Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass2021 Cosmic Frontier CF6 White Paper: Multi-Experiment Probes for Dark Energy – Transients

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Abstract

This invited Snowmass 2021 White Paper highlights the power of joint-analysis of astronomical transients in advancing HEP Science and presents research activities that can realize the opportunities that come with current and upcoming projects. Transients of interest include gravitational wave events, neutrino events, strongly-lensed quasars and supernovae, and Type Ia supernovae specifically. These transients can serve as probes of cosmological distances in the Universe and as cosmic laboratories of extreme strong-gravity, high-energy physics. Joint analysis refers to work that requires significant coordination from multiple experiments or facilities so encompasses Multi-Messenger Astronomy and optical transient discovery and distributed follow-up programs.

Contents

1 Executive Summary

A broad range of transient science requires diverse data sets that can only be obtained from multiple experiments/surveys. Optical telescopes are needed to associate transient counterparts of gravitational wave standard-siren discoveries made by LIGO & Virgo to measure the Hubble constant H_0, and the neutrino masses from the IceCube experiment. Spectroscopic, near-infrared, and enhanced temporal sampling are needed to get precise and accurate distances of Type Ia supernovae discovered by the Rubin Observatory to measure the properties of the Dark Energy responsible for the accelerating expansion of the Universe. Similarly, high spatial-resolution and enhanced temporal sampling are needed to get precise time delays and modeling of strongly-lensed systems discovered by the Rubin Observatory to measure the Hubble constant. The peculiar velocities derived from the distances of standard sirens and supernovae can be compared with the density perturbations within the same volume as measured by DESI to measure the strength and length-scale of gravity.

Multi-experiment time-domain science engenders new considerations that do not arise in a self-contained experiment. One facet is experimental design. Designs can be optimized for a joint, rather than stand-alone project. A joint analysis of low-level data products (e.g. pixels) can preserve significantly more information than the combination of lossy final data products. Infrastructure for real-time inter-experiment communication can be needed.

The community must now address inconsistencies between different experiments and/or cosmological probes. The Hubble constant as measured from the cosmic microwave background, baryon acoustic oscillations, and Type Ia supernovae are in tension. The solution may lie in new fundamental physics, unaccounted astrophysics, or experimental systematic errors.

New support is needed to enable this time-domain science. Multi-experiment analysis can require human and computing resources beyond the sum allocated to the individual experiments. Simulations that account for different probes, and not just a single experiment, are needed to interpret the multi-experiment data self-consistently. New experiments must be developed and supported when existing experiments are insufficient.

2 Dark Energy in the New Era of Multi-Messenger Transients with Gravitational Waves

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2.1 Dark Energy in a nutshell

The accelerated expansion of the present-day Universe [1, 2] is one of the most challenging puzzles in contemporary physics [3]. The most straightforward theoretical explanations require a new – beyond the standard model – component of the Universe with physical properties that lead to repulsive gravity. This new component is named dark energy and accounts for about 70% of the mass-energy in the Universe. As the high-energy physics (HEP) community top aspiration is to understand how the Universe works at its most fundamental level, dark energy is a high-priority subject of our research program.

Many theoretical models have been proposed as attempts to provide a compelling explanation for the nature and magnitude of dark energy. For example, a spatially homogeneous, slow-rolling scalar field can provide a negative pressure that drives the cosmic acceleration. This light scalar field could provide a possible mechanism for explaining dark energy. For a comprehensive overview of these models, we refer the reader to the Snowmass White Paper “Cosmology Intertwined” [4]. In this section, we will be considering three of the most popular dark energy parameterizations within a cosmological model, which can be summarized as:

- ΛCDM: In this model, dark energy is a cosmological constant (Λ), and it provides a good fit for most of the observations currently available. Cold dark matter (CDM) is the other main ingredient of this model. If dark energy is indeed Λ, its equation of state (EoS) parameter is $w = -1$ at all times. Although ΛCDM provides a satisfactory description of the Universe’s behavior, e.g. the emergence of late-time cosmic acceleration and structure formation, this model suffers from what appears to be a fatal flaw: assuming that Λ corresponds to the energy density of empty space, it can be shown through quantum field theory (QFT) calculations that its value should be many orders of magnitude away from the observed one. This problem motivates the pursuit of alternative models such as those discussed below.
- wCDM: In this more generic model, we let the dark energy EoS parameter w be free to vary. In the wCDM model, the simplest parameterization corresponds to the case of w assuming a constant value over time.
- CPL: This model describes a dynamical dark energy. It represents a more complex, but likely more physical, scenario in which the EoS varies with time. This evolution of w, in this model, is often described as a function of the scale factor a by the so-called Chevallier–Polarski–Linder (CPL) parameterization: $w(a) = w_0+w_a(1-a)$, where w_0 and w_a are free parameters and the scale factor is defined as $a = (1 + z)^{-1}$. Sometimes it is also called w_0w_aCDM model. One advantage

of this parameterization is that it can provide a good description for a scalar field EoS; that is, in the case dark energy is a dynamical fluid with an EoS that varies with time.

2.2 The report of the Dark Energy Task Force revisited

We can measure the impact of dark energy on cosmological observations through its influence on the large-scale structure and dynamics of the Universe. Based on this fact, a series of cosmic surveys has been pursued by the HEP community with the goal of achieving a better understanding of dark energy. This series of experiments was outlined in the report of the Dark Energy Task Force (DETF), published in 2006 [5].

The DETF was established in the early 2000's by the Astronomy and Astrophysics Advisory Committee (AAAC) and the High Energy Physics Advisory Panel (HEPAP) as a joint sub-committee to advise the Department of Energy (DoE), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF) on a experimental program for dark energy research [5]. The DETF report served as a guide to develop the landscape of dark energy experiments throughout the last two decades including the DES, DESI, JWST, and LSST. Here, we revisit the major findings of the DETF and present an updated view of the dark energy experimental program for the next two decades.

Cosmic surveys for dark energy rely on two main classes of cosmological observables. In the first class, known as geometric methods, we study the effect of dark energy on the expansion rate of the Universe as a whole. It can be probed through the distance-redshift relation using standard candles such as type Ia supernovae, standard rulers such as the baryonic acoustic oscillations in the large-scale distribution of galaxies, and more recently, using gravitational wave (GW) as standard sirens. The second class of observations relies on measuring the impact of dark energy on the growth rate of large-scale structures. For example, we have measurements of the weak lensing effect on the large-scale structures (e.g. cosmic shear), redshift-space distortions in the distribution of galaxies, and measurements of the abundance of galaxy clusters. A major finding of the DETF is the fact that we can significantly improve constraints on the dark energy EoS by combining these two classes of methods.

Following the DETF report, the dark energy experimental landscape has been designed to probe dark energy using a diverse set of instruments (e.g. imaging, spectroscopic) capable of probing multiple observables. The DETF report organized these experiments in four categories (Stages), corresponding to increasing levels of constraining power on the EoS of dark energy. Here, inspired by the DETF report, we expand the definition of the dark energy experiments' stages into the future:

- Stage I: represents what was known at the time of the DETF report.
- Stage II: represents the then anticipated state of knowledge upon completion of projects that were in progress at the time.
- Stage III: comprises short-term, low/medium-cost projects proposed back then.
  - At the time of this writing, most Stage III experiments are completed or close to completion.
  - Examples include: DES, SDSS-III, SHOES, Planck.

- Stage IV: comprises long-term, medium/high-cost projects proposed back then or soon thereafter.
  - At the time of this writing, Stage IV experiments are taking data or in construction.
  - For the purpose of this study, we define Stage IV as the anticipated state of knowledge upon completion of these ongoing projects.
  - Examples include: DESI, JWST, LSST.
  - Note that Stage IV was the last stage described in the DETF report. The next stages in this list are newly proposed stages defined in this White Paper for the purpose of guiding the next generation of dark energy experiments.
- Stage V: near-term, low/medium-cost future projects.
  - This is the first new Stage in the series. It represents beyond Stage IV experiments of medium scale, which are proposed to be completed in a 5-10 years timescale.
  - Examples: MegaMapper, MSE, DESI-2, CMB-S4, LIGO Voyager.
- Stage VI: long-term, medium/high-cost future projects.
  - This is the second additional Stage in the series. It represents future experiments of larger scale and longer time frame.
  - Examples: Cosmic Explorer, Einstein Telescope.

2.3 New challenges and goals for dark energy research in the next two decades

The figure of merit used by the DETF to compare different experiments was the inverse of the area constrained in the $w_0 \times w_a$ parameter space. This figure of merit is no longer sufficient to capture the potential of future experiements to achieve our current dark energy science goal. Beyond measuring the EoS with increased precision, we aim at *distinguisihing* between dark energy models. For example, we want to be able to confidently say whether or not the universe is currently dominated by a dynamical dark energy fluid. In other words, we want to be able to reliably test/falsify the ΛCDM hypothesis.

A path towards this goal is to explore the observed tensions between results arising from different observables and experiments. Measurements of the rate at which the Universe is expanding today (i.e. the Hubble constant, H_0) derived from the cosmic microwave background (CMB) and late-time observations exhibit a significant tension at a level of $\sim 4-6\sigma$ [6]. Moreover, measurements of the matter fluctuation amplitude σ_8 and the matter density Ω_m from galaxy cluster samples and lensing present systematically lower values in comparison with the results from CMB [7].

With the experiments and precision that we have today, we cannot distinguish whether these observed tensions are due to unaccounted-for systematic uncertainties or if they are evidence that ΛCDM is incorrect or incomplete. In particular, performing measurements of the late time Universe with highly non-linear physics, combined with the difficulty of adequately accounting for systematic errors, are a difficult task even in the timeline of the Stage IV experiments [5]. Therefore, it is essential to look for new independent observables and to perform robust joint analyses [8].

One goal for future experiments is to go beyond achieving per cent-level precision to identify statistically significant tensions between the multiple observables for dark energy in order to test and exclude dark energy models if they are not realized in nature. In order to quantify progress towards this goal, we define a new figure of merit to compare different proposed experiments for Stages V and VI dark energy science. This new figure of merit is defined as the *tension significance* that each experiment would achieve, if instead of ΛCDM, dark energy is better described by a time-evolving equation of state.

In the next sections, we present the potential of transients, particularly gravitational wave standard sirens, to achieve this goal in the next decade.

2.4 Dark energy science with gravitational wave standard sirens

Compact object binary mergers are promising novel probes of cosmology. Often referred to as standard sirens, such events can be used as multimessenger probes. Gravitational waves emitted during the inspiral of compact binary mergers are used to determine their absolute distances, while their redshifts can be determined via traditional astronomical observations, if an electromagnetic counterpart (and/or its host galaxy) is found. Thus, these standard sirens are used as distance indicators, analogous to type-Ia supernovae.

The primary motivation to pursue standard sirens for cosmology is that, contrary to supernovae, their distances are determined from first principles. By removing the need for multiple astrophysical calibration steps, we eliminate some challenging systematic uncertainties. As we mentioned, out of the several key parameters of modern cosmology, distance indicators are particularly sensitive to the expansion history of the Universe as a function of redshift, the Hubble parameter $H(z)$. Nearby sources in particular are used to measure the current rate of expansion, H_0. A breakthrough in understanding the physics of dark energy is a core goal of our community to understand the accelerated expansion of the cosmos and the absolute value of today's expansion rate is important – per cent-level precision measurements of H_0 are required to cease being a limiting factor on dark energy model limits.

Compared to the well-established cosmology probes such as supernovae, the emerging field of multimessenger cosmology with gravitational waves is advancing in leaps. Since the first observation [9] of a compact binary system merger by the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo Collaboration (LVC), less than five years ago, over 90 merger events and candidates have been reported [10], one has had its electromagnetic counterpart identified [11–13], and a handful of events without counterpart have been used for measurements of H_0 with an uncertainty of $\sim 14 - 20\%$ [14–18]. As the GW detector network continues to be upgraded, the sample sizes are expected to grow exponentially in the coming decade. Therefore, the ambitious goal of per cent-level H_0 measurements from standard sirens is a realistic possibility. A precision measurement of H_0 from nearby GW sources, out to the distances expected for binary neutron star mergers from current generation GW detectors, is also a powerful mean to break degeneracies between cosmological parameters from future CMB experiments (in particular the geometrical degeneracy) or from BAO measurements from e.g. DESI [19]. Besides that, detection of gravitational waves events at higher redshifts ($z \sim 0.7$), which is also expected for binary neutron stars with next generation (XG)[1] GW detectors [20], might allow us to probe other cosmological parameters beyond H_0, e.g. the EoS of dark energy.

Beyond measuring these cosmological parameters with high precision, we propose that an entirely new program be designed to build a large sample of standard sirens with identified electromagnetic counterparts in support of an analysis capable of distinguishing between ΛCDM and the different dark energy models with high significance. This program will rely on a high-efficiency search and discovery campaign using ground-based telescopes in tandem with the next generation of gravitational waves detectors. A pioneering version of this program is currently being pursued by the Dark Energy Survey collaboration (the DESGW program [21]) using DECam for imaging and other telescopes for spectroscopic follow-up to confirm candidates. Here, we do not describe in detail the scope of future observations, but we anticipate that a new telescope/instrument systems will be required to perform rapid follow-up observations. Lessons learned from DESGW will be useful in designing and optimizing such a future observational program.

2.5 A precursor follow-up instrument for the XG era

While we anticipate the need for an instrument dedicated for GW transients searches in the 2030s to fully establish a dark energy program with gravitational waves, we also believe that this program will benefit from a near-term – from now to 2030s – dedicated optical instrument for follow-up search. As an example, one of the most efficient instruments used for this purpose today is the DOE/DECam at the Blanco Observatory in Chile. DECam's ~ 3 sq. deg. field of view allows us to quickly cover the GW probability sky area in $griz$ or Y filters out to the limits necessary to detect an optical counterpart at the distances expected in future GW observing runs. DECam has been used for target of opportunity (ToO) observations by several groups. In particular, the DESGW group has demonstrated the potential of DECam in following up GW events [22–26]. Additionally, LSST will be online in the near-term timeline. Although it has a transient program planned, LSST will not provide the most effective set up for *fast* follow up observations. While LSST is not a prime instrument for GW follow ups, its data will be essential for finding GW transients. Then, we argue that coordination between dedicated DECam searches and LSST will enhance our ability to find many GW transients.

In summary, an existing 3-4m optical instrument could be leveraged up as a precursor instrument for dark energy science through the search and discovery of GW and other transients — see subsection 4.2, for possible synergies with the Time Delay Machine, that could establish them as the two leading new techniques for Hubble constant's measurements in the XG era.

2.6 Experiments and stages

To demonstrate the constraining power we may achieve in the future with a DESGW-like program operating in coordination with future GW observatories, we have exam-

[1]After the Snowmass Community Summer Study Workshop, it was proposed to adopt the initials XG for the next generation of GW detectors instead of 3G.

ined the landscape of currently proposed facilities using our definitions of post-DETF dark energy science stages. An estimated timeline for these stages and experiments is presented in Figure 1:

- In Stage IV, the LIGO detectors as well as Virgo and KAGRA will be online and will undergo upgrades in order to achieve the proposed LIGO (HLI+), Virgo+ (V+), and KAGRA+ (K+) sensitivies. During this time, telescopes such as LSST [27] and DESI will also be operating.
- Next, Stage V will include the HLIVK+ network with the improved LIGO Voyager detector. During this time, we anticipate telescopes such as MegaMapper, MSE and DESI-2 to come online. During this era, GW detectors could be pushing the redshift horizon beyond z $\sim$ 1 for binary mergers.
- Finally in Stage VI, the addition of Cosmic Explorer and the Einstein telescope will bring the ground based detector network sensitivity to $z > 4$. Note that during this era, there are no anticipated telescopes that are planned to be powerful enough for optical follow up of these events.

For the purpose of a dedicated standard siren dark energy program, we need to efficiently detect electromagnetic counterparts (a task requiring deep and wide imaging as well as spectroscopy). Remarkably, the bottleneck to fully exploiting the potential of standard sirens for dark energy research is in the traditional cosmic survey arena instead of the GW observatories. Already in Stage V, it will be challenging to meet those requirements with the proposed experiments. In Stage VI there are no telescopes currently planned for this purpose. In this paper, we show how powerful our dark energy results would be if we can obtain electromagnetic counterparts for about 5-10% of the events that are expected to be seen by the currently proposed GW observatories.

2.7 Forecasts

In this section, we quantify how powerful standard sirens are as a tool to distinguish between ΛCDM and two other dark energy models. We explore the induced bias caused by some wrong assumption of the cosmological model and the sensitivity of this cosmological probe to the cosmic expansion rate (h, which is H_0 in units of 100 km/s/Mpc), the energy density of dark matter (Ω_m) and the dark energy EoS parameters (w_0 and w_a). Note that, until now, standard siren analyses have only been able to measure h, fixing the other parameters to the ΛCDM values, or letting them vary (but without being able to obtain useful constraints). In the future, however, we expect standard sirens to be detected out to greater redshifts, which will drastically improve their constraining power beyond h, provided that successful campaigns for electromagnetic counterpart detection are also pursued.

For this forecast analysis, we simulated three data vectors based on different model universes: ΛCDM, wCDM, and CPL. We used the current best-fit values of ΛCDM, and we set the EoS parameters of the other two models to be no more than one standard deviation away from the current state-of-the-art constraints [29, 30]. The only change was in the value of the EoS parameters, all other relevant cosmological parameters are set to the best-fit values of the Planck 2018 results. The chosen parameters are shown in Table 1.

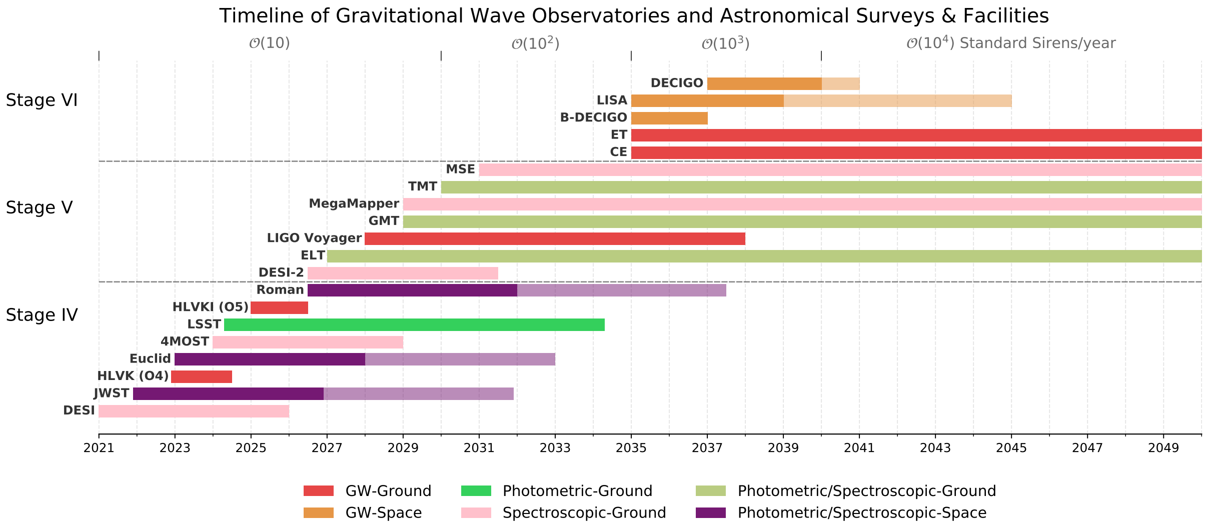

Figure 1: Timeline of current and planned gravitational wave detectors and astrophysical surveys/facilities. The horizontal dotted lines indicates the dark energy experiment stages outlined in this White Paper. The darker colors represent the nominal lifetime of the facility, and lighter colors are possible extensions. The numbers in the top are the expected number of standard sirens that will be detected per year based on projections from [28]. We estimate that standard siren experiments for dark energy must yield samples corresponding to 5-10% of the total number of events detected by the GW observatories in order to achieve the Stage V and Stage VI goals.

The basic idea of this forecast analysis is that, if we assume ΛCDM for all three universes and attempt to fit the simulated data, we will find h and Ω_m values that are in significant disagreement with the input. This is because the effect of a dynamic equation of state can be mimicked by changing the values of these two parameters. After defining the key parameters of the observable data set, the forecast is done by determining the significance of the bias caused by the wrong assumption of the cosmological model. If our goal is to falsify ΛCDM, we should aim for at least a 5σ level tension. Ideally, the combination of GW with other independent probes (and therefore, distinct bias) will induce considerable internal tensions in the model. But this approach is not explored in this work.

The observable data set parameters for Stage IV, V, and VI experiments are defined in Table 2. The key parameters are the number of events and the GW's redshift range. Here we assume the values given by the proposed GW experiments and assume that our search and discovery program for electromagnetic counterparts will be successful in amassing a sample of about 5-10% of the best GW events. Another important factor in determining the constraining power is, of course, the distance uncertainty. Here we estimate an overal 5% uncertainty on the distances, as estimated by the GW teams for their top events.

We produced simulated datavectors drawn from each of the cosmological model (ΛCDM, wCDM or CPL) and statistically consistent with the expected observational setup (e.g., number of detections, maximum redshift) for each of the different experiment stages. We then fit each simulated datavector assuming the ΛCDM model. In this way, we can estimate the disagreement between the input parameters (truth) and the

	ΛCDM	wCDM	CPL
h	0.67	0.67	0.67
$\Omega_{\rm m}$	0.265	0.265	0.265
w_0	-1	-0.92	-0.877
w_a	0.0	0.0	0.12
Ω_k	0.0	0.0	0.0

Table 1: Parameter choices for GW datavector simulations. We chose values for equation of state parameters, w_0 or (w_0, w_a), inside the 1σ confidence level of the current best constraints. All other relevant parameters are set to the Planck 2018 ΛCDM nominal values [29].

Stage	GW network type	z range	No. of events
IV	HLVKI	0.5	110
V	Voyager	1.0	1300
VI	Cosmic Explorer	4.0	6000

Table 2: Summary of GW ground-based observatories that are anticipated at each stage. For each stage we list an approximate redshift range and number of events with an identified electromagnetic counterpart per year, which we used for our simulations. In this estimates, we assume a search and discovery program capable of identifying about 5-10% of the GW events.

fitted parameters [31].

We consider a uniform volume rate of detection, and the maximum redshift of detection as $z = 0.5$, $z = 1.5$, $z = 4.0$ for the stages IV, V, and VI, respectively [28]. We assume a typical value to the signal-to-noise ratio of SNR=20, implying $\sigma_{d_L}/d_L \sim 5\%$ and spectroscopic redshift determination of the host galaxy. For this exploratory discussion, we are considering only detection of optimally oriented events, i.e. face-on and overhead with respect to the detectors.

A summary of our results is found in Figure 2. On the left panel, using a single realization of the simulated data, we show how the different dark energy models affect the result in the $h - \Omega_m$ plane for the Stage VI experiments. Note that there is a very prominent shift between the contours, showing a significant bias in the constrained parameters. We estimated the significance of this bias and repeated this exercise for Stages V and VI. The results are shown on the right panel of Figure 2.

In summary, our results show that if the EoS of dark energy for the observed Universe has a deviation from $w = -1$ in 1σ c.l., at the end of the Stage V, we may observe a bias with a significance of up to 7σ in the $h - \Omega_m$ plane, which will induce a high level of tension in the combined analysis of GW with other independent probes (e.g. large-scale structure, BAO). For the observational scenario considered in the Stage VI, the deviation in the (h, Ω_m) from its true value, may reach 18σ of c.l. for the most divergent scenario investigated here. This result shows that standard sirens will be a truly powerful tool for dark energy science in the next two decades, if we are capable of observe a significant fraction of them with the available and proposed facilities.

We note that here we used our forecasting tools specifically to quantify the impact

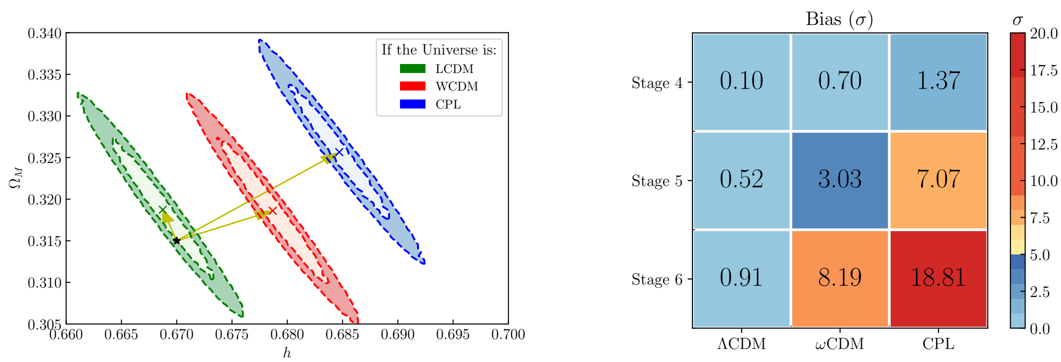

Figure 2: Left: Parameter constraints using a single realization of a Stage VI-like simulated data. This result illustrates the magnitude of the tension expected in $h - \Omega_m$ space due to the assumption of ΛCDM as cosmological model. We show the resulting constraints when fitting simulated datavectors with distinct dark energy models, namely, wCDM (red), CPL (blue), and the ΛCDM (green). We also show the truth input parameters for reference (black star). For each of the simulations, we have (h, Ω_M)= (0.67, 0.315) and the shift is caused by the wrong model assumption. Right: Assuming ΛCDM as fitting model, we show the parameter bias in confidence level (c.l.) units when the realization of simulated datavector is based in different cosmological models. For example, for a Stage V experiment, if the true dark energy model in the Universe is CPL, we would exclude ΛCDM at the 7σ level. For wCDM the situation is more challenging, and we would need a Stage VI experiment to achieve the same level of confidence in excluding ΛCDM.

of standard sirens as a novel cosmological probe. The rationale and the tools used here can be used in principle for comparison with other models and probes as well.

2.8 Discussion

Standard sirens are a new tool for dark energy research. Our community has just started exploring this new tool and its full potential is yet to be achieved. In this paper, we present a study that makes a strong case for establishing a high-efficiency search and discovery program for GW events with electromagnetic counterparts.

Inspired by the report of the dark energy task force, we define the new upcoming stages for the field of dark energy: Stage IV are the ongoing experiments, Stage V and Stage IV are the next and next-to-next generation of proposed experiments.

The goal of the HEP community for dark energy science has shifted from measuring the EoS parameters with greater precision to testing the ΛCDM paradigm with high-precision and high-accuracy experiments capable of significantly distinguishing between ΛCDM and other dark energy models. In this context, the new metric for comparison between dark energy experiments is the significance of the bias that could be measured between models.

In this study, we quantify this statement by estimating the statistical significance that could be achieved in excluding ΛCDM if the Universe is instead dominated by a dynamic form of dark energy (wCDM and CPL). We assume that the observational data will be typical of the proposed next generation of dark energy experiments, and that our future search and discovery programs will be efficient in identifying counterparts for the top 5-10% of the events. We showed that standard sirens alone would be able to exclude ΛCDM with significance well above 5σ c.l. in this scenario. This result bodes well for the future of multi-messenger cosmology with gravitational wave standard sirens. Observations of surprise counterparts to some fraction of stellar mass binary black holes could also further improve the constraints presented here [32].

We stress that the use of GW standard sirens is complementary to that of Supernovae as standard candles. First, by providing an absolute measurement of luminosity distance, standard sirens are free of the cosmic distance ladder systematics that are relevant in Supernova cosmology. More in general, because they are sensitive to a very different set of systematics than standard candles, they provide an independent measurement of cosmological parameters that is relevant where tensions between cosmological parameters arise (e.g. in te case of the Hubble constant tension). Secondly, XG gravitational wave detectors will provide exquisite luminosity distance measurements, with a precision down to 1%, which Supernovae are not expected to reach due to their intrinsic scatter in luminosity. As such, GW standard sirens from the Cosmic Explorer will allow us to build very precise maps of the nearby Universe, and measure the galaxies' peculiar velocity field to derive constraints on the growth of large scale structure and gravity models [33] (see Section 4 for a description on peculiar velocities from Supernovae). Moreover, observations of LISA sources will be able to extend the Hubble diagram beyond what is achievable with Supernovae (e.g. [34]).

In order to fully exploit the outstanding potential of standard sirens for dark energy research, we need to efficiently detect electromagnetic counterparts (a task requiring deep and wide imaging as well as spectroscopy). Remarkably, the bottleneck here is in the traditional cosmic survey arena instead of the GW observatories. In particular, one of the limitations to GW counterpart identification has been the lack of rapid classification of transients found through imaging. This will also be a bottleneck for time domain research from LSST more generically, beyond GW follow-up. Multi-object spectroscopy with e.g. DESI and DESI-2 will be able to provide a solution to this problem [35]. We therefore recommend that multi-object spectroscopic experiments, together with wide-field imagers such as LSST, in the future, will have a dedicated program for GW follow-up. Observations by these wide-field multi-object spectrographs can further support GW follow-up campaigns by other instruments with the observations of potential host galaxies in the GW localization region. Once the counterpart is identified, additional precision measurements of the transient can enable further characterization of the GW system geometry, which can be used jointly with GW observations to improve on the distance measurements and hence on the cosmological parameters [36, 37]. Rapid, spectrophotometric observations from a space telescope, such as the one we mention in Section 4, with a dedicated GW follow-up program, would be ideal for this task.

Already in Stage V, it will be challenging to meet those requirements with the proposed telescope facilities. In particular, because they will not provide capabilities for efficient and fast follow-up observations. Therefore, we argue that will be highly beneficial in this stage to re-purpose one of the existing 4m telescopes (e.g. DECam) as a dedicated instrument for the search and discovery of GW and other transients. In Stage VI there are no telescopes currently planned for this purpose. Based on these results, we propose that the community develops a novel standard siren survey program coordinating with the GW observatories to fully incorporate this new observable into our research portfolio for dark energy science.

3 Multi-Messenger Physics With Neutrinos

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Neutrino events detected by DOE projects such as DUNE, nEXO, LZ, Xenon1T, KamLAND, etc., as well as non-DOE projects such as Super-Kamiokande, IceCube and KM3Net, enable a range of fundamental, gravitational, and astrophysical science when associated with optical and gravitational wave counterparts. Potential high-impact measurements include the detection of possible neutrino decay, bounds on keV-mass sterile neutrinos, tests of Lorentz-invariance violation, measurements of the speed of neutrinos, and observations of neutrino interactions in high-energy environments beyond the reach of human-built accelerators [38, 39].

The optical component of the suite of multi-messenger data consists of prompt, highly-cadenced, and multi-wavelength observations that generally require triggered targeted follow-up. Obtaining these data thus requires fast access to telescopes and an accompanying infrastructure that facilitates making scheduling decisions derived from information from a diverse set of independent experiments.

The US HEP program supports surveys with large telescope time allocations equipped with wide-field ($\gtrsim 10$ sq.deg.) imaging and spectroscopic cameras that are ideal for multiplexed observation of tens of thousands to millions of potential transient sources and their host galaxies. For example, DECam has performed triggered follow-up observations of IceCube neutrino events and estimated the production of TeV neutrinos in core-collapse supernovae [40], while the highly-cadenced ZTF survey has identified a possible associations between neutrinos and tidal disruption events [38, 41]. As another case in point, DESI, through an internal secondary target time allocation, performed triggered observations [42] of IceCube event 210922A [43]. In the next decade, the combination of spectroscopic redshifts at $z \lesssim 0.3$ from surveys such as DESI with observations of cataclysmic transients from facilities like DECam and the Vera C. Rubin Observatory Legacy Survey of Space and Time will significantly improve constraints on the origins of astrophysical neutrinos [40].

The multi-messenger observations of a burst of $\mathcal{O}(10\ \mathrm{MeV})$ neutrinos from a nearby core-collapse supernova, as well as associated gravitational waves and electromagnetic radiation, present a once-in-a-lifetime opportunity to study flavor oscillation effects unique to the dense supernova core [44–46] and a range of physics beyond the Standard Model [47–50]. Matched temporal features in the fluxes of supernova neutrinos and gravitational waves from a nearby core-collapse or a distance compact binary merger would probe the speed of gravitational waves [51], and could provide a signature of the formation of a black hole [52, 53]. Finally, the observation of supernova neutrinos would provide a crucial early warning minutes to days before the detection of optical signals.

To take full advantage of the scientific opportunity of a nearby core-collapse supernova, support is needed for both theoretical modeling and follow-up infrastructure. Non-linear neutrino flavor mixing in extremely dense media is challenging to simulate but crucial to understanding the observed neutrino signal and the effect of neutrinos on the explosion itself. Similar modeling constraints apply to the current understanding of gravitational wave production in a core collapse. Follow-up observations will be coordinated through SNEWS2.0 [54], a global network of neutrino and dark matter detectors likely to detect the first evidence of a nearby supernova. Matched temporal features in the neutrino flux detected across the globe can be used to localize the direction of the supernova with participation from a large number of detectors [55–57].

We conclude:

- The Rubin LSST survey, DESI, and other cosmic frontier projects should provide target-of-opportunity allocations for the follow-up of rare neutrino (and other multi-messenger) events.
- The small-projects portfolio should accommodate support for instrumentation and facilities that provide a full suite of multi-messenger information that supports the science.
- Support infrastructure for the real-time optical follow-up of neutrino-triggered events (see §5.1).

4 New Projects for Multi-Survey Science With Rubin Observatory and other Transient Finders

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In the upcoming decade, wide-field imaging surveys, including the Rubin Observatory's LSST, will discover transients that have the potential to probe dark energy and gravity through their cosmological distances and motions. Getting those precision distances and motions often cannot be obtained from the searches alone but requires supplemental data from other targeted follow-up programs.

4.1 SNe: LS4, PV, Space

4.1.1 La Silla Schmidt Southern Survey

The La Silla Schmidt Southern Survey (LS4) is a 5-year public, wide-field, optical survey using an upgraded 20 square degree QUEST Camera on the ESO Schmidt Telescope at the La Silla Observatory in Chile. It will have first light in late 2022 and use LBNL fully-depleted CCDs to maximize the sensitivity in the optical up to 1 micron. This survey will complement the *Legacy Survey of Space and Time* (LSST) being conducted at the Vera C. Rubin Observatory in two ways. First, it will provide a higher cadence than the LSST over several thousand square degrees of sky each night, allowing a more accurate characterization of brighter and faster evolving transients to 21^{st} magnitude. Second, it will open up a new phase-space for discovery when coupled with the LSST by probing the sky between 12–16th magnitude – a region where the Rubin Observatory saturates. In addition, a Target of Opportunity (ToO) program will be able to trigger on Multi-Messenger Astronomy (MMA) events with localization uncertainties up to several hundred deg^2 in multiple colors very quickly. This project has direct relevance to several cosmology and fundamental physics efforts including: peculiar velocity measurements, and hence fundamental constraints on general relativity, with supernova as standardized candles; gravitational wave standard sirens as probes of the expansion of the Universe and gravity and measurements of the Hubble constant through Type Ia and II-P supernovae.

Why consider a shallow, optical survey in the south at a time during which it will not only overlap with the Rubin observatory, but also with the BlackGEM and DECam facilities? The answer can be broken down into several themes that form the basis of the science case for LS4. The first notion one has to dispel is that the LSST is the do-all and end-all of surveys for transient cosmology and astrophysics. The design of the Rubin Observatory and the LSST is set to achieve several goals in astrophysics, transient science being just one of them.

- *The cadence of the LSST WFD survey is not optimal for many transients.* While the reach of the LSST Wide-Fast-Deep survey is impressive, it will leave large gaps in the temporal-color light curves of cosmologically-valuable transients, including spotty early coverage when such transients need to be photometrically-screened as a precursor to spectroscopic follow-up, and gaps in the scientifically important period around peak magnitude due to saturation.
- *Not all volumes are created equally.* The follow-up capabilities of most of the world's telescopes can only handle the brighter sources discovered by the Rubin Observatory and there is a large swath of transient science in which a timely spectrum is the only path forward for new science. Moreover, nearby peculiar velocity measurements are more accurate. In addition, much of the local universe is inaccessible to the Rubin Observatory due to saturation.
- *One survey is not the path forward for cosmology and transient astrophysics.* What has become increasingly apparent in astronomy is the power of two or more overlapping surveys. This now forms the backbone of MMA as well as the desire to initiate collaborations between such surveys as Euclid and Roman with the Rubin's LSST, or the DES and DECaLS imaging surveys paving the way for spectroscopy with DESI.

To facilitate the dissemination of new transients discoveries, LS4 will stream its alerts, in near real-time, to all the major transient brokers. Coupled with the Rubin Observatory, the science of both is greatly enhanced. Examples of this include the recent detections of both pre-supernova[58] and post supernova outbursts[59, 60], in a variety of both core-collapse and thermonuclear supernovae, likely due to mass loss and interaction. While at distances < 100 Mpc, many supernovae saturate for weeks with Rubin, LS4 will accurately observe their lightcurves. Prior to explosion and several years post explosion, Rubin will be sensitive to outbursts at $M_V \leq -11$ mag. These measurements have implications for determining the progenitors of SNe, and hence can help the measurements of the cosmological parameters by removing systematic biases. Operationally, DOE scientists are well placed to aid in the discovery pipeline work, real-time alert stream as well as triggering and carrying out follow-up for several of the cosmology-focused projects. As the survey compliments several existing DOE Cosmic Frontier projects, such as DESI and LSST-DESC, DOE scientists can play joint roles in each for several of the science goals which overlap with these other surveys.

4.1.2 Spectroscopic Follow-up of Supernovae for Peculiar Velocities

Spectroscopic facilities are needed to take advantage of Rubin Observatory supernova discoveries for peculiar velocity research [61]. Spectra provide transient typing and redshifts of the $z \lesssim 0.1$ Type Ia supernovae discovered within the LSST footprint over the course of its survey. Typing (and sub-typing) is required to determine a supernova's intrinsic luminosity, which when combined with observed flux yields its radial distance. Removing the contribution of cosmological redshift (inferred from the radial distance) from the observed redshift yields the supernova peculiar velocity. This information cannot be drawn from Rubin data alone and must be drawn from other facilities.

A peculiar velocity follow-up program obtains for each supernova an $R > 100$ spectrum to obtain a redshift from the transient/host light and a transient classification. The measurement is facilitated with an integral-field-unit (IFU) spectrograph, from which contributions of the transient and the spatially-structured host galaxy can be distinguished. The program observes $\sim 10,000$ supernovae per year up to $z \sim 0.1$ with magnitudes brighter than $m < 21$ over the duration of the LSST Survey. Access to the survey area of LSST (the southern sky) is essential, though peculiar velocity science would benefit from additional northern searches and follow-up.

A baseline program that collects the above data can be scoped based on extrapolations from the exemplar SNIFS instrument on the University of Hawaii 88" telescope, which the Nearby Supernova Factory (SNFactory) experiment used to construct spectrophotometric light curves of SNe Ia in the target redshift range $0.03 < z < 0.08$. The limited number of SNe Ia that explode within the local $z \lesssim 0.1$ Universe can be followed with two 2-m class telescopes instrumented with IFU spectrgraphs that collectively monitor the observable extra-Galactic sky. Incomplete follow-up of half of Rubin discoveries with one telescope still provides unmatched measurements of the local peculiar velocity field.

One model for this program is for DOE scientists compete for instrumentation and survey time on existing telescopes, or to collaborate with observatory partners to obtain non-competitive time. DOE project responsibilities would be in contributing to the design, development, installation, commissioning, and operations of the (IFU) spectrograph. This scope of this activity would fit within the small projects portfolio.

4.1.3 Coordination of Multi-Project SN Cosmology

As discussed throughout this white paper, a wide variety of transients that can be used as cosmological probes – and that we will discover with the Rubin LSST survey – will lead to significantly more scientific results if we can obtain rapid follow-up spectroscopy and non-optical-band photometry of the transient, ideally within hours or days of the discovery, depending on the timescale of the transient's progression. Currently, we are already planning for include supernovae, lensed supernovae, and gravitational-wave-triggered optical counterparts, but we also expect other rarer and/or previously uncataloged transients to be discovered when the large surveys turn on. We therefore wish to develop multiple routes to obtaining such spectroscopic and non-optical-band followup, some of which might be directly built and/or paid for, and operated by the DOE and some of which may become available through collaborative agreements. It will be important for the US HEP collaborations to have flexibility in how they engage with other scientific teams if the best science is to be obtained, and for the DOE to be ready to support some bridging efforts and follow-up efforts that don't necessarily fall within any one science collaboration so that these efforts to get the best science don't fall between the cracks.

One particularly important bridging effort which is good to plan for early on relates to the combination of collaborations including several involving space-based telescopes. The astrophysics and cosmology community has long recognized that many, if not all, of the transients will need a sequence of observations from more than one of Rubin, Roman, Euclid, and ideally JWST, HST, or other space-based assets that can obtain UV-to-near-IR spectroscopy. Each of these sources of observations has different collaborations that the community will want to bridge.

We note here that an international space telescope specifically designed around UV-to-near-IR spectrophotometry follow-up of transients is currently being studied, and may well be an additional Rubin/LSST follow-up route. If this project proceeds, it is likely to be built and operated by philanthropic funding, but there is an opportunity for the US HEP-community to build a new collaboration to lead and manage DOE-mission science with this facility. Such a collaboration could well position itself to provide observing plans that would optimize the dark-energy science obtained, and build and run data reduction pipelines and archives – and, finally, analyze and publish the cosmology results from these transients.

Given this positive landscape for the transient science, US-HEP can also take a leadership role by putting in place and supporting a science coordination center that can help bring together the rapidly collecting data from each of the collaborations and enable the on-the-fly follow-up decision making that will need to be made by each separate collaboration concerning which targets to follow next and with what priorities and observing options. This coordination center would not by itself be part of any of the existing collaborations, although members of them could work together there, but it would make it possible for any or all of them to share real-time observations as appropriate and provide an independent "neutral" home for this work.

4.2 Time Delay Cosmography: US-ELTP and the Time Delay Machine

High cadence high precision monitoring is proposed to carry out precision cosmology with the large number of multiply imaged variable sources that will be discovered in the next decade.

Time delays between multiple images of gravitationally lensed sources such as quasars or supernovae provide an absolute direct distance measurement [62, 63]. With sufficiently large numbers (several hundreds) they can be used to determine the Hubble constant [64] and the cosmic expansion history and the properties of dark energy [65].

The wide field imaging surveys carried out by the Euclid, Roman, and Rubin Observatories will discover thousands of multiply imaged quasars and supernovae [66]. The top100 sample (e.g. 100 quadruply imaged quasars or supernovae with time delays in the range 30-100 days and with deflectors bright enough for detailed kinematics) will be selected for in depth studies. The larger samples will be available to expand the statistical power of the method based on the lessons learned from the detailed studies.

Recent experience with the Dark Energy Survey [67, 68] shows that multiply imaged quasars can be discovered in large numbers using ground based imaging data, and confirmed using existing and planned spectroscopic and adaptive optics capabilities [69]. The United Sates Extremely Large Telescope Program will be essential to provide deep adaptive-optics assisted spectroscopy to measure spatially resolved stellar kinematics of the deflectors and break the mass sheet degeneracy [64]. If the Rubin Observatories continues to carry out a time domain survey during its second decade the US-ELTP will also be crucial to take spectra of lensed supernovae and obtain stellar kinematics of the deflectors.

A crucial bottleneck will be the determination of the time delay themselves. The COSMOGRAIL [70] experiment has shown that stability and control over the schedule is a key factor in the success of any monitoring program. While Rubin might deliver 100s of quasar time delays and discovery hundreds of lensed SN over its 10-year life time [66, 71, 72], only with a dedicated telescope can one achieve single-season time delays at a few percent precision and build up the top100 sample rapidly enough to achieve breakthroughs in this decade. Control over the schedule is particularly critical to realise the promise of lensed SNe. Lensed SN time delays can be most easily measured in the first few weeks after explosion [72, 73]. Typically fainter and with shorter time delays than lensed quasars these targets require an early investment of telescope time to yield few percent precision time-delays. It is therefore important to have the ability to reallocate observing priority to a lensed SN in the rare times that a promising target is live.

The observational requirements for monitoring are millimag relative precision with daily or quasi-daily cadence, and median image quality of arcsecond or better for deconvolution of blended sources and foreground deflector. In practice, since the bulk of the top100 sources will have i-band magnitudes in the range $i \sim 20-22$, this requires a 3-4m class telescope in a good site, in order to complete the monitoring well within the decade. In terms of instrumentation, the top priority is an optical imager with field of view of $10-30'$ to capture reference stars. A non-thermal infrared channel to the imager would provide additional gains for supernovae light curves. Second priority in terms of instruments is a optical integral field spectrograph with field of view of 10-30" that would deliver redshifts for the lensed sources (especially the time critical supernovae) and nearby perturbers. Some spectroscopy will be available from surveys like DESI or 4MOST, but a dedicated spectroscopic capability will accelerate the collection of the detailed spectroscopy needed for the study of the top100 sample, and be crucial for real time spectroscopy of lensed supernovae.

The Time Delay Machine (TDM) experiment can be realized by DOE by re-purposing and managing an existing 3-4m class telescope (or a fraction of one in the North and of one in the South for full hemispheric coverage). In some cases existing instrumentation is sufficient, in others it will have to be built. A non-exhaustive list of telescopes that would be a strong foundation for TDM includes: 4.1m SOAR; 4m Blanco; 4m VISTA; 3.8m UKIRT: 3.5m NTT; 3.5m Galileo; 3.5m Starfire USAF; 3.5m WIYN Arizona; 2.6m VST; 2.6m NOT; 2.2m MPIA; 2$\times$2m LCOGT. A newly built fully robotic telescope would also be excellent of course.

5 Pan-Experiment Infrastructure

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5.1 Communication Tools, Data Access, Software

Transients as multi-experiment probes necessitate a change in paradigm for how information is shared and analysed between experiments. The Vera Rubin Observatory, Advanced LIGO & Advanced Virgo, and IceCube will provide a rich array of optical and multi-messenger transient discoveries. Their full science potential can only be realised with supplemental data from triggered observations at follow-up telescopes.

The previous generation of surveys were largely self-contained, hosting experiment-specific cyberinfrastructure to share information internally, or externally through annual (or longer) data releases. Transients were announced via Astronomers Telegrams, or the Transient Name Server typically only after the survey team had secured a spectroscopic classification, while transients that were newly discovered in images, but were as yet unclassified, were generally treated as proprietary information and never released. The Zwicky Transient Facility [ZTF, 74] changed this landscape by publicly releasing "alerts" – information on sources that have varied significantly with respect to some reference or "templat". These alerts are processed through broker systems such as the Arizona-NOIRLab Transient Alerts and Response to Events System [ANTARES, 75, 76] which allow scientists to execute their own algorithms on these alerts to find new transients from ZTF's public Mid-Scale Innovations Program (MSIP) *in real-time*, scheduling spectroscopic followup within hours with queue-based observatories such as those of the Las Cumbres Observatory.

In the coming era of multi-messenger astrophysics and the large volume of transient alerts from Rubin, there is a need for generic alert/event layered triggering system that works in real-time laterally and serially *across multiple experiments* to enable swift, efficient decision-making. While individual projects are responsible for identifying and distributing their alerts, alert clients (such as the LSST-DESC) that rely on multi-facility data need processing pipelines that handle the following elements:

- **Alerts to targets:** Broker systems interface with project alert streams and allow users to supply algorithms that identify specific targets of interest. While the broker systems exist, most do not allow users to provide their own algorithms (ANTARES is a notable exception). Efforts such as the Photometric LSST Astronomical Time-series Classification Challenge [77, 78, PLAsTiCC,] and it's upcoming successor, the Extended LSST Astronomical Time-series Classification Challenge (ELAsTiCC) are preparing the LSST community for the significant challenge posed by automated classification of the entire LSST alert stream, and driving the development of algorithms. However, much work remains to be done to optimize these algorithms *for detecting MMA events using alerts from multiple experiments*, though work has begun to combine alerts from LVK and optical surveys [El-Cid, 79] and using only host-galaxy information [GHOST, 80].

- **Human Assessment:** "Marshals" provide a platform by which collaborators can discuss and make decisions about targets. These systems have to be sufficiently general that they can be adapted to meet the needs of data from different surveys, e.g. LVK's GraceDB interface is very different from the YSE-PZ marshal system used for the Young Supernova Experiment [YSE, 81] because the nature of the data is very different. Additionally, survey scientists must be able to modify these components without the additional latency introduced by having to consult with system administrators, suggesting that the infrastructure needs to be containerized as far as possible. Given the importance, fast-evolving nature and rarity of MMA events, these marshals must also be tightly integrated with the communication tools (e.g. Slack) used by survey scientists.
- **Targets to observations:** "TOM"s combine targets with observing resources to surveys/research groups/individual investigators schedule observations. TOMs can automate the communication of the requested schedule and allow retrieving of the resulting reduced observing products. Increasingly, for the majority of sources, these observations will need to be scheduled automatically as LSST will provide more alerts for common transients than can be feasibly inspected visually, however given the rarity and importance of MMA events, we expect human inspection to always be a crucial step of the analysis of these events.
- **Identity and Access Management:** Multi-messenger astrophysics emphasizes the need to combine information from different sources and facilities to glean a complete picture of these enigmatic events, and while the alerts are generally public, value-added information added by surveys (e.g. cross-matching sources against a DESC galaxy catalog with photo-z information) may not be. Similarly, follow-up observations scheduled through TOMs are not generally public. The infrastructure needed to enable multi-experiment probes must a) accommodate users from multiple collaborations, all with their own identity providers, b) make all users aware of the existence of proprietary data sets to avoid redundant observations and c) provide a method to negotiate data rights and share information across different surveys or groups.
- **High-Performance Research Computing:** MMA data is inherently more diverse, heterogeneous and complex than observations from a single survey. Given the low intrinsic rate of these events, relative to normal transients such as supernovae, understanding the population of MMA events with data from multiple experiments will be a complex computational problem. Each experiment has custom tools and pipelines for inference with their data. To understand the demographics of the population fundamentally requires the posterior probability of several competing models, across all MMA events of a specific class like kilonovae, given all of the data. This means that any cyberinfrastructure will have to accommodate each experiment's tools, and provide a unified interface for inference in high-dimensional spaces with this complex data.

The elements of the architecture we describe above are typically considered a "data lake" in the parlance of cloud computing, and have typically been called "research platforms" within the academe. This kind of integrated cyberinfrastructure implementing a functional pipeline that is useful for Cosmic Frontier science – a data lake for multi-messenger astrophysics – requires support for development, training, deployment and operations. The same cyberinfrastructure developed for the more complex MMA data and used as a research platform by experiments such as LSST DESC will be flexible enough to address the simpler requirements of individual surveys. Implementing innovative computing cyberinfrastructure will dramatically modernize the paradigm for how scientific research is done in physics and astronomy in the 21st century.

5.2 Simulation: Digital Twins of Supernovae

Complete confidence in typical SNe Ia as cosmological distance indicators requires complete confidence in our theoretical understanding of them. This demands highly realistic explosion models verified by their use in highly realistic radiative transfer calculations that reproduce observed light curve and spectrum data. Though great progress has been made over 6 decades, complete theoretical confidence has not been reached in radiative transfer techniques (i.e., radiative transfer proper and thermal state solution techniques). Recent advancement in statistical treatment of supernova observations especially when combined with deep neural network (NN) is enabling the consolidation of extensive amount of observational data and theoretical models to construct 'digital twins' of Type Ia supernovae [82–85]. The digital twins will represent our best knowledge of each individual supernova both observationally and theoretically, which may for the first time allow for the advancement of supernova cosmology from the current purely empirically based status to the stage backed-up by first principle physics. The construction of the digital twins requires both high quality observational data and high fidelity theoretical models. Physics-informed neural networks (PINNs) is a new method that may offer significant advantages: e.g., PINNs treat mixed boundary conditions straightforwardly and they allow redundant constraints such as explicit energy conservation which may speed/enable convergence of the Lambda iteration. PINNs are a new trend in scientific computation, which takes advantage of the considerable computational advancements made by the machine learning community in order to train deep neural networks. There is now a vast high-performance software and hardware infrastructure (e.g., Tensorflow, Google Collab, github) that has been spurred by the deep machine learning revolution, which becomes directly available to PINNs applied to scientific computation problems. PINNs are meshless numerical solvers, which makes them particularly suited to high-dimensional problems in irregular domains, such as radiative transfer modeling [86].

PINNs also have the ability to integrate observational data easily, and can produce predictions with quantified uncertainty by means of Bayesian or ensemble neural network methods. In fact, PINNs offer the possibility of solving the theoretical models of each supernova as an inverse problem starting with the observational data and theoretical framework. A digital twin can be constructed by a complete simultaneous solution of the radiative transfer throughout the spacetime domain of SN Ia emission evolution for each supernova with the composition and kinematics determined to the best the observational data and our theoretical understandings may allow for.

5.3 Cosmology Data Repository

Time-domain events benefit from external data that contain value-added information about host galaxies, e.g. whether a host galaxy spectroscopic redshift is already known or whether prior photometry from other projects has seen a transient at this location. Detailed analysis of the transients may require access to large amounts of pixel-level image data for "scene modeling" while refitting the per-image point spread function (PSF) and astrometry, thus requiring more than just on-the-fly postage stamp images around the transient itself. These external data sources are currently distributed across multiple data archive centers (e.g. hosted by NSF, NASA, and ESA), complicating their large-scale and/or real-time joint use. We advocate support for a cross-site DOE Cosmology Data Repository to facilitate easy realtime access to the multiple datasets needed to support time-domain analysis combined with the computing resources necessary to analyze them, as described in Computational Frontier White Paper "Data Preservation for Cosmology" [87].

6 Conclusion

Projects supported by the US HEP community can yield powerful value-added science through coordination across existing probes and experiments, and modest investment in new projects that leverage off of existing ones. In particular, we explored the outstanding potential of standard sirens for dark energy research. We noted that the bottleneck to developing this potential is in the current cosmic surveys and facilities instead of the GW observatories. In particular, to ultimately distinguish between dark energy models, we need to develop the standard sirens methodology fully. In order to do that, we must efficiently detect their electromagnetic counterparts, which requires immediate, deep and wide imaging and spectroscopy. While it is still possible to coordinate this task with current and planned facilities, it will be challenging to meet the requirements to fully develop standard sirens as a significant probe with the proposed telescope facilities. We advocate support of

- Small Projects ($<$ \$10M) that get supplemental data that enhance the science reach of transients discovered by Rubin.
- Infrastructure that enables cross-experiment, cross-facility coordination and data transfer for time-domain astronomical sources.
- Theory/modeling that improves understanding of the astrophysical probes being used to study cosmology.
- A US-HEP multi-messenger program, supported with dedicated target-of-opportunity allocations on US-HEP facilities for the follow-up of gravitational wave and rare neutrino events.
- Re-purposing of an existing 3-4m class telescope as a dedicated instrument for high-efficiency search and discovery of GW and other transients (e.g. time delays).
- The development of a novel standard siren survey program coordinating with the GW observatories to fully incorporate this new observable into our research portfolio for dark energy science.

7 Acknowledgements

MESP is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306. AGK is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under contract No. DE-AC02-05CH11231. AP acknowledges support for this work was provided by NASA through the NASA Hubble Fellowship grant HST-HF2-51488.001-A awarded by the Space Telescope Science Institute, which is operated by Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555.

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