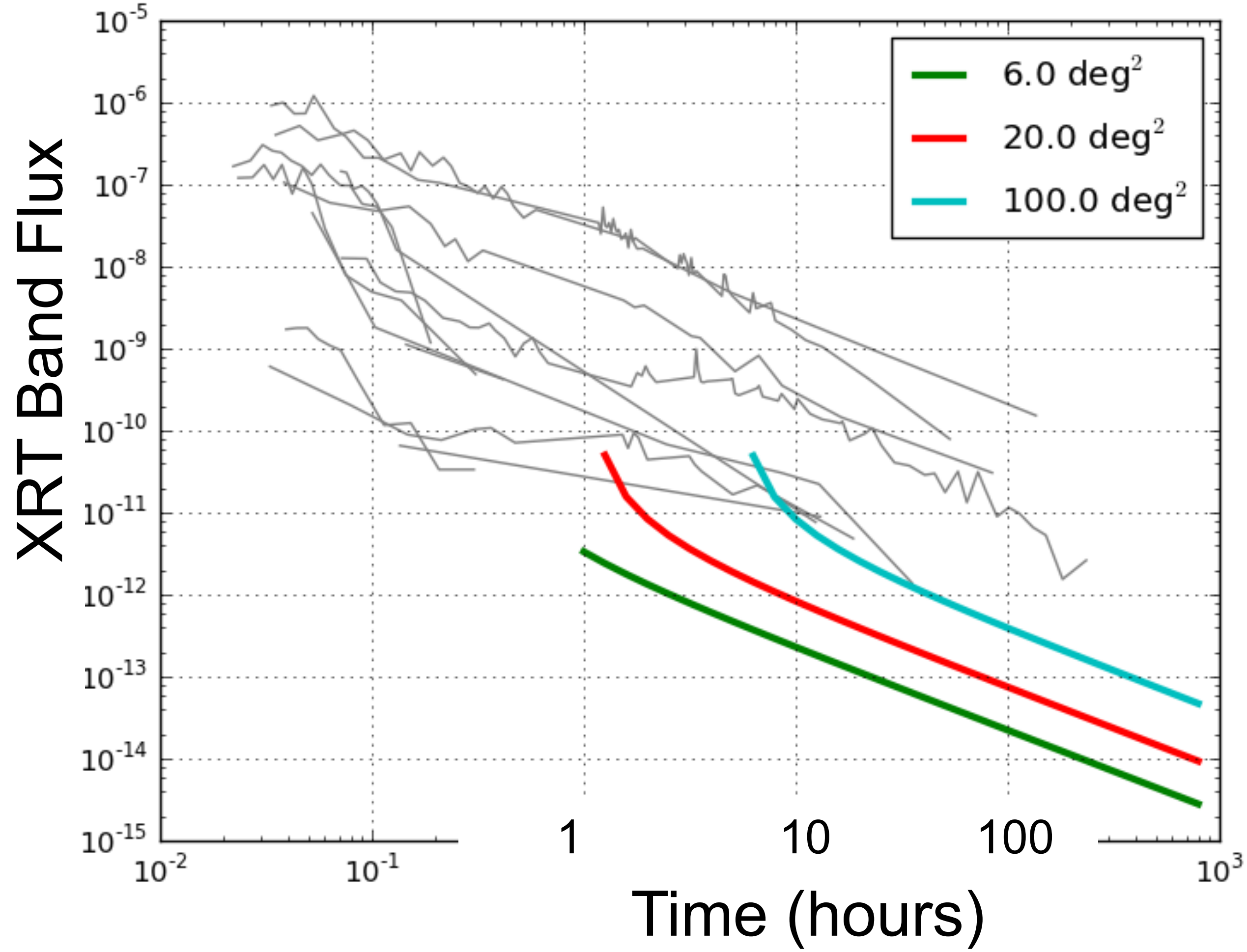
Slide courtesy Swift team



Tiling with Swift/X-ray Telescope

An X-ray afterglow at 200 Mpc could be bright for ~24 hours (Grey Curves)

The X-ray telescope on Swift could use short exposures to tile ~20+ square degrees in this time (Red Curve)



Strategy II: "Guessing" the Host Galaxy

Pros & Cons

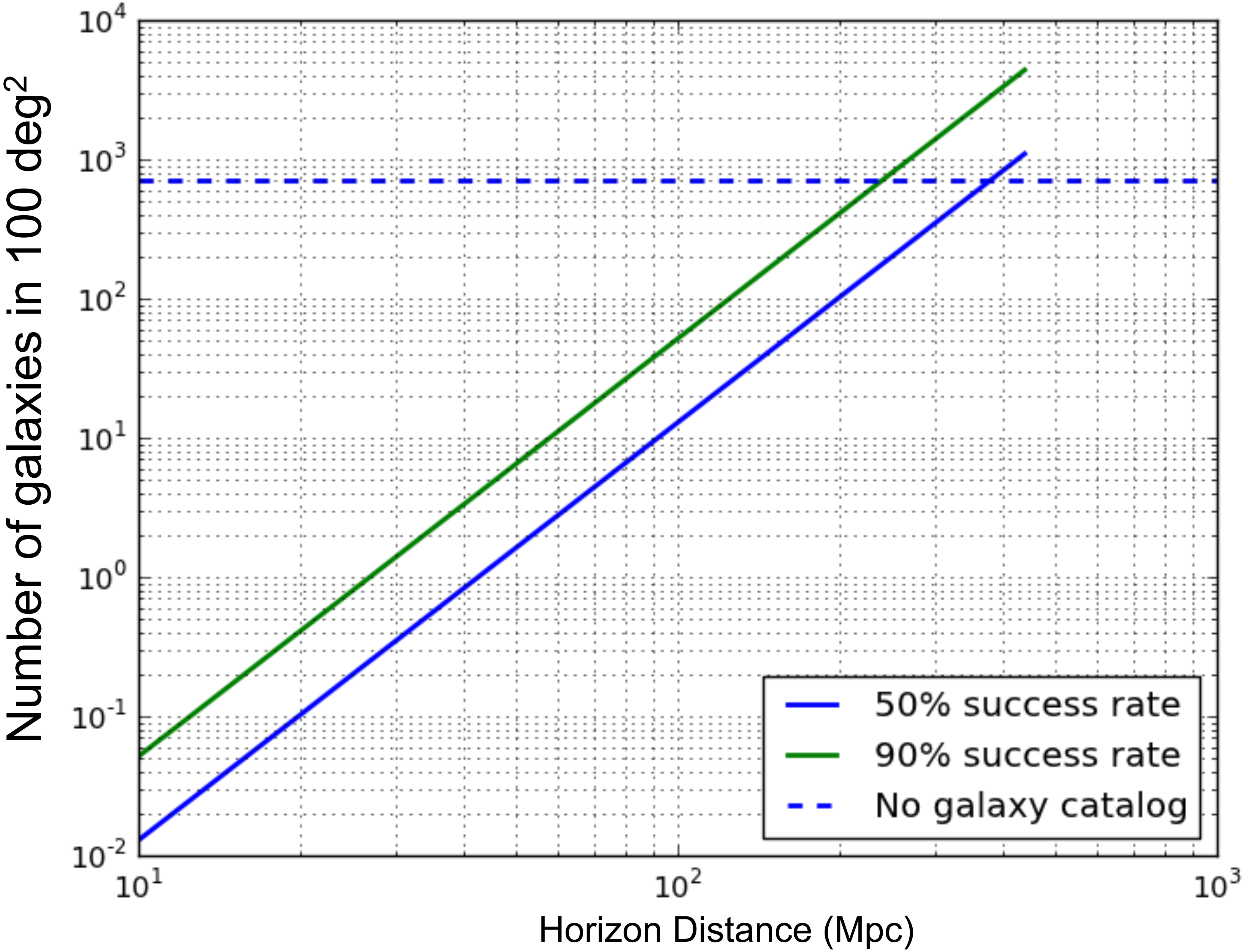
Pros

- Could allow smaller FOV instruments to seek counterpart
- Greatly reduces false positive rate
- Allows observations to be deeper rather than wider
- Different observing strategies for Burst (< 10 Mpc) and CBC (< 200 Mpc)

Cons

- No catalog is truly complete (~70% to 100 Mpc)
- Horizon distance is model dependent NS/NS ≠ NS/BH
- Not feasible for large horizon distances (> 200 Mpc)
- If kicks are large, some mergers outside hosts

How many galaxies?



Summary

- Last LIGO/Virgo science run saw great strides!
  - Low-latency analysis, position reconstruction, & EM-follow-ups
- 3 Equally sensitive detectors localize sources to 10-100 square degrees, strong SNR dependence
  - Adding a 4^{th} site is a big improvement
- Early years (2015-2018) will see rapidly evolving detectors → rapidly evolving localization
- Observing whole uncertainty regions is realistic for some instruments, possibly with many tiles
- For intermediate range detectors (~100 Mpc), galaxy targeting can reduce the area to observe