Astro2020 APC Project White Paper

TSO: A nUV-MidIR Rapid-Response 1.3-1.5m telescope for TDA at L2

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation

☒ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics

☒ Stars and Stellar Evolution ☒ Resolved Stellar Populations and their Environments

☒ Galaxy Evolution ☒ Multi-Messenger Astronomy and Astrophysics

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Executive Summary:
Time-domain Astrophysics (TDA), a foundation of Astronomy, has become a major part of current and projected (2020's) astrophysics. While much has been derived from temporal measures of flux and color, the real physics comes from spectroscopy. With *LSST* coming on line in 2022, with TDA one of its original drivers, the deluge of Transients and new types of variables will be truly astronomical. With multi-wavelength targeted EM surveys and multi-messenger (e.g. LIGO-international and super ICECUBE), and the possibility of full-sky/full-time X-ray imagers (see *4piXIO* APC-WP), the discovery of new Transients and Variables will flood telescopes on the ground and in space, and this just for multi-band imaging without spectroscopy. In this White Paper we briefly summarize several long-standing major science objectives that can be realized with TDA imaging and spectroscopy (nUV – mid-IR) from space. We provide a brief description of how these can be achieved with the Time-domain Spectroscopic Observatory (*TSO*), a Probe-Class mission concept that ELTs on ground and Flagship missions in space can not achieve alone.

We give a condensed summary of the *TSO* Science Objectives and description given in our *TSO* Science Overview Science WP (Grindlay+2019). We then present Technical Requirements for *TSO* to accomplish this Science and a brief Cost Estimate developed by Ball Aerospace for our Nov. 2016 proposal for the *TSO* Concept Study, with costs not inflated to 2019, but including current Falcon 9 launch cost. The Concept Study proposal was for a 1.5m telescope which we reduced to 1.3m for our Science WPs to ensure cost below the current NASA $1B cap for Probes.

Science Objectives and Urgent Need for the TSO Mission

1. *Direct detection of individual first (Pop III) stars from their core collapse GRBs. JWST* might detect a population of stellar mass black holes (BHs) (from core collapse of PopIII stars) accreting from binary companions but only by observing the strong lensing magnification of such a population in a primordial galaxy by a foreground massive cluster with a decade or more of monitoring (Windhorst +2018). Even in the unlikely case that collapse of a massive Pop III star produced a supernova (e.g. from core bounce from an intermediate neutron star), its AB magnitude would be far fainter than *JWST* could detect. As outlined in the Tanvir +2019 WP *GRBs as Probes of the Early Universe with TSO*, direct detection of Gamma-ray Bursts (GRBs) from the inevitable core collapse of PopIII stars is finally feasible with the rapid response and nearly full-sky response (to full-sky GRB triggers; see Grindlay et al *4piXIO* APC_WP) of a 1.3m telescope at L2 with imaging and spectroscopy over the 0.3 - 5μm band. The *Time-domain Spectroscopic Observatory (TSO)* is a Probe-class Mission Concept that may be the *only way to detect the existence of what surely would be a Pop III star if observed as a GRB afterglow at redshift z ≥12, a comfortable lower limit on the first Pop III stars.*

2. *GRBs at z > 6 – 10 can map the Epoch of Reionization (EOR).* This will be done by using their luminous afterglow emission to map the ionization of the host galaxy vs. local IGM as outlined by McQuinn et al. 2008. The answer is yes, but only if we have at least a modest aperture (e.g. 1.3m) cold telescope in space with imaging and spectroscopy (for prompt identification and followup) that extend to the mid-IR. Such a telescope must be able to *rapidly slew* to a large fraction of the sky, ideally ~90% which is possible from L2 as proposed for *TSO*. Within ~0.5 days of the GRB, the afterglow is bright enough (AB <23) that the GRB redshift and deep diagnostic spectroscopy (for the EOR) can be done. *JWST* cannot do this for every optically dark GRB, and certainly not within ~0.5 days. The past 14 years of GRB observations from the pioneering Neil Gehrels *Swift*

Observatory have detected 9 GRBs at z >6 from a sample of ~28% of ~1200 GRBs that are optically dark. Many of these are self-absorbed by dust in their star-forming regions, but those with low NH in their X-ray afterglow spectra are at z >7. These have not been possible to follow up (weather, scheduling) with 8 - 10m telescopes. Typical magnitude limits for J, H, K photometry are <21.5, even from 8 -10m telescopes, due to the bright OH backgrounds. The Tanvir et al WP shows this too can be done with the large sample, possibly ~100/year (full-sky) for GRBs at z >6. *GRB afterglow spectra with TSO would enable multiple sight-lines for exploration of the clumpiness of the EOR as well as its evolution with z back to Pop III.*

3. *Measuring the origin of the r-process elements.* The recent discovery of the LIGO event GW170817 and its simultaneity with a short Gamma Ray Burst showed conclusively that these are neutron star binary mergers. The prompt and followup emission also showed that the "Kilonova" event that followed was rich with lanthanides indicative that the enormous neutronization from the merger produced significant r-process element production, thereby answering a decades long endeavor to explain their abundance. The Metzger et al 2019 *TSO*-WP shows that these events could be detected out to ~10X distance with the imaging and spectroscopic sensitivity of *TSO*, thereby opening up the exploration space for r-process production well beyond the current LIGO sensitivity limits. In fact LIGO may not be required: short GRBs can be located to ~10arcsec by future wide-field hard X-ray imagers such as the proposed *4piXIO* concept so that immediate followup nUV-mid-IR imaging and spectroscopy with *TSO* can immediately discover and study Kilonovae out to ~1Gpc distances for sufficiently long exposure times.

4. *"Classic" Reverberation Mapping (RM) can measure SMBH masses back to the first Quasars at z >7.* As shown in the Shen et al *Mapping the inner structure of quasars with Time-domain Spectroscopy TSO*-WP, this can be done with a 1.3m telescope at L2 and the broad-band coverage (0.3 - 5μm) for imaging and spectroscopy (R = 200 and 1800) which would enable Hβ RM to be done and SMBH masses derived for Quasars back to z = 8. This is done by repeated spectra of a known quasar at z >7, over months and years, following a flare trigger discovered in the dense sky coverage of that quasar if in the ~2/3 sky monitored by *LSST*. The same measurements can be made on any obviously flaring quasar (at given z) or any object with colors that prompt spectroscopy to confirm it is a quasar. This enables a large sample of quasars over a range of z to be followed (with *LSST*) for RM measures SMBH mass and thus SMBHmass(z) and also the BLR(z) evolution, which in turn probe dependences on metallicity (Z) at z >3. The *TSO* 1.3m telescope at L2 provides the required deep multi-band imaging and both low and high resolution spectroscopy. AGN flaring studies also include TDEs from both quiescent and active AGN.

5. Understanding the mysterious Red Transients discovered in the Spitzer InfraRed Intensive Transients Survey (SPIRITS), including 64 very luminous IR transients (SPRITES) with no optical counterparts (Jencson +2019 *TSO*-WP).

Many other variables (exoplanet transits, PMS stars, …) can be studied with *TSO*. It provides a unique capability to rapidly respond with both photometry and spectroscopy in 4 bands, simultaneously. This is not possible with *JWST* or *WFIRST* which both have >1day response times and then only to (much) more limited sky than the 90% possible with *TSO* at L2. The broad wavelength range cannot be done from ground, and the nIR to mid-IR sensitivities are exceptional without OH background, and the Zodi-limit backgrounds enabled by the cold mirror (110K).

Description of the proposed Probe-Class Time-domain Spectroscopic Observatory (*TSO*)

TSO was proposed as a Probe-class mission concept for study in the 2016 proposal call but not selected, in part because its predecessor the InfraRed Telescope on the *EXIST* mission proposed for Astro2010 had been studied. *TSO* is now a streamlined and easier to build (as Probe) than the IRT. The telescope and focal plane parameters are given in Table 1. The telescope is designed with significant baffling to permit maintaining the radiatively-cooled primary, secondary mirrors and optical bench at T = 110K for pointings ≥30^{o} from the Sun. Slews of up to 180^{o} can be done in ≤8 min to permit rapid acquisition of GRBs. The telescope would be placed at L2 for 90% sky access (or in a Geosync orbit over *LSST* for 80%), with provision for rapid command uploads for either.

Table 1: Telescope	1.3m R-C
FoV (arcmin)	8 x 8
Imaging detectors	2x2 H2RG
Pixel size (arcsec)	0.25
Imaging/Spectra bands	4 (parallel)
4 Bands(μm): 0.3-0.73-1.38-2.63-5.0	

The schematic layout of the focal plane is shown in Fig. 1. The incoming telescope beam is directed to either low-resolution (R = 200) IFU optics to provide spectra in an array of 10 x 10 pixels (0.25”) around the central object, OR, if target is bright enough (AB <23) to a high resolution grating for R = 1800 spectra. Images in each of the 4 bands (Table 1) between 0.30 – 5.0μm are obtained in the 4 H2RG image planes as shown for one such band in Fig. 2. This provides a very powerful combination of imaging and spectroscopy that extends from the nUV to mid-IR, as needed to carry out the science objectives of *TSO*. AB mag sensitivities vs. exposure time for imaging vs. spectroscopy are given in Table 2.

Table 2. *TSO* AB mag sensitivities vs. T_{exp}			
Operating Mode vs. T_{exp} =	10^3 s	10^4 s	10^5 s
Imaging (*each of 4 bands*)	25.5	27	28
IFU (R =200) spectra (“)	22	24	25.5
Slit (R =1800) spectra (“)	19.8	21.7	23

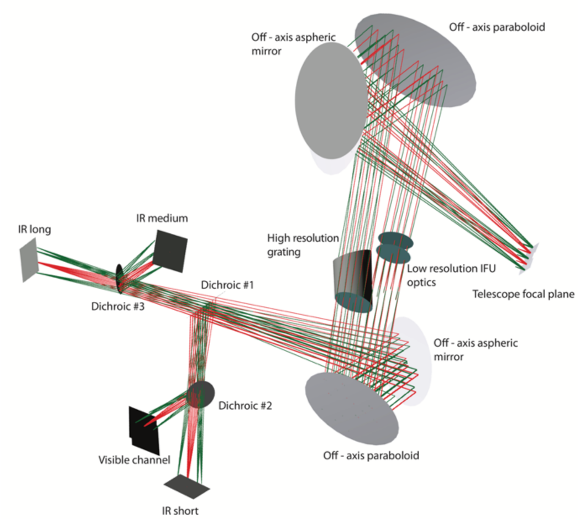

Fig. 1. Optical design of the *TSO* focal plane for imaging and spectroscopy in each of the 4 bands (simultaneous) in Table 1. Spectra are either IFU (R = 200) or grating (R =1800).

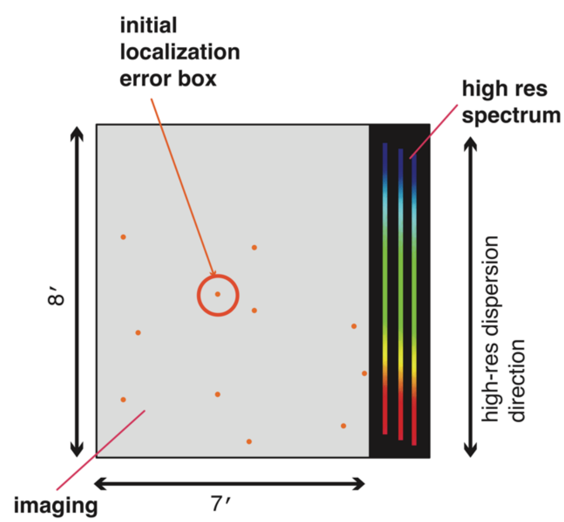

Fig. 2. The IFU provides initial R = 200 spectoscopy and spatially resolved (10 x 10 0.25” pixels) spectroscopy for the GRB and host or target to enable hi-res spectroscopy with a 0.5” slit.

Telescope and Instrument Requirements for TSO

In order to meet the primary Science Goals 1 – 5 for *TSO*, as well as the many secondary science goals too numerous to describe here, we require a Telescope and Instrumented focal plane that can meet the requirements given in Table 3. For Science Goal #1, Fig. 2, constructed for the *TSO* design and instrument described below, shows that spectra of GRBs with redshifts z ≥ 6 – 8 requires a ≥1.5m telescope in space with mirrors and focal plane optics radiatively cooled to T ≤ 150K, the band 3 limit for Zodiacal light backgrounds. While GRBs from Pop III stars at z ~20 would require spectral coverage (for Lyman break) out to λ ~ 2.5μm, or mid-band 3, all other Goals require (or benefit from) coverage through band 4. To maintain ~constant AB mag sensitivity out to 5μm (band 4) and be Zodi-background limited, requires telescope and instrument temperatures ~110K, which is the adopted requirement for *TSO*. The telescope must be able to access (at any instant) ≥ 80% of the full sky to maximize the number of high-z GRBs that can be measured from full-sky imaging 3-200 keV telescopes with <15" GRB positions (>10σ detections) as could be realized with a Constellation of 2 SmallSats (*4piXIO*). [An Engineering Model for a single ¼ scale detector plane is currently under development (Grindlay+ 2019b).] Even with *Swift* and the 2021 launch of the French-Chinese mission *SVOM*, ~20 – 30% of the sky will be imaged with GRB positions ≤3 arcmin (vs. ~15% with *Swift* alone). This sets the required *TSO* imaging FOV (6' x 6'), to fully contain SVOM error boxes if GRB is not detected by *Swift*/XRT. TSO cannot operate in LEO, with <25% of sky available to a telescope that must be pointed >30^{o} above the Earth limb to maintain radiative cooling, and so must be either in a Geosynch orbit (GEO) or at L2. The specified Required Number of GRBs at z >7 – 8 is based on the EoR patchiness modelling of GRBs of McQuinn+ 2008 for determining ionization fractions x_H from fits to the damping wings of Ly α.

Table 3: TSO Telescope and Instrument requirements (per target observation)

Science Goal	**No. Req. Images/Target**[1]	**Critical Bands**[2]	**Pos. δ for IFU**[3]	**δ,AB for R200 Spectra**[3,4]	**δ,AB for R1800 Spectra**[3,4]	**No. Req. Targets**
1. GRBs @z >7-8 as Probes of EoR	1-9 @300 s (6' x 6' ea.)	1 (dropouts) - 3 (and 4)	1" ≤ δ ≤3"	δ <1", AB ≤ 25	δ ≤0.3", AB ≤ 23	≥30 - 300
2. aLIGO IDs (NS-NS, NS-BH)	1-10 @10^4 s	1 - 4	1" ≤ δ ≤3"	δ <1", AB ≤ 25	δ ≤0.3", AB ≤ 23	≥10 - 100
3. SMBH $M_\odot(z)$	1-10 @10^4 s	1 - 4	1" ≤ δ ≤3"	δ <1", AB ≤ 25	δ ≤0.3", AB ≤ 23	≥100
4. TDE $M_{BH\_vs\_gal}$	1-10 @10^4 s	1 - 4	1" ≤ δ ≤3"	δ <1", AB ≤ 25	δ ≤0.3", AB ≤ 23	≥100
5. IR transients	1-10 @10^{2-4} s	1 - 4	1" ≤ δ ≤3"	δ <1", AB ≤ 25	δ ≤0.3", AB ≤ 23	~1000

Notes: 1. ID object by dropout or variability

2. Bands in Table 1

3. Align target on IFU

4. Align target on 0.3" slit

The overall design of TSO and its focal plane borrows significantly from, but greatly extends, the design for the Infrared Telescope (*IRT*) that was part of the *EXIST* mission concept as proposed to the Astro2010 Decadal Survey (Grindlay+ 2010). A technical description of the *EXIST-IRT* is given by Kutyrev+ 2010. The LEO orbit proposed for *EXIST* vs. the GEO or L2 orbit required for *TSO*, as well as the extended wavelength range (0.6 – 5.0μm for *TSO*, vs. 0.4 – 2.4μm for IRT) require many important details to be studied. However, our prior work for IRT enable us to be confident that the basic design features for *TSO* and the overall mission can be achieved.

The *TSO* telescope is a 1.5m Ritchey–Chrétien that would be designed, built and tested by Ball Aerospace, who did the same for the 1.4m Kepler mission. The major difference from Kepler is the need to operate the telescope mirrors, optical bench, and instrument components (dichroics, grisms, mirrors and lenses) all at radiatively cooled and stable (with servo heaters) of 110K. The telescope and its baffle with 30^o scarf angle that permits pointing and stable temperature control at angles $>30^o$ from the Sun, which enables 93% sky coverage (!) from L2 and 85% sky coverage if a 45^o Sun offset limit is chosen. Preliminary studies have shown this is possible, with no technical innovations needed. However, many details and some choices require Study.

***TSO* Mission Requirements**

In Table 4, we summarize the Mission Requirements and associated Telescope and Instrument Requirements (not explicitly called out in Table 3).

***Table 4*: *TSO* Top-Level Mission Requirements are Well-Defined and Derived from Science Objectives (as derived in 2016 Concept Study proposal)**

Mission Requirements	
Launch Date	2028 for maximum overlap with *LSST* (2022-2032)
Mission Lifetime	5 years (Design lifetime); thruster fuel for 10y if Mission extended
Orbit	Sun-Earth L2 (or Geosynchronous)
Pointing Control	IRU + Fine Guidance Sensor within instrument
Pointing Stability	0.03 arcsec over 1000 s
Absolute Pointing vs. Ref. stars	0.02 arcsec
Instantaneous Sky Accessibility	≥ 85% (L2) or ≥ 65% (GEO) of full sky at all times **Note 1**
Slew and Settle Time	<8 min [TBR] to any accessible target location
Telecom – Science Downlink	Ka-band to White Sands ground station
Telecom – Uplink	<3 min for commanding of transient events (24/7)
Data Production Rate	50Mb per exposure; minimum exposure time typically 300s

Data Compression Ratio	4:1
Data Storage	10 GB
Telescope Thermal Control	Telescope passive-radiation cooled 110K with servo heater control
Detectors Thermal Control	4 x H2RG Detectors @ 75K with Cryocooler
Telescope and Instrument Requirements	
Telescope Diameter	1.5 meter
Telescope Design	Ritchey–Chrétien
Focal Plane Field-of-View	6 arcmin x 6 arcmin
Focal Plane Pixel Scale	10μm pixels
Wavelength Range	0.6 μm – 5.0 μm
Telescope Temperature	110 K (radiatively cooled mirrors, optical bench; htrs maintain ±0.5K)
Telescope opt. bench Htr. Pwr.	TBD in Study
Detectors	4 x H2RG HgCdTe Teledyne detectors each with 10μm 2K x 2K pixels
Detector Temperature	≤55 K (Cryocooler)
Integration Time	300s – 10ksec (typical range)
Observation Mode: Image	Pointing; small offsets for fine adjustments (<1arcsec) from acqusition
Observation Mode: Spectra	Pointng: target directed on F.P pos. 2 or 2a (R200) or 3 (R1800)
Detector Readout	TBD in Phase A Study
Detector Power	3 x IR FPA+Sidecar: 0.4W; 1 x VIS FPA+Sidecar: 0.1 W -- TBD
Detector Associated Power	Main Electronics Box: 66W; Heater Pwr Supply: 67 W -- TBD

Notes: 1. Sky coverage depends on minimum Sun avoidance angle. Values in Table assume conservative 45^{o} limit. For 30^{o} limit (which yields stable mirror temperatures), values are ≥ 93% (L2) or ≥ 76% (GEO).

The *TSO* telescope and location in fairing is shown in Fig. 10 with the thermal shield visible on the back side of the telescope. The shielding concept between the solar array and the telescope and between the telescope and the spacecraft was effectively used for the *Spitzer* Telescope design. The struts mounting the telescope to the spacecraft are made of gamma-alumina to reduce the parasitic conductance of heat into the telescope.

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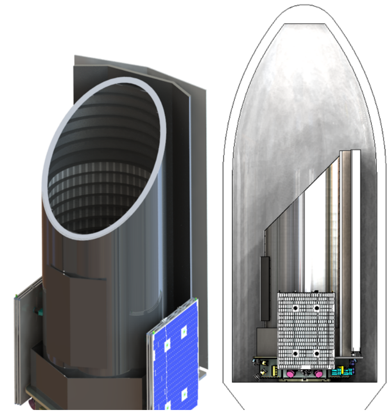

Fig. 3: *TSO* and spacecraft, shown here with a 45^{o} scarf for minimum solar avoidance, easily fits within the Falcon 9 fairing and is designed to meet all TSO science requirements. A 30^{o} scarf on the

TSO Mission Operations and Interface to LSST

How would *TSO* operate? For GRBs (Science Goal 1; hereafter SG1), it is obvious: as described above within 3 min of a GRB trigger (*Swift, SVOM* or followon missions with <3' positional capability), a slew would be initiated and completed. This operational goal will be reviewed in this Study. As indicated in Table 1, there would be either initial imaging (target position, uncertain by δ ≤3' is centered in the ~6' imaging FoV, Fig. 8, or either R200/objective prism spectra for δ ≤30" to accurately measure the GRB position. Before proceeding with R = 1800 spectra if the object is brighter than AB ~22-23, on board decisions would be made: 1) if the object is not detected in Band 1, but is Band 2 and above, it immediately becomes highest priority and is followed with successive R200 or R1800 spectra (1ksec, initially; then increasing to 3ksec and eventually perhaps longer (to be Studied; hereafter TBS) as the object fades. For objects with z < 6-7 (determined on board; TBS), but z > 3, these will be observed by GO programs that have proposed for them and in general would be followed for up to 3 hours (TBS) for Legacy programs.

All other high-priority external trigger programs (e.g. LSST scanning of ALIGO/VIRGO error boxes with tentative candidates), would be scheduled for the same prompt followup as GRBs although in some cases delays of up to ~1 day might be acceptable. On board scheduling software (TBS) would handle this following (of course) initial operations testing. The scheduling for essentially all other *TSO* observations of ongoing TDA programs (e.g. the SG3 program for RM-monitoring of AGN with variability triggers from LSST) would be scheduled in GO-based priority order at a *TSO* Operations Center as shown in Fig. 1. The *TSO* mission would then operate much like *Swift* or *Kepler*, responding to prioritized TDA events from the deluge of candidates produced by LSST and all other fast transient telescopes or facilities, and as proposed by GO programs.

The ***interface of TSO to*** **LSST** is a key part of *TSO*. The Large Synoptic Survey Telescope (LSST; http://lsst.org) will survey approximately 10,000 deg^2 of the sky every few nights in six optical bands from 320 to 1050 nm (Ivezic+ 2008). Over the planned 10-year baseline survey, it will uniformly and repeatedly image about 18,000 deg^2 of the sky over 800 times. The rapid cadence and scale of the LSST observing program will produce approximately 15 TB per night of raw imaging data. The large data volume, the real-time aspects, and the complexity of processing involved makes it impractical to defer the data reduction to the LSST end-users. Instead, the data collected by the LSST system will be automatically reduced to scientifically useful alerts, catalogs, and images by the LSST Data Management system (Juriic+ 2015). These products are designed to be sufficient to enable a large majority of LSST science cases, without the need for raw pixels.

Estimated *TSO* Mission Cost (from 2016 Concept Study Proposal)

In Table 5 we provide a rough mission development and science operations (Phase A – E) cost estimate. The Telescope cost and spacecraft and I&T were derived from scaling actual costs for development of the 1.4m Kepler telescope and spacecraft. As mentioned above, costs were scaled for the proposed 1.5m aperture of the *TSO* telescope. This produced a total estimated cost of $918M (including Reserves) which the *TSO* team regards as too close to the current NASA $1B limit for Probes (although the Astro2020 guidelines define a "Medium" class mission as $0.5M - $1.5M. Accordingly, we scaled back the telescope design to 1.3m (which lowers sensitivities by ~0.35 magnitudes) in our Science WPs. This reduced telescope cost is not included in this Table and the costs are given in FY18$, not FY20$. These two corrections may partially offset each other, so we provide this estimate as it stands. The cost number for the launch is likely OVER-estimated: a recent NASA purchase of a Falcon 9 launch for the DART mission (to an asteroid) was $69M. If we apply this value to correct the cost total in Table 5, the current best estimate for a 5 year *TSO* mission becomes $837M, which may still be an overestimate given that the reduction from 1.5m to 1.3m has not been included.

Table 5: Estimated cost for *TSO* as a 1.5m cold telescope derived Nov. 2016

<table>
<tr><th>WBS</th><th>Description</th><th>Estimate FY18$</th><th>HQ Example</th></tr>
<tr><td>1, 2, 3</td><td>PM/SE/MA</td><td>$ 77</td><td>$ 40</td></tr>
<tr><td>5</td><td>Telescope & Instrument</td><td>$ 205</td><td rowspan="2">$ 460</td></tr>
<tr><td>6, 10</td><td>Spacecraft + System I&T</td><td>$ 180</td></tr>
<tr><td>4, 7, 9</td><td>Pre-launch Ground & Science</td><td>$ 51</td><td>$ 60</td></tr>
<tr><td>4, 7</td><td>Phase E (5 years)</td><td>$ 77</td><td>$ 75</td></tr>
<tr><td>8</td><td>Launch Vehicle</td><td>$ 150</td><td>$ 150</td></tr>
<tr><td></td><td>Subtotal</td><td>$ 740</td><td>$ 785</td></tr>
<tr><td></td><td>Reserves (30% excluding LV)</td><td>$ 177</td><td>$ 215</td></tr>
<tr><td></td><td>Total</td><td>$ 918</td><td>$ 1,000</td></tr>
</table>

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