Neutron Star Astronomy in the E-ELT Era

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- On behalf of the OPTICON HTRA Working Group -

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Science Background

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Overview

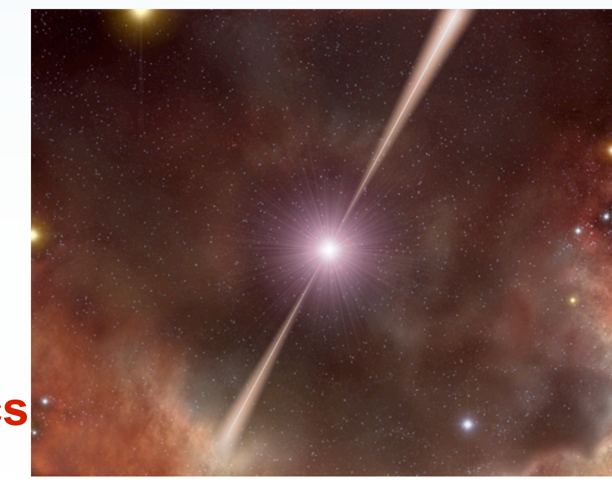
- After their discovery in 1967, **~1800** pulsars have been identified in radio
  - $P = 1.5$ ms - 10 s
  - $dP/dt = 10^{-20} – 10^{-11}$ s s^{-1}

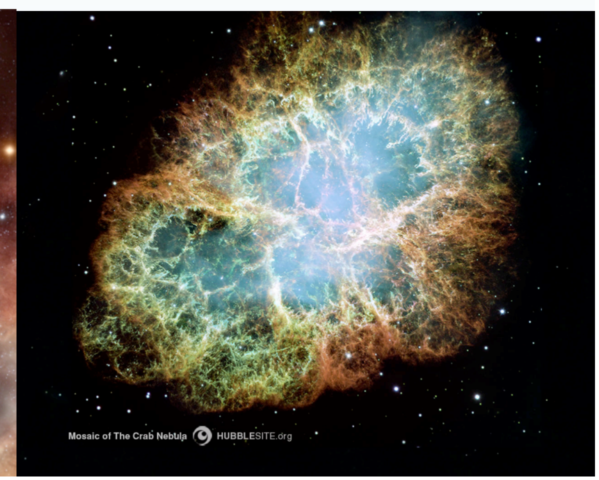
- **Fast spinning Isolated Neutron Stars** (INSs) born in **SN explosions** (Pacini 1968; Gold 1968) from progenitors of **8-20 M_{Sun}**

- $R_{NS} \approx 10$ km
- $M_{NS} \approx 1.4\ M_{sun}$
- $\rho_{NS} \approx 10^{14}$ g cm^{-3}

- Magnetic dipole model ($I=10^{45}$ g cm^2)
  - $B_p = 3x10^{19} (PxdP/dt)^{1/2}$ G
  - Age = P/(2 dP/dt) yrs
  - Edot = 2π (dP/dt)/P^2 erg/s

- **Radio observations alone do not yield to a complete understanding of NS physics**





Multi-wavelength observations of NSs

- Together with AGNs, pulsars are the only astrophysical objects which feature a **complete multi-wavelength phenomenology**, from radio to high-energy γ-rays
- The first pulsars to be detected outside the radio band was the **Crab**, detected **in X-rays** through balloon-borne experiments, right followed by the **Vela** pulsar
- The Crab and Vela pulsars were soon after detected in **γ-rays** by the NASA *SAS-2* satellite
- The 1980s/90s marked a turnover with many more pulsars detected in X-rays by *Einstein, ROSAT, ASCA* and in the γ-rays by *GRO*
- By now, thanks to *XMM*, *Chandra, Suzaku,* a total of **~90 pulsars** have been detected in **X-rays**, while **~50** have been detected in **γ-rays** by *Fermi*
- What about the optical/UV/IR (UVOIR)?

Science Background

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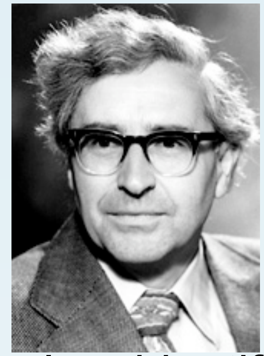
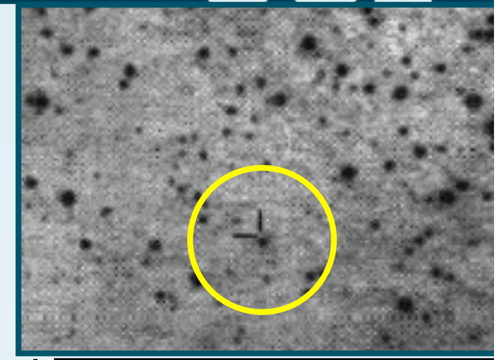
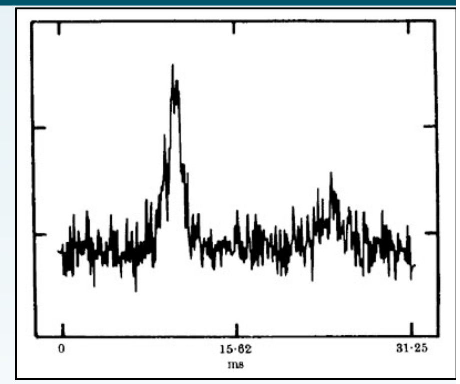
The First Years





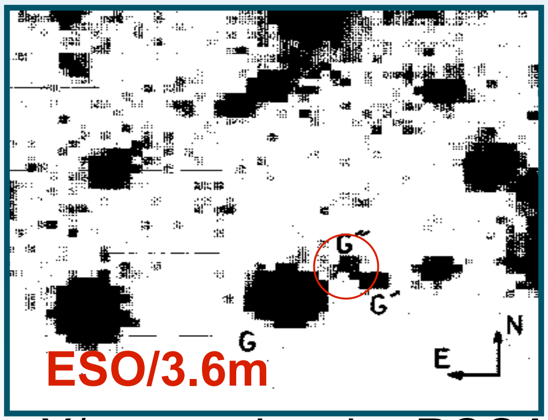
- The first pulsar B1919+21 (Hewish et al. 1968) was the natural target for optical observations (Ryle & Bailey 1968, **Nature**, 217, 907)
- The Crab (aka Baade's star) was the first optical pulsar identified (Cocke et al. 1969, **Nature**, 221, 525)

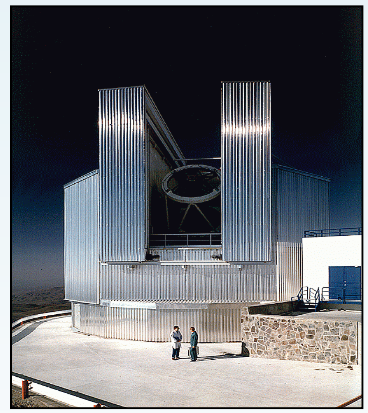


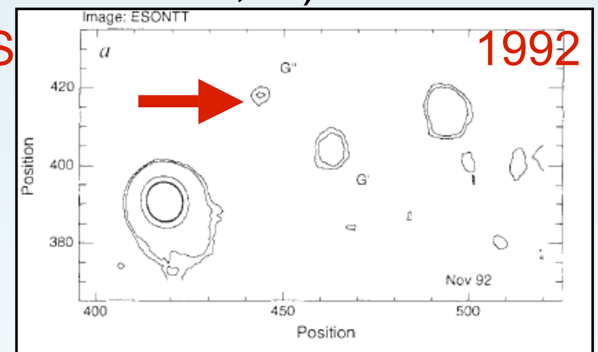
- The Crab optical polarisation was measured soon after (Cocke et al. 1969, **Nature**, 223, 576)
- Next most promising target: the Vela pulsar (Cocke et al. 1969, **Nature**, 222, 359)
- First attempts (Warner & Nather 1969, **Nature**, 222, 254; **Nature**, 223, 281; Hesser 1969, **Nature**, 223, 485) unsuccessfull
- Optical counterpart (Lasker 1976) confirmed by pulsations (Wallace et al. 1977, **Nature**, 266, 692)
- Optical pulsar (PSR B0540-69) discovered in the LMC (Middleditch & Pennypacker 1985, **Nature**, 313, 659)

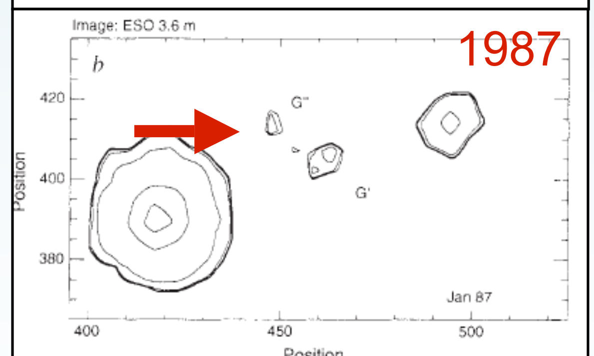
The turn-off years

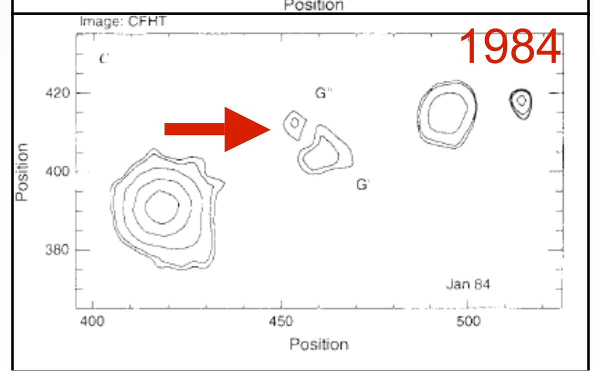
- Geminga, an unidentified γ-ray source discovered by *SAS-2* and *COS-B*
- X-ray counterpart from *EINSTEIN* (Bignami et al. 1983)
- V=25.5 counterpart from the *CFHT* & *ESO/3.6m* (Bignami et al. 1987,88) ⇒ INS
- Proper motion with *NTT/SUSI* (Bignami et al. 1993) ⇒ INS



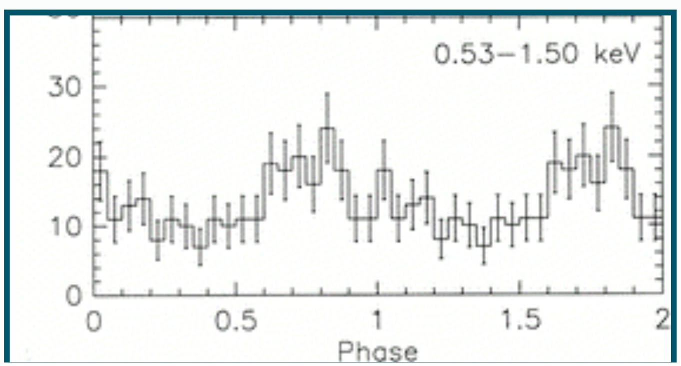


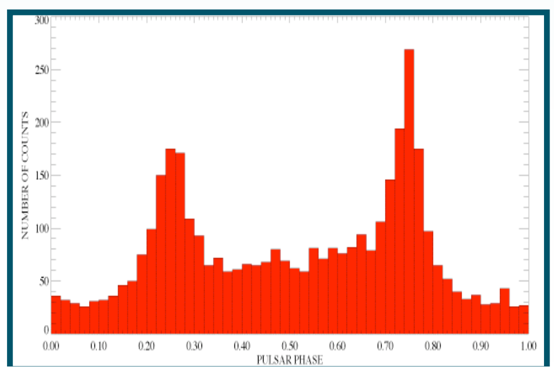






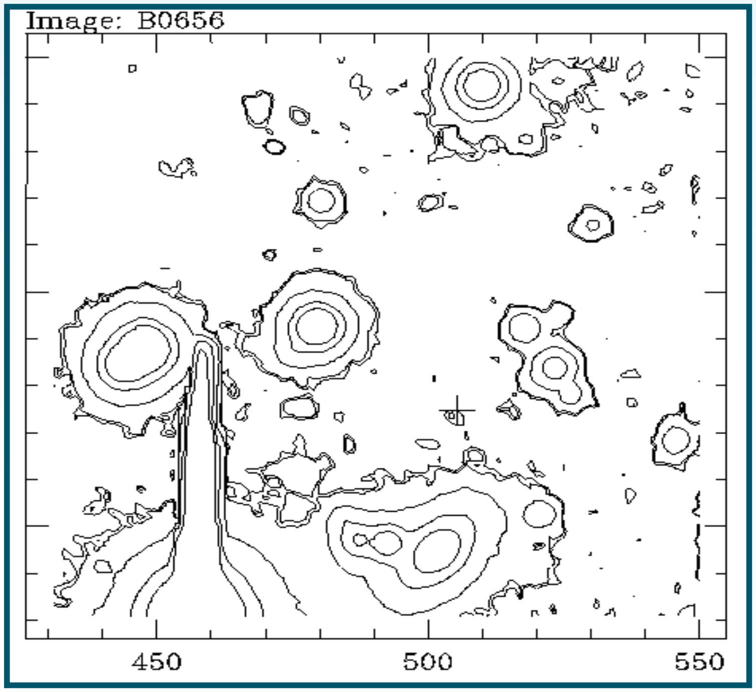
- Identified as an X/γ-ray pulsar by *ROSAT/GRO* (Halpern&Holt 1992; Bertsch et al. 1992)
- The first radio-silent pulsar !

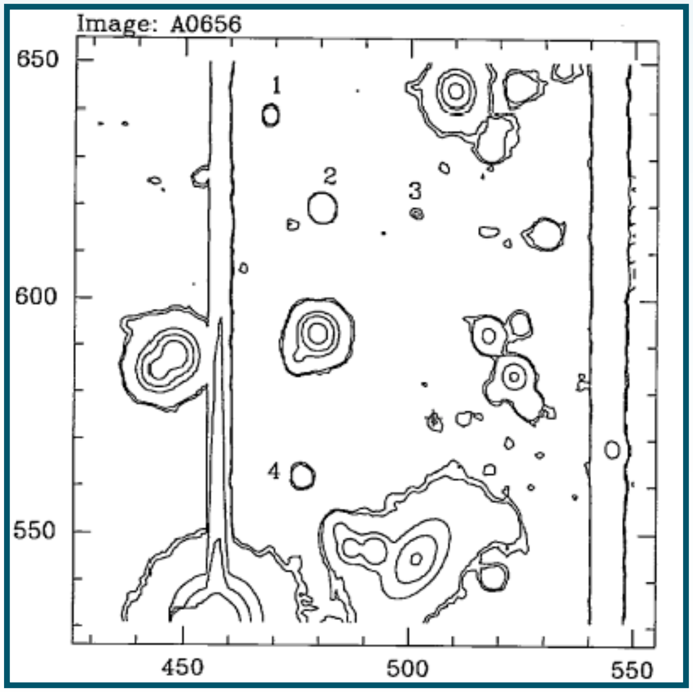




Riding the Wave

- PSR B0656+14 was the next target: a pulsar of the Geminga class (but radio loud), also detected in X-rays by *EINSTEIN*
- Possible optical counterpart (V=25) identified in *ESO/3.6m* images in 1989
- Counterpart detection confirmed by *NTT/EMMI* observations (Caraveo et al. 1994a)





The NTT Era

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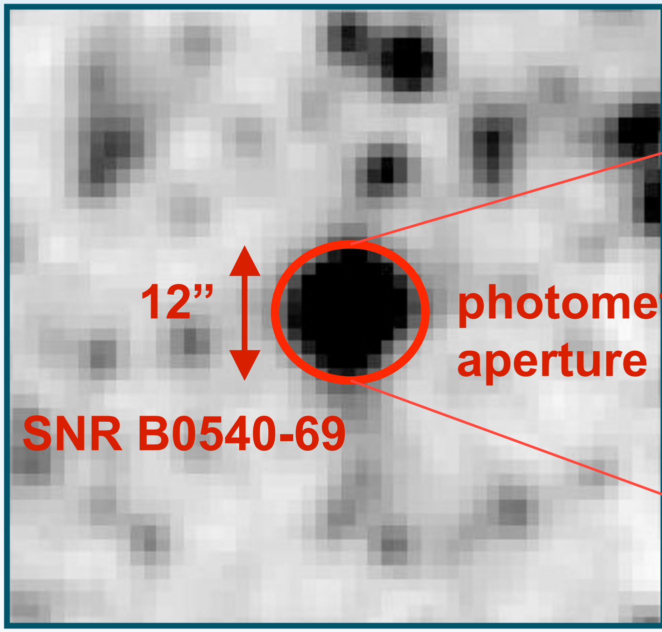
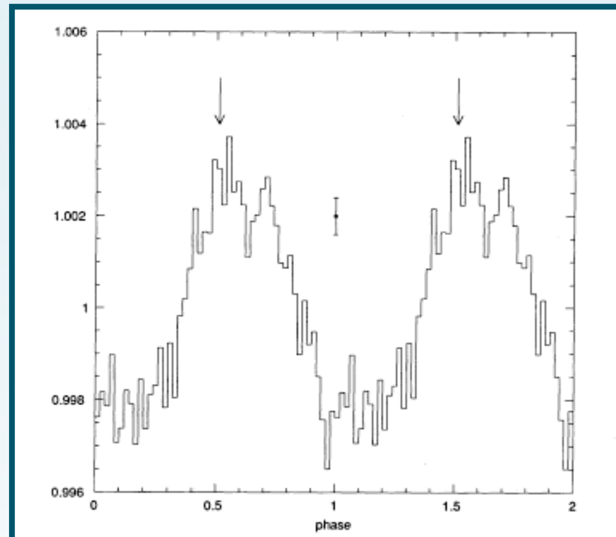
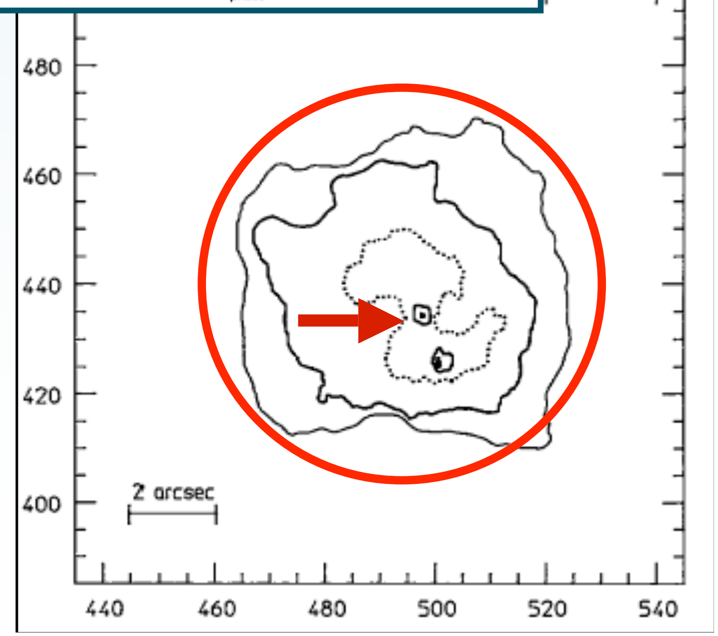
Riding the Wave (cnt’d)







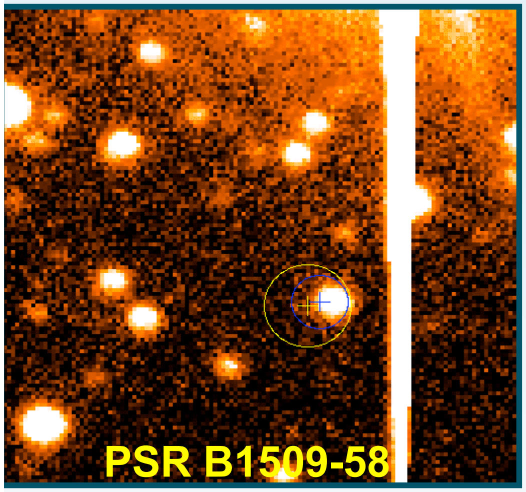
- Timing of the LMC PSR B0540-69 at the *3.6m* allowed to measure the dP/dt and its derivative ⇒ the braking index (Gouiffes et al.1992), ν scaling as a power law

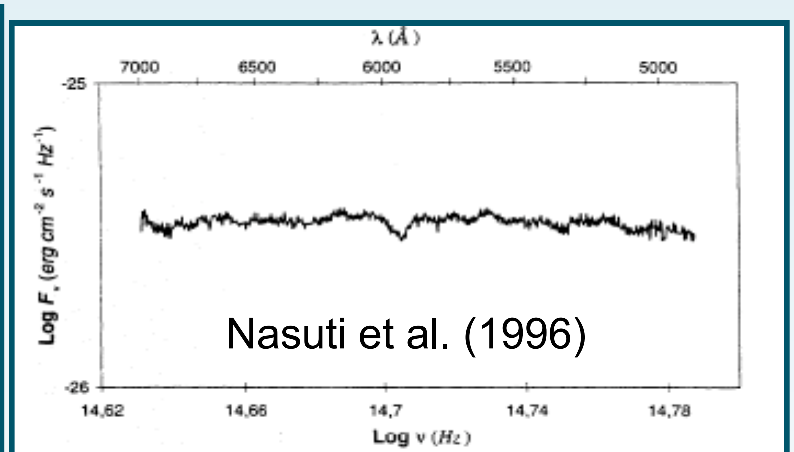
- High-resolution imaging with *NTT/SUSI* identified a likely V=22.5 counterpart (Caraveo et al. 1992)

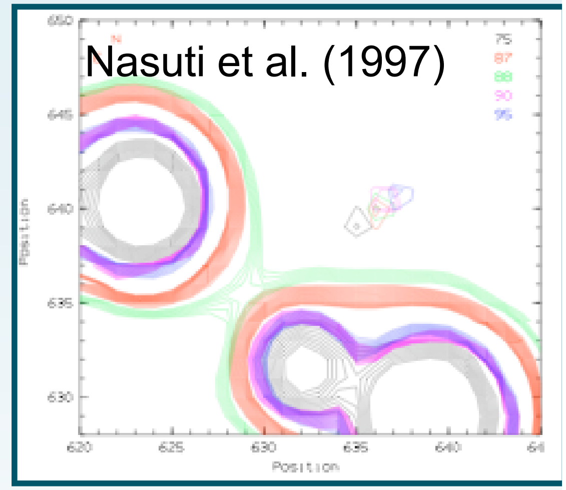
- Confirmed by time-resolution imaging at the NTT (Shearer et al. 2004) with the *TRIFFID* guest instrument

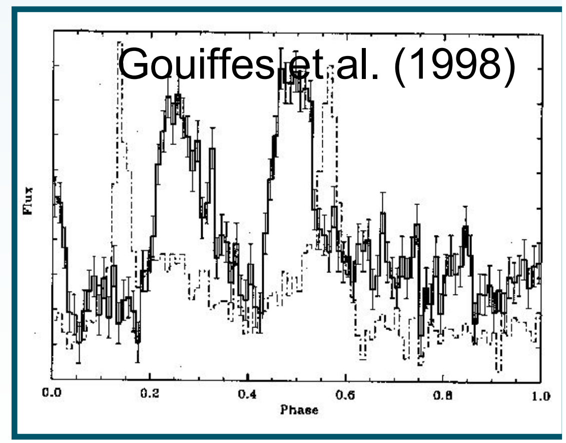
Riding the Wave (cnt'd)

- Pulsar observations continued both with the *NTT* and the *3.6m* (Mignani et al. 2000)









- Exploratory observations of several other pulsars
- The first high quality optical spectrum of the Crab
- The first proper motion ever of the Vela pulsar
- Monitoring of the Vela pulsar light curve
- Take part to the search for the pulsar in SN 1987A

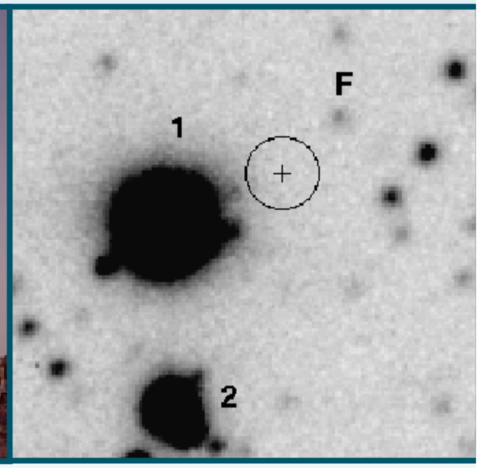
¬ **The *NTT* score triggered interest from the community.**

¬ **A new horizon was opened for pulsar studies !**

¬ ***NTT* observations paved the way to follow-up observations with the *HST***

The Wave does not break

- Optical observations of pulsars was a test case for the *VLT/UT1* Science Verification



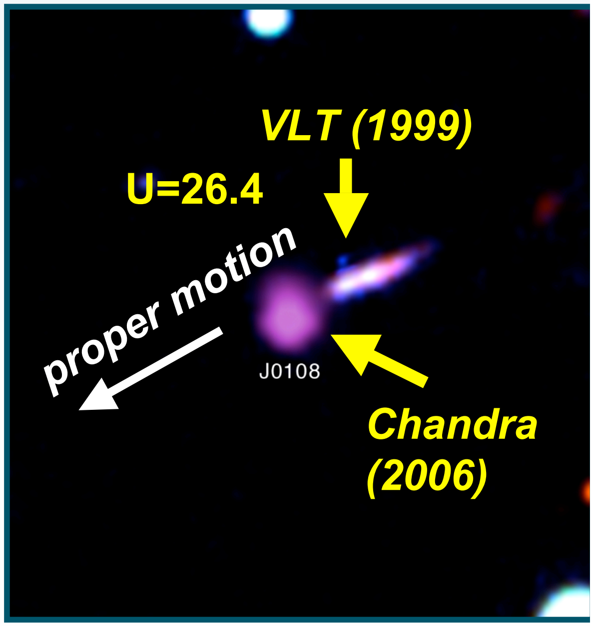
- The Vela-like PSR B1706-44 observed with the *Test Camera* (Mignani et al. 1999)

- First paper submitted from VLT !

- Pulsar observations continued with *FORS* and *ISAAC*

- Likely identification of the pulsars PSR J0108-1431 (Mignani et al. 2008) and B1133+16 (Zharikov et al. 2008)

- The first detection of the Vela pulsar in the IR (Shibanov et al. 2002)



The VLT Era

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More in-depth investigations

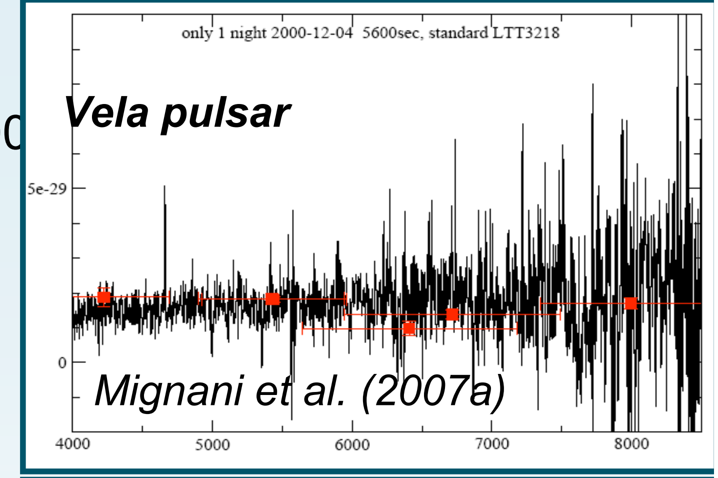
- **Infrared spectrum** of the Crab (Sollerman et al. 2000)

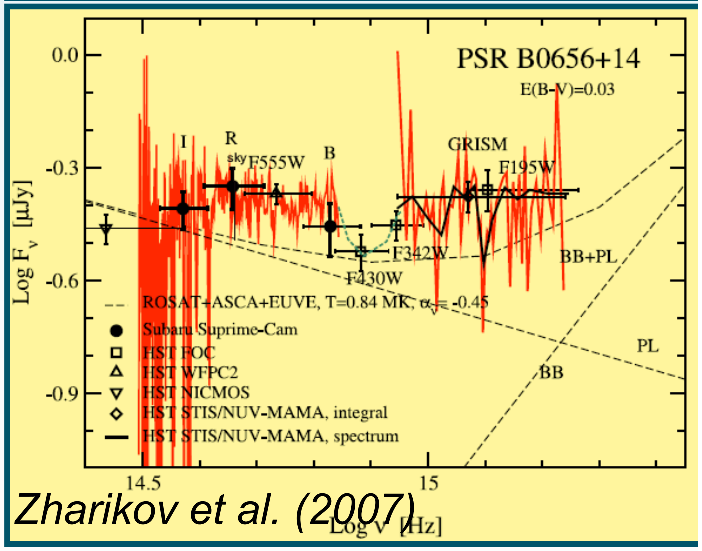
- **Optical spectrum** of Vela, PSR B0656+14 and the LMC pulsar B0540-69 (Serafimovich et al. 2004)

- Multi-band photometry follow-up of *HST* detections (e.g., Zharikov et al. 2004)

- The first **optical polarimetry** observations of pulsars (Wagner&Seifert 2000; Mignani et al. 2007b), with P~5%-10% level (*albeit with large errors*)

- **Pulsar timing** tested on the Crab with the *FORS2 HITI* mode (ESO PR 40/99). Mostly carried out with guest instruments (e.g. *U-Cam*)

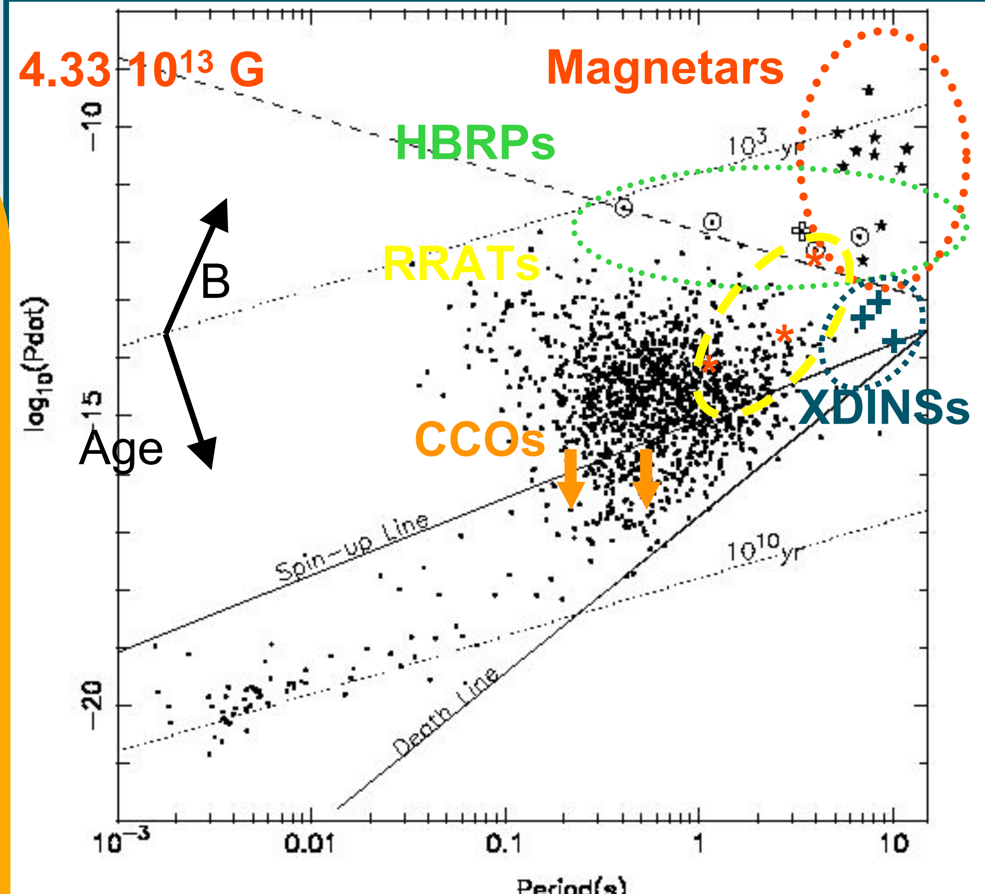


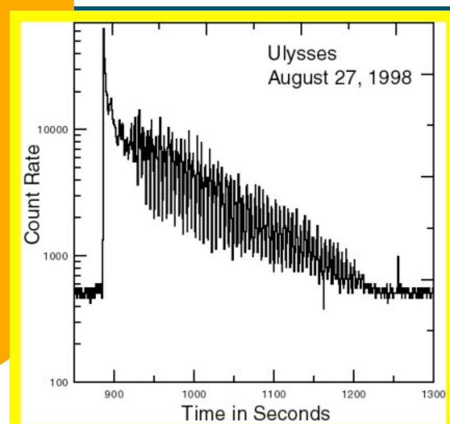


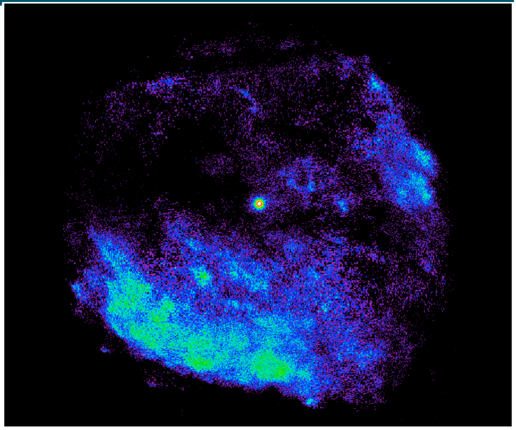
- The pulsar optical emission is due to the combination of **synchrotron radiation** (neutron star magnetosphere) and **thermal radiation** (neutron star surface)

Discovery of new INSs

- **Central Compact Object (CCOs)**
- P=0.105-0.424s
- T> 100 kyrs ; >> SNR age
- Born slowly spinning with low ($B < 10^{11}$ G) magnetic fields (**anti-magnetars**)
- Binary systems in SNRs ?
- Ultra-slow magnetars ?







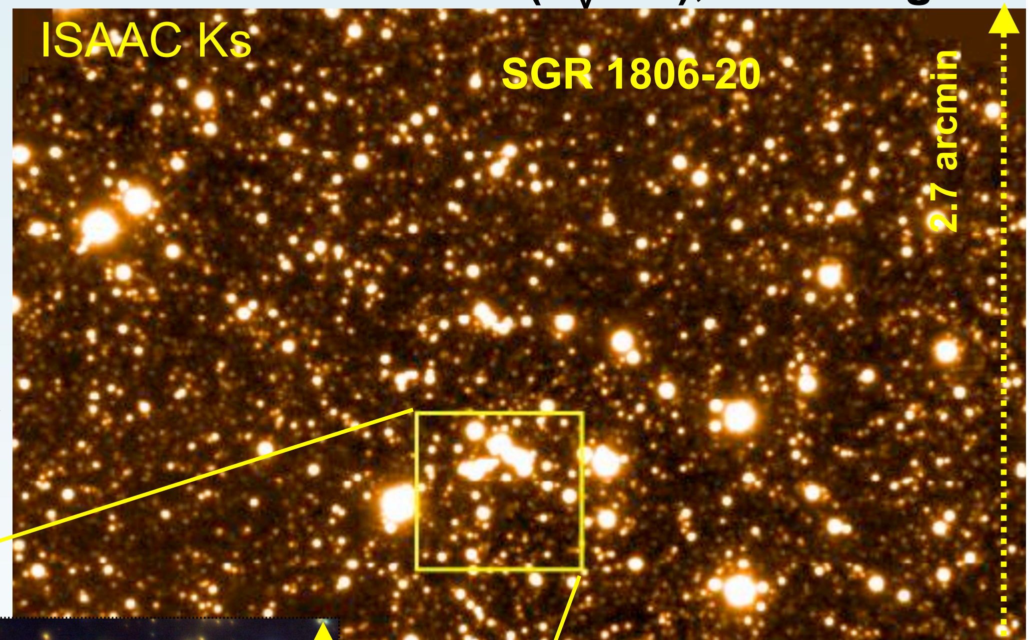
VLT observations of Magnetars

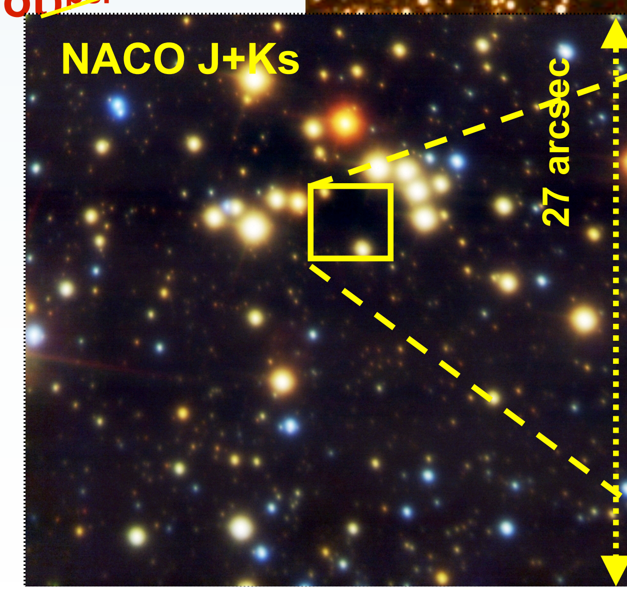
- Magnetars are at 3-15 kpc in the Galactic Plane ⇒ **extinction (A_V~30), crowding**
- Deep, high resolution **AO** imaging
- Bursting ⇒ **quick ToO** response to a *Swift* trigger.
- Most magnetars identified by VLT

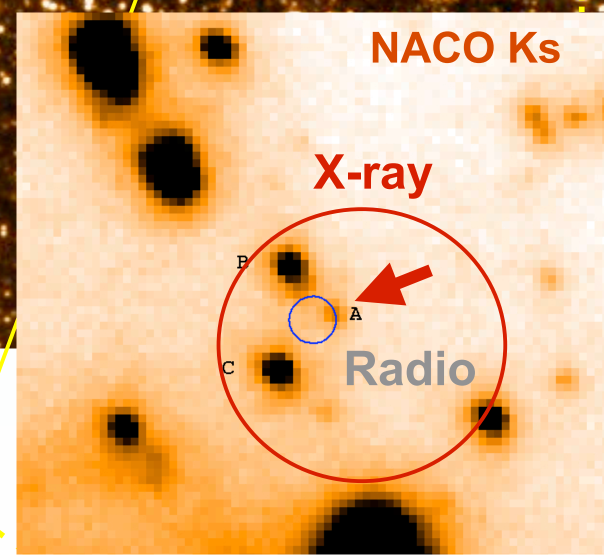
- Accretion models ruled out ⇒ support the magnetar scenario

- **$(L_{IR}/Edot)^{mag}$ >> $(L_{IR}/Edot)^{psr}$**

- IR also powered by the **magnetic field** or by X-ray reprocessing in a **fallback disc** formed out of the SN ?



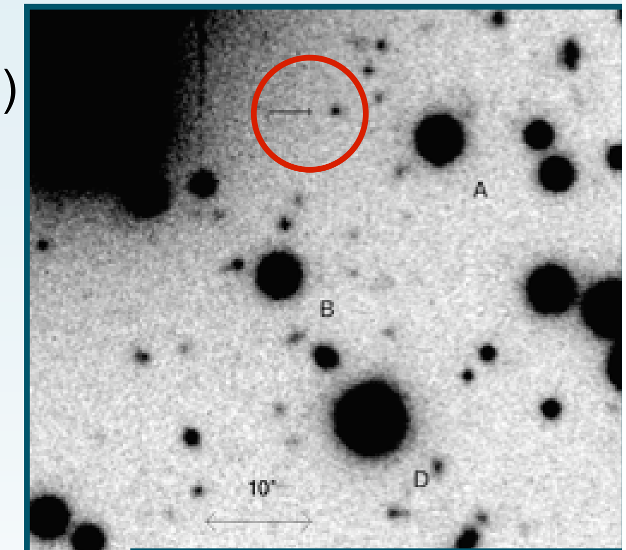




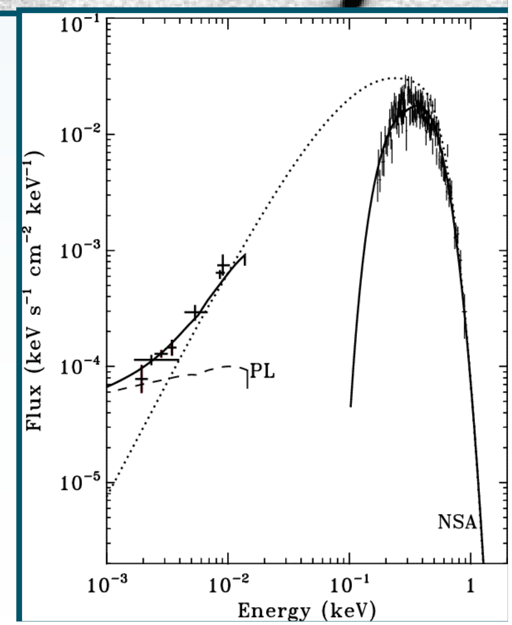
The VLT Era

VLT observations of X-ray Dim INS

- Optical identification of RX J0720.4-3125 with the *NTT* (Motch&Haberl 1998)



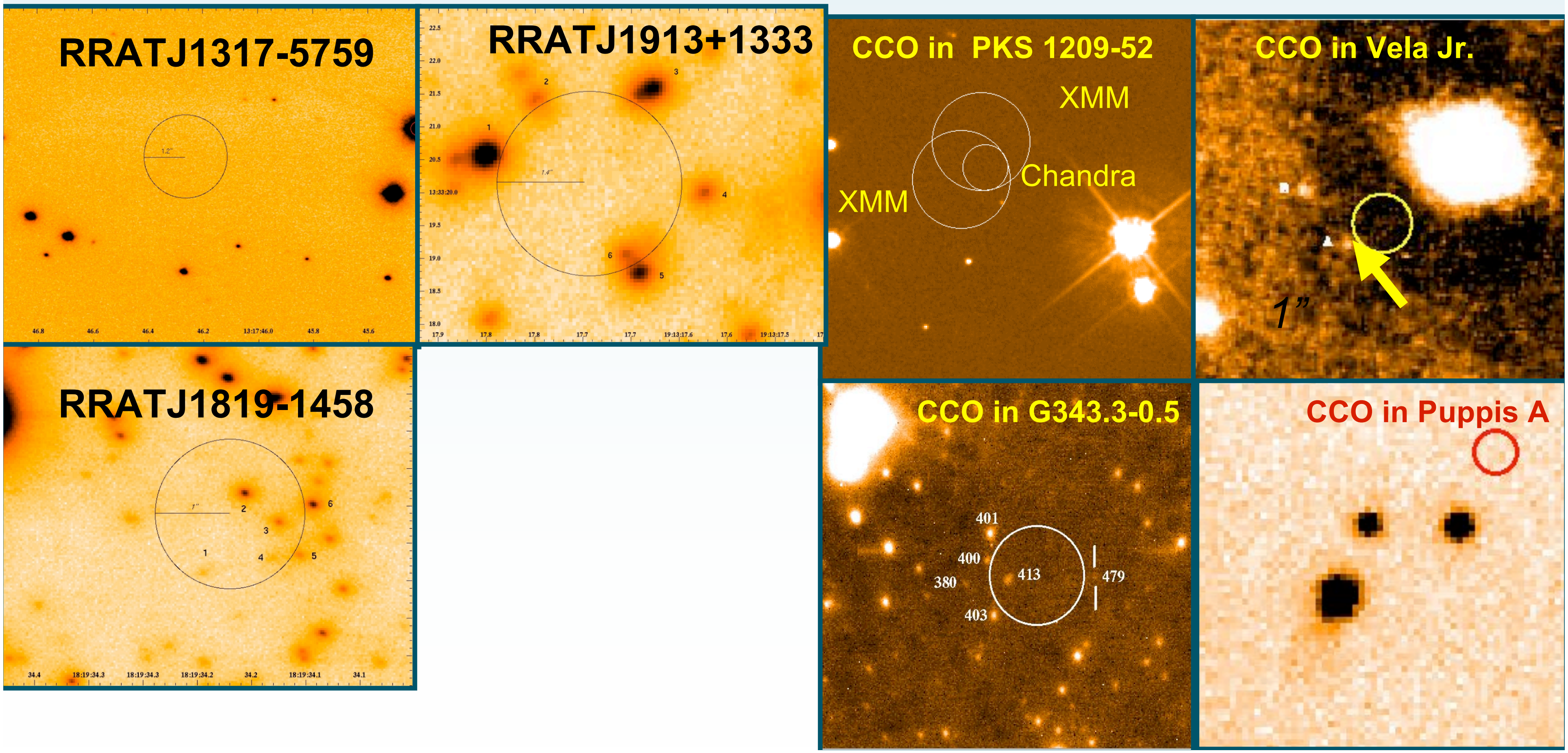
- Proper motion measured with the *VLT* (Motch et al. 2003)
- *HST* parallax ⇒ V>>10 km s^{-1} ⇒ **no ISM accretion**
- **X-ray/optical thermal radiation** from the NS surface
- Evidence from *VLT* low-resolution spectroscopy of RX J1856-3754 (Kulkarni & van Kerkwijk 2001)
- However, not the case for RBS 1774 (Zane et al. 2008), the X-ray Dim INS **with the largest magnetic field**



- Non-thermal radiation **powered by the magnetic field** ?
- **A possible link with the magnetars** ?

VLT observations of other INSs

- For all other INS types, the *VLT* took the lead of optical/IR follow-ups
- CCO upper limits consistent with undetected <M5 companion, NS, disc (Mignani et al. 2007; 2008; 2009)
- For the RRATs, deep investigations still in progress (Rea et al. 2009)



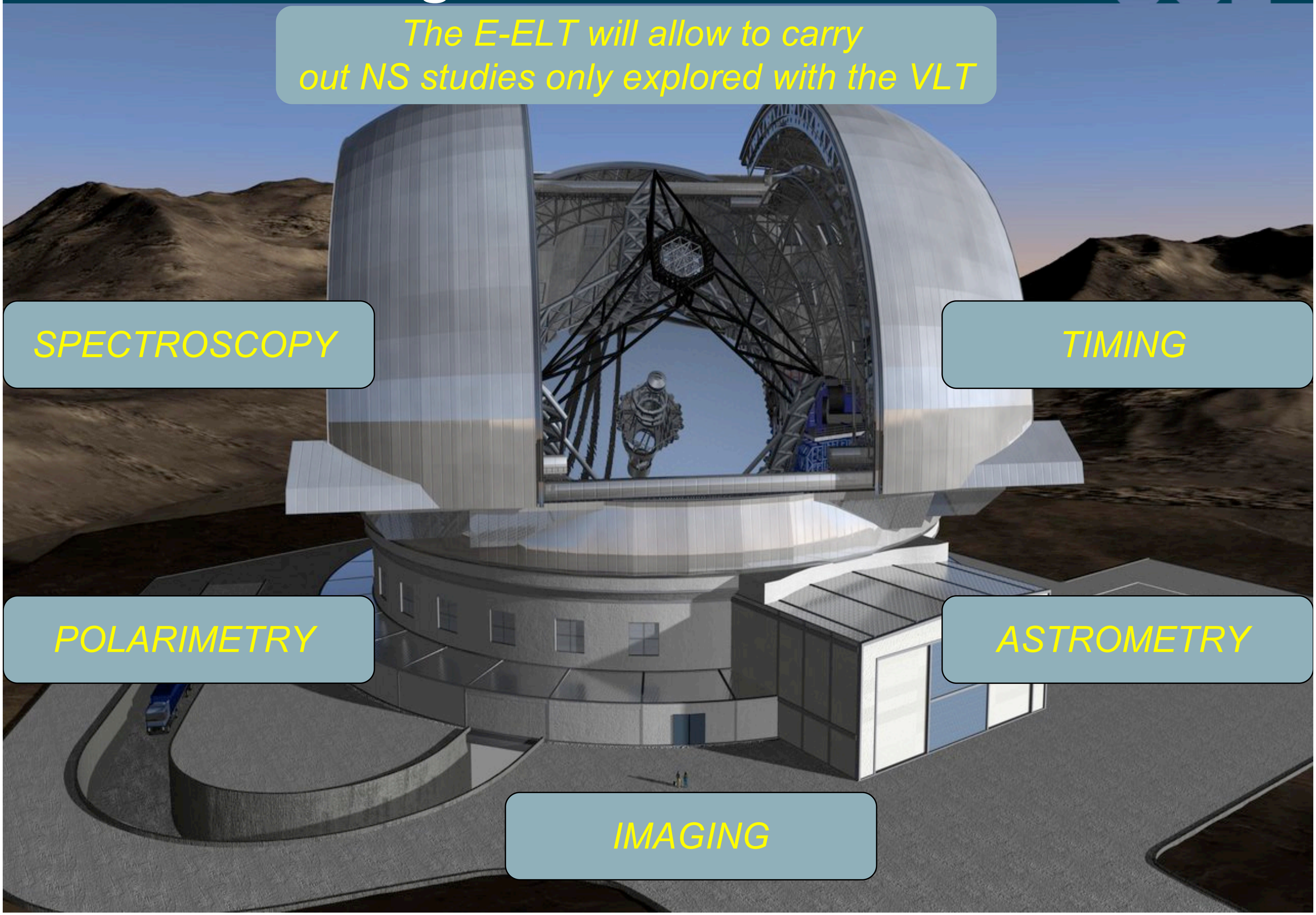
The Full Monty

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

Need for a colleting power larger than that Of the VLT

Moving into a New Era

The E-ELT will allow to carry out NS studies only explored with the VLT



SPECTROSCOPY

TIMING

POLARIMETRY

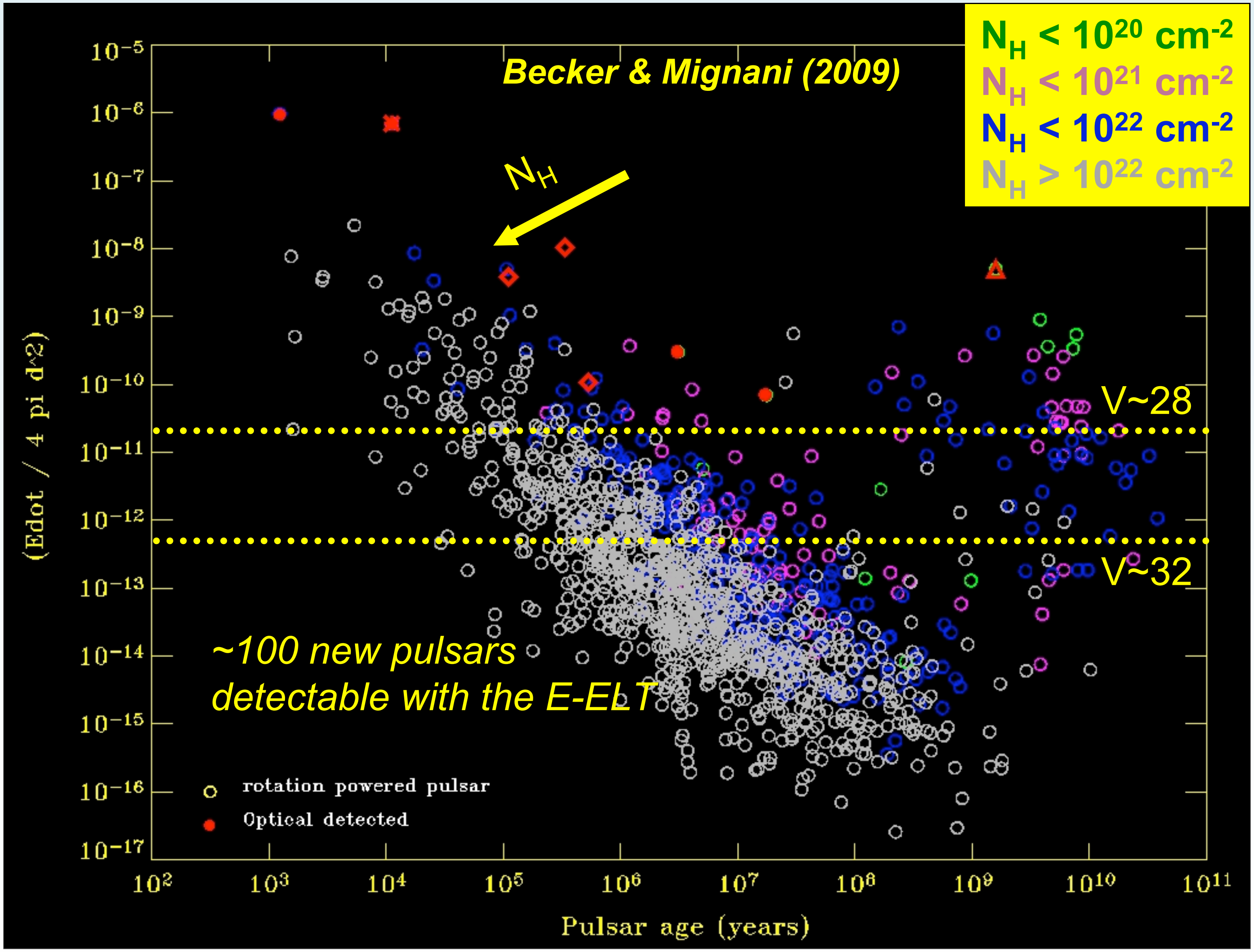
ASTROMETRY

IMAGING

Science Cases for the E-ELT: NS Imaging

- Imaging gives detections. AO to cope with crowding in the GC.
- Radio-loud INSs still represent the largest fraction of the known INS population
- Natural targets for INS imaging with the *E-ELT* (*positions more accurate, distance known from Dispersion Measures, pulsar parameters from timing*)
- After 40 years, the optical emission properties of pulsars are still poorly understood
- More detections are needed to test the predictions of the $L_{opt} \propto B^4 P^{-10}$ (Pacini & Salvati 1983)
- More detections are needed to study the dependence of the optical luminosity vs. the pulsar age and the Edot $L_{opt} \propto Edot^{\alpha}$, where α~0.9-1.6 (Shearer et al. 2001; Mignani et al. 2004)
- More generally, a statistically improved sample is needed for a comparison of the pulsar behavior at   other wavelengths

The E-ELT Era



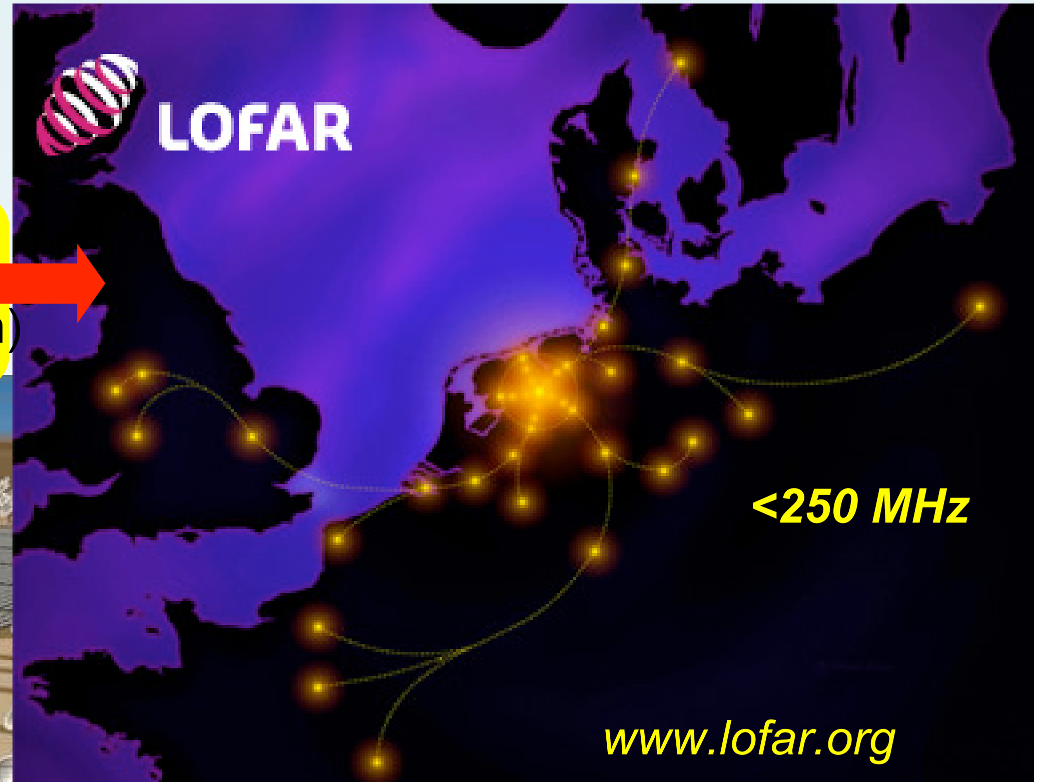
Becker & Mignani (2009)
$N_H < 10^{20}$ cm^{-2}
$N_H < 10^{21}$ cm^{-2}
$N_H < 10^{22}$ cm^{-2}
$N_H > 10^{22}$ cm^{-2}
N_H
V~28
V~32
~100 new pulsars
detectable with the E-ELT
rotation powered pulsar
Optical detected
(Edot / 4 pi d^2)
Pulsar age (years)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

Science Cases for the E-ELT: NS Imaging

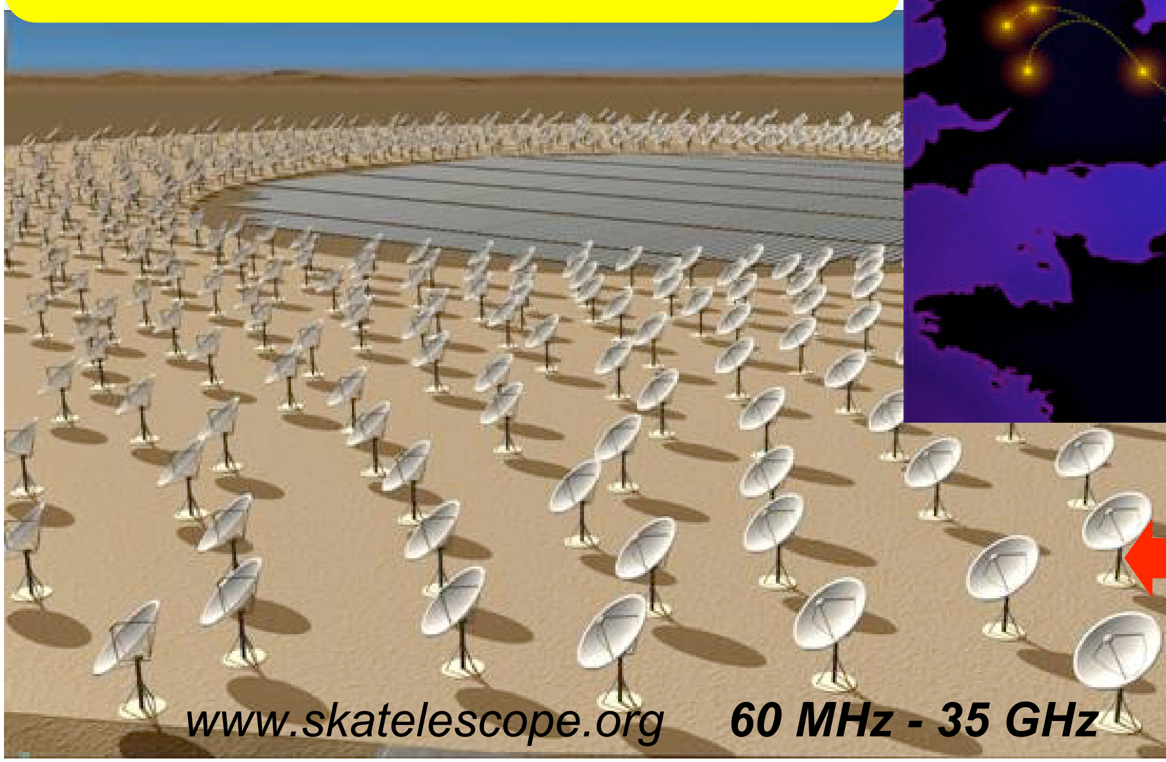
- **1000s** of new pulsars to be discovered by future radio surveys

- Wherever the *E-ELT*, major radio facilities planned in both hemispheres

Low Frequencies Array - LOFAR
(NL, UK, France, Germany, DK, Sweden)



Square Kilometer Array - SKA
(South Africa or Australia)



The E-ELT Era

Science Cases for the E-ELT: NS Imaging

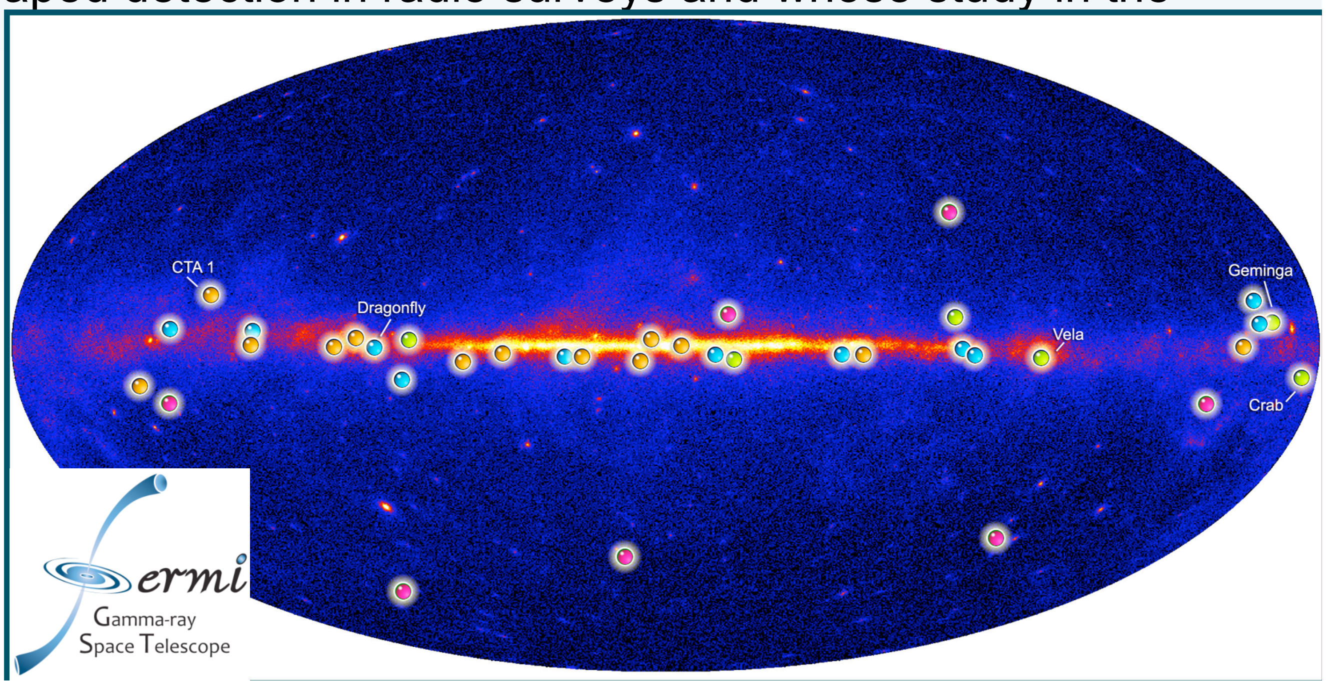
- Optical/IR detections proved crucial to understand the nature of peculiar, radio-silent, INSs detected through X-ray observations

Advances in X-ray satellites require advances in optical/IR telescopes for deeper follow-ups

- 1990s: *ROSAT* and *NTT*
- 2000s: *XMM* and *VLT*
- **2020s: *IXO and E-ELT***

- Like Geminga, many more radio-silent INSs are now emerging in γ-rays from *Fermi* observations, which escaped detection in radio surveys and whose study in the optical/IR might need the *E-ELT*

- **E-ELT is not too late!** Multi-λ follow-ups will continue beyond the *Fermi* operational lifetime



The E-ELT Era

Science Cases for the E-ELT: NS Spectroscopy

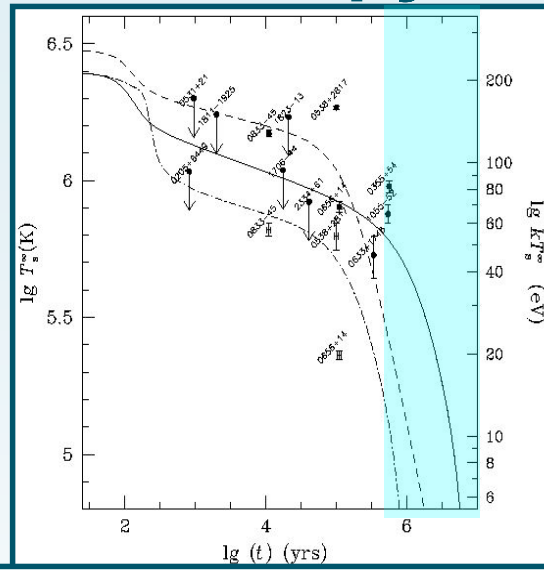
- **Spectroscopy** will allow to:

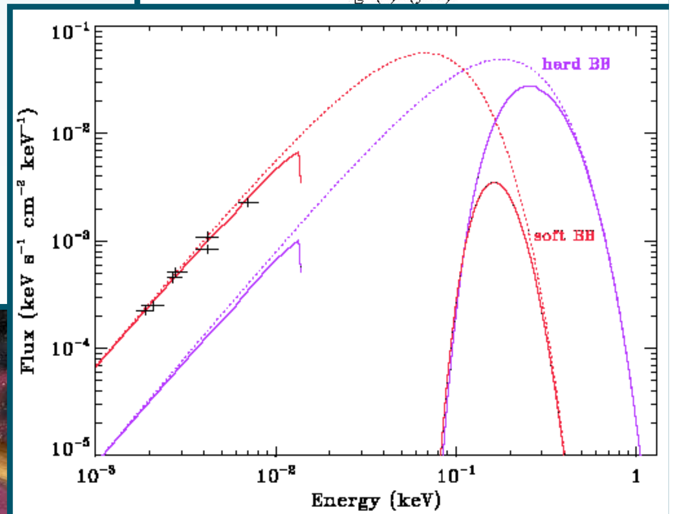
  - **better disentagle spectral components**
  - find spectral features (e.g. cyclotron) and **direct measurement** of the NS magnetic field
  - find features from ISM/disc accretion, atmosphere

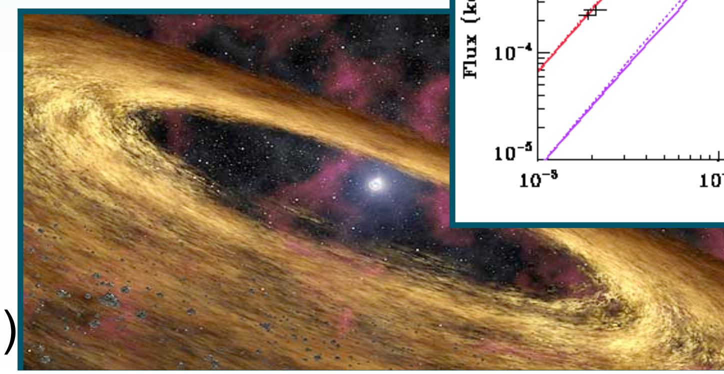
  - **determine the temperature of thermal radiation**
  - test cooling curve models
  - better map the temperature distribution
  - study conductivy in the neutron star interior
  - investigate re-heating processes

  - **detect fallback discs** (size, temperature)
  - test SN explosion models
  - trace the post-SN NS evolution
  - disc/NS torque, accretion
  - investigate planet formation

- *Goals possible with HARMONI* (0.8-2.4 μm) and *METIS* (3-13 μm)



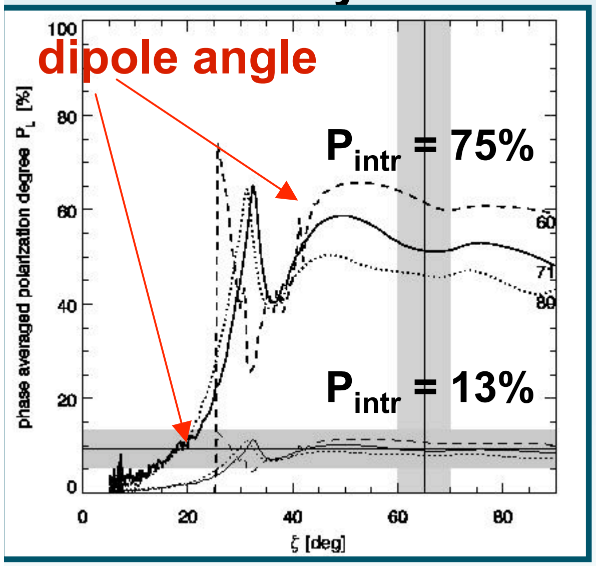


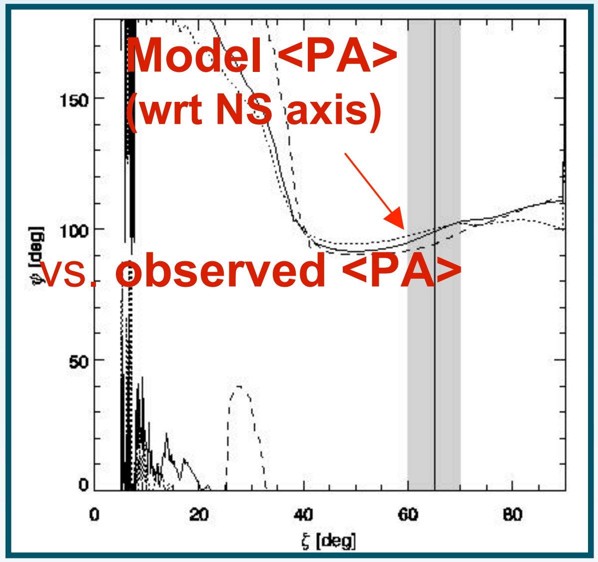


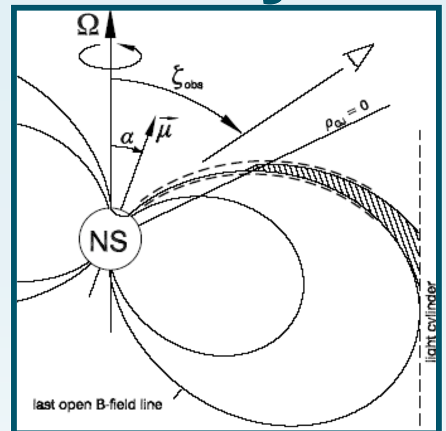
The E-ELT Era

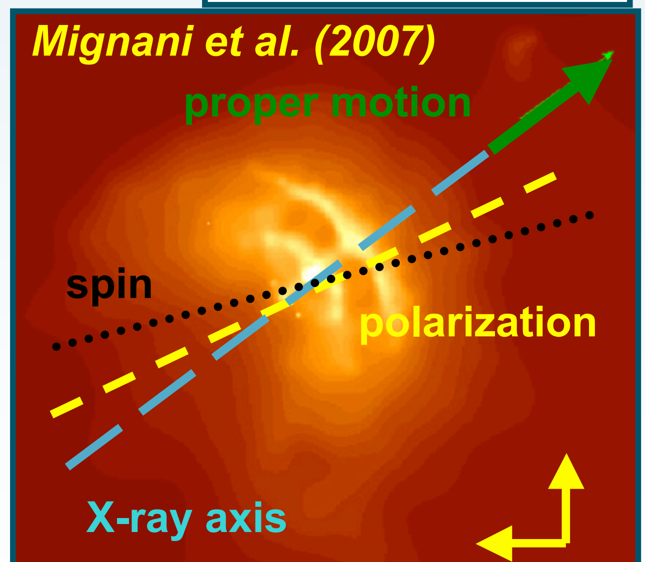
Science Cases for the E-ELT: NS Polarimetry

- **Polarimetry** will 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 magneto-dynamical interactions and
- spin/velocity/polarisation alignments

- **study the magnetic field evolution following a magnetar burst**

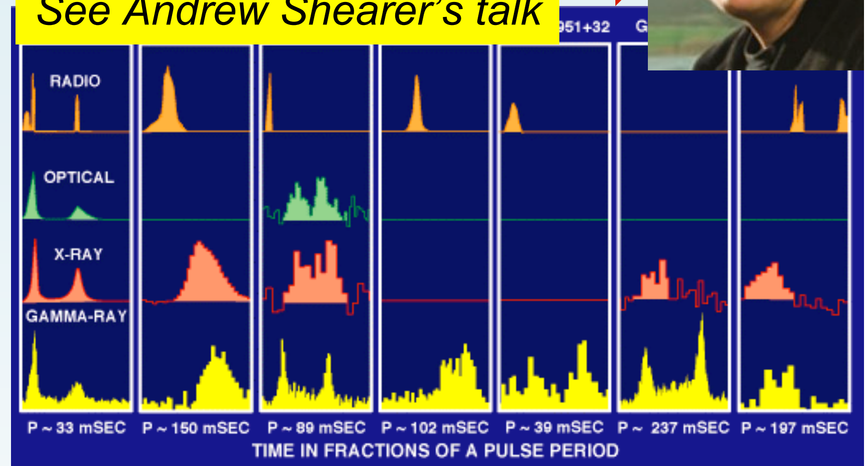
- **investigate the existence of a magnetised atmosphere around the neutron star**

The E-ELT Era

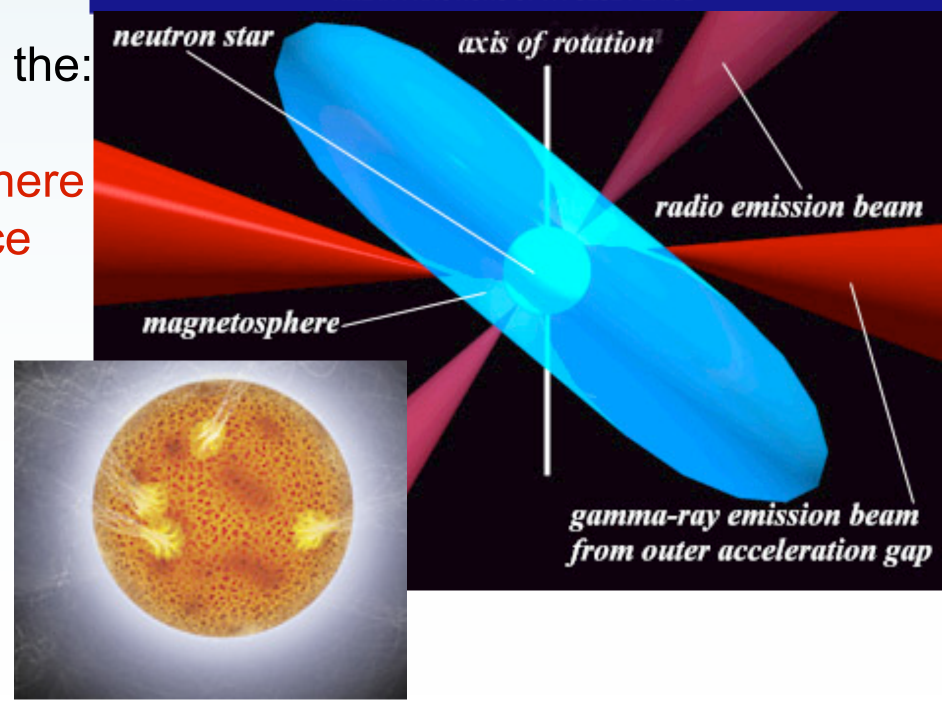
Science Cases for the E-ELT: NS Timing

- **Timing** will allow to study:
  - the λ dependance of a pulsar light curve and **magnetosphere emission models**
  - the production of Giant Pulses and the link between **coherent/incoherent radiation**
  - **radiation reprocessing** in fallback discs (delay,smearing)

See Andrew Shearer's talk



- **Time-resolved** spectroscopy allows to map the:
  - **particle distribution** in the NS magnetosphere
  - **temperature distribution** on the NS surface



- **Time-resolved** polarimetry allows to map:
  - the **geometry** of the NS magnetic field (polarisation varies across the period)

UCL

Science Cases for the E-ELT: NS Astrometry

- Most of the INSs detected at high-energies are **radio-silent**
- **Proper motions and parallaxes can not be measured through radio astrometry**

Λ X-ray astrometry with *Chandra* requires a long time baseline

Λ Plus, *Chandra* is 10 years old already. Not a solution for the future !

Λ *IXO* (>2020) will not have the spatial resolution of *Chandra !*

- From the Geminga experience, the only possibility is **optical/IR astrometry**
- Optical/IR astrometry with *MICADO* (0.8-2.4 μm) will allow to measure with unprecedented accuracy proper motions up to the LMC and parallaxes at >1 kpc

⌉ **Multi-λ luminosity, galactic orbits, birth place localisation, progenitor stars**

Science Cases for the E-ELT: The NS Origin

- **INS manifet in a variety of flavours. What explains the INS diversity?**
- **The progenitor ? The NS birth? The post-SN phase?**

- Many questions can be addressed by studing the INS progenitor stellar population

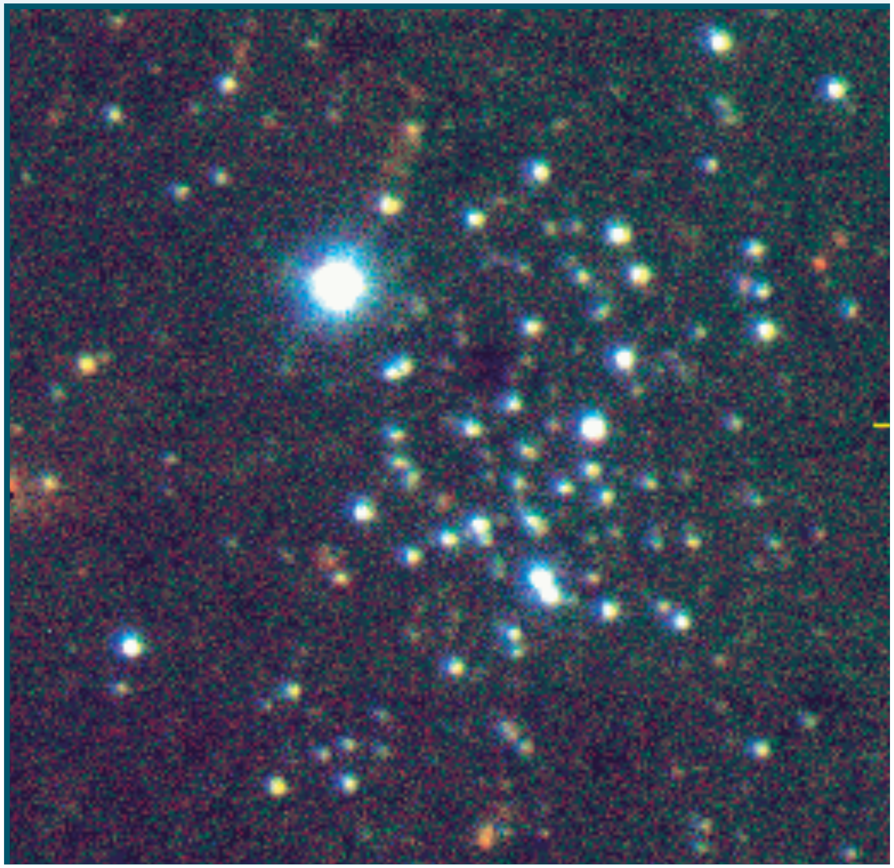
- **Why some NSs are born as magnetars? How is the magnetic field produced ?**

- Some magnetars might be associated with distant cluster of **super massive** (>40 M_{sun}) stars (to be confirmed by *astrometry*)

- Dynamo process in the proto-NS after an **hyper-energetic SN** ?

- Collapse of **hyper-magnetic** progenitor?

- **Spectro-polarimetry** of the faint cluster stars yields their magnetic field from the Zeeman line splitting



Conclusions

- 40 years after identification of the Crab, optical astronomy of INSs is still a very active field, where ESO marked important milestones with both the *NTT* and the *VLT*

¬ Optical studies represent an important tile to characterise the multi-wavelength phenomenology of INSs

¬ Optical studies are crucial to understand the diversity of different type of INSs

¬ Optical studies are fundamental to address several issue on neutron star physics, formation, and evolution

- This requires more in-depth investigations, so far only explored with 8m-class telescopes. **Only the *E-ELT* can provide this opportunity**