Polarimetry measurements of isolated neutron stars

current status and future perspectives

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Maximum observed and expected degree of polarisation

Radio	
galactic continuum	70%
quasars (integrated / resolved)	15% / 70%
Crab nebula	30%
pulsars (linear / circular)	80% / 70%
Optical	
planets	$> 20\%$
interstellar dust acting on starlight (linear)	10%
interstellar dust acting on starlight (circular)	0.05%
Sun and A_p stars (Zeeman effect)	100%
white dwarfs (Zeeman effect)	12%
symbiotic stars (Raman scattering)	8%
reflection nebulae (including Herbig–Haro and bipolar	60%
post–AGB stars and proto–PN (global polarisation)	30%
synchrotron (Crab nebula, blazars)	50%
synchrotron (extragalactic jets)	20%
Crab pulsar	10%
X–ray (mainly 'expected')	
solar flares	5%
Crab nebula	15%
accreting X–ray pulsars	80%
rotation–powered X–ray pulsars	10%
black hole (Lense–Thirring effect Cyg X–1)	2%
active galactic nuclei	20%
Seyfert accretion disc reprocessing	5%
γ–ray ('expected')	
pulsars	100%

Scientific impact

- Study the emission physics of the neutron star magnetosphere and track the particle energy/density distribution

$$F_\nu \propto \nu^{-\alpha}$$

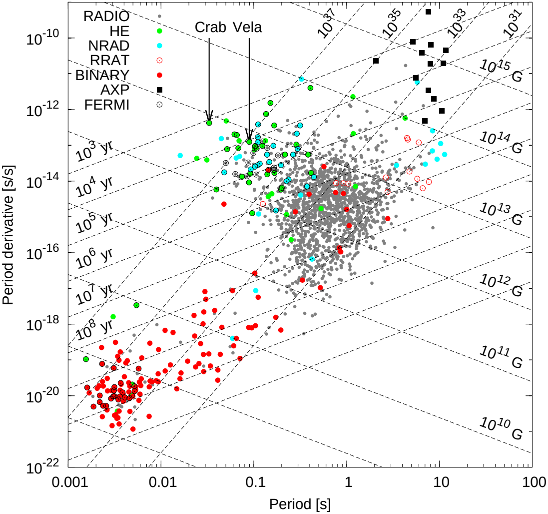
- Study the polarisation properties of the magnetosphere/atmosphere
- Study the emission geometry of the multi-wavelength radiation
- Determine the thermal map on the INS surface (anisotropies) and study the decay of cooling curve for ages > 1 Myr
- Study Giant Pulses, so far only detected in radio and in the optical
- Giant Optical Pulses observed from the Crab pulsar (Shearer et al. 2003) linked in time with Giant Radio Pulses (coherent vs. incoherent radiation)
- Investigate the presence of debris disks

H–R diagram for pulsars (P–$\dot{P}$)

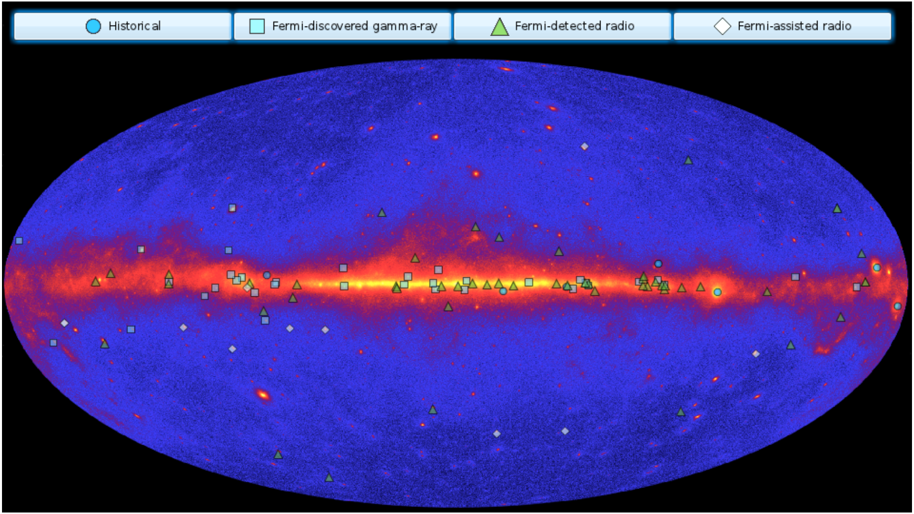
$$\dot{E} \propto \dot{P} P^{-3}$$

$$B \propto \sqrt{P\dot{P}}$$

$$\tau \propto P\dot{P}^{-1}$$



The 2nd Fermi Large Area Telescope gamma-ray Pulsar Catalog (2PC)



https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

UV, O, IR observations of pulsars

	Name	Year	Age	mag	D(kpc)	A_V	Phot	Spec	Pol	Tim	Astrom
	Crab	1969	3.10	16.5	1.73	1.6	UVOIR	Y	Y	P	PM
	B1509-58	2000	3.19	26	4.2	5.2	OIR		UL*		
	B0540-69	1984	3.22	22	49.4	0.6	OIR	Y	Y*	P	PM (UL)
	Vela	1976	4.05	23.6	0.23	0.2	UVOIR	Y	Y*	P	PM,PAR
	B0656+14	1988	5.05	25	0.29	0.09	UVOIR	Y	Y	P	PM
	Geminga	1984	5.53	25.5	0.16	0.07	UVOIR	Y		P	PM,PAR
	B1055-52	1997	5.73	24.9	<0.72	0.22	UVO				PM
pulsars	B1929+10	1996	6.49	25.6	0.33	0.15	UV				PM
	B0950+08	1996	7.24	27.1	0.26	0.03	UVO				
	B1133+16	*2008*	*6.69*	*28*	*0.35*	*0.12*	*O*				
	J0108-1431	*2008*	*8.3*	*27.*	*0.3*	*0.05*	*O*				
	J0437-471	2004	9.20		0.14	0.11	UV	Y			
	J1308.6+2127	2002	6.17	28.6	<1	0.14	O				
	J0720-3125	1998	6.27	26.7	0.35	0.10	O				PM,PAR
	J1856-3754	1997	6.60	25.7	0.14	0.12	O	Y			PM,PAR
	J1605.3+3249	2002	-	26.8	<1	0.06	O				PM
XDINs	RBS1774	2008	-	27.4	<0.5	0.2	O				
	J0806-4123	2011	>6.5		<0.5		O				
	SGR1806-20	2004	3.14	20.1	15	29	IR				
	1E 1547.0-5408	2009	3.14	18.5	9	17	IR		Y*		
	1E 1048.1-5937	2004	3.63	21.3	3	6.1	OIR		UL*	P	
magnetars	XTE J1810-197	2004	3.75	20.8	4	5.1	IR		UL*		
	SGR 0501+4516	2009	4.1	19.1	~2	5	IR			P	
	4U 0142+61	2002	4.84	20.1	>5	5.1	OIR			P	
	1E 2259+586	2002	5.34	21.7	3	5.7	IR				

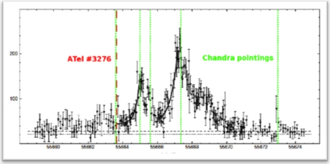
*** phase-averaged**

10 PSRs identified, plus 2 candidates, mostly in the optical, 8 also in the nUV and 6 also in the nIR,

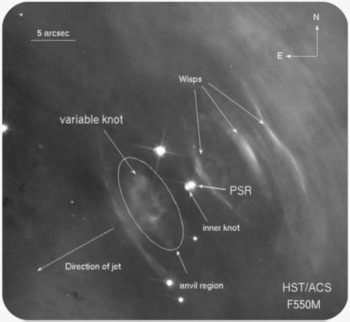
low-res spectroscopy for 5 PSRs only

The Crab nebula

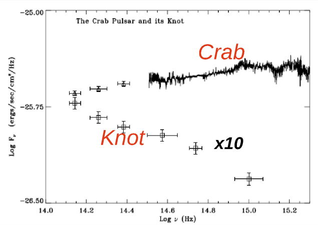
- October 2010 γ-ray flare detected by Agile and Fermi (Tavani et al. 2011)



Tennant et al.



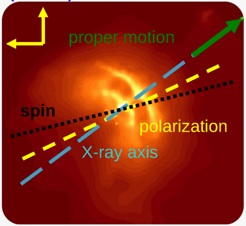
- New γ-ray flare in April 2011 but no HST observations due to visibility
- Continuous monitoring with Chandra+HST + ToO (PI. M. Weisskopf)



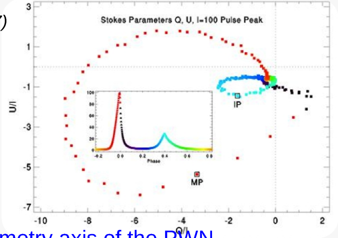
Sollerman (2003)

Pulsar polarimetry

- Phase-res polarisation only for the **Crab** and **B0656+14** but only on 30% of the phase (Kern et al. 2003)
- PD max in the inter-pulse and PA swings before the peaks. DC component (knot?) subtraction crucial (Slowikowska et al. 2009, 2012)



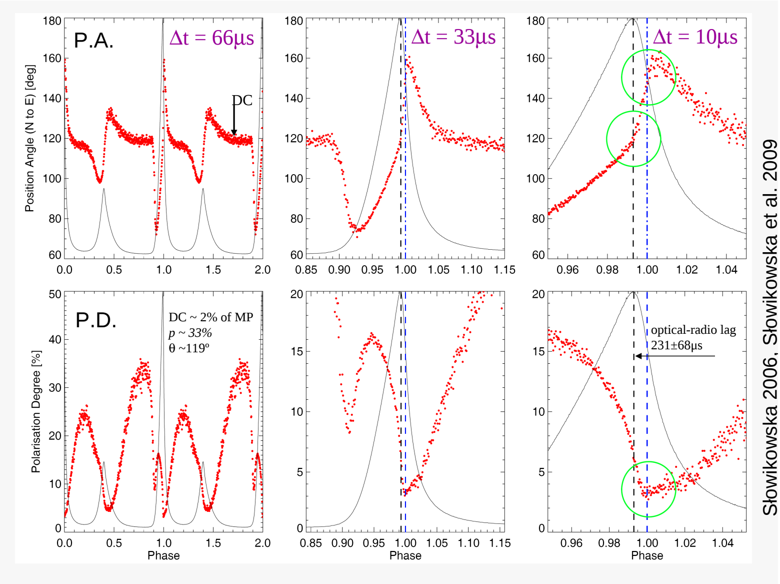
Mignani et al. (2007)



<PA> aligned with the PM vector and symmetry axis of the PWN

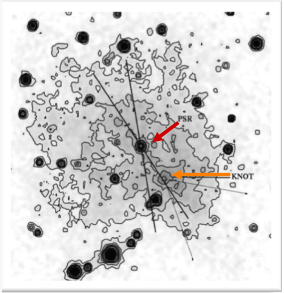
	<PD>	<PA>	Ref.
Crab phase av phase av. DC sub	9.8%+/–0.1% 5.5%+/–1%	109.5° 96.4°	Slowikowska et al. (2011)
B0540-69	16.6%+/–4%	22°	Mignani et al. (2010)
Vela	9.2%+/–0.6%	165.9°	Moran et al.

Phase resolved Crab pulsar polarimetry



PSR B0540–69

- For PSR B0540-69, only a P_L~*5%* obtained with the *VLT* (Wagner and Seifert 2000) *but without errors* and probably polluted by SNR



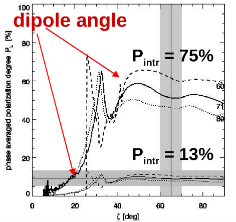
- WFPC2 observations 0º, 45º, 90º, 135º angles, from 4 different HST roll angles. Polarisation measurement affected by the *WFPC2* calibration accuracy (~ 2%) and by its polarisation.

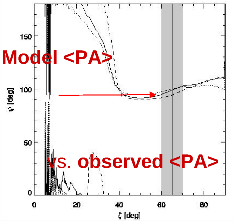
- Subtraction of foreground polarisation from P_L of field stars

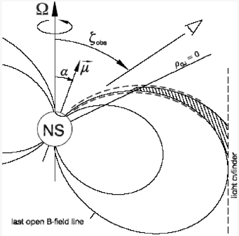
- Pulsar polarisation: <**PD> = 16% +/– 4%**; <**PA>= 22º +/– 12º** (Mignani et al. 2010a)

- Phase-resolved polarimetry of B0540-69 proposed for OPTIMA@NTT

Vela



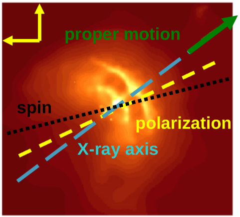




- Phase-averaged polarimetry with the VLT

- **<PD>= 9.4%+/-4%**; **<PA>=146°+/-11°**(Mignani et al. 2007)
- **<PD>= 9.2%+/-0.6%**; **<PA>=165°+/-4°**(Moran et al. 2012)

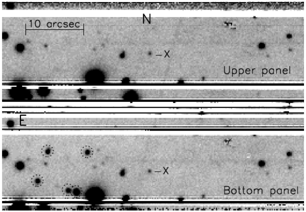
- Optical polarimetry of Vela allowed to: 1) tests models on the neutron star magnetosphere, 2) constrain the magnetic field angle wrt spin axis, and 3) the spin axis angle wrt the plane of the sky



- Phase-resolved polarimetry of Vela proposed with GASP(

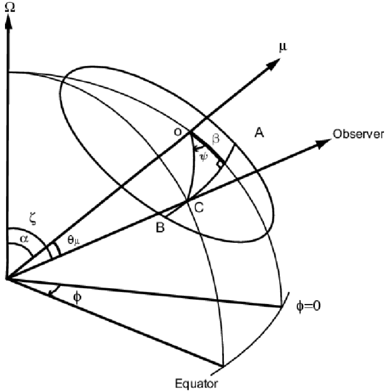
Circular polarisation of magnetar 4U 0142+61

- The first imaging circular polarimetry of the anomalous X-ray pulsar (AXP) 4U 0142+61 at optical wavelengths
- 4U 0142+61 is the only magnetar that has been well studied at O and IR
- Observations: 8.2-m Subaru telescope with FOCAS at I-band
- Results: V = 1.1±2.0%, or $|V| \leqslant 4.3\%$ (90% confidence), large uncertainty is due to the faintness of the source (I = 23.4–24.0)
- Not sufficiently conclusive to discriminate the models
- Future: linear polarimetry (strong expected)



Wang et al. 2012

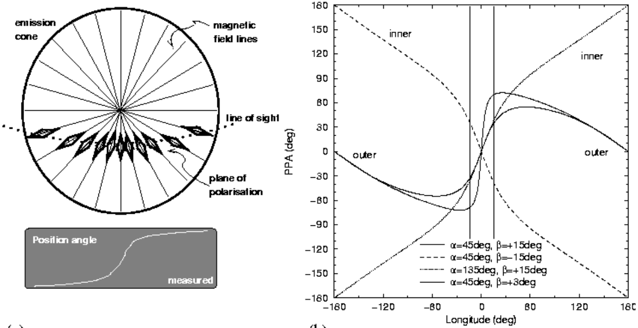
Pulsar radio beam



α – an inclination angle of the magnetic dipole with respect to the rotation axis
β – the minimum angle between an observer's line of sight and magnetic axis (impact angle)

Rotation Vector Model (RVM)

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



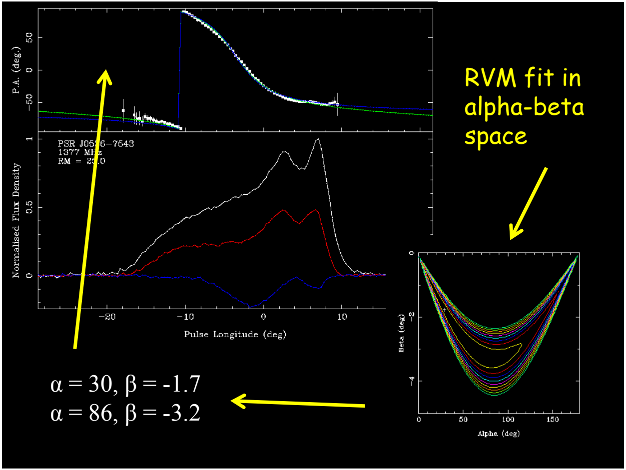
(a) (b)

$$\mathrm{tg}(\Psi - \Psi_0) = \frac{\sin\alpha \sin(\phi - \phi_0)}{\sin(\alpha+\beta)\cos\alpha - \cos(\alpha+\beta)\sin\alpha\cos(\phi-\phi_0)}$$

Radhakrishnan & Cooke 1969

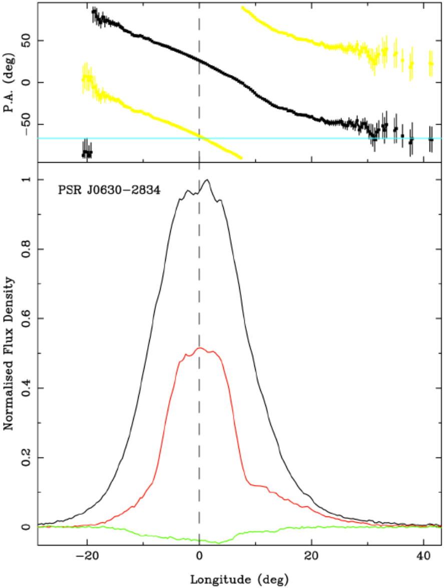
Relativistic modification to the RVM – Blaskiewicz, Cordes, Wasserman 1991, Dyks et al. 2008

RVM fit



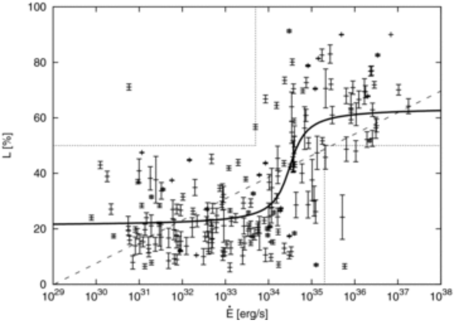
RVM is a useful tool and geometry is crucial for testing models of radio emission. Now with 100+ γ-ray pulsars knowledge of the geometry is even more crucial! In practice, hard to constrain (Johnston 2012).

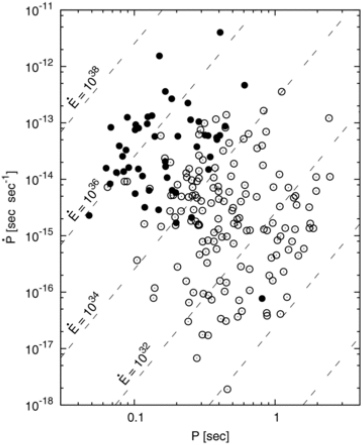
Profile polarisation



Use polarisation and proper motions to determine the alignment between the velocity vector and the rotation axis. (Johnston et al. 2005, 2007, Rankin et al. 2008, Noutsos et al. 2012, Weisberg et al. 2020)
In summary: There is an alignment between the rotation axis and the velocity vector – pulsars emit in both normal and orthogonal modes.

Linear polarisation fraction vs. $\dot{E}$

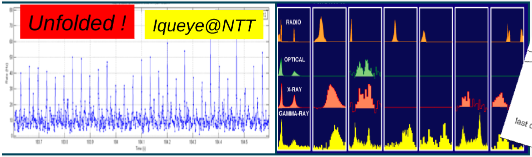


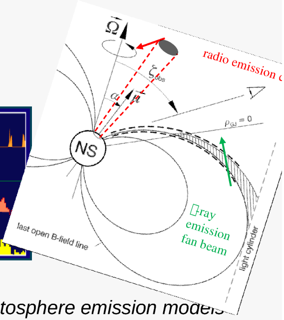


Abrupt transition between from low to high polarisation states around $\dot{E}$ of $10^{34.5}$ (Weltevrede & Johnston 2008).

E–ELT timing

- *the light curve morphology to an unprecedented deta*



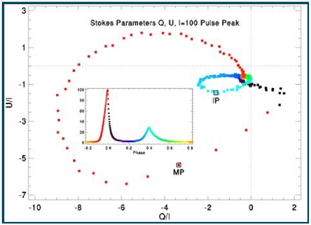


Zampieri et al., 2010, ASpR, in press

- *the light curve wavelength dependance and test magnetosphere emission models*

- *Giant Optical Pulses (Shearer et al. 2003, Science, 301, 493) and their link with Giant Radio Pulses (coherent vs. incoherent radiation)*

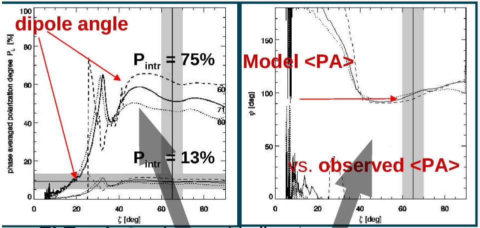
- **E-ELT phase-resolved polarimetry** would allow to map NS magnetic field geometry (polarisation varies across the period)

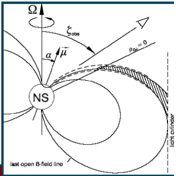


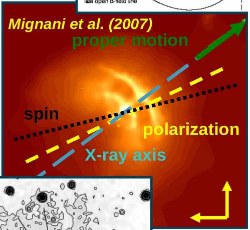
Slowikowska et al. 2009, MNRAS, 397, 103

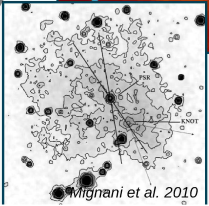
E-ELT polarimetry

- Radio-silent NS polarimetry only possible in optical/IR









- **ELT polarimetry** would allow to:

✓ **tests models on the neutron star magnetosphere**

✓ constrain the magnetic field angle wrt spin axis

✓ constrain the spin angle wrt the plane of the sky

✓ Test spin/velocity/polarisation alignments

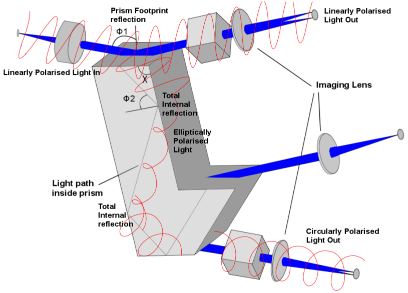
✓ Resolve the polarisation map in PWNe and SNRs

High Time Resolution Astrophysics detectors

Instrument	dT	Detector	Note	Reference
OPTIMA	4 ns	SPAD	- black hole binary transient KV UMa - optical magnetar - phased resolved polarimetry of the Crab pulsar - timing egress times of polars – detection of extrasolar planets	Straubmeier et al. 2001 Kanbach et al. 2003 Stefanescu et al. 2008 Słowikowska et al. 2009
UltraCam	5 ms	CCD	Very successful, frequent guest instrument at VLT and WHT	Dhillon et al. 2007
UltraSpec	1 ms	emCCD	Spectrometer version of UltraCam	Dhillon et al. 2007
GASP	ms ns	sCMOS SPAD	Full-Stokes Polarimeter, various detectors	Kyne et al. 2010
IquEye	100 ps	SPAD	Precursor to ELT class instrumentation	Barbieri et al. 2009

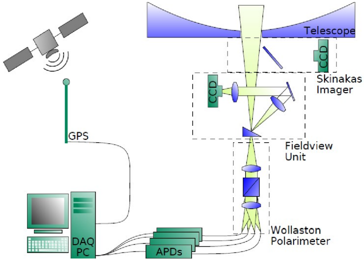
GASP and OPTIMA

GASP – Galway Astronomical Stokes Polarimeter



Andy Shearer (NUI,Galway)

OPTIMA – Optical Pulsar TIMing Analyzer



Gottfried Kanbach (MPE, Garching)

E-ELT

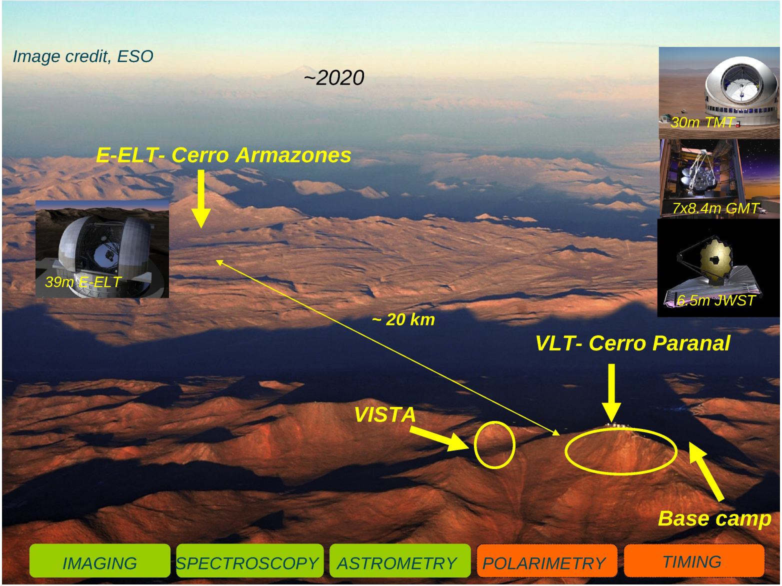


Image credit, ESO
~2020
E-ELT- Cerro Armazones
39m E-ELT
30m TMT
7x8.4m GMT
6.5m JWST
~ 20 km
VLT- Cerro Paranal
VISTA
Base camp
IMAGING
SPECTROSCOPY
ASTROMETRY
POLARIMETRY
TIMING