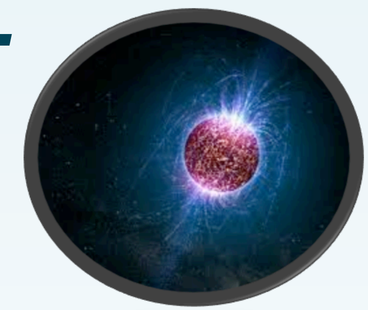
Neutron Star Astronomy at ESO
- from the NTT to the E-ELT-



***Roberto P. Mignani*[1,2]**

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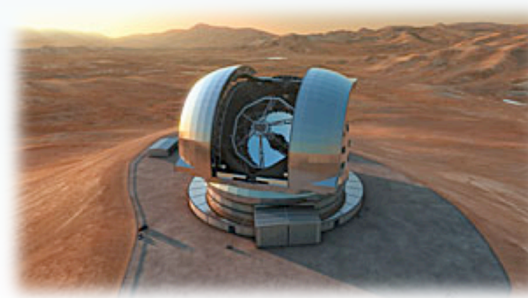
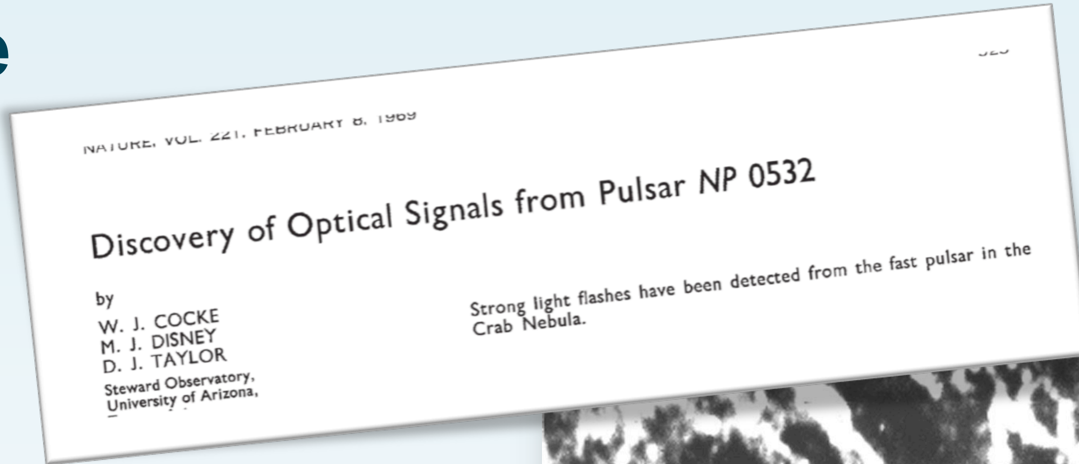
[2]Kepler Institute of Astronomy, University of Zielona Gora, Poland



ESO@50 - the first 50 years of ESO

Prologue



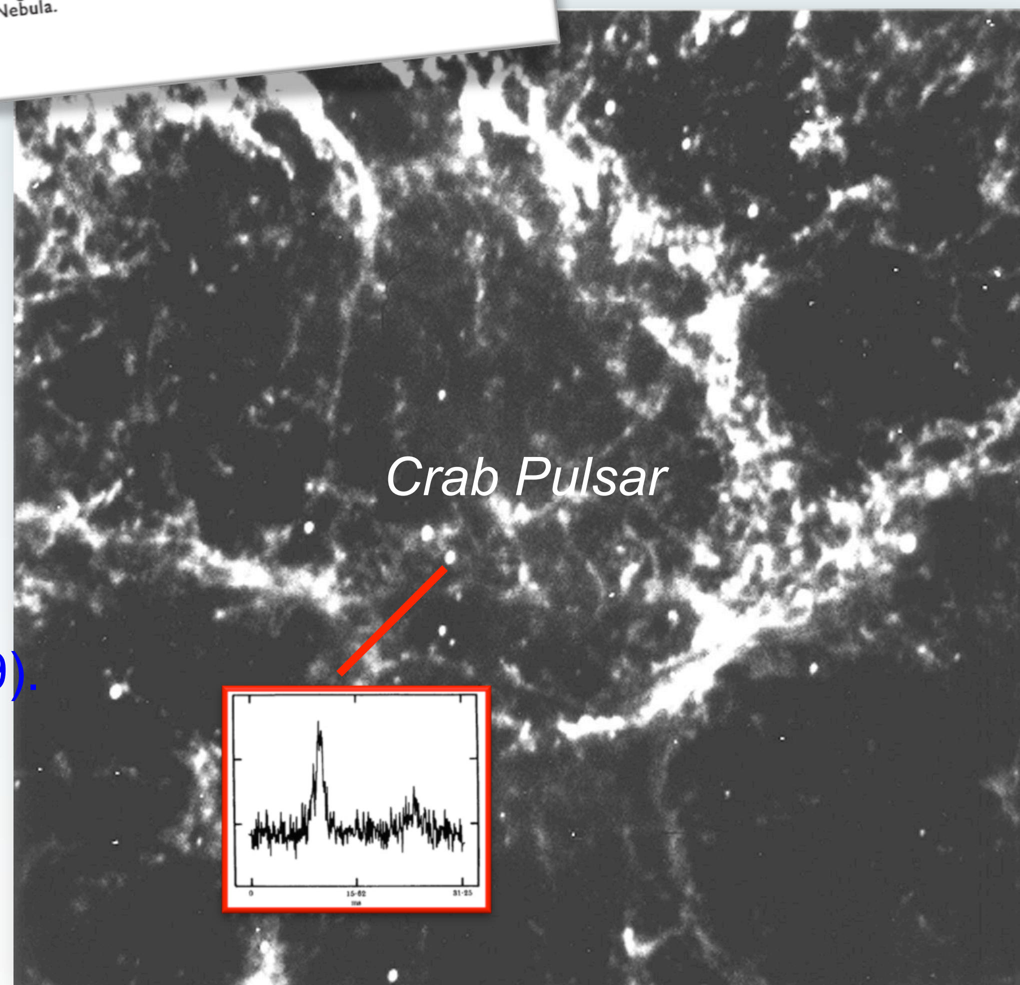
NATURE, VOL. 221, FEBRUARY 8, 1969

Discovery of Optical Signals from Pulsar NP 0532

by
W. J. COCKE
M. J. DISNEY
D. J. TAYLOR
Steward Observatory,
University of Arizona,

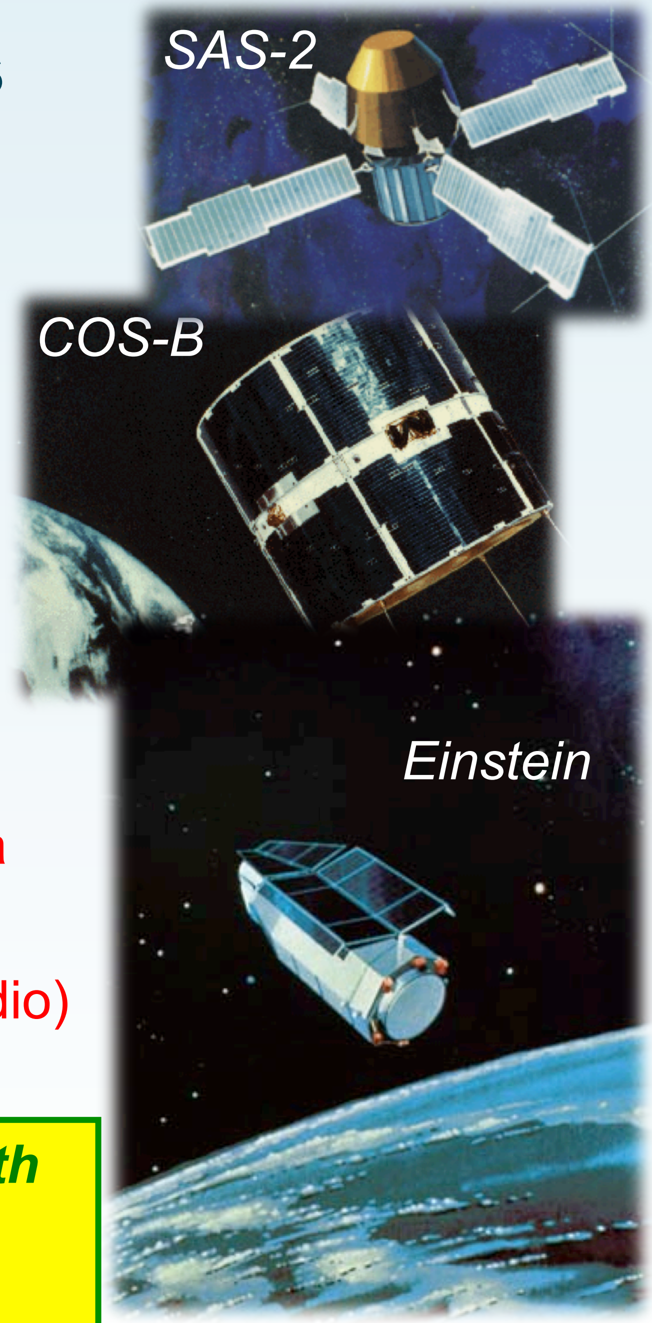
Strong light flashes have been detected from the fast pulsar in the Crab Nebula.

- 1967: Pulsar Discovery
- **1969**: The first neutron star detected in the optical
- Crab pulsar (V=16.5): optical pulsar detected (Cocke et al.1969). Identified with the Baade and Zwicky's "South Preceding star"



1967-1982: not just *radio* pulsars

- ~300 pulsars detected in radio
- A few pulsars detected at high energies
- NASA's *SAS-2* (1972-1973) and ESA's *COS-B* satellite (1975-1982) in gamma-rays
- NASA's *Einstein* satellite (1978-1982) in X-rays
- 2 pulsars detected in gamma-rays: Crab and Vela
- 10 pulsars detected in X-rays (some not yet in radio)



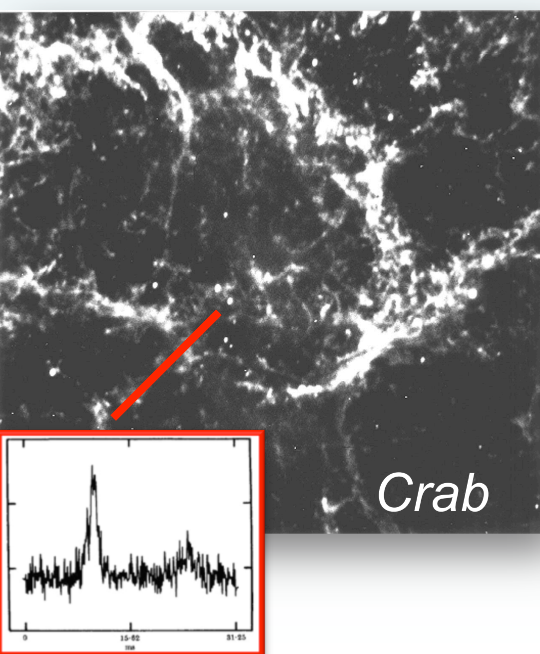
Pulsars had become targets for multi-wavelength astronomy.
What about the optical ?

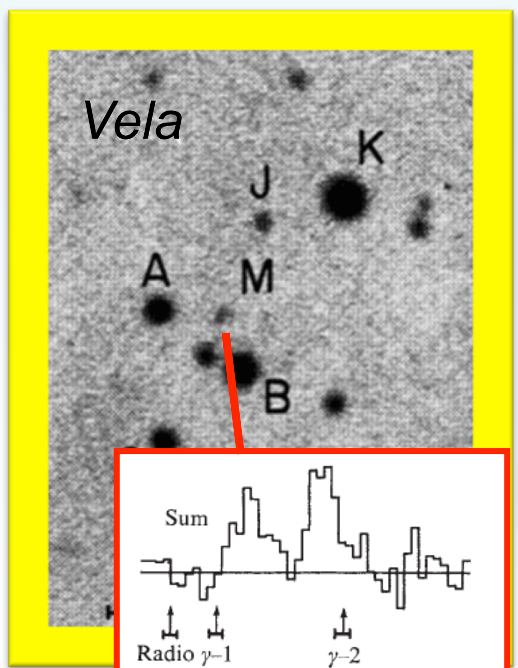
Pulsars in the optical

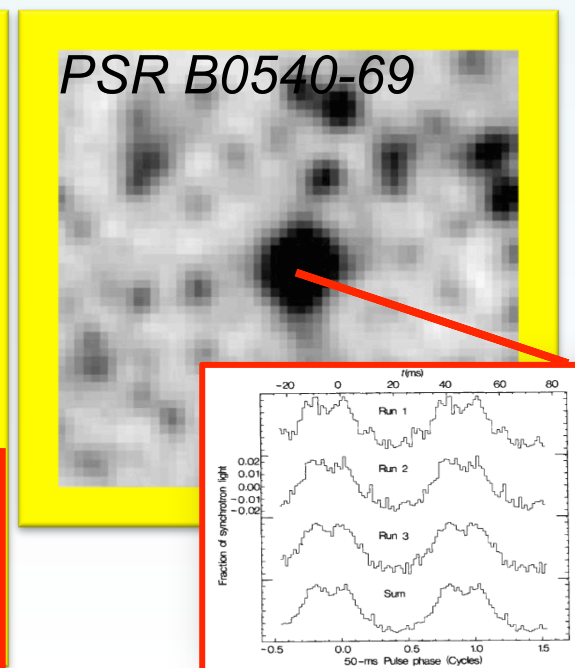
- Vela pulsar (V=23.6): counterpart detected (Lasker 1976) at the CTIO 4m Blanco, confirmed by optical pulsations (Wallace et al. 1977)

- PSR B0540-69: Optical pulsations (50 ms) detected by Middleditch & Pennypacker (1985) with the AAT. Optical counterpart remained unidentified in the spatially unresolved SNR

1976





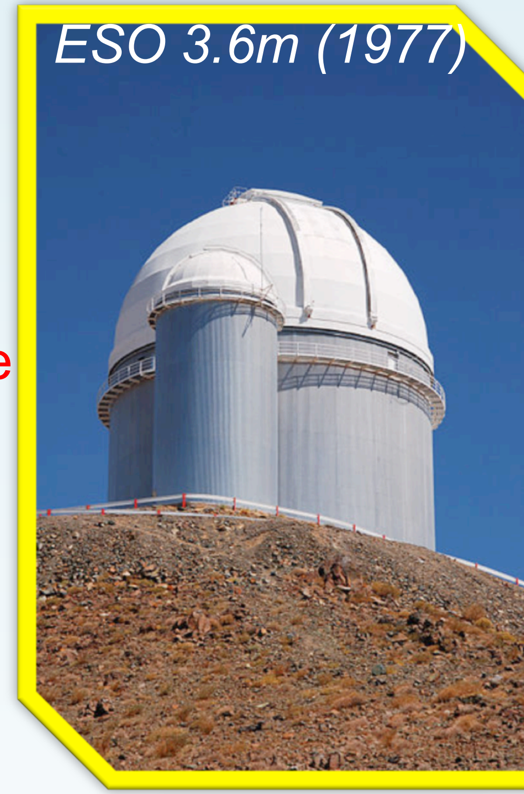


The Giants, back then

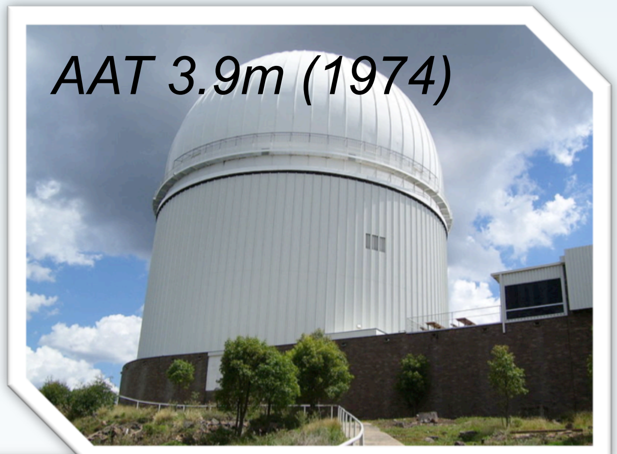
- Neutron star astronomy requires big telescopes

- Mostly available in US and AUS

- With the advent of the 3.6m (1977), ESO broke into the scene and neutron star astronomy in Europe started

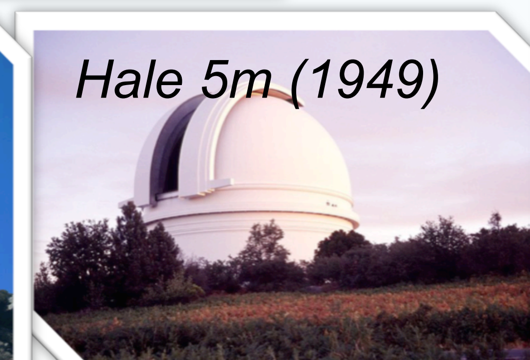

ESO 3.6m (1977)


Shane 3m (1959)


AAT 3.9m (1974)

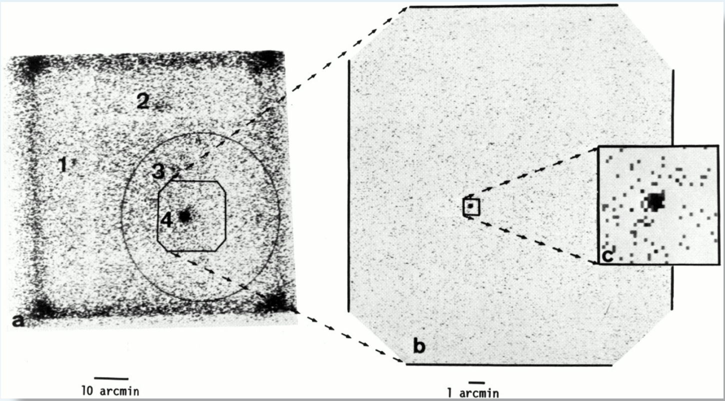

BTA 6m (1975)

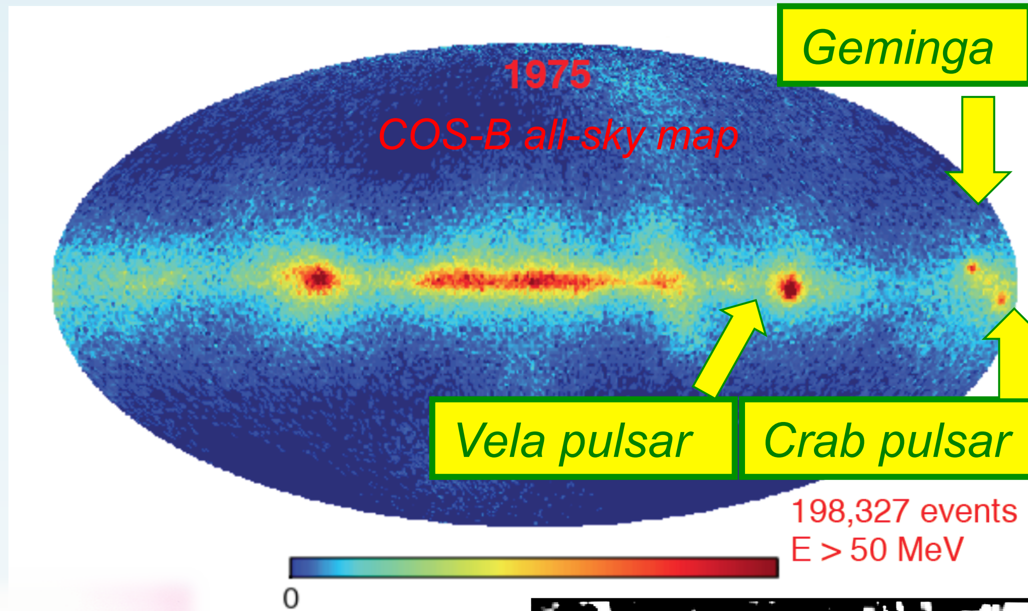

Mayall 4m (1973)

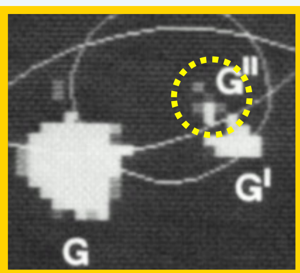

Hale 5m (1949)

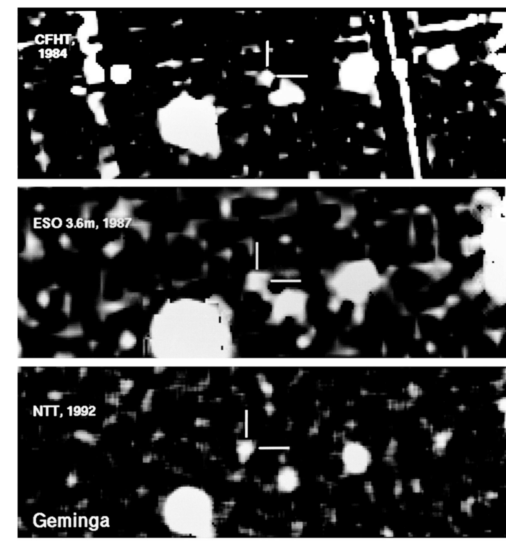

Blanco 4m (1976)

The Geminga chase







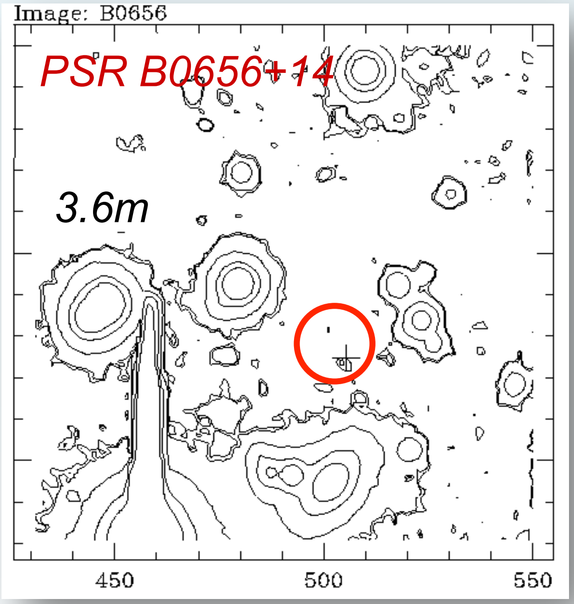


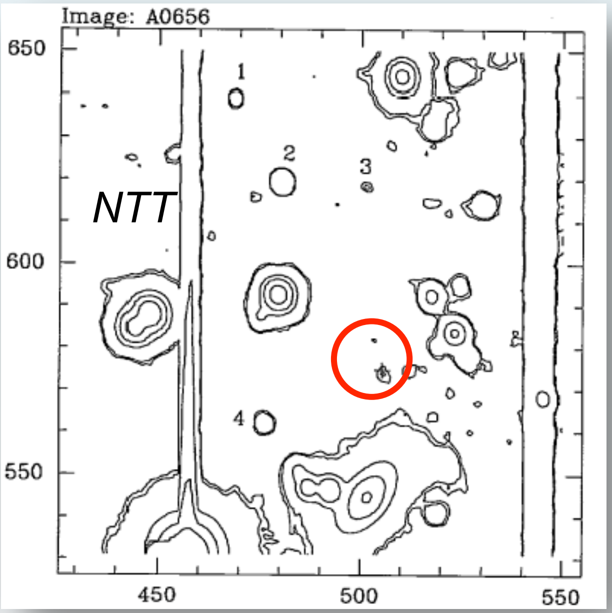
- *Einstein* map the COS-B error box → X-ray ctp
- Counterpart **G"** detected with the 3.6m (Bignami et al. 1988) $L_\gamma/L_X \approx 1000$ & $L_X/L_{opt} \approx 1000$ → INS
- NTT measured G" proper motion (Bignami et al. 1993)

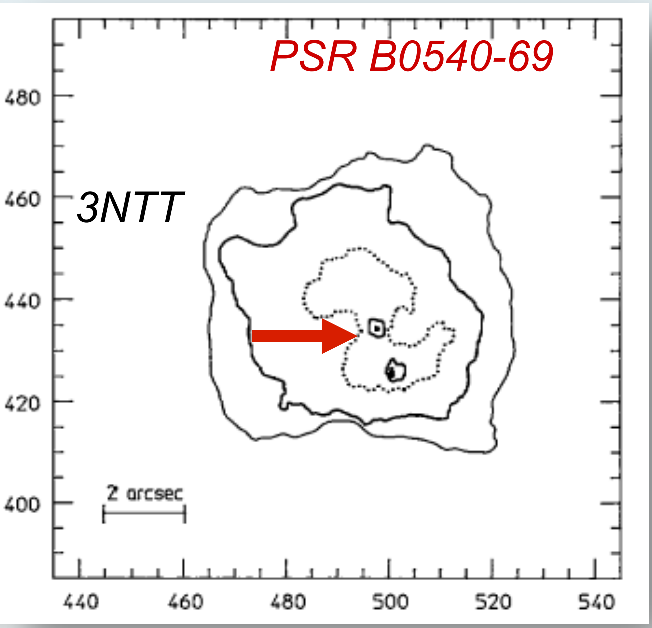
In the 1990s, the Geminga identification **renewed the interest in optical observations of neutron stars**, as follow-ups of ROSAT and CGRO and showed **NTT potential for neutron star astronomy**

Riding the wave

- PSR B0656+14: Counterpart (V=25) identified with the 3.6m (Bignami et al., unpublished) and confirmed by the NTT (Caraveo et al. 1994)







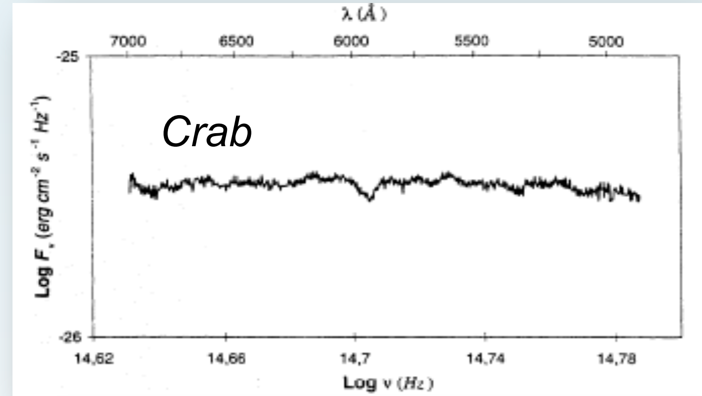
- PSR B0540-69: High-resolution imaging with NTT/SUSI identified a likely V=22.5 counterpart (Caraveo et al. 1992; Shearer et al. 1994).

- Candidate counterpart (V=22) for PSR B1509-58 (Caraveo et al. 1994b) plus many others observed both with the *NTT* and the *3.6m* (Mignani et al. 2000)

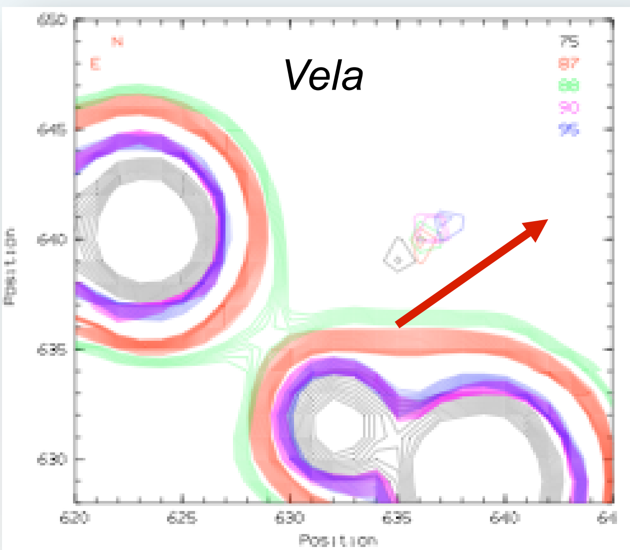
Riding the wave

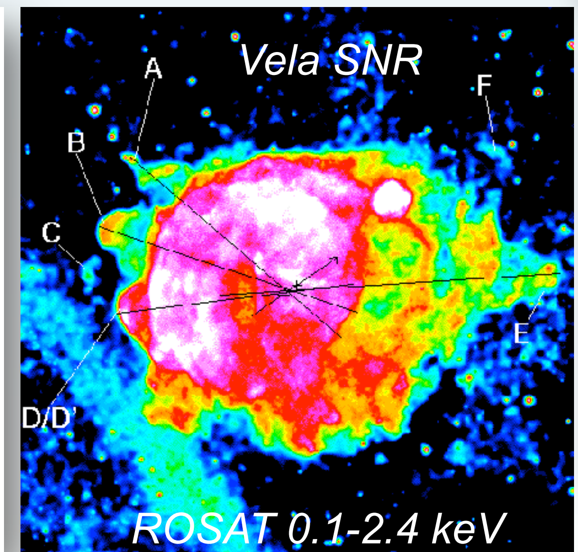
See Mignani et al. 2000, The Messenger, 99, 22 for a review

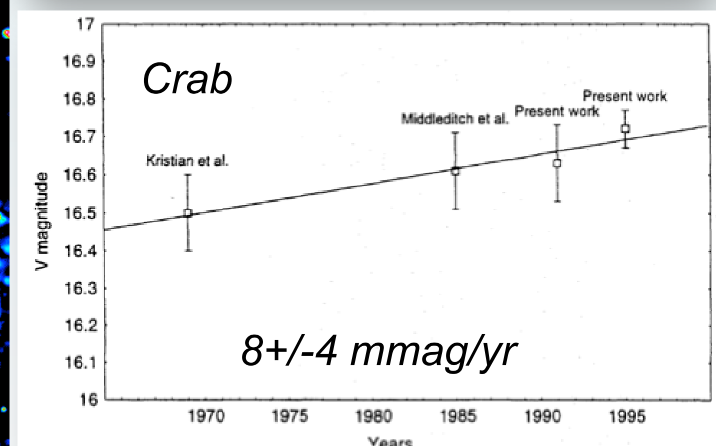
- First CCD optical spectrum of the Crab measured with the *NTT* (Nasuti et al. 1996)



- First tentative measurement of the secular decrease of the Crab optical luminosity, predicted by Pacini&Salvati (1983)



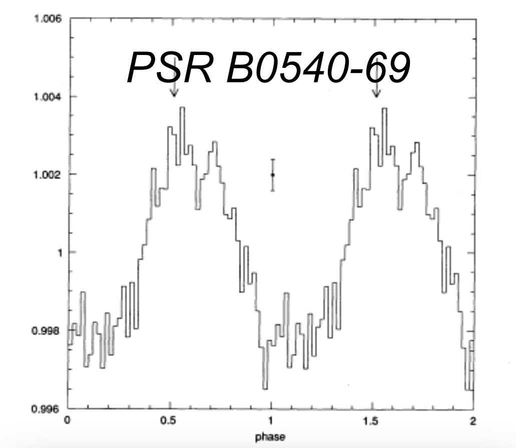


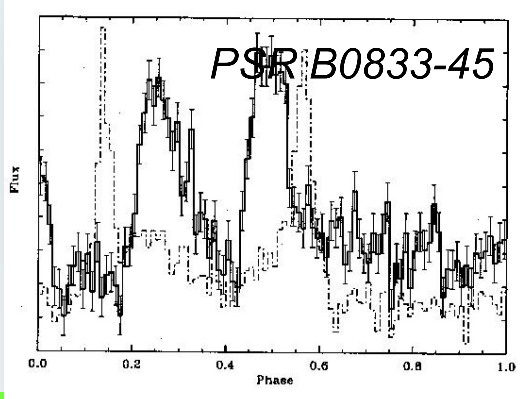


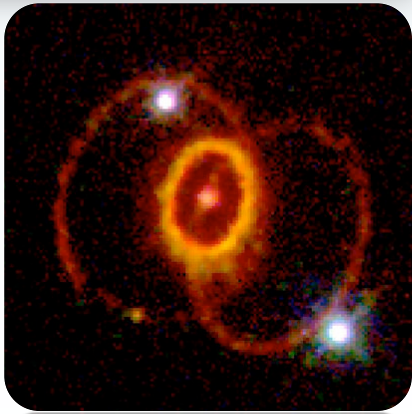
- First proper motion for the Vela pulsar (Nasuti et al. 1997), with the *NTT.* Confirmed SNR association and pulsar birth place.

Pulsar Timing at the 3.6 and NTT

- Fast photometer at the 3.6m
- ESO became leader in optical timing of pulsars
- Timing of PSR B0540-69 (Gouiffes et al.1992)
- Vela pulsar light curve (Gouiffes et al. 1998)
- Search for a pulsar in SN1987A (Ogelman et al. 1990)
- *IQuEye* at the NTT *(*Naletto et al. 2009*)*
- Braking index measurement for B0540-69: $\dot{\omega} = -K\omega^{n}$
  n=2.087±0.007 (Gradari et al. 2011). Measured for a handful of pulsars only; n=3 for a perfect dipole.
- Detection of Giant Pulses from the Crab (Collins et al. 2012)

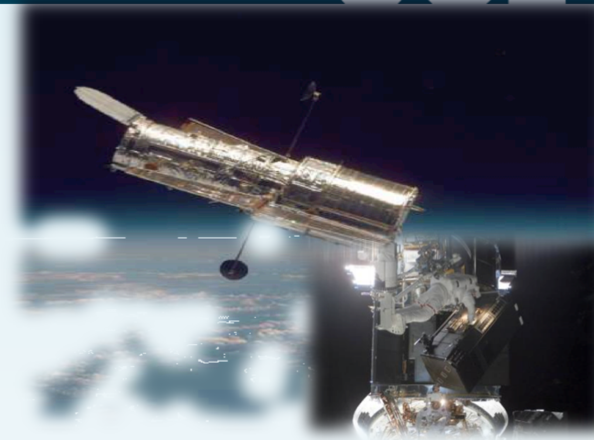






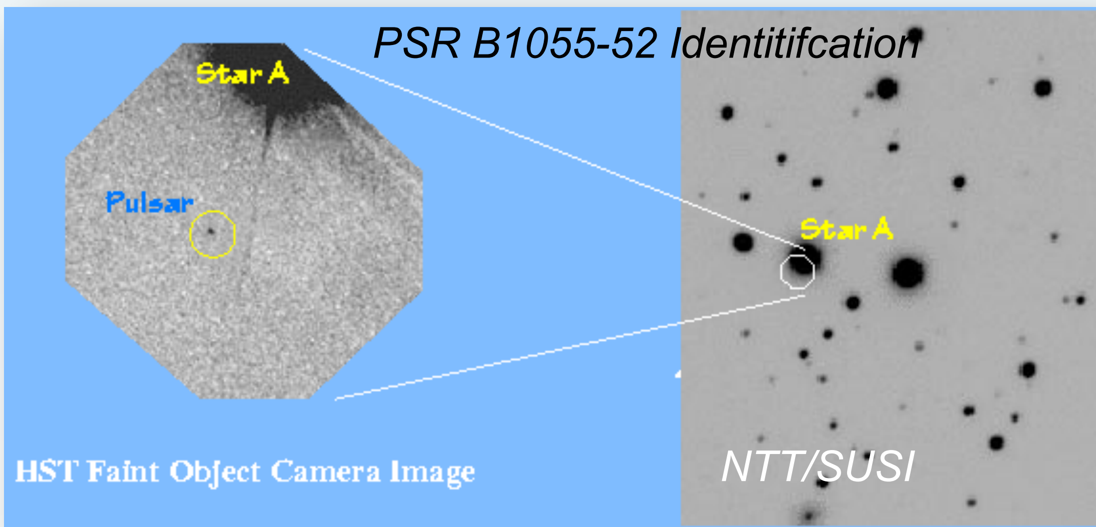
NTT and the HST

- In the mid 1990s, the NTT achieved most pulsar identifications

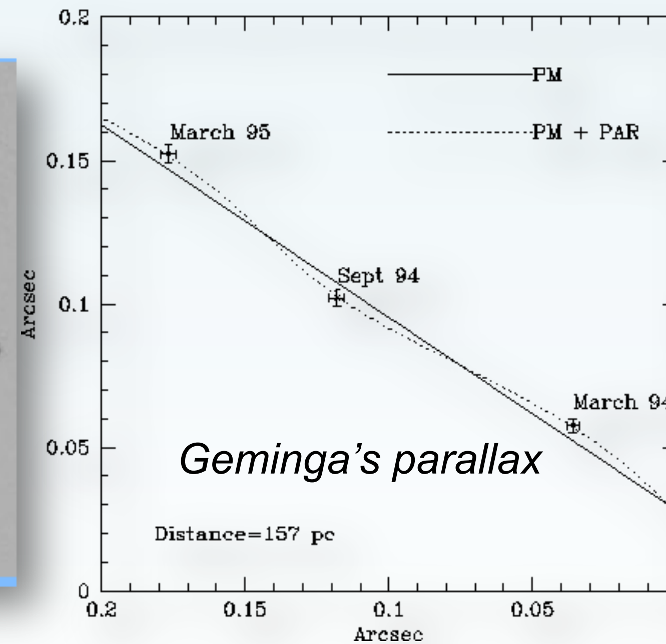


- Seminal work for the refurbished HST (1993): PSR B1055-52 identification (Mignani et al. 1997), Geminga's parallax (Caraveo et al. 1996), etc.

PSR B1055-52 Identitifcation



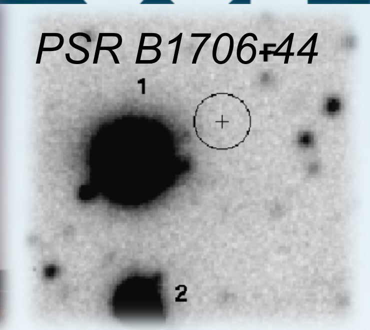
Geminga's parallax



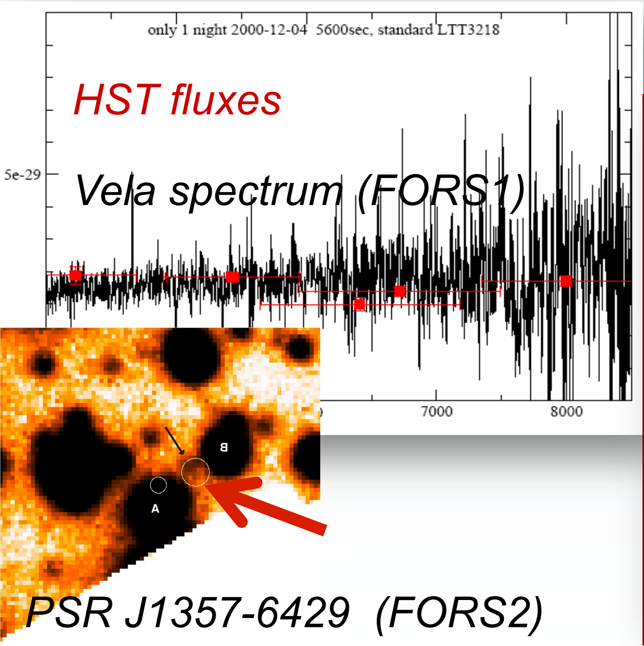
***Spurred more and more interest in the Community**. More groups involved. Consolidated optical as an important branch for neutron star astronomy*

The VLT Era

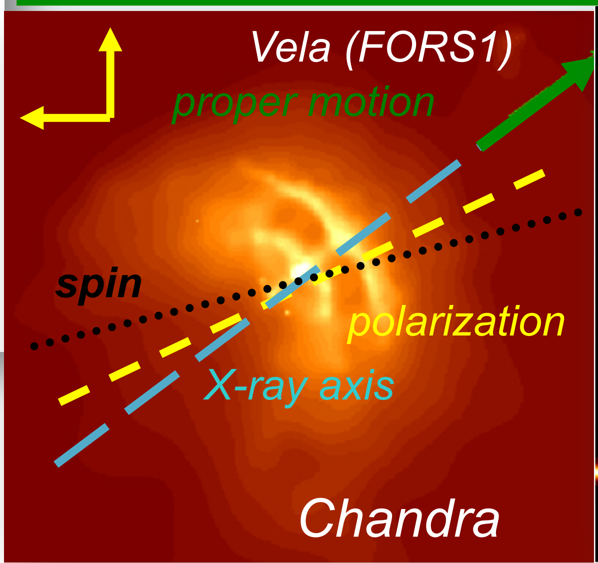
See Mignani 2009, The Messenger, 138, 19 for a review

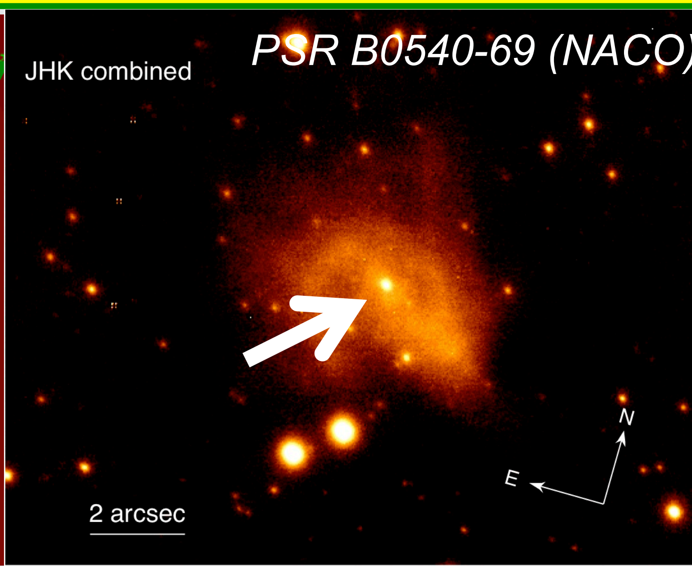


- Pulsar observations were a test case for the *VLT/UT1* Science Verification (Mignani et al. 1999, *A&A, 343, L5 Special Edition: First Science with the VLT*)
  - The first optical spectrum of the Vela pulsar (Mignani et al. 2007a)
  - The first optical polarisation of the Vela pulsar (Mignani et al. 2007b)
  - The first IR detections of pulsars (Mignani et al. 2012a)
  - The first observations of *Fermi* pulsars (Mignani et al. 2011a; 2012b)



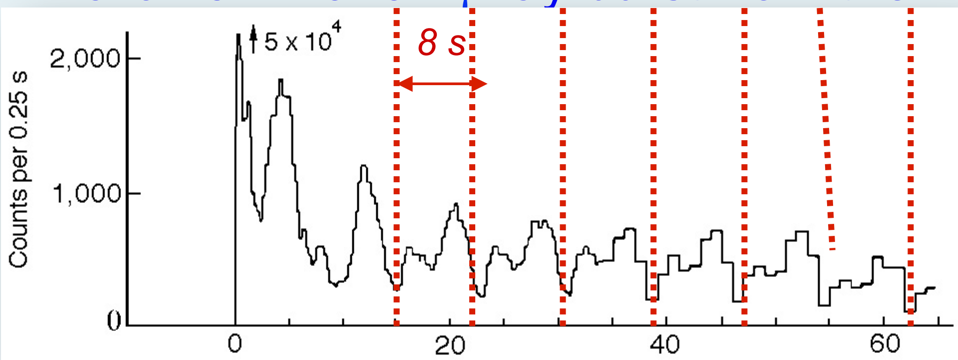
Competition with the HST spurred VLT observations





Magnetars

- March 5th 1979: γ-ray burst from the LMC



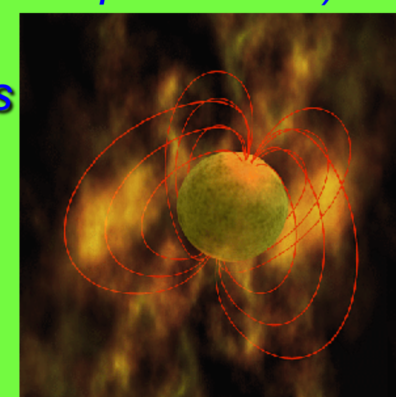
  - Recurrent (not like GRBs) → Soft Gamma-ray Repeater (SGR)
  - 8s period in the light curve
  - **Associated with young SNR**

- Anomalous X-ray Pulsars (AXPs)
  - No X-ray bursts
  - Long periods
  - **Associated with young SNR**

Magnetars ? (Duncan & Thompson 1992)

X-ray emission and bursts powered by a huge magnetic field

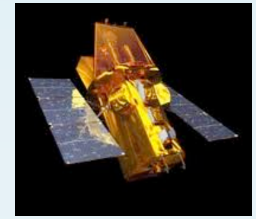
AXPs and SGRs have 10^{14} G magnetic fields

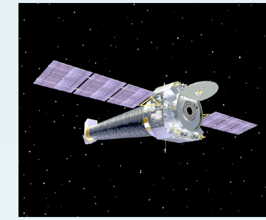


- **X-ray luminosity >> rotational energy**
- Binary or isolated ? X-ray powered by accretion? gamma-ray bursts origin ?

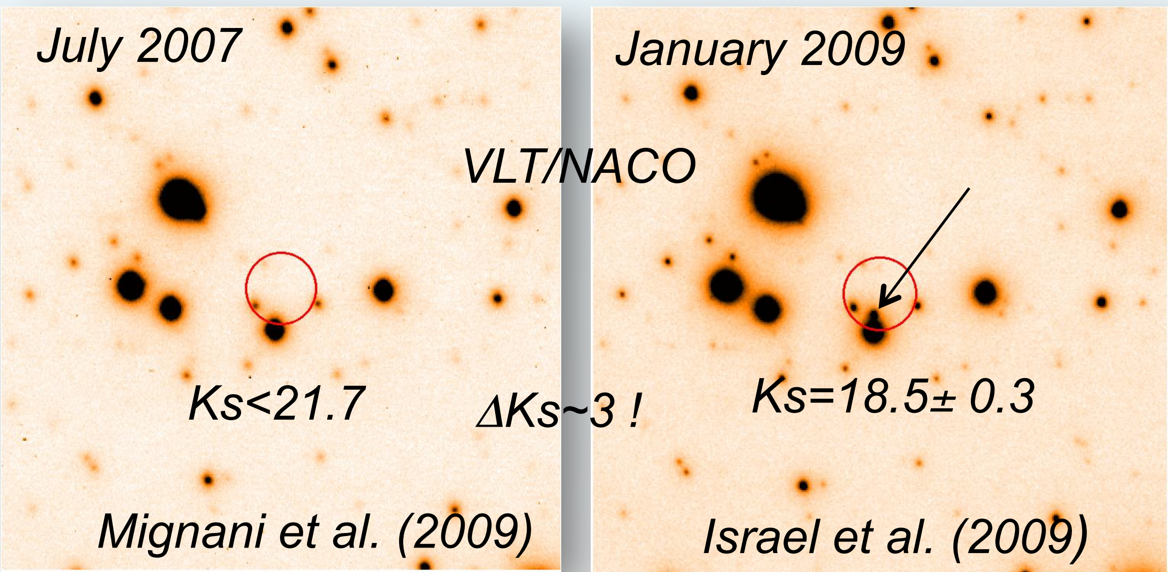
Optical/IR observations crucial to discriminate between different models

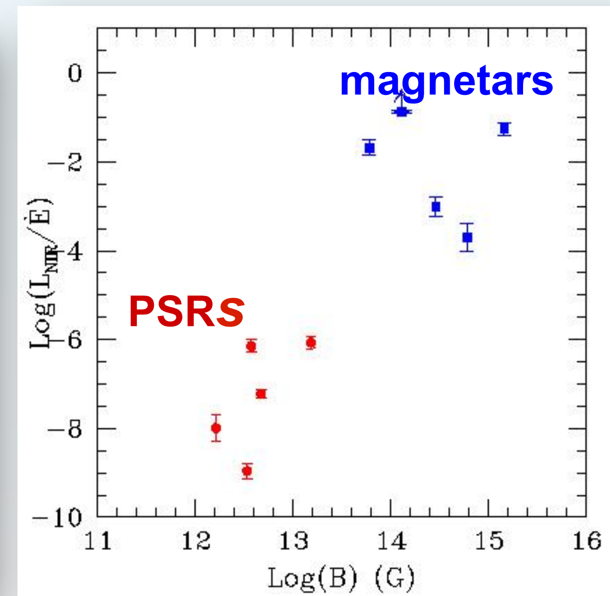
Identification strategy





- High extinction → deep IR observations
- High crowding → sub-arcsec CXO positions + Adaptive Optics IR detectors
- Bursting/transient → quick ToO response to Swift triggers
  → NACO@VLT

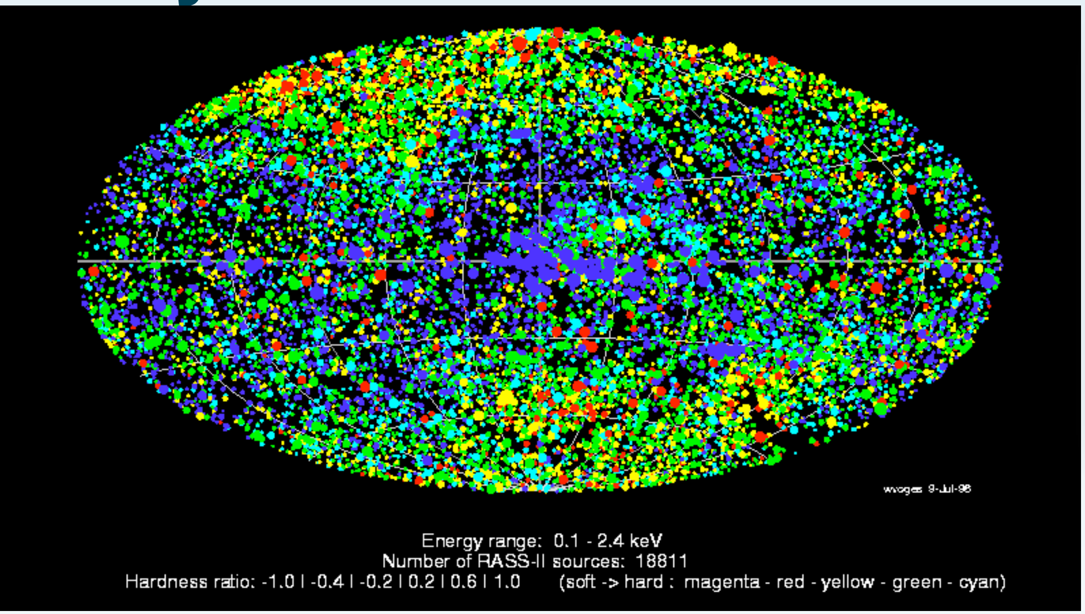


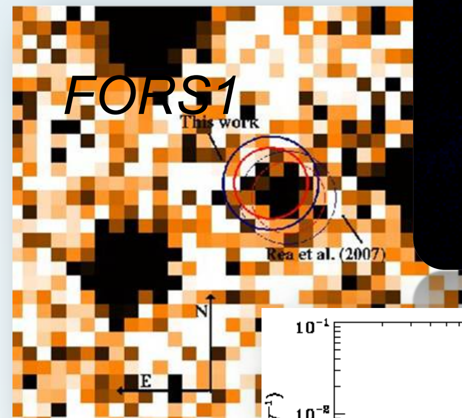


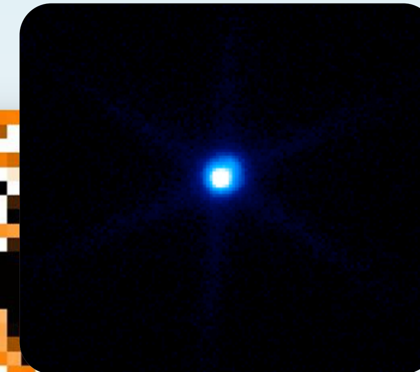
Tight constrain on accretion from a companion star or a debris disk →
observational evidence to support the magnetar model

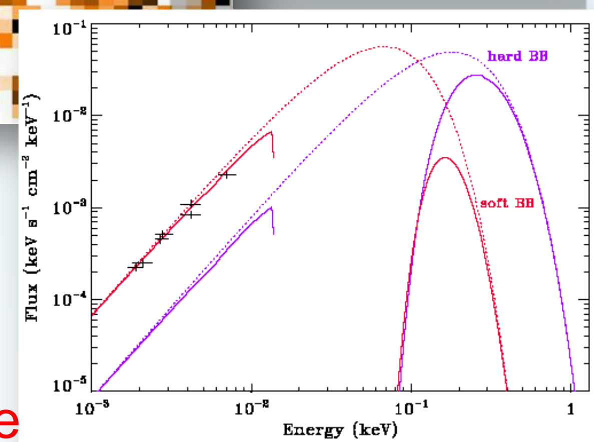
- IR emission also powered by the magnetic field (Mignani et al. 2007b)

X-ray Dim Isolated Neutron Stars









- 7 nearby sources with <u>purely thermal</u> X-ray emission found by ROSAT, not in SNR, thought to be no-longer active radio pulsars accreting from the ISM

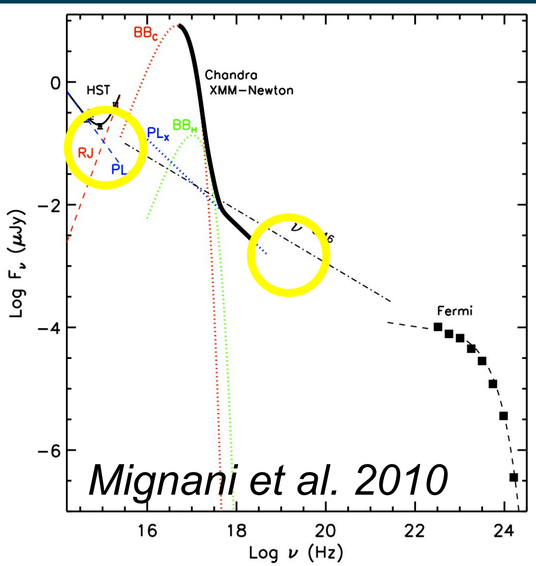
- *Deep NTT observations → extreme F_X/F_{opt} → INS identification certified*
- *Optical proper motions & parallaxes → velocity wrt ISM → **no accretion***

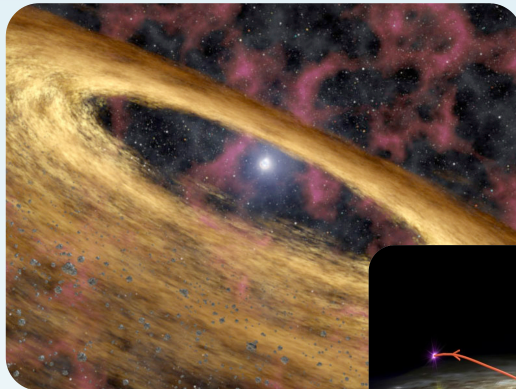
- New VLT identifications (Zane et al. 2008; Mignani et al. 2009) and study of the thermal optical spectrum – NS surface temperature distribution

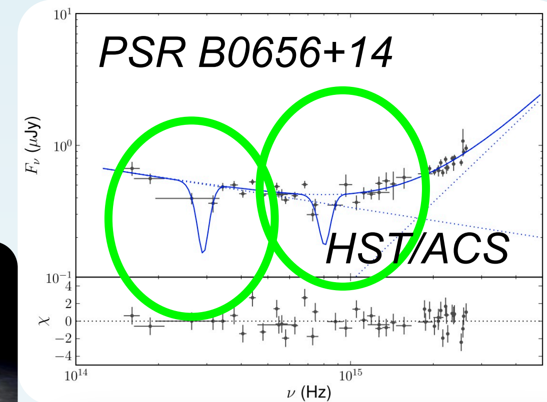
Name	Year	Age	mag	D(kpc)	A_V	Phot	Spec	Pol	Tim	Astrom
Crab	1969	3.10	16.5	1.73	1.6	UVOIR	Y	Y	P	PM
B1509-58	2000	3.19	26	4.2	5.2	OIR		UL*		
B0540-69	1984	3.22	22	49.4	0.6	OIR	Y	Y*	P	PM (UL)
Vela	1976	4.05	23.6	0.23	0.2	UVOIR	Y	Y*	P	PM,PAR
B0656+14	1988	5.05	25	0.29	0.09	UVOIR	Y	Y	P	PM
Geminga	1984	5.53	25.5	0.16	0.07	UVOIR	Y		P	PM,PAR
B1055-52	1997	5.73	24.9	<0.72	0.22	UVO				PM
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
RBS1774	2008	-	27.4	<0.5	0.2	O				
J0806-4123	2011	>6.5		<0.5	0.06	O				
J0420-5022	2009	>6.5	27.5	<0.5	0.07	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	
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				

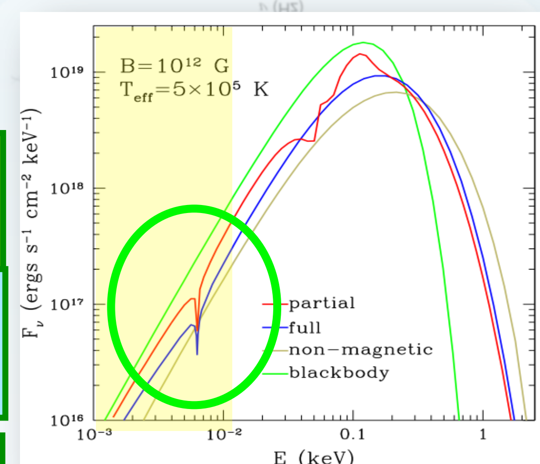
* phase-averaged

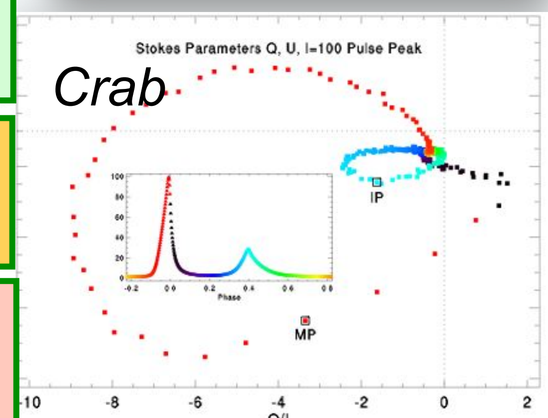
ELT potentials











⇒*Imaging:* more (and faster) multi-band detections, SKA and Fermi follow-ups

⇒*Spectroscopy:* SED, NS temp., cyclotron/atmosphere features (B field; composition), disks (size, mass)

⇒*Polarimetry:* B field in NS atmosphere/magnetosphere, PWNe and SNR polarisation maps

⇒*Timing:* pulsars, giant pulses, phase-resolved polarimetry (B field geometry) and spectroscopy (T map)

⇒*Astrometry:* proper motions up to the LMC and parallaxes at >1 kpc, ***crucial for radio-silent INSs***

E-ELT INSTRUMENT CONTRIBUTION

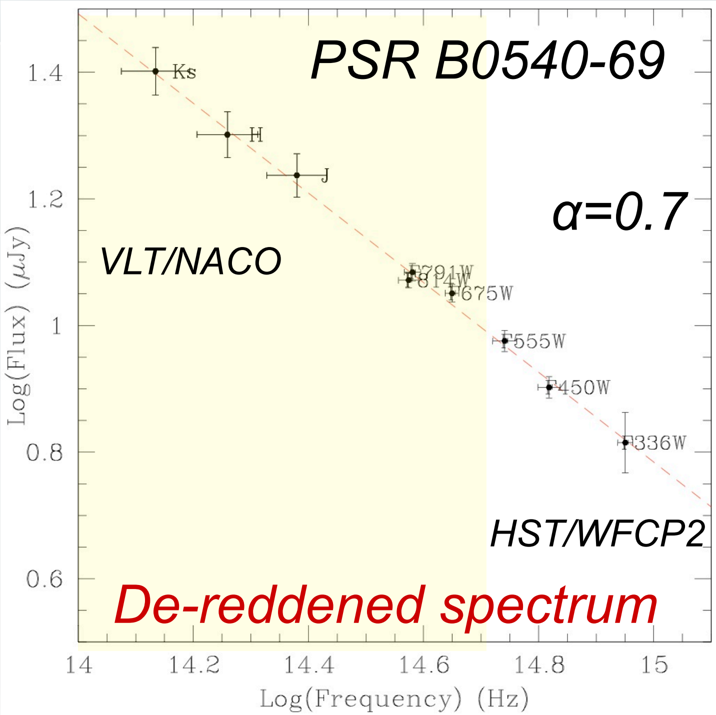
METIS - Imager/Spectrograph & Polarimeter (2.9-14 μm)
17.6"x17.6" FOV (20 ms); R ~ 900-5000

MICADO - Imager & Spectrograph (0.8-2.5 μm)
53" x 53" FOV (3 mas); R < 3000

OPTIMOS/DIORAMAS – Imager & Spectrograph (0.37-1.6 μm)
6.78' x 6.78' FOV (50 mas); R ~ 300-2500

EPICS/EPOL - Imaging Polarimeter (0.6-0.9 μm)
– 2" x 2" FOV (1.5 mas)

E-ELTs will be optimised for λ>5000 Å
but, *contrary to common belief*,
pulsars are not always **blue** objects.
They can be quite **red**

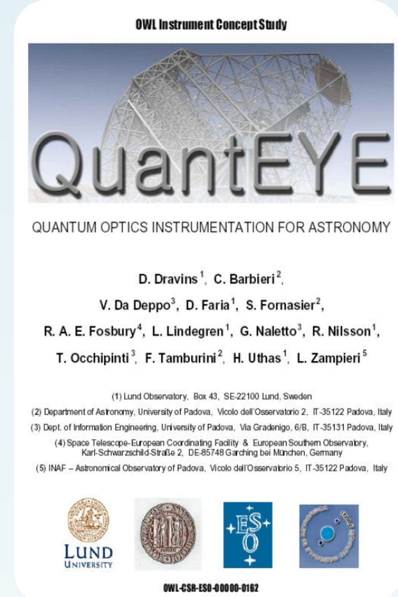


- What about timing ??

Mignani et al. (2012a)

A Quantum Eye for the E-ELT

- *QuantEye:* pilot study for the *OWL* 100m telescope (Dravins et al. 2005), based on quantum detectors technology
  pico-s time resolution



OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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V. Da Deppo[3], D. Faria[1], S. Fornasier[2],
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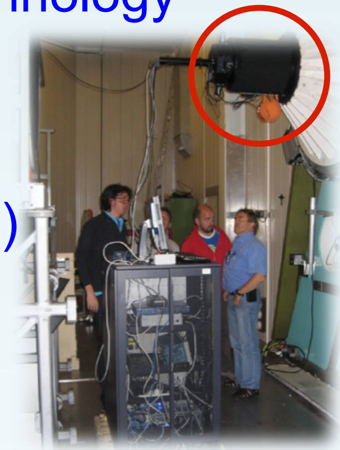
LUND UNIVERSITY

OWL-CSR-ESO-00000-0162



- ➢ *AQuEye@*Asiago 182cm (Barbieri et al. 2009)
- ➢ *IQuEye@NTT (*Naletto et al. 2009*)*

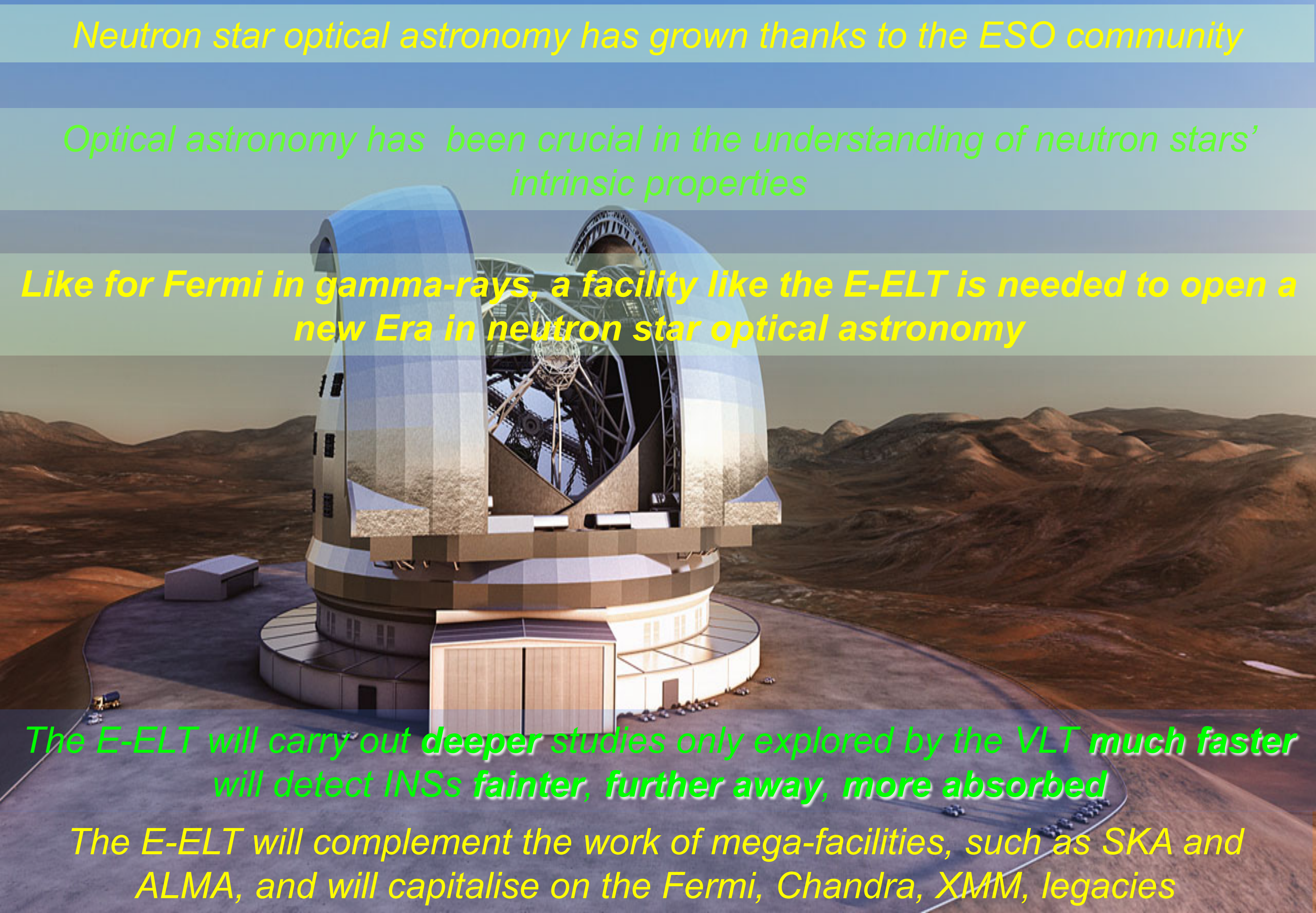
- VLT prototype *(VQuEye)* under study – PI C. Barbieri (U. Padua, Italy) and proposal submitted to ESO for an E-ELT prototype (*EQuEye*)

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

Submitted by: Cesare Barbieri[1] as P.I
and by: Giovanni Bonanno[2], Dainis Dravins[3], Roberto Mignani[4], Giampiero Naletto[1], Erez Ribak[5], Andrea Richichi[6], Andrew Shearer[7], Luca Zampieri[2] as Co.I.'s

[1]University of Padova, Italy; [2]INAF, Italy; [3]Lund Observatory, Sweden;[4]MSSL, UK; [5]Technion, Haifa, Israel; [6]ESO and NARIT Thailand; [7]NUI Galway, Ireland



Neutron star optical astronomy has grown thanks to the ESO community

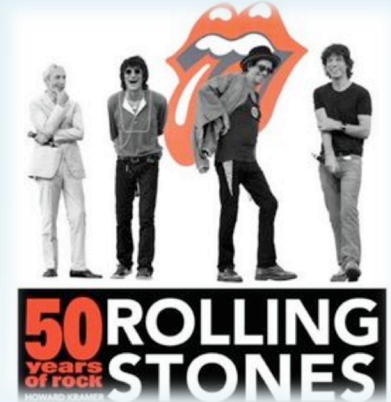
Optical astronomy has been crucial in the understanding of neutron stars' intrinsic properties

Like for Fermi in gamma-rays, a facility like the E-ELT is needed to open a new Era in neutron star optical astronomy

*The E-ELT will carry out **deeper** studies only explored by the VLT **much faster** will detect INSs **fainter**, **further away**, **more absorbed***

The E-ELT will complement the work of mega-facilities, such as SKA and ALMA, and will capitalise on the Fermi, Chandra, XMM, legacies

The 2012 Golden Jubilees



50 YEARS 1962–2012

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