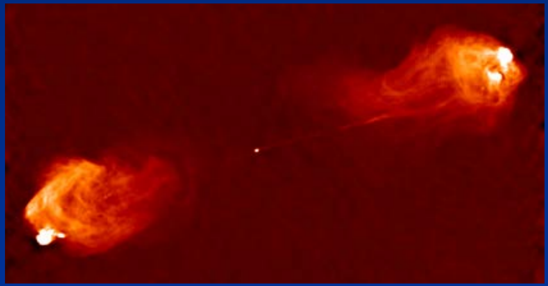
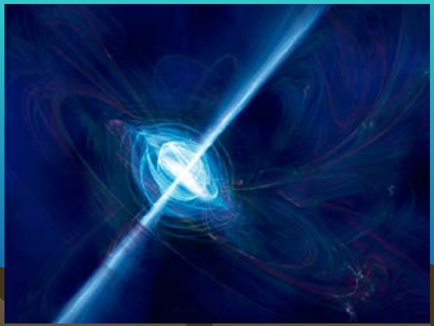
Radio Astronomy

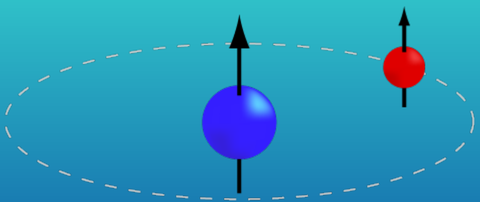
PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg







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Tentative Schedule:
16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer (HB)
11.12. Line radiation (HL)
18.12. Visit to Effelsberg (all)
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

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<u>Topics for today:</u>

- some details for line widths

- more about masers

- pulsars

One addendum to kinematics and line shapes

As mentioned earlier: in absence of peculiar motions, the thermal line broadening is the dominating mechanism to shape the (molecular) line shapes

But why do we expect Gaussian line shapes and usually fit the lines with a Gaussian?

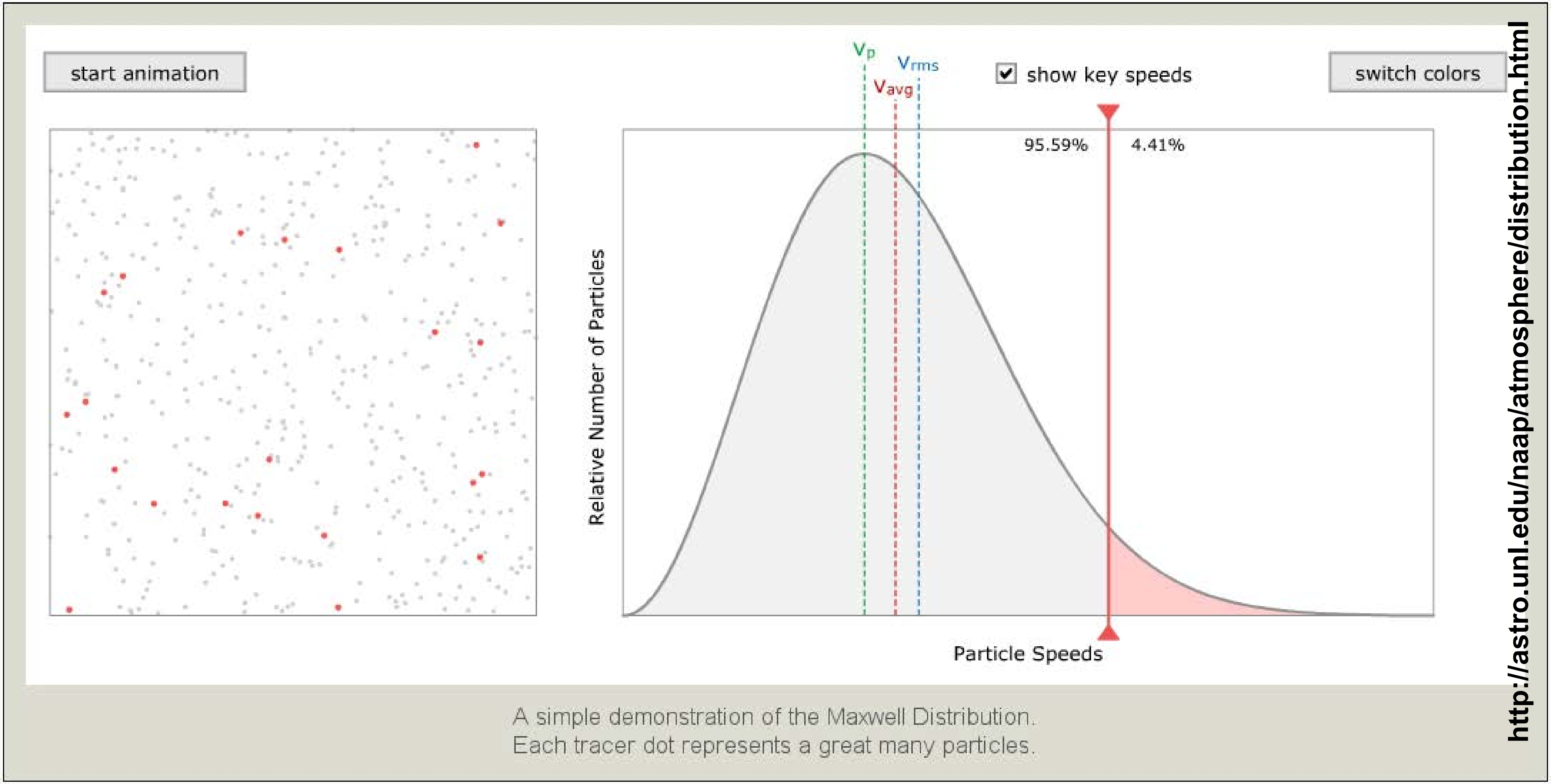
Remember: in collisional equilibrium, the velocity distribution in the gas is given by the Maxwell distribution

One addendum to kinematics and line shapes

The Maxwell distribution is slightly asymmetric and has a high-velocity tail

V_p (most probable velocity) = sqrt(2 k_B T_{kin} / m) < V_{avg} < V_{rms} = sqrt (3 k_B T_{kin} / m)

But as first approximation, the general shape is similar to a Gaussian ...



http://astro.unl.edu/naap/atmosphere/distribution.html

One addendum to kinematics and line shapes

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Important for a Doppler broadening of the lines is the 1D projection of the thermal motion of the gas molecules along the line of sight … therefore: "thermal broadening"

Motions away from us or towards us give a frequency shift in the emitted lines wrt the rest frequency of the transition.

1D projection of the Maxwell velocity distribution → translates into a line shape that is Gaussian to 1st approximation

Deviations from Gaussians indicate peculiar motions/kinematics (i.e., outflows, shocks)

Cosmic Masers

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H2	C3*	c-C3H	C5*	C5H	C6H	CH3C3N	CH3C4H	CH3C5N	HC9N	c-C6H6*	HC11N
AlF	C2H	l-C3H	C4H	l-H2C4	CH2CHCN	HC(O)OCH3	CH3CH2CN	(CH3)2CO	CH3C6H	C2H5OCH3?	C60*
AlCl	C2O	C3N	C4Si	C2H4*	CH3C2H	CH3COOH	(CH3)2O	(CH2OH)2	C2H5OCHO	n-C3H7CN	C70*
C2**	C2S	C3O	l-C3H2	CH3CN	HC5N	C7H	CH3CH2OH	CH3CH2CHO			
CH	CH2	C3S	c-C3H2	CH3NC	CH3CHO	C6H2	HC7N				
CH+	HCN	C2H2*	H2CCN	CH3OH	CH3NH2	CH2OHCHO	C8H				
CN	HCO	NH3	CH4*	CH3SH	c-C2H4O	l-HC6H*	CH3C(O)NH2				
CO	HCO+	HCCN	HC3N	HC3NH+	H2CCHOH	CH2CHCHO(?)	C8H–				
CO+	HCS+	HCNH+	HC2NC	HC2CHO	C6H–	CH2CCHCN	C3H6				
CP	HOC+	HNCO	HCOOH	NH2CHO		H2NCH2CN					
SiC	H2O	HNCS	H2CNH	C5N							
HCl	H2S	HOCO+	H2C2O	l-HC4H*							
KCl	HNC	H2CO	H2NCN	l-HC4N							
NH	HNO	H2CN	HNC3	c-H2C3O							
NO	MgCN	H2CS	SiH4*	H2CCNH(?)							
NS	MgNC	H3O+	H2COH+	C5N–							
NaCl	N2H+	c-SiC3	C4H–								
OH	N2O	CH3*	HC(O)CN								
PN	NaCN	C3N–	HNCNH								
SO	OCS	PH3?	CH3O								
SO+	SO2	HCNO									
SiN	c-SiC2	HOCN									
SiO	CO2*	HSCN									
SiS	NH2	H2O2									
CS	H3+*	C3H+									
HF	H2D+										
HD	SiCN										
FeO?	AlNC										
O2	SiNC										
CF+	HCP										
SiH?	CCP										
PO	AlOH										
AlO	H2O+										
OH+	H2Cl+										
CN–	KCN										
SH+	HO2										
SH	FeCN										
HCl+											

Detected molecules in space (outside of stellar atmospheres): > 170 (as of 11/2012)

Known cosmic molecules that show one or a few transitions with MASER properties

In addition to these rotational molecular transitions, masers have also been seen in Hydrogen recombination lines (for instance In the disk around the stellar object MWC 349)

Some more words about masers
(Microwave Amplification by Stimulated Emission of Radiation)

For masers, two physical circumstances are important:

– the existence of “stimulated emission” as a non-classical emission type

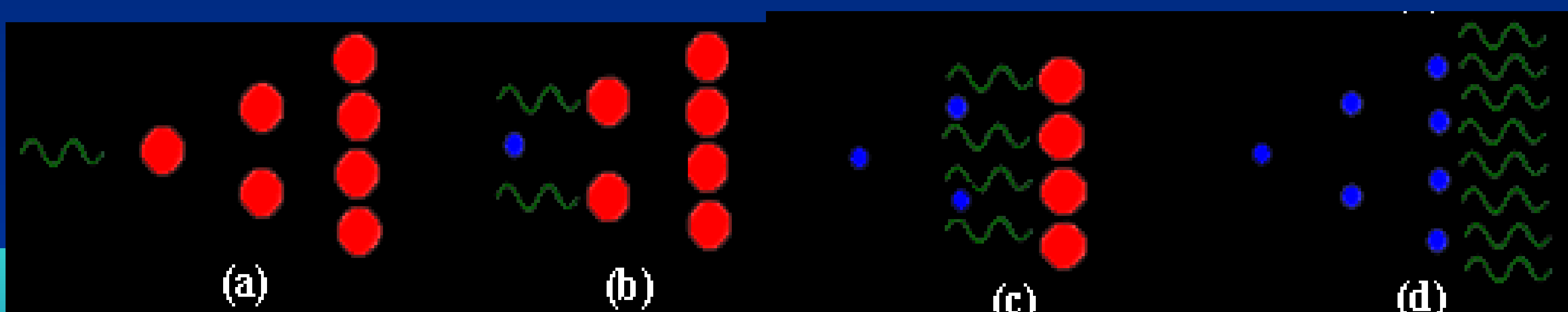
– a pumping mechanism to create a population inversion

Some more words about masers
*(**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation)*

"stimulated emission" as a non-classical emission type (B_{21}) …

in competition with the usually known "spontaneous emission" (A_{21})

Remember: for stimulated emission, an incoming seed photon (which must have the correct frequency though) stimulates the decay of an excited molecule to a lower (rotational) state, thereby emitting a second photon with the same frequency and direction. → snow-ball effect



Green waves: photons, red circles: molecules in high state,
blue dots: molecules in low state

Some more words about masers
(Microwave Amplification by Stimulated Emission of Radiation)

Pumping of the population numbers of the different (rotational) levels up to the point of a population inversion (i.e., strongly deviating from the normal Boltzmann distribution that would arise from collisional excitation alone)

Pumping mechanisms include continuum radiation arising in shocks, or mid- to far-infrared radiation (in old giant-star atmospheres, or close to young forming stars)

Often, the upper level of the maser transition is not directly pumped/ inverted, but a 3rd level is important as well

Furthermore, many maser transition upper levels are "**meta-stable**"

Some more words about masers
(Microwave Amplification by Stimulated Emission of Radiation)

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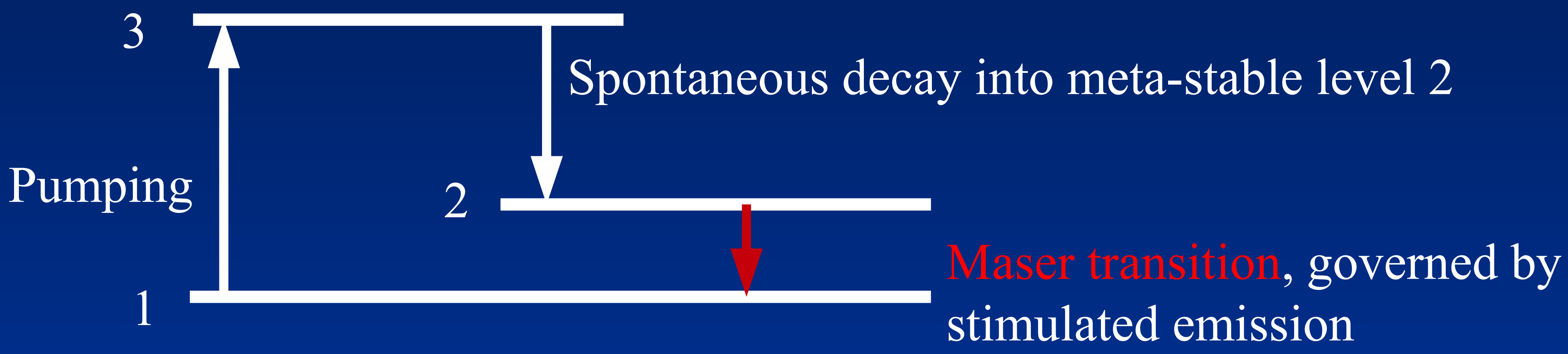
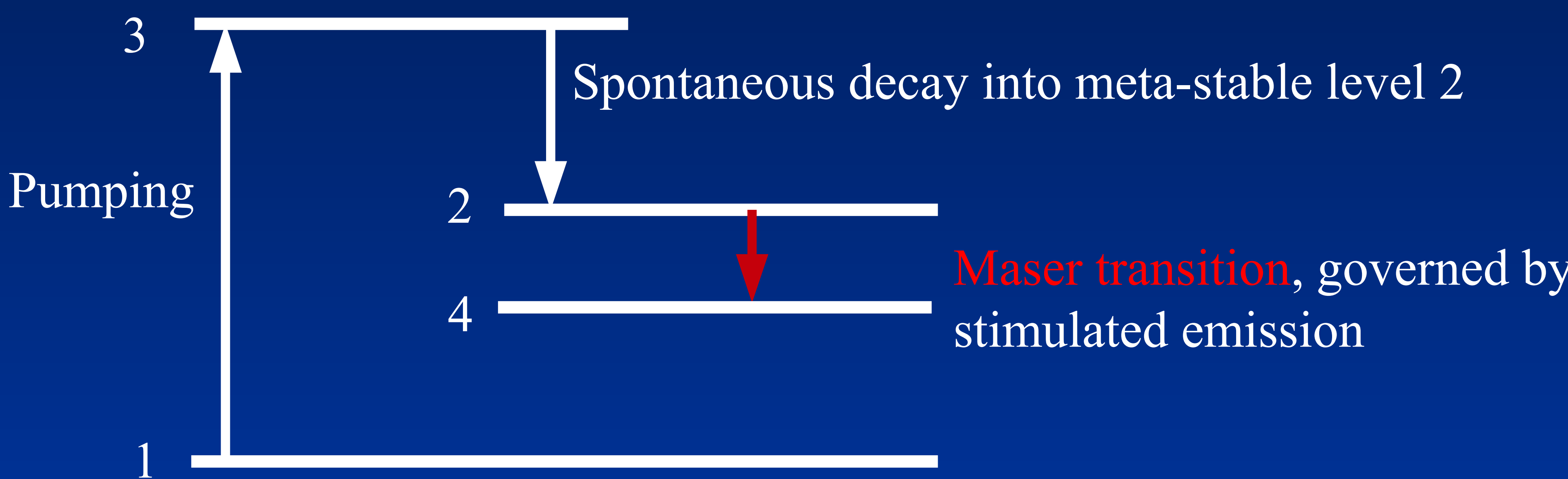


Meta-stable: also this level would be subject to spontaneous radiative decay eventually, but corresponding Einstein rate coefficient A_{21} is smaller than normal … stimulated emission B_{21} has time to act

Some more words about masers
(Microwave Amplification by Stimulated Emission of Radiation)

Furthermore, many maser transition upper levels are "**meta-stable**"



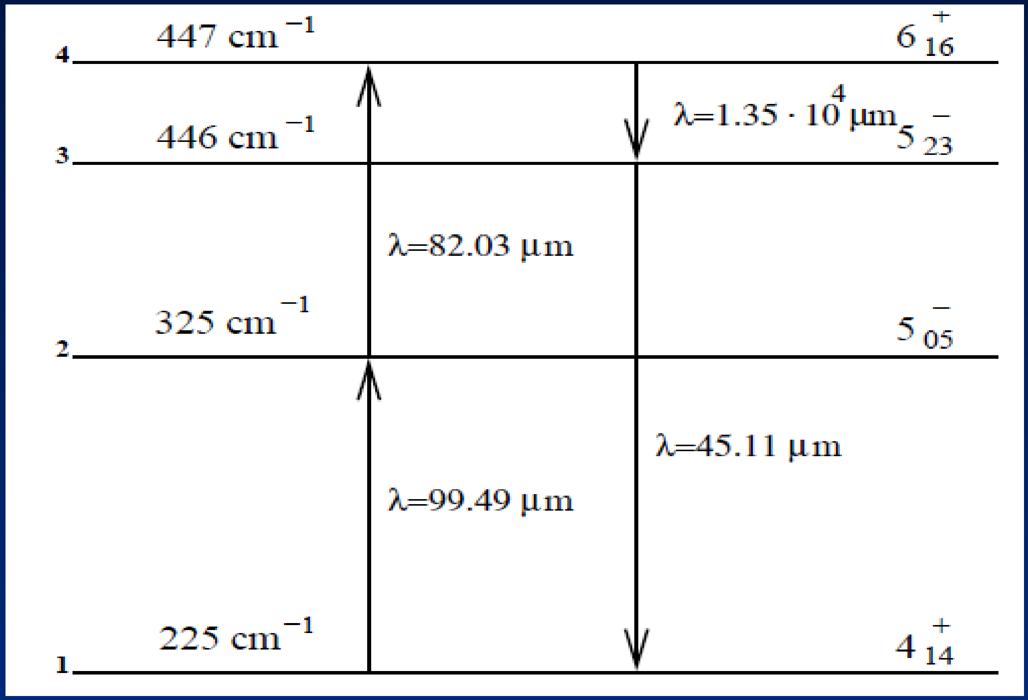
Often: pumping levels quite distinct from maser transitions regarding the energy differences involved …

Energy diagram for the pumping of the well-known water maser line at 1.35 cm (~22.23 GHz)

Sometimes, maser upper levels do not have to be strongly meta-stable, if other circumstances come into play:

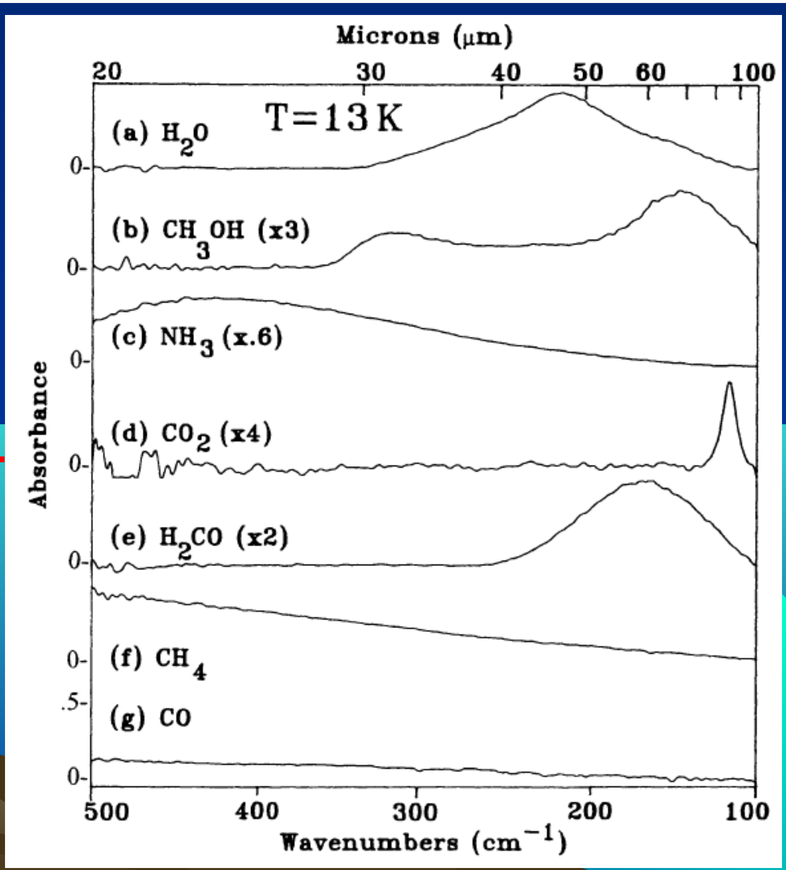
Far-infrared radiation in dusty colder environments provides a plenty of continuum radiation also covering the wavelengths 82.03 and 99.49 µm, this is populating the Level 4 (upper maser Level)

The population of the maser lower level 3 is slightly suppressed since the necessary 45.11 µm photons are subject to larger dust extinction (at the shorter wavelength compared to 82 and 99 µm). Even more important: H_2O ice absorption feature between 40 – 50 µm leads to stronger absorption of potential pump radiation for Level 3 due to water ice on the dust grains, see curve (a) →



Babkovskaia & Poutanen 2004, A&A 418, 117

A transition between the rotational sub-levels $5_{23} \leftrightarrow 5_{05}$ is not allowed for electric dipole radiation!



Moore & Hudson 1994, A&AS 103, 45

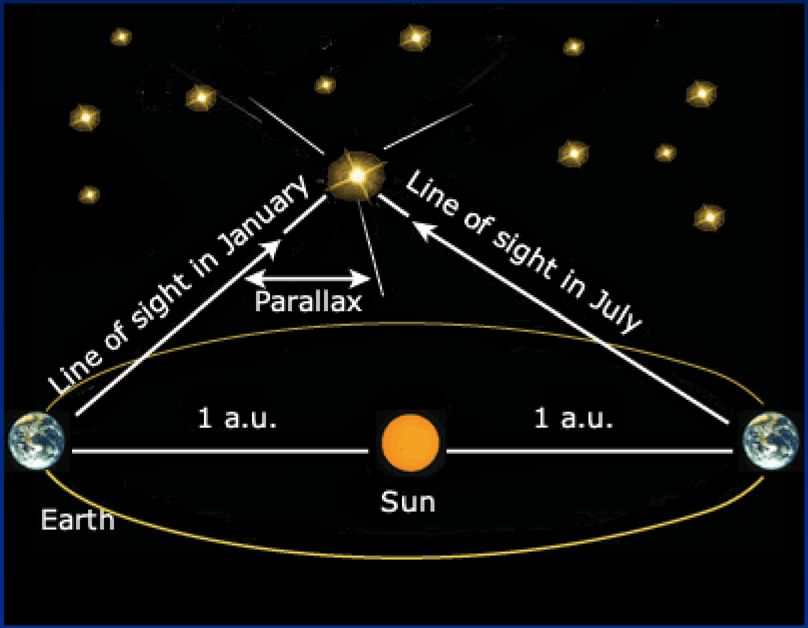
Masers as tools for distance measurements: Renaissance of the Parallax method

Parallax: first measured by Bessel in 1838

Apparent shift in position on the sky when measured 6 months apart

D [pc] = 1 / Π [arcsec]

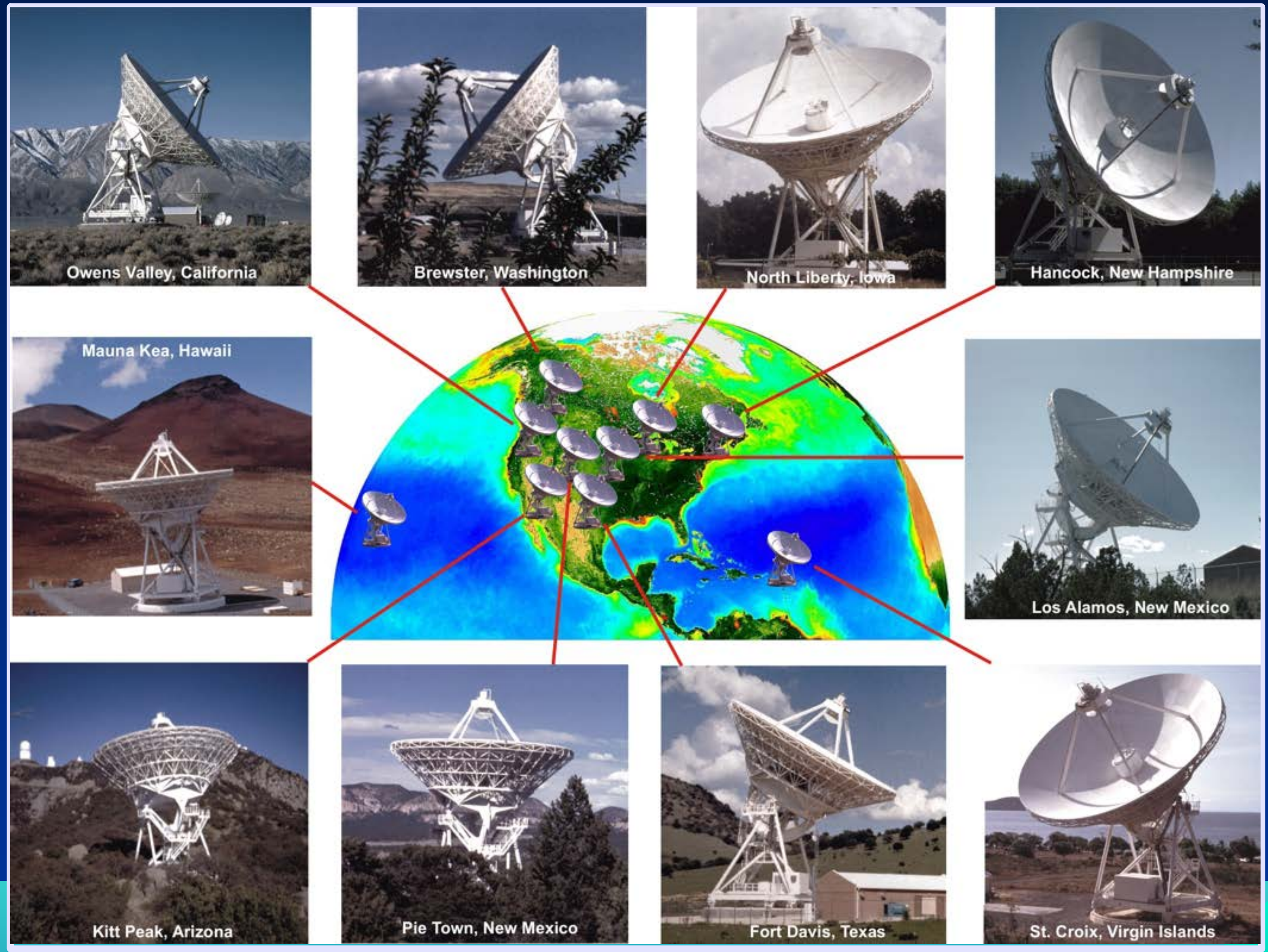
Optical satellite projects HIPPARCOS (1990s) and GAIA (to be launched end of 2013)



One drawback: working in the optical problematic when going towards star-forming regions ... strong extinction due to high columns of dust

Radio emission is not subject to dust extinction per se …
But in order to achieve accuracy better than milli-arcseconds, one needs to apply Very Long Baseline Interferometry (e.g., with the VLBA)

The Very Large Baseline Array (VLBA)



10 antennas à 25 m diameter, distributed over North America (from Hawaii to the Virgin Islands), Maximum baselines 8611 km!

The BeSSeL survey with the VLBA interferometer

The BeSSeL Survey (Bar and Spiral Structure Legacy Survey) is a VLBA Key Science project and led by people from MPIfR Bonn and CfA Harvard.

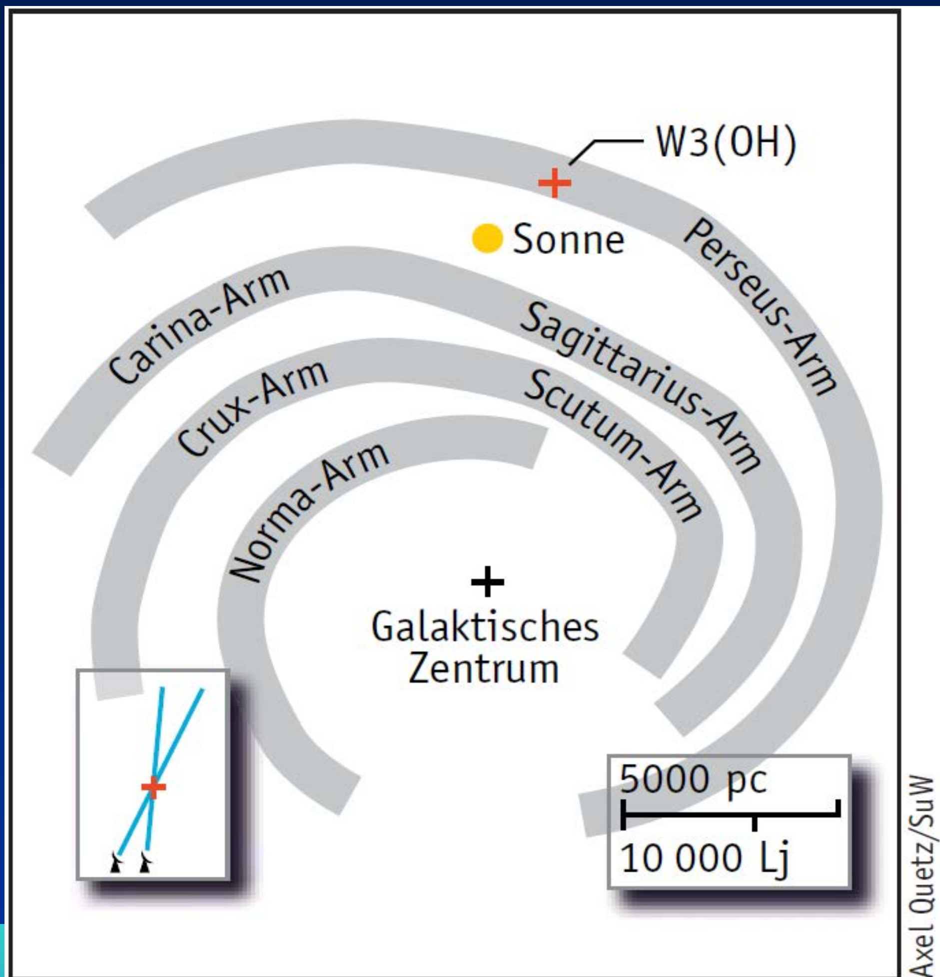
Goal : study the spiral structure and kinematics of the Milky Way

Tool : methanol masers at 6.67 and 12.2 GHz, water masers at 22.23 GHz,
Located in star-forming regions in all Galactic spiral arms.
High brightness and compactness makes masers good beacons that can be used and survive the extreme spatial filtering of the VLBA.

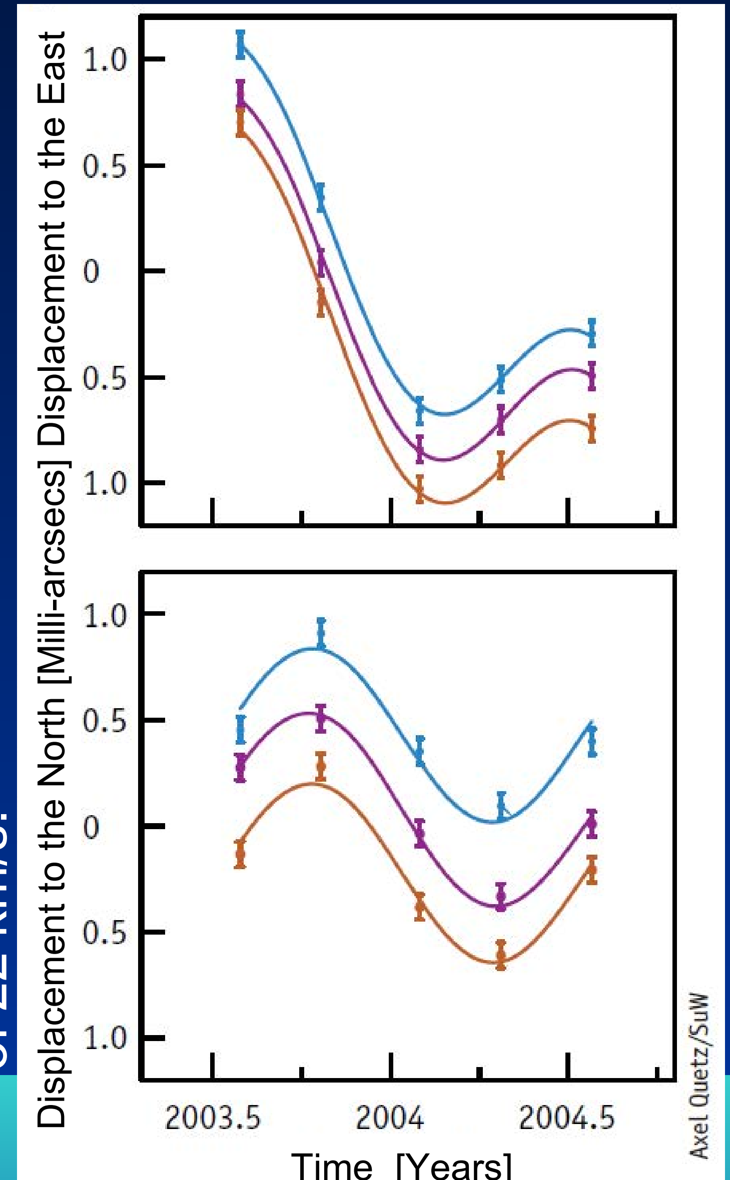
Method: determining distances, via trigonometric parallax, and proper motions of star forming regions in the Milky Way with up to 10^{-5} arcsec accuracy!

Program: measure accurate distances and proper motions of up to 400 high-mass star forming regions in the Milky Way between 2010 and 2015.
→ catalogue of accurate distances to most Galactic high-mass star forming regions visible from the northern hemisphere
→ accurate estimates of distance to the Galactic center (R_o), and the rotation velocity of the Milky Way (Θ_o)

Initial investigation by Xu et al. 2006, Science 311, 54 towards the W3 star-forming region



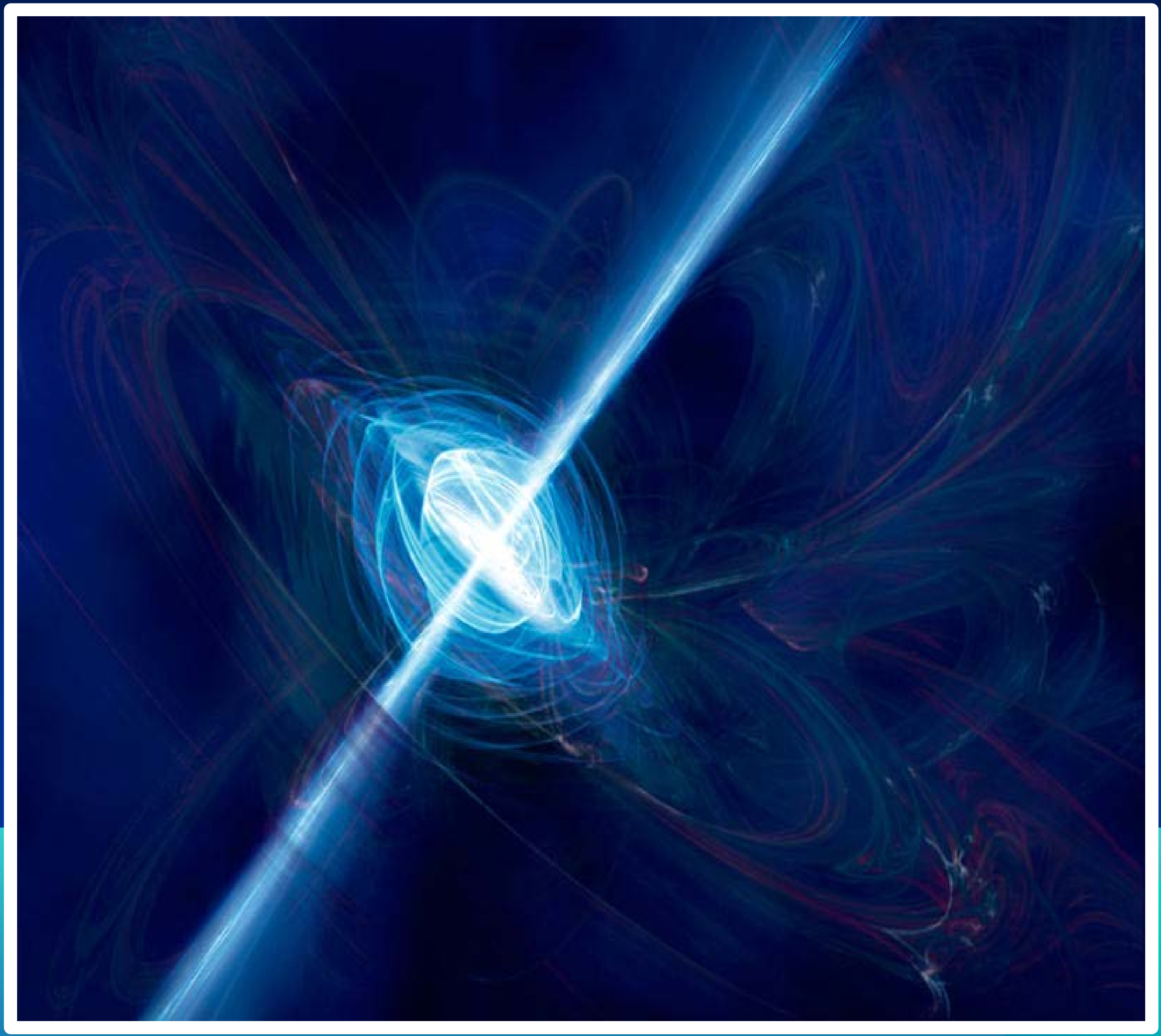
An artificial shift has been introduced to better distinguish the curves. The East displacement curve indicates an additional peculiar motion component of 22 km/s.



Distance estimated to 1.95 ± 0.04 kpc, much different from previous values based on circular rotation curves (~ 4 kpc)

One year of measurements, referenced to the absolute position of 3 background quasars ...

Radio astronomy and Pulsars : a powerful team



SPACE ART, Ralf Schoofs

Radio astronomy and Pulsars : a powerful team

Differently from some other new phenomena that 20th century astronomy has revealed (e.g., White Dwarfs), in case of Neutron Stars, all started with theoretical predictions:

1932: Lew Landau postulates that very massive stars might contain degenerate fermion matter

1939: Oppenheimer & Volkoff compute the equation of state for a hypothetical neutron star

1967: Cambridge professor A. Hewish and his PhD student J.S. Bell find periodic radio signals while looking for radio scintillation at 81.5 MHz: period 1.34 s and very stable → Little Green Men?

Only on Feb 24, 1968, they published the results in Nature magazine: Existence of "pulsars" and connection to neutron stars

1974 → Nobel Prize in physics for Hewish (but not for Jocelyn Bell!)

Radio astronomy and Pulsars : a powerful team

Differently from some other new phenomena that 20th century astronomy has revealed (e.g., White Dwarfs), in case of Neutron Stars, all started with theoretical predictions:

1932: Lew Landau postulates that very massive stars might contain degenerate fermion matter

Abstract: Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory.
The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

Only on Feb 24, 1968, they published the results in Nature magazine:
Existence of "pulsars" and connection to neutron stars

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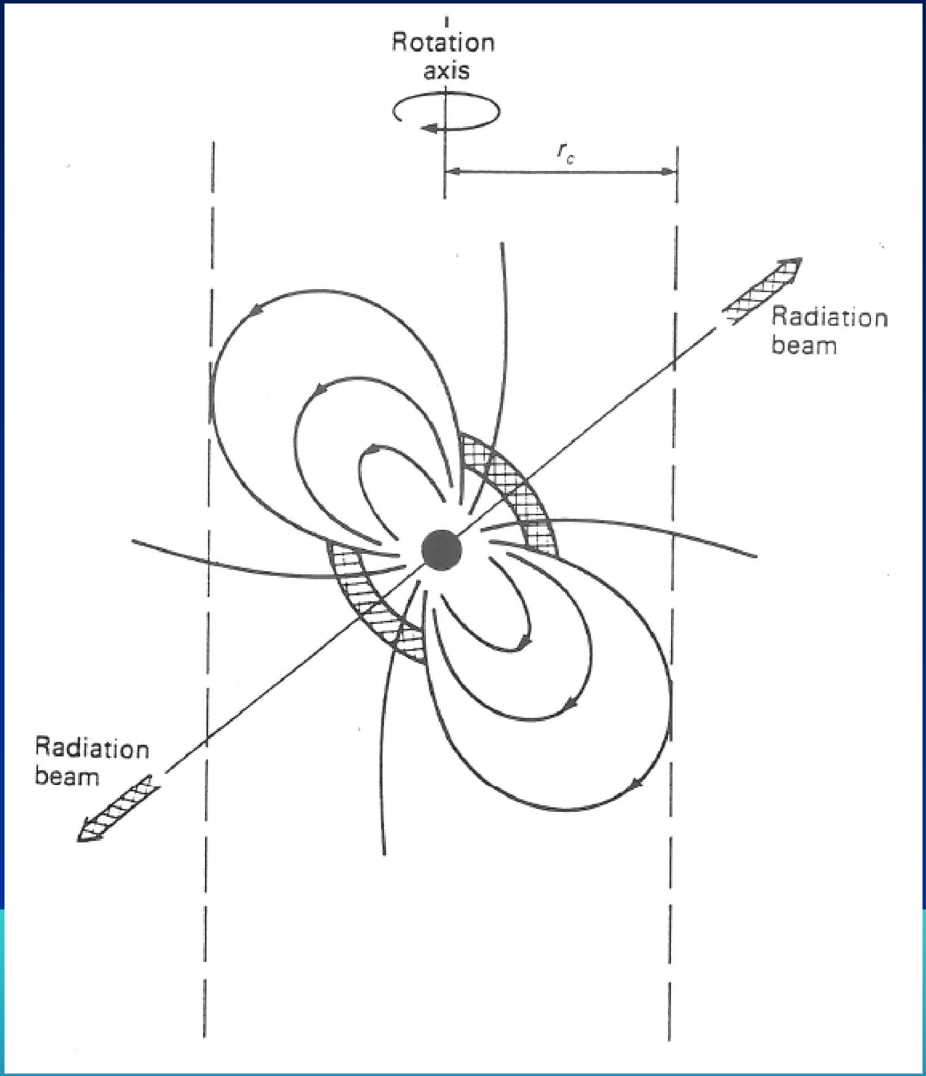
Pulsars : stellar zombies … remnants of certain supernova explosions



Pulsars are fastly rotating neutron stars!

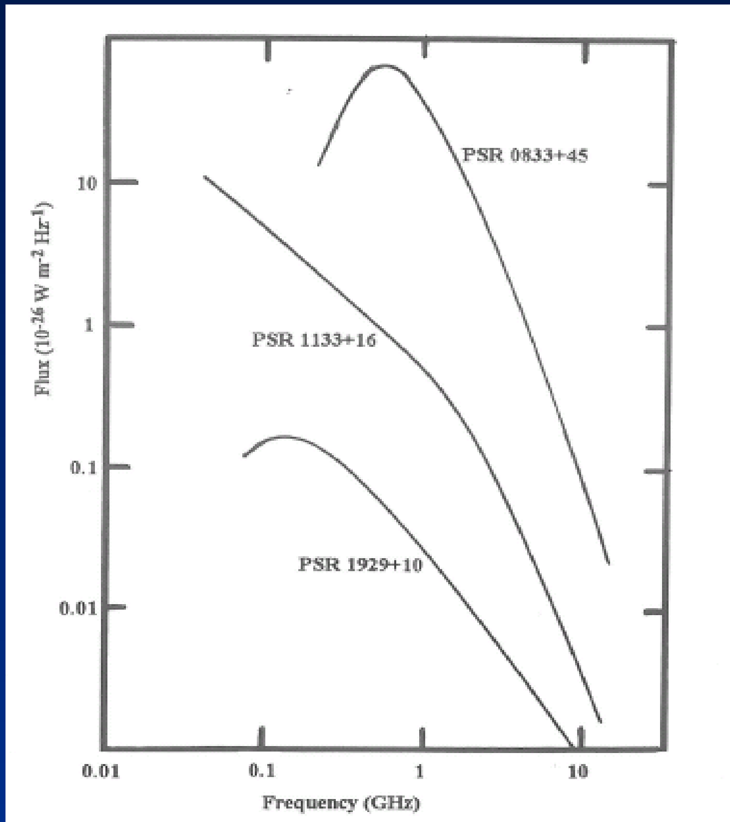
Rotation periods of several seconds down to milli-second levels

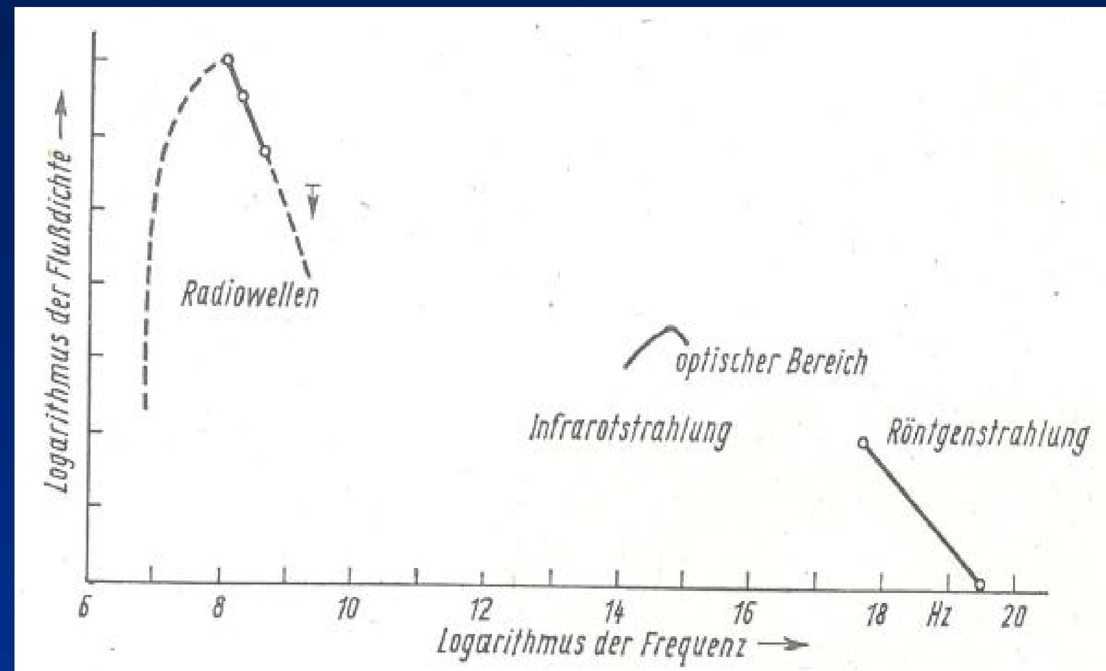
Extremely high magnetic field strengths (10^6 – 10^{10} Tesla)

Strongly beamed radiation → radio light house

Within $r_c = c / \omega$ (the "light cylinder"), one has a co-rotating magnetosphere, field lines touching the cylinder define the edge of the polar caps. Radio emission occurs from the hatched regions of these polar caps → the penetrating B-field lines there must be open since a closed field loop outside r_c had to rotate with $v > c$!

Pulsars : powerful radio emitters

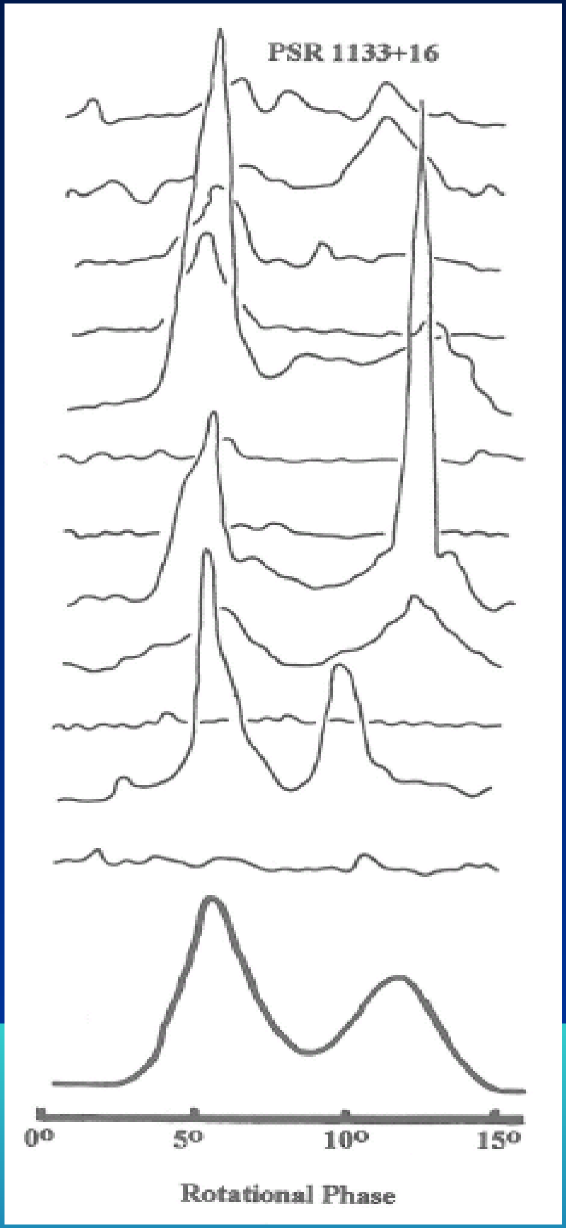




Low-frequency radio SEDs of some pulsars. Often there is a turn-over at very low frequencies and a strongly negative slope towards higher frequencies (steeper than usual Synchrotron)

The full SED of the Crab Nebula (M1) which harbours a pulsar. The nebula as well as the pulsar itself also emit at high frequencies (IR, VIS, X-rays). But the strongest emission is released at low frequencies.

Pulsar radio emission mechanisms remains a conundrum



Individual and time-integrated pulse structure for the Pulsar PSR 1133+16.

Many studies after the initial discoveries …

Analysis of sub-pulses and the frequency drifts, their (change in) polarisation … all this results in a complex picture.

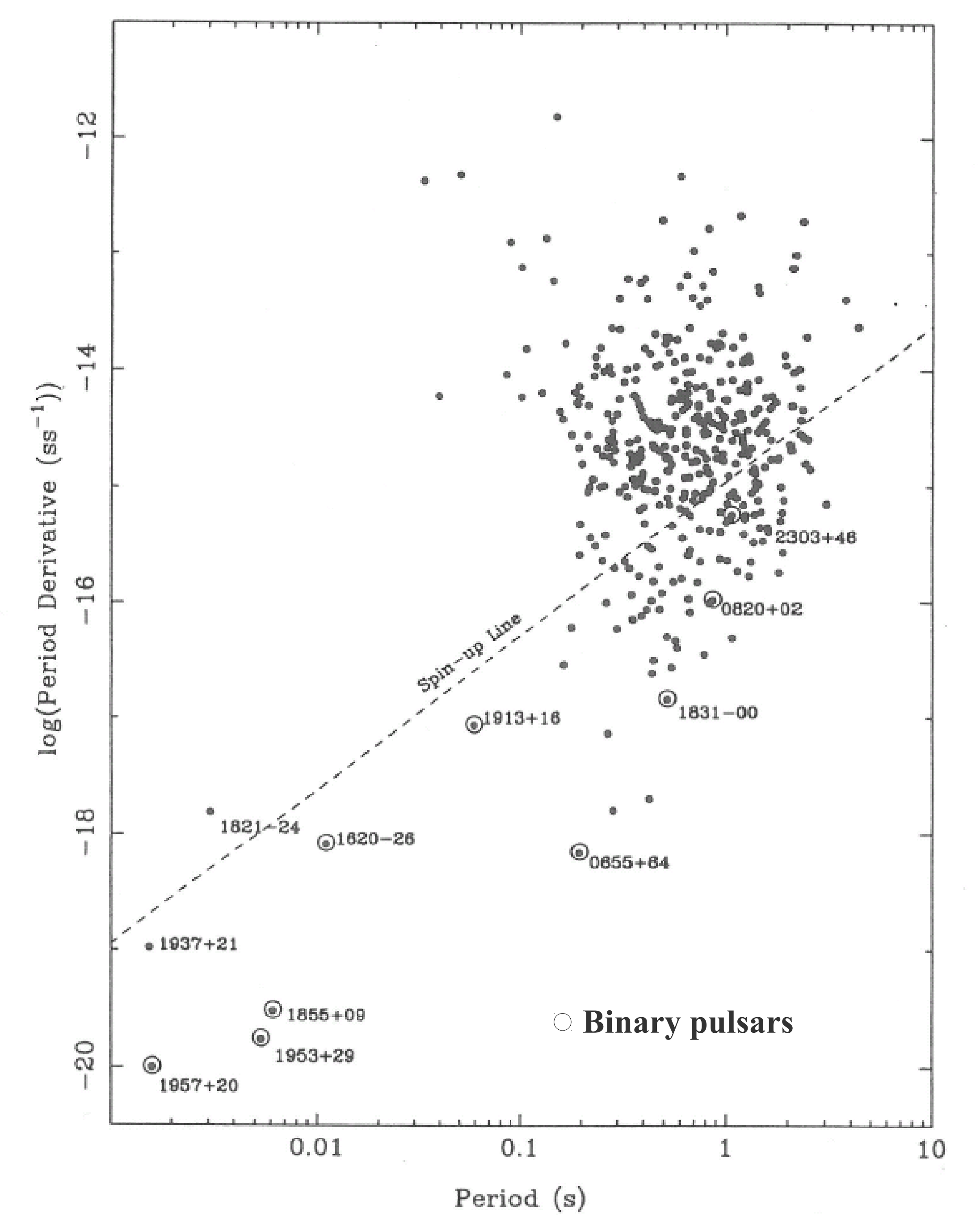
Main surprise: pulsar radio emission very bright, not in terms of high flux densities, but regarding intensities (energy per small solid angle) → $T_b \sim 10^{30}$ K in extreme cases

→ **coherent** emission mechanism at work!

Some indications: high-energy particles following the curvature of the B-field lines might do the trick (e.g., Mitra et al. 2009, ApJ 696, L141)

→ coherent curvature radiation!

The radio pulses of Pulsars: very precise cosmic clocks



Shown is the measured change in the pulse period over the period itself.

The periods for many pulsars are very stable.

Young pulsars tend to have relatively Large period changes (P rises)

The special group of "milli-second pulsars" is probably an old population that has been spun up by accreting surrounding matter.

These milli-second pulsars have ultra-stable periods (even after 13.7 Gyr, some of these clocks are wrong by just ~ 1 second or less!)

The radio pulses of Pulsars: very precise cosmic clocks

The (phase-integrated) pulses are very regular and reliable.

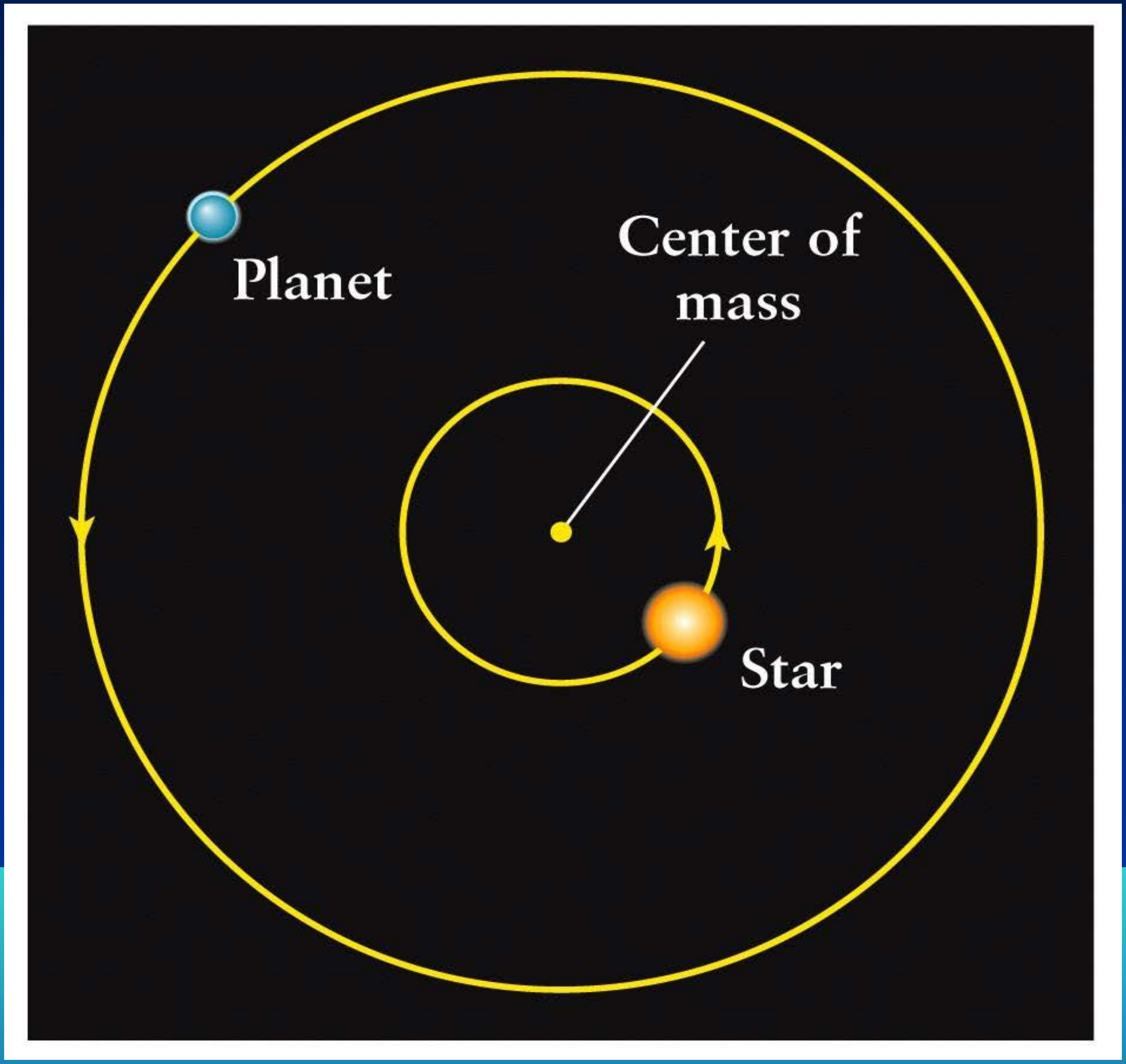
However, situations can arise where we as observers see deviations in the regularity of the pulse arrival :

a.) The Pulsar is located in a dynamical system and subject to orbital motion with a motion component along our observation line-of-sight.

b.) The pulses have to travel through different gravitational potentials (for instance due to a companion white dwarf or neutron star).

→ **<u>Pulsar Timing</u> as an important measurement technique**

Application 1: Pulsar timing to reveal Pulsar planets



Stellar mass and planet mass are very different. Hence the planet will have a much larger orbit around the center of mass than the star … but also the star has to move a bit!

In case the star is a pulsar, then the arrival of the pulses is modulated by the orbital motion.

Let's not discuss here whether a pre-existing planet could survive a SN explosion …

Application 1: Pulsar timing to reveal Pulsar planets

Wolszczan & Frail 1992, Nature 355, 145

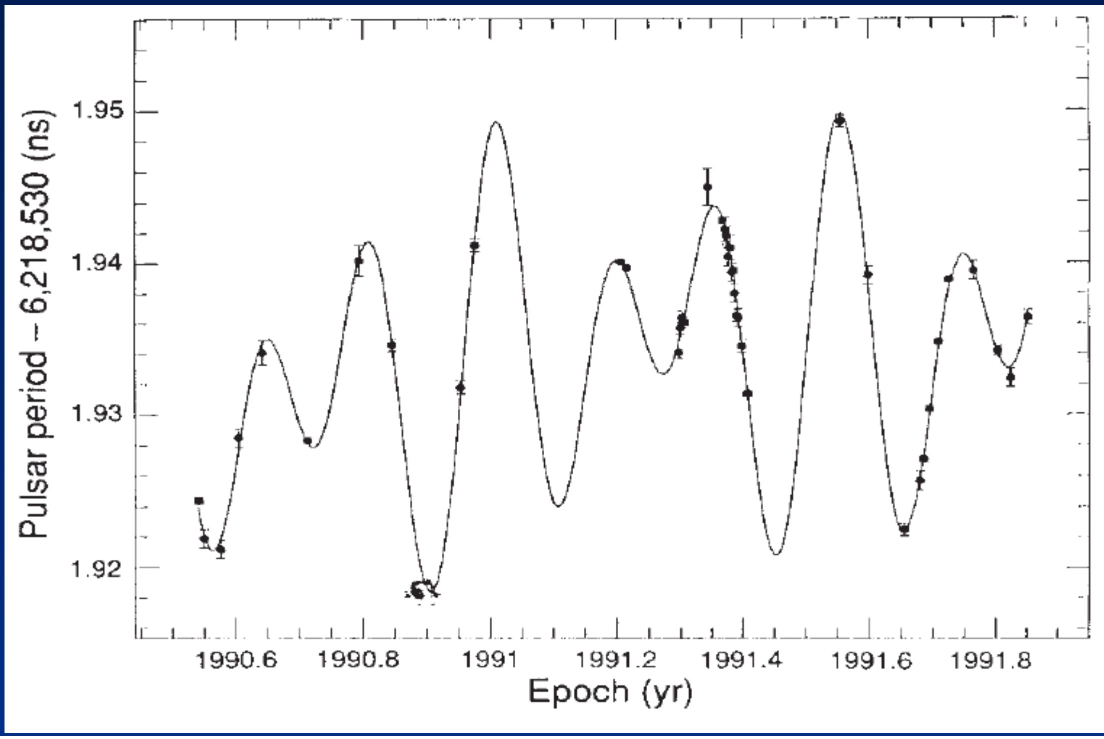


FIG. 3 Period variations of PSR1257+12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257+12 system.

Observations at 430 MHz with the 305-m Arecibo telescope to observe PSR1257+12, a milli-second pulsar with P ~ 6.2 ms.

Report on revealed timing variations consistent with the orbit of 2 planet-mass bodies:

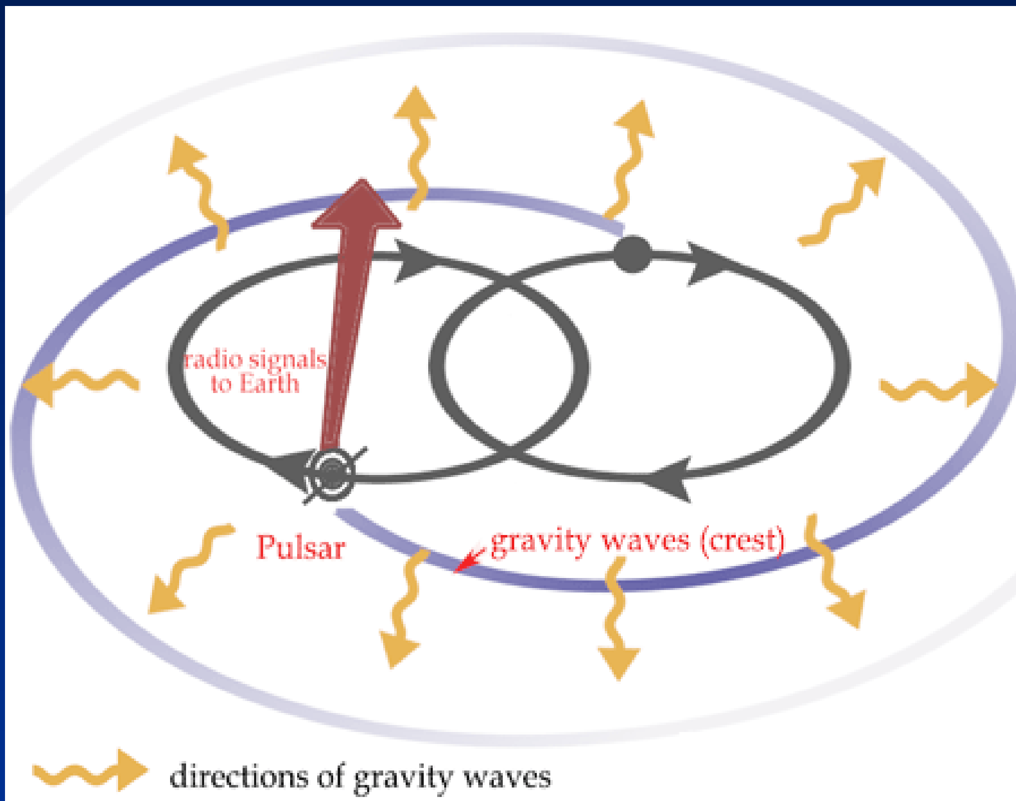
$M_1 = 3.4\ M_{earth}$, $P_1 = 66.6$ d

$M_2 = 2.8\ M_{earth}$, $P_2 = 98.2$ d

→ The first known Exo-planets ... 3 years before the report of the first "radial-velocity" planet by Michel Mayor around 51 Peg!

Note: The apparent period variations are on the order of +/- 15 picoseconds !
(maximum pulsar displacement: 900 km, v_{max} ~ 0.7 m/s)

Application 2: Testing fundamental physics with binary pulsars



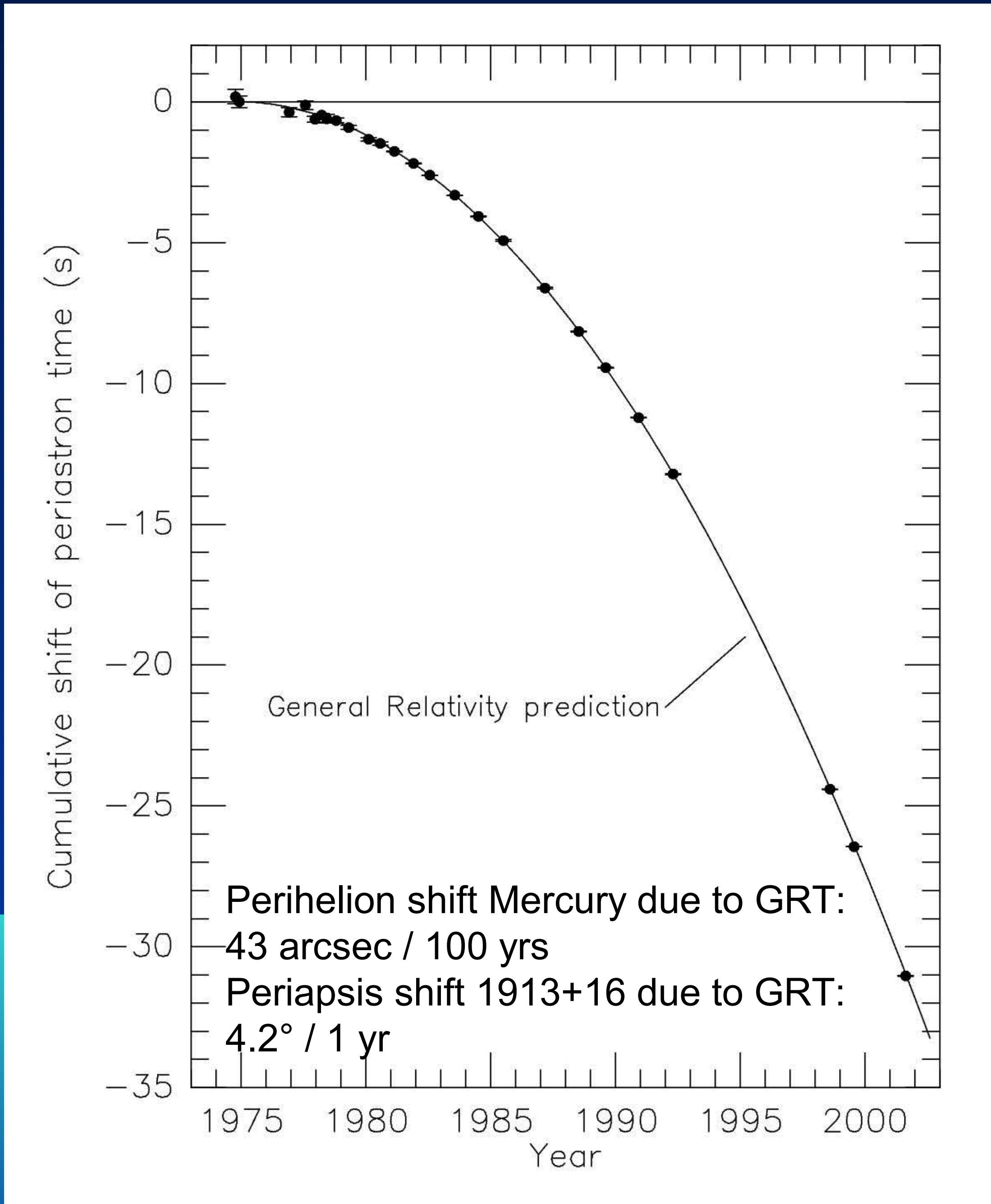
Binary pulsars: two neutron stars orbiting each other, at least one of them appear as a pulsar to us

Pulsar timing can reveal orbital motion … but in addition to this short-term modulation: secular effects due to general relativity (GRT)

→ prediction of gravitational wave generation that takes away orbital momentum

Hence, the orbital diameter will shrink, and the orbit will get tighter with time … if GRT is correct!

Application 2: Testing fundamental physics with binary pulsars



1974: the binary pulsar PSR 1913+16 is discovered by Hulse & Taylor

Pulsar period = 59 ms
Binary orbit with P = 7.75 h, ellipticity ~ 0.62, both components ~ 1.4 M_{sun}

Monitoring of the orbit change over the next years and decades:
Indeed, the periapsis time changes on the order of (tens of) seconds, the orbit shrinks … rate of decrease of orbital period is 76.5 microseconds per year

Measurements in very good agreement with GRT gravitational wave prediction!

→ Nobel Prize 1993 for Hulse & Taylor

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Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

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