The Time-domain Spectroscopic Observatory (TSO)

White Paper for an Astrophysics *Probe-Class* Mission Concept

P.I. Prof. Jonathan Grindlay
Harvard University, Center for Astrophysics, josh@cfa.harvard.edu , 617-495-7204

Co-I's: E. Berger, G. Djorgovski, N. Gehrels, P. Green, F. Harrison, D. Hartmann, S. Kahn, A. Kutyrev, B. Metzger, G. Melnick, H. Moseley, B. Peterson, G. Rieke, N. Tanvir, T. Tyson, & Z. Ivezic

Summary: A *Time-domain Spectroscopic Observatory (TSO)*, enabled by a 1.5m OIR (0.4-5μm) telescope in Geosynch orbit above *LSST*, will reveal the time-domain astrophysics from the deluge of *LSST* transients and current and future wide-field surveys. Of particular importance to Astro2010 and (likely) Astro2020 objectives, TSO would provide the sensitivity and rapid response to at long last identify optically "dark" long GRBs at z > 6 as probes of the rates of star formation and growth of structure during the entire Epoch of Reionization (EOR, z ~6 – 20) in response to GRB triggers from current and future imaging GRB missions. By providing near simultaneous spectroscopy with nightly *LSST* survey measures of AGN flares on enormous samples of AGN out to z ~7, *TSO/LSST* will measure the SMBH *M-sigma* relation and growth of SMBH masses over cosmic time. *TSO* enables low-cost continuous data/commanding and ≥TRL-6 telescope/instrument systems at known cost.

Spectroscopy is the key to the physical understanding of astrophysical systems. The *Time-domain Spectroscopic Observatory (TSO)* would serve the rapidly growing field of Time Domain Astrophysics (TDA), for which time-critical spectroscopy is needed for fields from Exoplanets and Galactic black holes to cosmologically distant GRBs. A dedicated imaging and spectroscopy telescope that can provide continuous and/or immediate response must be in space, where the sensitivity increase (per unit area telescope aperture) is particularly significant in the ~0.8 – 2.2μm band by the lack of OH airglow backgrounds and the sensitivity gains by modest radiative cooling of the telescope. *Spectroscopy (R = 5) for a 1.5m TSO is ~10X more sensitive than imaging (R =1) in the J,H,K bands is for the 8.4m Subaru telescope* (Fig. 1) or VLT. Key *TSO* telescope, instrument and mission parameters and heritage are given in Table 1. The focal plane and detector design is based on the extensive studies (Kutyrev+2010) for *EXIST* for Astro2010. Design studies were also done for the radiative cooling of the optical bench and 1.1m IRT proposed for *EXIST*. The *TSO* mission operations design is particularly advantageous, given the continuous LOS data/commanding link that would be available to White Sands from the *LSST*-longitude Geosync orbit. Mission operations for this purely point-and-stare mission include semi-autonomous target

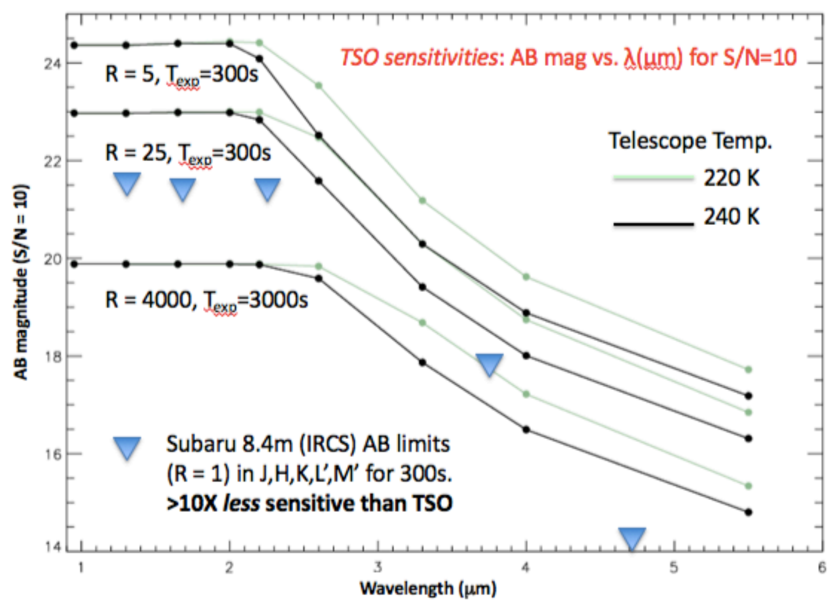

Figure 1. *TSO* sensitivity (S/N=10) vs. resolution R and Texp.

Table 1. Parameter	*TSO*	Heritage
Spectral range	0.4 – 5μm	*JWST*/NIRSPEC
Spectral resolution	R = 5, 25, 4000	*EXIST*/IRT study
Imaging detector	H2RG/HyViSi arrays	NIRSPEC
FoV; pixel resolution	5 x 5arcmin; 0.15arcsec	NIRSPEC
Telescope; rapid slew	1.5m R-C, rad.cooled -50C	*Swift, JWST*
Orbit	Geosync.; over *LSST*	Commercial

selections from real-time *LSST, Swift, LIGO…* triggers and pre-planned targets. Our estimated total mission cost, including a Falcon 9 launch, 5y of operations and a Guest Observer program, is $650M. The telescope would use a light-weighted Schott Zerodur "space mirror", and the focal plane imager-spectrograph and rapid-slew spacecraft (for GRBs) are well understood (Table 1). Major *TSO* science objectives include:

Measuring the Growth of Structure and Star Formation Rate in the EOR. Only ~30% of *Swift* GRBs have redshifts due to the inadequacy of ground-based rapid response spectroscopy and nIR sensitivity. The highest spectroscopic redshift GRB at z = 8.2 (Tanvir+2009) was recorded (R = 500) with VLT/ISAAC ~17h after the burst with marginal S/N. This same event could be measured at 8h (if Earth blocked) by *TSO* with R = 4000 at z = 15. With a conservative 90% redshift yield from *TSO*, the *Swift* 10y sample of 5 GRBs at z >6 would be ~20, including the ~22% contribution of "dark" bursts at z >5 (Greiner+2011). With a future 4π sr imaging X-ray (and GRB) SMEX mission instead of the 1.5sr FoV of *Swift/BAT*, the total would be ~200, or ~20/year. These numbers increase to >30/year if GRB imagers with sensitivity 3-200 keV provide the GRB triggers. Over its 5y mission, *TSO* can then measure the damped Lyα profiles of ~150 GRB host galaxies at z >6 with R = 4000 spectroscopy to measure the neutral vs. ionized H fraction in the host galaxy vs. local IGM and thus trace the EOR vs. z, as proposed by McQuinn+2008. Just as exciting, the distribution of GRBs vs. z would measure the star formation rate SFR(z) for z ~6-15. Even *JWST* cannot trace supernovae, or galaxies, over most of this range.

Measuring the Growth of Supermassive Black Holes over z = 0 - 7: The intended synergy with *LSST* allows *TSO* to make another fundamental contribution: measure the supermassive black hole (SMBH) mass spectrum over z = 0 – 7. This is enabled by the *essential* spectroscopic capability to continuously track and measure AGN spectra of a large (>$10^{3\text{-}4}$) sample and derive SMBH masses by reverberation mapping (Peterson 2014) of AGN flaring by timing the response of the broad line region (BLR) spectrum and line widths (*TSO*) to optical flaring from the central SMBH (*LSST*). *LSST* with its ~3day cadence to return to a given patch of sky for ~8months over its 10y lifetime, will measure truly enormous samples of AGN and their flares. All classes, from Seyfert II's to luminous FSRQs (with BLRs) are included so that SMBH mass vs. host morphology and SFR can be separately studied vs. z. *TSO* absorption line spectra beyond 1μm will constrain galaxy masses and metallicities where the AGN continuum falls off. Even Compton-thick AGN can be measured (*TSO* Br-γ vs. z,y *LSST* magnitudes).

Discovering EM counterparts to *ALIGO* NS-NS and NS-BH mergers: In the era of *TSO*, the *ALIGO, AVIRGO,* and *KAGRA* gravitational wave telescopes will detect many BH-BH mergers (GW150914) and neutron star (NS) mergers with NSs and BHs. NS mergers produce SGRBs and kilonovae with optical/IR signatures (Metzger and Berger 2012) as likely detected just after SGRB130603B. In response to a *ALIGO-AVIRGO* (at least) trigger, *LSST* could do a ~3-5h raster imaging search of the ~30-100 deg^2 gravitational wave error box and find the predicted (more rapid decay in blue than red than IR; Kasen+2015) lightcurves arising from a lanthanide-rich disk wind of neutronized material ejected from the merger. *TSO* spectra would measure wind velocities and composition to probe the merger physics, NS equation of state, and constrain the progenitor system as NS-NS vs. NS-BH.

From exoplanets to stellar black holes and tidal disruption in galactic nuclei: With the *TSO* sensitivity and thus speed ~10X that of Keck or VLT at ~1 - 5μm, there are numerous new opportunities. *Exoplanets* in habitable zones around M dwarfs can have their transit spectra stacked to search for H_2O (1-4μm) and CO_2 (1.5-4.5μm) absorption features, and debris disk spectral variability probes terrestrial planet building. *SgrA* flares and quiescent BH-LMXBs vs. magnetic CVs* producing the "diffuse" hard X-ray emission in the Galactic Center region (Perez+2015) can be distinguished with *TSO* spectra, as can *Tidal Disruption Events vs. SNe* in obscured galactic nuclei. If a detailed design study shows the rapid-slew *TSO* telescope can be cooled to ~150K rather than the (conservative) 220K or 240K shown in Fig. 1, the AB sensitivities at 2μm extend flat to 5μm. MgII in galaxies is then detectable for GRB afterglows at z = 15, and Hβ line widths for SMBH masses at z = 9.

References: Greiner+2011, A&A, 526, A30; Kasen+2015, MNRAS, 450, 1777; Kutyrev+2010, Proc. SPIE, vol. 7731, 77311Z; McQuinn+2008, MNRAS, 388, 1101; Metzger & Berger 2012, ApJ, 746, 48; Peterson 2014, Sp.Sci.Rev., 183, 275; Perez+2015, Nature, 520, 646; Tanvir+2009, Nature, 461, 1254