Relativistic Positioning Systems and their Scientific Application, Brdo, Slovenia, 19-21. Sep. 2012

DEEP SPACE NAVIGATION WITH PULSARS

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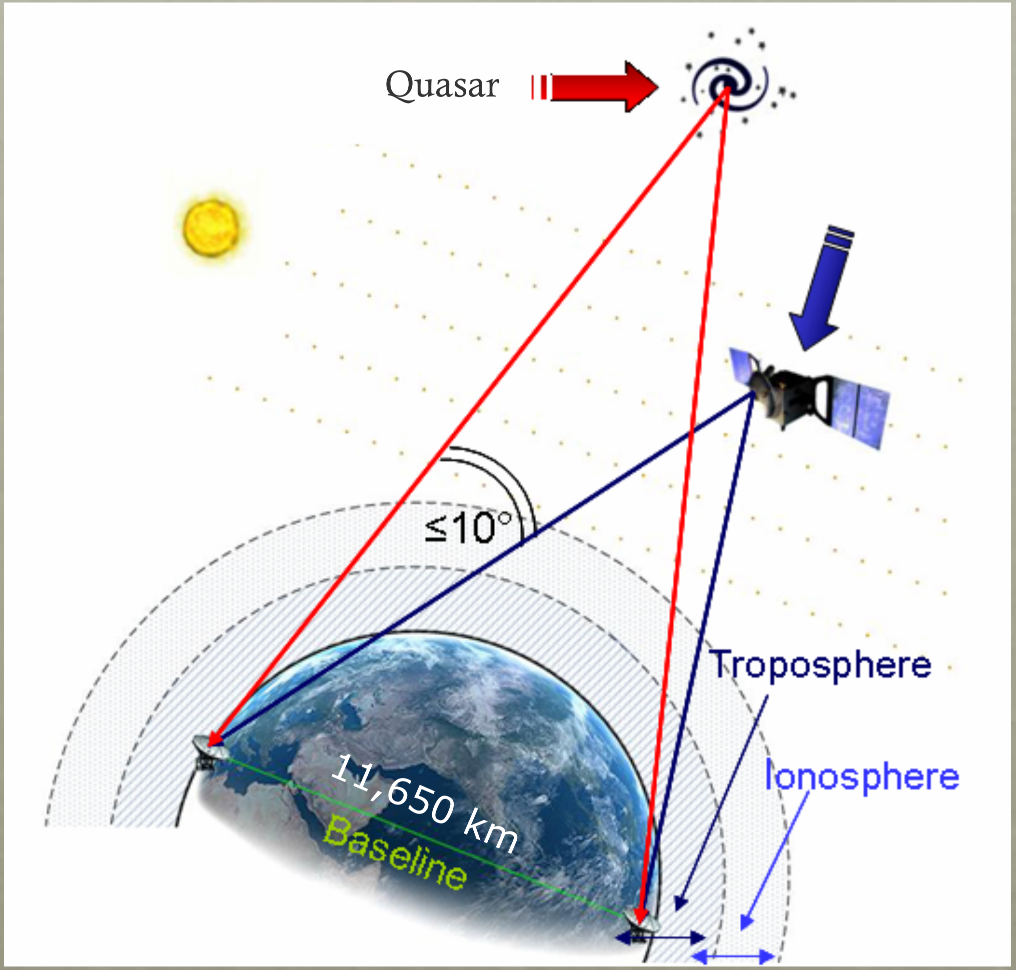
OUTLINE

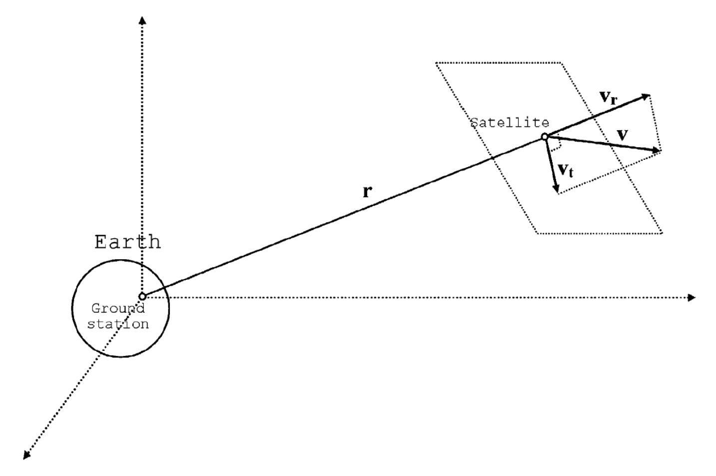
- Conventional Spacecraft Navigation
- Intermezzo: What are Pulsars ?
- Pulsars as Navigation Beacons
- Radio and X-ray Technology for Pulsar Navigation
- Summary

RADIO TRACKING



Delta-DOR:

- **D**oppler **O**ne-way **R**anging provides radial velocity (v_r) and range (r). The components in the sky-plane are not provided directly.



RADIO TRACKING

Typical Errors:

Range ~ 1 m
Velocity ≈ 0.1 mm/s

Along the line of sight

Angular resolution ≈ 0.005’’

≈ ± 4 km per AU

On the plane of sky

ACHIEVABLE ACCURACY OF RADAR TRACKING

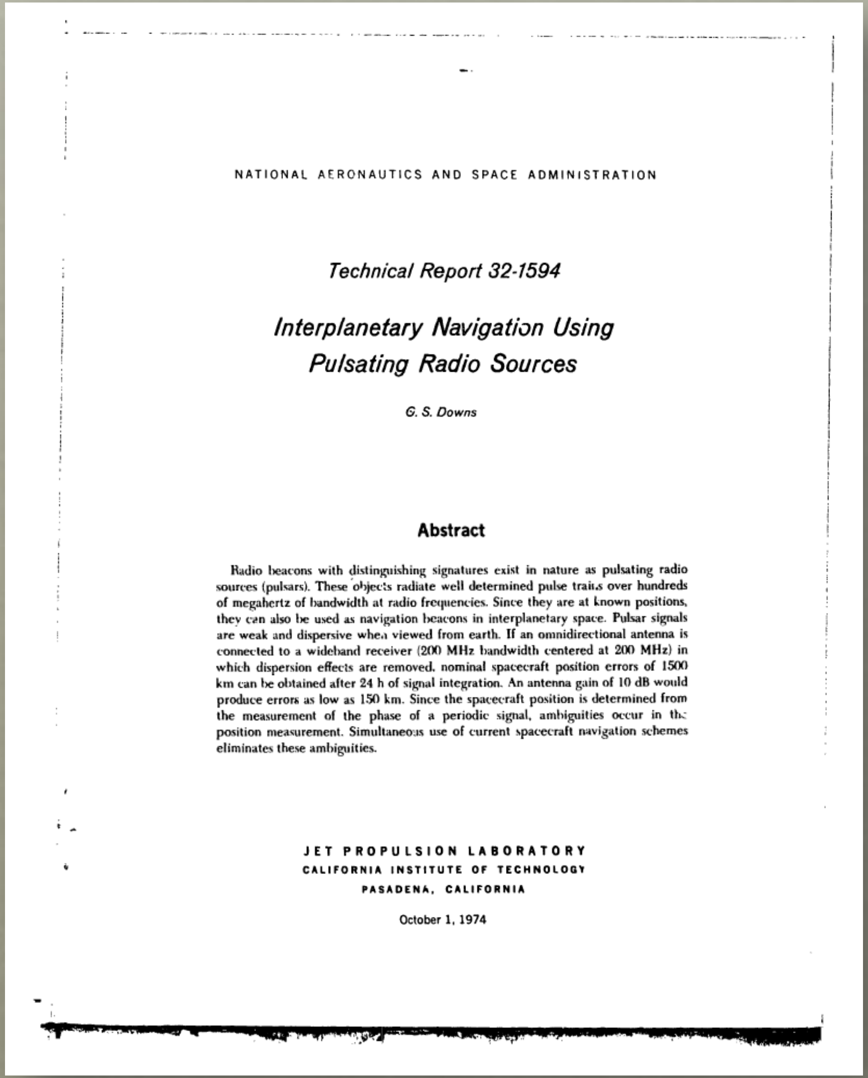
Position error: ≈ ± 4 km per AU

Example	Max. Distance from Earth (AU)	Position Error (km)
Mars	3	± 12
Jupiter	7	± 28
Saturn	10	± 40
Uranus	20	± 80
Neptune	30	± 120
Pluto	50	± 200
Voyager 1	115	± 460

DISADVANTAGES OF CONVENTIONAL DEEP SPACE NAVIGATION METHODS

- Errors grow with distance from Earth
- No instantaneous course corrections, e.g. light travel time to Voyager is currently 16h, and another 16h for the answer to receive
- **Does not support autonomous navigation**

INTERPLANETARY NAVIGATION USING PULSATING RADIO SOURCES



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1594

Interplanetary Navigation Using Pulsating Radio Sources

G. S. Downs

Abstract

Radio beacons with distinguishing signatures exist in nature as pulsating radio sources (pulsars). These objects radiate well determined pulse trains over hundreds of megahertz of bandwidth at radio frequencies. Since they are at known positions, they can also be used as navigation beacons in interplanetary space. Pulsar signals are weak and dispersive when viewed from earth. If an omnidirectional antenna is connected to a wideband receiver (200 MHz bandwidth centered at 200 MHz) in which dispersion effects are removed, nominal spacecraft position errors of 1500 km can be obtained after 24 h of signal integration. An antenna gain of 10 dB would produce errors as low as 150 km. Since the spacecraft position is determined from the measurement of the phase of a periodic signal, ambiguities occur in the position measurement. Simultaneous use of current spacecraft navigation schemes eliminates these ambiguities.

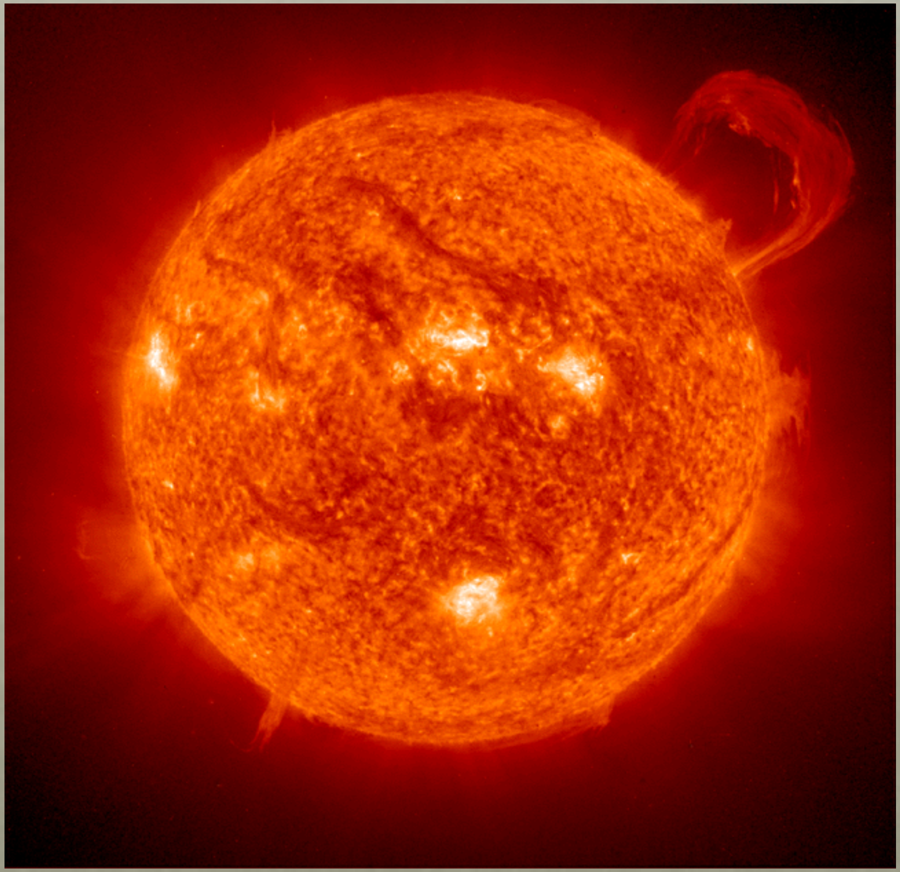
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

October 1, 1974

G.S. Downs 1974
JPL Report 32-1594

... by making use of the peculiar properties of radio pulsars …

INTERMEZZO: WHAT ARE PULSARS ?



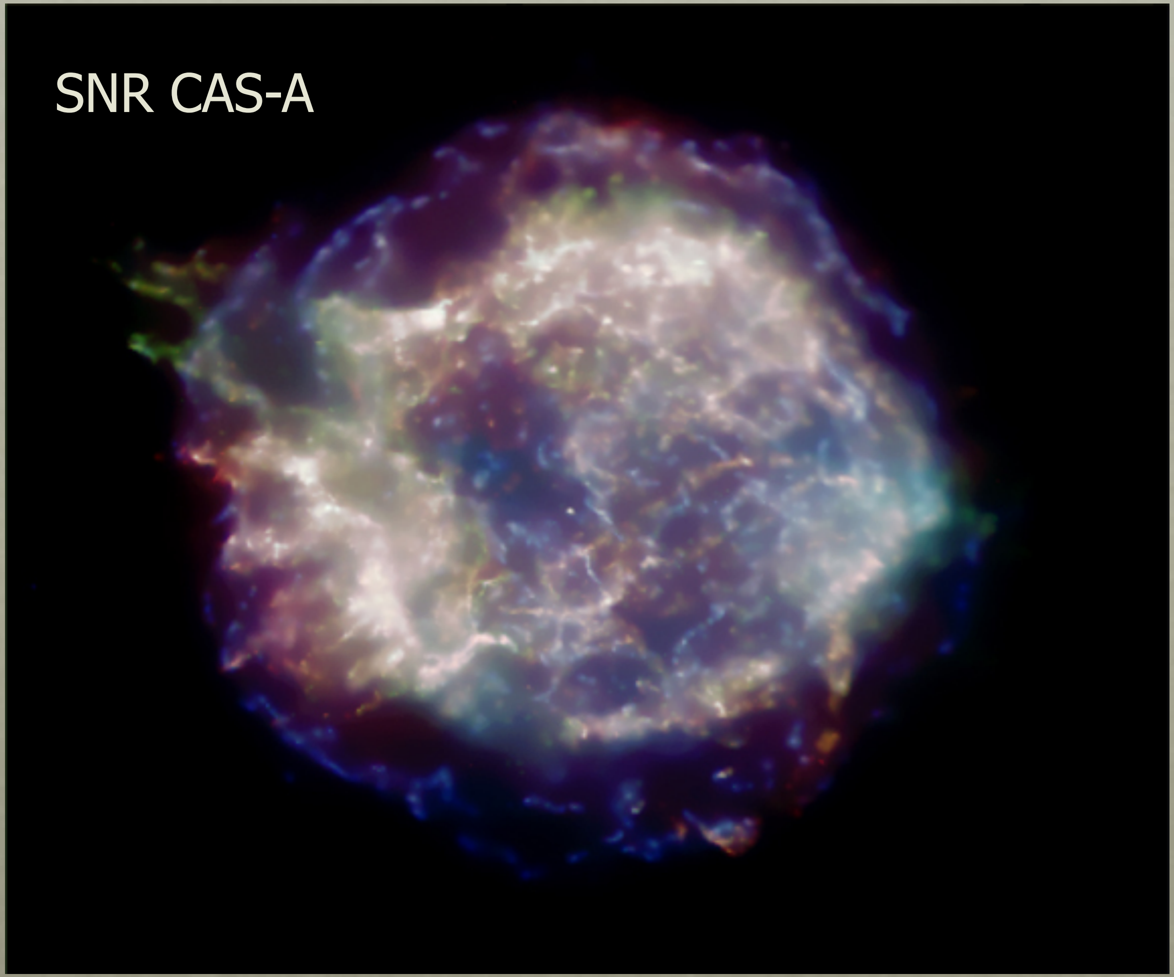
Stars are stable because of a balance between the thermonuclear energy and the gravitational force

INTERMEZZO: WHAT ARE PULSARS ?

The details of stellar evolution depend on the star mass …

- M = 1 – 8 Mo : Star develops to become a white dwarf or explodes
  in a type Ia supernova (nuclear C-detonation)
- M > 8 - 30 Mo : Star collapses in a type Ib, Ic or II classified supernova to
  become a neutron star
- M > 30 Mo : Star collapses to become a black hole

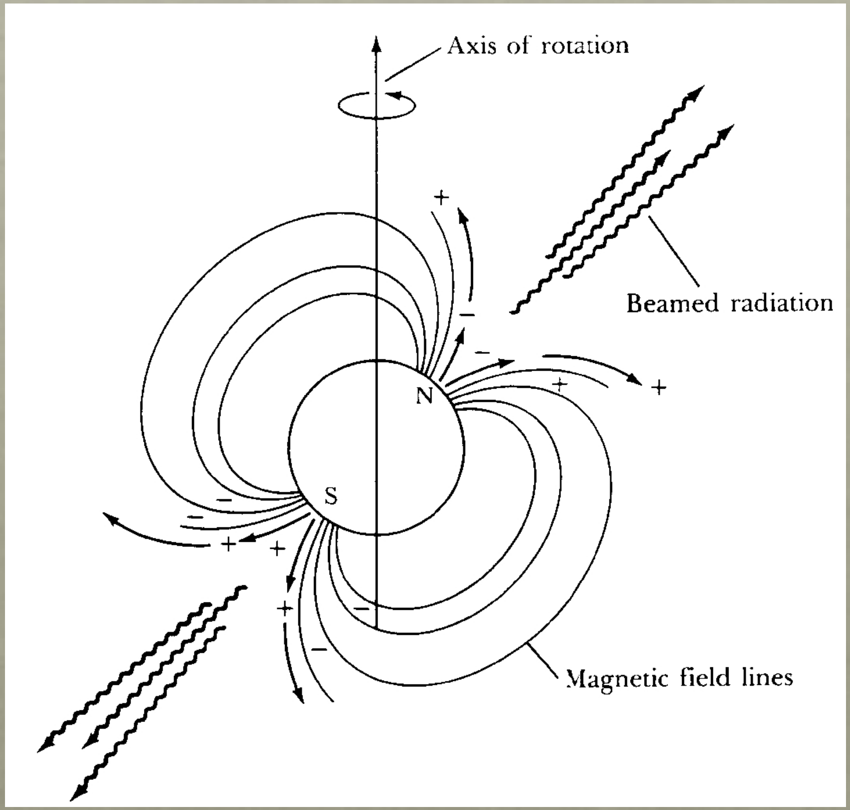
INTERMEZZO: WHAT ARE PULSARS ?



SNR CAS-A: Historical supernova observed 1667 / distance ca. 10 000 LJ

INTERMEZZO: WHAT ARE PULSARS ?

- Neutron stars are observable as pulsars

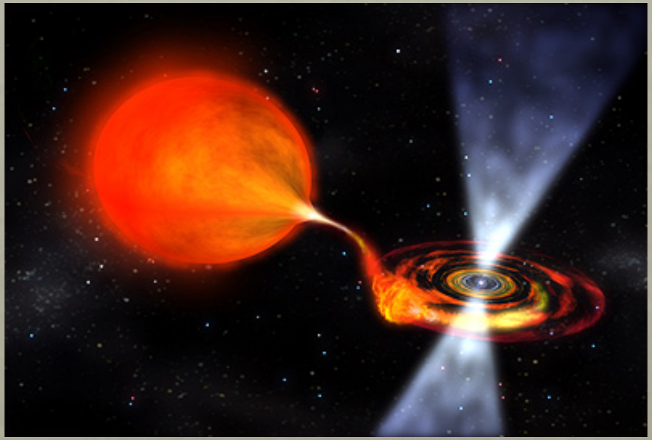


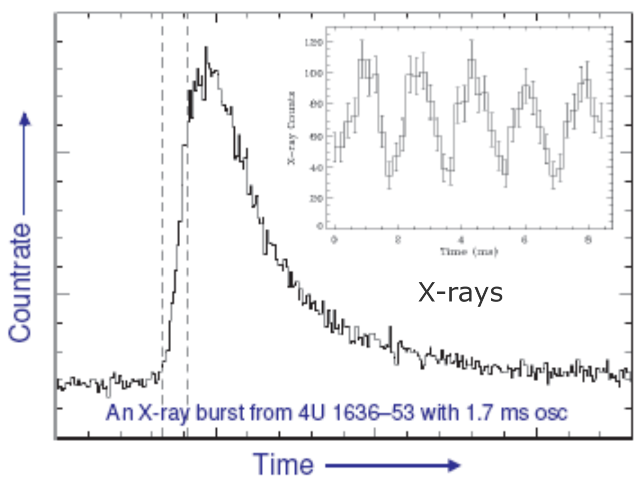
- Pulsars are strongly magnetized and fast spinning neutron stars which radiate beamed electromagnetic radiation along narrow radiation cones …

- There are different kinds of pulsars in the universe ….

WHICH PULSARS ARE BEST SUITED FOR THE PURPOSE OF DEEP SPACE NAVIGATION?

Accretion-powered pulsars

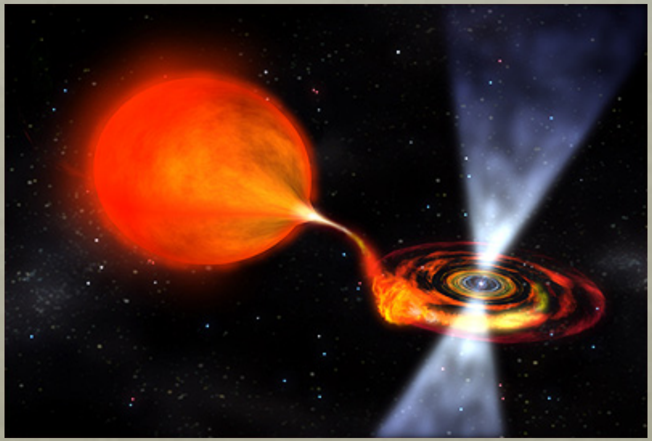


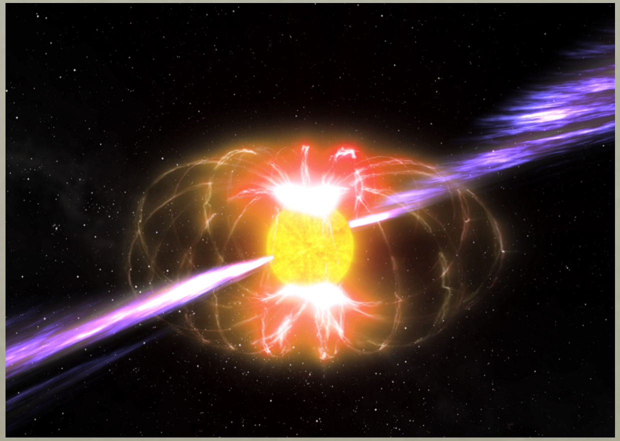


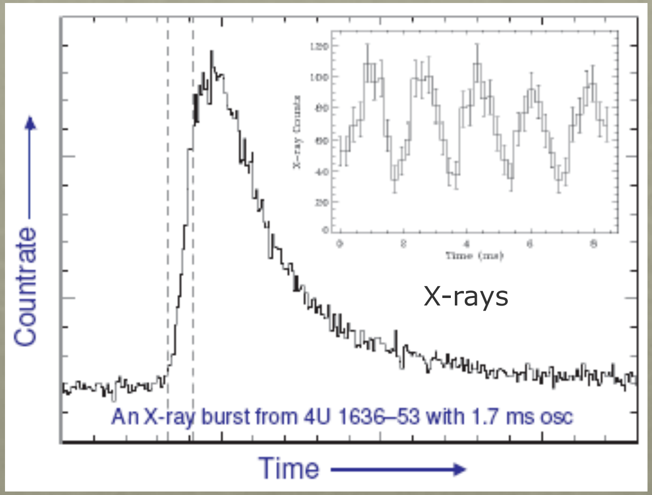
WHICH PULSARS ARE BEST SUITED FOR THE PURPOSE OF DEEP SPACE NAVIGATION?

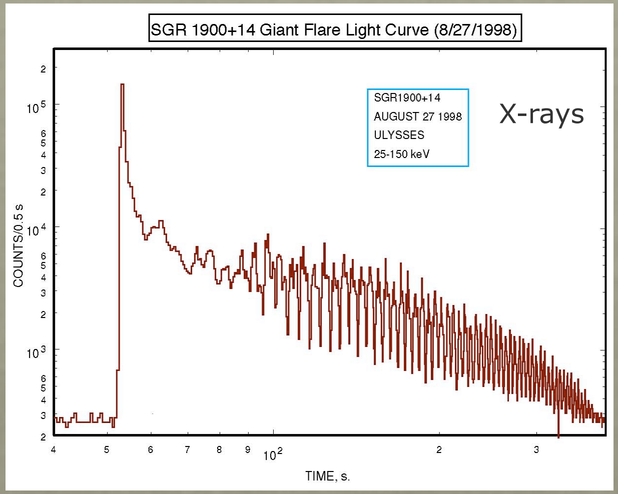
Accretion-powered pulsars

Magnetars



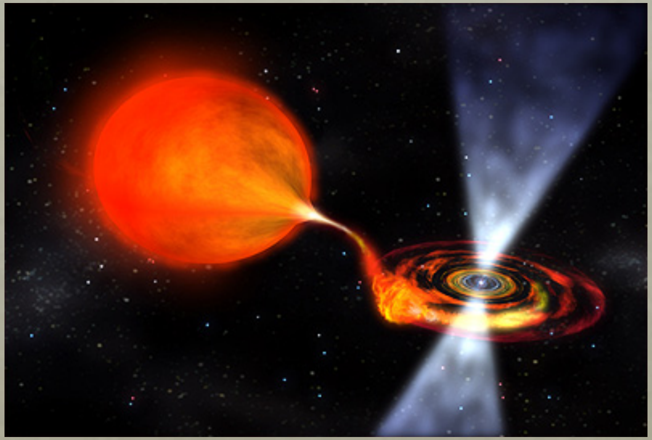


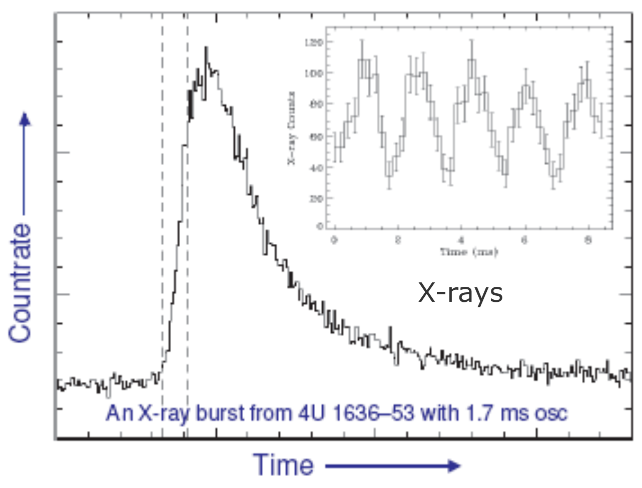




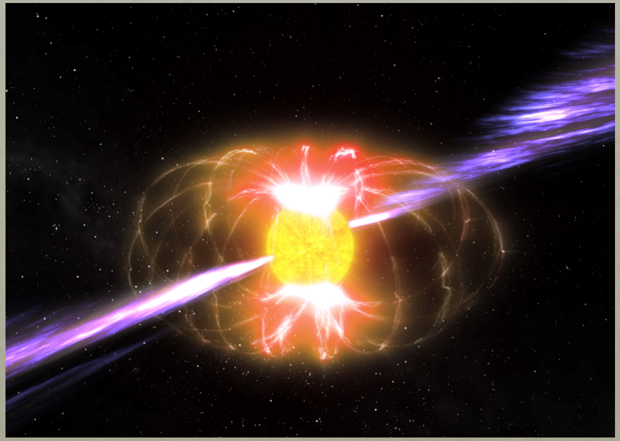
WHICH PULSARS ARE BEST SUITED FOR THE PURPOSE OF DEEP SPACE NAVIGATION ?

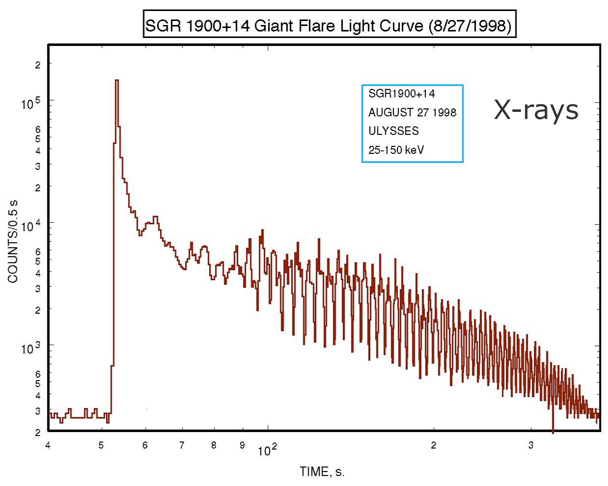
Accretion-powered pulsars



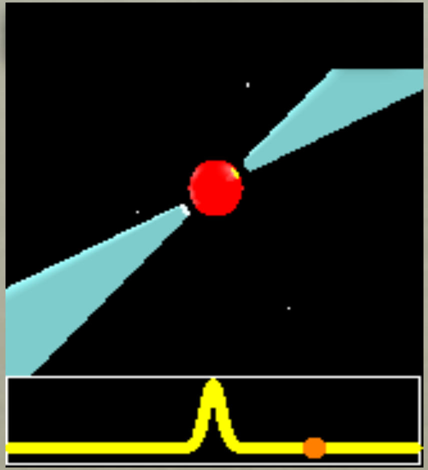


Magnetars





Rotation-powered pulsars

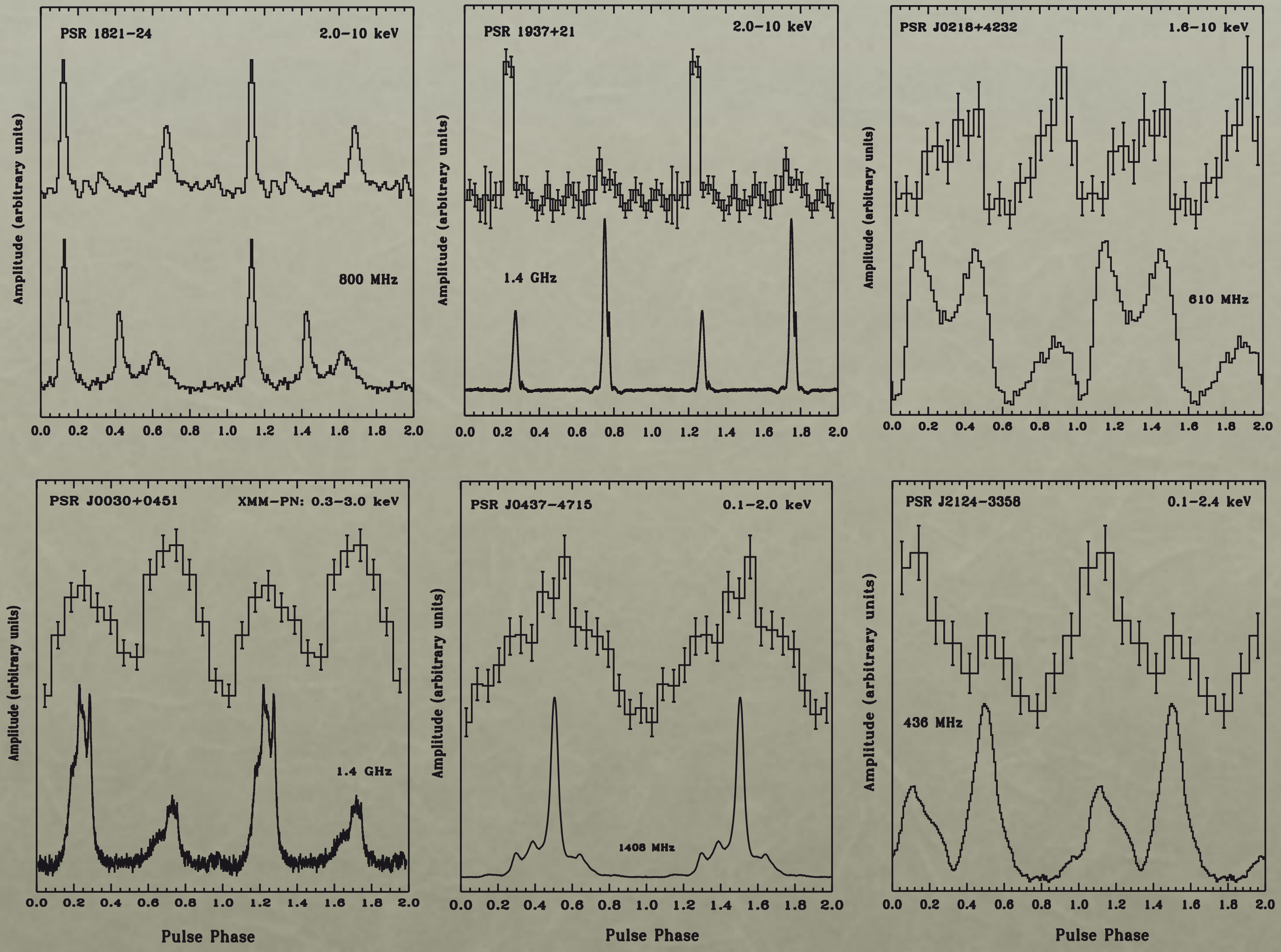


Rotation stability comparable with the accuracy of atomic clocks!

TEMPORAL X-RAY & RADIO EMISSION CHARACTERISTICS

MSPs

Pulsed fraction between ~ 30 - 100%



Becker 2010

Pulse arrival time and relative phase relation between X-ray and radio pulses is known

WHICH PULSARS ARE BEST SUITED FOR THE PURPOSE OF DEEP SPACE NAVIGATION?

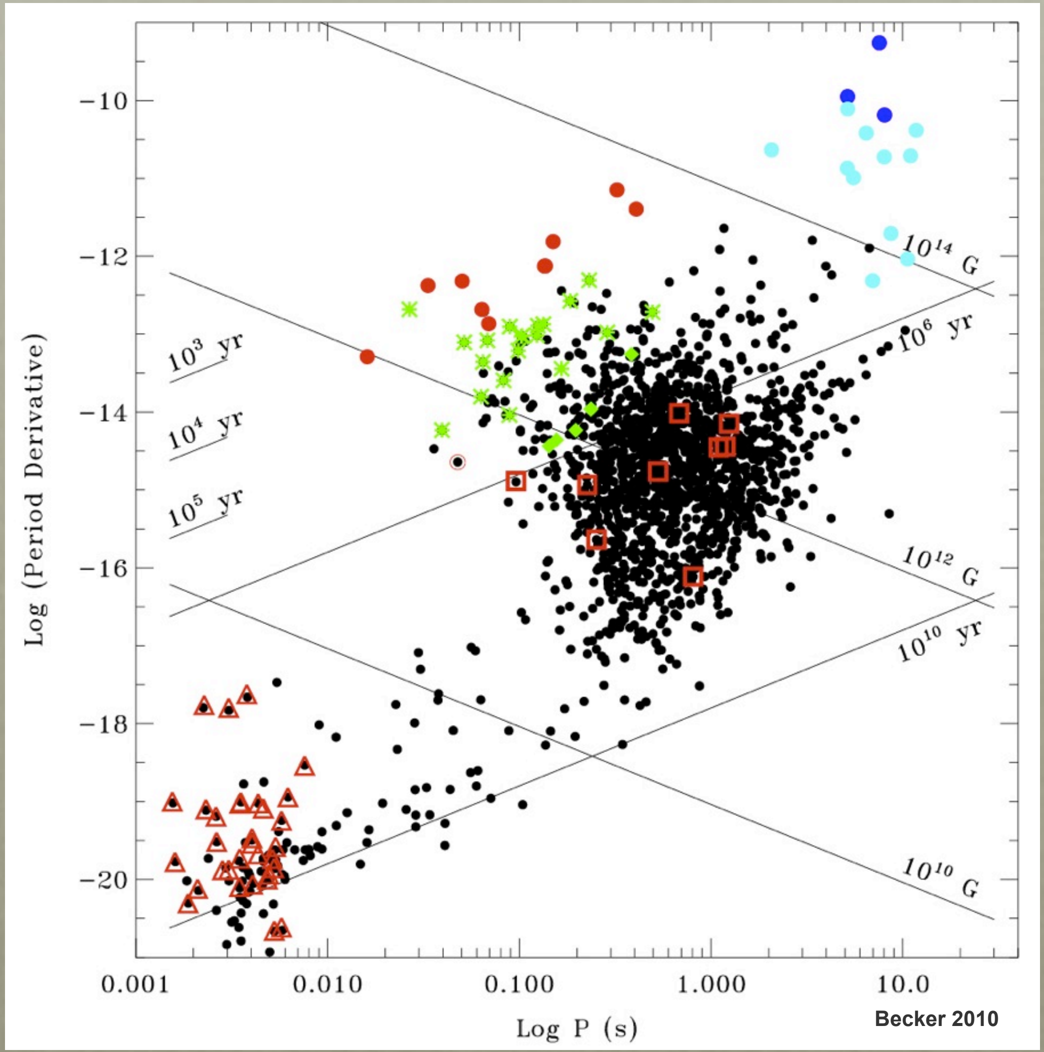
Today ….

2008 radio Pulsars

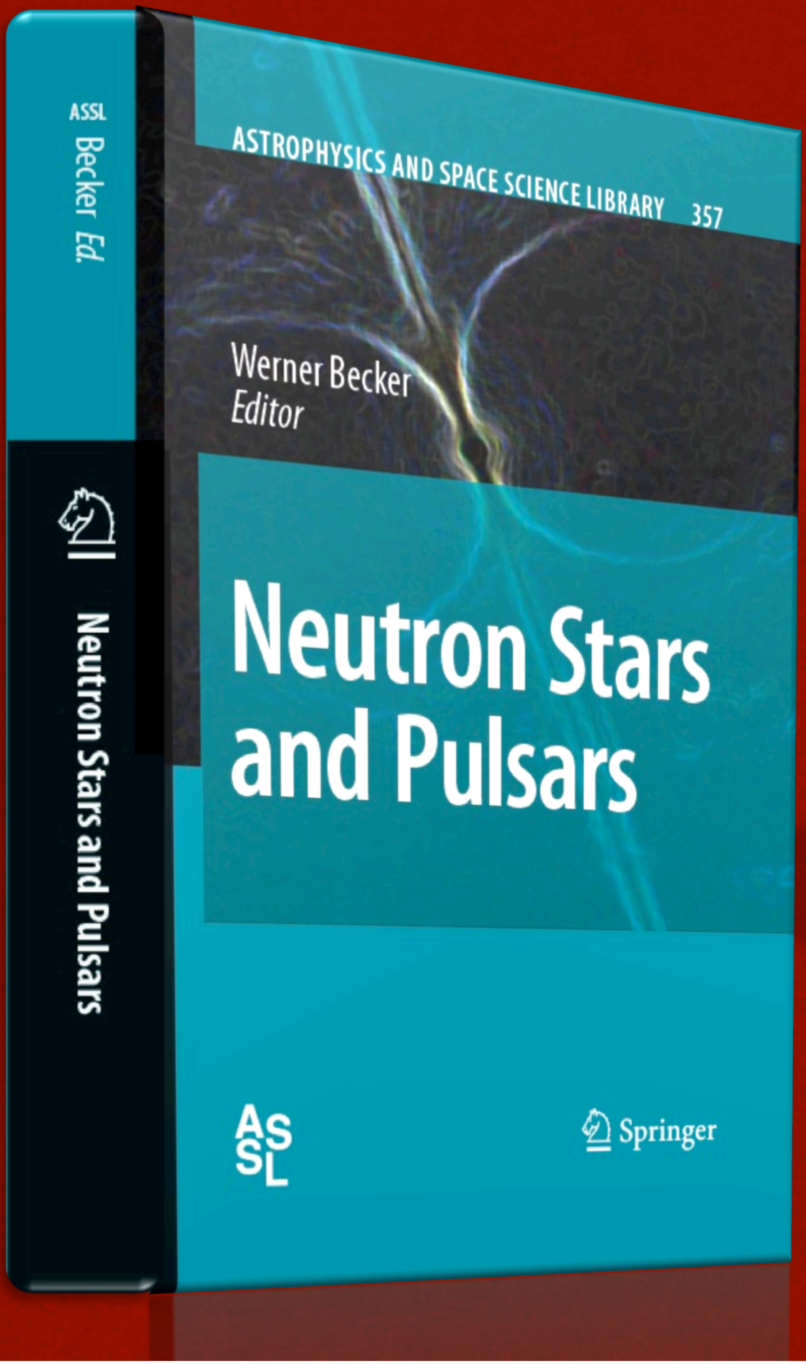
of which we see

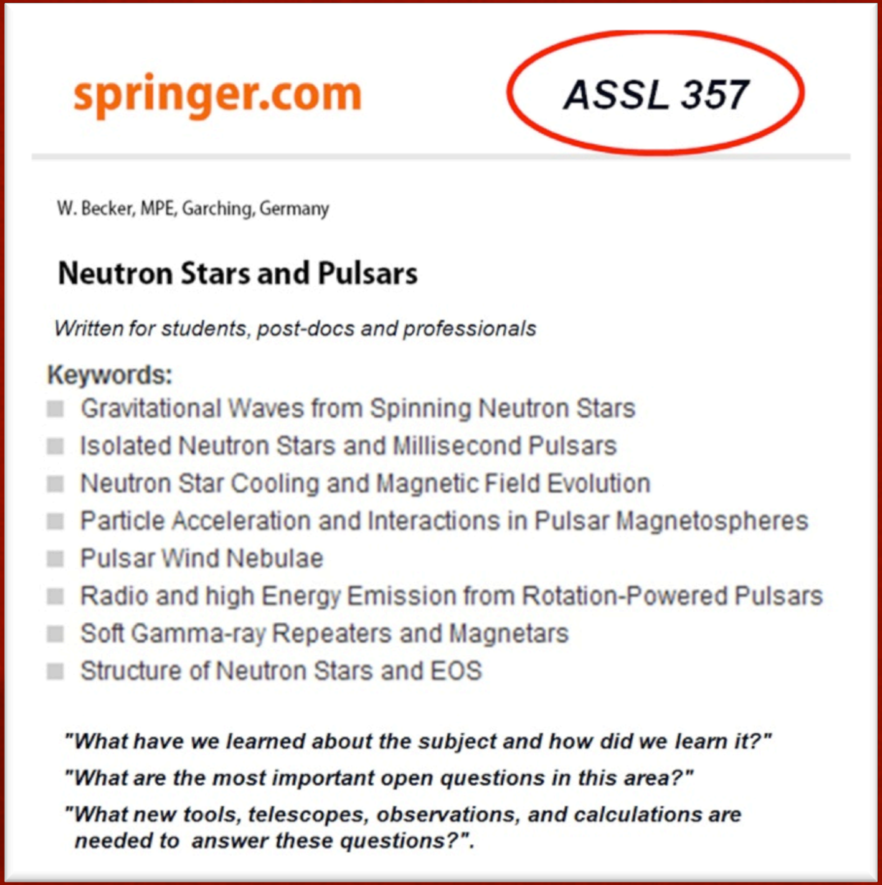
133 in X-rays

(colored symbols)



Becker 2010





springer.com

ASSL 357

W. Becker, MPE, Garching, Germany

Neutron Stars and Pulsars

Written for students, post-docs and professionals

Keywords:

- Gravitational Waves from Spinning Neutron Stars
- Isolated Neutron Stars and Millisecond Pulsars
- Neutron Star Cooling and Magnetic Field Evolution
- Particle Acceleration and Interactions in Pulsar Magnetospheres
- Pulsar Wind Nebulae
- Radio and high Energy Emission from Rotation-Powered Pulsars
- Soft Gamma-ray Repeaters and Magnetars
- Structure of Neutron Stars and EOS

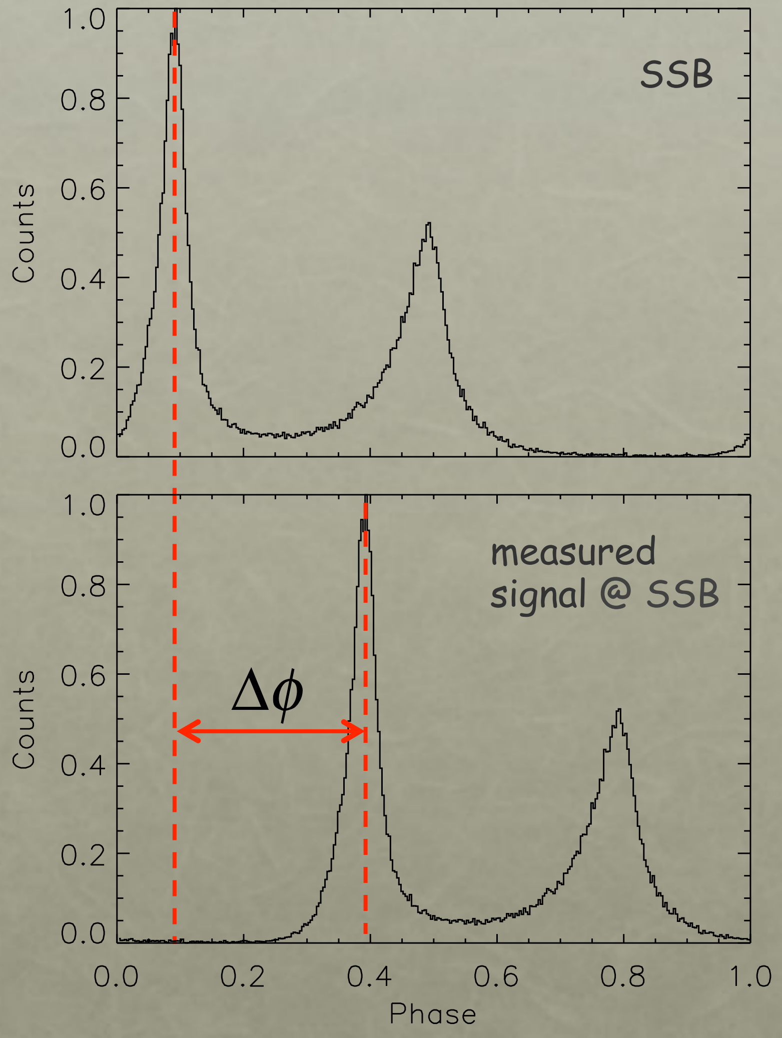
"What have we learned about the subject and how did we learn it?"

"What are the most important open questions in this area?"

"What new tools, telescopes, observations, and calculations are needed to answer these questions?".

With contributions from:
D.Lorimer, R.N. Manchester, M. McLauglin, A.G. Lyne, M. Kramer, W. Becker, R. Turolla, J. Grindlay, V.E. Zavlin, F. Weber, D. Page, S. Tsuruta, U. Geppert, M. Ruderman, J. Arons, J. Kirk, O.C. de Jager, K.S. Cheng, A.K. Harding, J.M.E. Kuipers, K. Hurley, M. Weisskopf, D.A. Smith, D.J. Thompson, R. Prix

PRINCIPLE OF PULSAR-BASED DEEP SPACE NAVIGATION



Range difference along the line of sight:

$$\Delta x = cP(\Delta\phi + n)$$

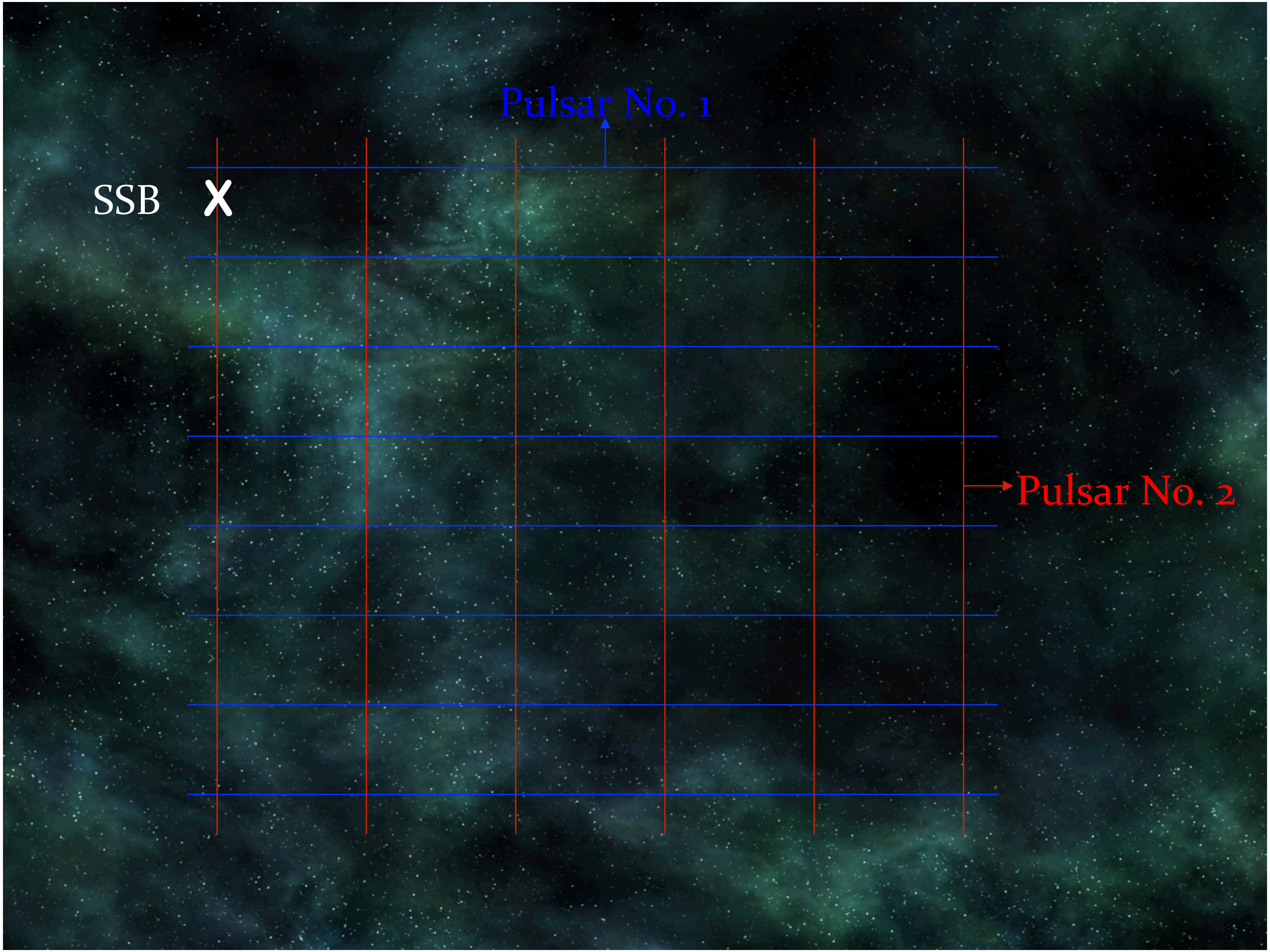
Pulse Period

Phase Shift

$n = 0, \pm 1, \pm 2\ldots$

(multiple solutions)

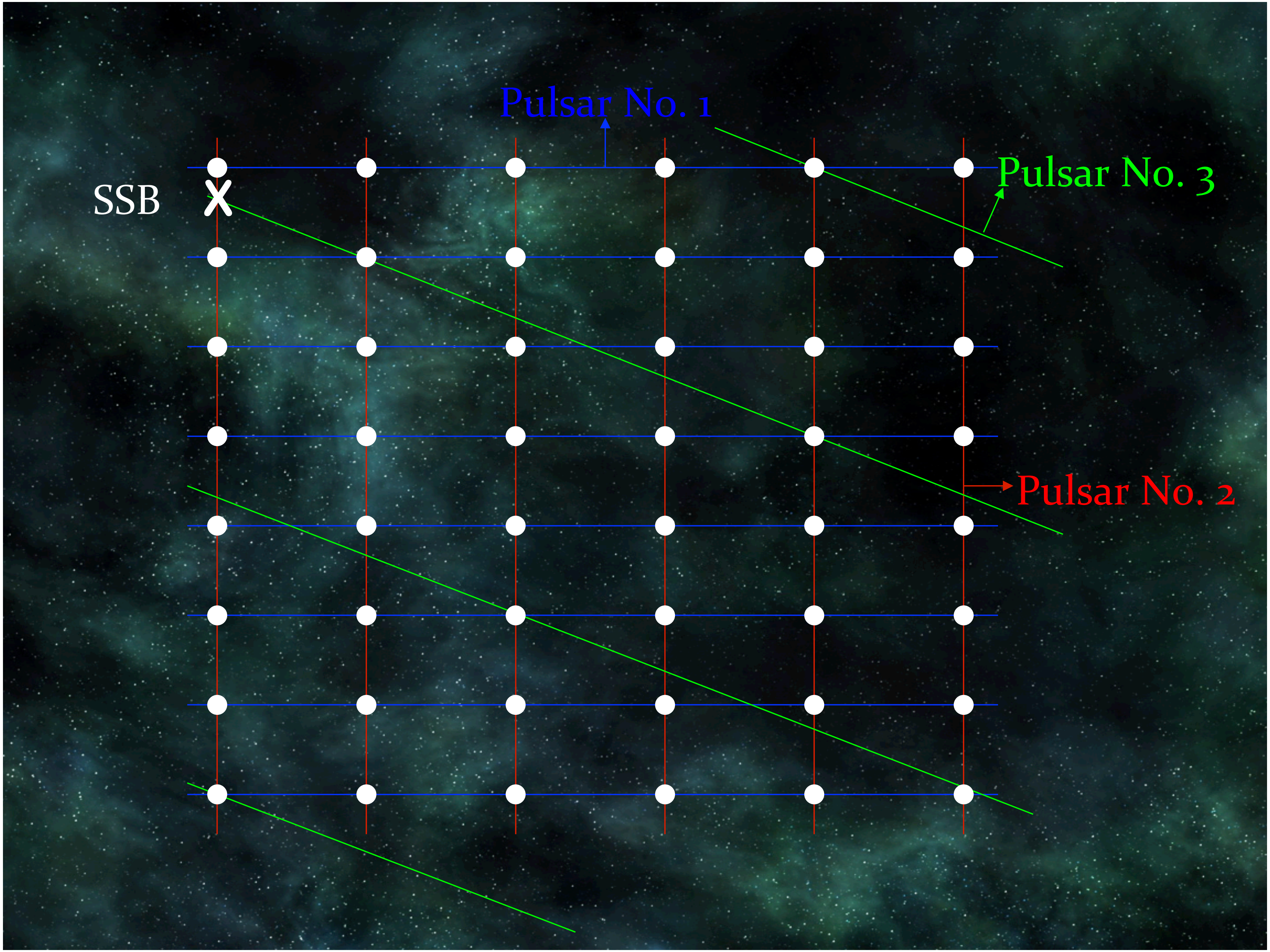

Pulsar No. 1
SSB
X

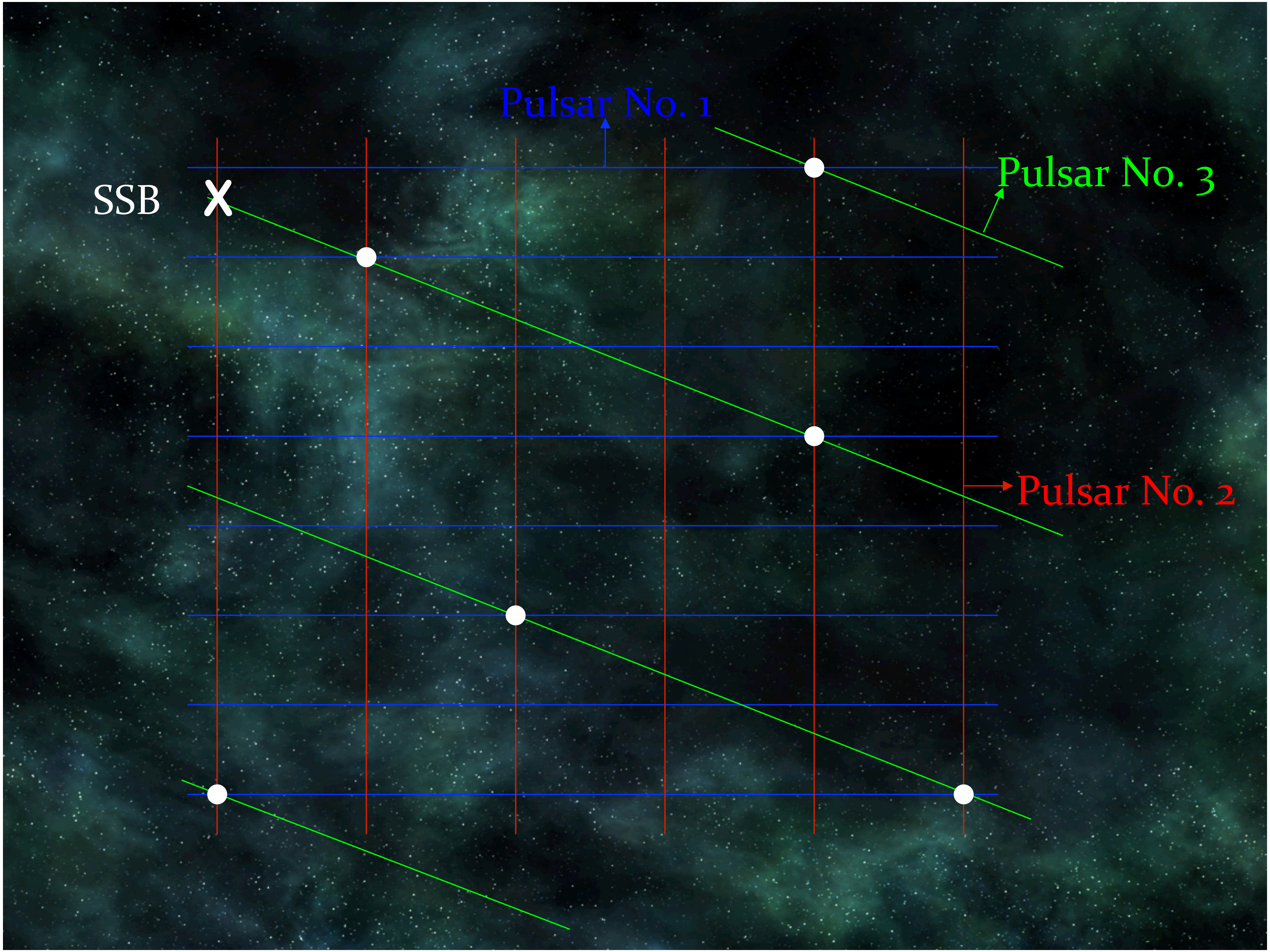

Pulsar No. 1
SSB
X
Pulsar No. 2

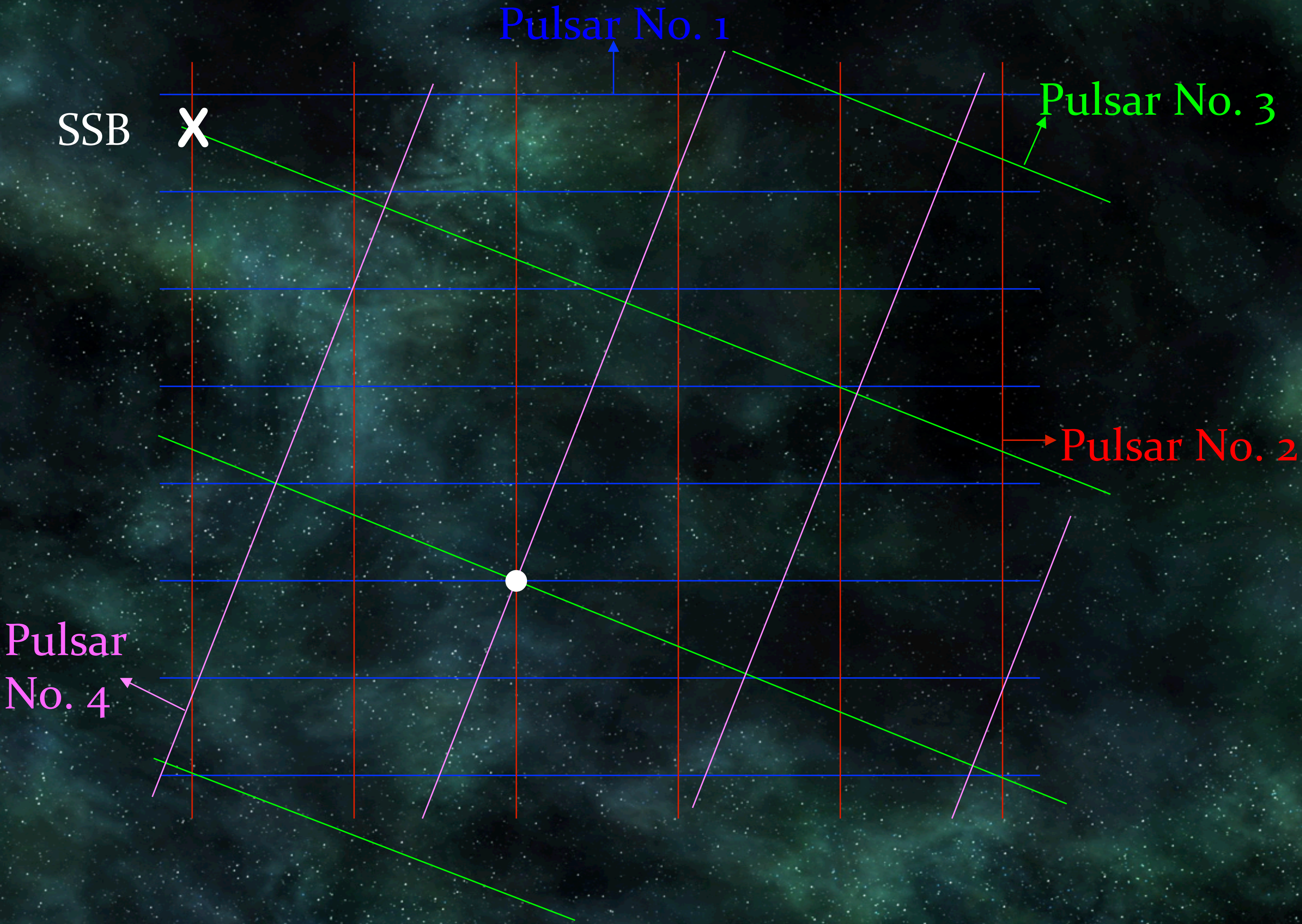
Pulsar No. 1

SSB

Pulsar No. 2


Pulsar No. 1
SSB
Pulsar No. 3
Pulsar No. 2


Pulsar No. 1
SSB
X
Pulsar No. 3
Pulsar No. 2



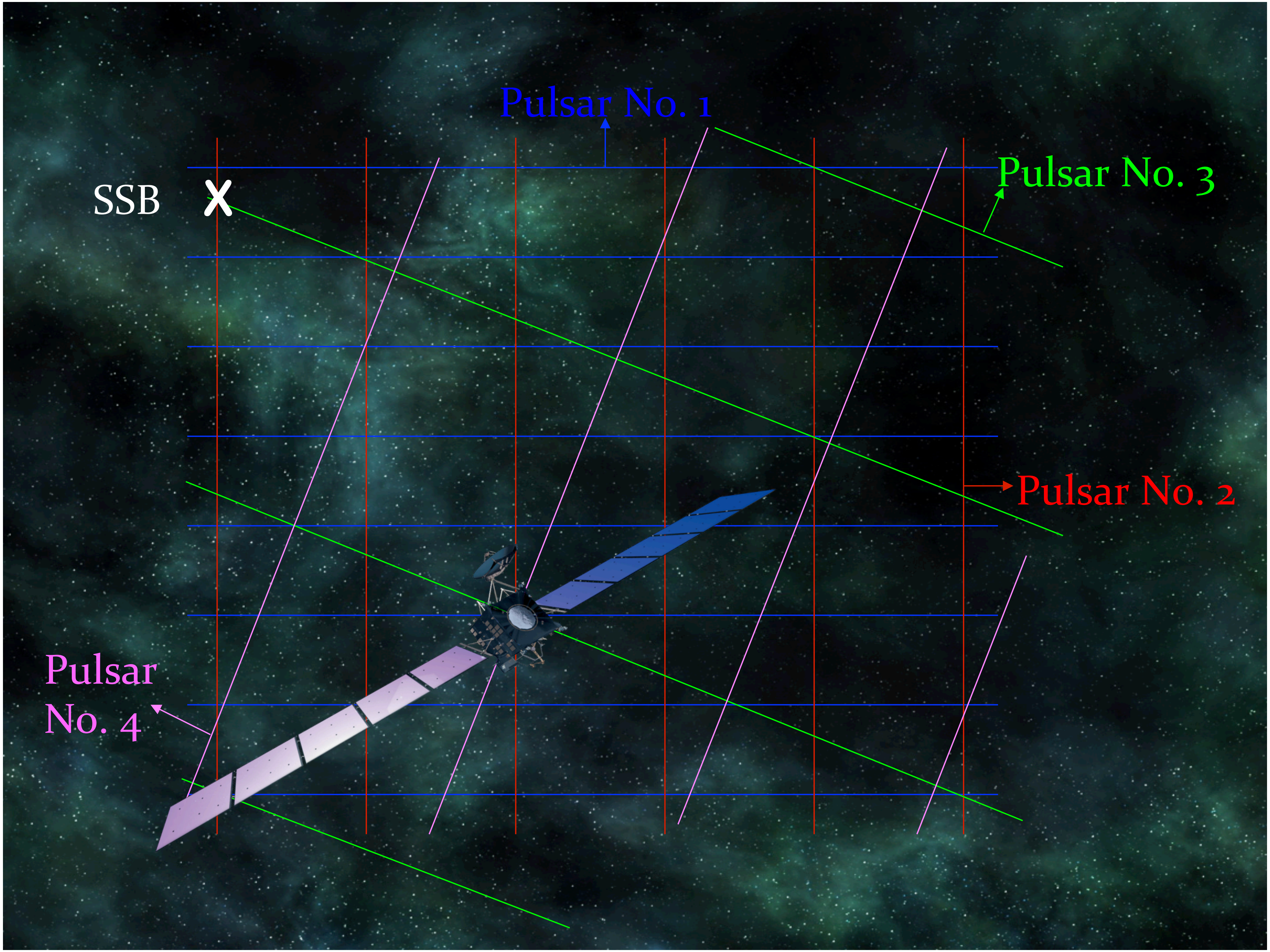
Pulsar No. 1

SSB

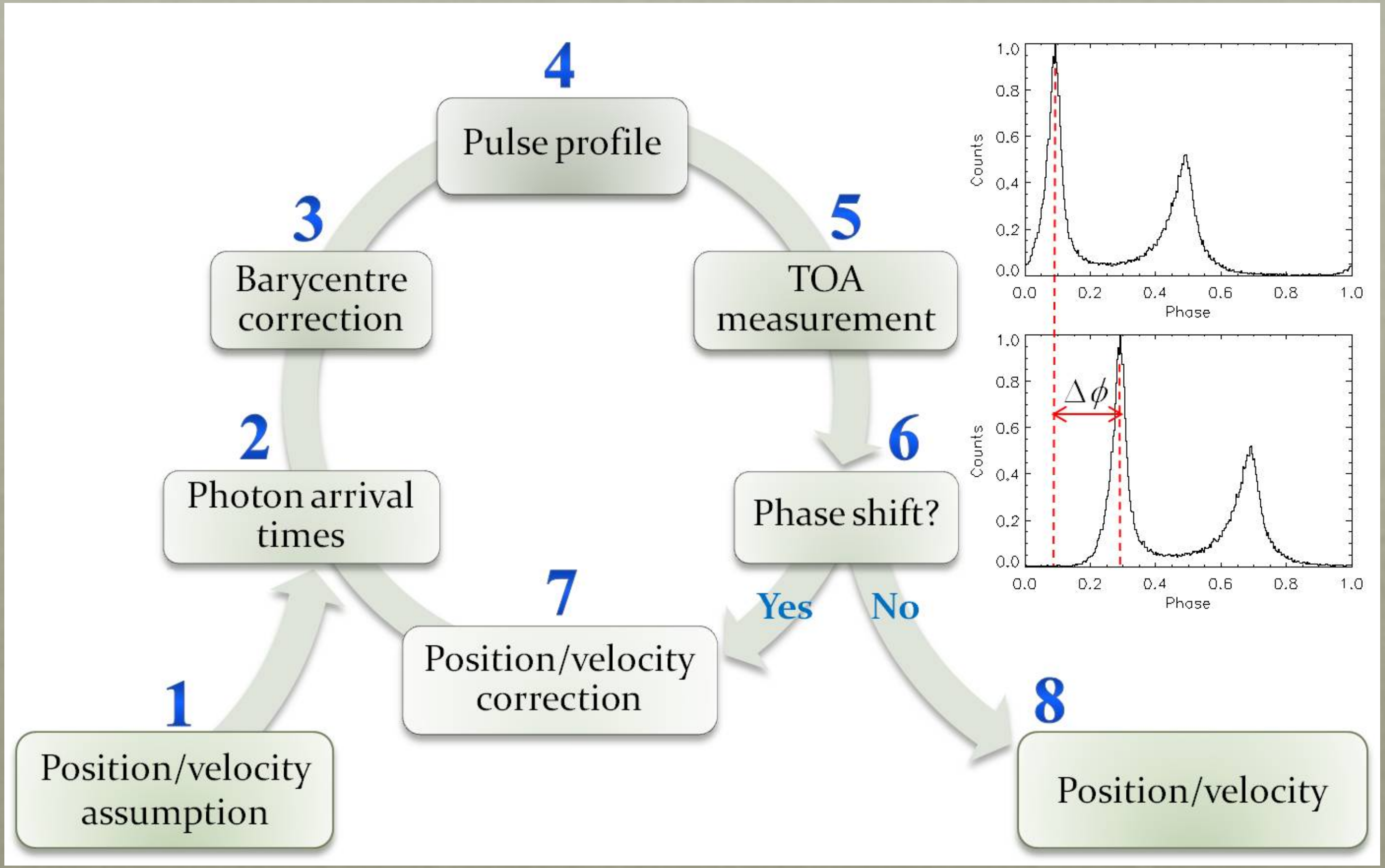
Pulsar No. 3

Pulsar No. 2

Pulsar
No. 4

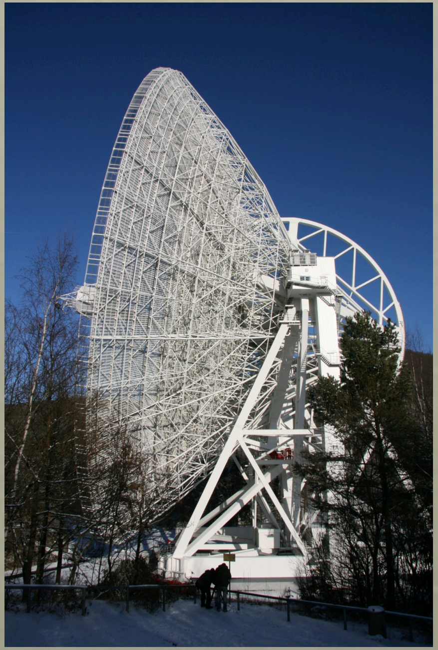

Pulsar No. 1
Pulsar No. 3
SSB
Pulsar No. 2
Pulsar
No. 4

PULSAR-BASED DEEP SPACE NAVIGATION



TECHNOLOGY
FOR PULSAR-BASED NAVIGATION

- Pulsars are very faint objects in the sky!



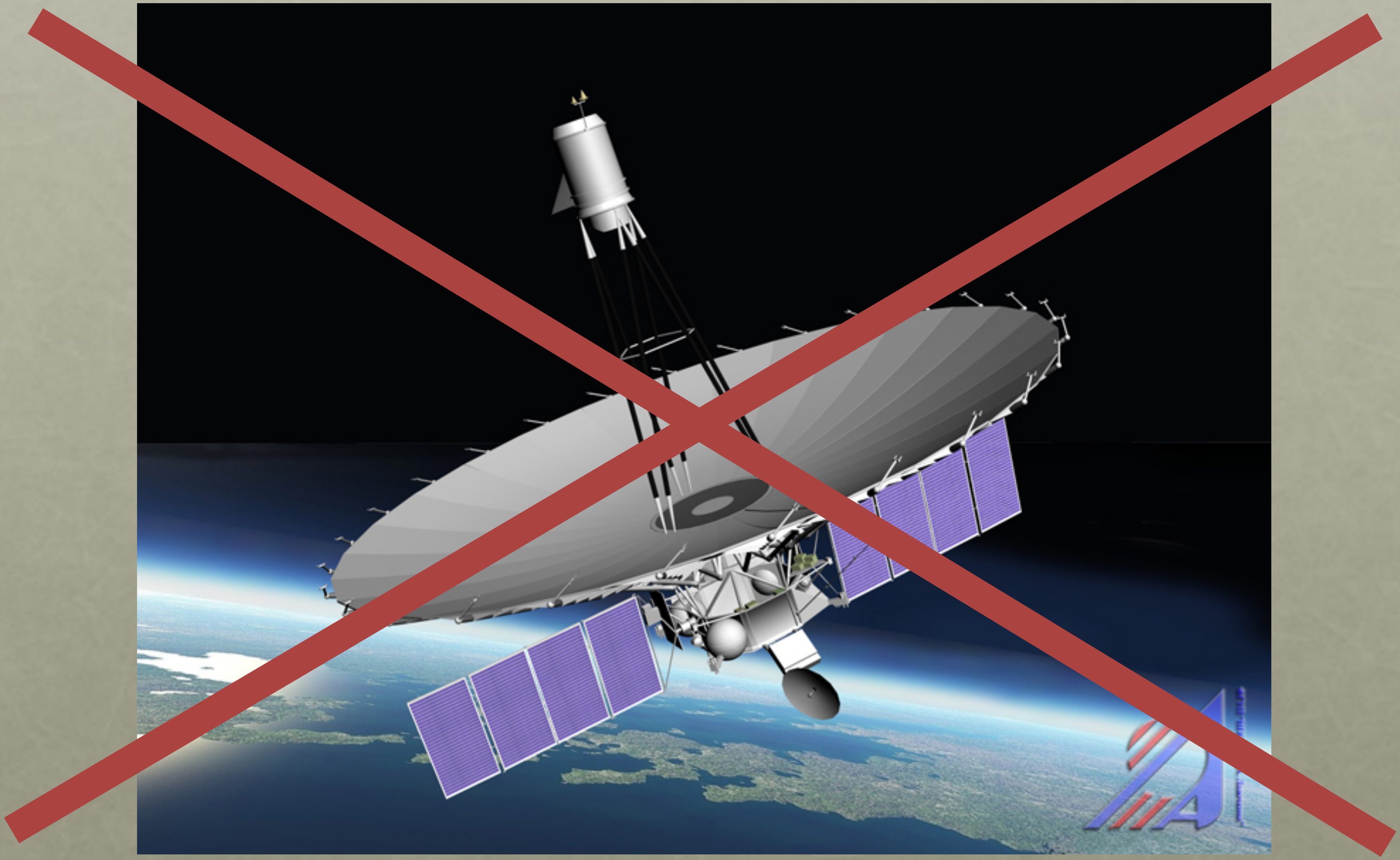
100 m radio telescope in
Effelsberg/Eifel

RADIO ANTENNA FOR PULSAR-BASED NAVIGATION

Disadvantages and problems of using a radio antenna for pulsar based navigation

- Parabolic antenna may not be applicable because of size and shadowing effects to the solar panels
- Radio antenna is not compact, minimum antenna area of 230 m^2 for a SN=10 and 4h integration time → antenna would be still huge and heavy …..
- Longer integration does not improve the signal to noise because of effects like the *Allan* variance, antenna noise, pulse phase and profile smearing due to the satellite movement
- Scintillation and dispersion effects
- Irradiation from the on-board electronics requires an efficient electromagnetic shielding to prevent signal feedback, high power consumption of 500W and a Teraflop GPU

RADIO ANTENNA FOR PULSAR-BASED NAVIGATION



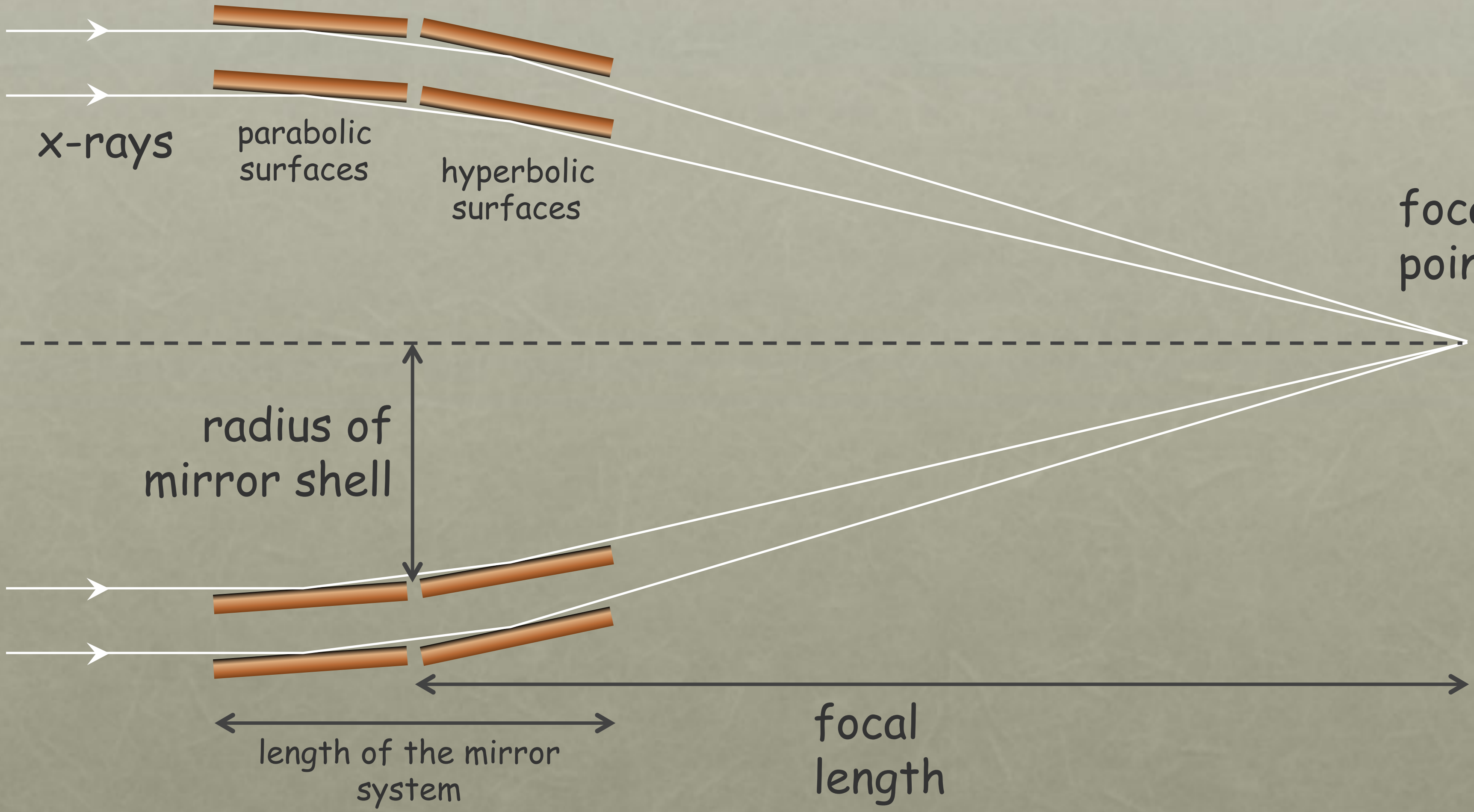
TECHNOLOGY FOR PULSAR-BASED NAVIGATION

- Progress in X-ray pulsar astronomy
- Advances in X-ray mirror & detector technology makes a clear choice for a X-ray pulsar-based navigation

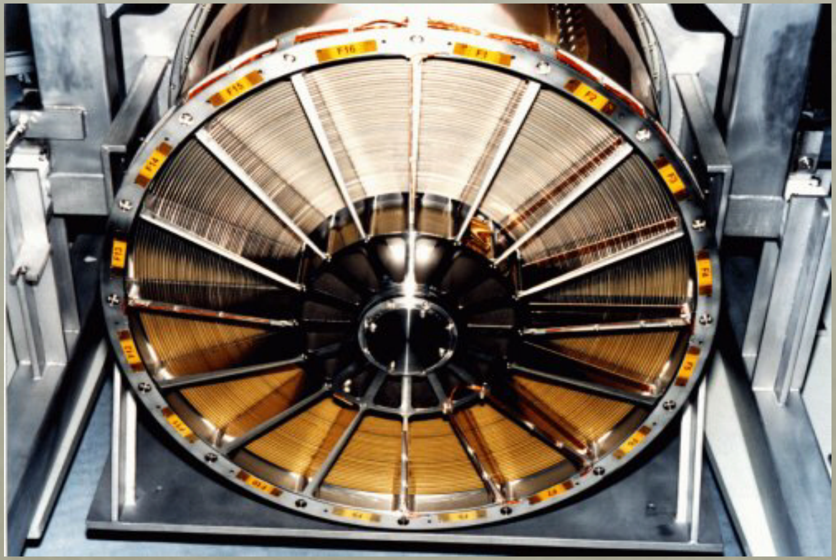
WORK IN PROGRESS….

- Simulations
- Feasible hardware configuration…
  which respects weight and power constrains
  of typical small satellites ….

WOLTER-1 TELESCOPE



ADVANCES IN X-RAY MIRROR- AND DETECTOR DEVELOPMENTS

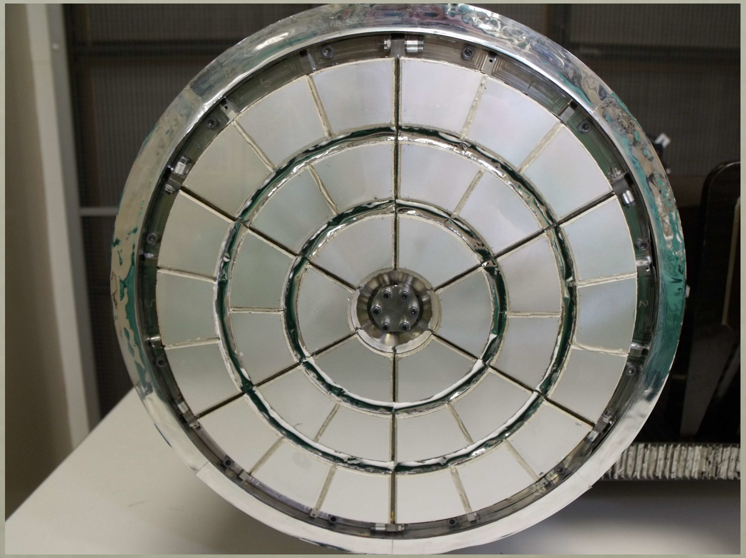


(Bavdaz & Peacock 2004)

XMM-Newton nickel optics:
15" (HPD) / 2300 kg m^{-2}

MCP/HPO optics:
30" (HPD) / 25 kg m^{-2}

ADVANCES IN X-RAY MIRROR- AND DETECTOR DEVELOPMENTS

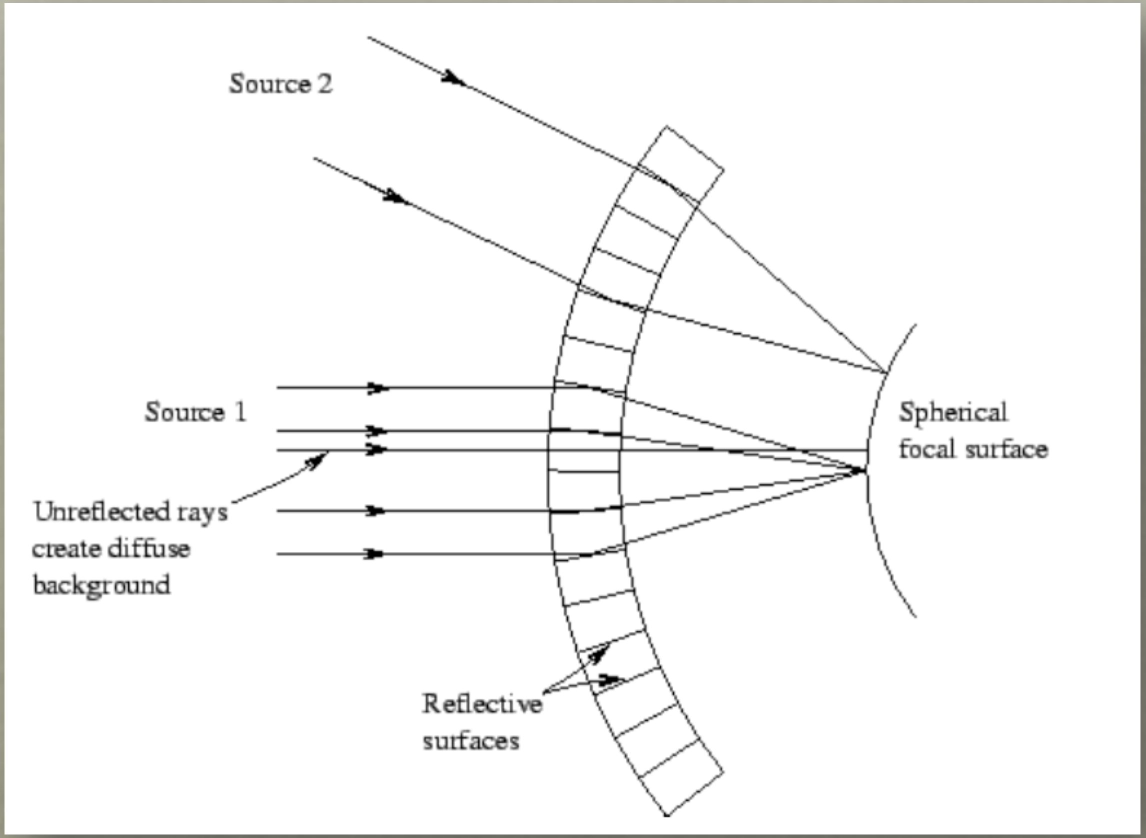


The aperture on MIXS STM on the **Bepi Columbo** mission. Each sector is populated by a pair of MCPs in Wolter I geometry. Total mirror mass **only 2 kg** (Willingale 2010). **Telescope effective area 50 cm^2**

(Bavdaz & Peacock 2004)

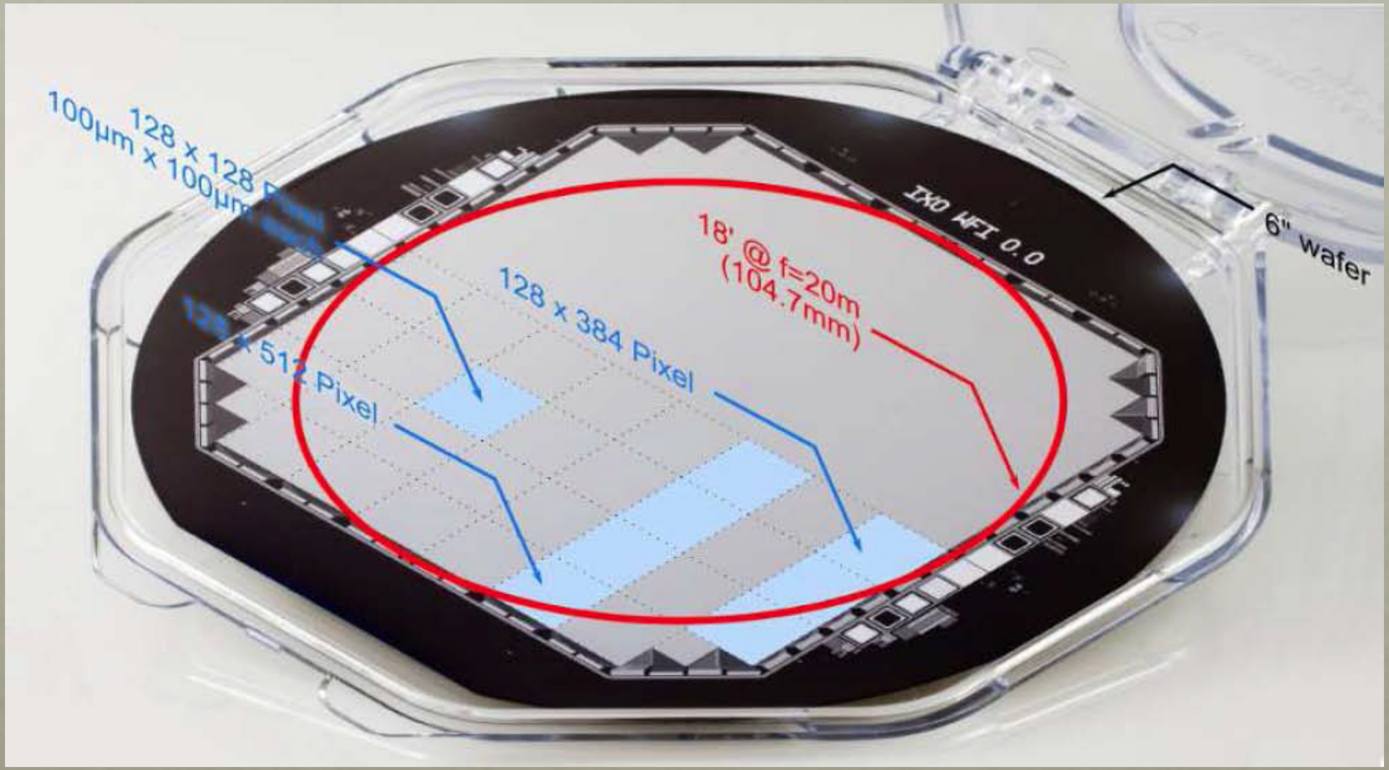
MCP/HPO optics:
30” (HPD) / 25 kg m^{-2}

ADVANCES IN X-RAY MIRROR- AND DETECTOR DEVELOPMENTS



LOBSTER-Eye configuration allows a large field of view

ADVANCES IN X-RAY MIRROR- AND DETECTOR DEVELOPMENTS



Mechanical sample of an ***Active Pixel detector*** (here 6-inch wafer-scale). Plotted over one hemisphere is the logical layout of the detector. It consists of roughly 1024 x 1024 pixels of 100 x 100 µm^2 size (Lechner et al. 2010) and supports a high temporal resolution while providing spectro-imaging information.

TECHNOLOGY
FOR PULSAR-BASED NAVIGATION

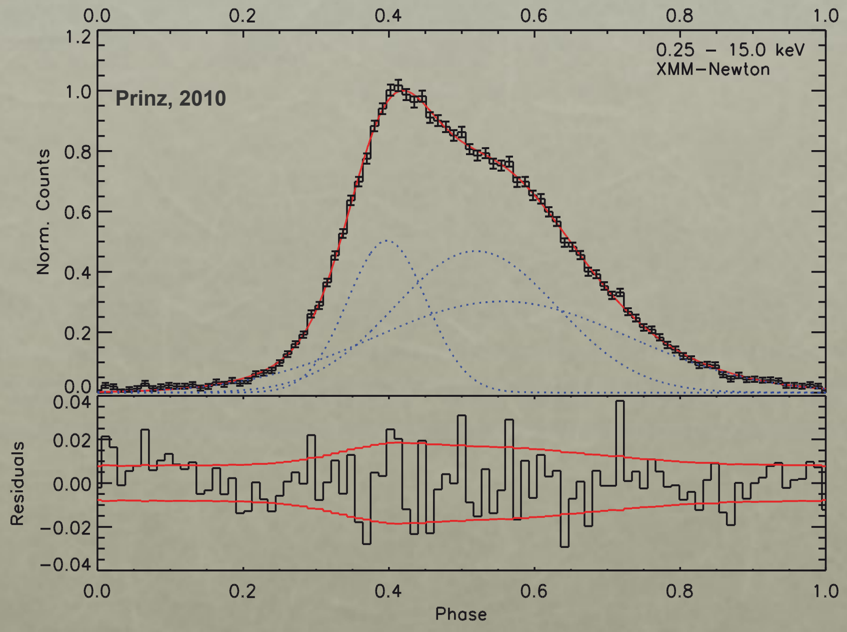
What accuracy is feasible using X-ray pulsars ?

Linear dependence on $\Delta x = cP(\Delta\phi + n)$

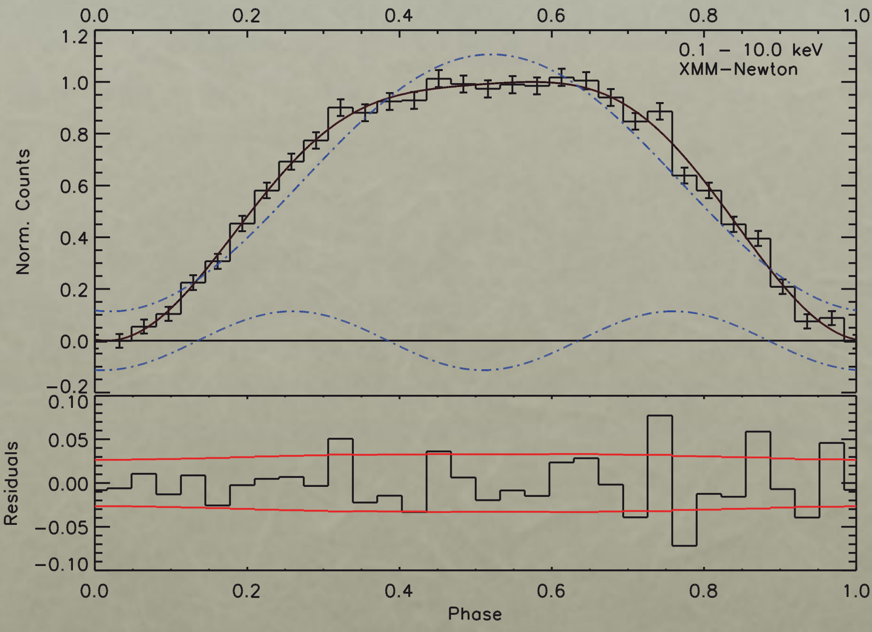
→ MSPs are better suited for pulsar based navigation than longer period pulsars.

ACCURACY ESTIMATE

PSR B1509-58



PSR J0633+1746



Minimal systematic phase uncertainty for the pulse profile templates in our database is of the order of $\Delta\phi$ = 0.001.

$\Delta\phi$ * P yields the uncertainty in pulse arrival time due to the limited information we have on the exact X-ray pulse profile.

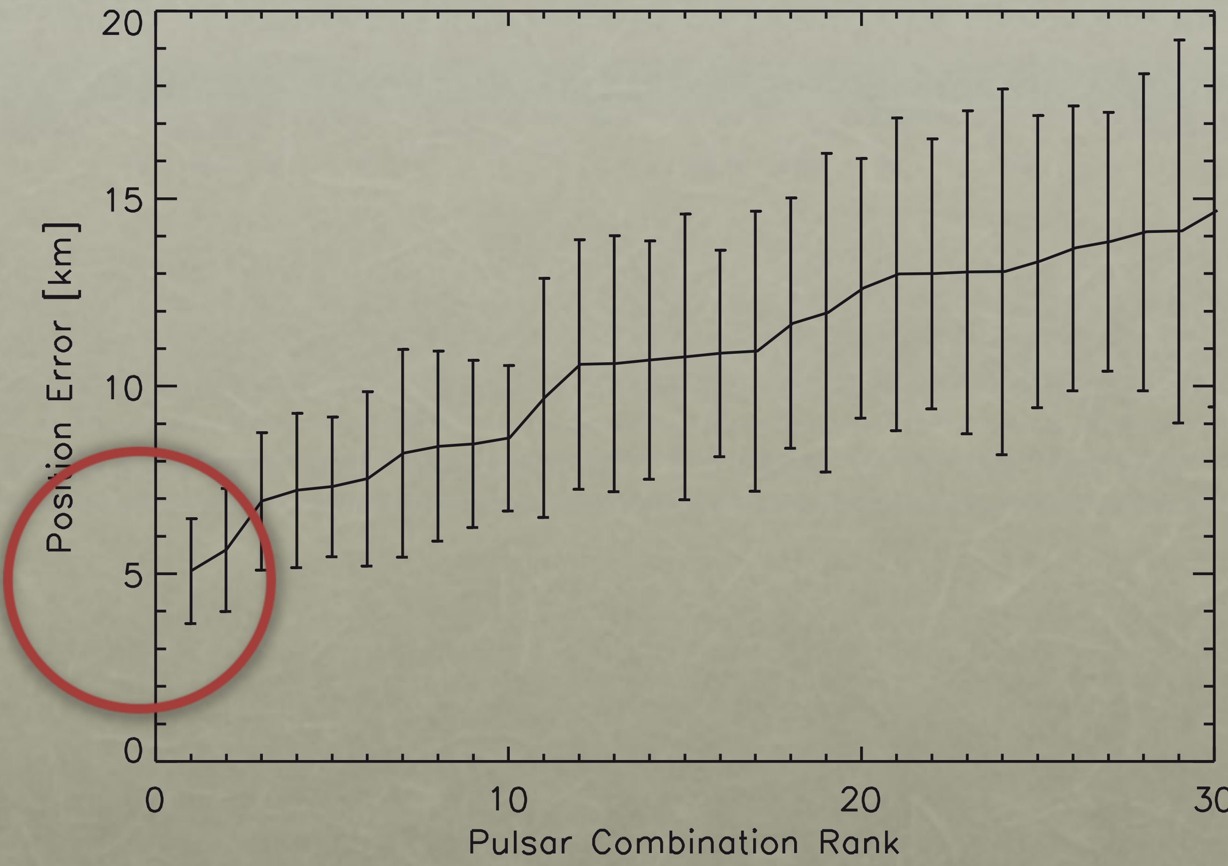
$\Delta\phi$ * P * C = spacecraft's position error along the line of sight to the pulsar!

ACCURACY ESTIMATE

Rank	Pulsar 3-Combination		
1	B1937+21	B1821-24	J0030+0451
2	B1937+21	B1821-24	J1023+0038
3	B1821-24	J0030+0451	J0437-4715
4	B1937+21	J1023+0038	J0218+4232
5	B1821-24	J1023+0038	J0437-4715
6	B1937+21	J0030+0451	J0218+4232
7	B1937+21	B1821-24	J0437-4715
8	B1937+21	J0218+4232	J0437-4715
9	B1821-24	J0218+4232	J0437-4715
10	J1023+0038	J0218+4232	J0437-4715

Bernhardt et al. 2010

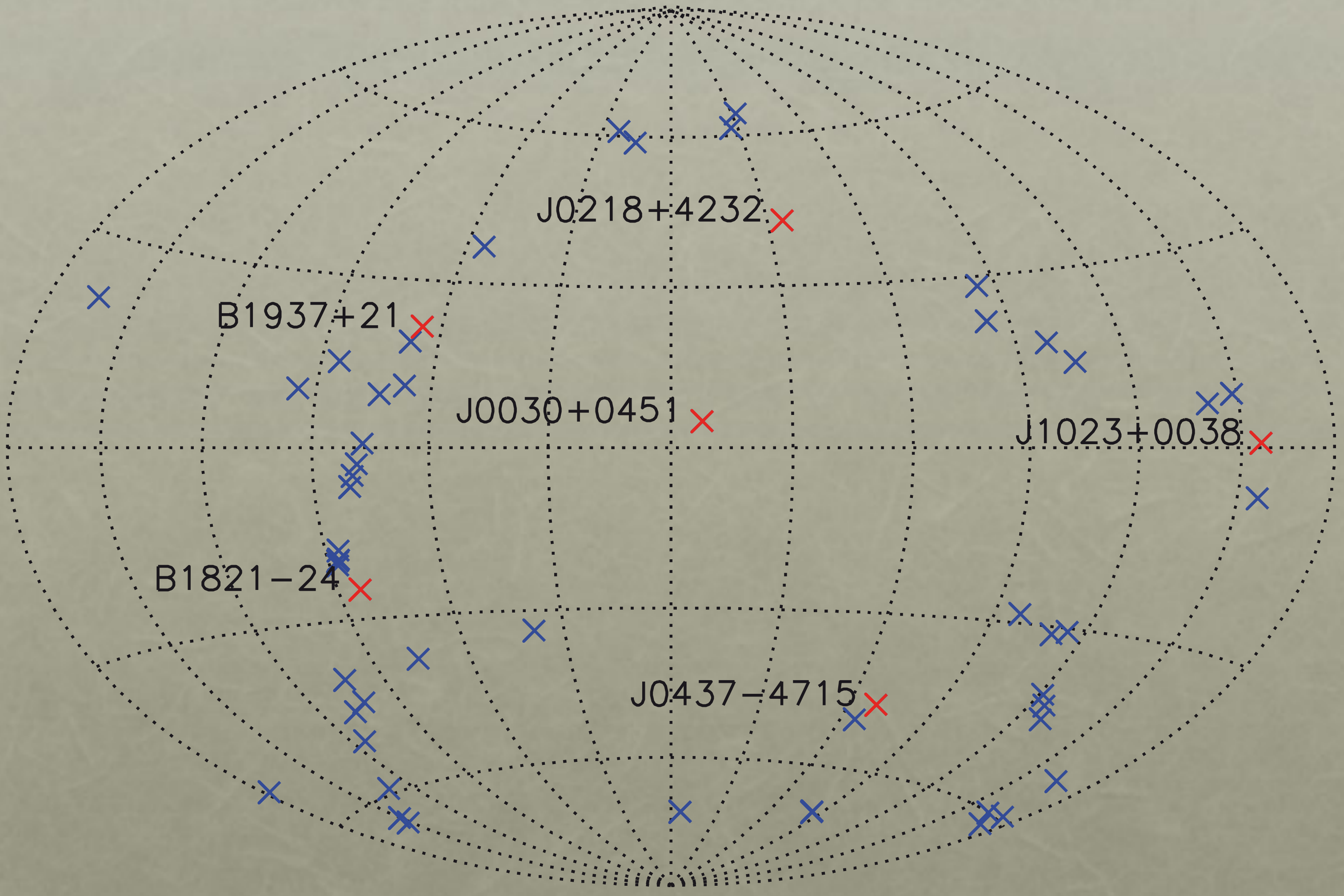
ACCURACY ESTIMATE USING X-RAY PULSARS FOR NAVIGATION



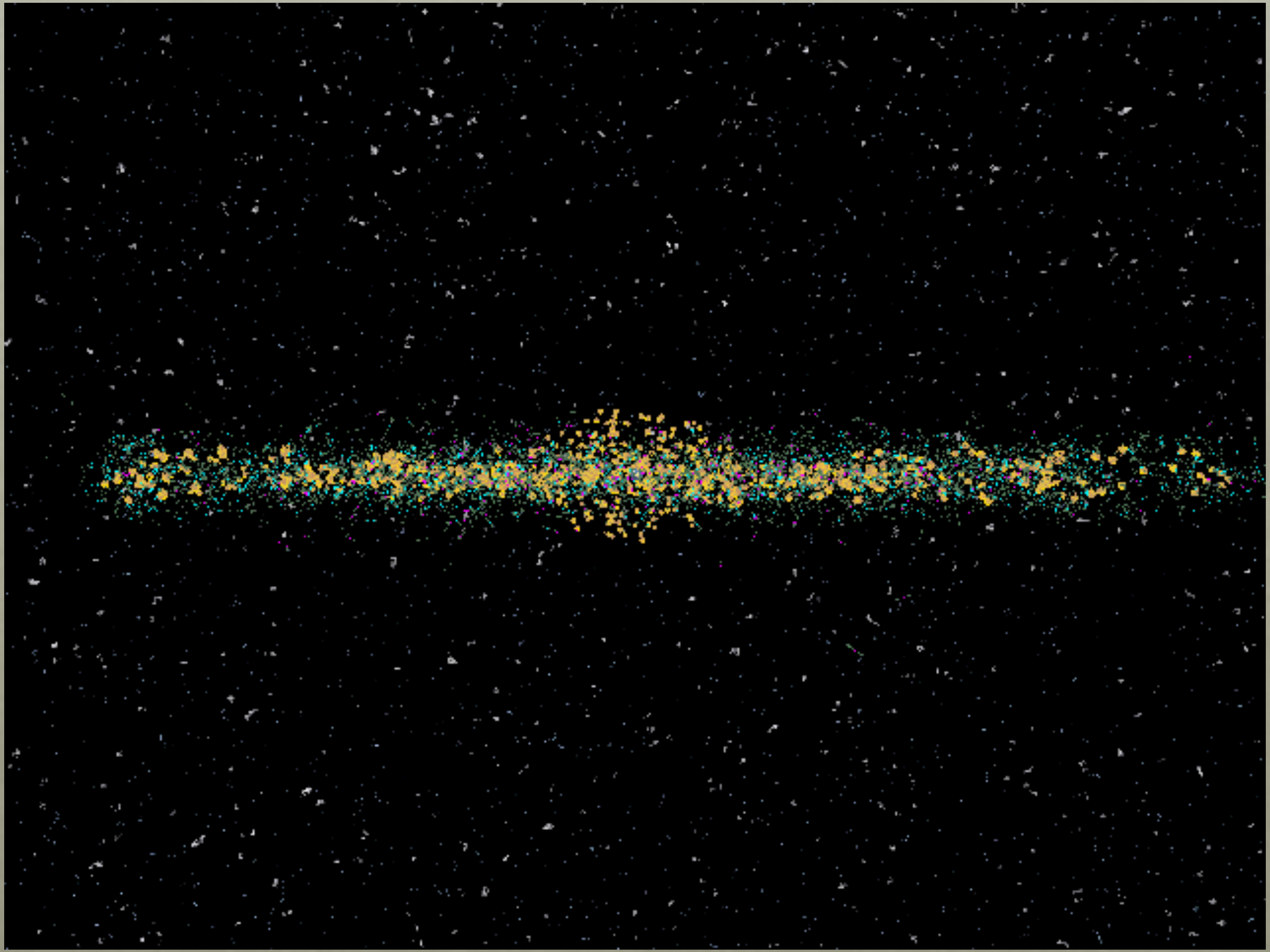
Bernhardt et al. 2010

Spacecraft position error as a function of possible pulsar 3-combinations. The diagram shows the mean position errors and standard deviations for the best 30 combinations.

MAP OF THE 6 PULSARS BEST SUITED FOR NAVIGATION



ARE THERE ENOUGH PULSARS IN OUR GALAXY SUITABLE FOR NAVIGATION ?



SUMMARY

Pulsar-based navigation is technically feasible, using

- low-mass X-ray mirrors & active pixel detectors or
- Radio: 230 m^2 eff. antenna area of e.g. a patched phased array in L-band
- Very exciting and promising alternative to conventional navigation
- Autonomous!!!!
- Position accuracies of ≈ 5 km achievable in the solar system and beyond even higher accuracies are possible using radio pulsar signals
- Augmentation of existing GPS/Galileo satellites
- Autonomous navigation for interplanetary space probes and future manned missions e.g. to Mars or beyond