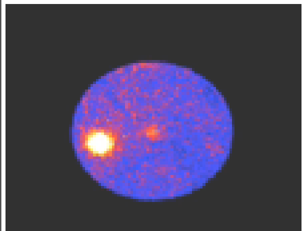
National University of Ireland, Galway
Ollscoil na hÉireann, Gaillimh

High Time Resolution Astrophysics and Extremely Large Telescopes

Andy Shearer
Centre for Astronomy
NUI, Galway
Ireland

on behalf of the Opticon
HTRA network



OPTICON
sfi science foundation ireland
COSMOGRID
NDP NATIONAL DEVELOPMENT PLAN

What objects?

Topics at the Galway and Edinburgh HTRA workshops in 2006 and 2007 - timescales minutes to microseconds

Binary Systems
- CVs
- LMXBs
- HMXBs

Neutron Stars
- Pulsars
- Magnetars
- Isolated NS

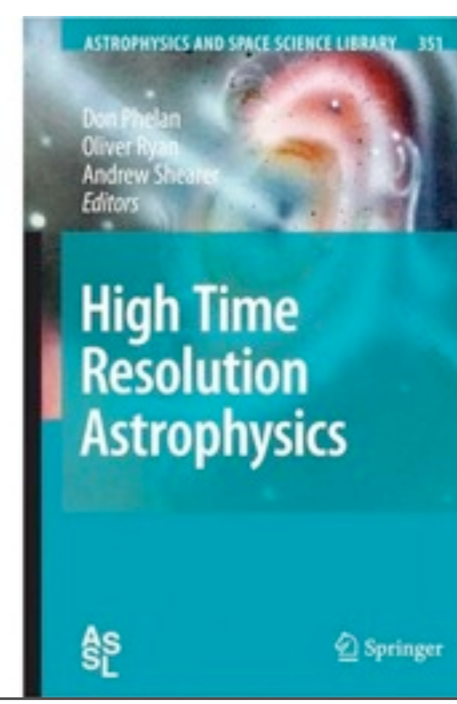
Normal Stars
- Asteroseismology
- Stellar Pulsations

Brown Dwarfs

Transients and Occulations

AGN

Most of these
- ★ are optical objects
- ★ show stochastic behaviour
- ★ are effectively point sources



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Transients and Occulations

AGN

- ★ They are examples of *Extreme Physics*
- ★ eg pulsars
  - ★ magnetic fields > 10^{15} G
  - ★ density ~ 10^{15} g / cm^3
  - ★ surface temperature ~ 10^6K
  - ★ plasma Lorentz factors γ > 10^9
  - ★ GR effects ~ 25% at surface
  - ★ neutron star structure
    - ★ Fe atmosphere
    - ★ Neutrionic 'mantle' and crust
    - ★ Inner region - free quarks???

Science drivers and time scales

		Time-scale (now)	Time-scale (ELT era)
Stellar flares and pulsations		Seconds/ Minutes	10-100ms
Stellar surface oscillations	White Dwarfs Neutron Stars	1-1000 μsec	1-1000 μsec 0.1 μsec
Close Binary Systems (accretion and turbulence)	Tomography Eclipse in/egress Disk flickering Correlations (e.g. X-ray & optical)	100ms++ 10ms+ 10ms 50ms	10 ms+ < 1ms < 1ms <1ms
Pulsars	Magnetospheric Thermal	1μsec-100ms 10 ms	nsec(?) <ms
AGN		Minutes	Seconds(?)

HTRA usage - UltraCam

Table 2. Breakdown of the percentage of time spent observing different cla[...] of astronomical object with ULTRACAM on the WHT and VLT. The right-hand column provides references to some of the ULTRACAM papers published in each area

Target	Time	References
Cataclysmic variables/accreting white dwarfs	22%	[24], [10]
Black-hole X-ray binaries	19%	[36], [37]
sdB stars/asteroseismology	15%	[1], [16]
Kuiper belt object occultations	11%	[34]
Eclipsing white-dwarf/red-dwarf binaries	10%	[5], [29]
Pulsars	5%	[8], [7]
Ultra-compact binaries	4%	[3]
Flare stars	4%	[28]
Extrasolar planet transits	3%	
Isolated white dwarfs	2%	[38]
Isolated brown dwarfs	2%	[25]
Gamma-ray bursts	1%	[45]
Active galactic nuclei/Blazars	1%	
Titan/Pluto occultations	1%	[11], [48]

from Dhillon, 2007 in High-Time Resolution Astrophysics, ASSL, vol 351

HTRA is primarily a detector and data problem

Instrument	Detector	Photometry@	Polarimetry*	Spectroscopy
Quanteye[1]	100 SPAD	ps–ns	No	No
Aqueye[2]	4 SPAD	ns–μs	AFOSC	AFOSC
GASP[3]	GaAs Image Tube	ns–μs	Full Stokes	possibly
Salticam[4]	2x1 CCD	100 ms–secs	No	UBVRI
RSS[5]	3x1 CCD	50 ms–1.6 s	L, C, SP, FS	VPH, filters
ULTRACAM[6]	3 CCD	0.237s–10s	No	3 colour
LuckyCam[7]	L3CCD	$>$ 40 frames/s	No	filters
TRIFFID[8]	3 APD, L3CCD	1 μs	No	3 colour
OPTIMA[9]	8 APD	1 μs	L	No
MPPP[10]	PSD	1 μs	Full Stokes	4 colour
FUSP[11]	PSD	1 μs	L, IP, SP	4 colour
IMPOL[12]	CCD	12 s frame rate	Full Stokes	No
ZIMPOL[13]	CCD	34 ms frame rate	Full Stokes	No
LRIS (Keck)[14]	CCD	72ms	L, C, IP+SP	Grism
FORS2 (VLT)[15]	CCD	2.3ms–2.3s	No, FORS1	Grism, VPH
FOCAS (Subaru)[16]	CCD	0.1s	L, C, SP	Grism, VPH
S-CAM3[17]	STJ	5 μs	No	Energy resolving, R 8–13
UCTPol[18]	photomultiplier tube	1 ms	L, C	UBVRI
AcqCam[19]	CCD	6–60 s	No	UBVRI
ISIS[20]	CCD	0.2–15 s	IP, SP	dichroics, blaze
Argos[21]	CCD	1 s	No	No
TES array[22]	TES	30μs	IP, LP, SP	Energy resolving, R $\sim$ 20

from Ryan and Redfern, 2007 in High-Time Resolution Astrophysics, ASSL, vol 351

42 m ELT stochastic limits - seeing limited

Table 2. Photon rates from a point source (1 arcsec assumed) collected by a 42 m telescope in V band* and integrating times for three detectors for S/N of 10

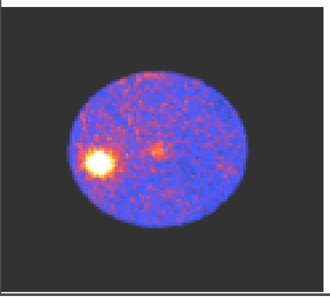
m_v	Photon Rates ph s^{-1} Telescope	Focal Plane	Detector cts s^{-1}	10 σ Exposure Times (s) GaAs[f]	SPAD array[g]	L3CCD[h]
18	510,000	410,000	290,000	570 μs	370 μs	220 μs
19	200,000	163,000	110,000	1.5 ms	1 ms	580 μs
20	80,000	66,000	45,000	4.2 ms	2.8 ms	1.6 ms
21	32,000	26,000	18,000	14 ms	9 ms	5 ms
22	13,000	10,000	7,000	5 ms	4 ms	2 ms
23	5,100	4,100	2,800	0.3	0.2	0.1
24	2,000	1,600	1,100	1.4	1.0	0.6
25	800	650	460	8.3	5.7	3.2
26	320	260	180	51	35	20
27	130	100	72	320	220	120
28	50	41	29	2,000	1,400	780
29	20	16	11	12,000	8,700	4,900
30	8	7	5	79,000	5,500	31,000

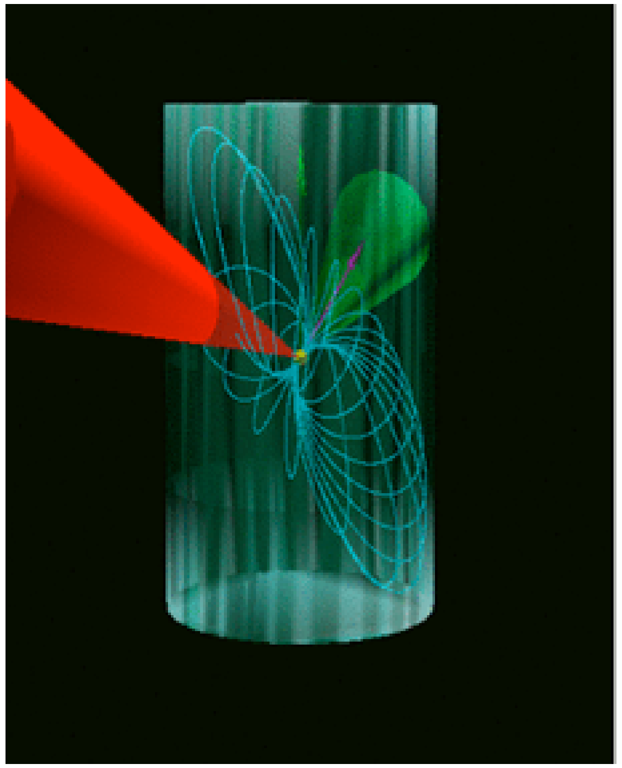
adapted from Ryan & Redfern, HTRA, ASSL, 351, 229

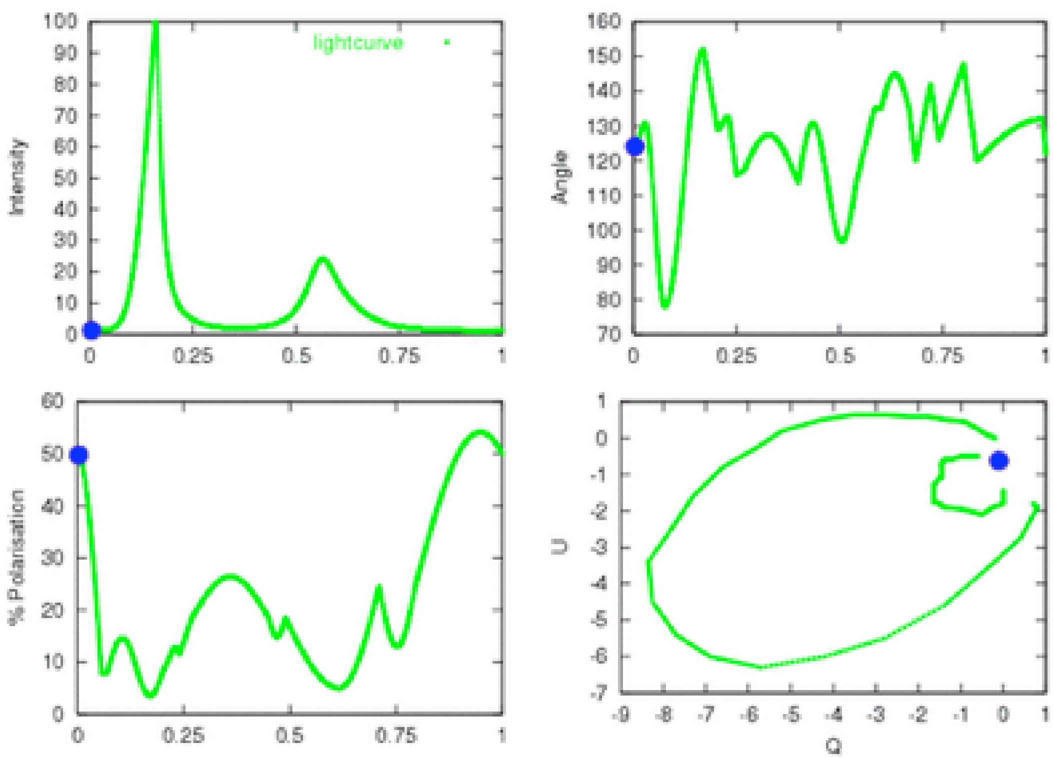
Pulsars - Extreme Case for HTRA

- Periodicities
  - 1ms to ~10 seconds
  - Time resolution required
    - < 1 microsecond (< 10 objects)
    - < 1 ms (< 100 objects)
    - < 1 sec (~1700 objects)
  - optical observations limited to seven objects pulsed and roughly twice as many integrated
  - **polarisation** and spectra also important

Shortest time scale measured to date <10ns from radio observations - Hankins et al 2003, Nature, 422, 141







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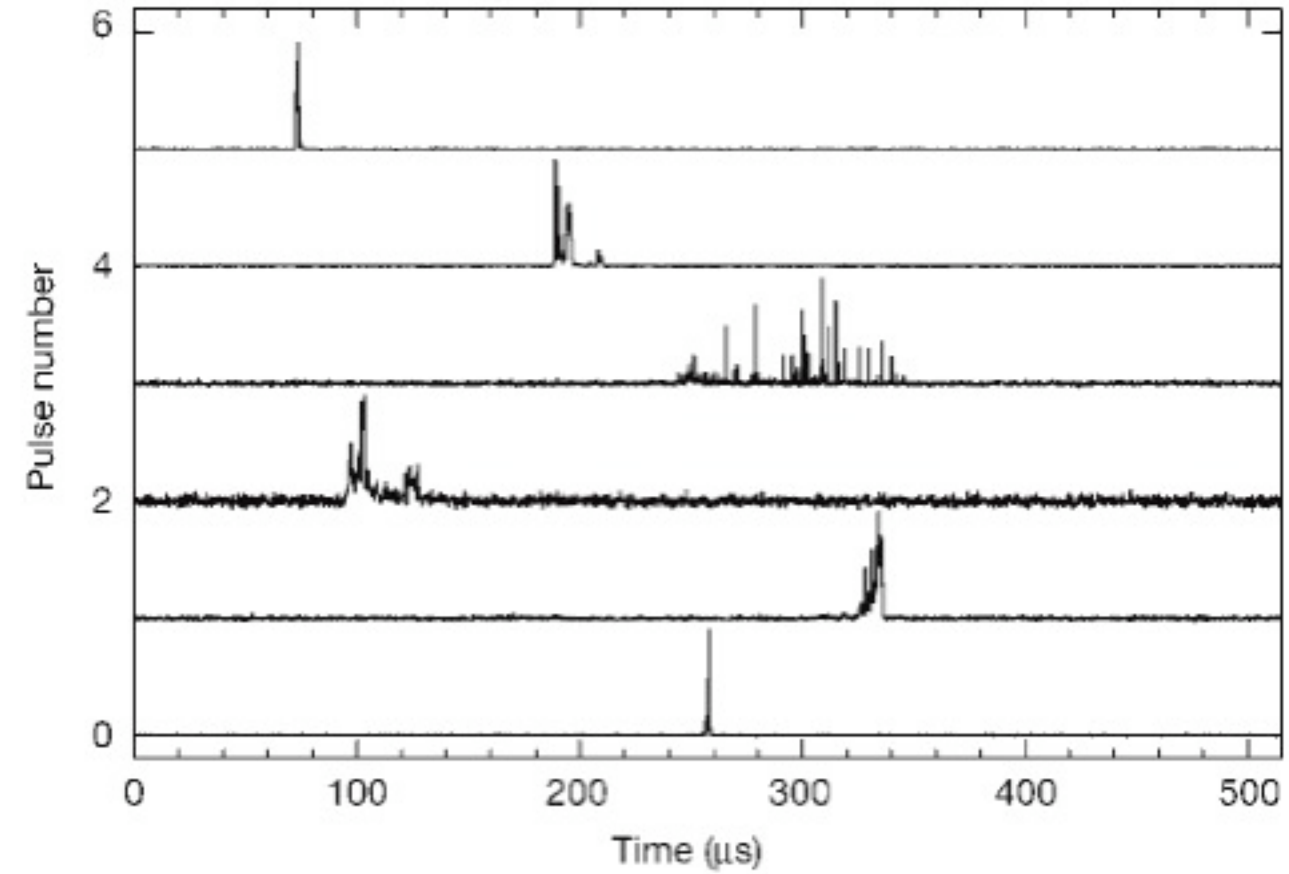
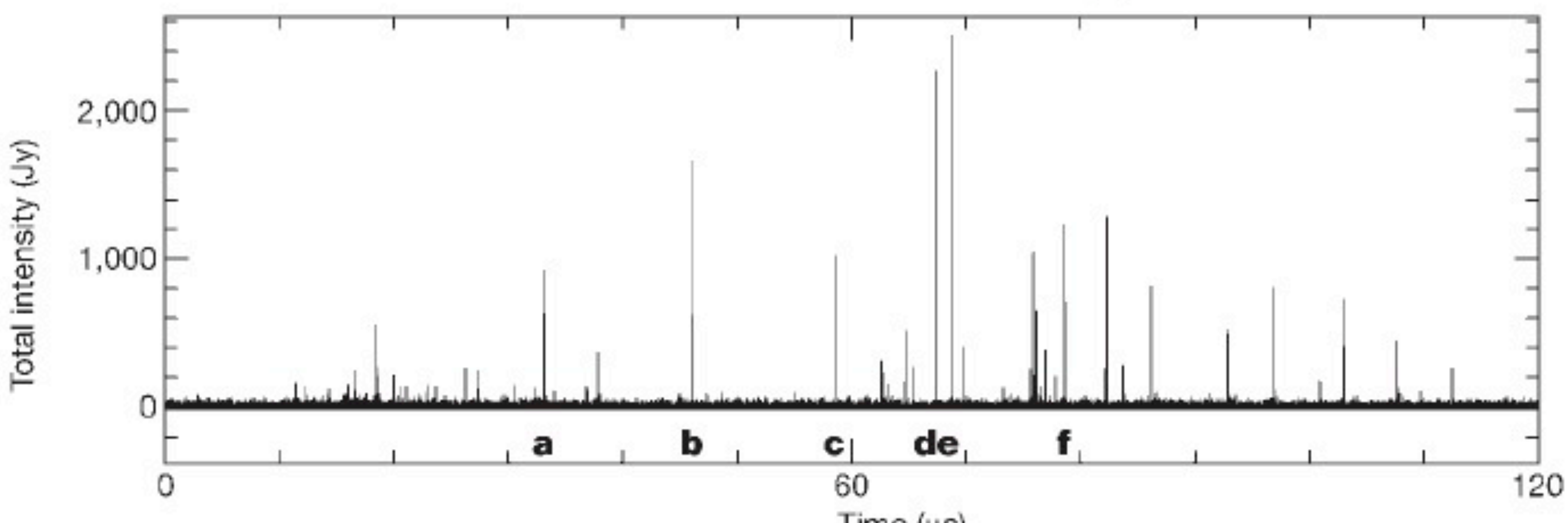
The fastest time-scale - radio observations

Hankins et al Nature, 2003, 422, 141

Structure at 3 nsec level

(resolving 1m at 2 kpc)





HTRA Science Case I - Pulsars

- **What do we know**

– pulsars are most likely magnetospherically active neutron stars

  - *"probably the only point of agreement between all these theories is the association of pulsars with magnetized, rotating neutron stars"* - Roger Blandford 1998

- **What we don't know**

– high energy emission mechanism

  - synchrotron / curvature

– where the plasma comes from

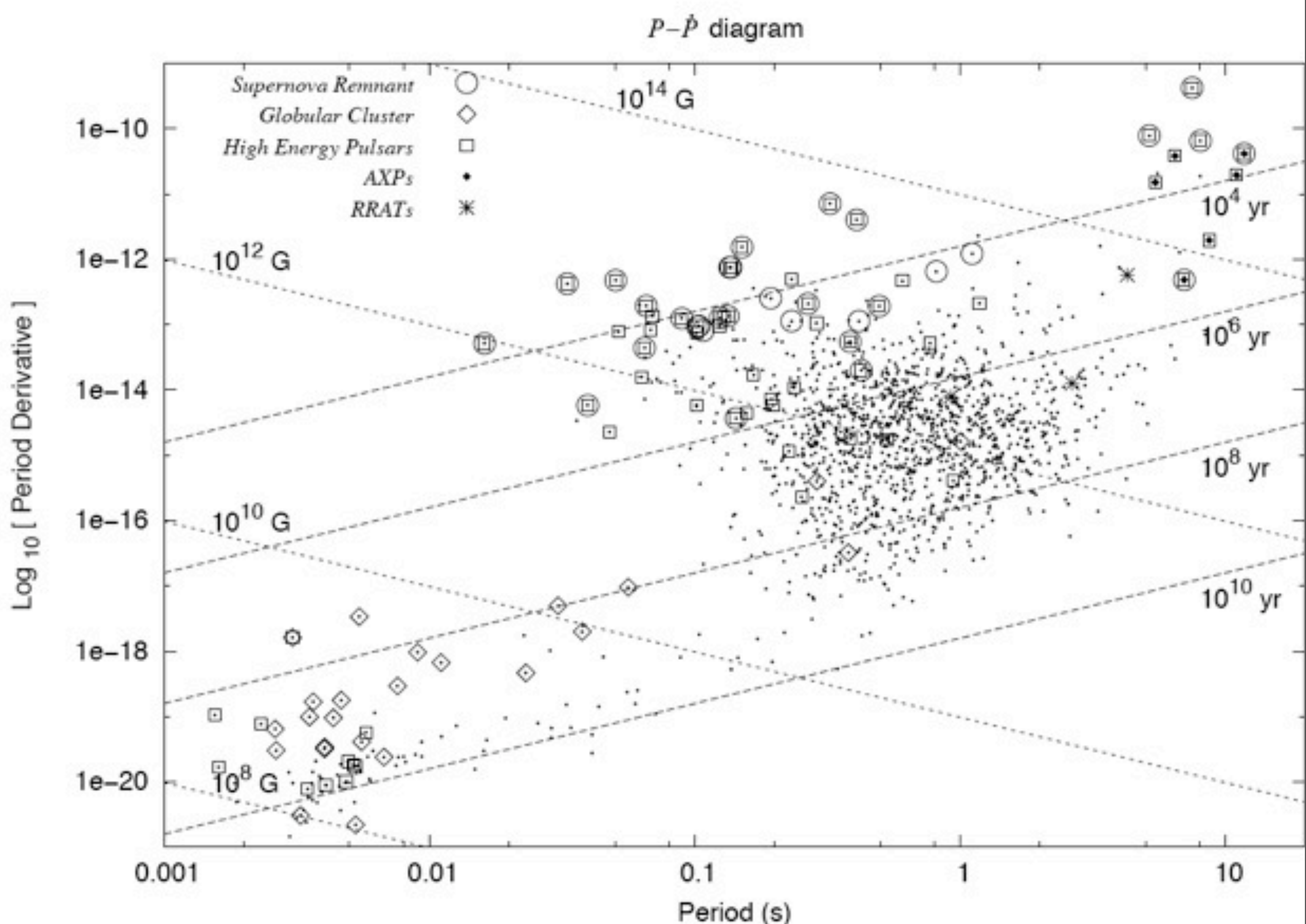
– population statistics

  - how many radio pulsars?
  - how many AXPs/SGRs?
  - how many radio quiet?
  - pulsar - SNR association?
  - beaming geometry?

– what happens during type II supernova?

– what are RRATs?

– what is the emission mechanism



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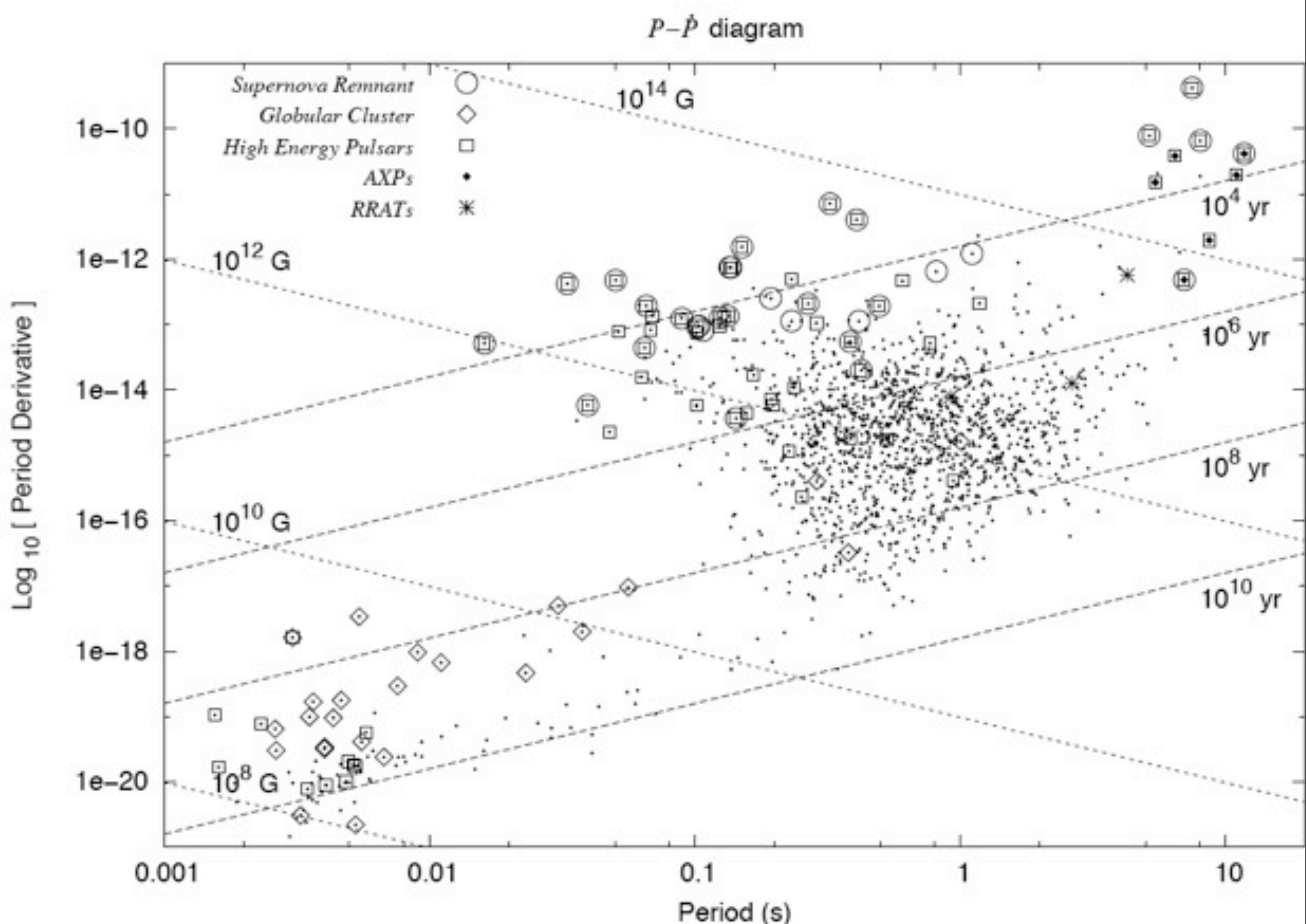


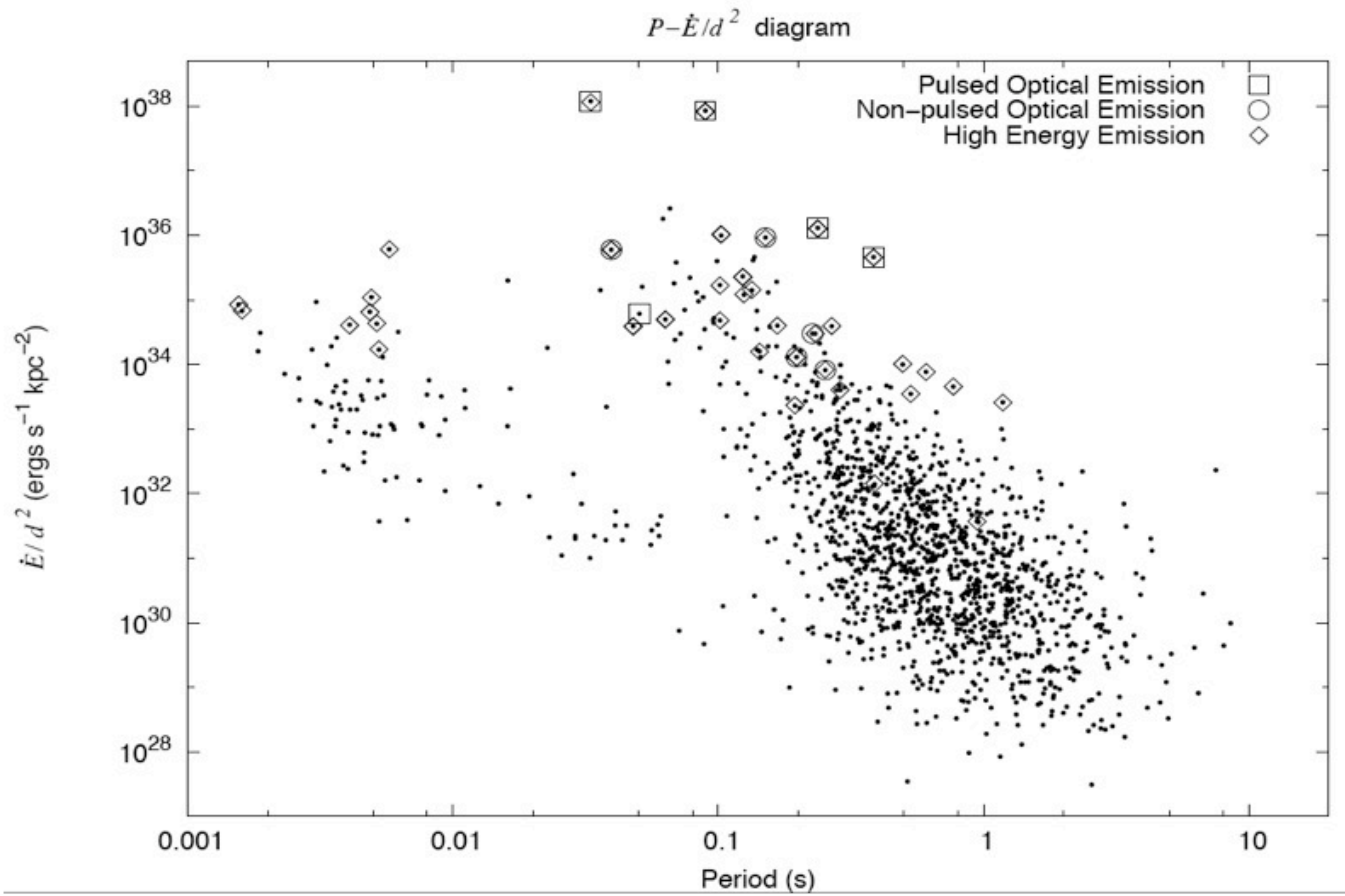
Pulsars - optical detector constraints

There are only 5 known ‘normal’ pulsars with pulsed magnetospheric optical emission

	m_B	Period (ms)	B VLT	B EELT
			photons/rotation	
Crab	**≈ 17**	**33**	**3,300**	**80,000**
PSR 0540-69	**≈ 23**	**50**	**17**	**410**
Vela	**≈ 24**	**89**	**12**	**440**
PSR 0656+14	**≈ 25.5**	**385**	**13**	**290**
Geminga	**≈ 26**	**237**	**5**	**120**
Crab like pulsar in M31				**~1**

The thermal signature is generally lower - see for example Kargaltsev et al, ApJ, 625, 307 (2005)

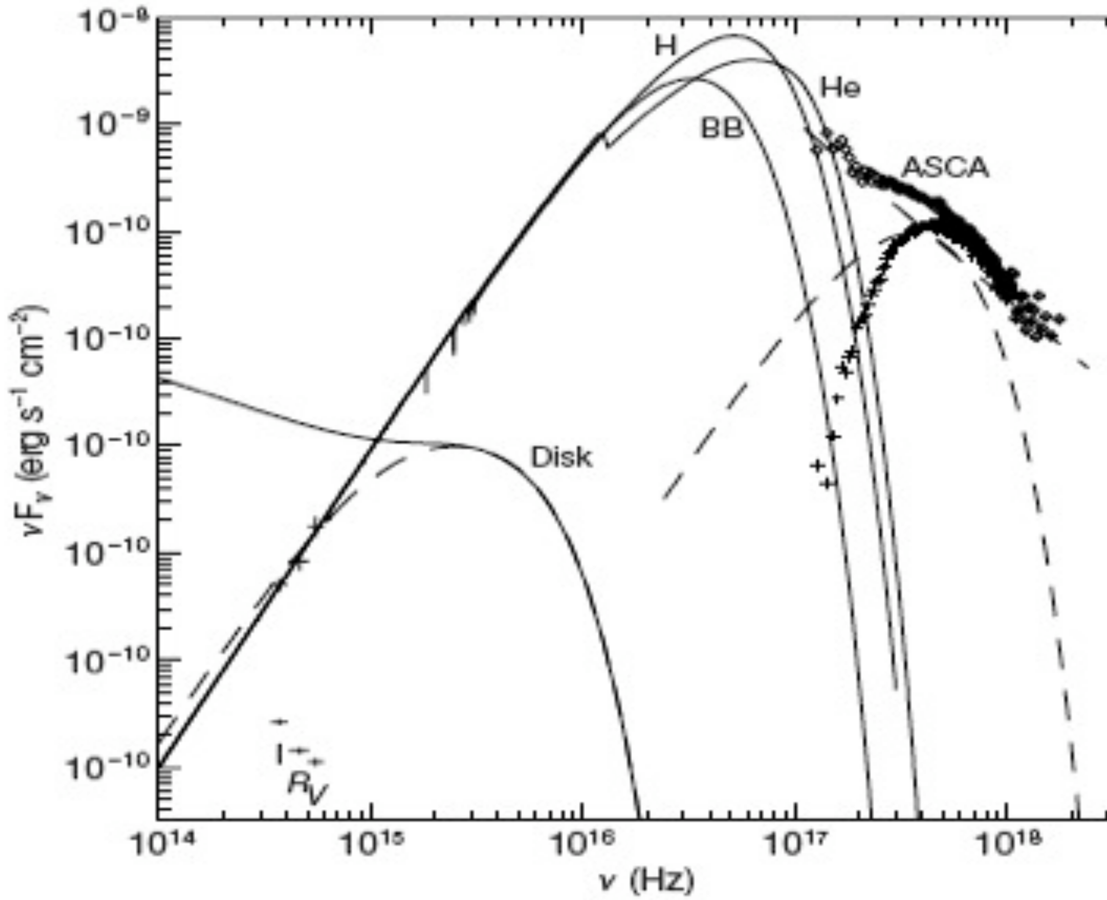
Pulsar ‘observability’ diagram

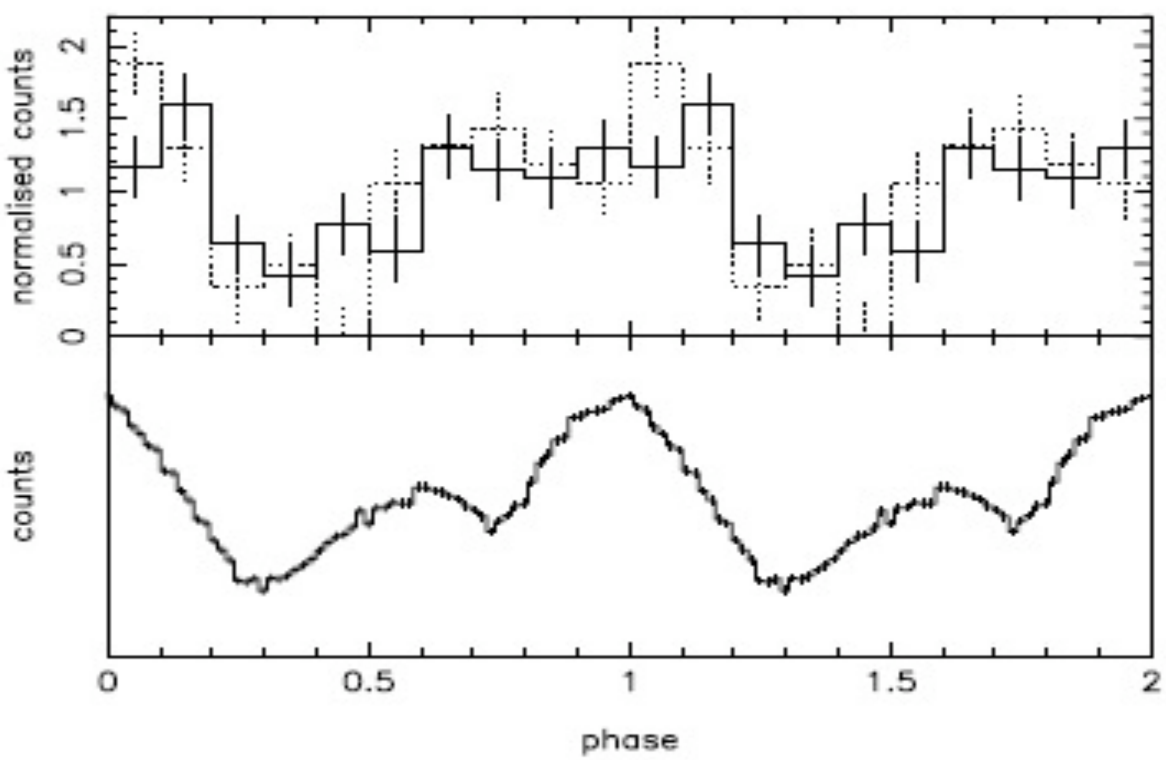


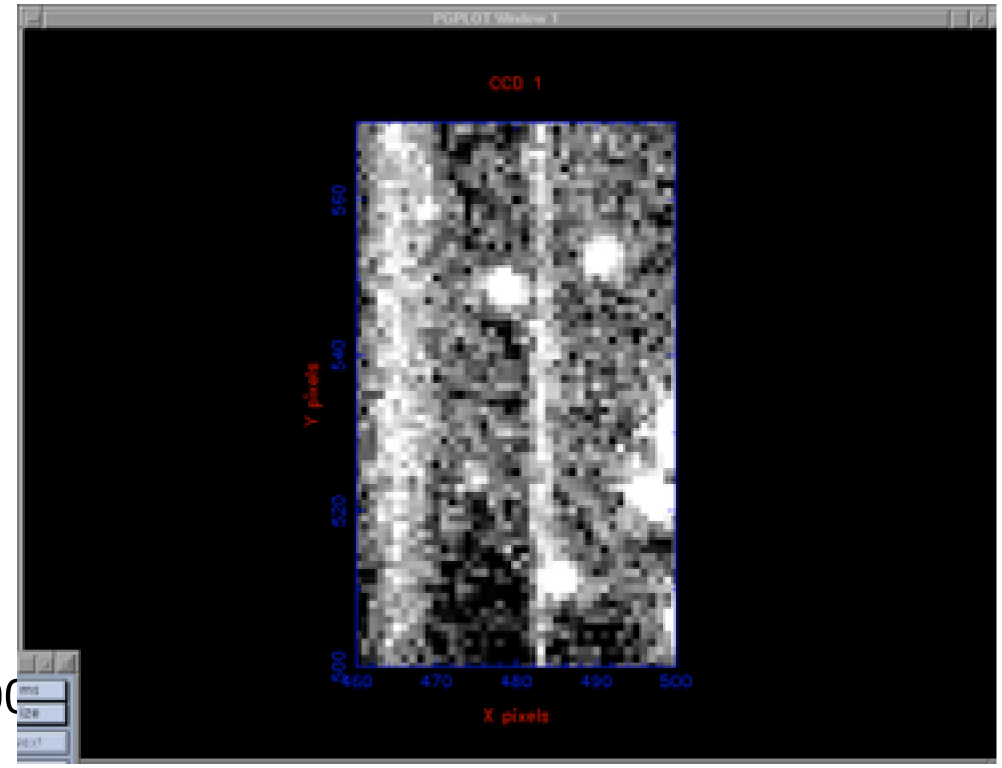
The E-ELT will increase the number of pulsars which can be studied in detail in the optical/NIR from 1 to 20+.

Anomalous X-Ray Pulsars

- Slow Period ~5-12 seconds
- Very high magnetic field $>10^{13}$G
- Optical counterparts
  - Hulleman et al, Nature, 408, 689 2000
    - too faint for an accretion disk R ~ 25
    - magnetar?
  - Optical pulsations detected for two AXPs
    - e.g 4U 0142+42
    - optical pulsed fraction 29% higher than in X-rays







AXPs and debris disks - 4U 0142+61

A debris disk around an isolated young neutron star

Zhongxiang Wang[1], Deepto Chakrabarty[1] & David L. Kaplan[1]

Wang et al, 2006, Nature, 440, 772

unpulsed

pulsed

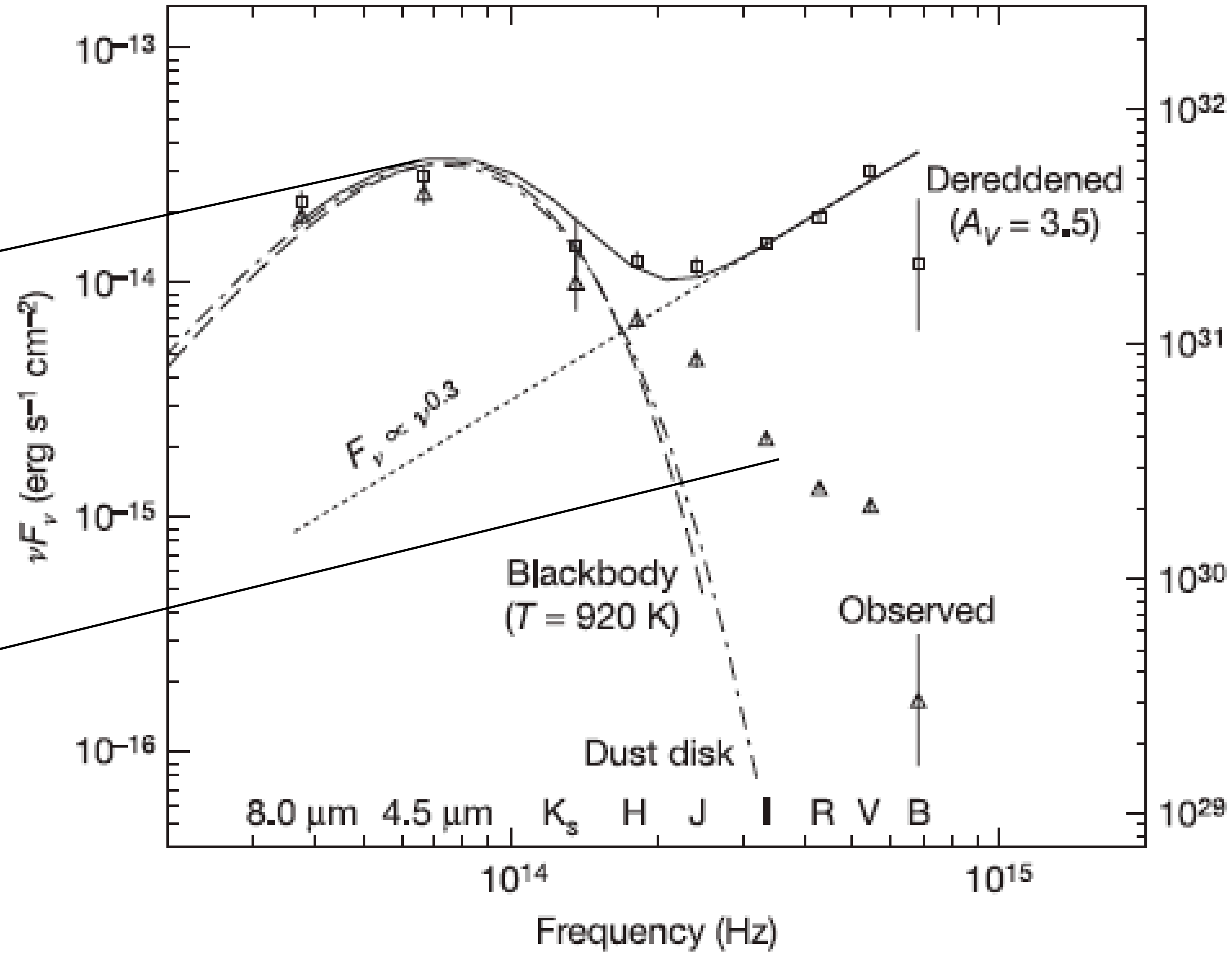
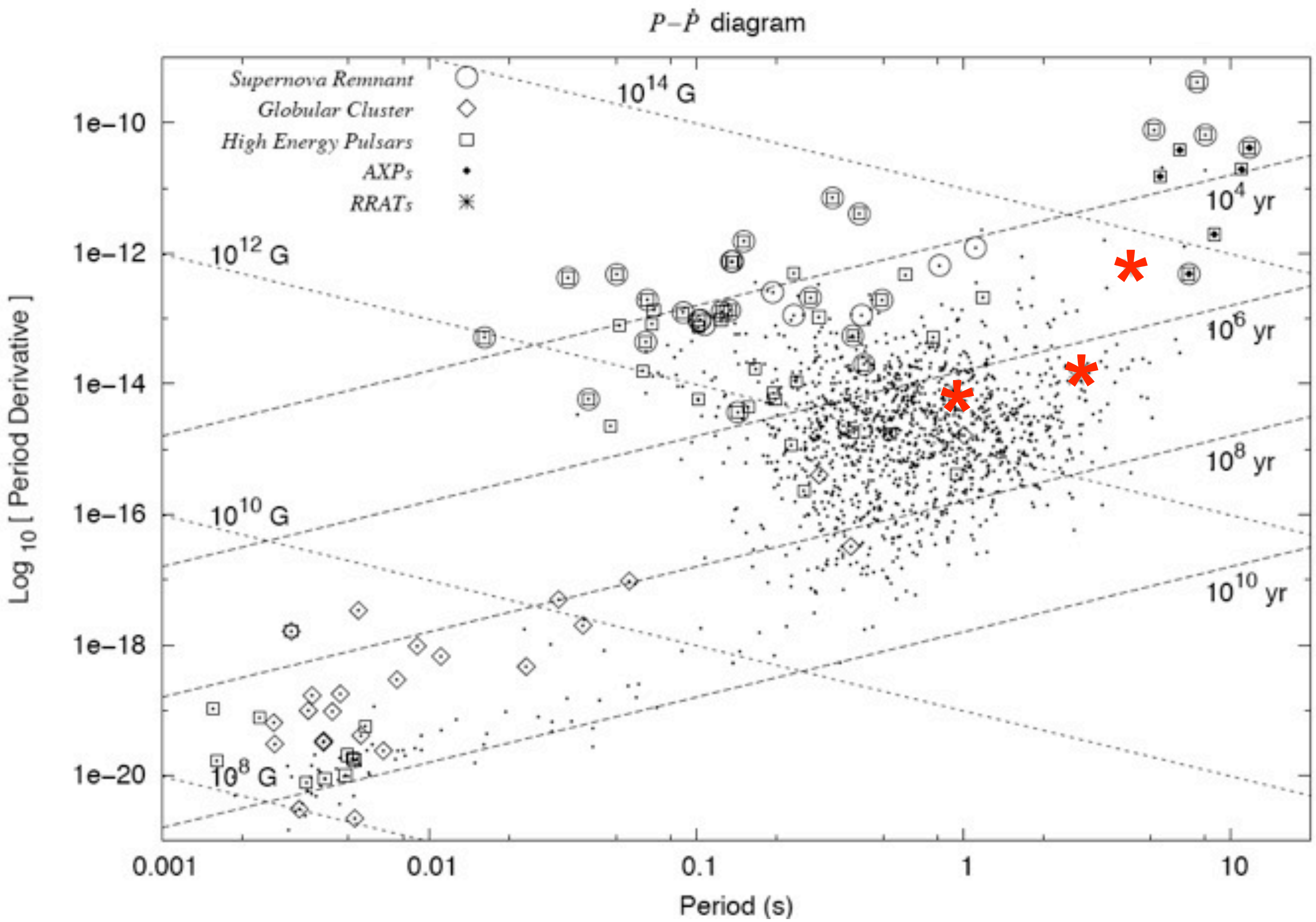


Figure 3 | Optical/infrared spectral energy distribution of 4U 0142+61. The vertical axes are both scaled by frequency ν. The left axis shows ν-scaled flux per unit frequency, νF_ν; the right axis shows ν-scaled luminosity per

Rotating RAdio Transients - RRATs

- Radio Transient Sources
  - Parkes survey - McLaughlin et al, Nature, 439, 817 (2006)
  - pulsar origin(?)
  - 2nd highest brightness temperature after GRPs
  - bursts last 10-30 ms and repeat every 4 minutes to 4 hours
  - Period ranges 0.4 to 6.8 seconds
  - Stochastic limit, V~22



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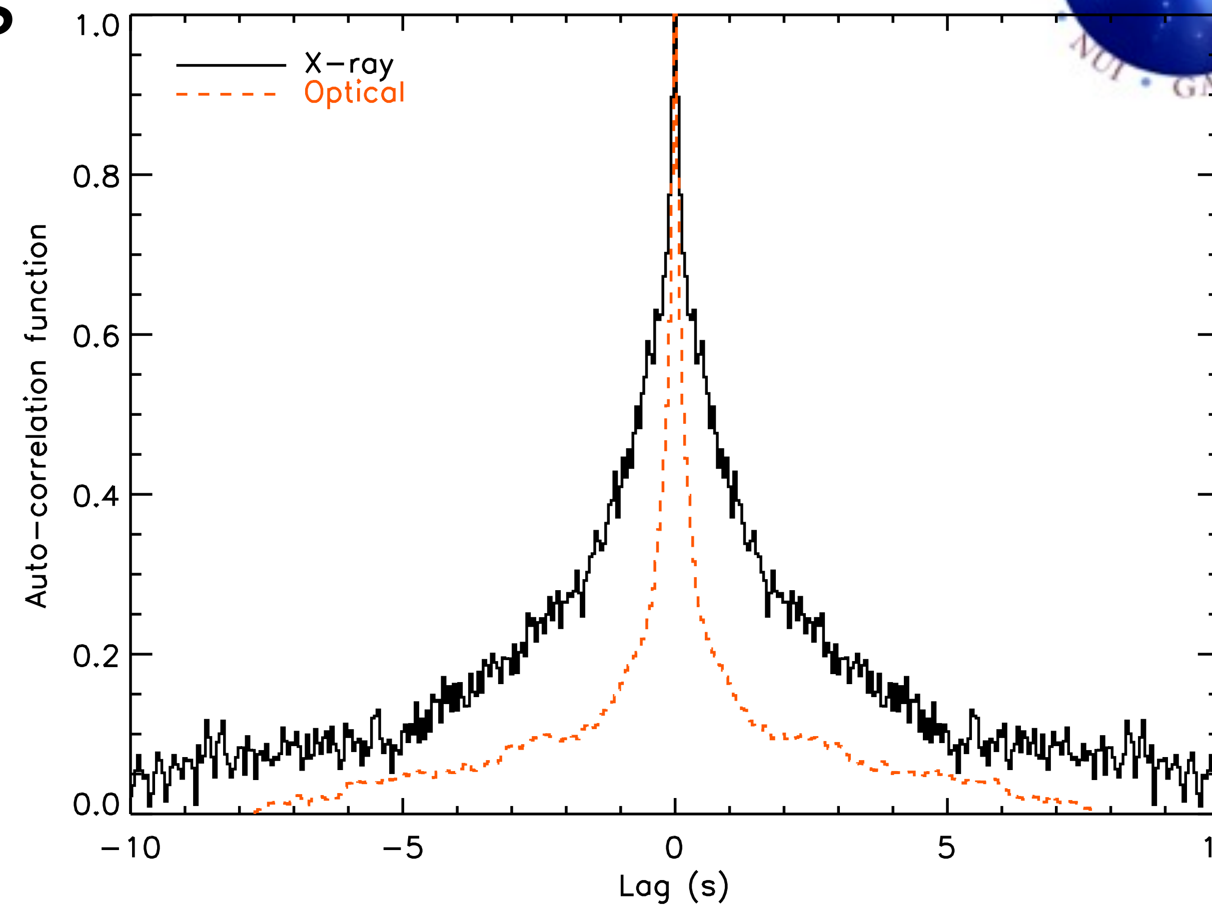
HTRA Science Case II
Close Binary Systems

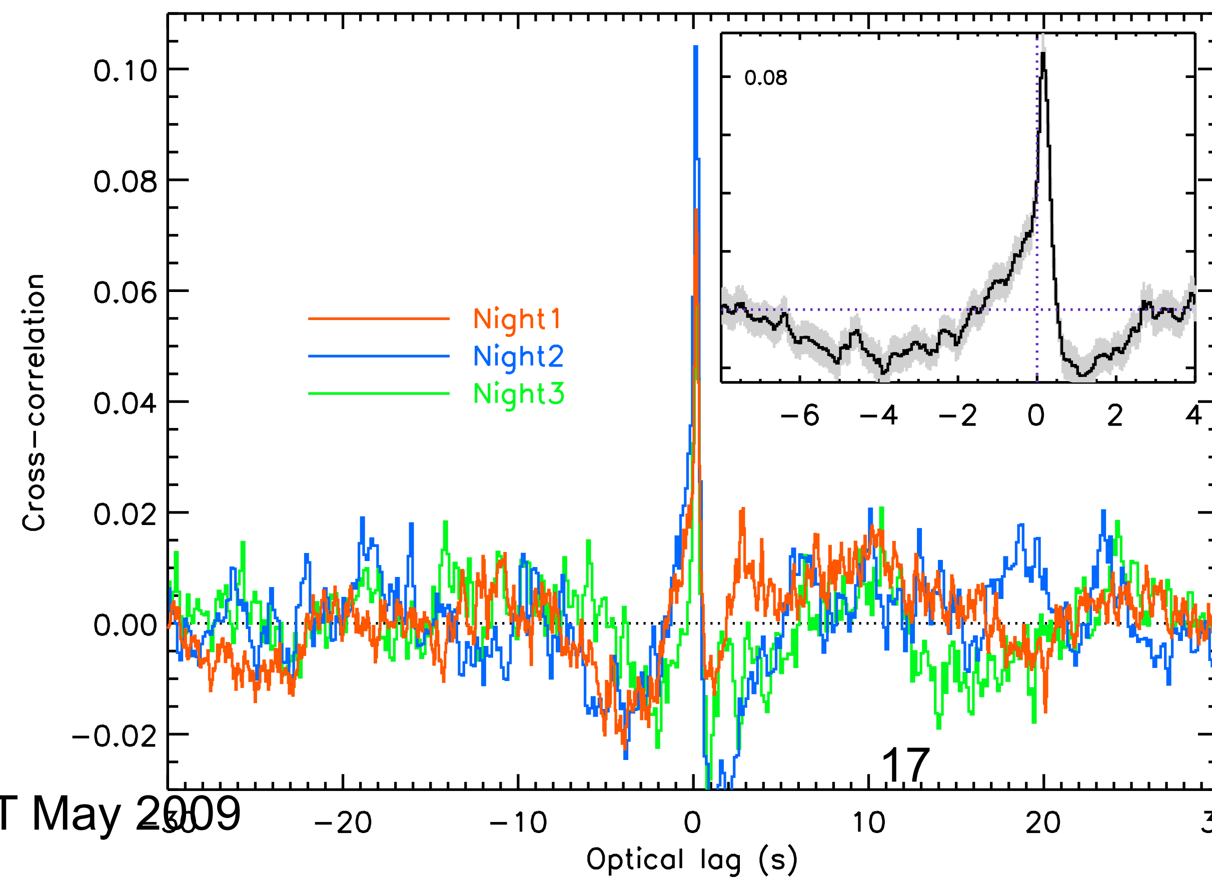
X-ray-Optical cross-correlations observed by UltraCam and Optima

Shown are UltraCam observations of the black-hole accretor GX339-4 - Gandhi et al (2008)

Time scales < 1 sec
Optical Autocorrelation indicated synchrotron emission from a possible jet structure rather than being driven by X-ray reprocessing.

GX339-4 is reasonably bright V~17. Other objects considerably fainter - E-ELT required to look at spectral variability



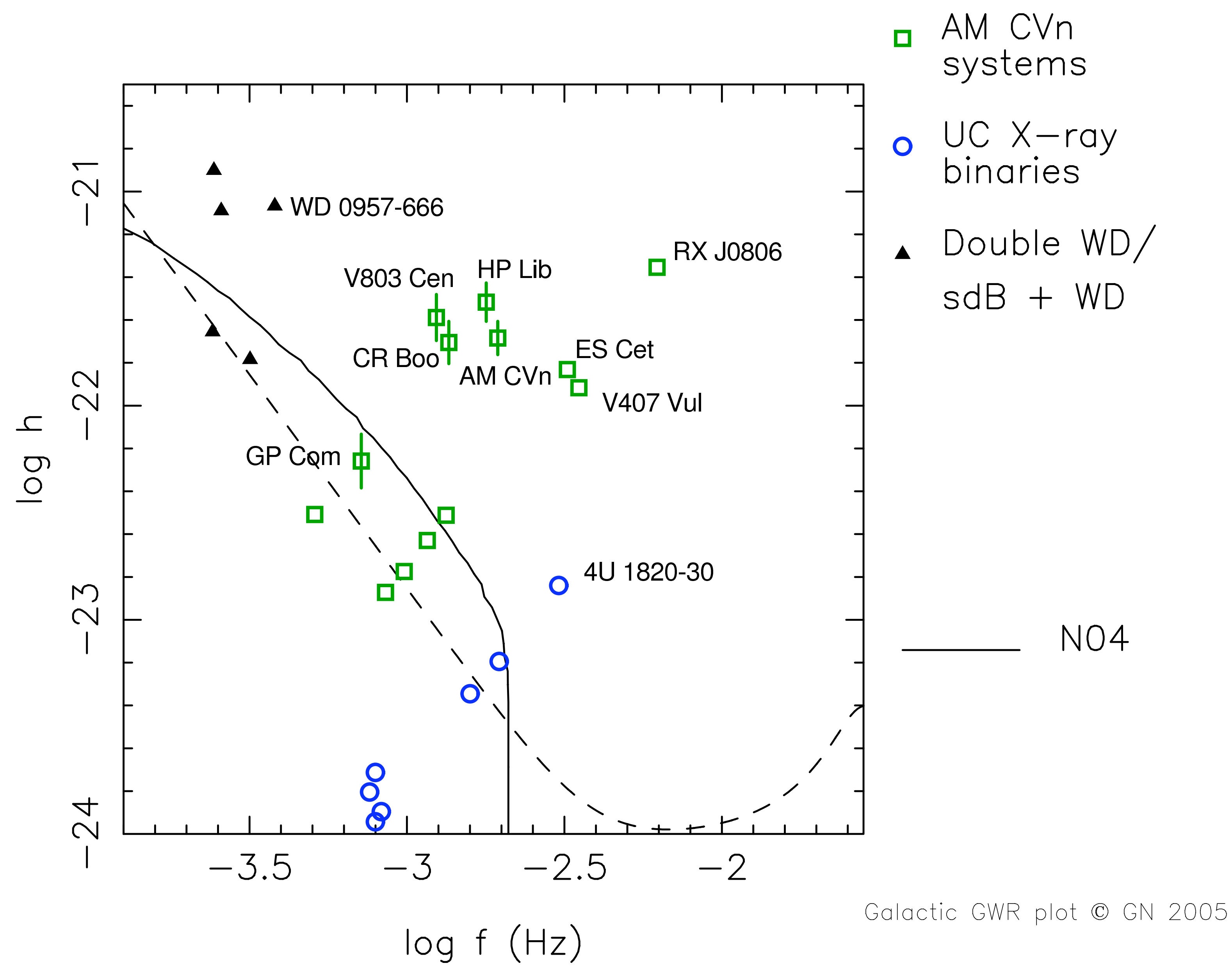


Thanks to Tom Marsh

Gravitational Wave Binaries

LISA should detect 1000s of close WD-WD binary systems

- Possible Sn 1a progenitors
- Orbital periods down to 100 s
- Faint
- HTRA as t~1-10 seconds and require low noise detectors
- Ideal HTRA - ELT target
  - tidal interactions
  - galactic merger rate
  - **are WD-WD systems Sn 1a progenitors?**



Nelemans et al (2009) arXiv:0902.2923v1 [astro-ph.SR]

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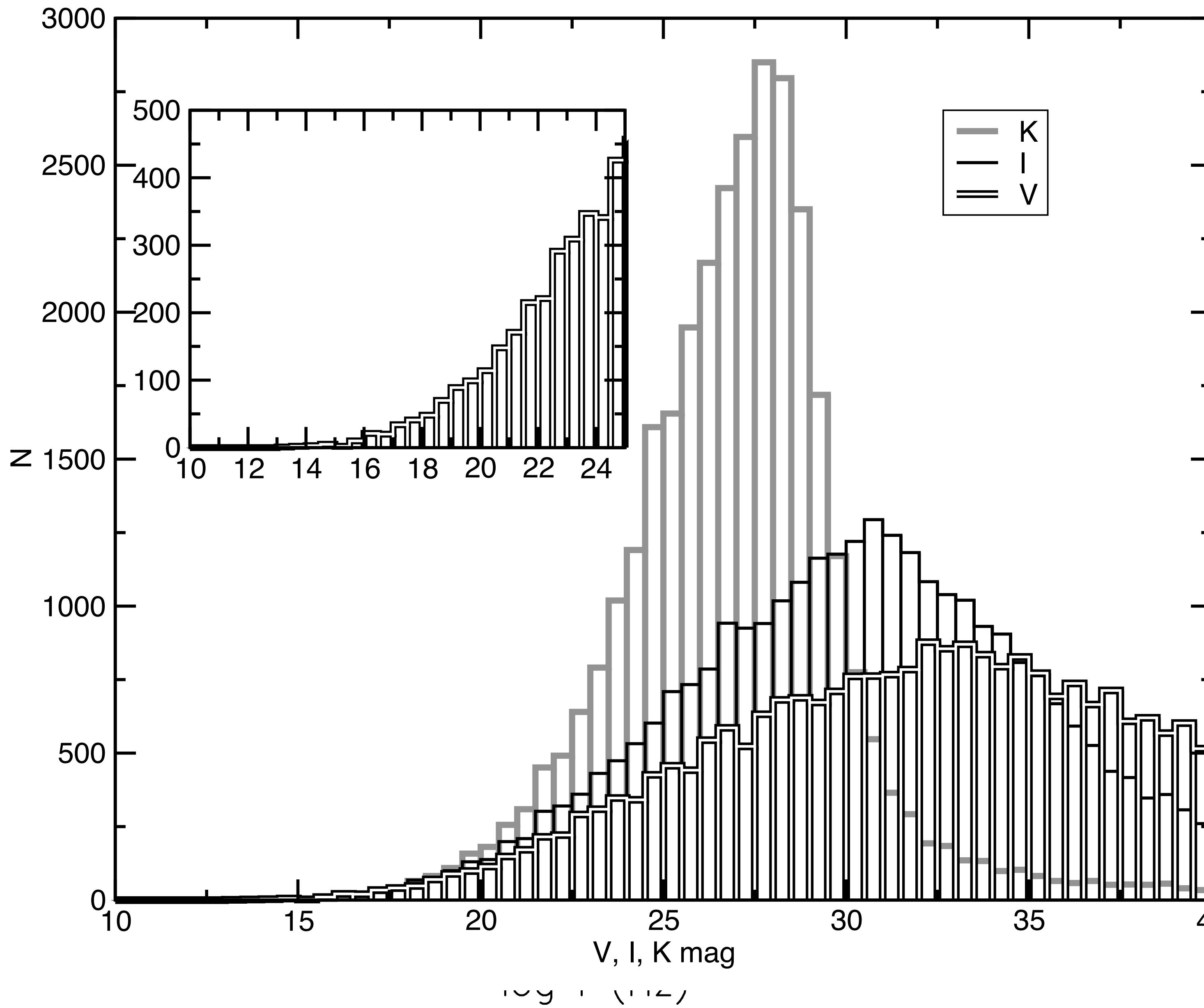

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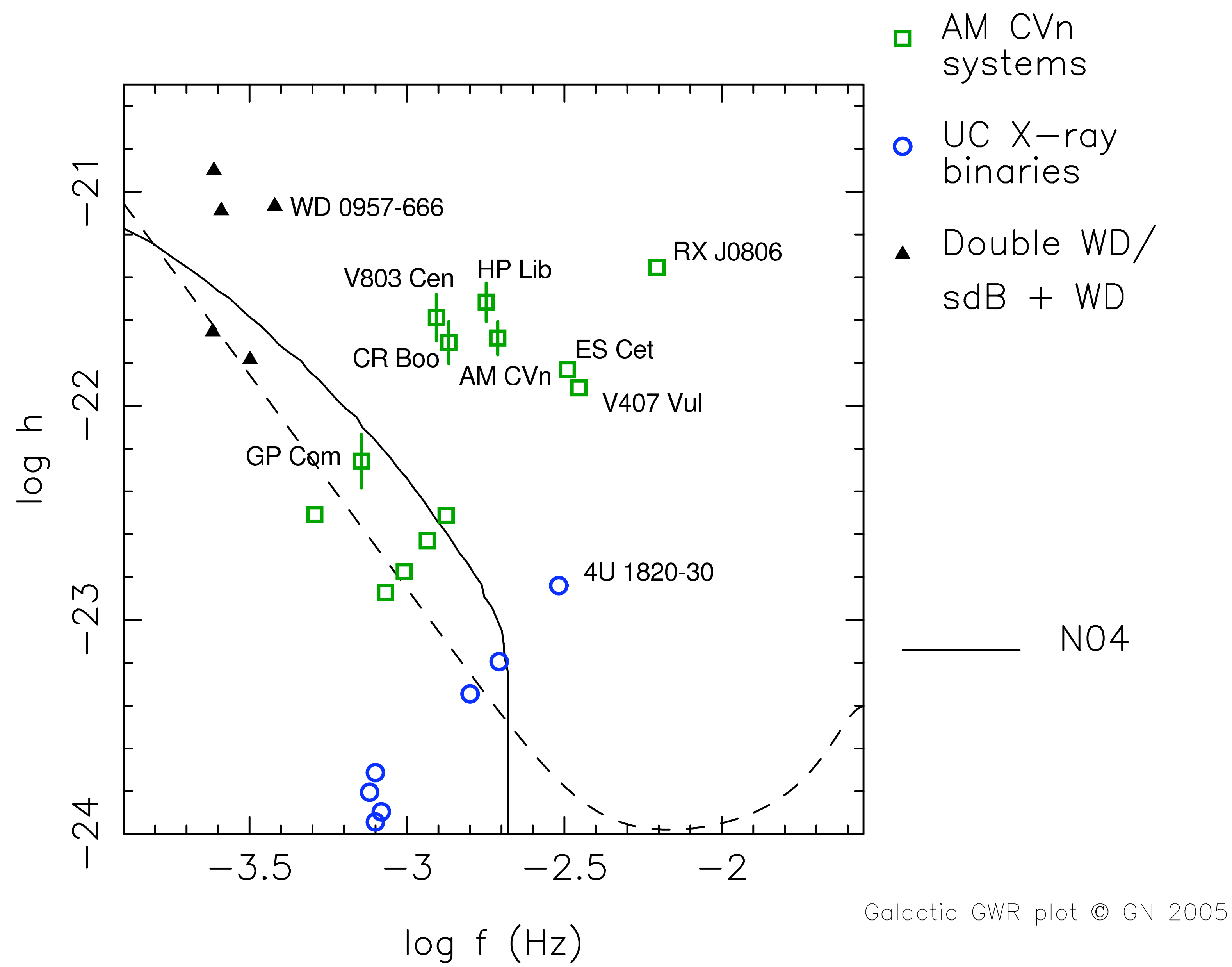

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Science Case III : Search for extragalactic Crab like pulsars

Pulsar V=~29th magnitude at M31 distance

SNR ~ 0.7” diameter

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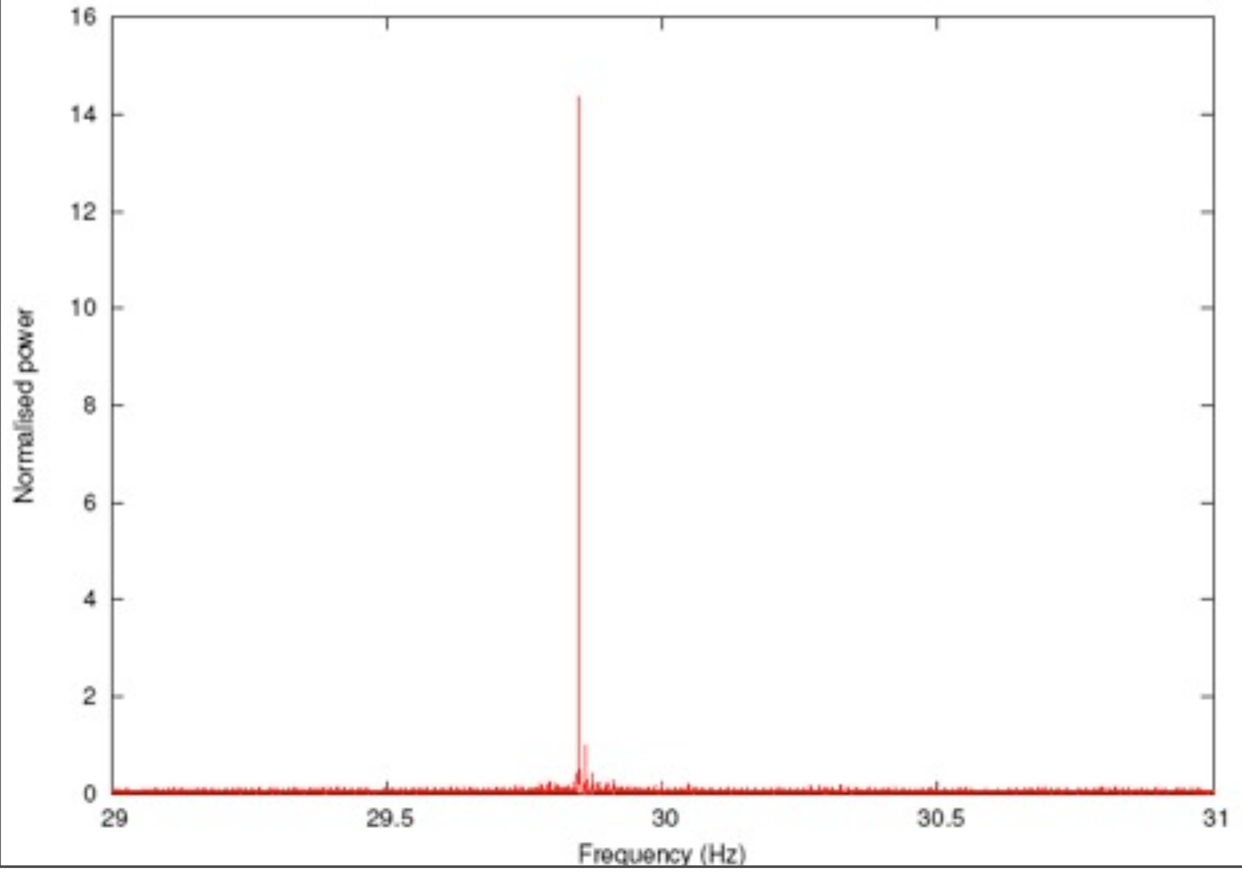
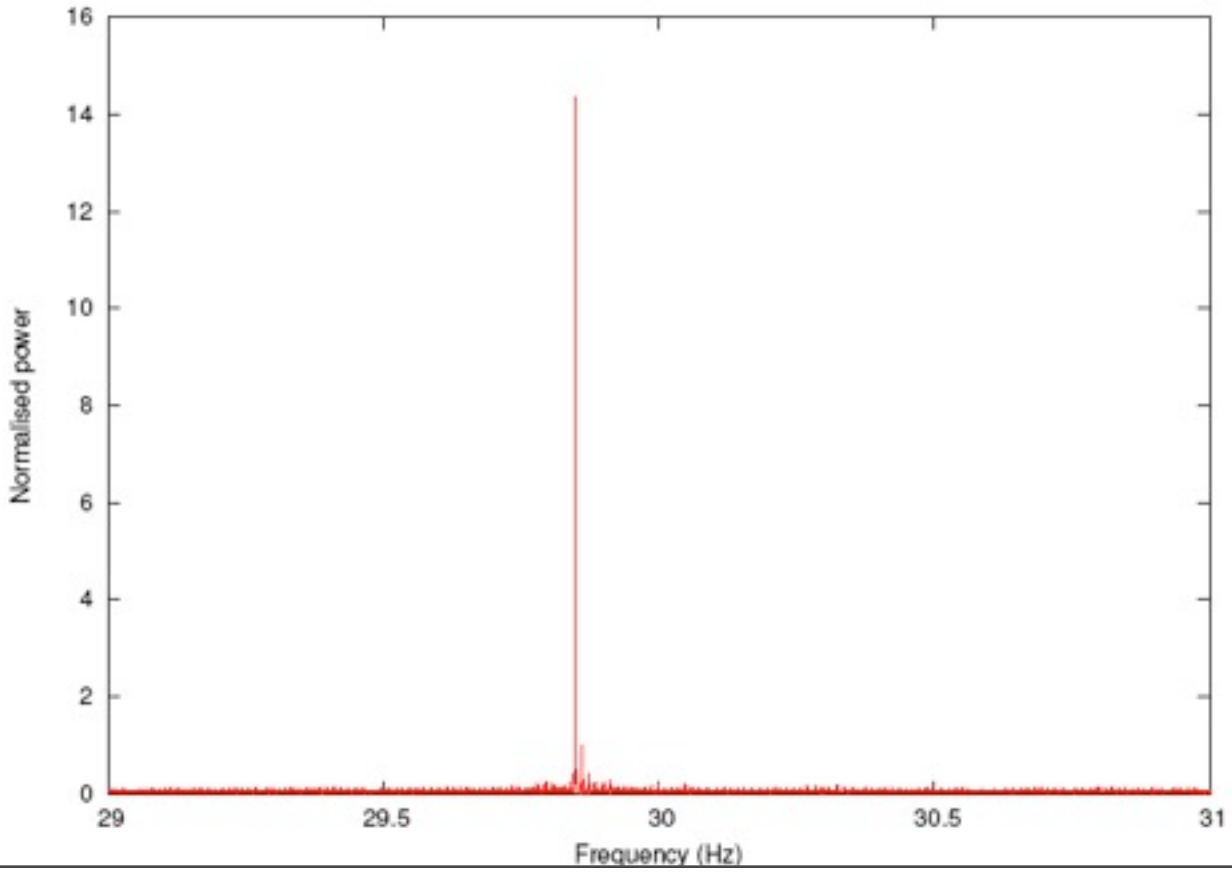


magnitude at M31

ıeter

ELT May 2009

Science Case III : Search for extragalactic Crab like pulsars



magnitude at M31

ıeter

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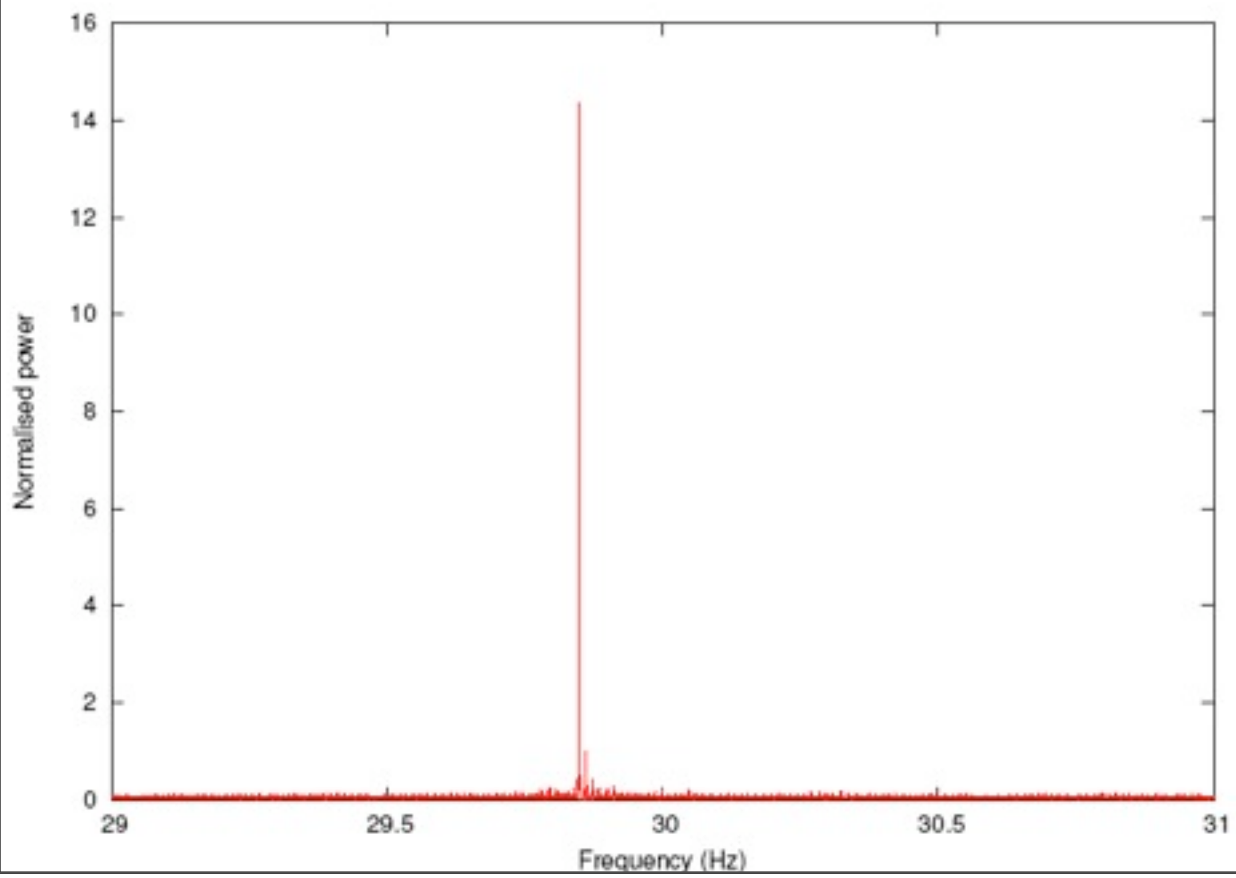

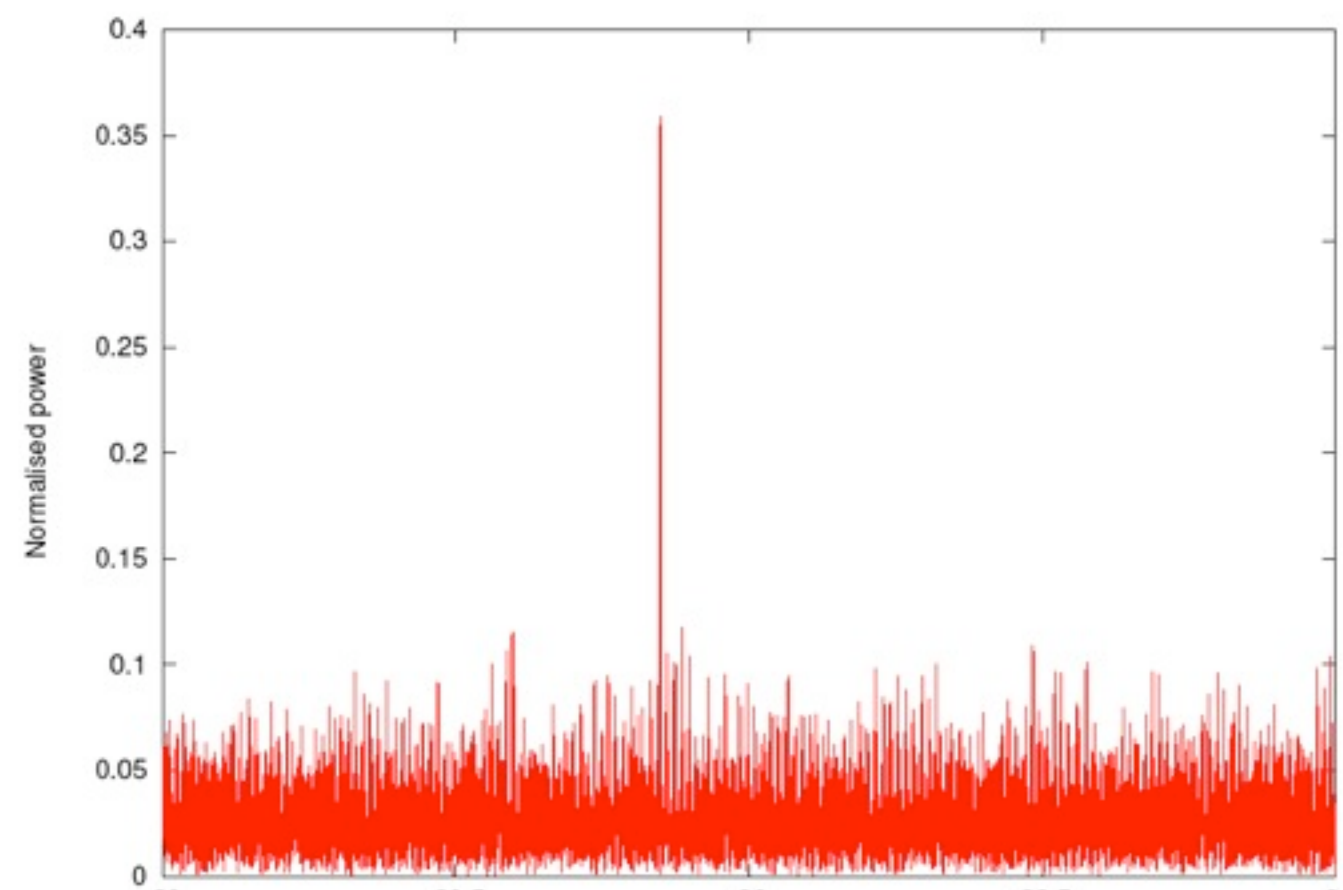

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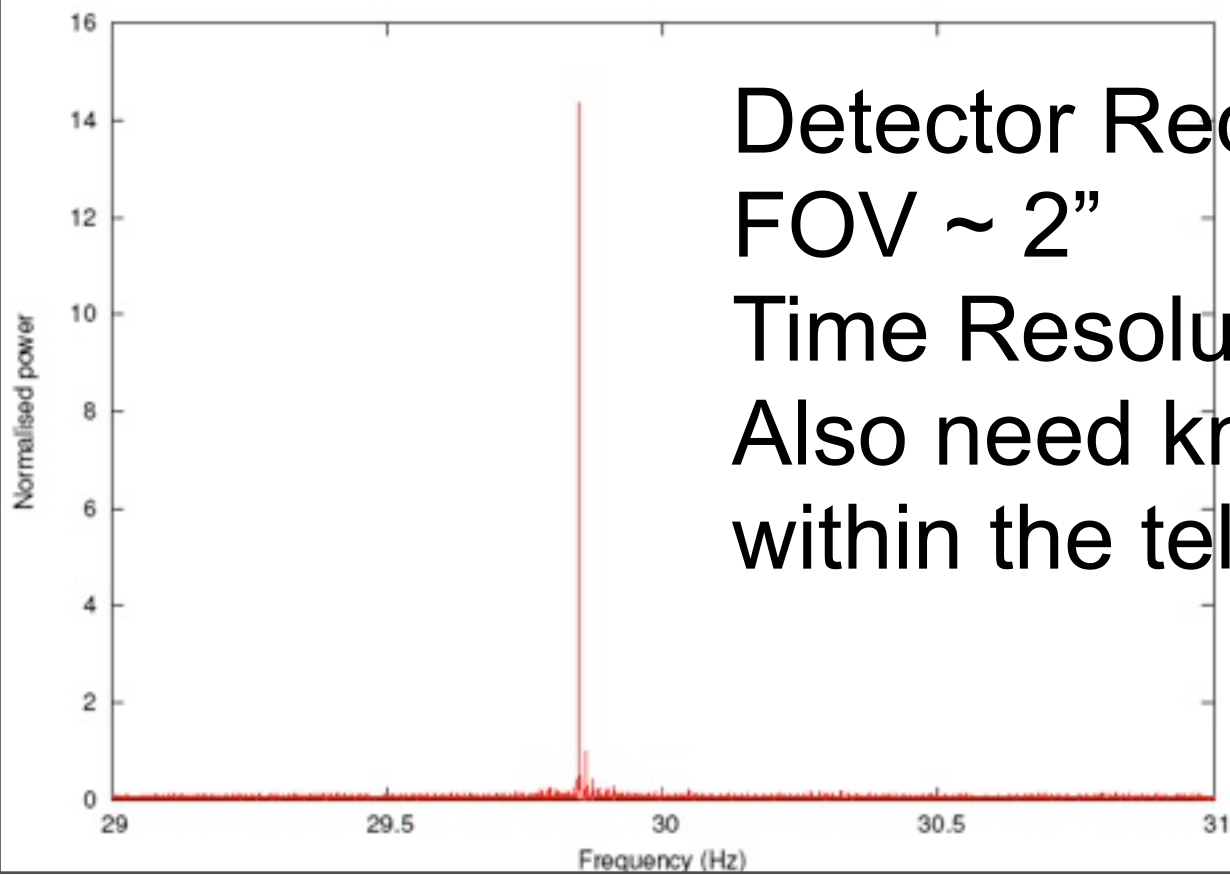
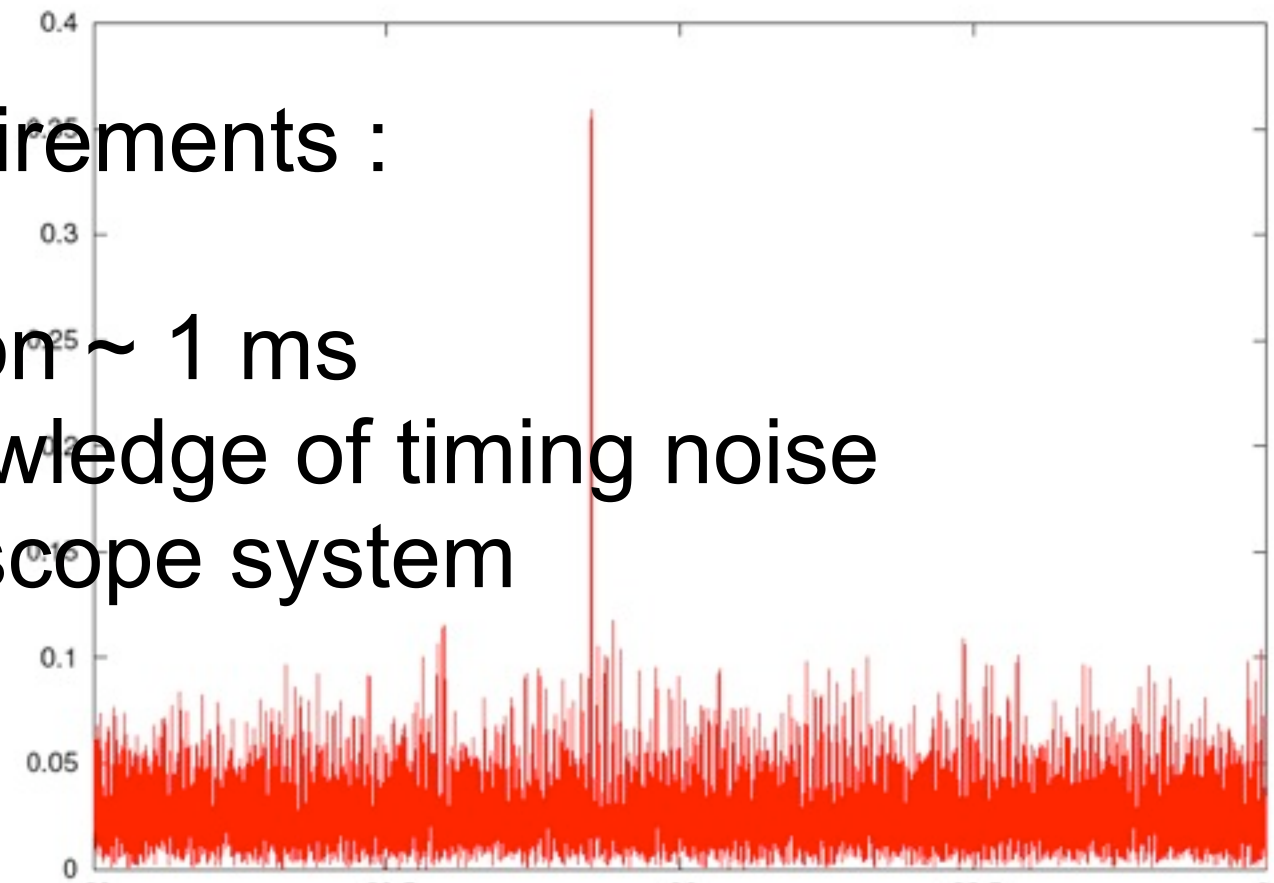


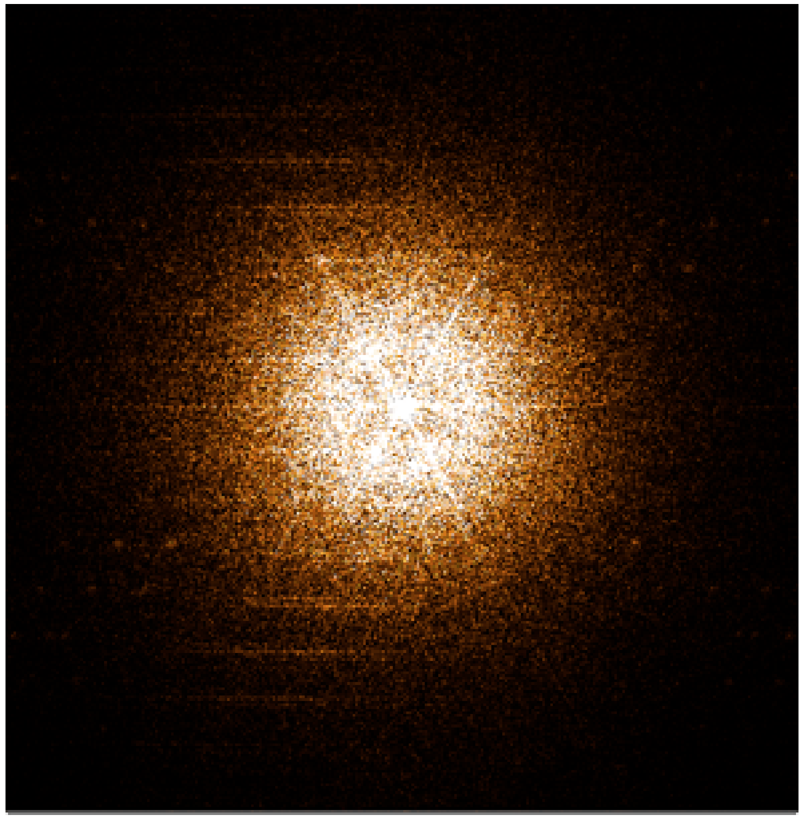


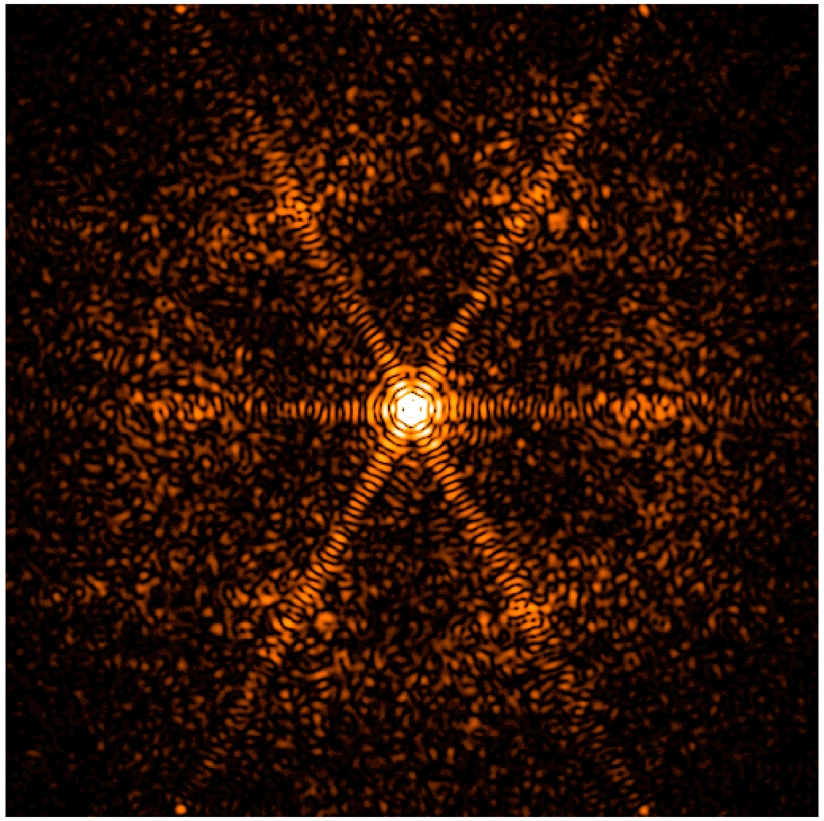
Detector Requirements :
FOV ~ 2”
Time Resolution ~ 1 ms
Also need knowledge of timing noise within the telescope system

EELT design and its implications for HTRA

Initially using Lund Euro50 - full end-end model, waiting for 42m E-ELT data covering more than 10 seconds

On-axis - fine for HTRA





PSF data from Lund telescope group

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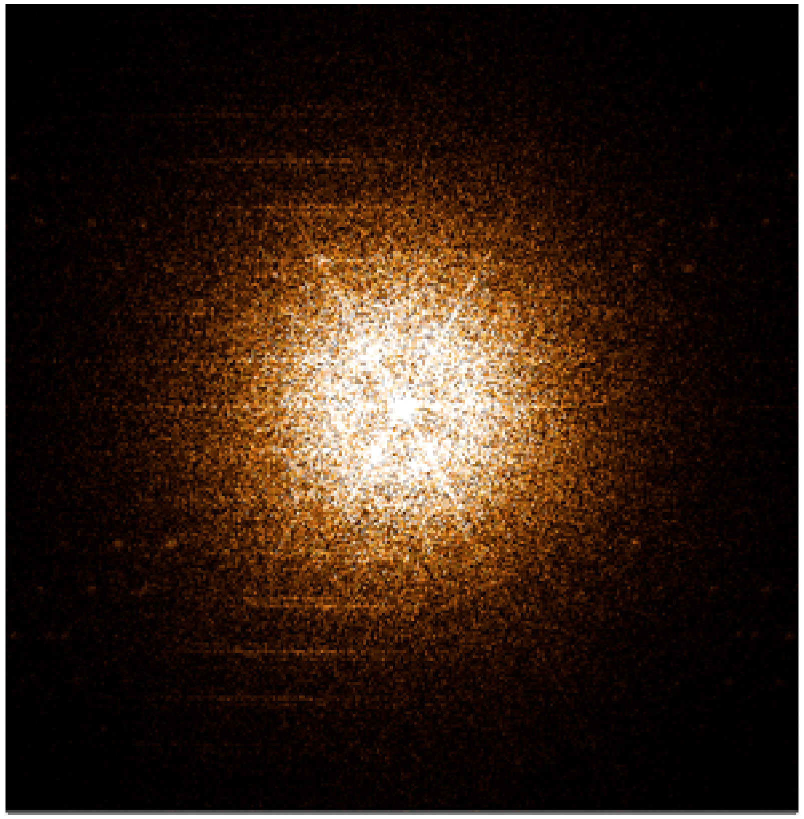
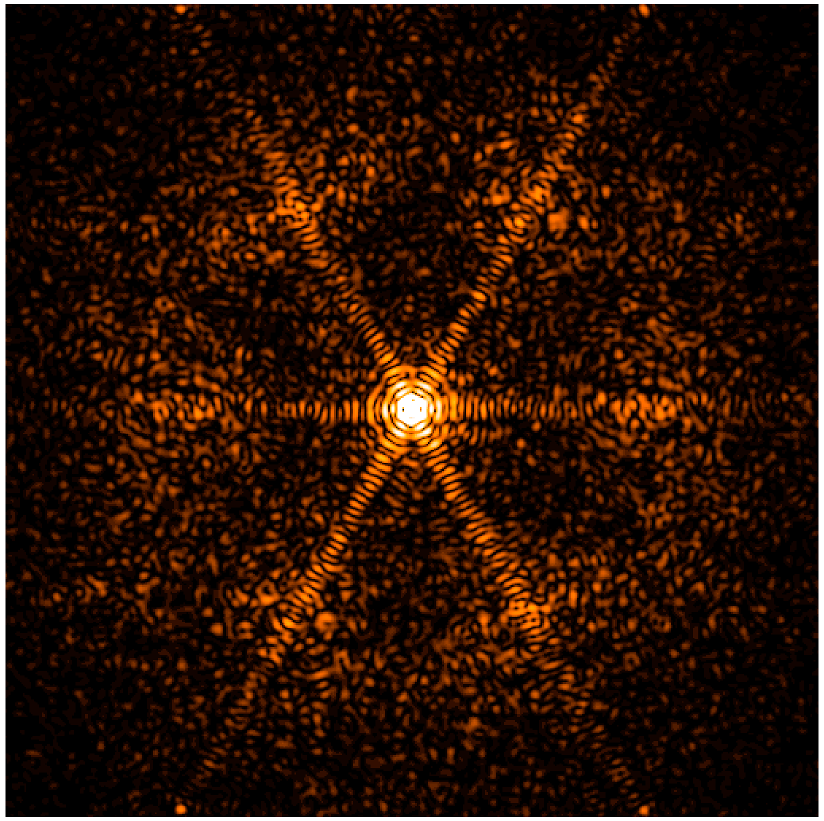
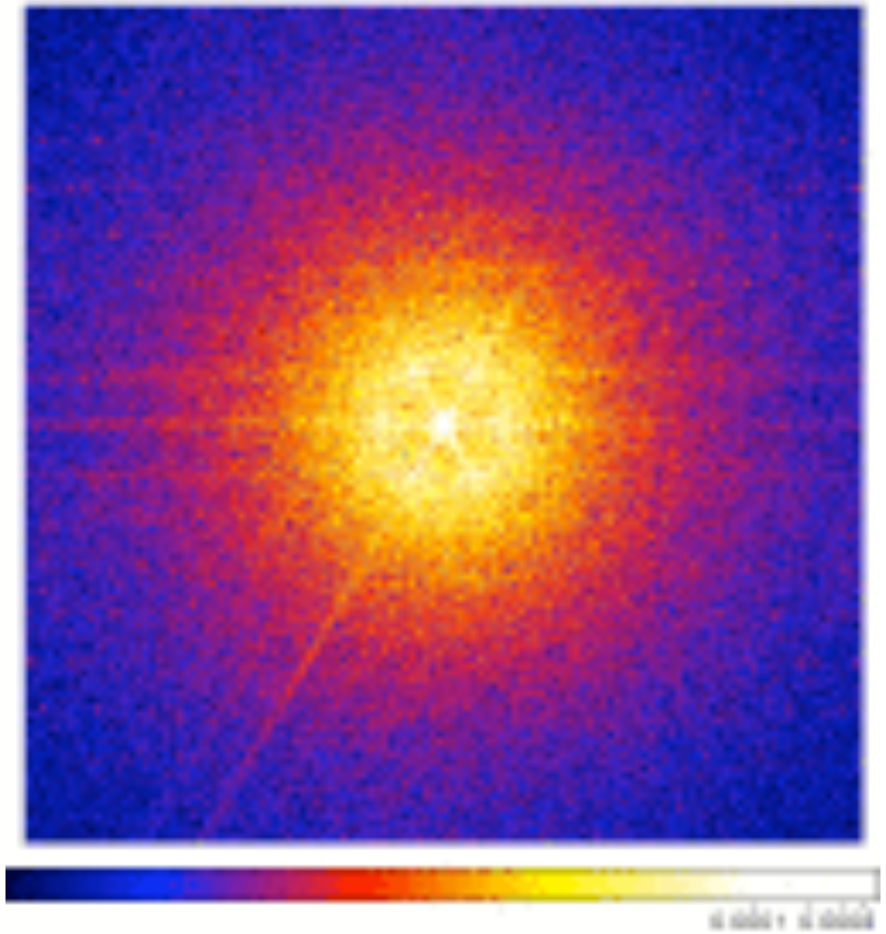
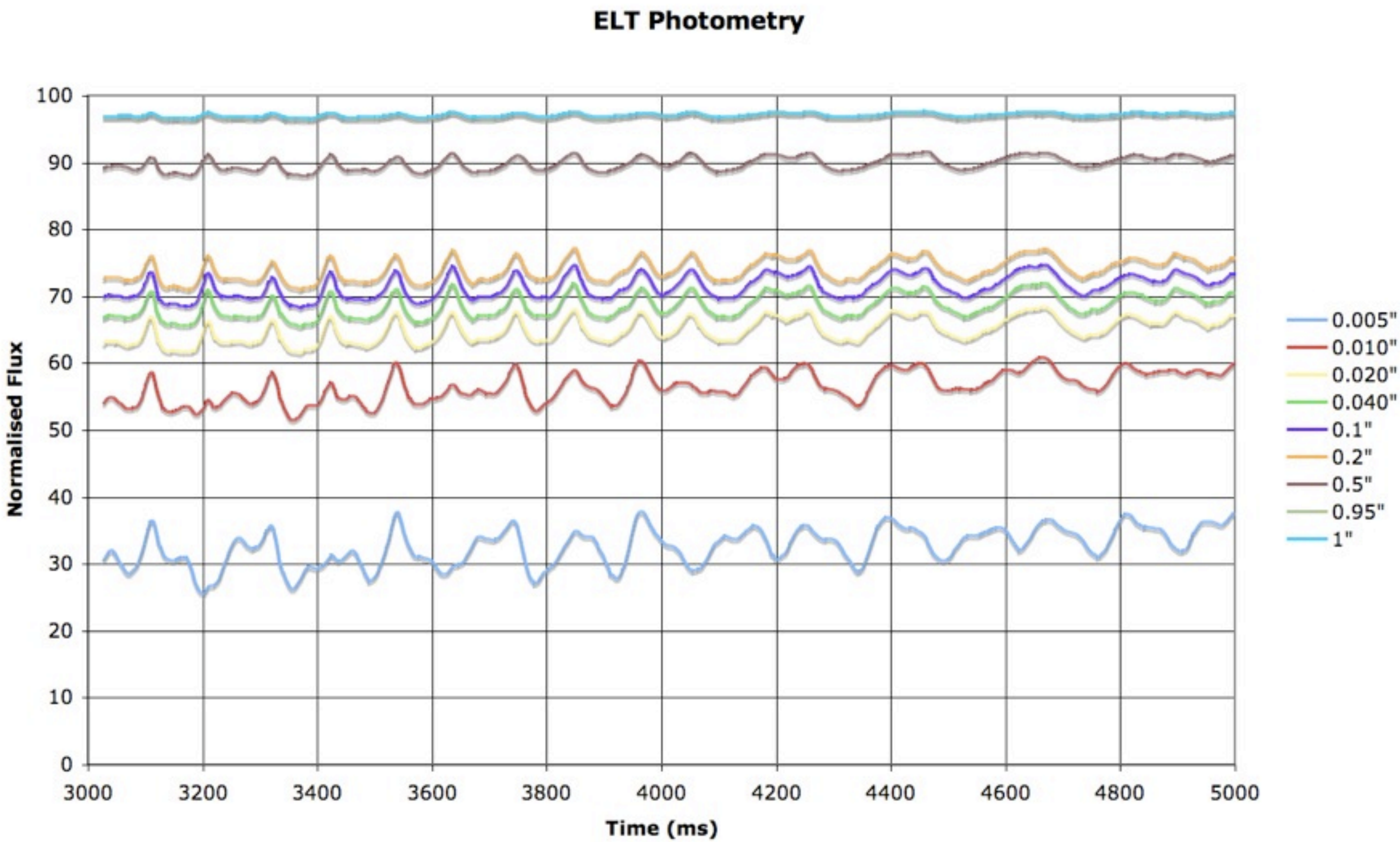






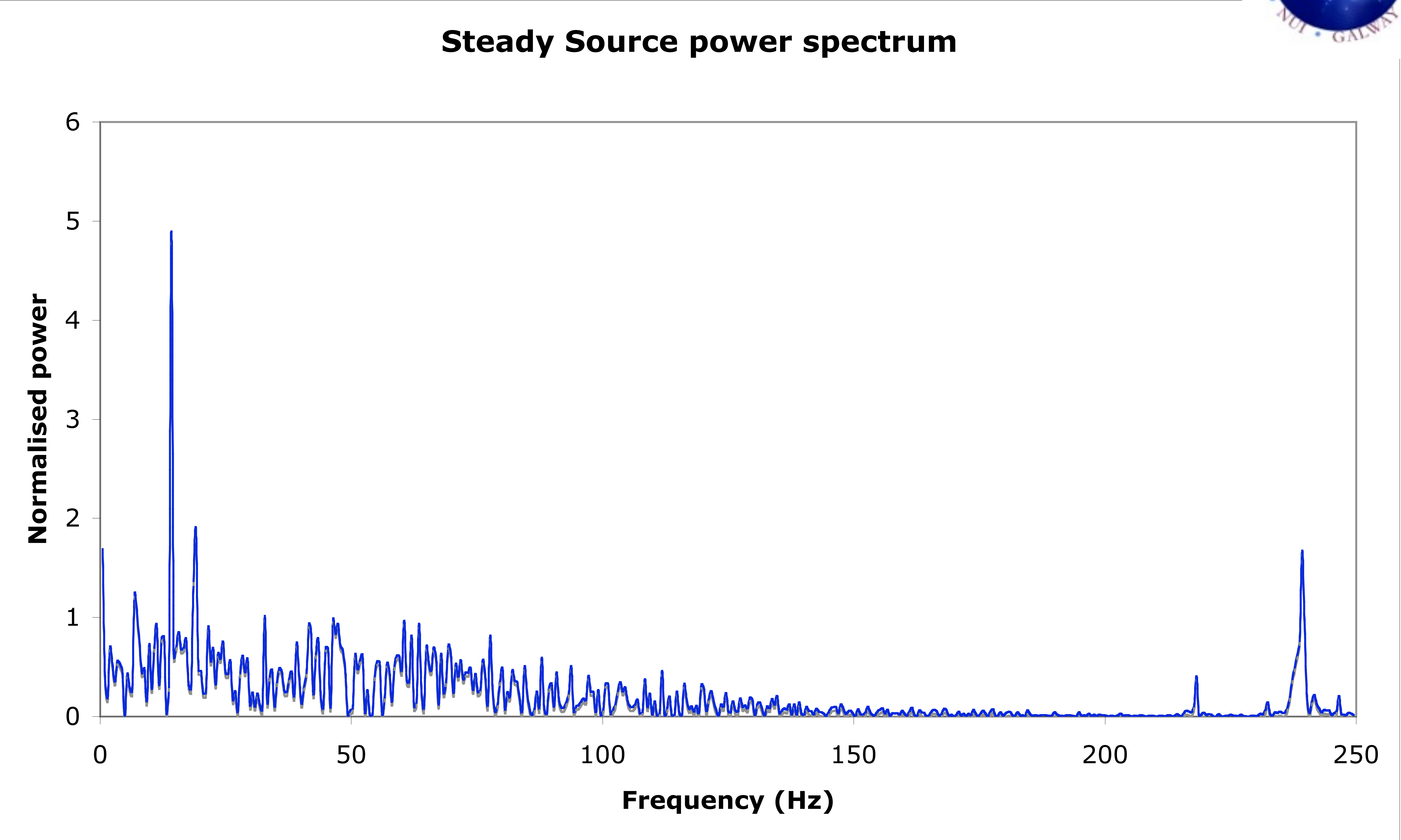
PSF data from Lund telescope group

ELT time series



Total simulation length ~3 seconds

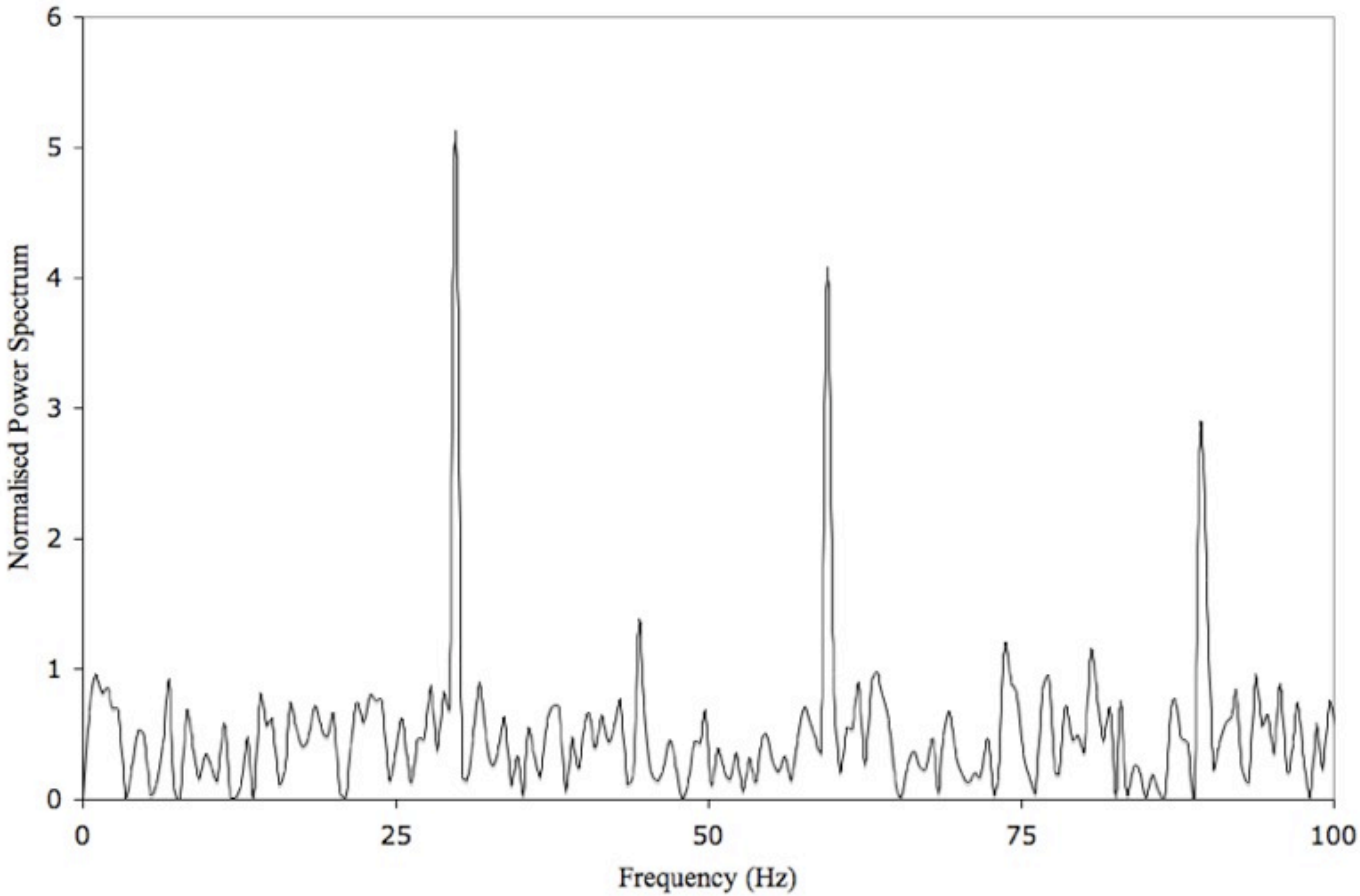
ESO- ELT May 2009


Steady Source power spectrum
Normalised power
Frequency (Hz)
0
1
2
3
4
5
6
0
50
100
150
200
250

Simulated Crab pulsar at LMC Distance

2 seconds data

0".01 aperture



HTRA Instrument for E-ELT

- Large percentage of time suitable for HTRA
  - VLT NAOS experience 20% of the time too fast for AO possibly higher
  - AO problems with non-photometric conditions
- Suggestions from the HTRA community
  - poor seeing / visitor instrument?
    - spectroscopy
    - polarisation
    - HTRA photometry
  - first light instrument?
    - E-ELT - 4+ year build time?
  - off axis piggy back instrument for transients?

HTRA detector/instrument requirements

Primary Requirements

- Time resolution
  - microseconds to a few seconds
  - currently possible with EMCCDs, pnCCDs and APDs
- at least 64 x 64 array
- Polarisation sensitivity at 0.1% level
- Energy resolution - broad - narrow band
- Sensitive to stochastic and periodic signals
- Low, preferably zero, noise

Secondary Requirements

- Sub-microsecond temporal resolution
- Spectra R~5000

HTRA meetings

- “HTRA for the next decade” meeting in May 2010
  – probable venue Crete?