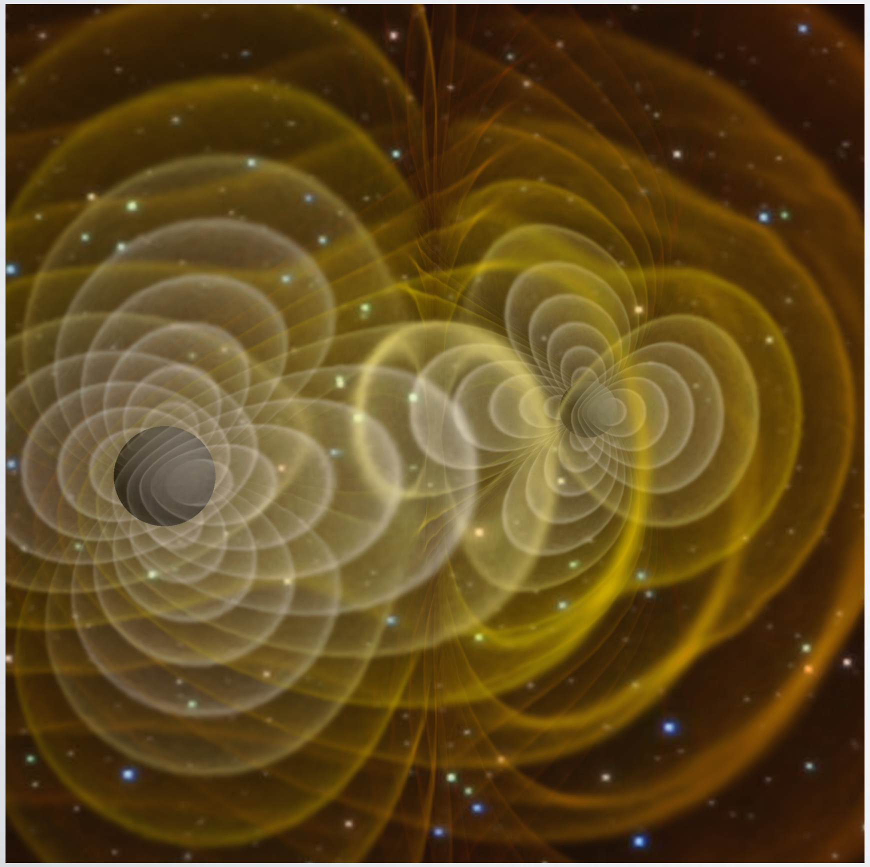
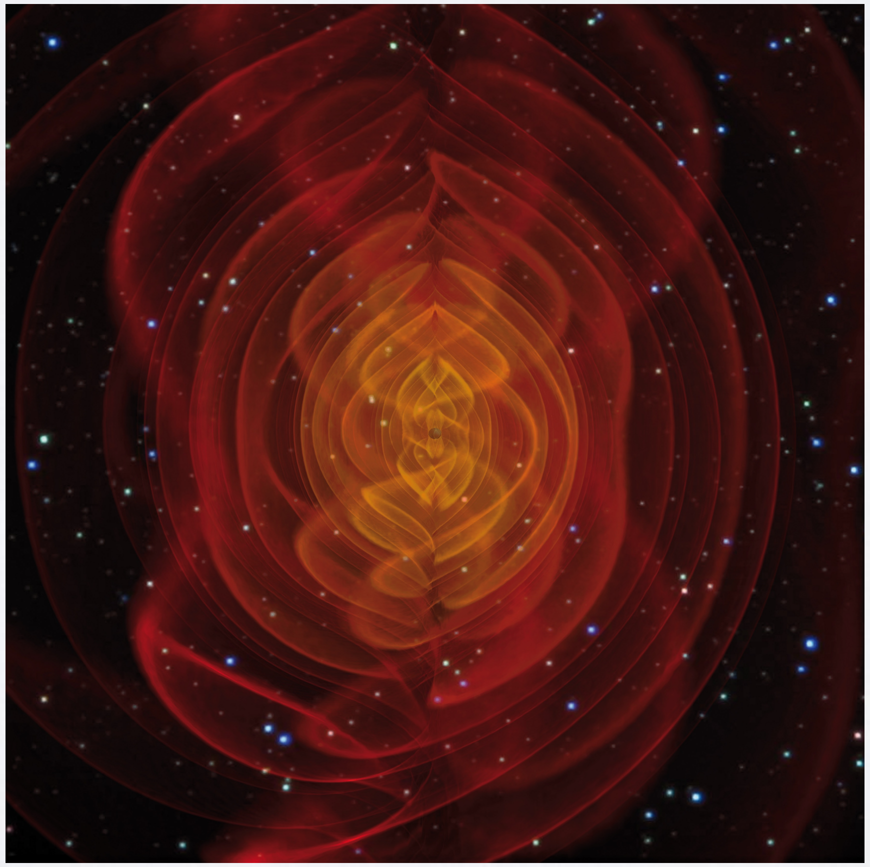
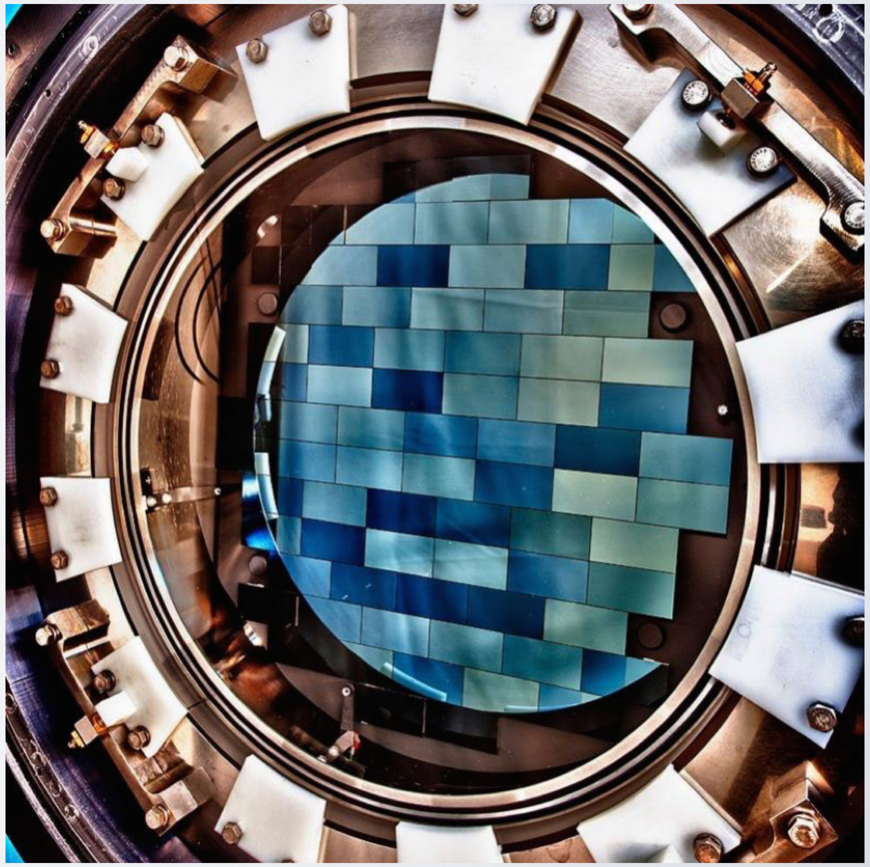
GRAVITATIONAL WAVES OPTICAL COUNTERPART OBSERVATIONS (NOW WITH DES, SOON WITH LSST)

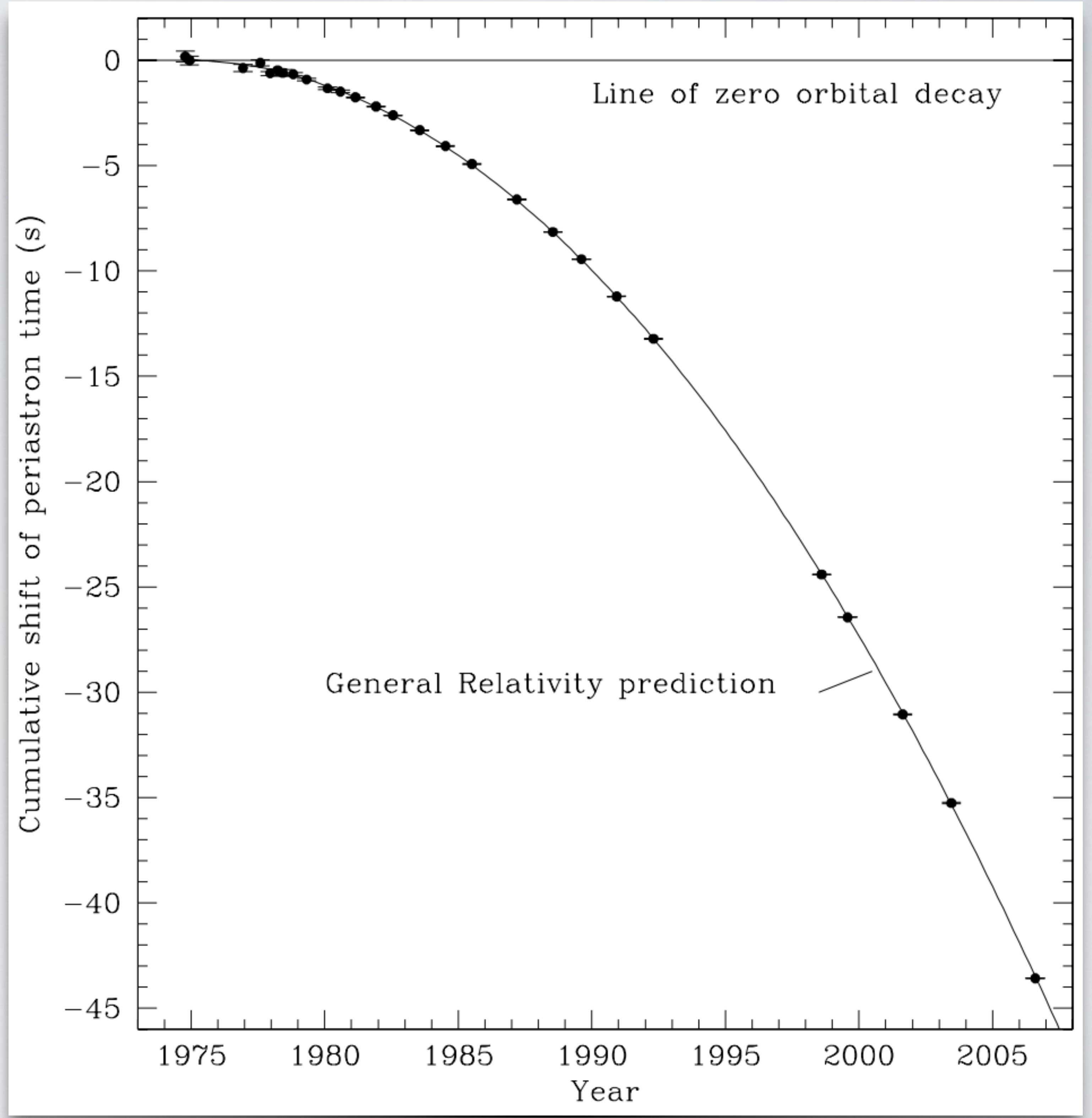
Marcelle Soares-Santos, Fermilab

LSST Observing Strategy Workshop — Bremerton, WA — August 20, 2015

PSR B1913+16

Weisberg, Nice & Taylor, 2010



Measurements of the decaying orbit of the Hulse & Taylor pulsar.

The era of GW detection has already started — **40 years ago!**

A great success of GR and the astronomical community.

GW "DIRECT" DETECTION

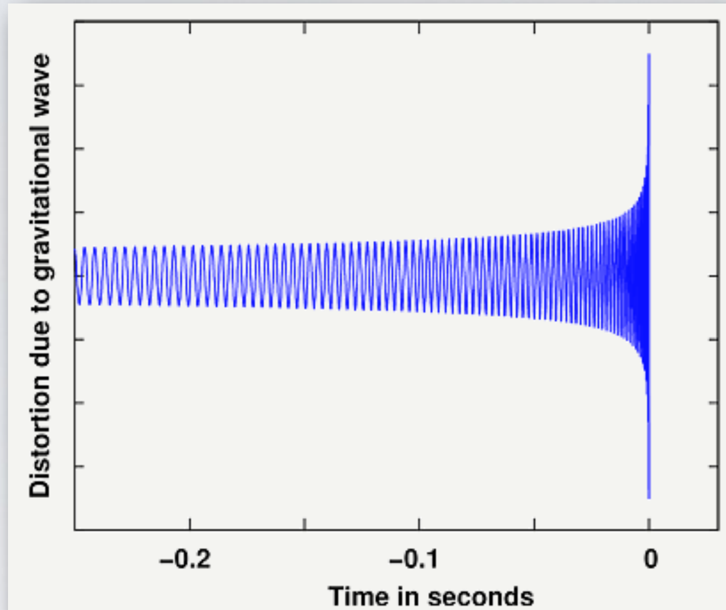
LIGO Livingston, LIGO Hanford, and Virgo

LIGO: arXiv:1304.0670

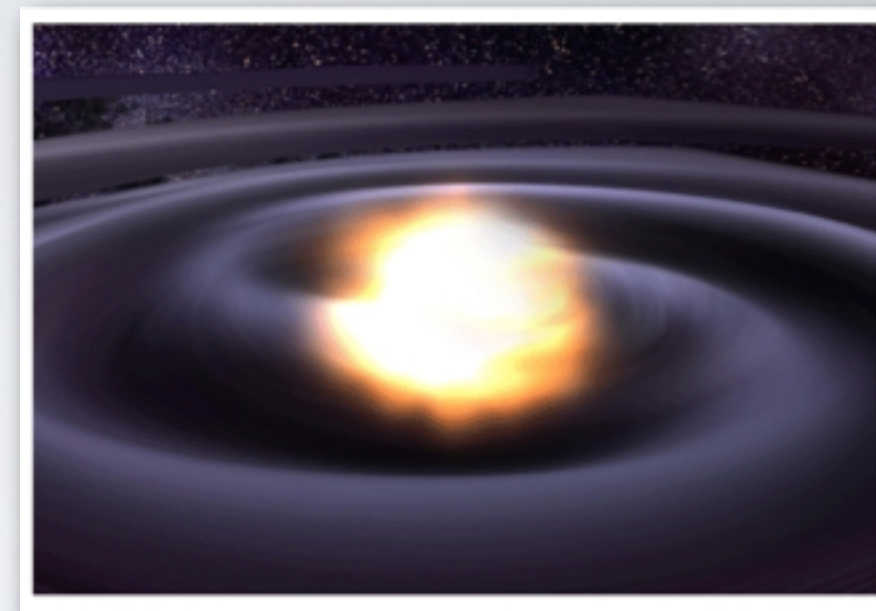
	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
aVirgo + aLigo	2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
aVirgo + aLigo	2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
	2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

STANDARD SIRENS

(cartoon illustration)

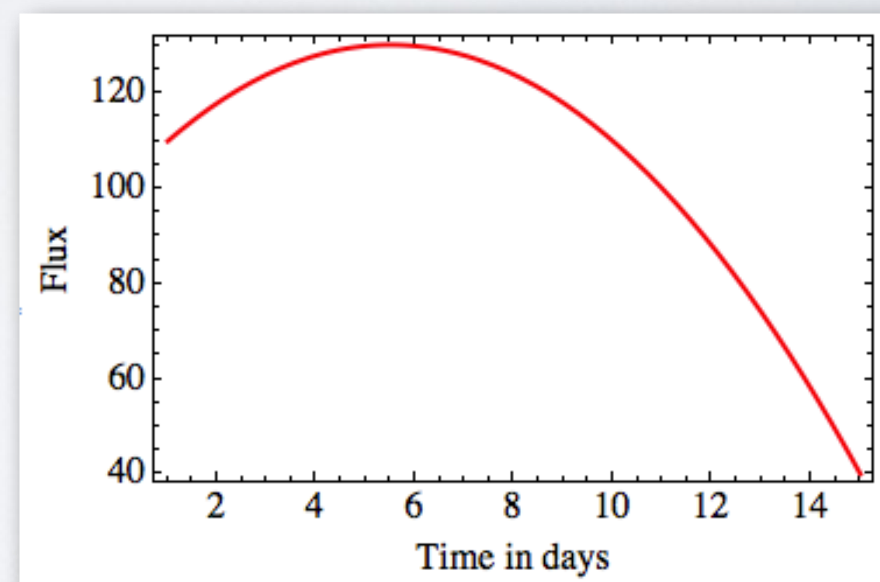


GW

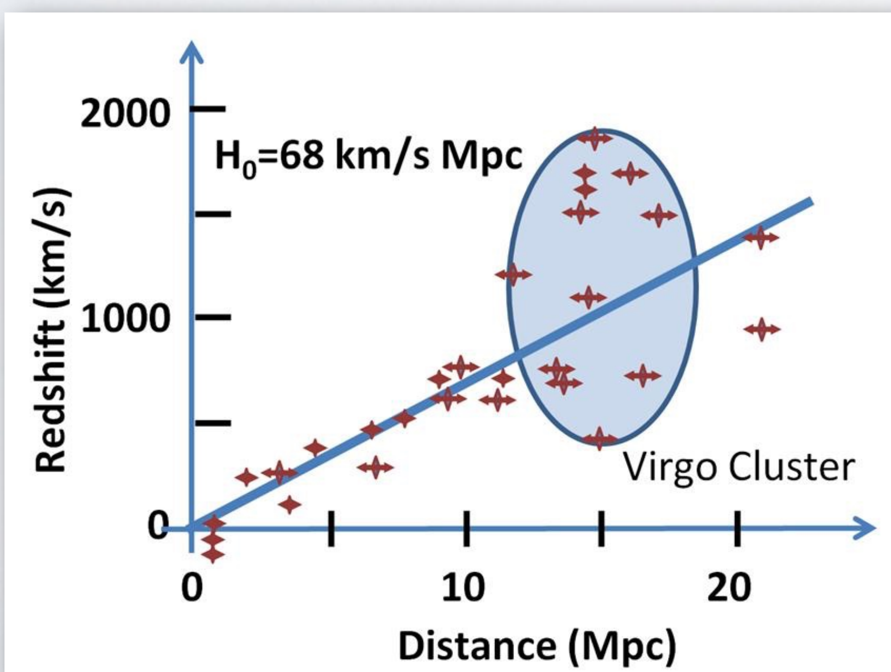


distance

EM



redshift



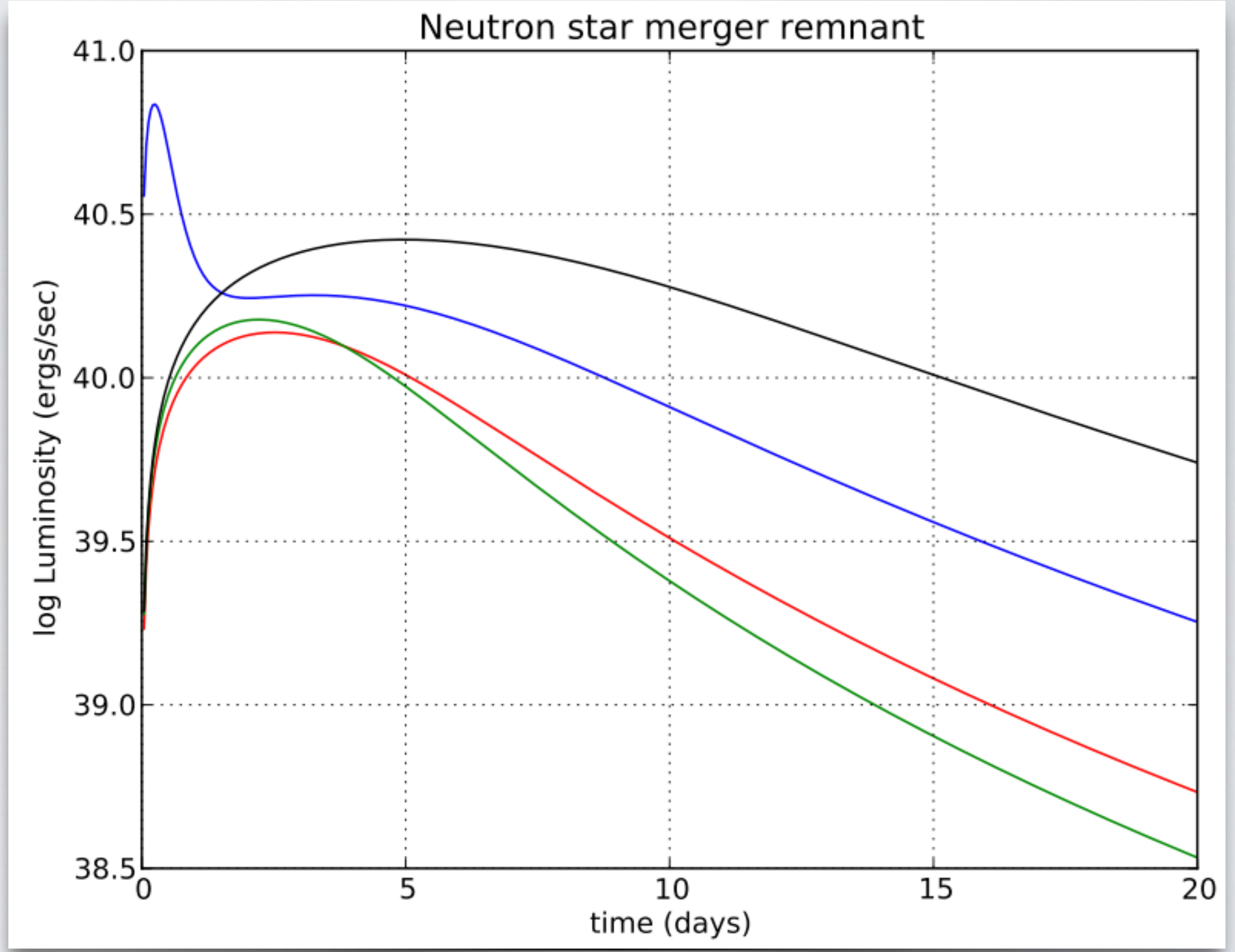
POSSIBLE COUNTERPART: KILONOVA

Semi-analytic models tuned with simulations (based on Grossman et al. 2014)

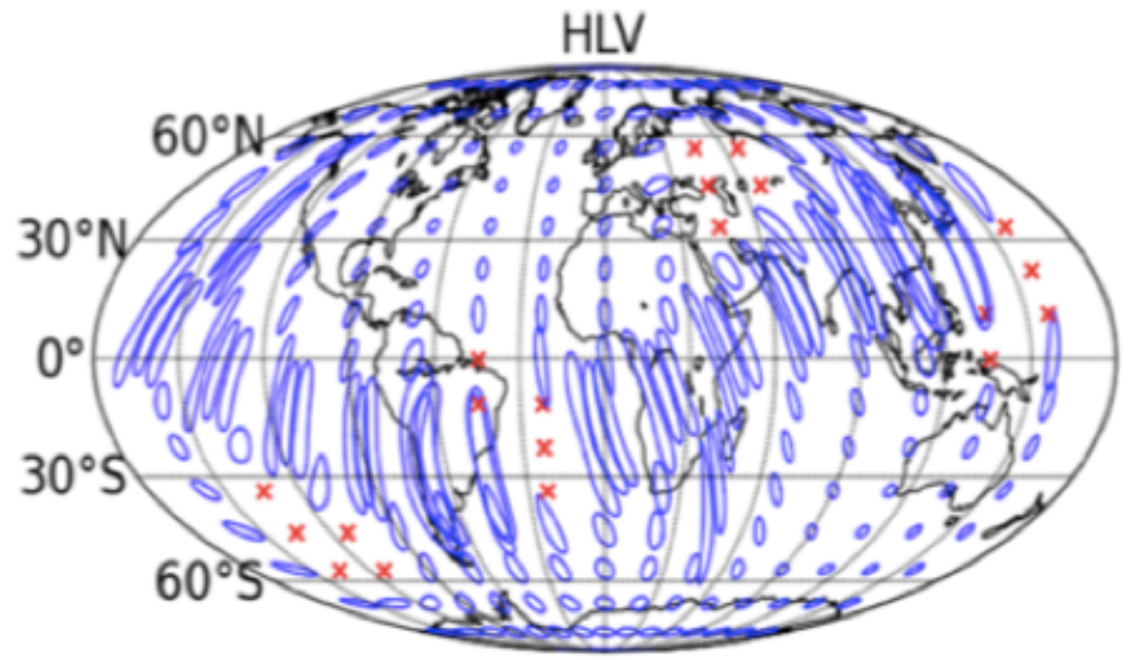
The red curve peaks at absolute mag *M* = -*11* in i-band.

Very red transient: i-z ~ 0.8 in all cases except for blue flash.

Red: Equal mass NS-NS merger
Green: Unequal mass NS-NS merger
Black: NS-BH merger
Blue: Neutron-driven wind (blue flash)

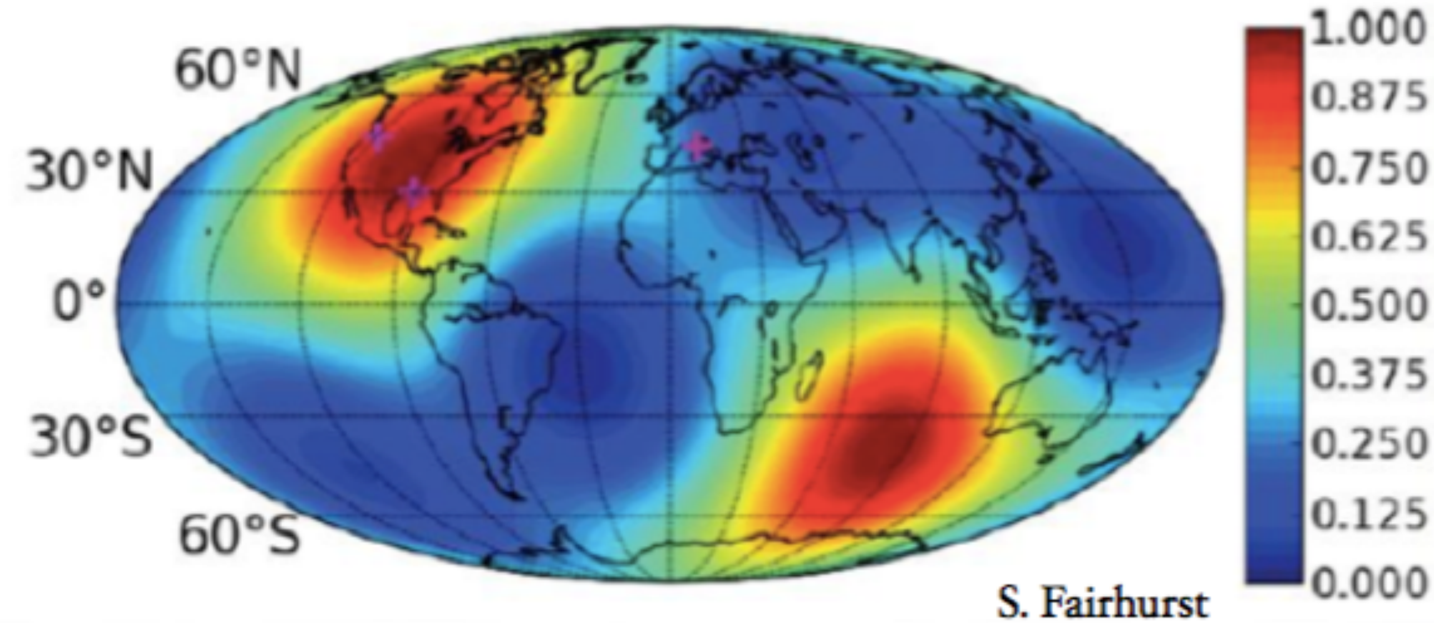


GW CANDIDATE EVENTS



LIGO: arXiv:1304.0670

Position localizations



Detection rates

GW events happening during CTIO day have the best chance of being detected and have better localization information.

8-12 hours later, the region of interest will be overhead during the night for DECam observations.

THE OPPORTUNITY

LIGO-VIRGO advanced GW detectors are ramping up over the next ~5 yrs (first run to start September 14, 2015).

DECam is one of the few imagers capable of timely 24th mag searches over large regions (unique in the southern hemisphere).

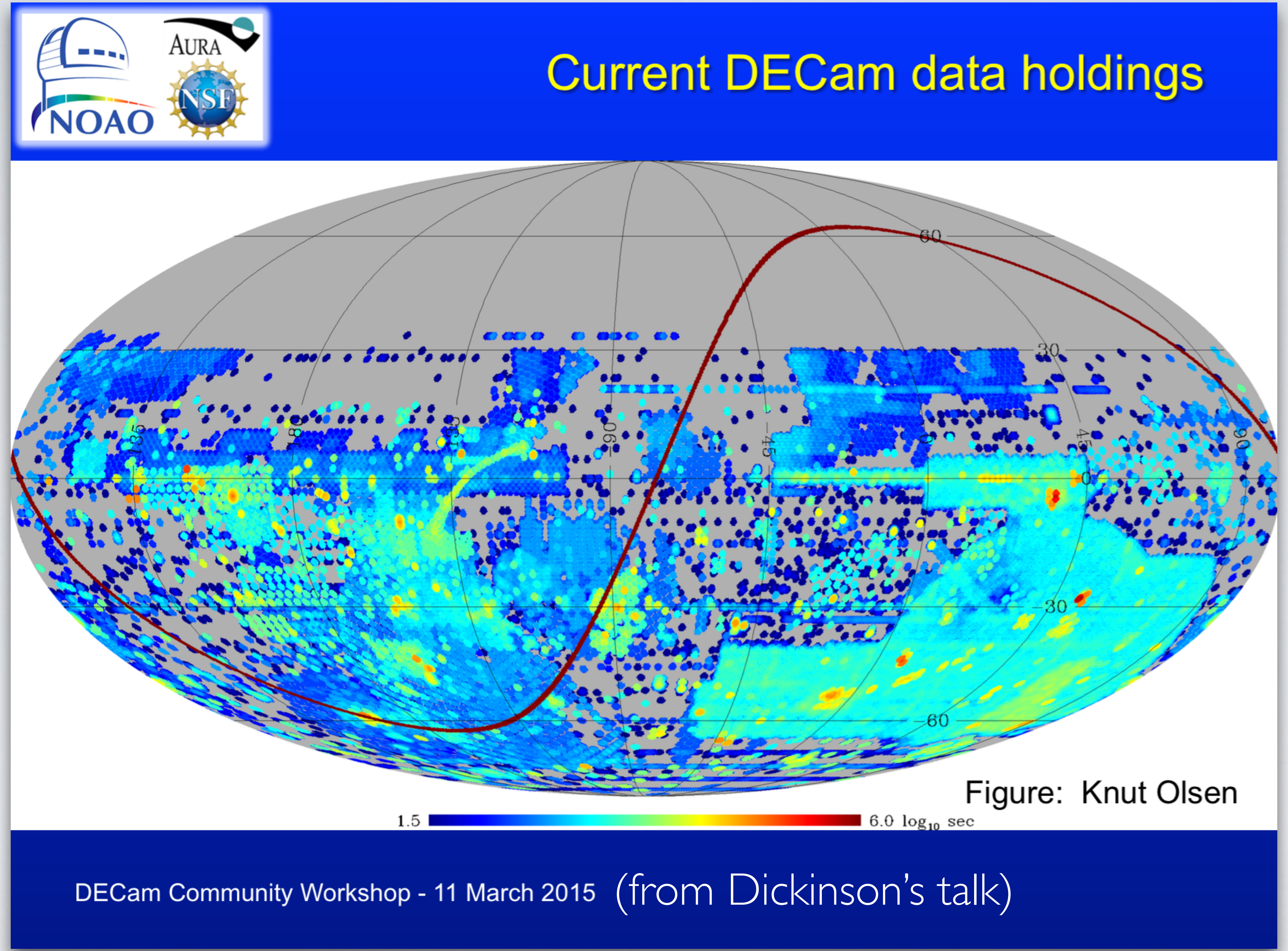
DECam community already has “templates” for thousands of sq-deg.

DES is on sky 2/3 of the time in B semesters through 2018.

DES has a transient detection pipeline and experience in adaptive scheduling observations.

LSST will be on sky when GW detectors will be mature. Ideal opportunity to launch a full fledged Standard Sirens program!

"TEMPLATE" IMAGES



(from Dickinson's talk)

PROGRAM CONCEPT

GW trigger

time stamp
sky region
distance

DECam/DES search system

build template image
schedule observations
take new images
perform image subtraction
detect, model counterpart

- <u>Near term goal</u>: background rate studies, preparations for searches starting in 2015
- <u>Long term goal</u>: a large scale program for 2016 and beyond
    - DECam — available throughout the LIGO-Virgo ramp up
    - LSST — to start in ~2020, will be faster than DECam
    - Synergy with future neutrino experiments — ToF experiment including neutrinos?

FORMING A WORKING GROUP

Initiated in June 2013 by MSS and Annis (in response to the LIGO–Virgo Collaboration open call for LOIs).

In collaboration with U Chicago LIGO group (led by Daniel Holz) since Aug 2013.

Obtained funding from Fermilab's LDRD grant program (FY15 and FY16).

Obtained 3 additional DECam nights for this TOO program, in collaboration with Edo Berger from Harvard.

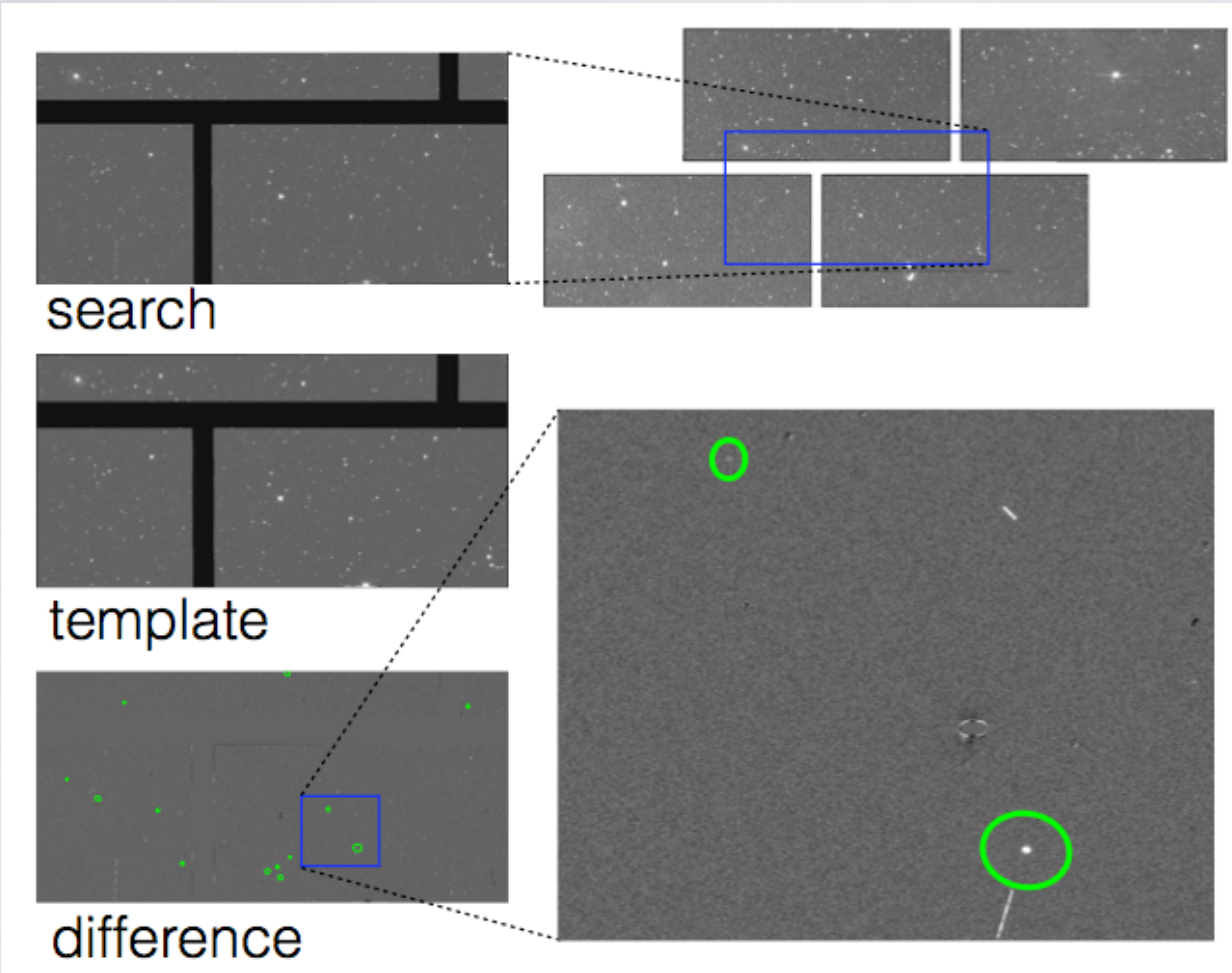
Preparing to start observations on September 14 2015.

AREAS OF ACTIVITY

*red = in this talk

Sensitivity study, analysis plan (Annis, Holz, Chen, Diehl, SS)
Study of background rates (Kessler, Holz, Lin, Annis, SS)
Optical signature model building (Annis)
LIGO detector performance model (Holz, Chen, Farr)
Light curve simulations, fitting code (Kessler)
DiffImg pipeline development (Masao, Kessler, Marriner, SS)
Production grid processing design (Yanny, Herner)
Observing strategy (Annis, Chen, Neilsen)
Template construction (Marriner)
Selection criteria design (Masao, Kessler)
Operations plan (Diehl, Neilsen)
Data management (Yanny)
Redshifts and galaxy catalogs (Lin, Annis)
On-sky test using Director's Discretionary time (Annis, SS)

DIFFERENCE IMAGING



Example of DiffIm
on the wide field survey.

90 sec i-band exposures
Sep 28,29 2013

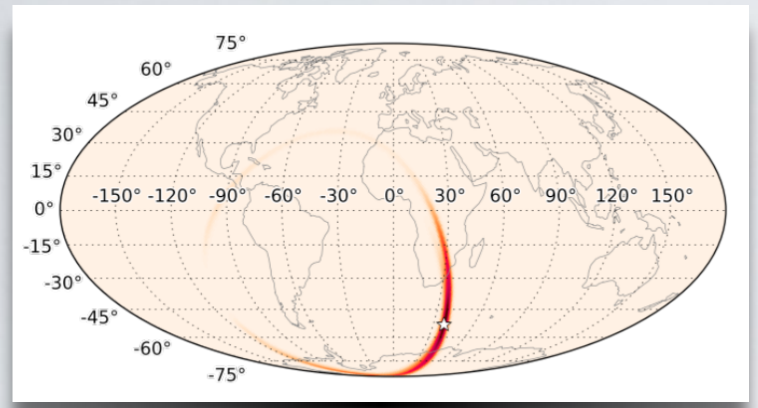
2 candidates:
$i = 23.3$ and $i = 20.2$

Next steps:
- Test on SNe field
- Apply to Std Star fields
- Deploy production software.

M. Sako

TEST: CTIO DD TIME (FEB 1-3, 2015)

Event # 20823, from 2014 LIGO simulations



LIGO sim event # 20823

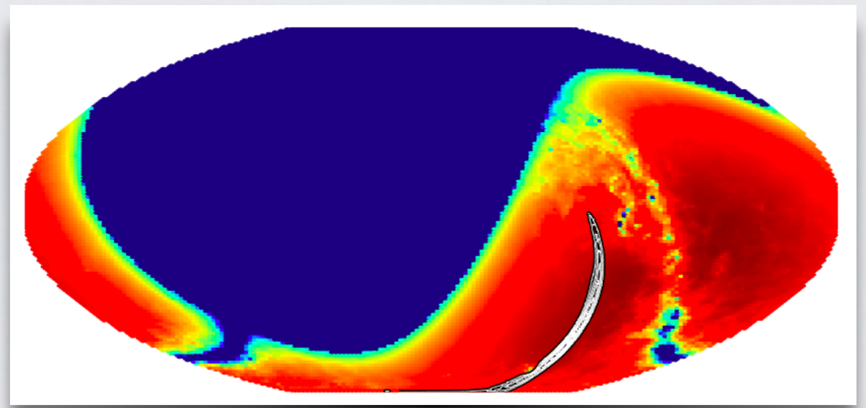
Date: 9/19/2010 (moved to 2/1/2015)

Distance: 81 Mpc

Masses: 1.47, 1.38 M_sun

SNR: 13.9

Area: 132 deg^2 @50% c.l.



DECam i-band limiting mag

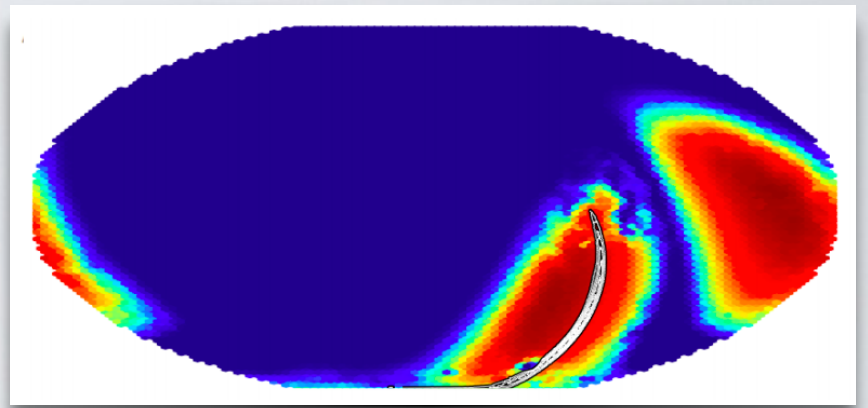
For 10-sigma point source

3 x 60 second exposures

Moon not included (although we did observe at full moon)

Max mag in this scale: i ~ 23

LIGO contours superimposed



DECam detection probability

For equal mass NSNS merger

Final map is DECam x LIGO probability maps (not shown)

DES default hex schema used
- 38% probability in top 33 hexes (9% in top 7)

LIGO contours superimposed

SUMMARY

Advanced GW detectors might offer a new window of opportunity for discoveries, including **the first coordinated detection of electromagnetic and gravitational radiation from the same events**.

This talk describes our ongoing effort towards taking advantage of such opportunity in DES. **We are on track to perform the first search campaign in 2015B.**

I expect the full potential of this program to be realized in the LSST era. **Let's make that happen!**

Backup Slides

SIGNAL RATES

Rates of mergers can be estimated from the observed rates of short GRB events (Chen & Holz, 2013)

$$r = r_{GRB} \times \frac{f}{(1 - \cos\theta_j)}$$

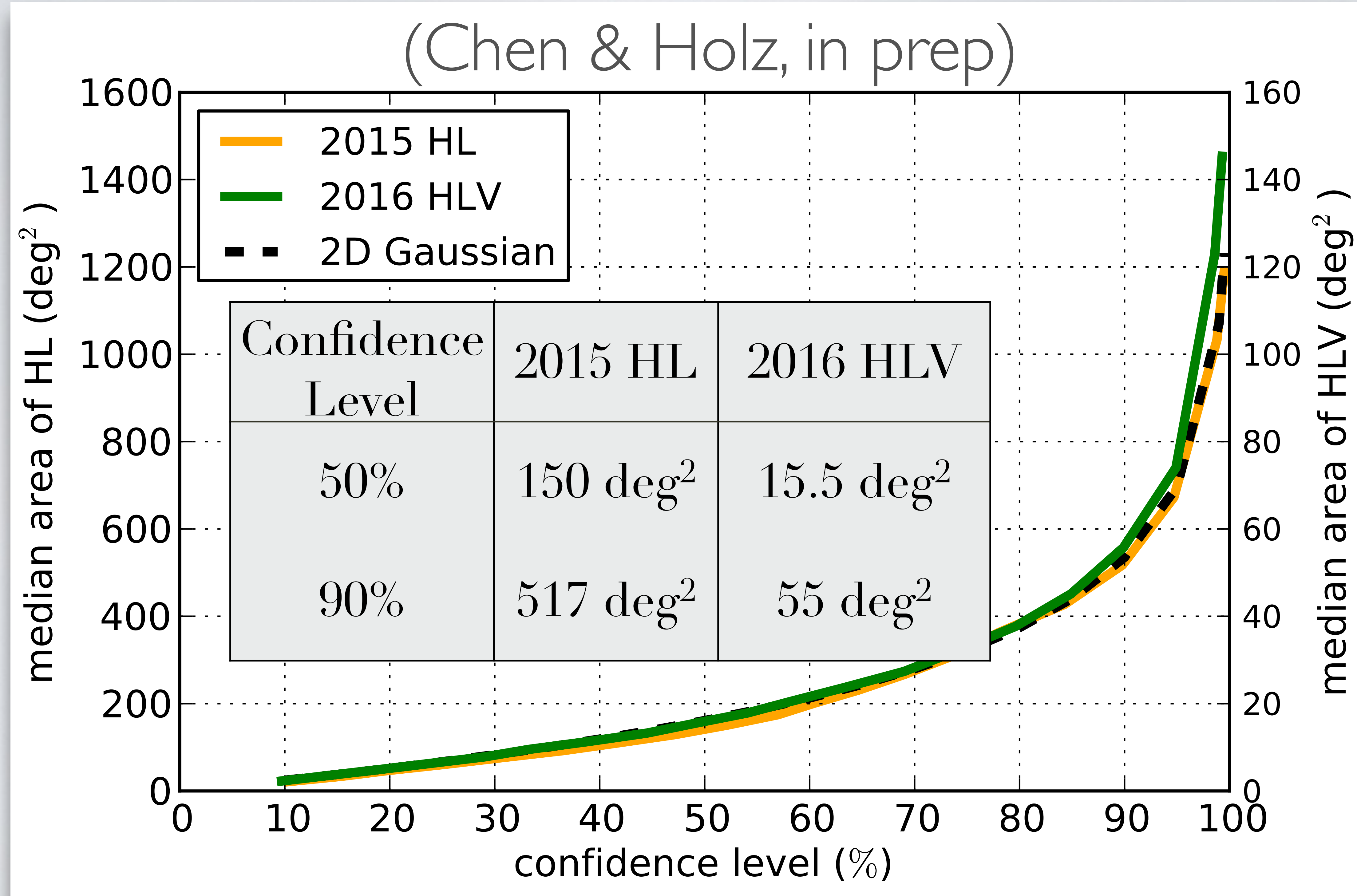
Example: DES SN fields

- $r_{GRB} = 10$ events/yr/Gpc^3
- $f = 1/2$
- $m_{lim} = 23.5, 24.5$
- $M_{abs} = -11, -15$
- season duration: 1/2 year
- DECam FOV = 3 square degrees
- shallow fields total area: 8 × DECam FOV
- deep fields total area: 2 × DECam FOV

Assumptions:

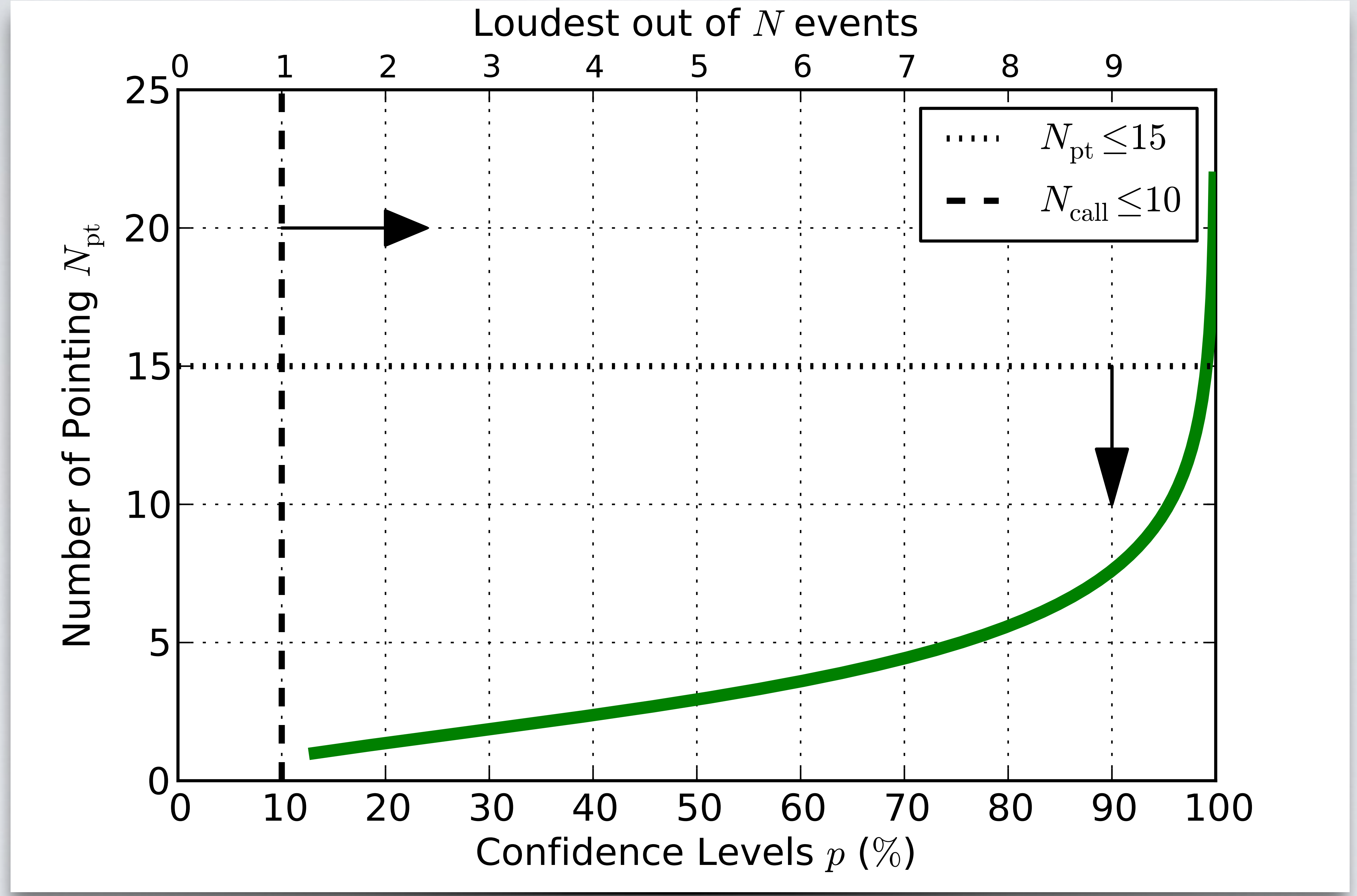
- beaming angle
- fraction of short GRBs that result from NS-NS mergers

MEDIAN LOCALIZATION AREA



Confidence Level	2015 HL	2016 HLV
50%	150 deg^2	15.5 deg^2
90%	517 deg^2	55 deg^2

OPTIMAL SEARCH STRATEGY



GW + EM DETECTIONS

Opportunities for (astro)physics

First detections of NS-BH merger

Binary history

Origin of r-process elements

NS equation of state

and cosmology

standard sirens

POSSIBLE COUNTERPARTS

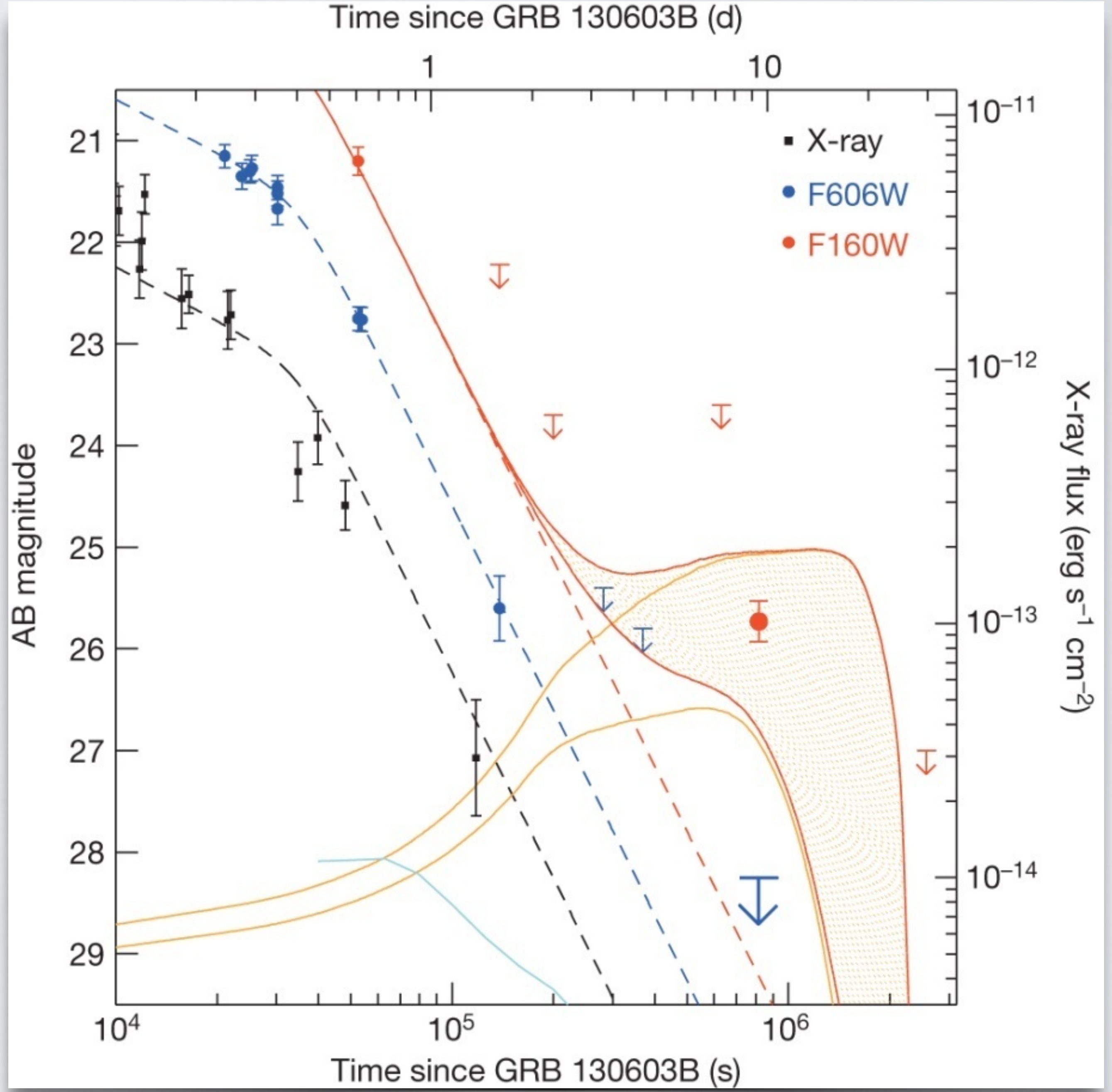
Tanvir et al. Nature (2013)

short GRB
(+ afterglow)

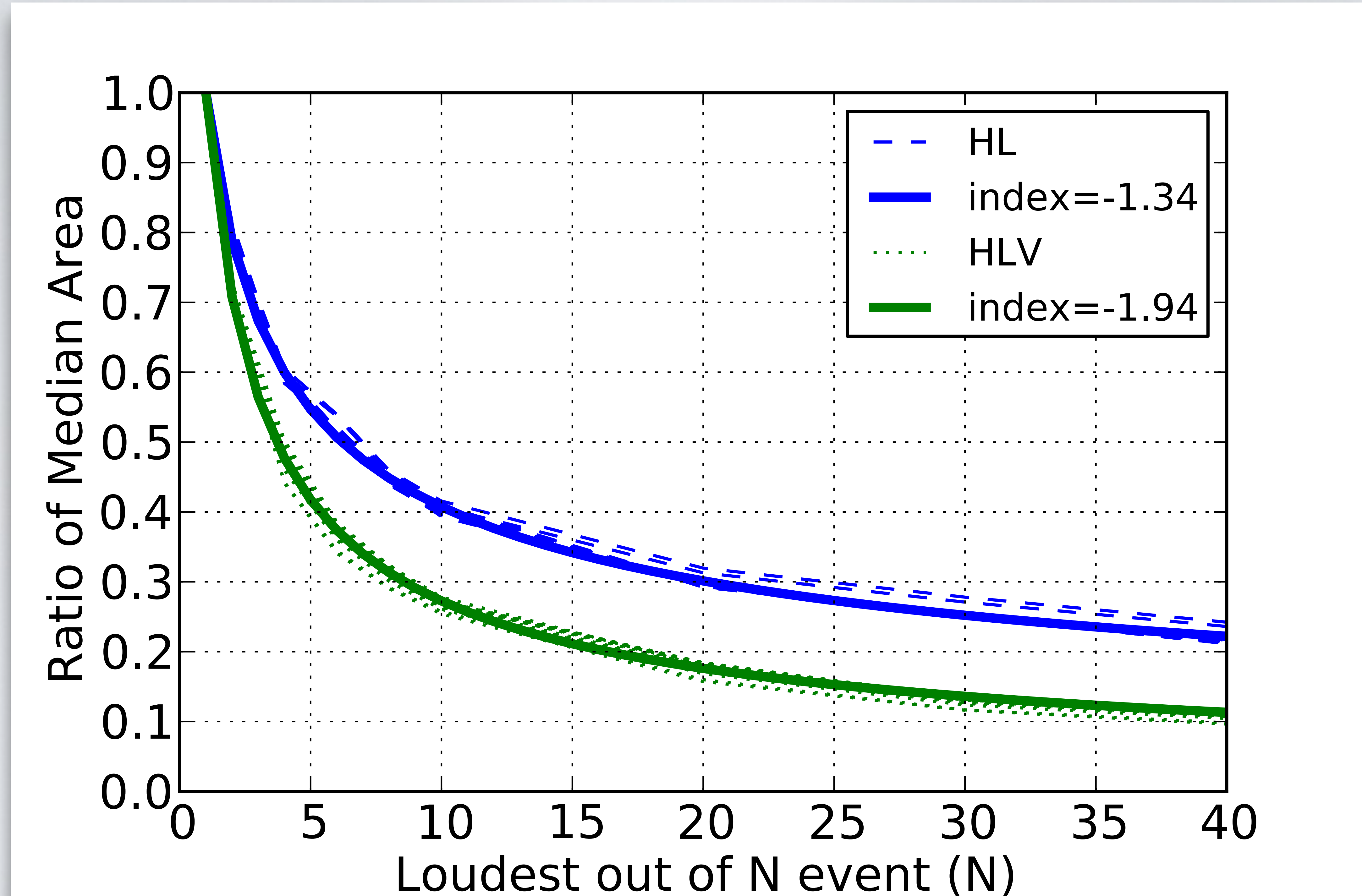
kilonova
(+ blue kinematic precursor)

radio afterglow

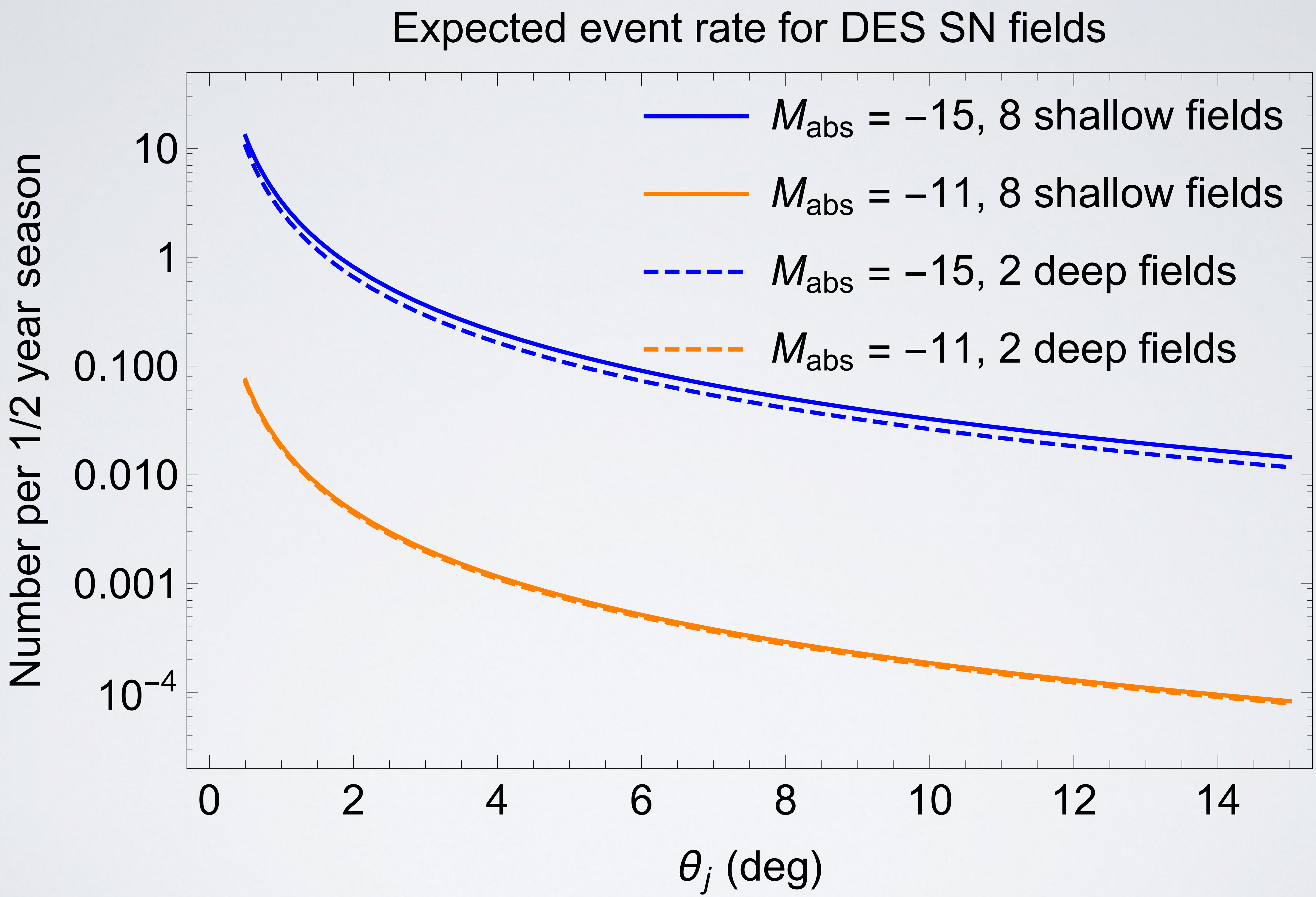
neutrinos



LOUDEST EVENTS



SIGNAL RATES



SENSITIVITY

(Soares-Santos, Annis, Chen, Holz, Kessler, Lin 2015, in prep)

SN shallow	SN deep	KN abs. mag.	θ_j Lower Limit	R_{KN} 90% Upper Limit ($yr^{-1}Mpc^{-3}$)
Yes	No	-11	$0.2°/0.3°$	$3.8 \times 10^{-3}/1.3 \times 10^{-3}$
No	Yes	-11	$0.2°/0.3°$	$1.9 \times 10^{-3}/6.3 \times 10^{-3}$
Yes	Yes	-11	$0.3°/0.5°$	$1.9 \times 10^{-3}/6.3 \times 10^{-3}$
Yes	No	-15	$3.2°/5.5°$	$1.5 \times 10^{-5}/5.0 \times 10^{-6}$
No	Yes	-15	$3.2°/5.5°$	$1.5 \times 10^{-5}/5.0 \times 10^{-6}$
Yes	Yes	-15	$4.5°/7.8°$	$7.5 \times 10^{-6}/2.5 \times 10^{-6}$

= 3 seasons of data

We can put one of the best limits on the rate of mergers, and inform LIGO-Virgo community before the 2015 science run even starts.

PRELIMINARY ANALYSIS

Turnaround time: 24h

We have 7 hexes in three tilings, taken three nights. Let us make a catalog level analysis by the following steps.

1. Selecting the psf magnitude for all objects
2. Demand objects in a given hex on a given night are present in all three tilings
3. The median difference between the hex and the template is the zeropoint for the hex
4. Demand that the objects are found in both i and z on each night
5. Demand that the objects are found in all three nights
6. For the remaining objects, match against template catalog

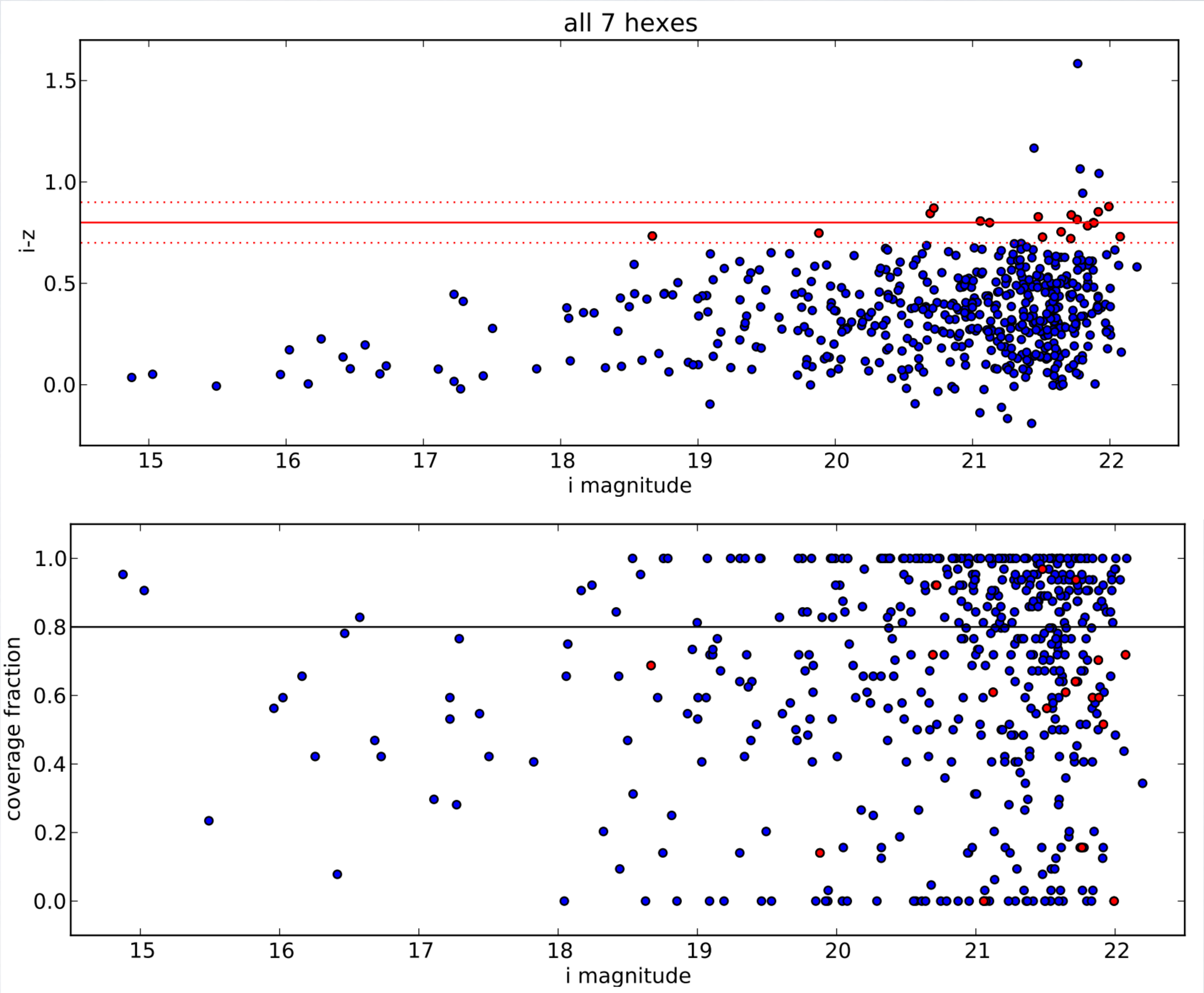
PRELIMINARY ANALYSIS

Candidates selected in color-mag space.

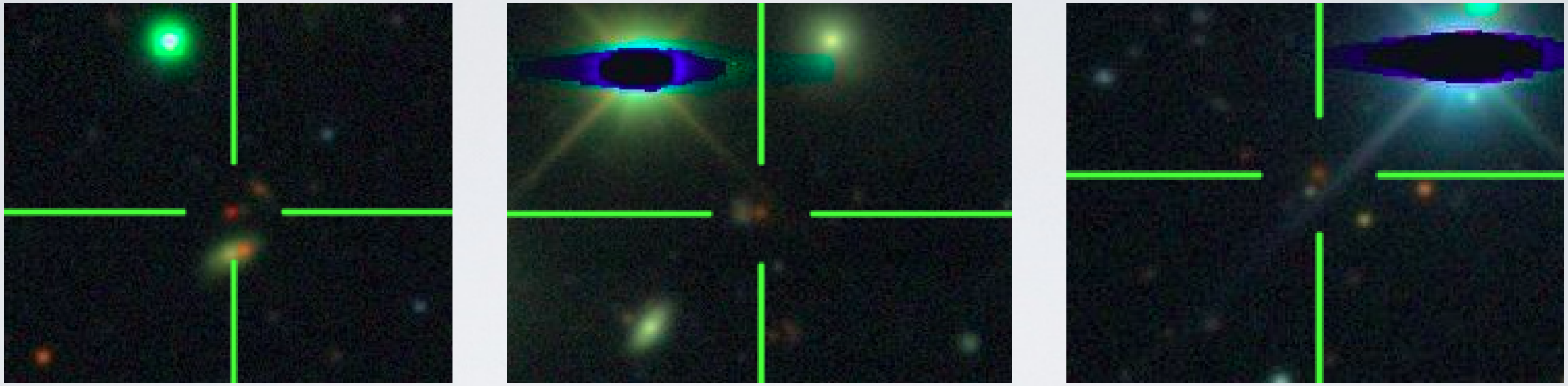
Tiling gaps in the templates creates false positives.

Eliminated 'gap candidates' by requiring coverage fraction > 80% in healpix.

Three candidates survived.



PRELIMINARY ANALYSIS



DES Science Portal tile viewer cutouts of the template regions around the three surviving red candidates.

Notice that in all three cases the red object actually exists in the template.

Likely the complex surroundings defeated the de-blending algorithm in these cases.

KN SEARCH (VERY PRELIMINARY)

Initial cuts:

— event duration < 22 days
— 3+ detections @ S/N > 3.5

Characteristic decay time cuts:

— 0.1 < tc < 3
— tc_err < 0.2

i-band magnitude cuts:

— i > 22.0 @ z = 0.05
— i > 23.5 @ z = 0.1

Candidates in SN field E1:

— **1255** after initial cuts

— **28** after tc cuts

– **26** simulated/real SNe
– **2** real new events

— **0** after mag, color cuts

Conclusion:
Background rate seem low.