Standard Siren Cosmology Program

Marcelle Soares-Santos (Brandeis U)
Jim Annis (Fermilab)

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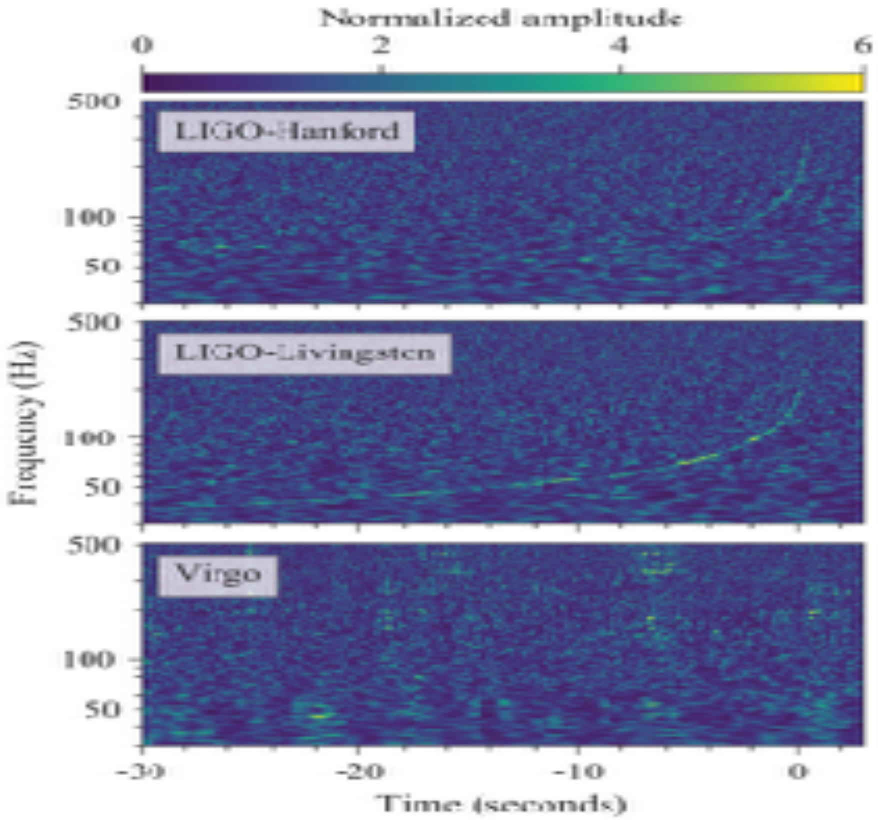
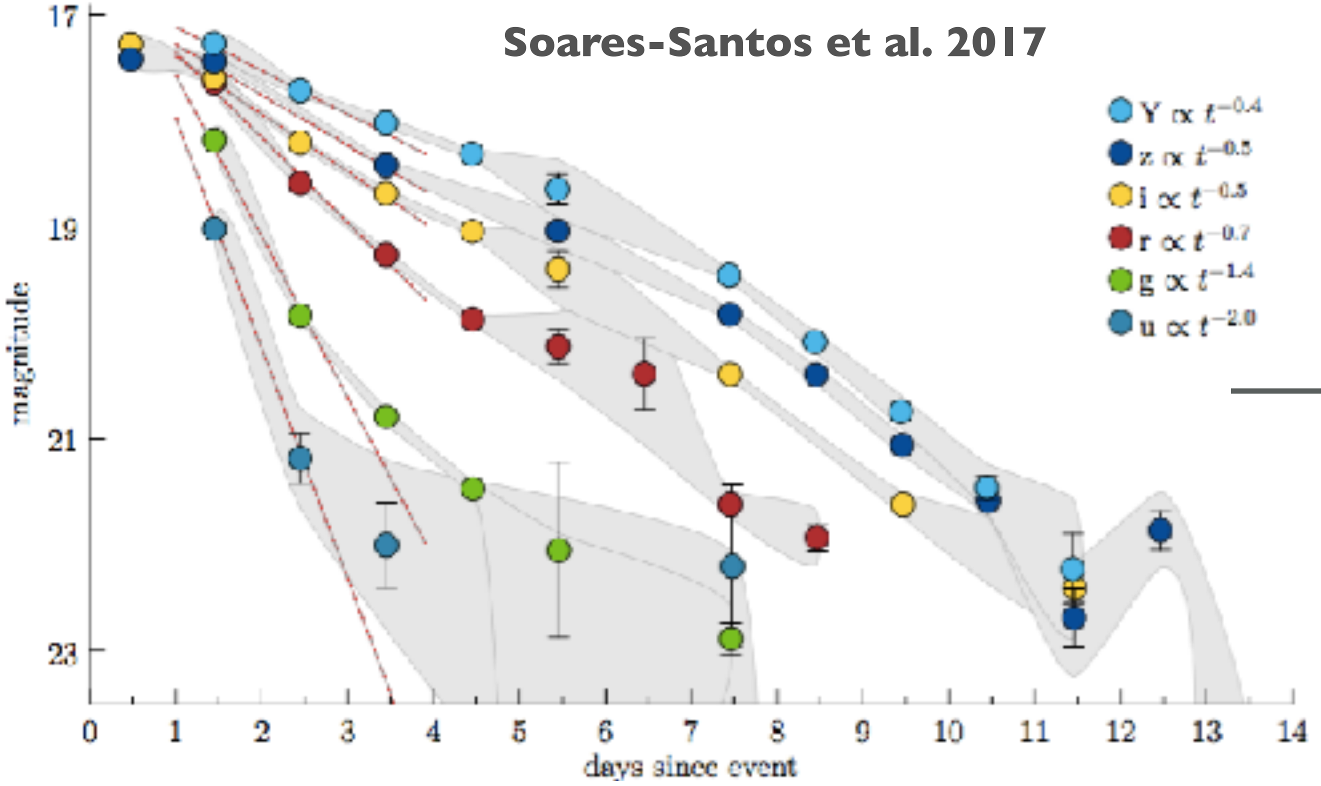
First Cosmology Result: a bright siren, GW170817

LIGO/Virgo

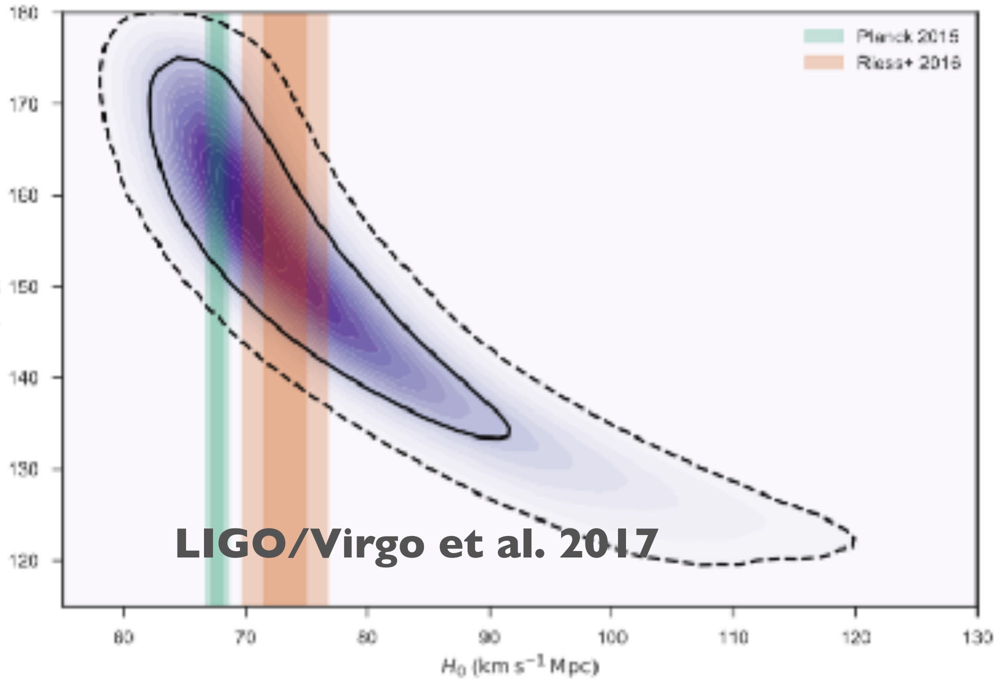


LIGO/Virgo Collaboration 2017

DES/DECaM

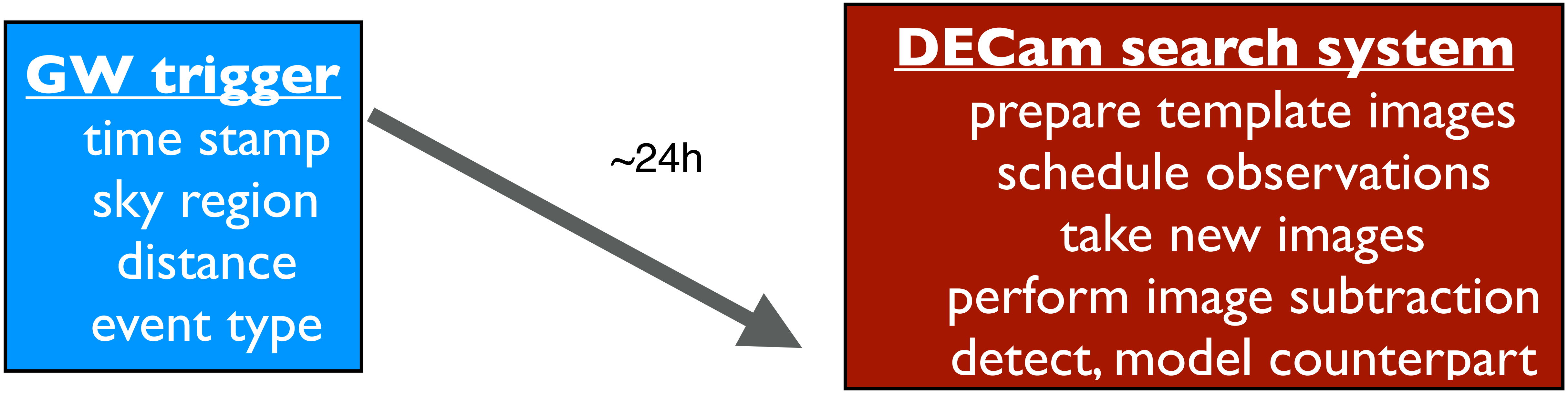


Soares-Santos et al. 2017



LIGO/Virgo et al. 2017

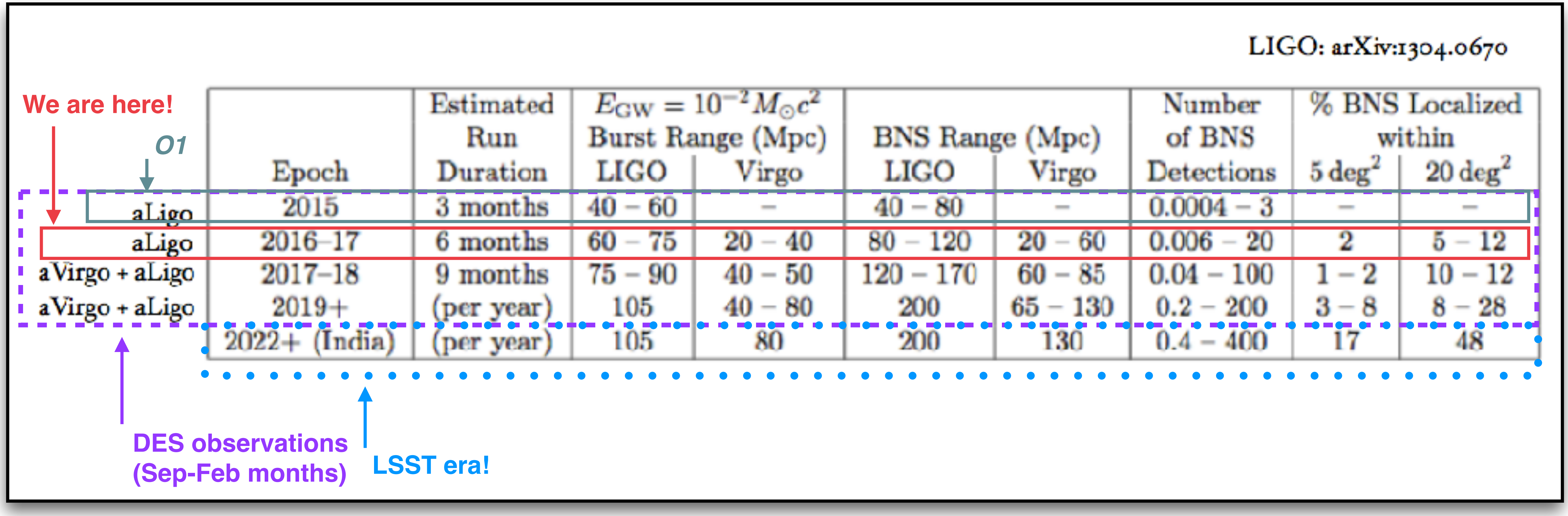
Today’s Program: discovery, first measurements



GW trigger
- time stamp
- sky region
- distance
- event type

~24h

DECam search system
- prepare template images
- schedule observations
- take new images
- perform image subtraction
- detect, model counterpart



LIGO: arXiv:1304.0670

	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
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

We are here!

O1

DES observations (Sep-Feb months)

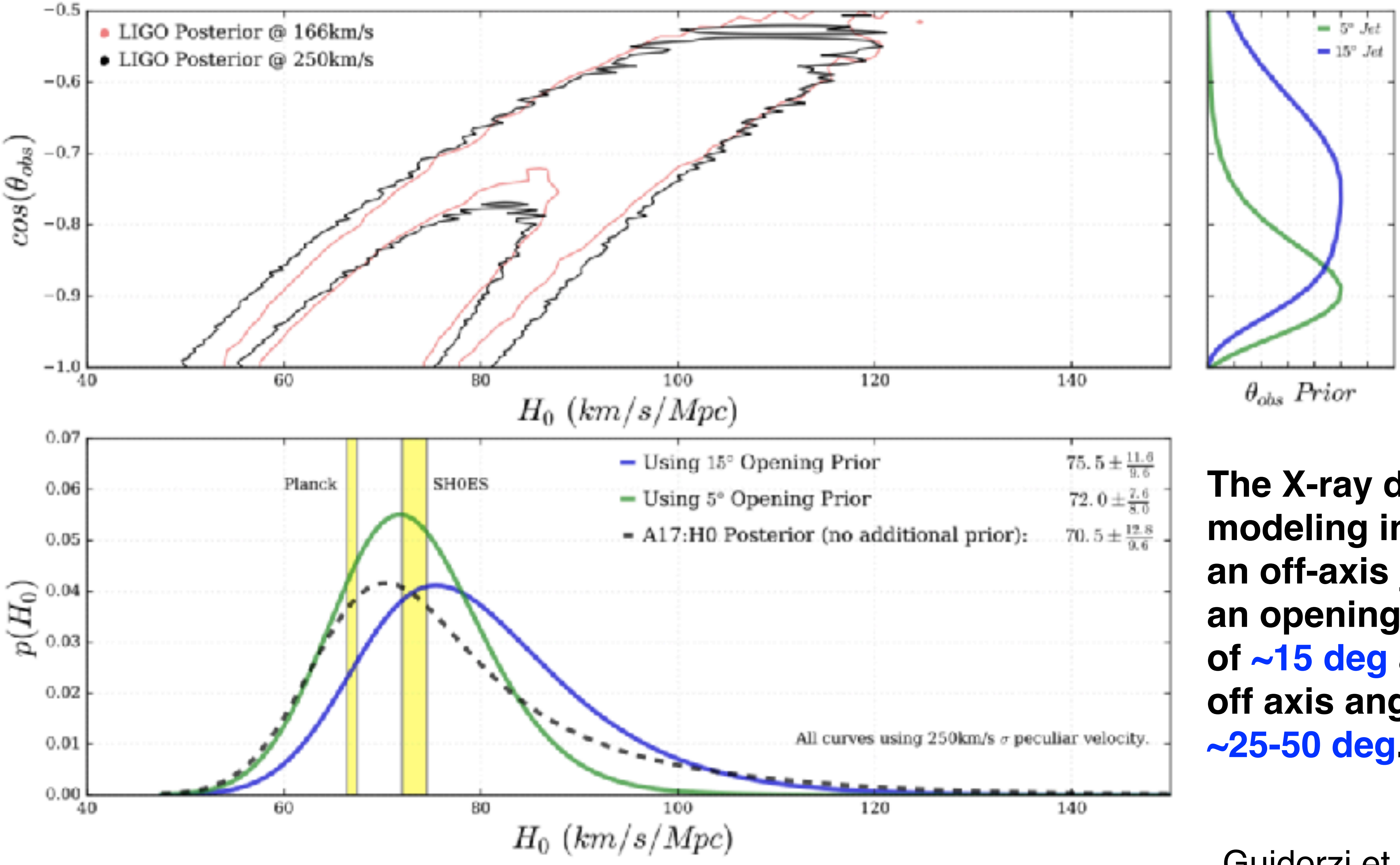
LSST era!

1 BNS, 4 BBH events to date

Lessons learned from GW170817

Improving cosmology measurements:

1) at d < 80 Mpc we need improved **peculiar velocity maps**
2) at d > 80 Mpc, **sources are fainter** and there is **probability of host galaxy confusion**
3) at all distances, **constraining the inclination is very helpful**



The X-ray data modeling indicates an off-axis jet with an opening angle of ~15 deg and an off axis angle ~25-50 deg.

Guidorzi et al. 2017

Lessons learned from GW170817

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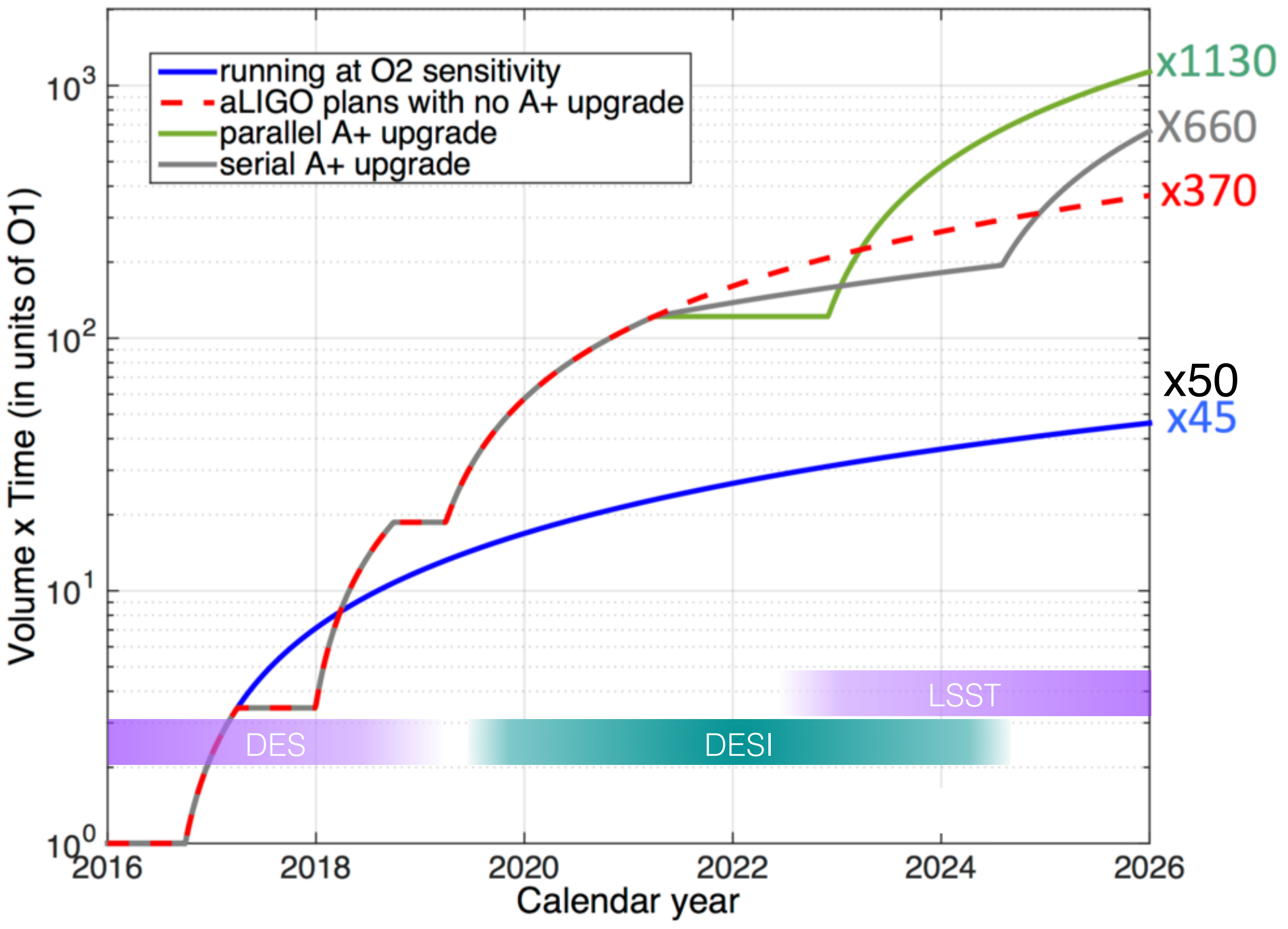
Constraining the inclination: three possibilities

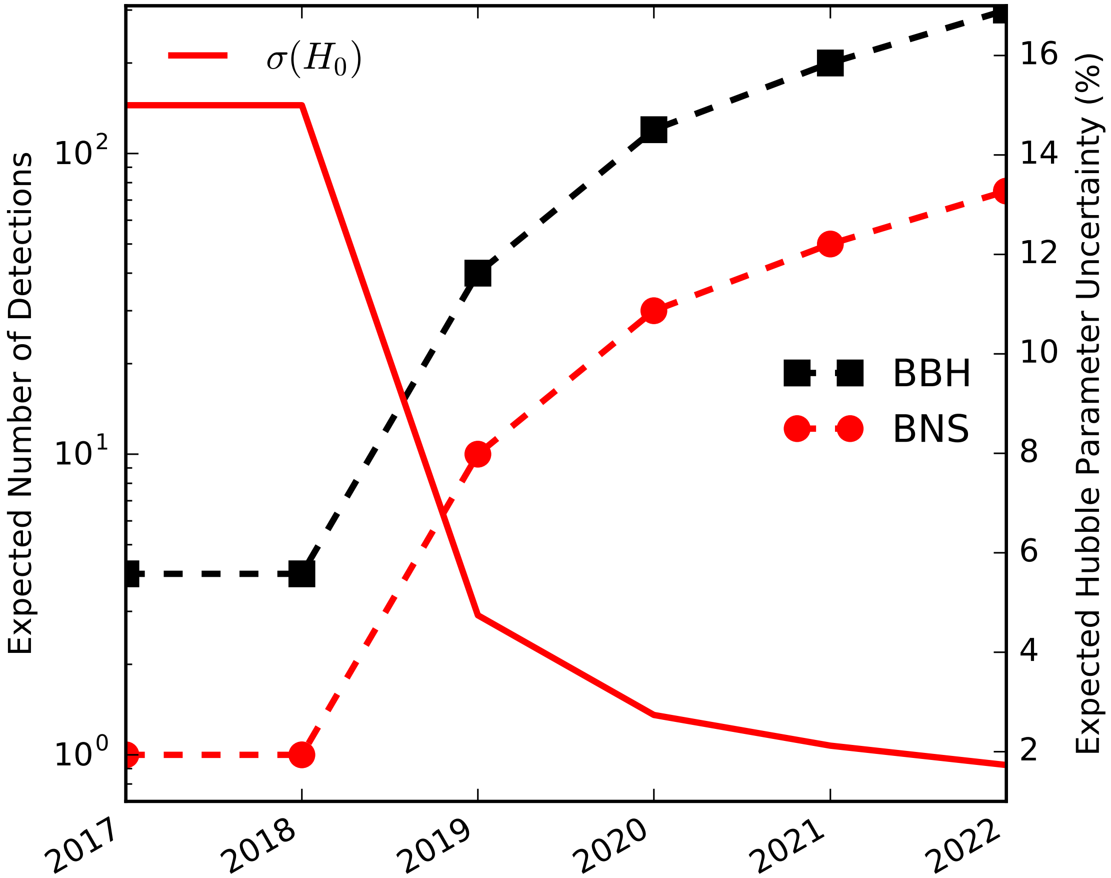
1) GW polarization measurements (improves with larger GW detector network)
2) radio & x-ray modeling of the jet (hard to achieve for large samples)
3) optical, infrared modeling of the ejecta shell (our best option if it works; worth trying)

Optical light curves and inclination (or, what is behind door no. 3)

- Edge-on mergers are expected to result in red kilonovae
- Face-on mergers are, in contrast, expected to be bluer and brighter
- We can explore this feature: use optical, NIR data to model the ejecta
- We need to include this information in the cosmology likelihood analysis
- Polarization of the optical signal might be helpful too

Future Program:
large samples, precision cosmology



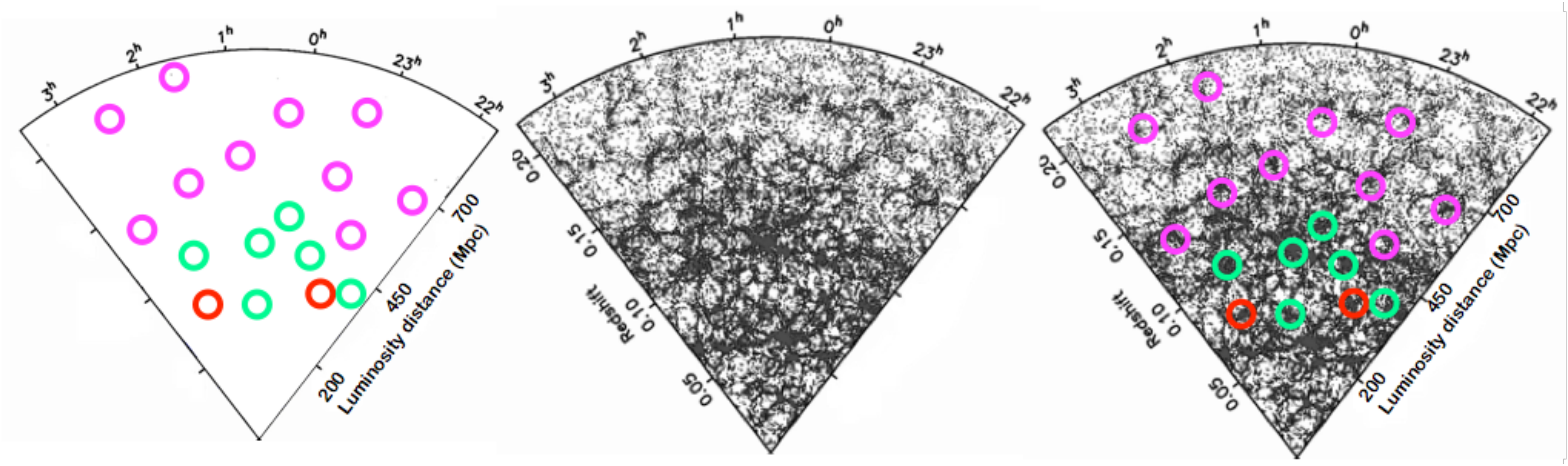


Figures adapted from the Dawn-II Workshop report, 2016.

Not all GW sources will have an EM counterpart…

… but we can use dark sirens for cosmology too!

Cross-correlation between large samples of BBH from aLIGO and galaxy samples of the cosmological surveys



BBH-based cosmological measurement is analogous, and complementary to BAO measurements.

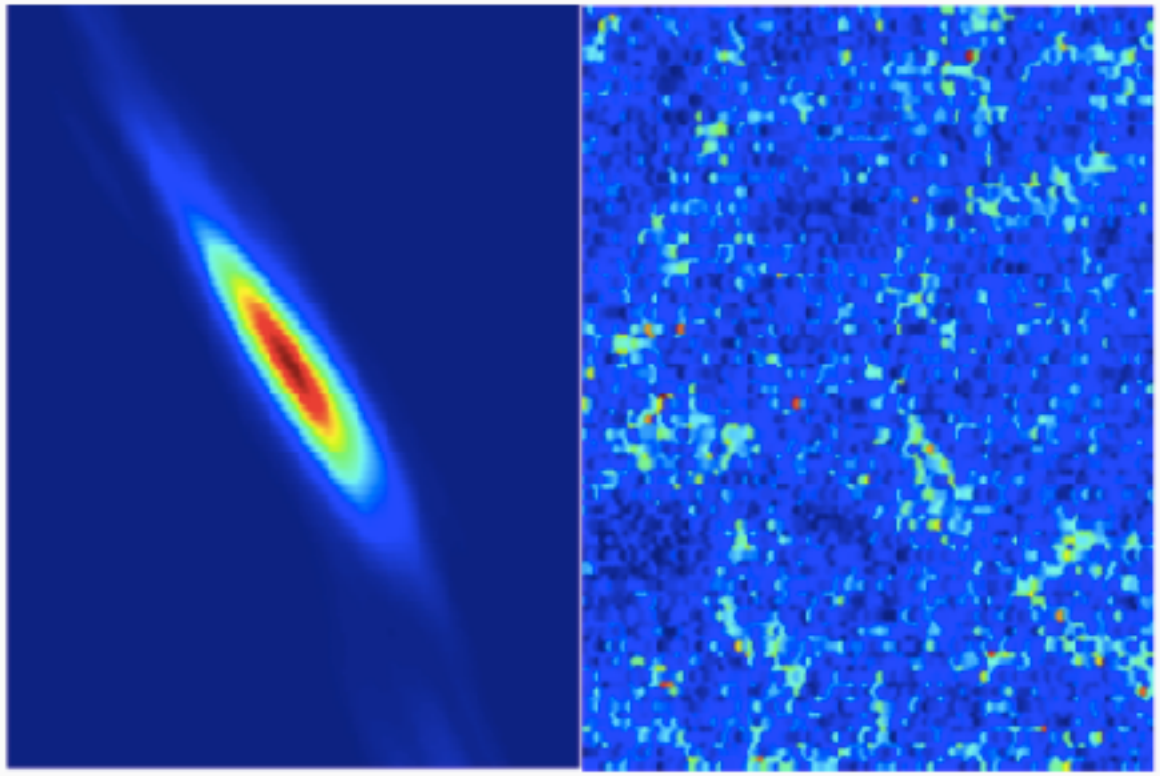
The idea of BBH merger progenitor formation in quasar disks is also testable (with low-z quasar catalogs).

(Figure: a simple cartoon illustration, using 2dF galaxies)

COSMOLOGY FROM DARK SOURCES

If black hole mergers are predominately dark- we still do the cosmology.

- Distance from GW measurement
- Spatial localization width suffices to pick out a filament
- As $\sigma_{gw} \approx 90$ Mpc, localizing to most likely 10 Mpc scale matter overdensity suffices
- Precision from many events



Left: HLV spatial localization- 40° × 30°, red ×10 more likely than light blue. Right: mock galaxy catalog, $M_i < -21, z \leq 0.2$. (Buzzard v1.1)

A galaxy catalog with space density of $> 1 \times 10^{-4} h_{70}^3$ gals/Mpc^3 suffices, if constant density over the whole redshift range of interest.

Future Program Plan

1) Scale up the imaging program: searches for optical counterparts of GW events

2) Establish the necessary spectroscopic program: redshifts, source models

3) Develop analysis framework and observing strategies for bright sirens

4) Develop analysis framework and observing strategies for dark sirens

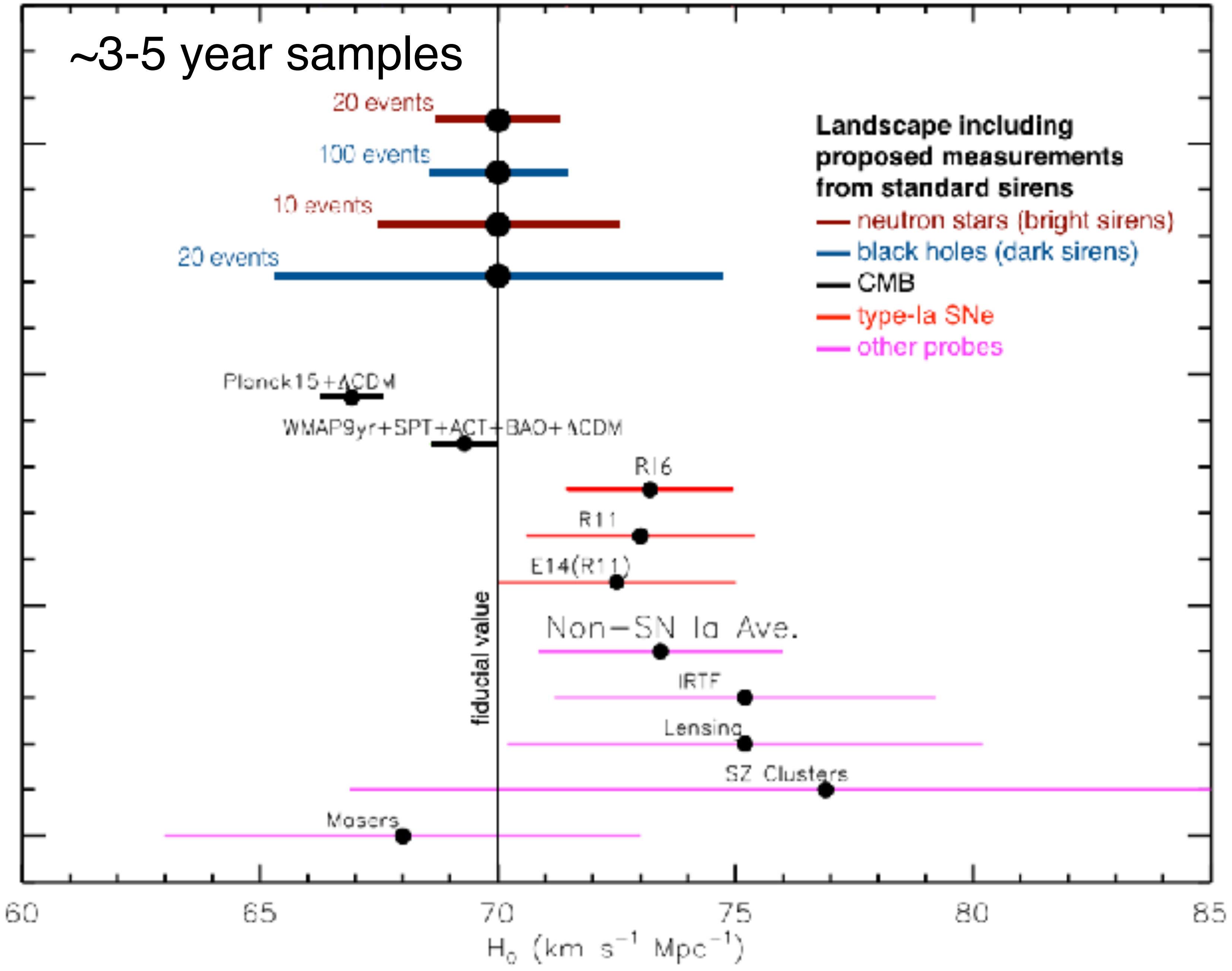


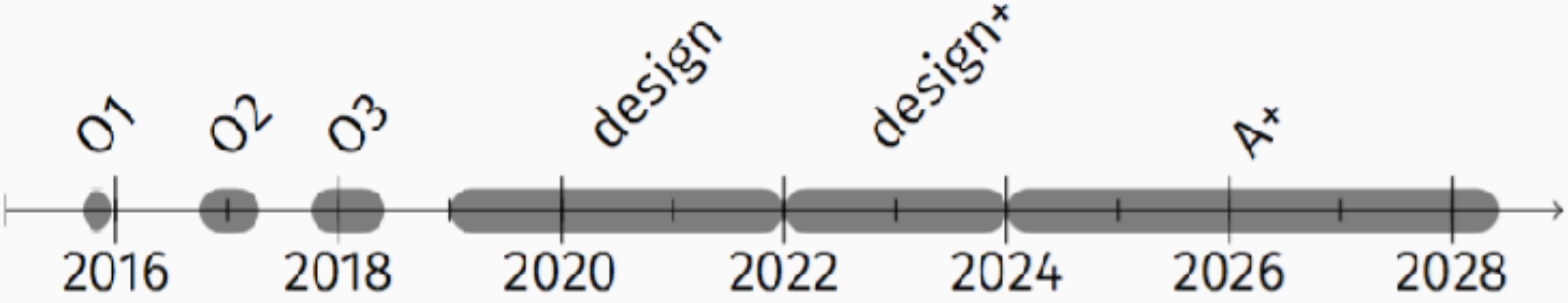
Figure adapted from Riess et al. 2016.

Future Program Landscape

Approximate Timescale	**GW Network Configuration**	**Cosmic Survey Instruments**	**Science**
2018-2022	LIGO/Virgo	DECam DESI Taipan	Sources at z~0.1 Hubble constant
2022-2028	LIGO/Virgo, Kagra A+	DECam, LSST DESI WFIRST	Sources at z<0.3 First all-sky peculiar velocity maps
>2030	3G	LSST SSSI WFIRST	Sources at z~0.5-1.0 Measure H(z), w
>2034	LISA	LSST SSSI-deep WFIRST	z~10, small areas very high precision cosmology

Backup

GROUND BASED GW OBSERVATORIES



period	number of BH-BH mergers	Network
O1	2.5	HL (Hanford & Livingston)
O2	~ 10	HL & HLV (Virgo)
O3	~ 35	HLV
design	~ 130/yr	HLV
design +	~ 130/yr	HLV & India & Kagara
A+	~ 650/yr	A+ & Kagara

By 2024, ~ 1000 BBH mergers measured, $D_L < 1360$Mpc ($z = 0.25\, h_{70}$)
By 2026, ~ 3000 BBH mergers measured, $D_L < 2240$Mpc ($z = 0.40\, h_{70}$)
In 2034 ESA plans to launch eLISA ($z < 10$).

The dates here are approximate.