High Time Resolution Astrophysics (HTRA) with the E-ELT

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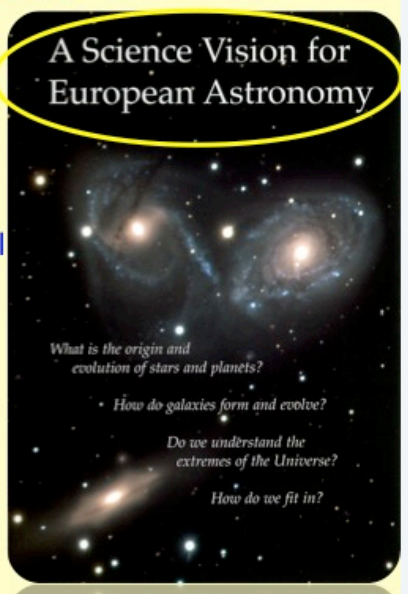
Abstract: Astrophysics in the high-time resolution domain, or High Time Resolution Astrophysics (HTRA), studies a variety of phenomena on milli- and microsecond scales, such as pulsations from rotating neutron stars, giant pulses in rotation-powered pulsars, radio/X-ray bursts in magnetars, and quasi periodic oscillations in black hole binaries. These are the fastest phenomena yet observed in astrophysical objects. Many of them can be detected also in the optical/infrared and studied with adequate instrumentation. The unprecedented light-collecting area of the E-ELT will produce very large photon fluxes that will enable novel studies of very rapid source variability. In this poster, we present some of the HTRA scientific drivers in support of high time resolution facilities at the E-ELT and introduce novel instrument concepts based on quantum detector technology.

Why is HTRA important?

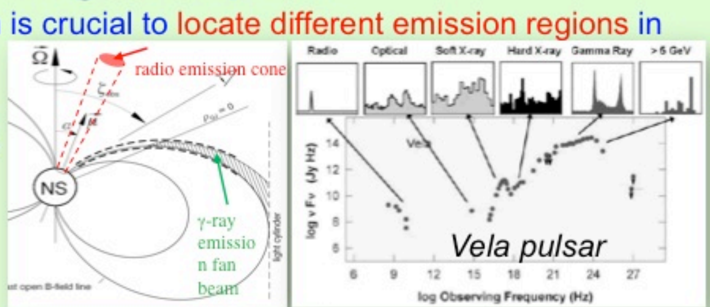
"Time is the only Astrophysical Quantity that we can measure down to (almost) absolute accuracy ..."
(D. Bersier, Liverpool Johnes Moores University)



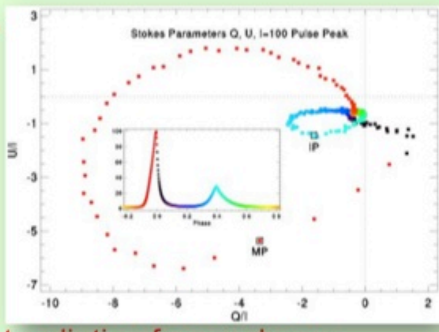
- Astronet's Panel A, developing *A Science Vision for European Astronomy*, identified 6 fundamental questions in the area of extreme physics:
  - *How did the universe begin?*
  - *What is dark energy and dark matter?*
  - *Can we observe strong gravity in action?*
  - *How do supernovae and γ-ray bursts work?*
  - *How do black hole accretion, jets and outflows operate?*
  - *What do we learn from energetic radiation and particles?*
- HTRA addresses at least the last 4 questions
- HTRA science covers a wide range of science topics and science targets, see Shearer et al. (2010), White Paper on HTRA

Pulsar Magnetosphere

- Timing at multi-wavelength is crucial to locate different emission regions in the neutron star (NS) magnetosphere (*left*) from the difference (phase shift, morphology) in the pulse profiles (*right*).



- Phase-resolved optical polarimetry of the Crab pulsar shows that the values of the Stoke parameres (I,Q,U) varie along the pulse phase (Slowikowska et al. 2009; *bottom*)
- Test of magnetosphere models and geometry

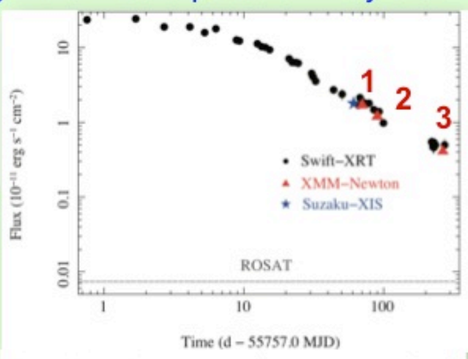


- Giant Pulses, erratic variation of the peak pulse intensity, are only observed in radio and in the optical (Shearer et al. 2003; Collins et al. 2012), where they occur simultaneously. So far, they were observed in the Crab pulsar only.
- Test relation between coherent and incoherent radiation from pulsars

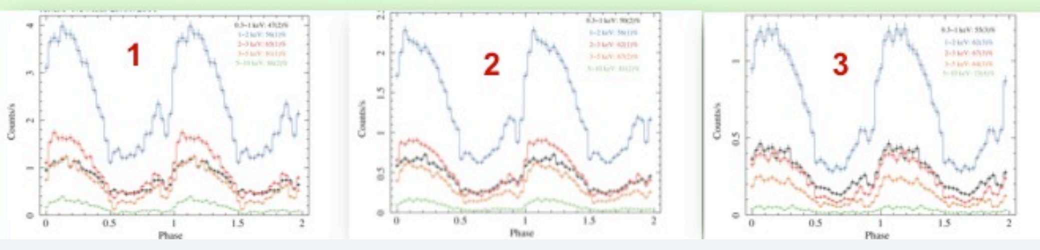
X-ray Bursts and Giant Flares in Magnetars

- Impulsive events produced by magnetars, isolated neutron stars with magnetic fields of up to 10^{14} G, ~100 stronger than radio pulsars. They are mostly radio-silent, but are detected as X-ray pulsars

- X-ray pulsation profile change after an X-ray burst or Giant Flare, likely associated with twists in the magnetar magnetosphere. Therefore, multi-wavelength timing of magnetars is crucial to track twists in the magnetosphere.
- Since most magnetars are radio-silent, timing is usually done in the X-rays and optical/infrared

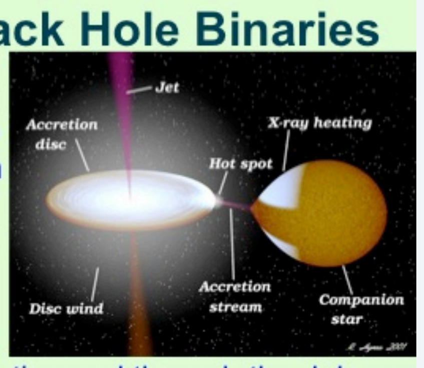


Top: X-ray light curve of the magnetar Swift J1822.3-1606 in outburst (Rea et al. (2012) and changes in the pulse profile (bottom)*

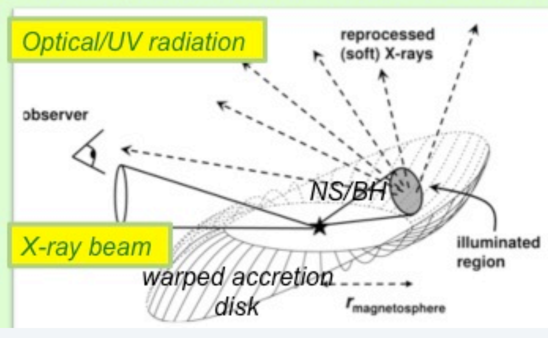


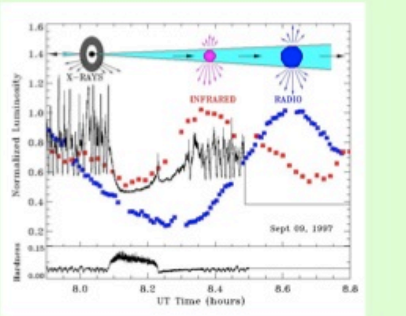
Accretion in neutron star & Black Hole Binaries

- X-ray ms/s pulsations and quasi periodic oscillations (QPOs), detected in NS/BH binaries, plus erratic variability, allow one to test accretion physics and directly probe the motion of matter in the accretion disk close to the NS/BH



- Optical/IR variability probe external parts of the disk allows one study the companion star irradiation and through the delay wrt X-ray light curves, track disk instabilities, obtain information on its structure (warps), albedo, inclination, size (*below, left*), X-ray emission geometry, follow the formation and propagation of jets (*below, right*).

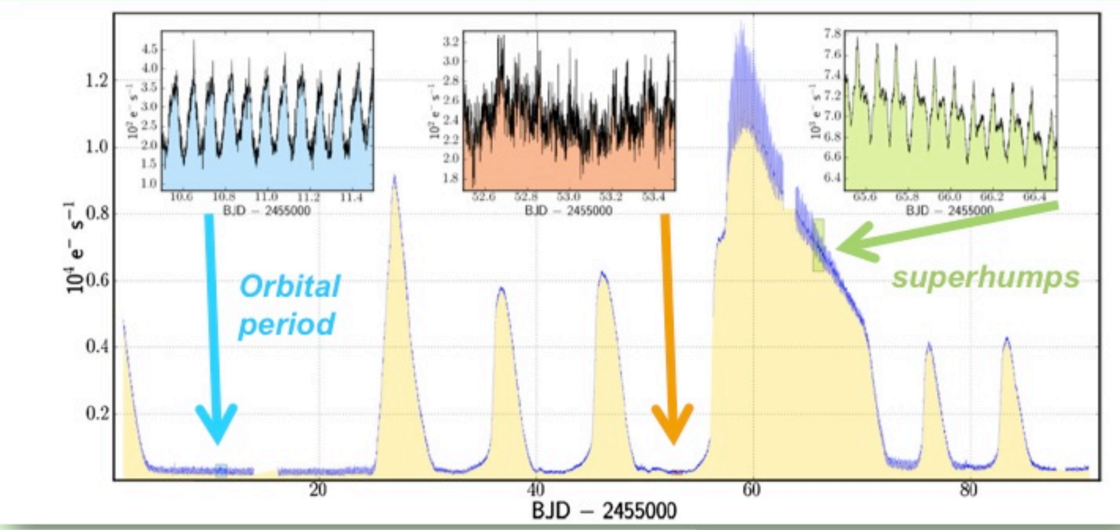




Cataclismic Variables & Ultra Compact Binaries

- Spin periods 10-1000s
- Orbital periods minutes-hours
- Pulsations periods 100s
- Dynamical timescale 1-10s
- Eclipses 10-1000s
- Accretion variability 1s

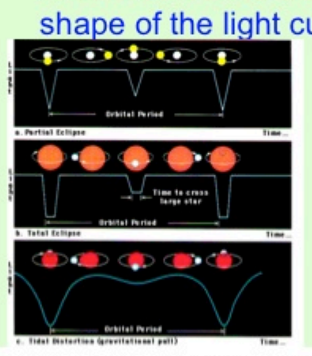
Optical/infrared variability allows one to study accretion phenomena, such as unstable accretion regimes and tidal phenomena

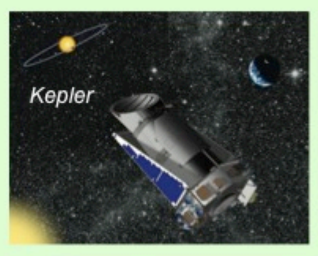


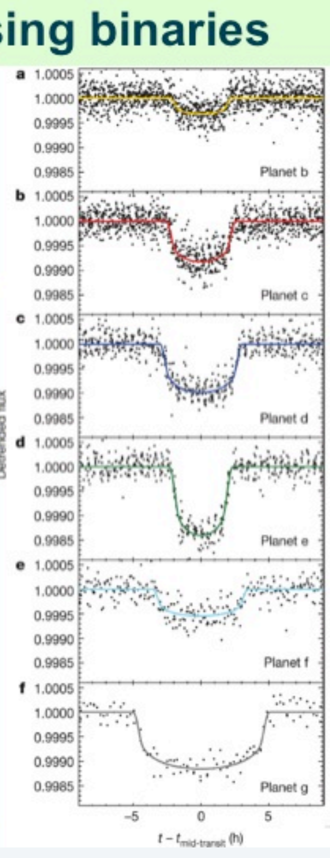
Top: Kepler light curve of the Dwarf Nova V334 Lyr (Still et al. 2010)

Transits in exoplanets and eclipsing binaries

- Diameter of the occulting body (star, planet) and system inclination are derived from the shape of the light curve, i.e. transit depth and width (*bottom left*).
- Star masses are inferred from radial velocity curves
- The presence of rings orbiting the occulting body are derived from dips before and after the occultation.
- Scale heights, temperatures, chemical composition and extinction of the planet/star atmosphere from the shape of the light curve and spikes.



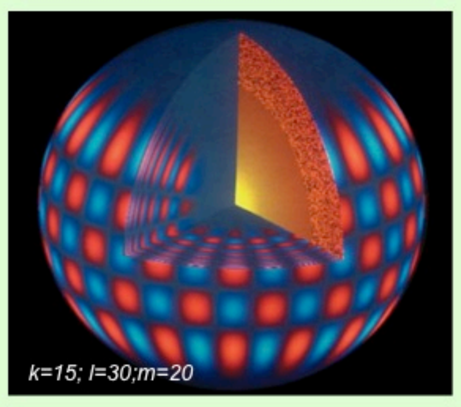


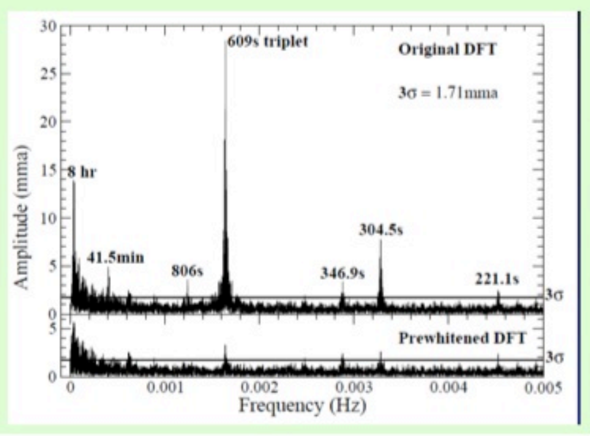


Right: Close-up of the transit of the six planets in the Kepler 11 system. Light curves are folded with the planet orbital period.

Asteroseismology

- Large-amplitude long-period variability in bright stars are recognised as pulsation produced by excitation of one or more normal modes. The coexistence of many modes, each propagating along a unique path in the stellar interior, allows asteroseismology to reveal stellar structure. Since pulsation occurs on a dynamical timescale, they require high time resolution techniques to be observed in compact stars (WD~minutes; NS<0.1s).
- Frequency spectrum allows one to study complex non-radial oscillation modes in the star interior

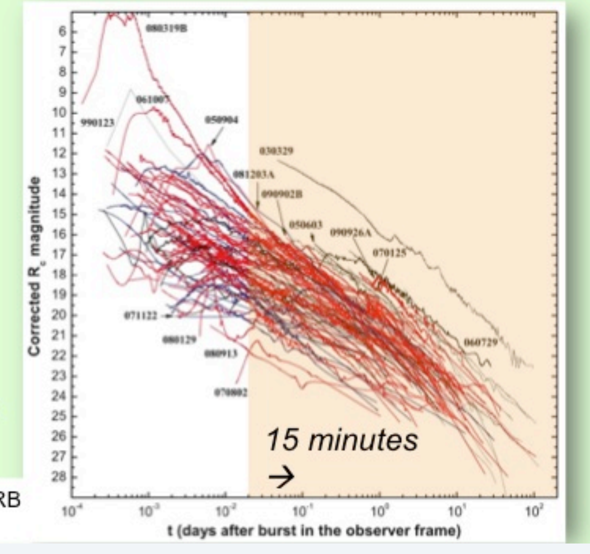




Left: Example of non-radial oscillations in a star. *Right*: FFT of the pulsating WD in SDSSJ161033.64-010223 (Mukadam et al. 2010)

Gamma-RAY Bursts (GRBs)

- Ms-photometry and time-resolved polarimetry for GRBs may allow one to disentangle different emission processes, GRB formation scenarios and give a handle on jet structure, disk formation, etc.
- The micro-variability of GRB at optical/IR wavelengths has never been tested so far and could give information on the compact central engine
- HTR observations of GRB would give important information on the characteristic and evolution of the magnetic field and on the formation of a compact remnant (e.g., do GRBs form magnetars ?)
- Although HTR observations may probably miss the GRB peak, they can still monitor the light curve of the afterglow from 15 minutes after the burst



Right: Compilation of the optical/UV light curves of GRB afterglows observed by Swift (Kann et al. 2010)

HTRA facilities

- Possibilities for HTRA on different ESO instruments, both at the NTT and VLT (Richichi et al. 2009)

Instrument	Modes	Detector	Time Rate (Window)	Configuration and Mode
VISIR	Burst	DRS	12.5 ms SF	imaging, visitor
SOFI	Burst, FastPhot	Hawaii	4 ms (8 x 8), 15 ms (32 x 32)	imaging, visitor
ISAAC	Burst, FastPhot	Hawaii-1, Aladdin	3 ms (32 x 32), 6 ms (64 x 64)	imaging, visitor, service
ISAAC	Burst	Hawaii-1, Aladdin	9 ms (1024 x16)	spectro, under commisioning
NACO	Cube	Aladdin	7.2 ms (64 x 64), 350 ms (1024 x 1024)	imaging, visitor
HAWK-I	Fast	Hawaii-2RG	6.3 ms (16 x 16)	imaging
FORS2	HIT	CCD (charge shift)	up to 2.3 ms	image/spec, visitor, service
VLTI	Fast	Various	up to 1 ms	image/spec, not foreseen

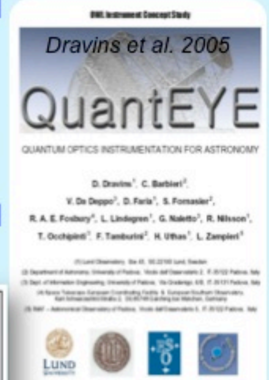
- Time resolution of current ESO HTRA facilities is down to a few ms only. Not sufficient for targets like pulsars. New-generation facilities are now available.

Instr.	Det.	Group	Res.	Type	Ref.
U-Cam	CCD	Warwick/Sheffield	5ms	imager	Dhillon et al.2007
U-Spec	emCCD	Warwick/Sheffield	1ms	spectrograph	Dhillon et al.2007
OPTIMA	SPAD	MPE	4 μs	photocounter/polarimeter	Kanbach et al. 2008
GASP	SPAD	Galway	1 ns	imager/polarimeter	Kyne et al. 2010
Iqueye	SPAD	Padua	0.1 ns	photocounter	Naletto et al. 2009

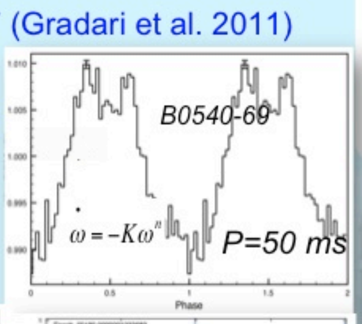
- Increasing time resolution, higher DQE at longer wavelengths (pn-CCD), possibility of performing time-resolved polarimetry and spectroscopy over a wide range of time scales, offer perspectives for new science projects.

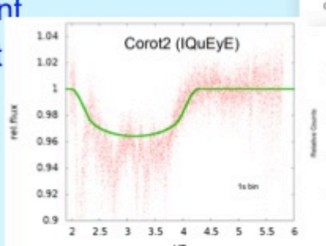
Quantum Detectors

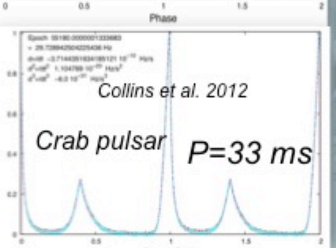
- *QuantEye:* pilot study for the *OWL* 100m telescope, based on quantum detectors technology **pico-s** time resolution
  - *AQuEye@*Asiago 182cm (Barbieri et al. 2009)
  - *IQuEye@NTT* (Naletto et al. 2009)



- Measurement of PSR B0540-69 light curve (*right, top*) and its braking index $n = 2.087 \pm 0.007$ (Gradari et al. 2011)
- Detection of giant optical pulses in the Crab pulsar, (*right, bottom*) simultaneous to giant radio pulses (Collins et al. 2012)
- New timing of the Vela pulsar
- Measurement of exoplanet transits in Corot2 systems

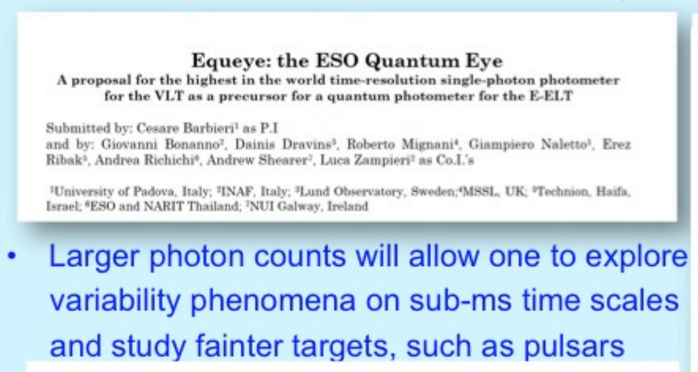






A Quantum Eye for the E-ELT

- Optical HTRA need to keep pace with future facilities, such as SKA, LOFAR, and LOFT (see next panel)
- A larger collecting power is required. HTRA facility at the E-ELT needed
- A VLT prototype *(EQuEye)* for an HTRA instrument at the W-WLT (Equeye) is currently under study – PI C. Barbieri (U. Padua, Italy)


Equeye: the ESO Quantum Eye

A proposal for the highest in the world time-resolution single-photon photometer for the VLT as a precursor for a quantum photometer for the E-ELT

		Time-Scale Now	Time Scale ELT era
Stellar flares and pulsations		Seconds/ minutes	10-100ms
Stellar Surface Oscillations	White Dwarfs Neutron Stars	1-1000 μs -	1-1000 μs 0.1 μs
Close Binary Systems accretion & turbulence	Tomography Eclipse in/egress Disk flickering Correlations (e.g. X & optical)	100ms++ 10ms+ 10ms 50ms	10ms+ < 1ms < 1ms < 1ms
Pulsars	Magnetospheric Thermal	1 μs- 100ms	ns ms
AGN		Minutes	Seconds

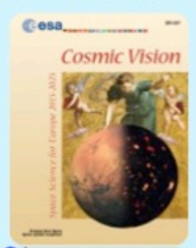
- Larger photon counts will allow one to explore variability phenomena on sub-ms time scales and study fainter targets, such as pulsars

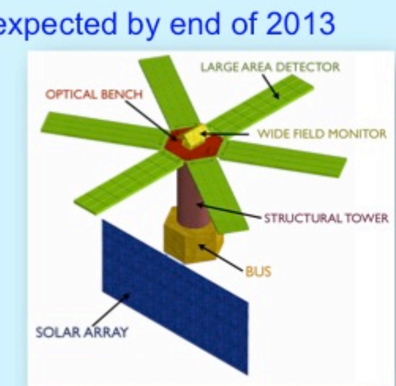
Right: Difference between the time scales which can be explored now and with a quantum detector at the E-ELT for different types of astrophysical objects.

- Larger photon counts will also allow to exploit the full potentials of phase-resolved spectroscopy and polarimetry, so far limited to bright objects only.

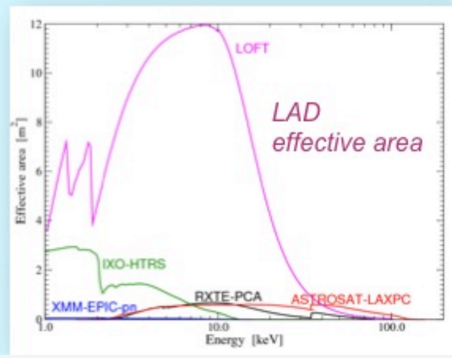
Large Observatory for X-ray Timing (LOFT)

- Candidate ESA M3 mission with down selection expected by end of 2013 (Feroci et al. 2012)
- 1820 kg. Launch in 2020-22 by a Soyuz rocket in a LEO, 600 km, 96 min period, 5° inclination





- Large Area Detector (LAD), PI: MSSL
  - Energy Range: 1–40 keV
  - Effective Area (2-30 keV): 12 m²
  - Time Resolution: 5 μs
- Wide Field Monitor (WFM), PI: IEEC-CSIC
  - Energy Range: 1–40 keV
  - Field of View: 13000 sq. deg
  - Point Source Localization: <0.5'
- The E-ELT with an HTRA facility would be a unique companion for the LOFT/LAD



Conclusions

- The universe at sub-s time scales is still largely unexplored.
- HTRA observations are important in many astrophysical contexts and HTRA is a natural component of present/past radio and high-energy observing facilities. Not much so for the optical, though. All future large facilities will have timing capabilities, creating important opportunities for multi-wavelength synergies. The E-ELT shouldn't be left behind.
- The potentials of optical time-resolved polarimetry and spectroscopy must be fully exploited and open new avenues wrt other wavelengths. Time is now ! Optical HTRA builds momentum, the Community expands, new detectors are being developed.
- HTRA science satisfies the fundamental E-ELT rationale of opening up new parameter space, as expressed by the Science Working Groups in the E-ELT Construction proposal.
- The E-ELT can start a new era in optical HTRA.

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Contacts and More Information

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- ***High Time Resolution Astrophysics (HTRA) IV - The Era of Extremely Large Telescopes:*** http://www.htra.ie/htra-iv/index.php
- ***Principles of Multi-wavelength High Time Resolution Astrophysics:*** www.htra.ie