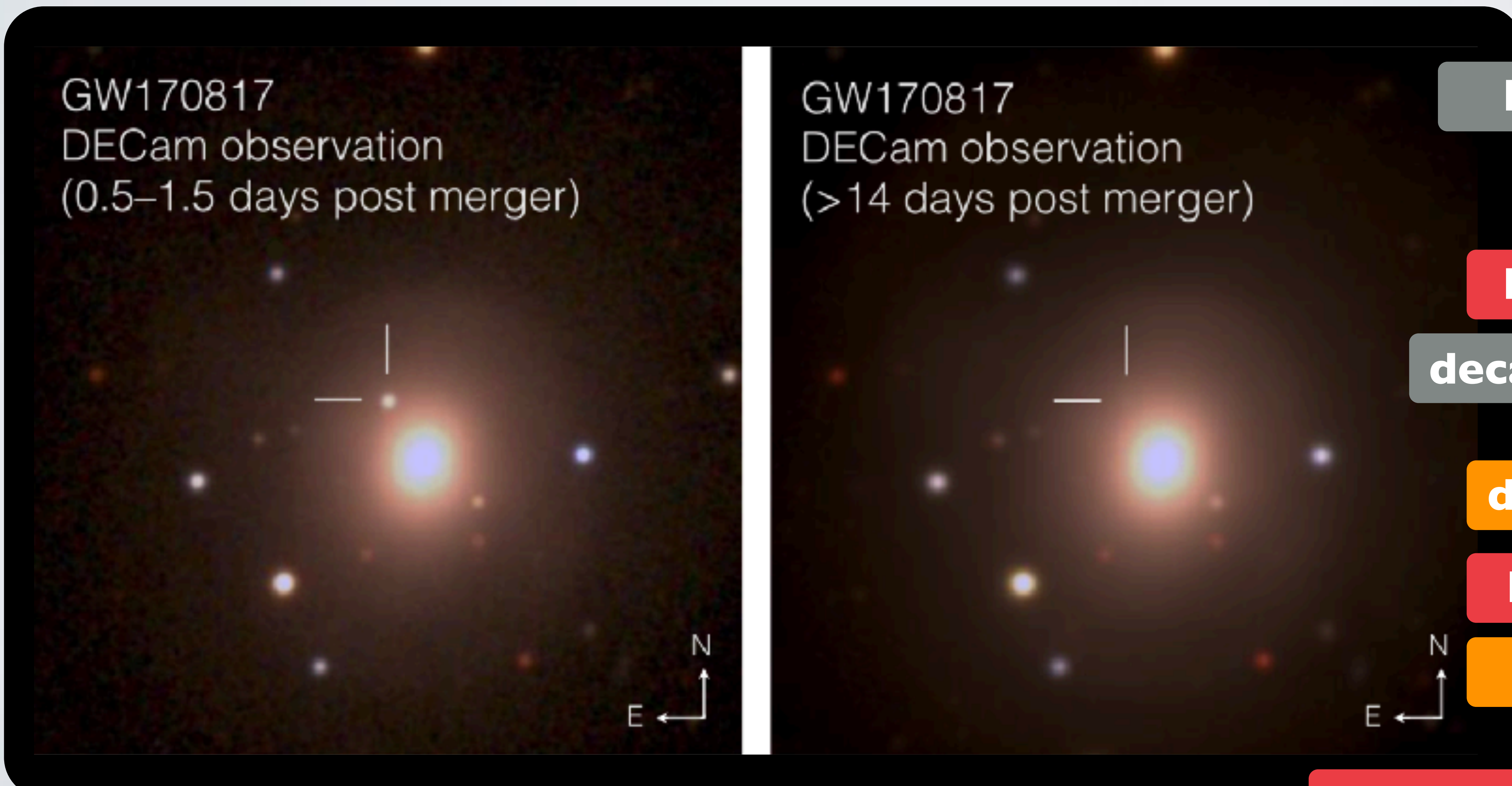
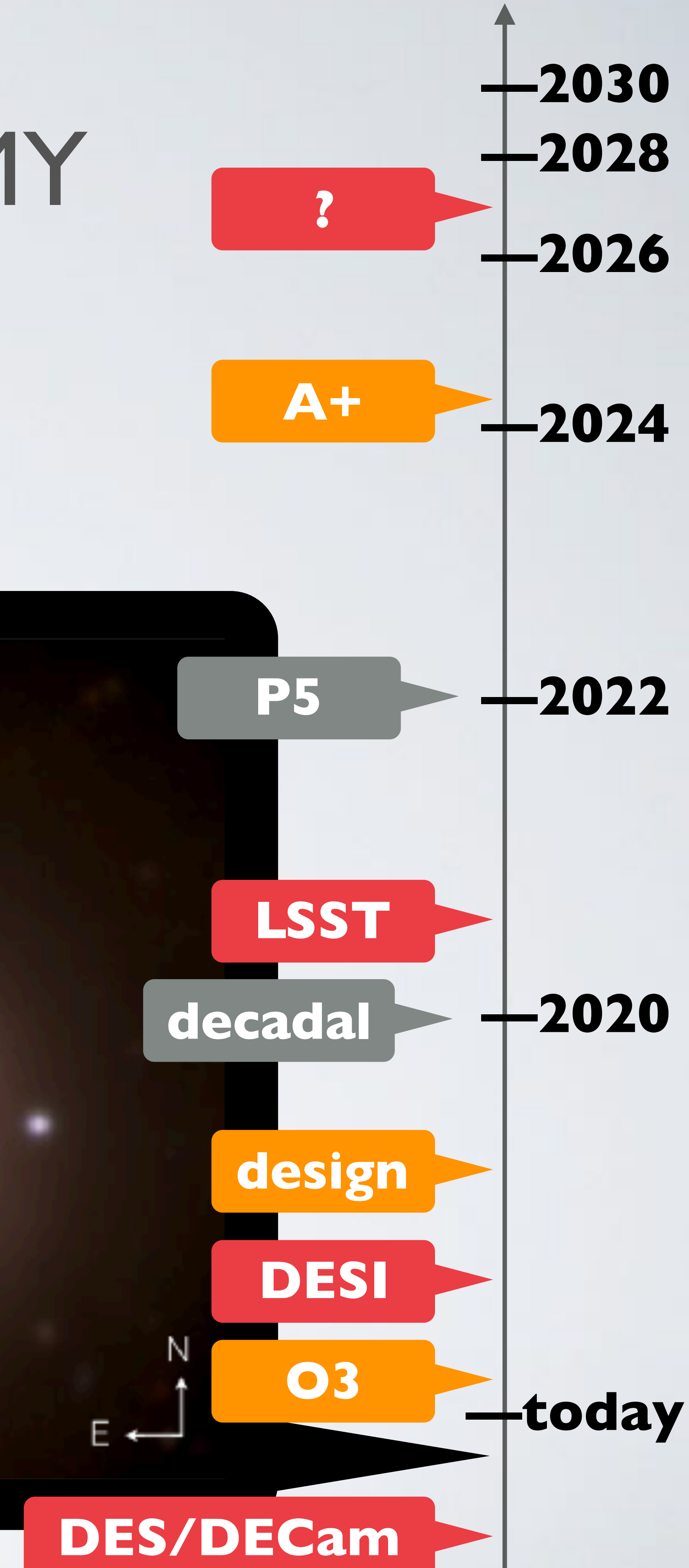
THE DAWN OF MULTI-MESSENGER ASTRONOMY WITH GRAVITATIONAL WAVES

Marcelle Soares-Santos ◆ Brandeis University
DES Collaboration



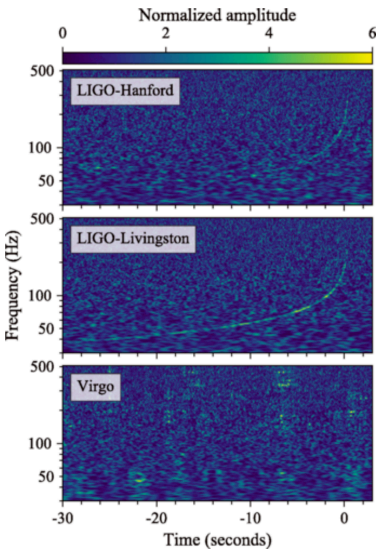


OSG All Hands ◆ March 20, 2018

GW+EM DATA & OSG

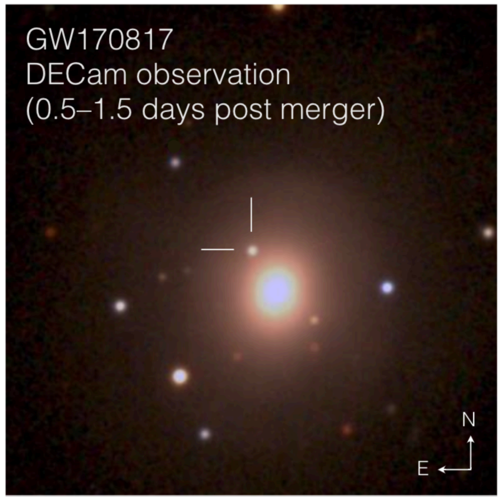
See slides from Herner's talk on Monday for more details on how our team uses OSG resources to process images searching for the EM counterparts of GW events.

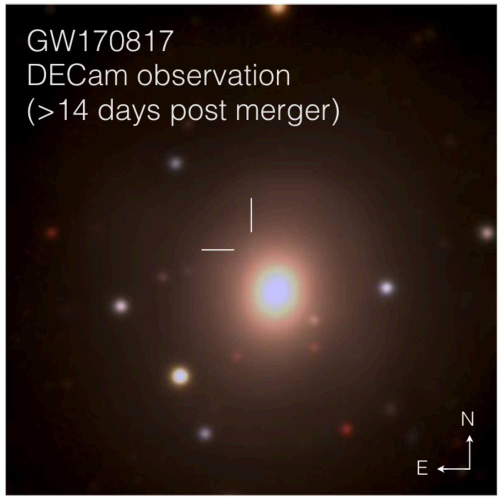
A bit on GW170817

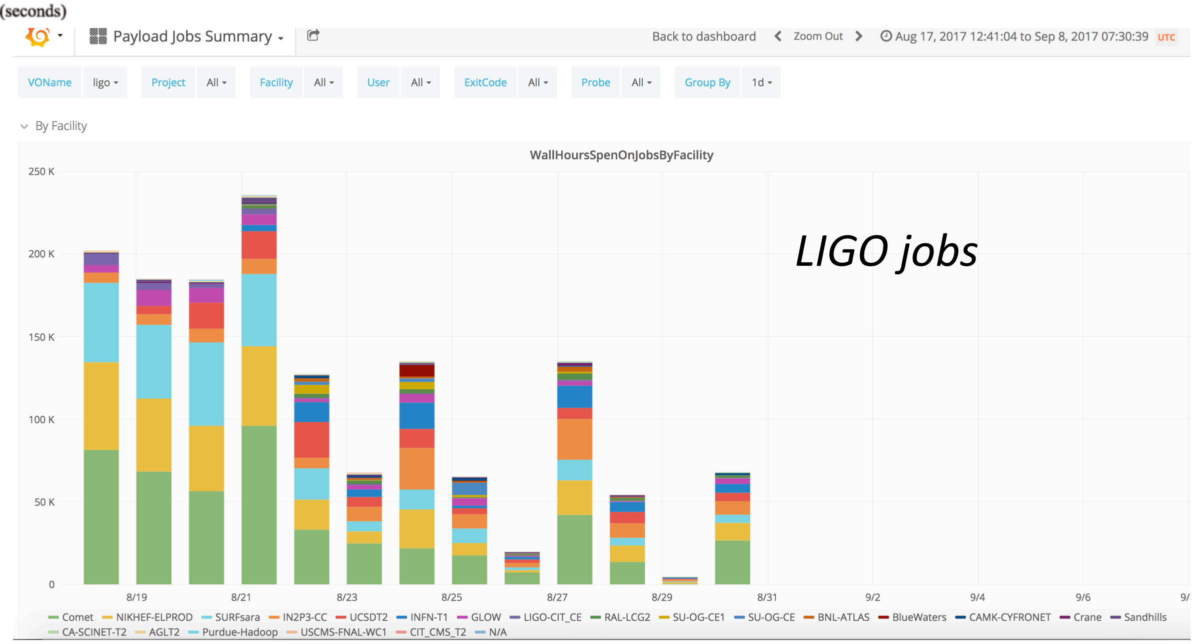


LIGO was no stranger to OSG…

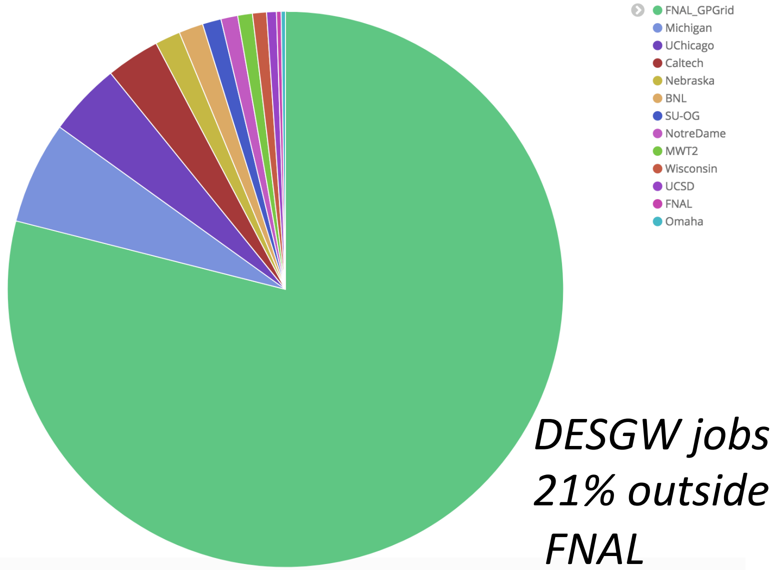
THE DARK ENERGY SURVEY







LIGO jobs



DESGW jobs 21% outside FNAL

- …Neither were some EM partners

1 3/20/18 K. Herner I DES

GW+EM OPPORTUNITIES

Astrophysics

First observations of NS-NS, NS-BH mergers

Evolution of binary systems and their environment

Origin of r-process elements in the Universe

Neutron Star equation of state

Potential for discovery of new astrophysical phenomena

Cosmology

Standard sirens (the GW-equivalent of standard candles)*****

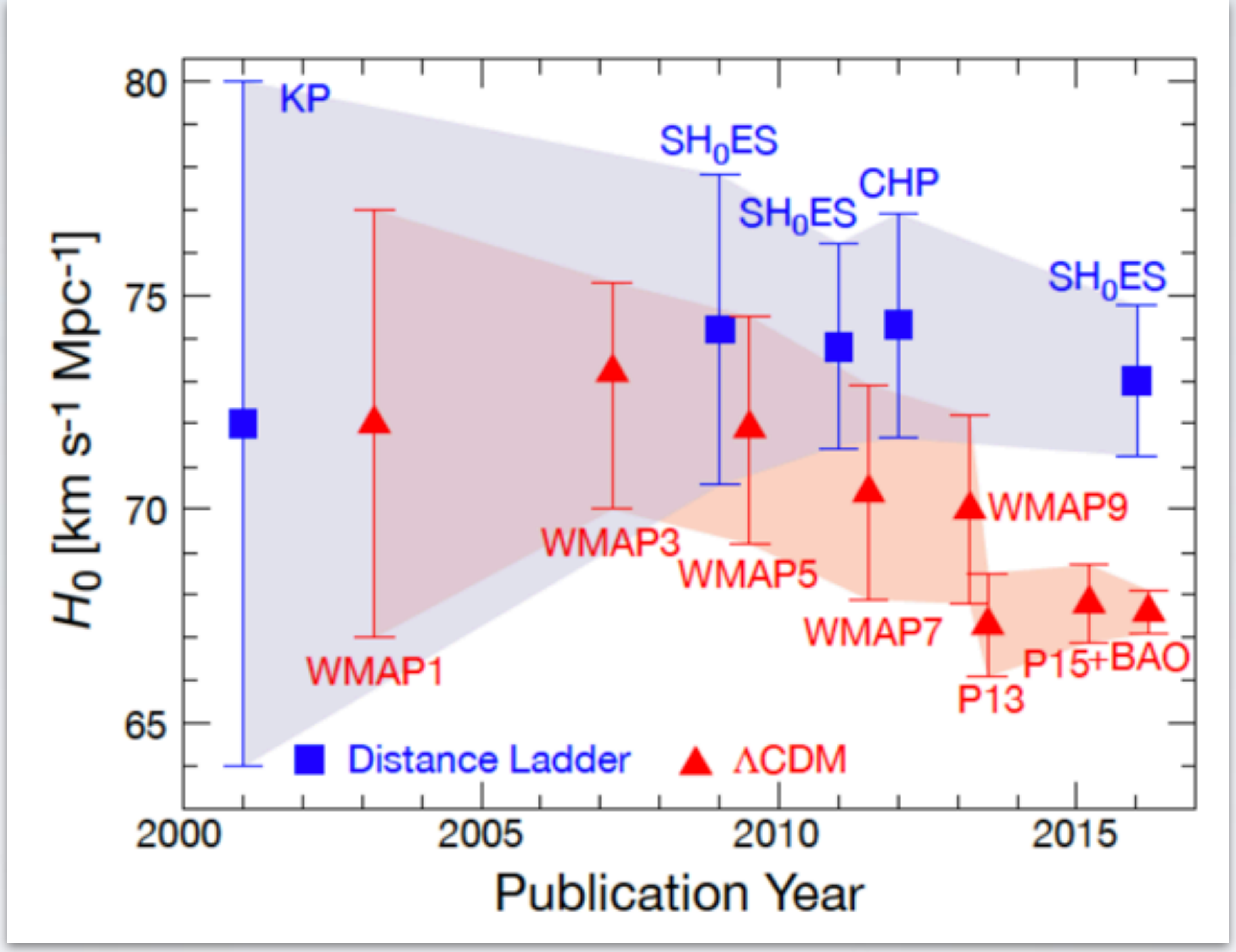
Physics of space-time

Time of flight experiments (including neutrinos)

Tests of General Relativity

***Speaker's favorite!**

COSMOLOGY MOTIVATION

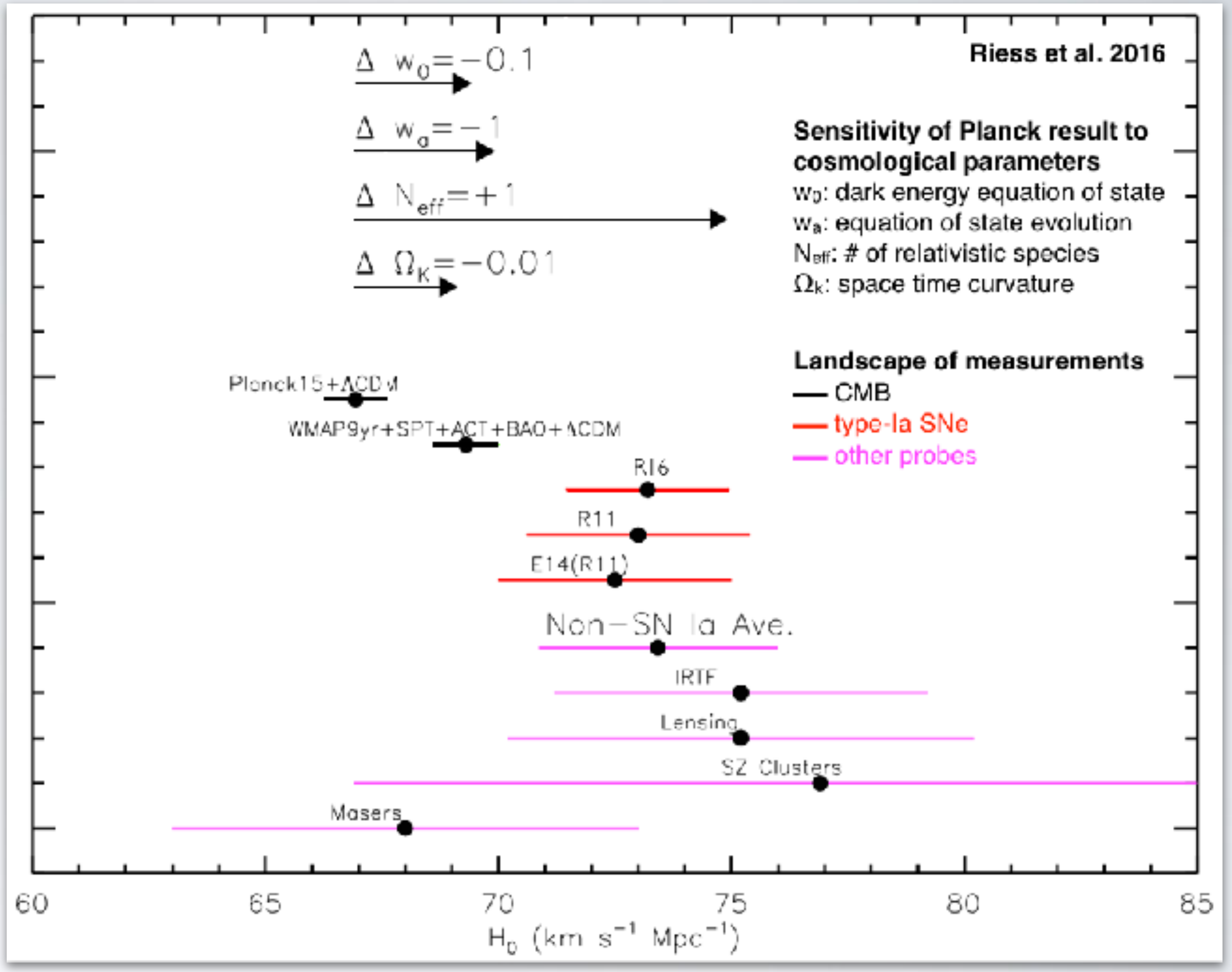


Freedman, W. 2017 (arXiv:1706.02739)

COSMOLOGY MOTIVATION

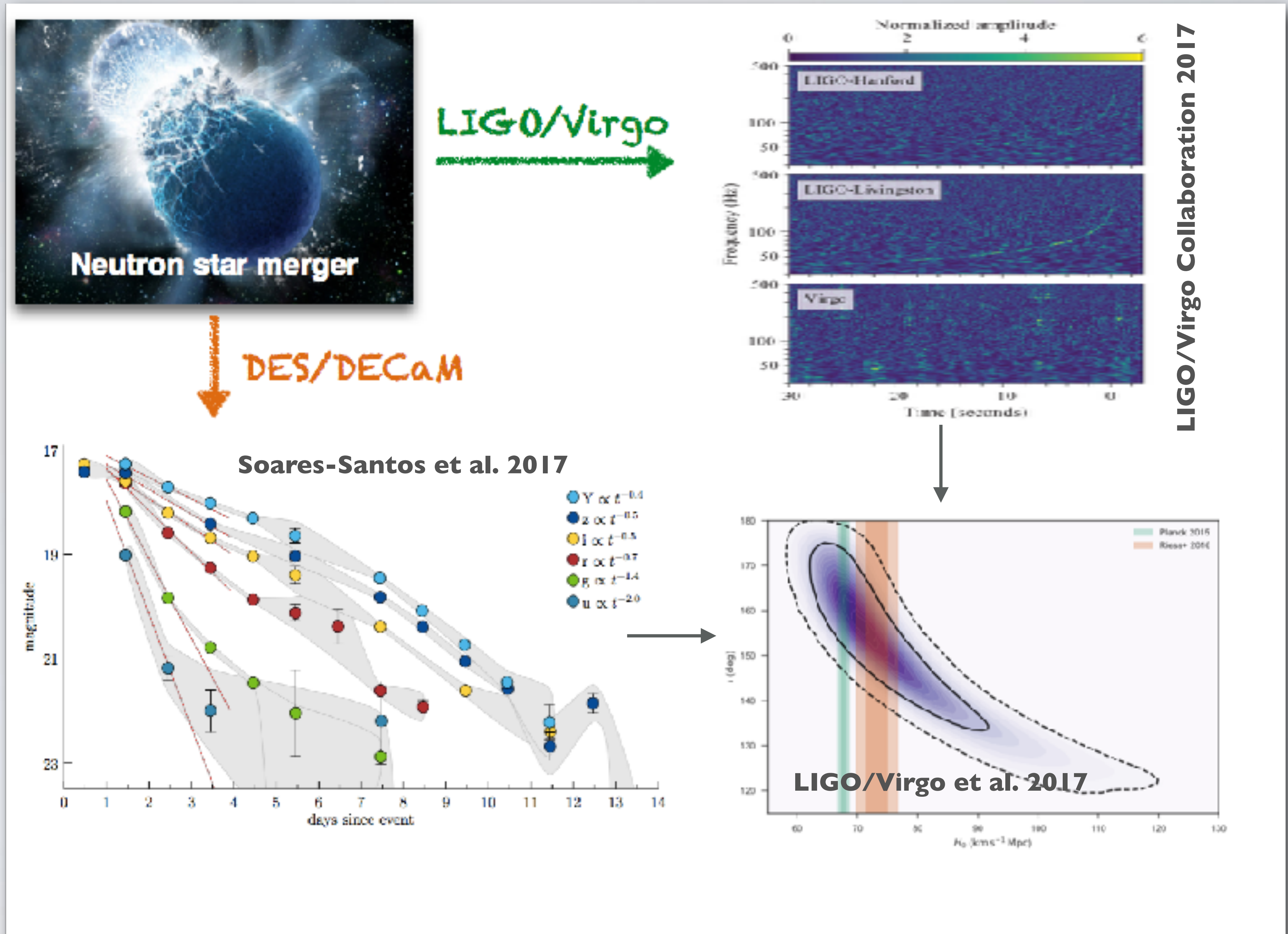
Growing discrepancy between SNe and CMB-based measurements of the current rate of expansion: **systematic effects, or new physics?**

A new, independent, measurement will be most helpful here!

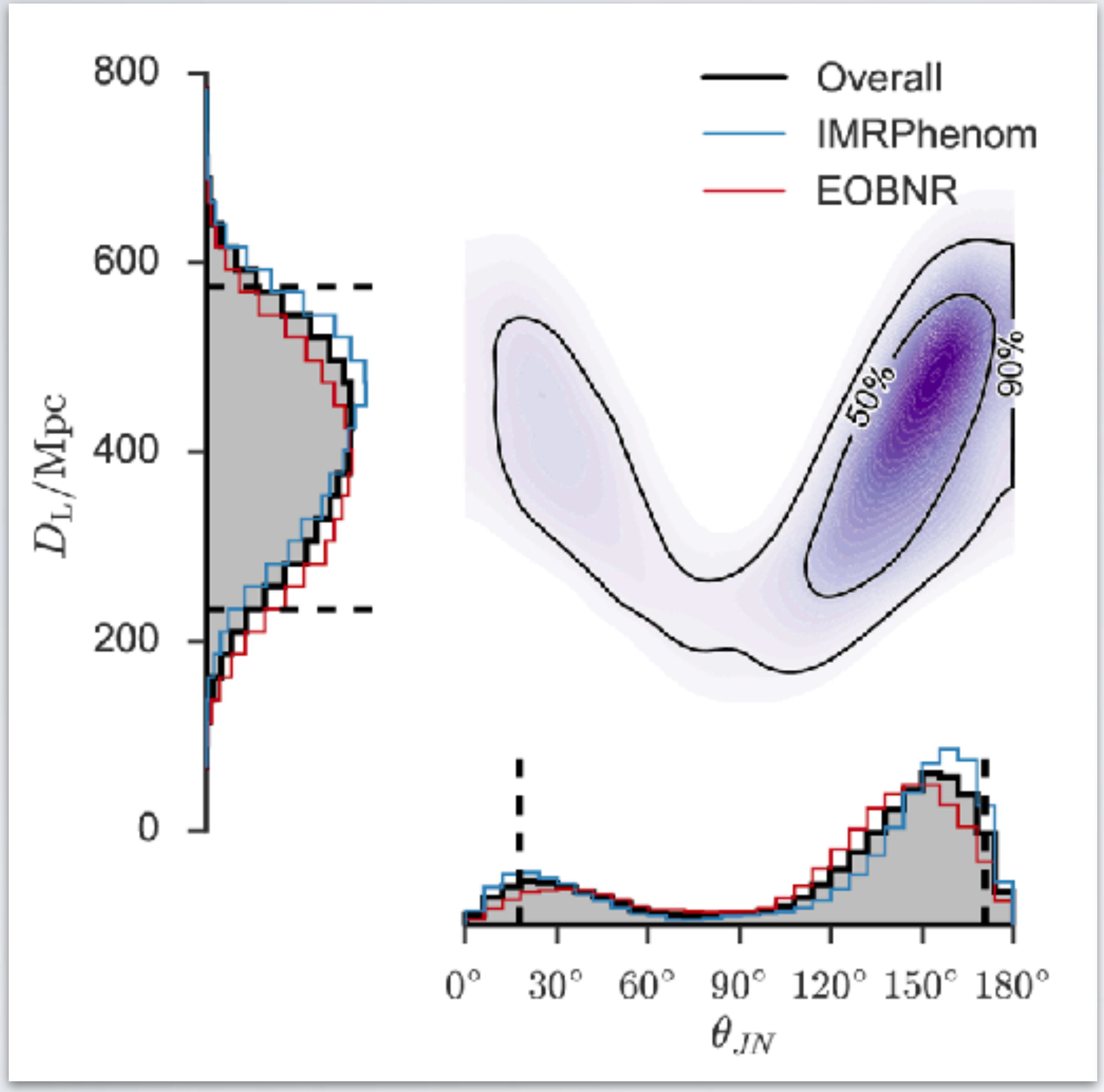


$$H \equiv \dot{a}/a \text{ , where } a = 1/(1+z)$$
$$H(z) = H_0 \cdot f(z; \Omega_m, \Omega_k, \Omega_{DE}, w_0, w_a)$$

GW170817: FIRST OBSERVATION



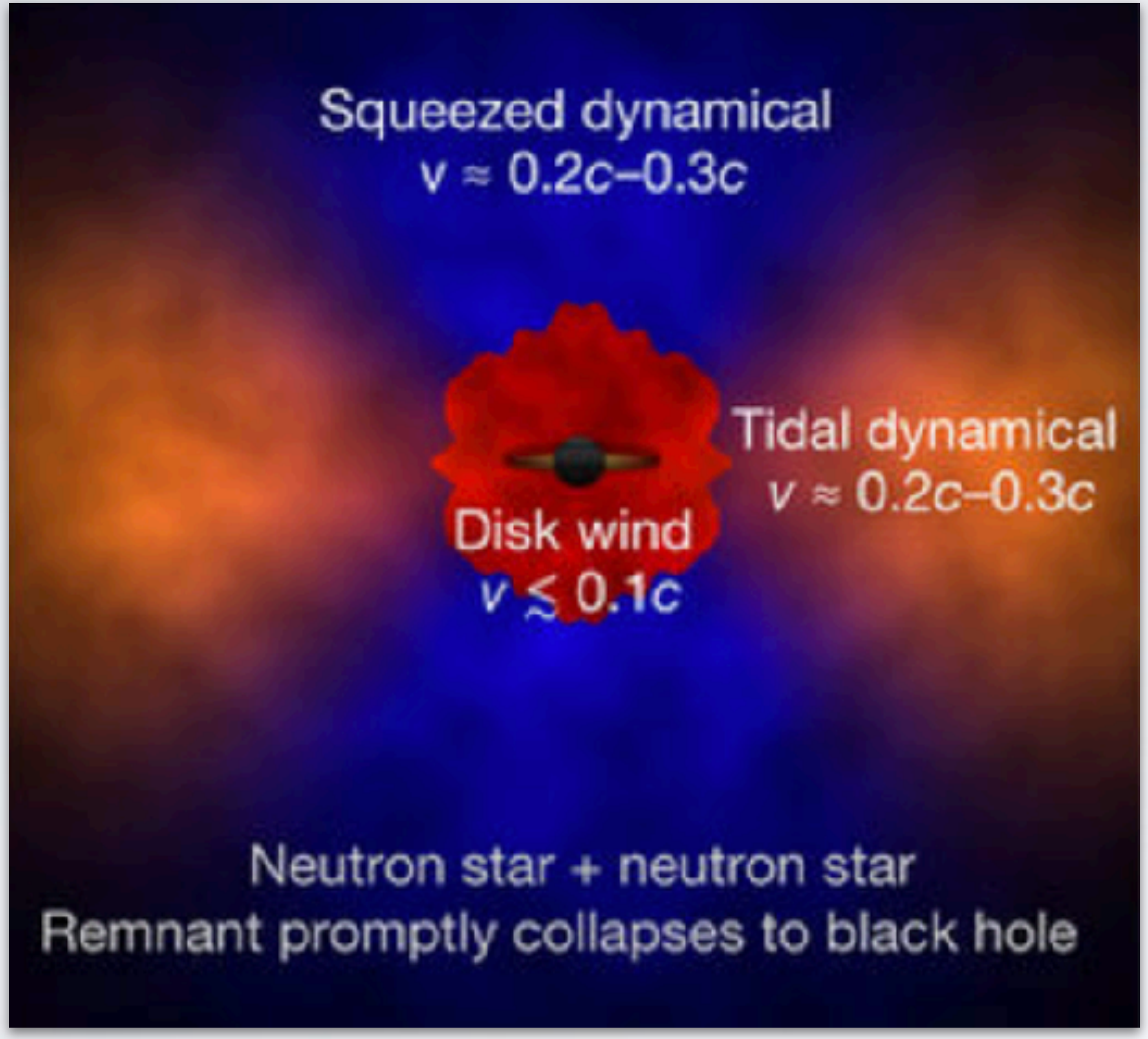
INCLINATION AND DISTANCE



Degeneracy between inclination angle and distance is a major source of uncertainty in cosmological parameters.

Example: GW150914

MERGER MODELS



Kasen et al. 2017 Nature 551, 80-84

Maybe modeling of the EM signal can help break the inclination-angle distance degeneracy.

This is one of many good reasons to study the astrophysics of these systems.

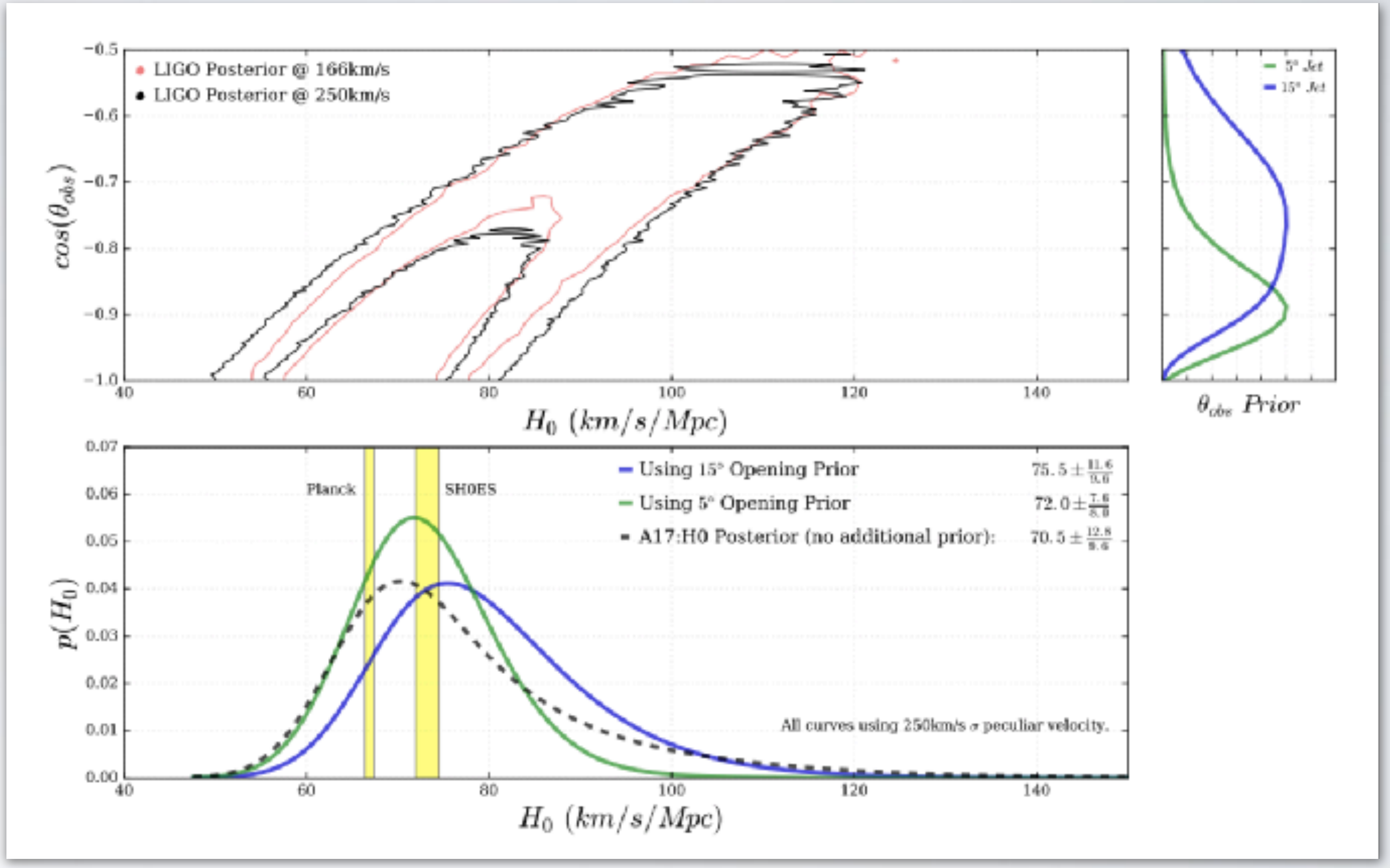
HUBBLE PARAMETER RESULTS

We can improve the Hubble parameter measurements significantly if we can put a prior on the inclination angle of the angle.

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

This results in an Hubble parameter measurement that is **slightly more consistent with the SNe measurements than with the CMB**.

Guidorzi et al. 2017 (arXiv:1710.06426)



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**

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

PROSPECTS FOR OBSERVING

*Binary neutron star merger rate density=1E-6 $Mpc^{-3}\ yr^{-1}$

*30-30 $M_\odot$ binary black hole merger rate density=2E-8 $Mpc^{-3}\ yr^{-1}$

	Average redshift	Redshift encloses 90% of events	# of Events
2018+ HLV O3	0.03 / 0.28	0.04 / 0.45	5 / 80
2020+ HLV Design	0.05 / 0.48	0.07 / 0.77	40 / 500
2024+ HLVJI Design	0.06 / 0.60	0.09 / 0.96	80 / 900

Chen & Holz (2016)

GW+EM CHALLENGES

All-sky effort covering large regions of interest

- **Ideally we would have capability to pursue all targets**
- Need a global network of resources (north and south)
- Search areas: 60-200 deg^2 , Mag = -16 or fainter

PROSPECTS FOR OBSERVING

90% confidence level localization

	Sky Area (deg^2)	Volume (Mpc^3)
2018+ HLV O3	**20 / 250**	**9k / 60M**
2019+ HLV Design	**10 / 200**	**20k / 200M**
2024+ HLVJI Design	**3 / 65**	**13k / 100M**

Chen & Holz (2016)

***Binary neutron star merger**

***30-30 $M_\odot$ binary black hole merger**

GW+EM CHALLENGES

All-sky effort covering large regions of interest

- **Ideally we would have capability to pursue all targets**
- Need a global network of resources (north and south)
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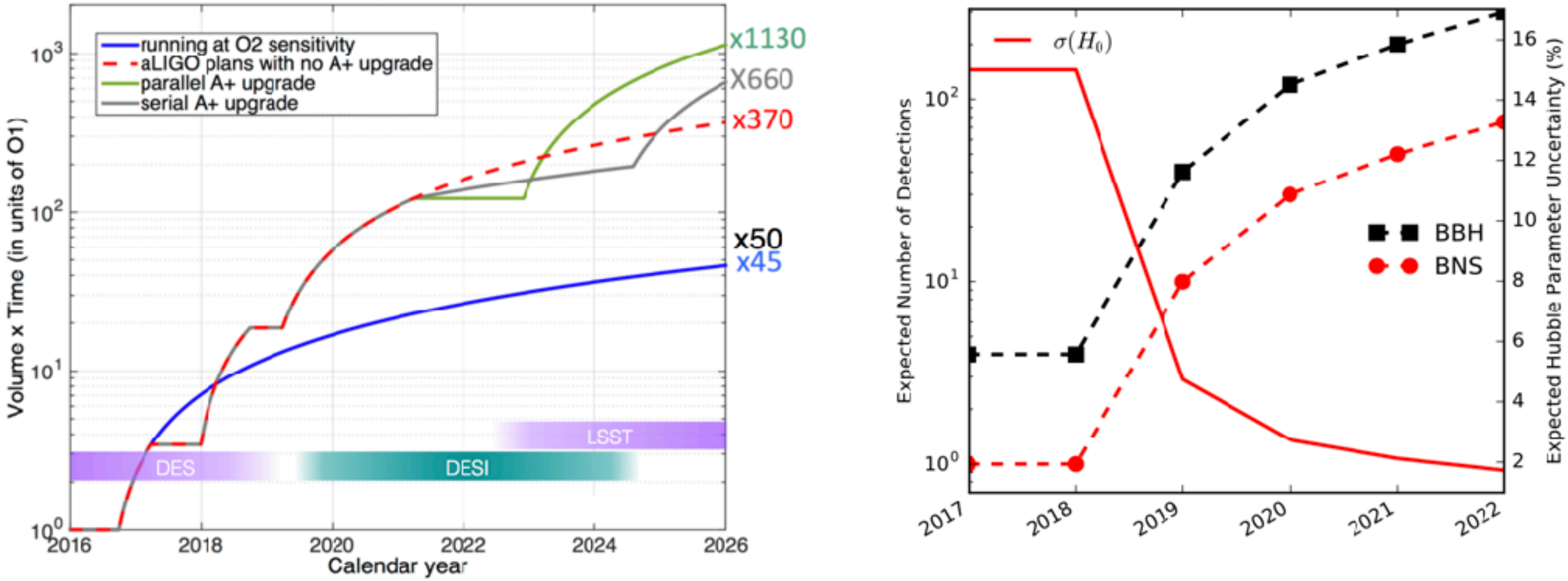
Targets of opportunity with external triggers

- **Triggers are provided by the GW observatories**
- Coordination needed between different communities
- Lessons learned from HEP/Astro projects will be useful here

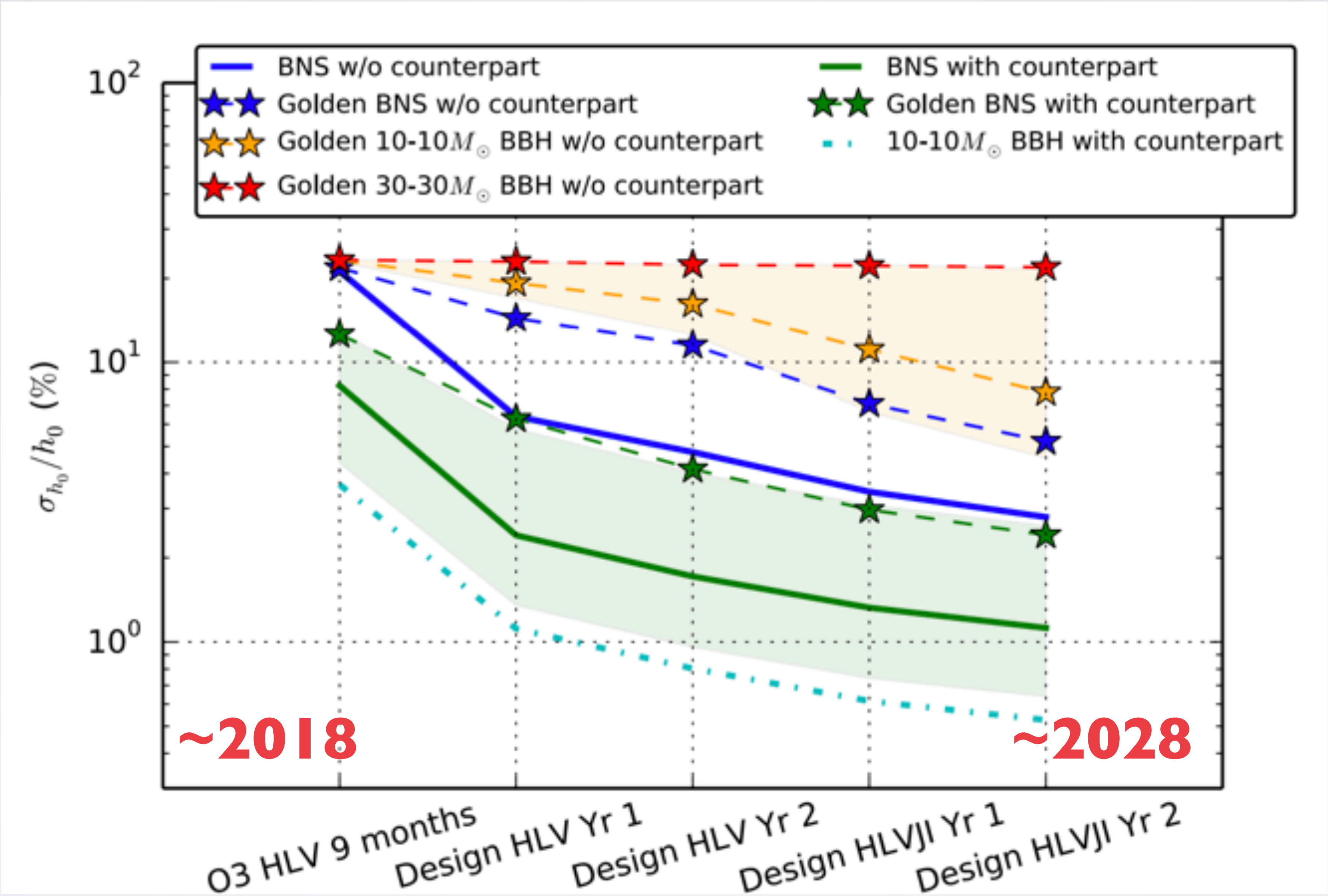
Rapid development in this emerging field

- **Optimal program must be flexible to adapt to new inputs**
- Uncertainties on rates, emission models, etc. are still large

5 YR PROJECTIONS



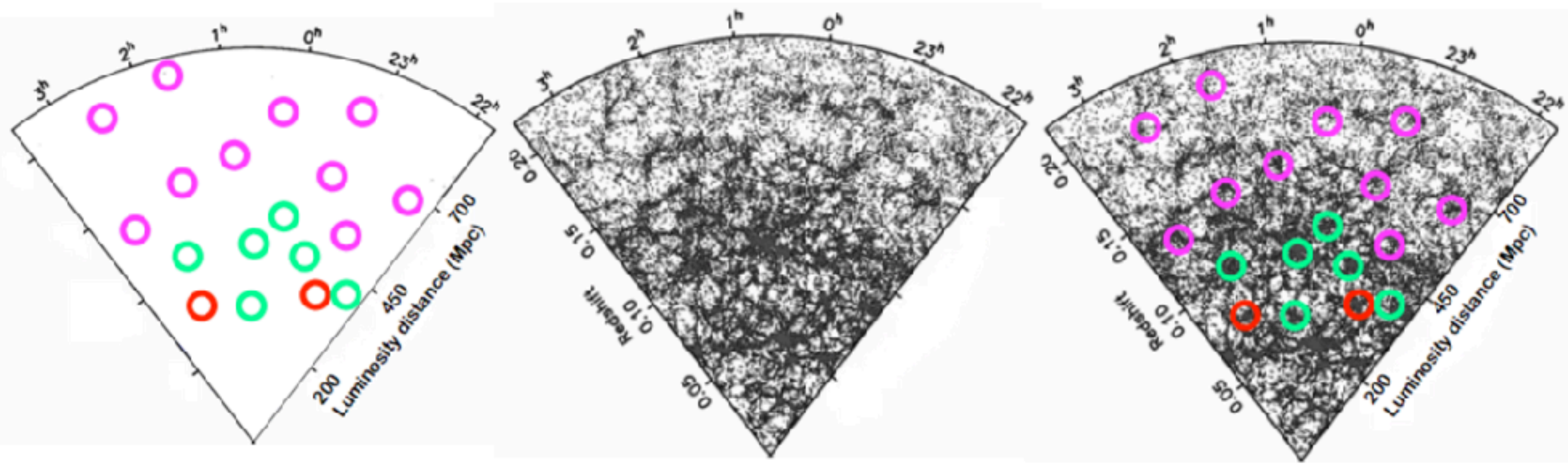
LONG TERM PROJECTIONS



Chen, Fishbach & Holz, 2017

… 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)

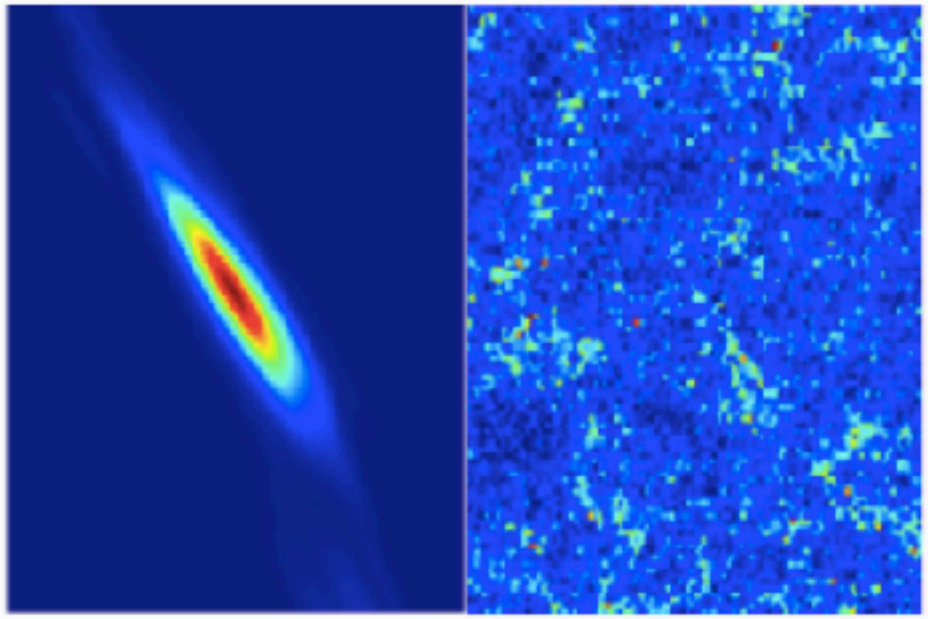
DARK SIRENS

Preliminary

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

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.

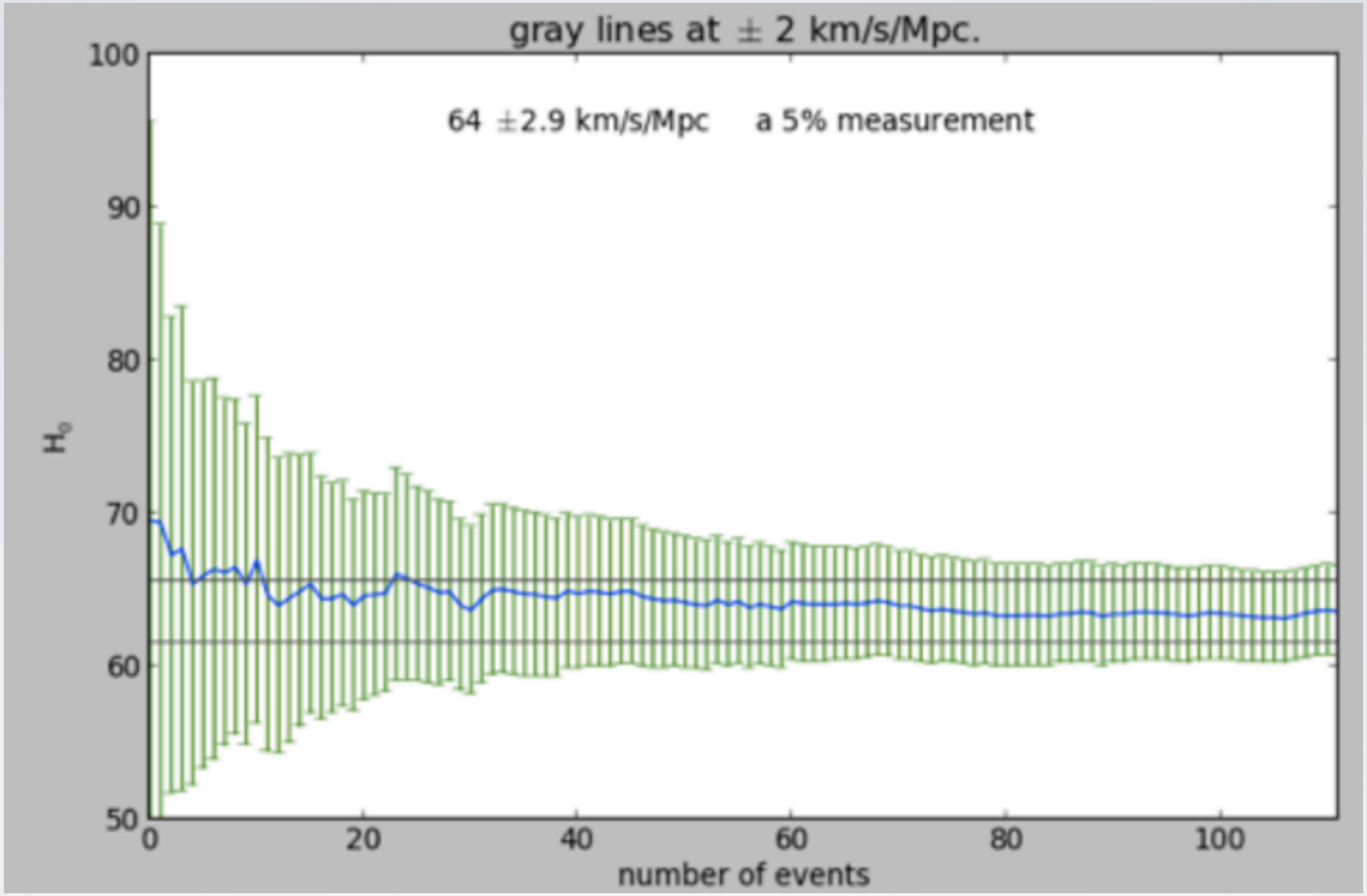


Left: HLV spatial localization- $40° \times 30°$, red $\times 10$ more likely than light blue. Right: mock galaxy catalog, $M_i < -21, z \leq 0.2$. (Buzzard v1.1)

(Annis & Brout)

DARK SIRENS

Preliminary



(Annis & Brout)

PROGRAM ELEMENTS

DECam is a great search & discovery machine for EM counterparts of GW events in the southern sky.

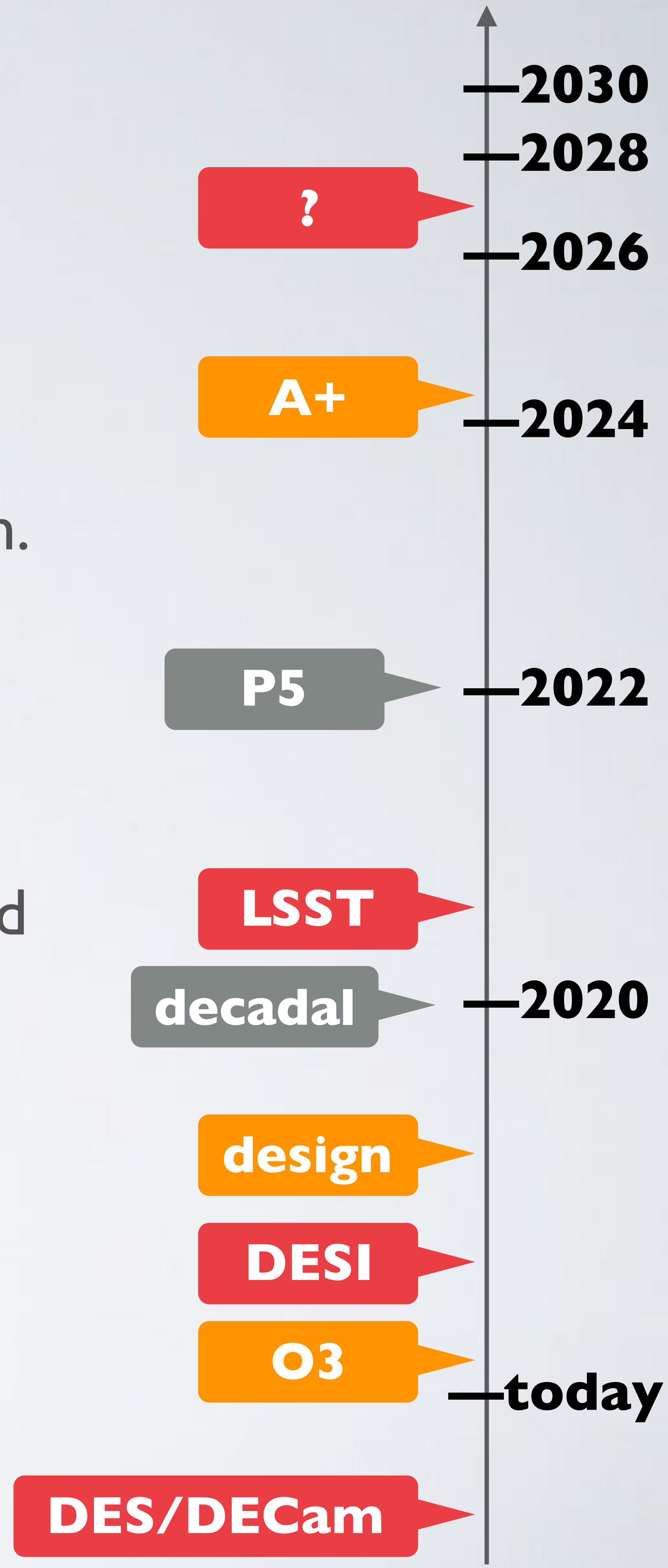
LSST will be the next generation machine in the south.

Spectroscopy capability is needed, for candidate classification, astrophysical modeling, and cosmology.

DESI is currently not planning to have TOOs, but could provide spectra for dark siren analyses.

New spectroscopic facilities in the south will be key.

Above all, coordination is needed a) between exiting, planned and new efforts b) with the GW community.



These are exciting times for **Multi-Messenger Astronomy** with **Gravitational Waves**.

DECam participated on the discovery of the first neutron star merger with an associated electromagnetic counterpart, **inaugurating the GW era of multi-messenger astronomy**, and **blazing a new trail for cosmology**. Now we have the opportunity to help shape the future of this emerging new field.