30 years of pulsar studies at ESO
- The Italian Contribution-

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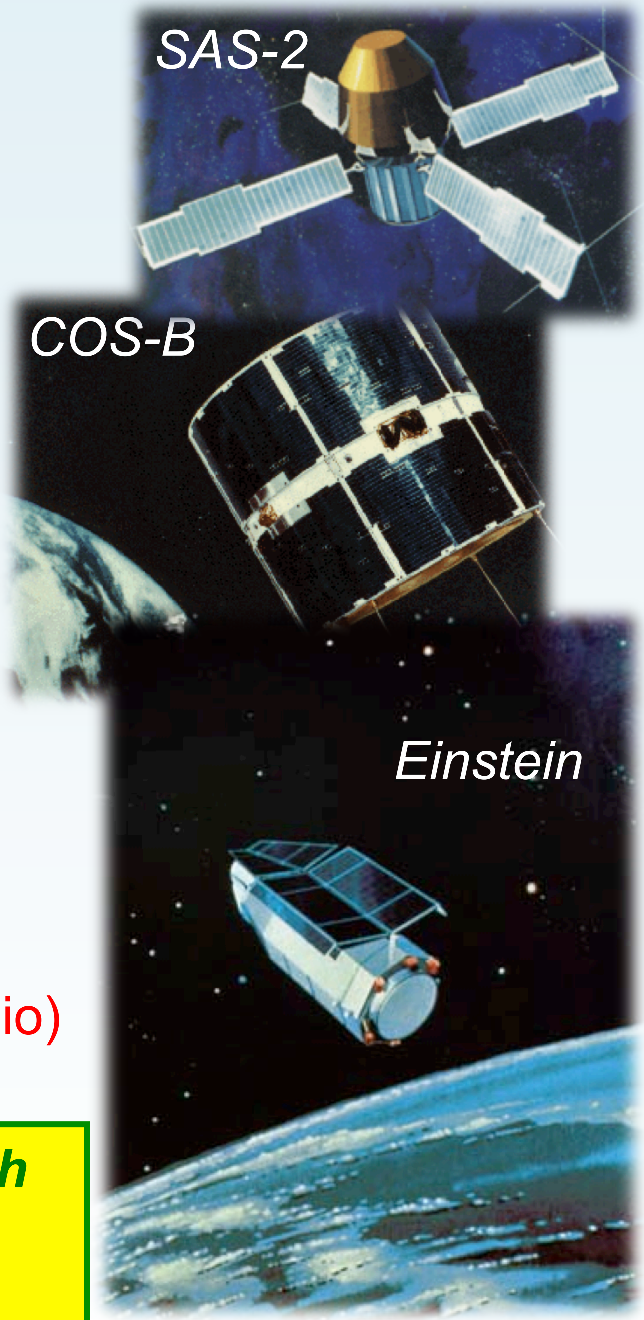
EWASS 2012, Rome, Symposium 10: 30 years of italian participation to ESO

Pulsars in 1982

- ~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)

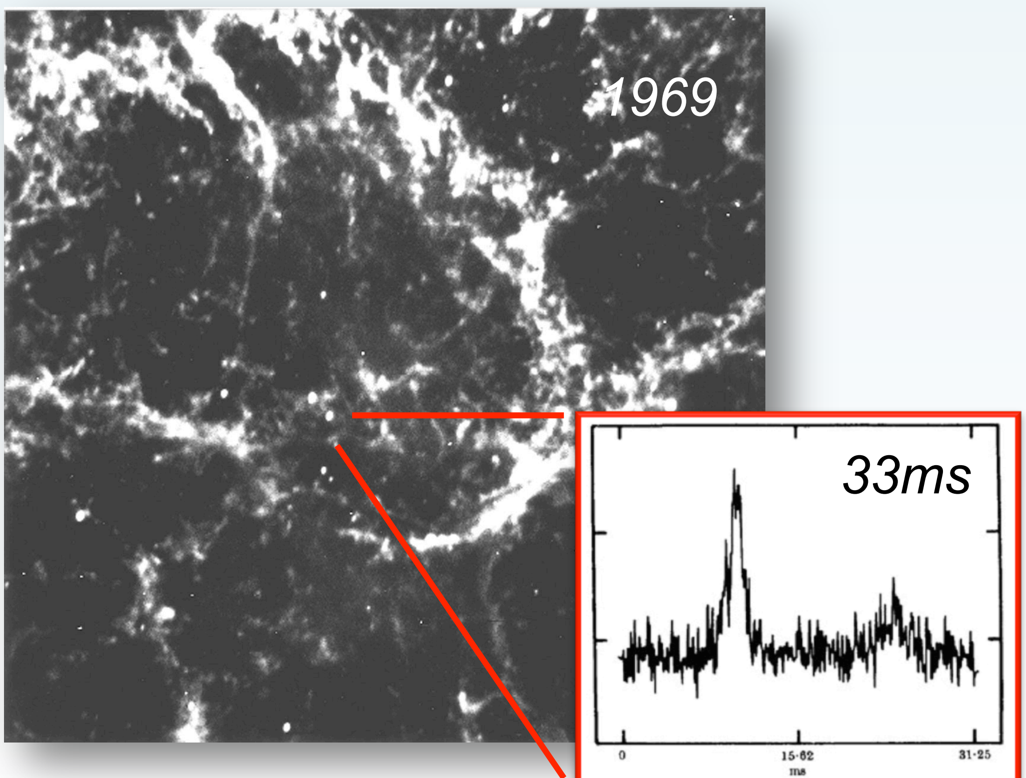


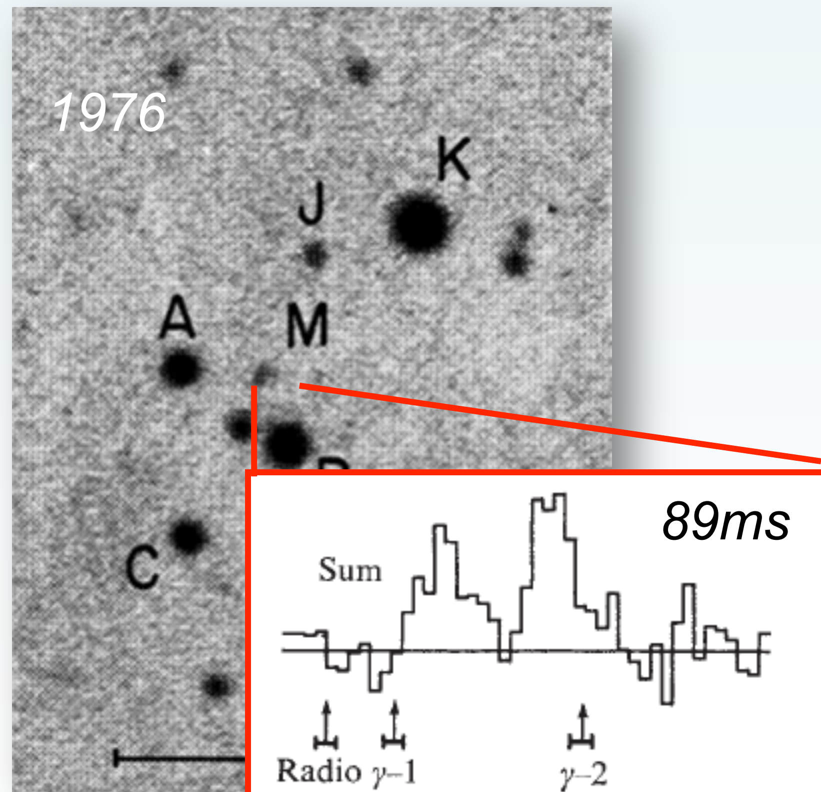
Pulsars had become targets for multi-wavelength astronomy.
What about the optical ?

Pulsars in the optical

- Crab pulsar (V=16.5): optical pulsar detected (Cocke et al. 1969). Identified with the Baade and Zwicky's "South Preceeding star"

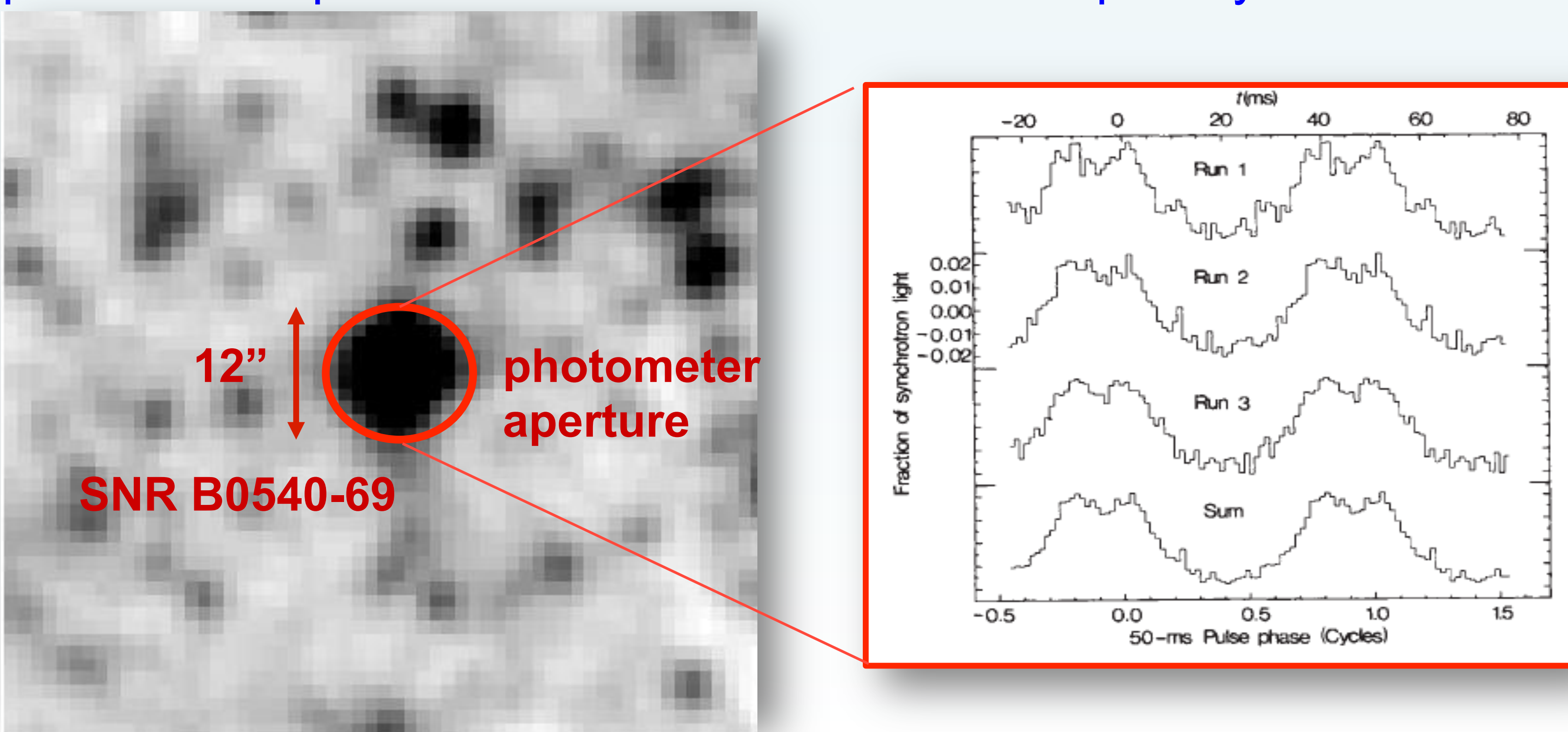
- Vela pulsar (V=23.6): counterpart detected (Lasker 1976) at the CTIO 4m Blanco and confirmed by optical pulsations (Wallace et al. 1977)





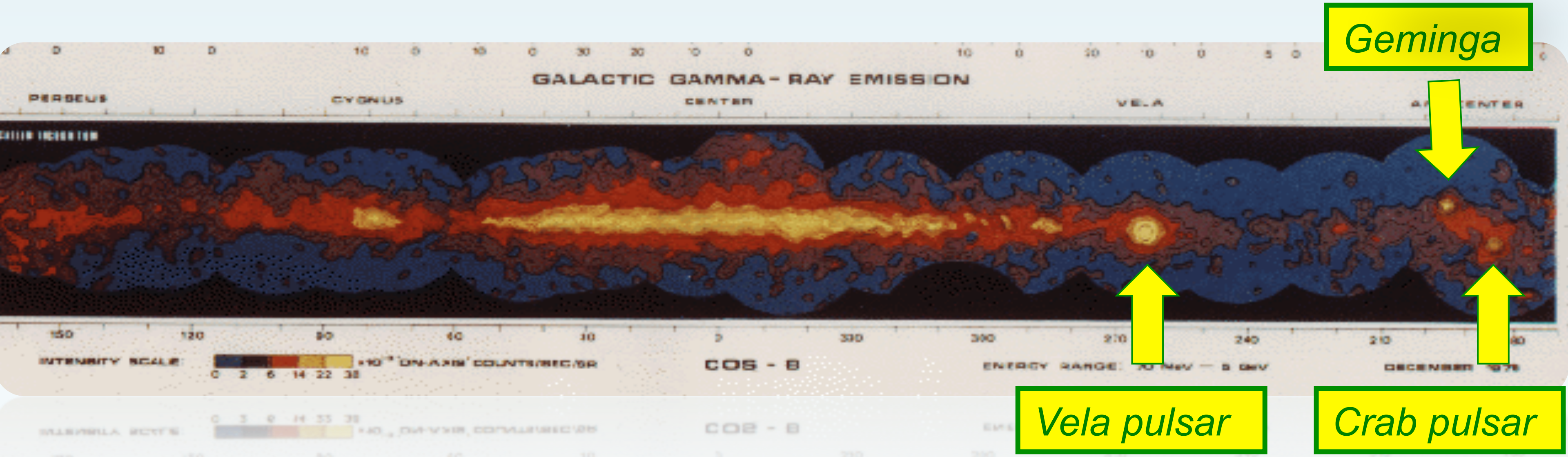
Pulsars in the optical

- PSR B0540-69. X-ray pulsar detected by *Einstein* in the LMC. Not detected yet in radio
- Optical pulsations (50 ms) detected by Middleditch & Pennypacker (1985)
- Optical counterpart remained unidentified in the spatially unresolved SNR



The discovery of Geminga

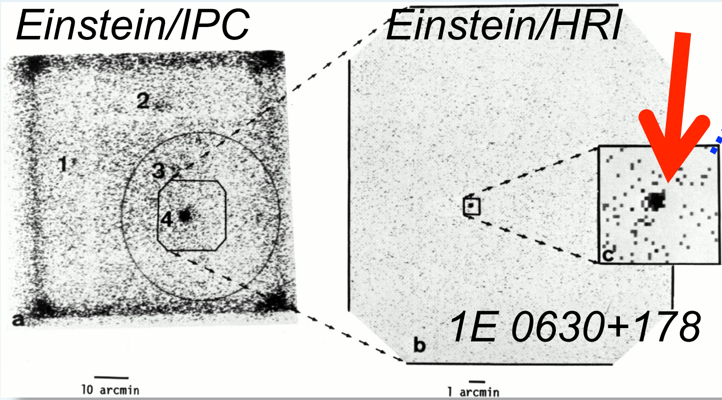
- Geminga, an unidentified γ-ray source discovered by SAS-2 and COS-B in the Galactic anticentre (Gemini) → Gemin Gamma-ray source

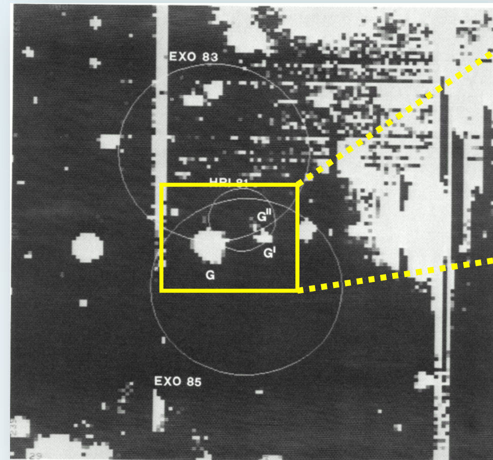


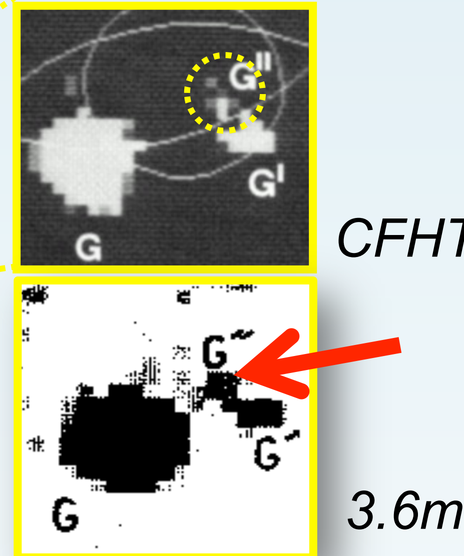
- The only two identified Galactic gamma-ray sources were Crab and Vela
- Third source suspected to be a pulsar but no gamma-ray pulsation detected
- Multi-wavelength identification campaign

The chase for the Geminga identification triggered new interest in optical observations of neutron stars

The Geminga Chase







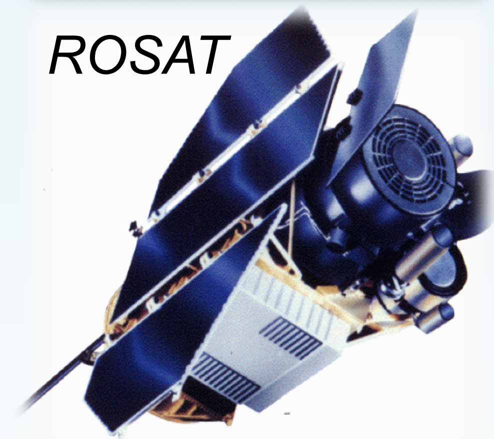
- *Einstein* map the COS-B error box → X-ray counterpart (1E 0630+178) discovered (Bignami et al. 1983)
- $F_{\gamma}/F_{X} \approx 1000$, like the Vela Pulsar, but no radio counterpart
- Optical counterpart G" (V=25.5) detected with the CFHT and the ESO/3.6m (Bignami et al. 1987; 1988)
- $F_{X}/F_{opt} \approx 1000$, like the Vela Pulsar → isolated neutron star

The First radio-silent one !

Pulsars in the 1990s

- New X-rays and γ-ray observations performed with the new generations of high-energy satellites
- The new Dynamic Duo
- The *Compton-GRO* (1990-2000)
  - 7 gamma-ray pulsars detected
- *ROSAT* (1990-1999)
  - 20 pulsars detected in soft X-rays
- 3 optical pulsar (one unidentified) plus one candidate identification (Geminga)

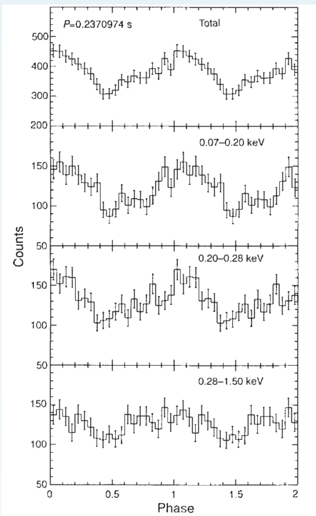
NTT became operational at La Silla in 1989, equipped with the high-resolution camera (0.13”) SUSI (Superb Seeing Imager)

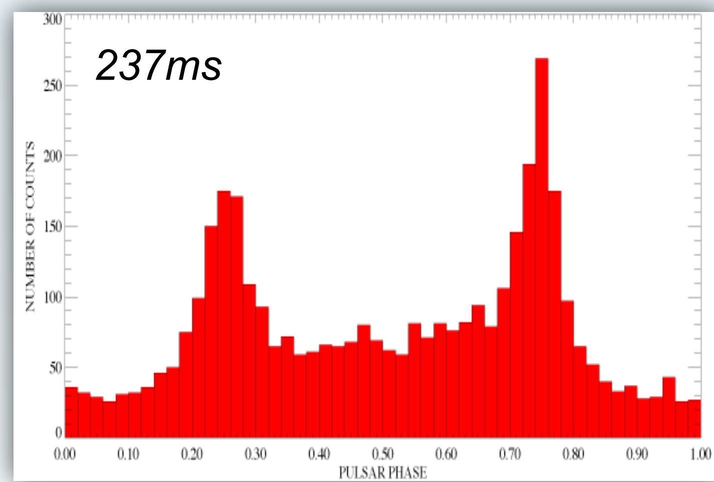


The Geminga Chase continues

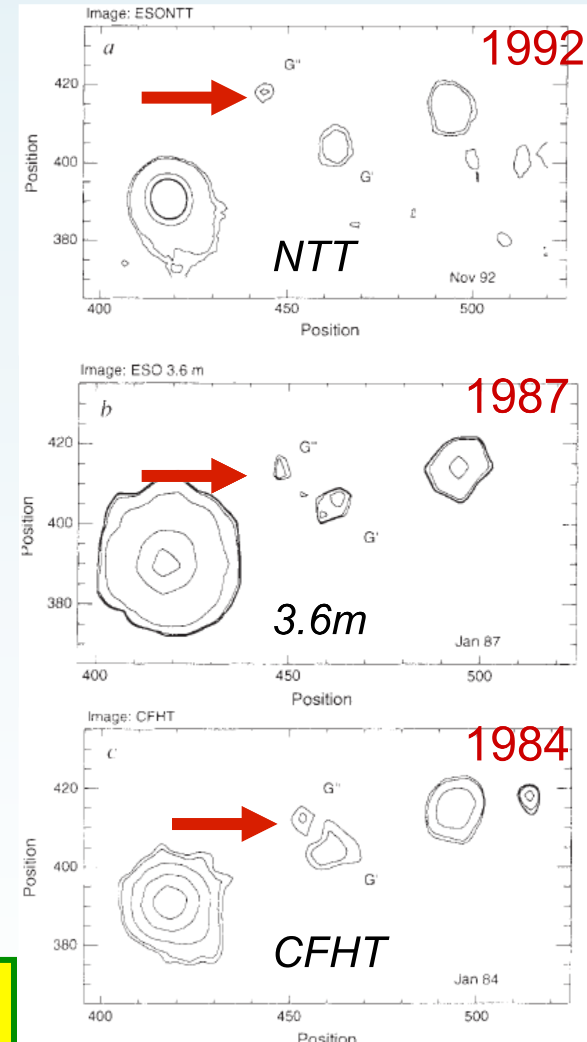
- γ-ray pulsations detected by GRO and X-ray pulsations detected by ROSAT → Geminga is a pulsar (still undetected in radio)

Halpern & Holt 1992





Bertsch et al. 1992



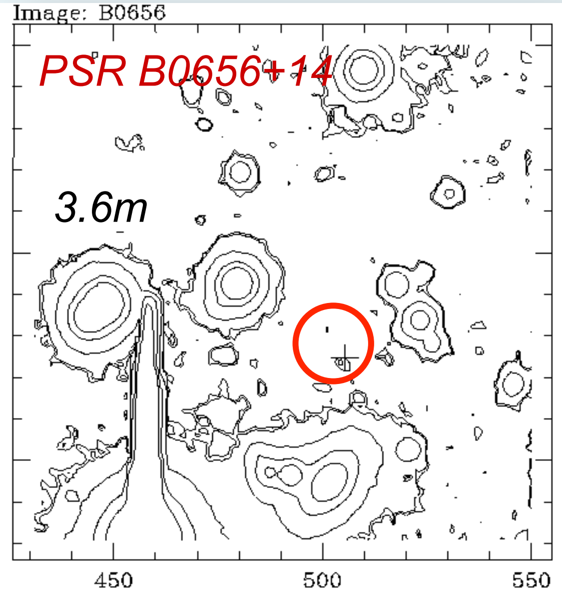
- Proper motion of G" measured with SUSI (Bignami et al. 1993), G" moves like a neutron star → Geminga optical identiifcation confirmed

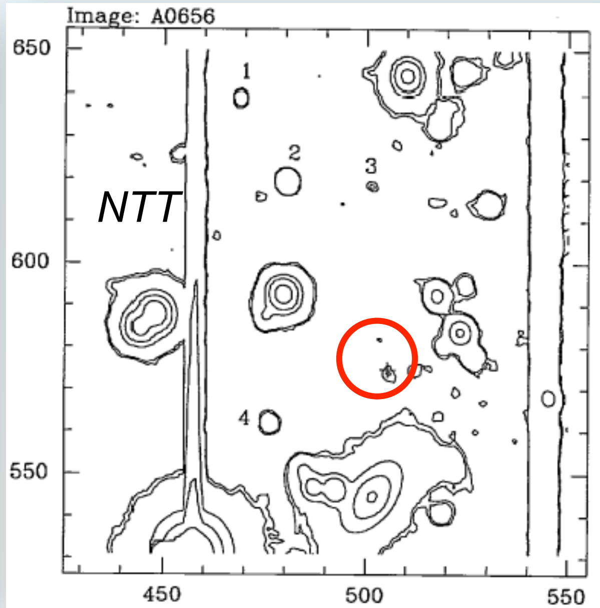
- Gamma-ray light curve sensitive to G" motion

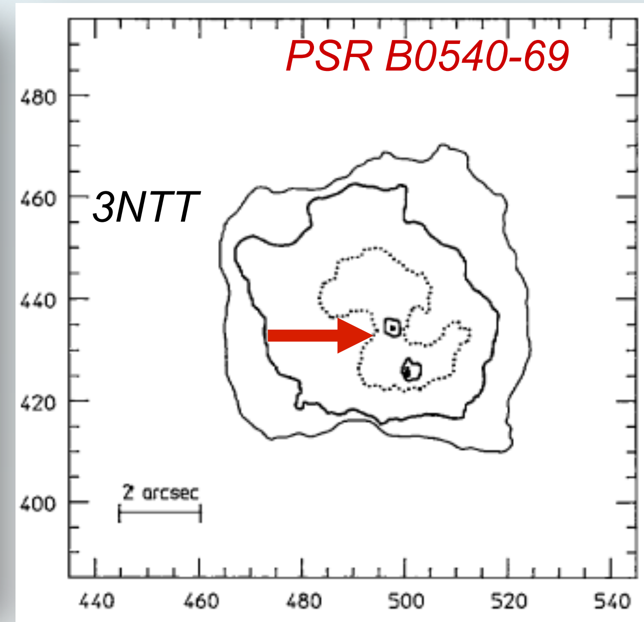
The identification of Geminga showed the NTT potentials for neutron star astronomy

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)





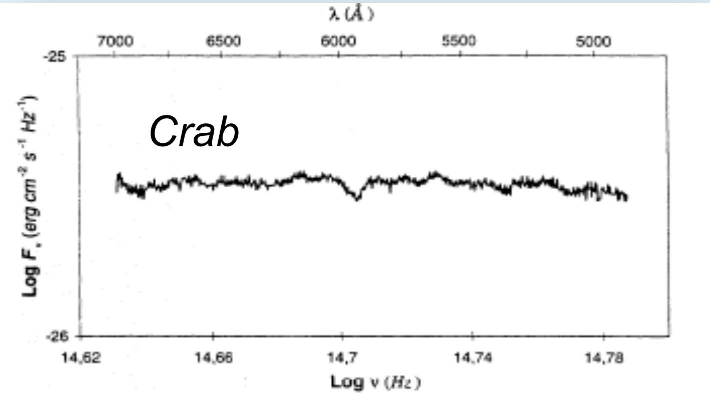


- PSR B0540-69: High-resolution imaging with NTT/SUSI identified a likely V=22.5 counterpart (Caraveo et al. 1992). Confirmed by time-resolution imaging with TRIFFID at the NTT (Shearer et al. 1994)

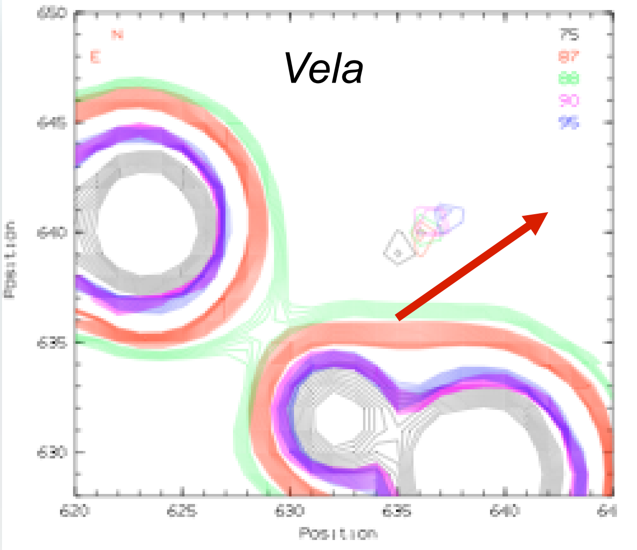
- Candidate counterpart (V=22) for PSR B1509-58 (Caraveo et al. 1994b) plus many others observed both with the *NTT* and the *3.6m* (Mignani et al. 2000)

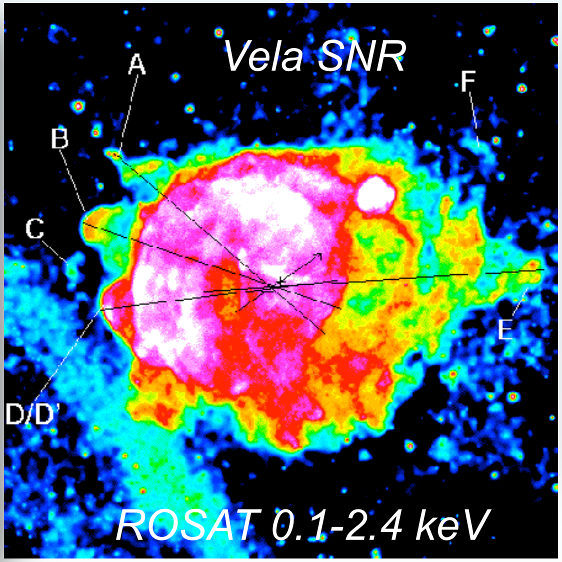
Riding the wave …

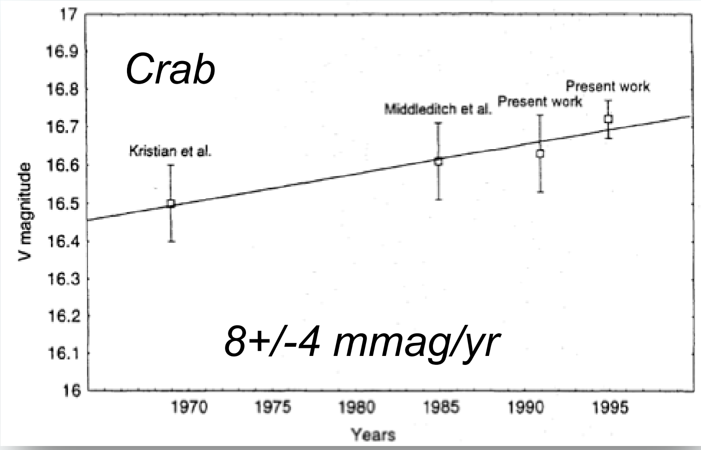
- First optical spectrum of the Crab measured with the *NTT* (Nasuti et al. 1996)



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



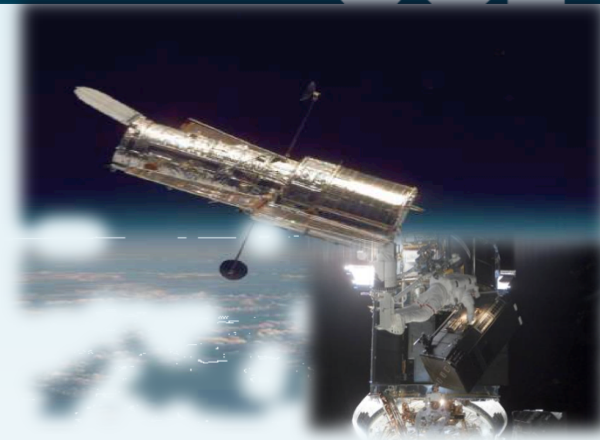




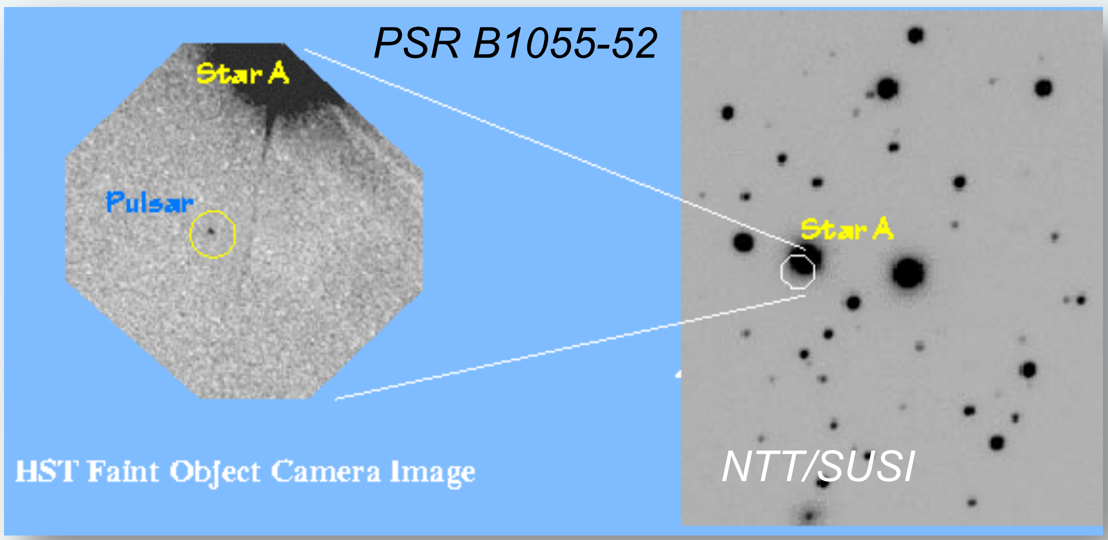
- First proper motion for the Vela pulsar (Nasuti et al. 1997), with the *NTT*. Confirmed SNR association and pulsar birth place.

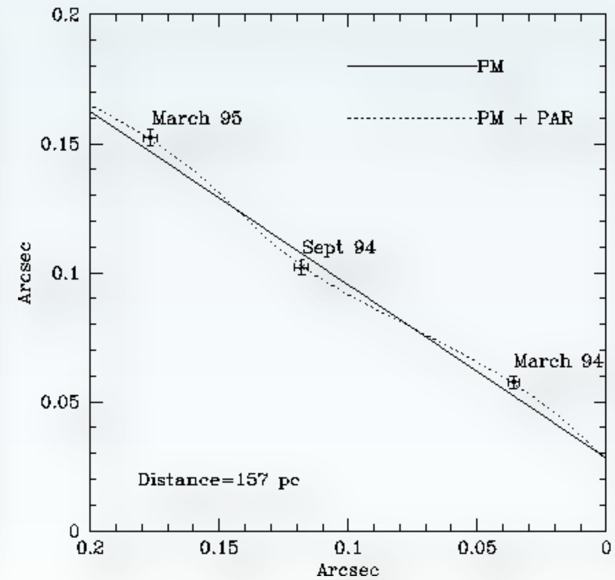
The HST era

- In the mid 1990s, ESO telescopes achieved most of the obtained pulsar identifications
  All new identifications from italian astronomers



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

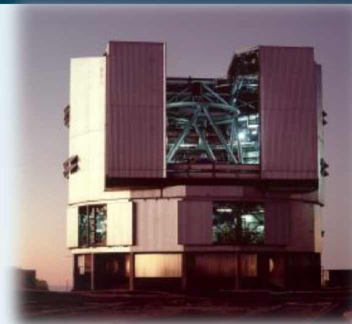


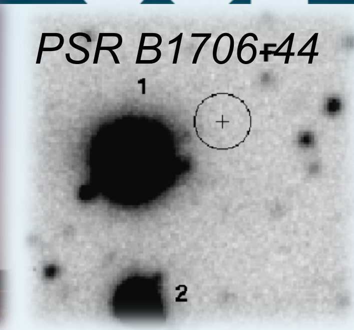


Spurred more and more interest in the Community*. More groups involved. Consolidated optical as an important branch for neutron star astronomy*

The VLT Era

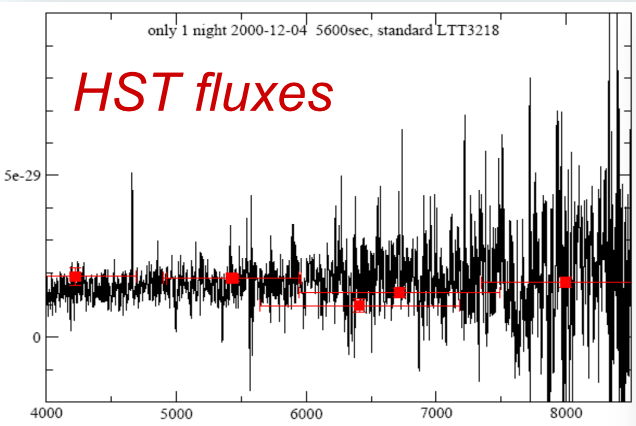
- Pulsar observations were a test case for the *VLT/UT1* Science Verification.



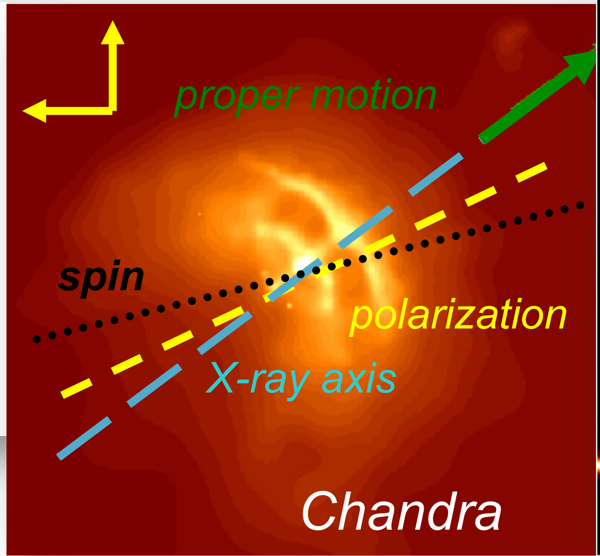


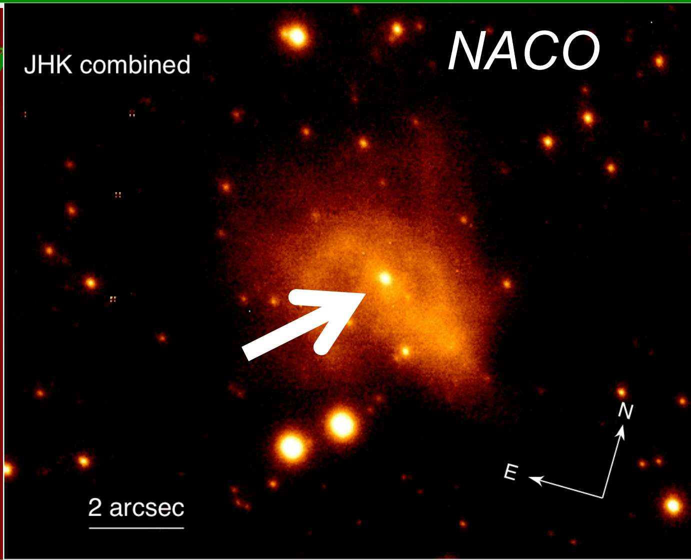
- First VLT science paper submitted (Mignani et al. 1999, *A&A, 343, L5 Special Edition: First Science with the VLT*)
  - The first optical spectrum of the Vela pulsar (Mignani et al. 2007a)
  - The first optical polarisation of the Vela pulsar (Mignani et al. 2007b)
  - IR detection of pulsars (Mignani et al. 2012)

Competition with the HST spurred VLT observations



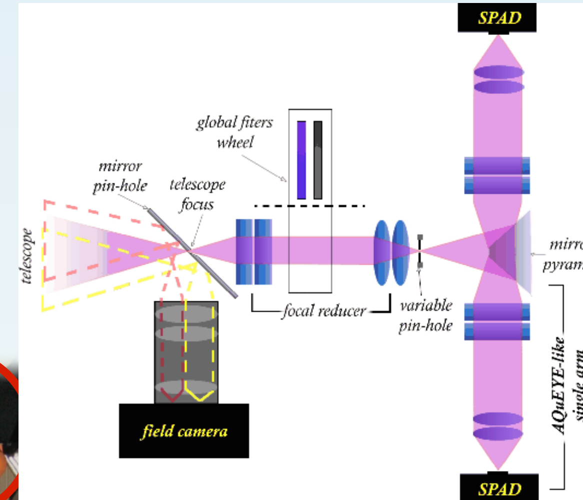
FORS1

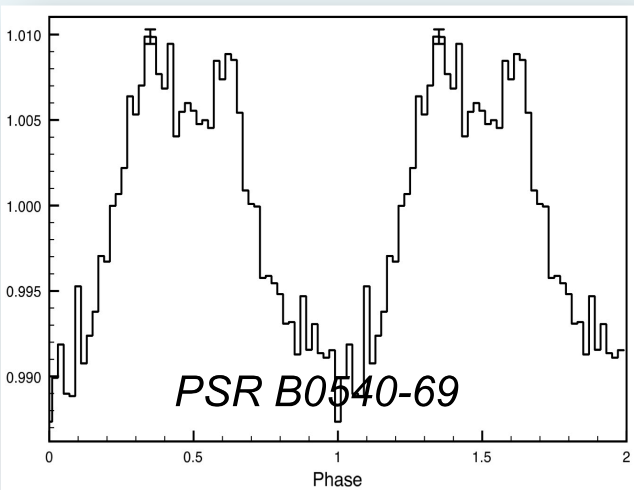




New Technologies

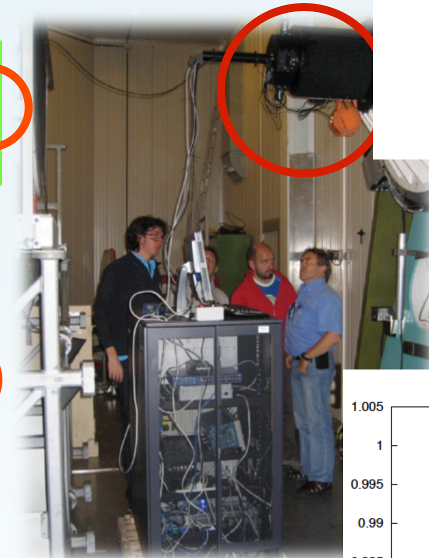
- Fast photometer at the 3.6m till the end of 1990s. Thereafter timing via guest instruments, e.g. *IQuEye* (Naletto et al. 2009), based on SPAD technology

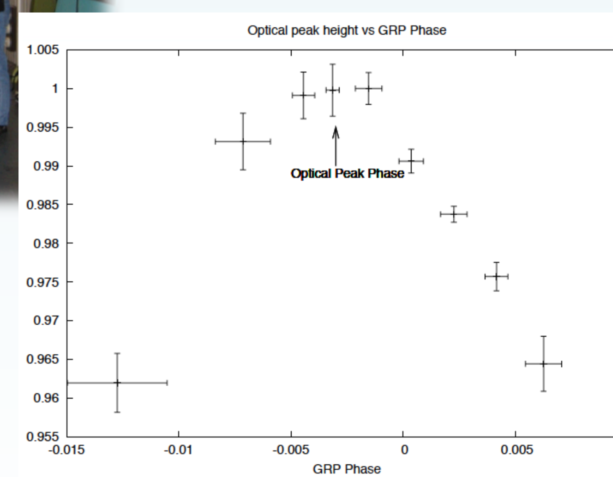




$$\dot{\omega} = -K\omega^{n}$$

$$\frac{\omega\ddot{\omega}}{(\dot{\omega})^{2}} = n$$



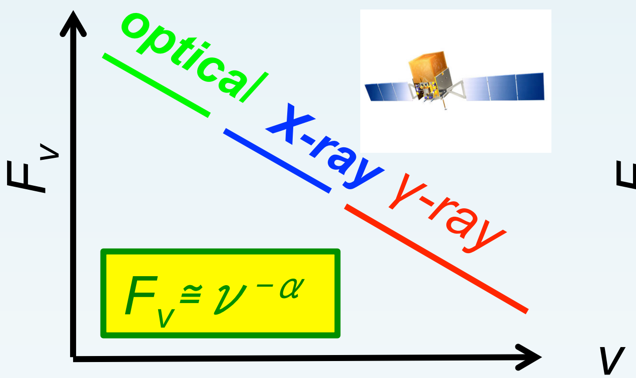


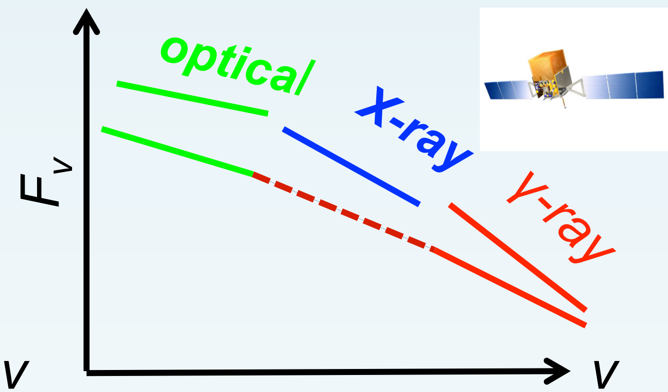
- Braking index measurement for B0540-69: *n*=2.087±0.007 (Gradari et al. 2011). measured for a handful of pulsars only; n=3 for a perfect dipole.

- Detection of Giant Pulses from the Crab (Collins et al. 2012)

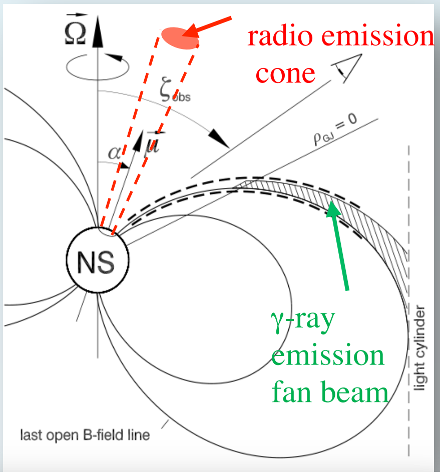
Scientific impact

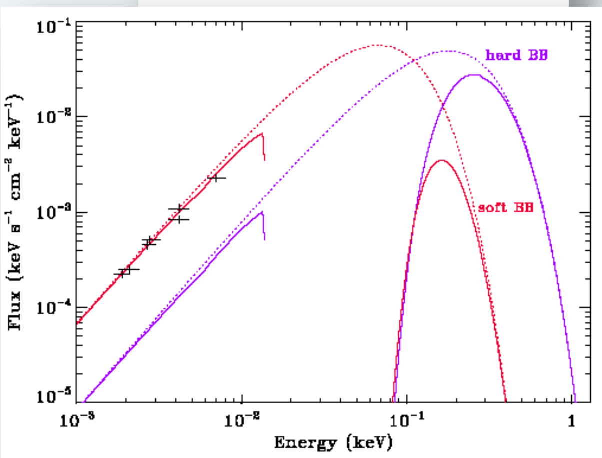
- Emission physics in the NS magnetosphere, particle energy/density distribution

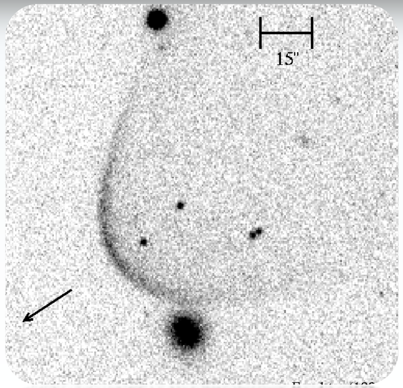


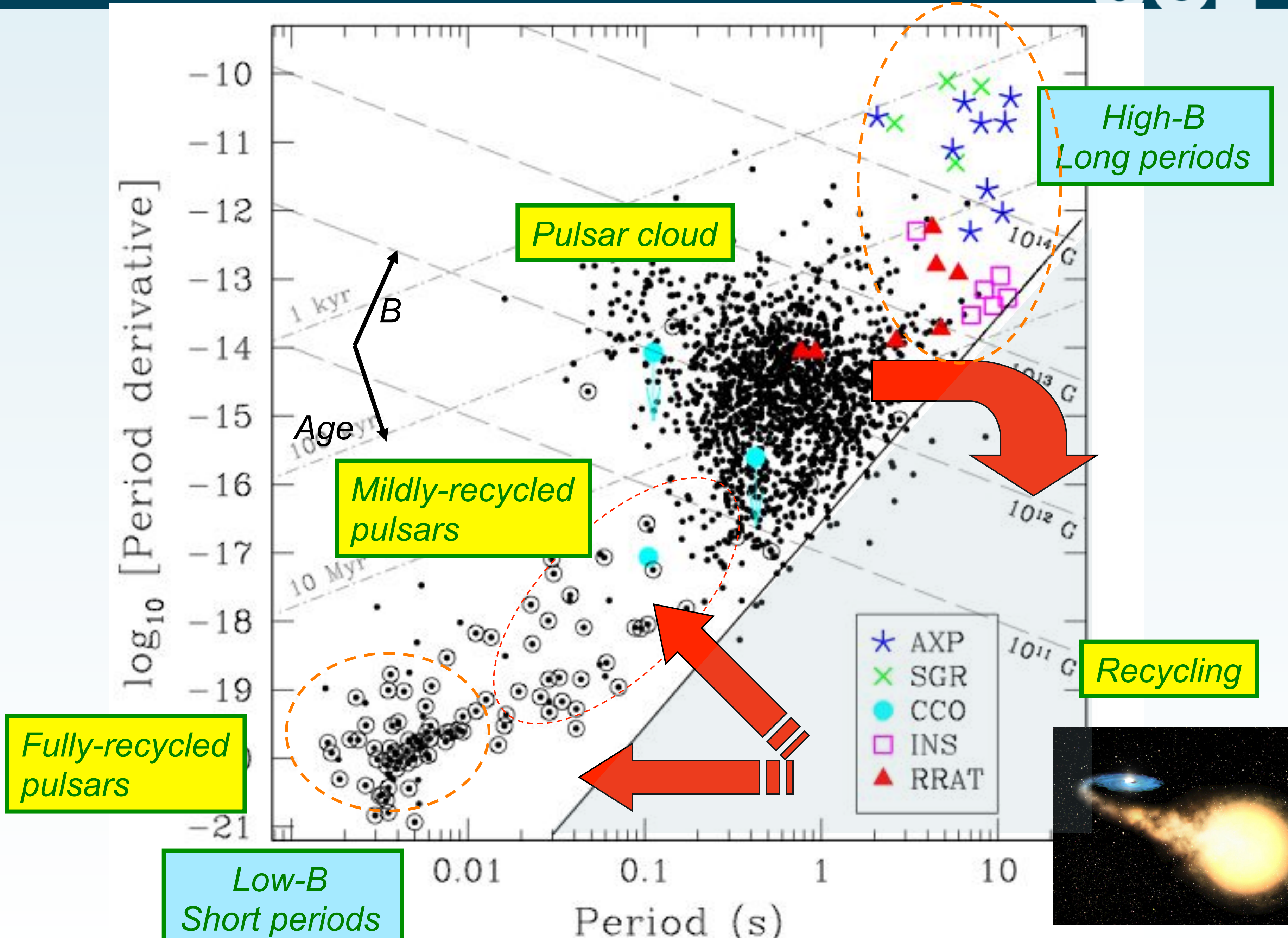


- NS magnetosphere properties, geometry, models
- NS thermal map, cooling curve decays, EOS
- Debris disks, nebulae, bow-shocks
- Proper motion, parallaxes, and absolute positions
- Understanding the nature of new, puzzling INSs





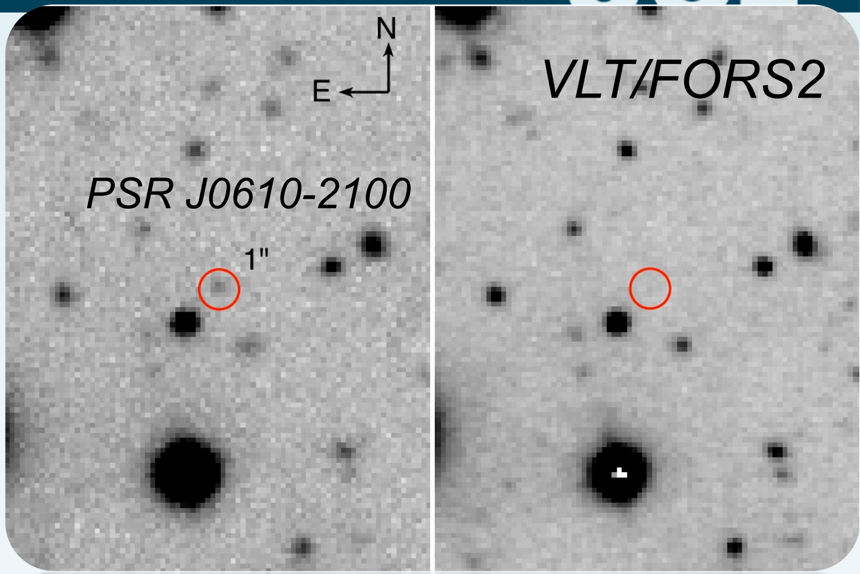



High-B
Long periods
Pulsar cloud
B
Age
Mildly-recycled pulsars
Fully-recycled pulsars
Low-B
Short periods
Recycling
1 kyr
10 Myr
10^{14} G
10^{13} G
10^{12} G
10^{11} G
AXP
SGR
CCO
INS
RRAT
$\log_{10}$ [Period derivative]
−10
−11
−12
−13
−14
−15
−16
−17
−18
−19
−21
0.01
0.1
1
10
Period (s)

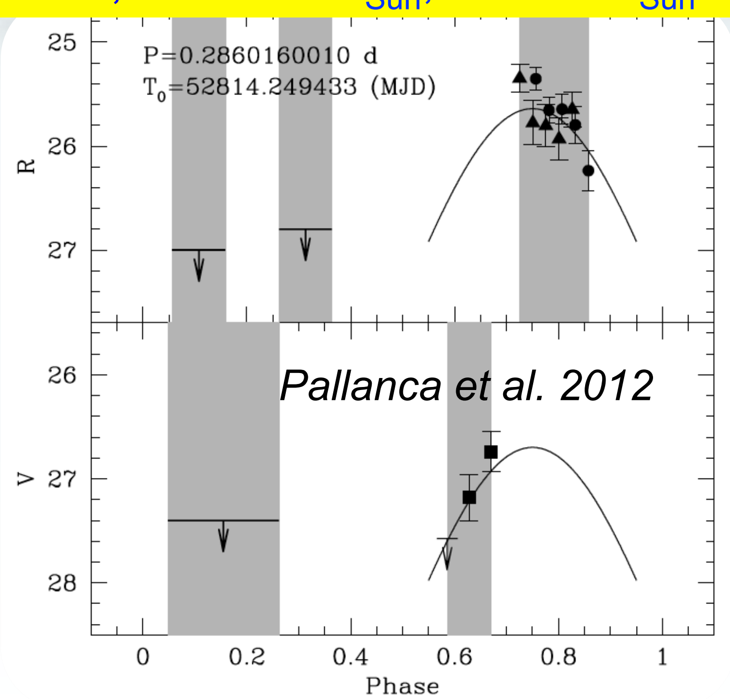
Binary pulsars

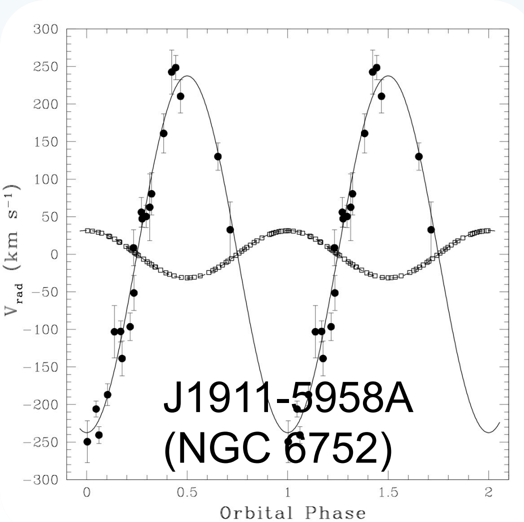
- VLT observations of MS/WD companions to binary pulsars important to study the system properties/evolution (Cocozza et al. 2006; Ferraro et al. 2003)

- Orbital variability (orbit angle)
- Radial velocity curves (masses)
- Chemical composition
- Accretion and pulsar spin up
- Companion irradiation (Black Widow pulsars)



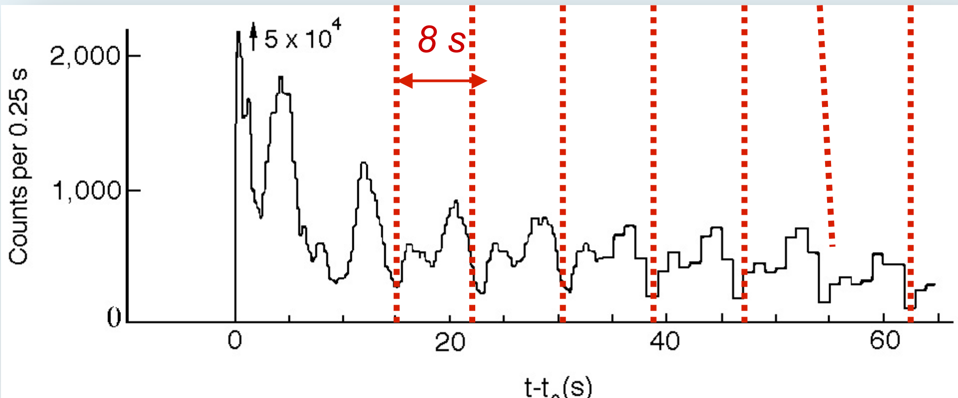
T~3500 K; L~0.0017L_{Sun}; R~0.14R_{Sun}

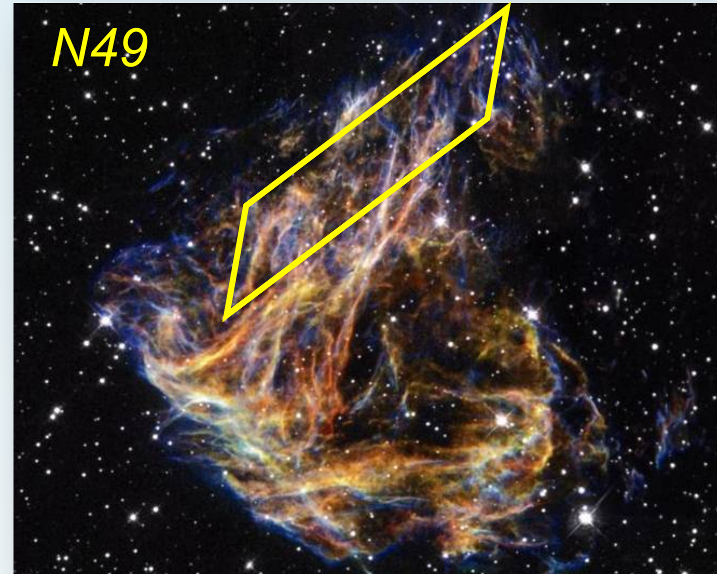




Magnetars

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



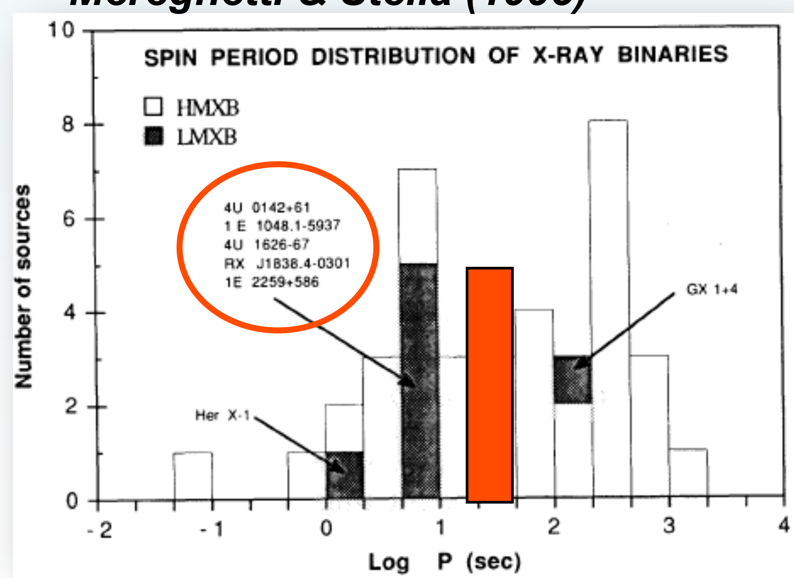


  - Recurrent (not like GRBs) → Soft Gamma-ray Repeater (SGR)
  - 8s period in the light curve decay
  - **Associated with young SNR**

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

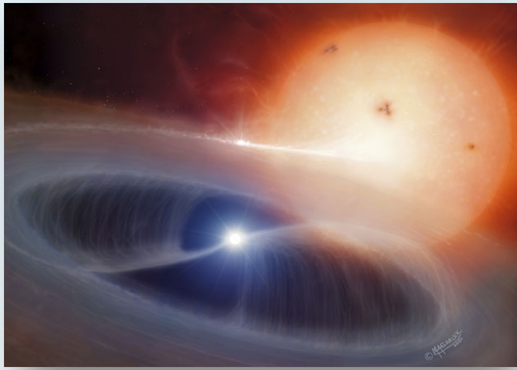
- **X-ray luminosity >> rotational energy**

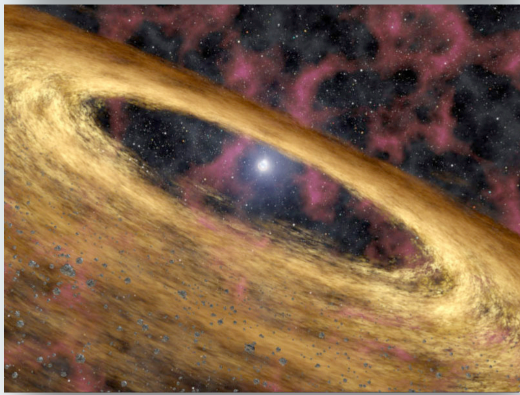
Mereghetti & Stella (1995)

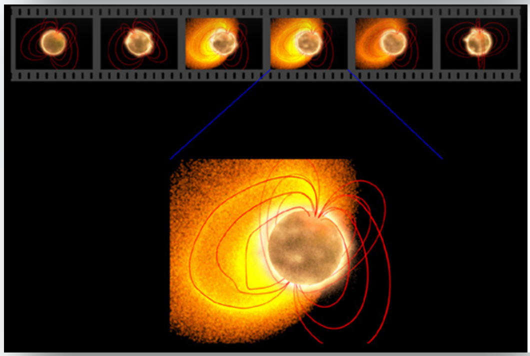


SGR/AXP nature

- X-ray luminosity powered by accretion ?
  - *No evidence for a companion star (X-ray eclipses, Doppler shifts)*
  - *Low-mass star? Debris disk ?*
- Origin of the gamma-ray bursts in SGRs?
- Magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995)
  - *Fast spin down via magnetic braking*
  - *X-ray powered by the magnetic field*
  - *Crust fractures and magnetic field → bursts*

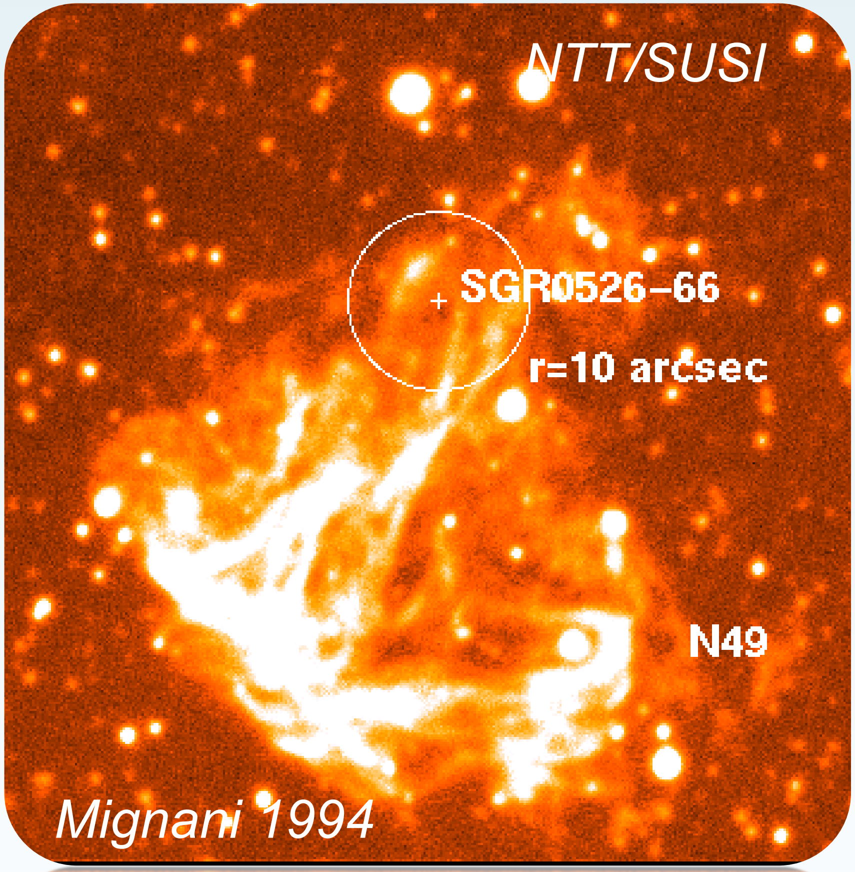


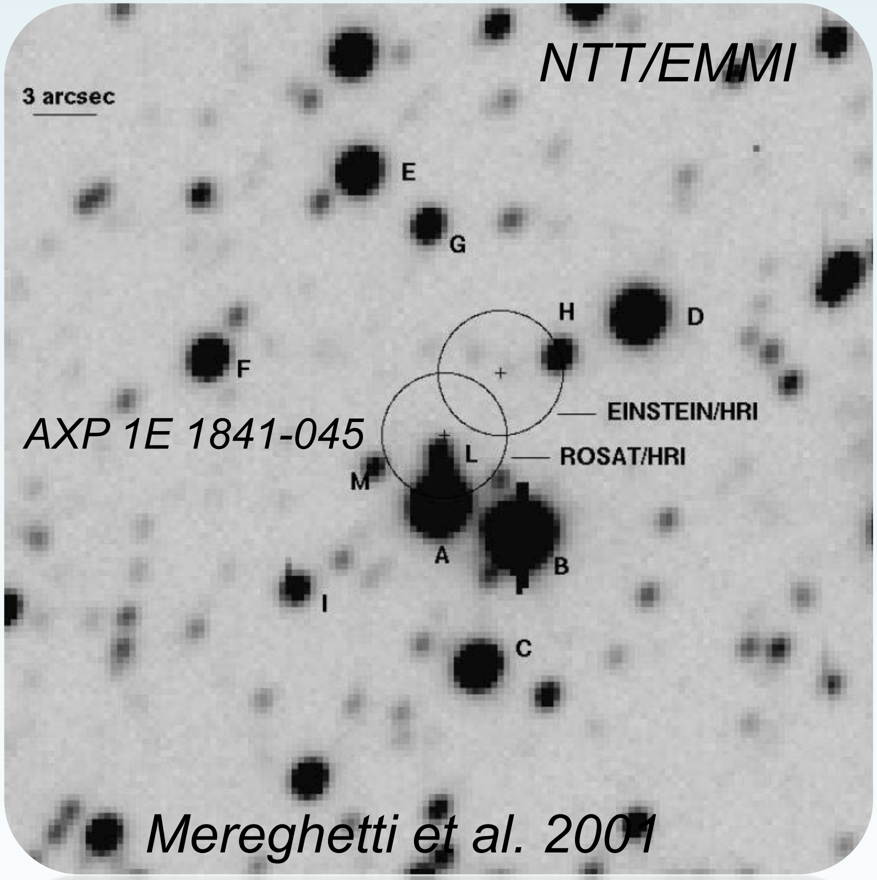




Optical/IR observations crucial to discriminate between different models

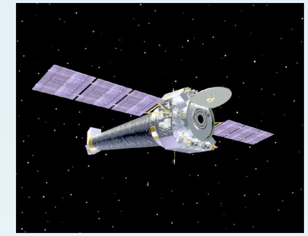
Early observations



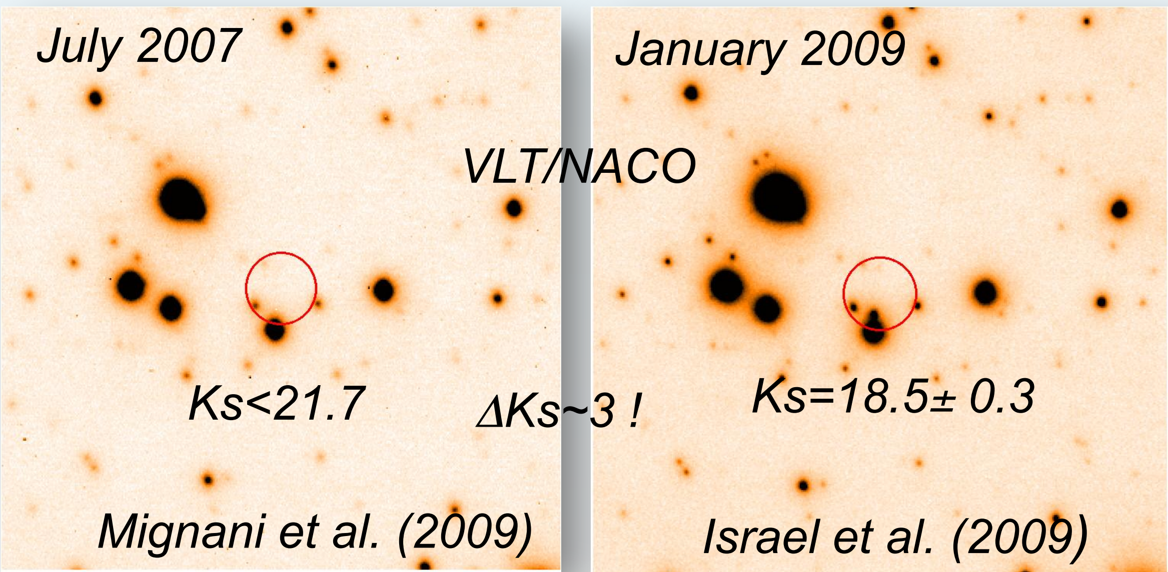


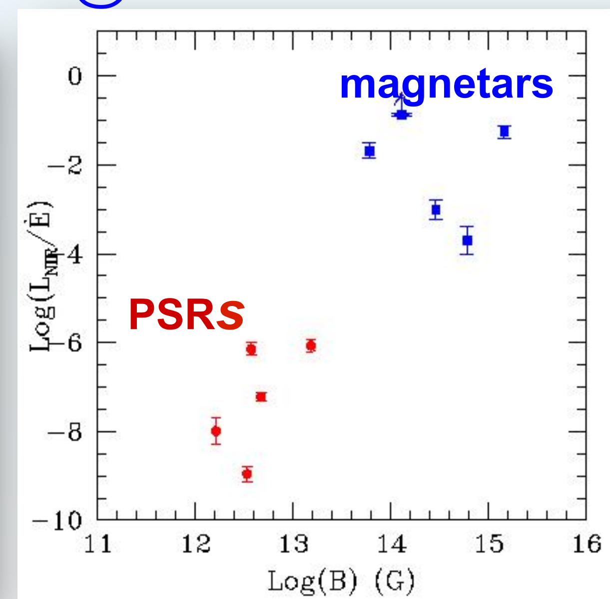
- Early NTT observations hampered by coarse X-ray position (from Einstein or ROSAT) and crowding

Identification strategy



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

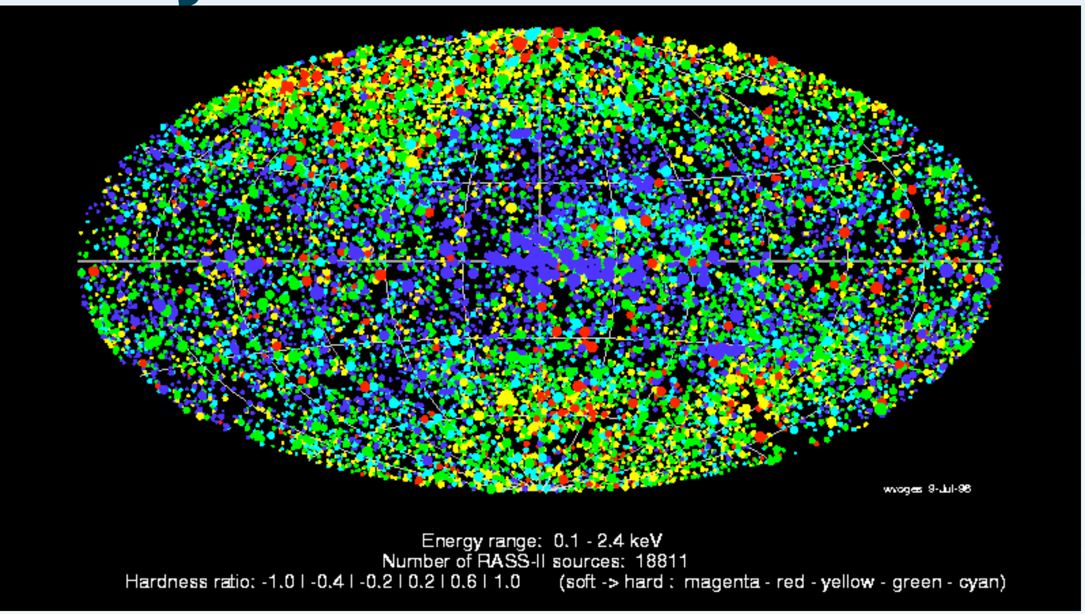


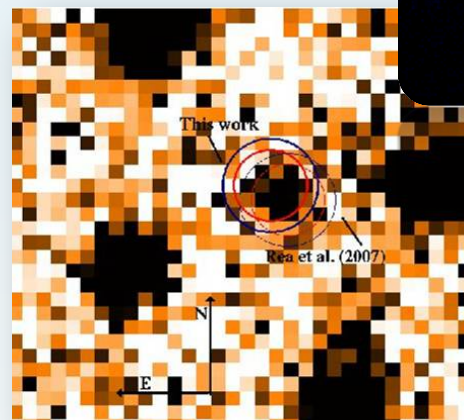


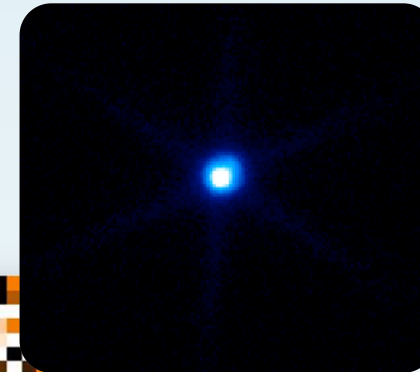
Tight constrain on accretion from a companion star or a debris disk →
observational evidence to support the magnetar model

- 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 – probably old magnetars

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

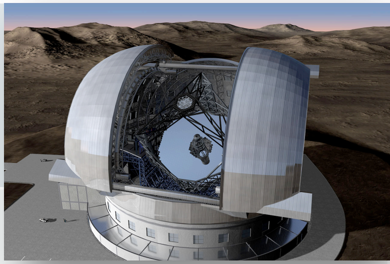
E-ELT contribution

- *25 INSs detected in the optical, still few compared with X and γ-rays (~100)*

- *Quantitative step → more identifications*
- *Qualitative step → more information (spectroscopy, polarimetry, timing)*

- *High collecting power (E-ELT) and suitable instruments*

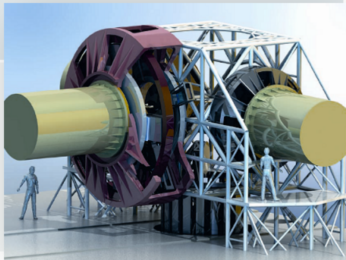
METIS - Imager/Spectrograph & Polarimeter (2.9-14 μm)
17.6"x17.6" FOV (20 ms); R ~ 900-5000



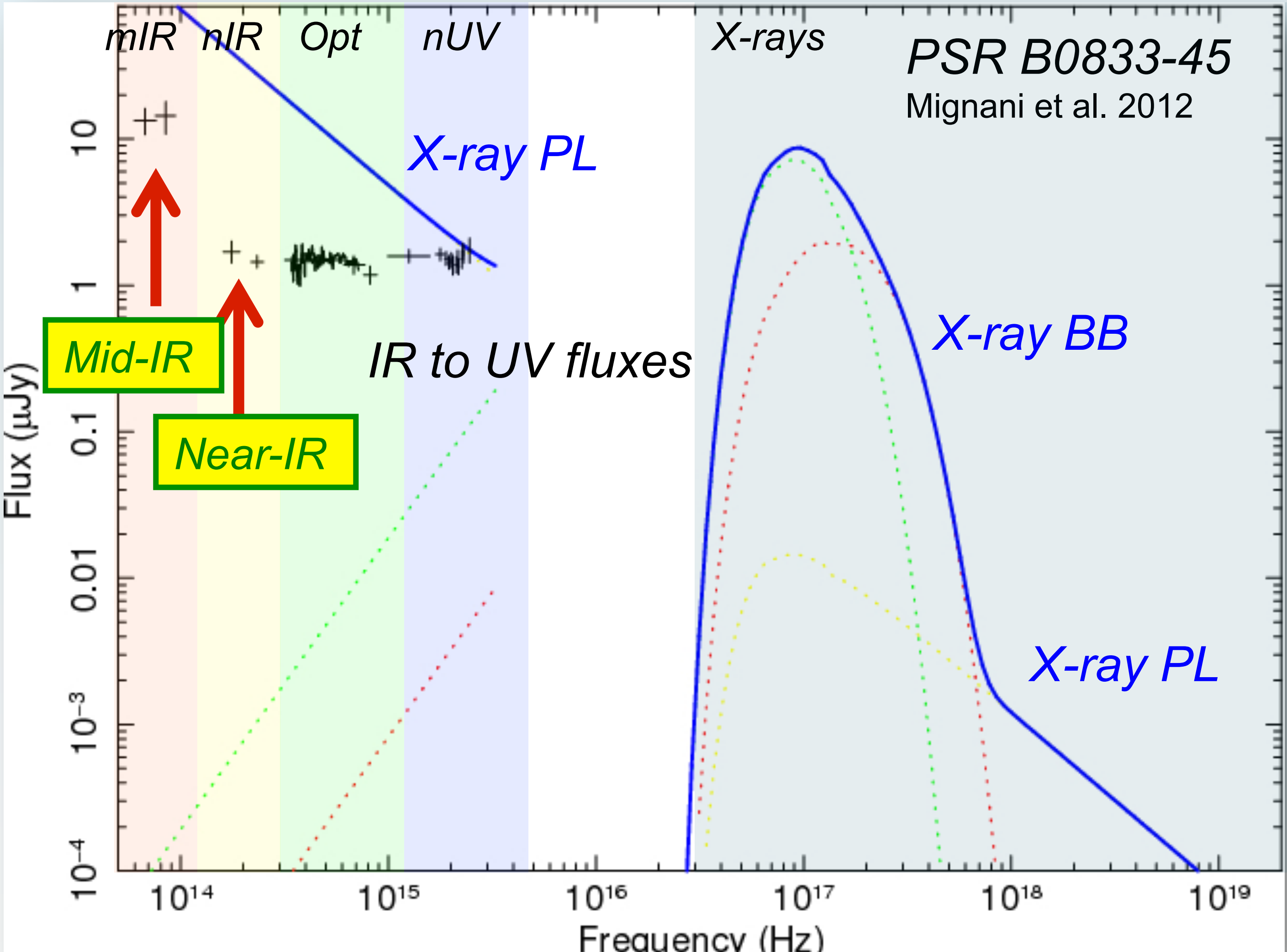
MICADO - Imager & Spectrograph (0.8-2.5 μm)
53" x 53" FOV (3 mas); R < 3000

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)



Neutron Stars are Cool !



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**

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

OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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OWL-CSR-ESO-00000-0162

- 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

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E-ELT potentials

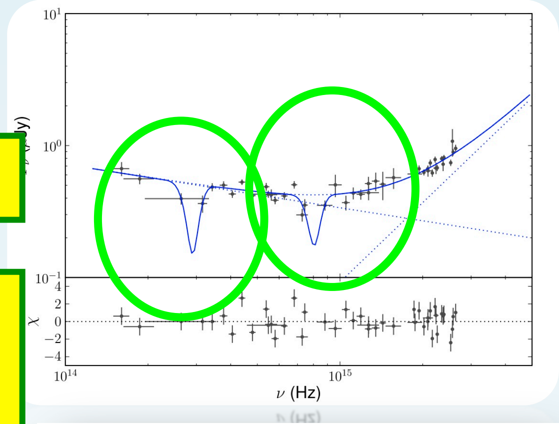
⇒*<u>Imaging:</u> more detections, SKA and Fermi follow-ups*

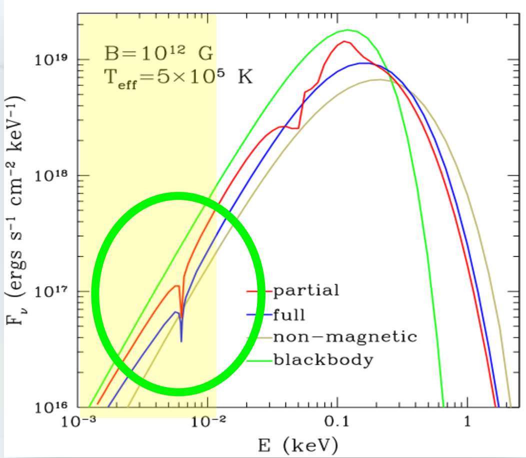
⇒*<u>Spectroscopy:</u> SED, thermal/non-thermal, NS surface temperature, cyclotron spectral features, atmosphere (composition), debris disks (size, mass)*

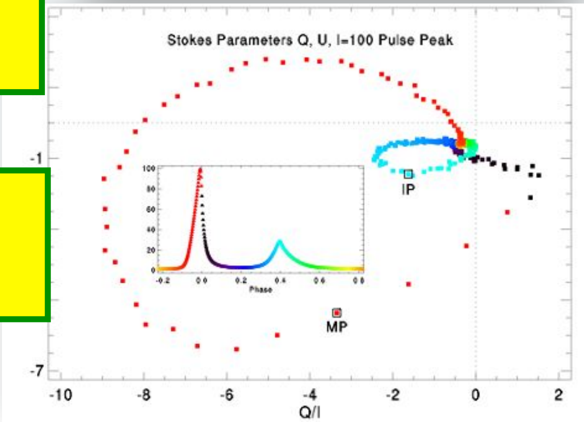
⇒*<u>Polarimetry:</u> atmosphere/magnetosphere magnetic field, PWNe and SNR polarisation maps, polarisation orientation vs spin axis and proper motion*

⇒*<u>Timing:</u> pulsars, giant pulses, phase-resolved polarimetry and spectroscopy*

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







Neutron star optical astronomy has grown thanks to the enduring work of italian astronomers, mainly in Milan, Padua, Bologna, and Rome, plus the expatriates

Neutron star optical astronomy has proven crucial in their multi-wavelength studies and in the understanding of their intrinsic properties

The NTT represented the beginning, the VLT the glorious continuation, with the E-ELT a new Era in neutron star optical astronomy is coming

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

*The E-ELT will detect INSs **fainter**, **further away**, **more absorbed***

*The E-ELT will carry out **deeper** studies only explored by the VLT **much faster***