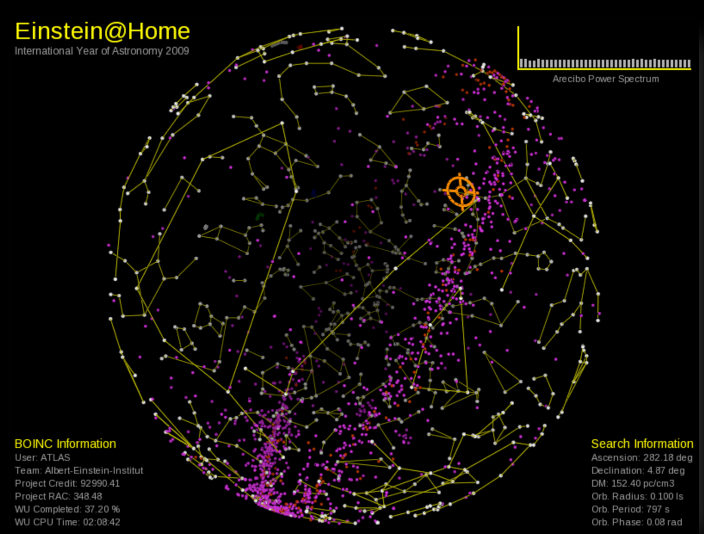
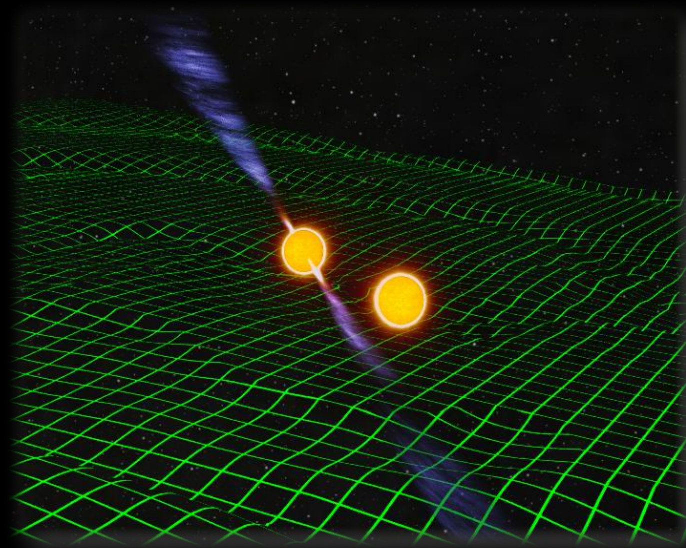
The Einstein@Home Search for Binary Pulsars in Arecibo Radio Data





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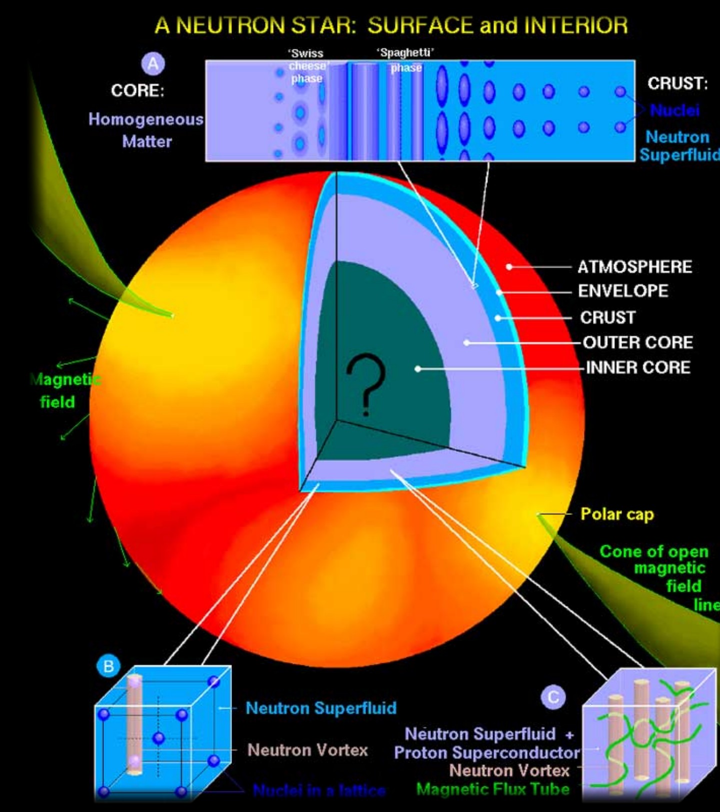
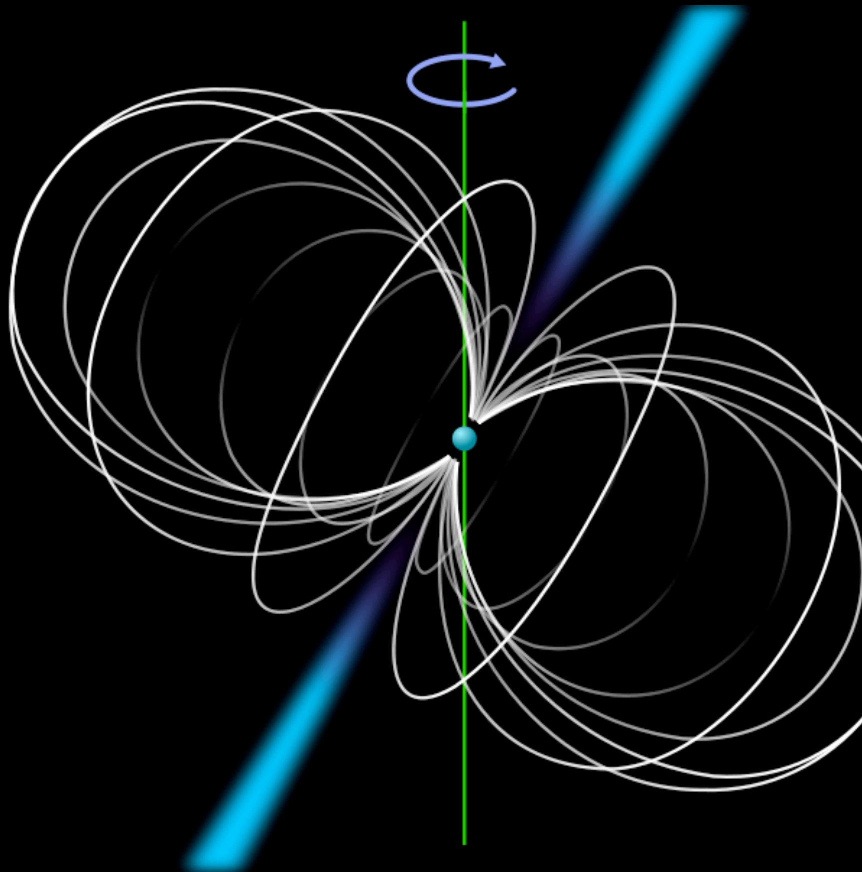
J. Cordes, J. Deneva
(Cornell University)

Neutron Stars

- **neutron stars**
  - formation in supernova explosion
  - solar-mass atomic nucleus ~20ish km in diameter
  - unknown EoS, densities ~10^{18} kg m^{-3}
  - Strong gravity: $R_{\text{Schwarzschild}} \approx 0.3\, R_{\text{neutron star}}$
  - Strong magnetic fields: 10^8 to 10^{14} G

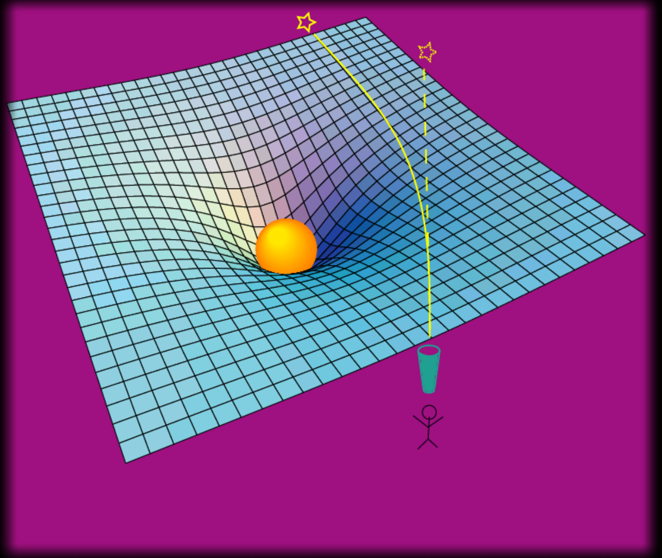


- **pulsars**
  - lighthouse emission of electromagnetic radiation
  - fast spin (ms to s)
  - very stable clocks

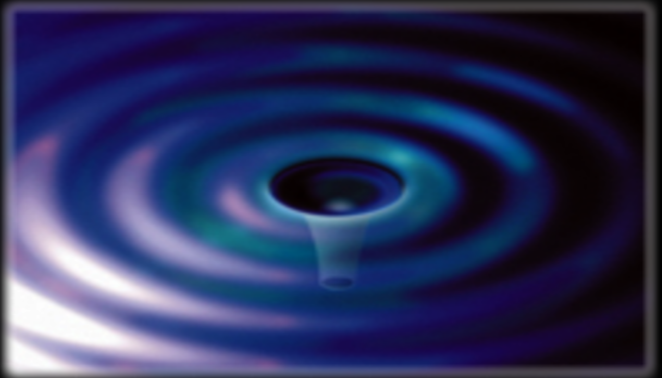


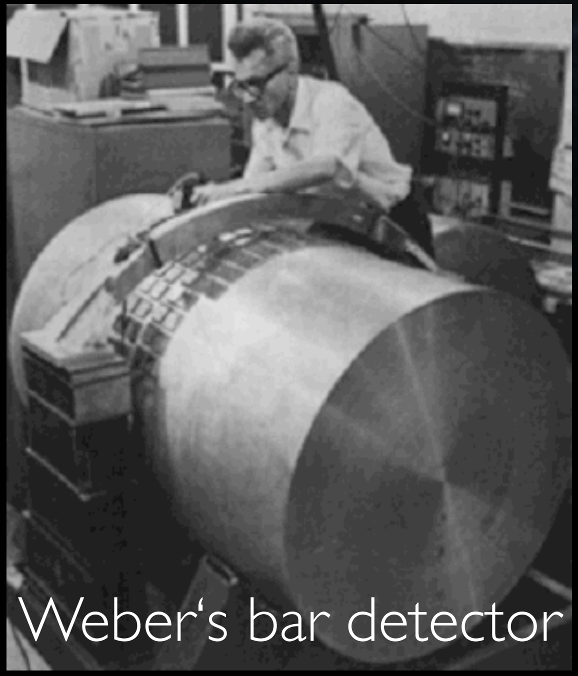
Gravitational Waves

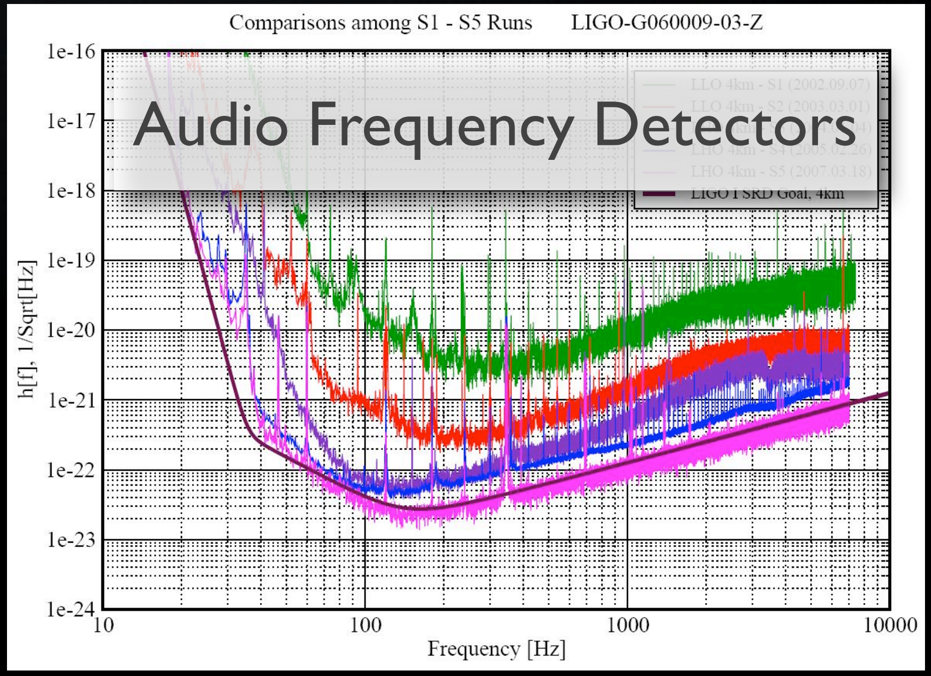
- **GR:** mass / energy curve geometry of space-time
- objects move on the shortest paths through this geometry



- **wave-like solutions**
  - "ripples" in space-time travel at the speed of light
  - These propagating curvature = "gravitational" waves (GW)
  - A. Einstein: amplitude estimates ➛ GW too weak to detect!

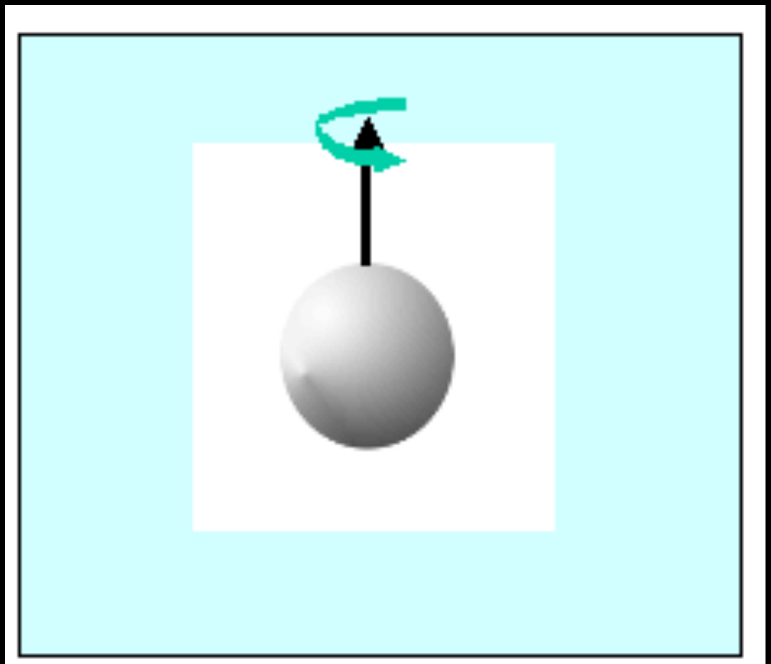




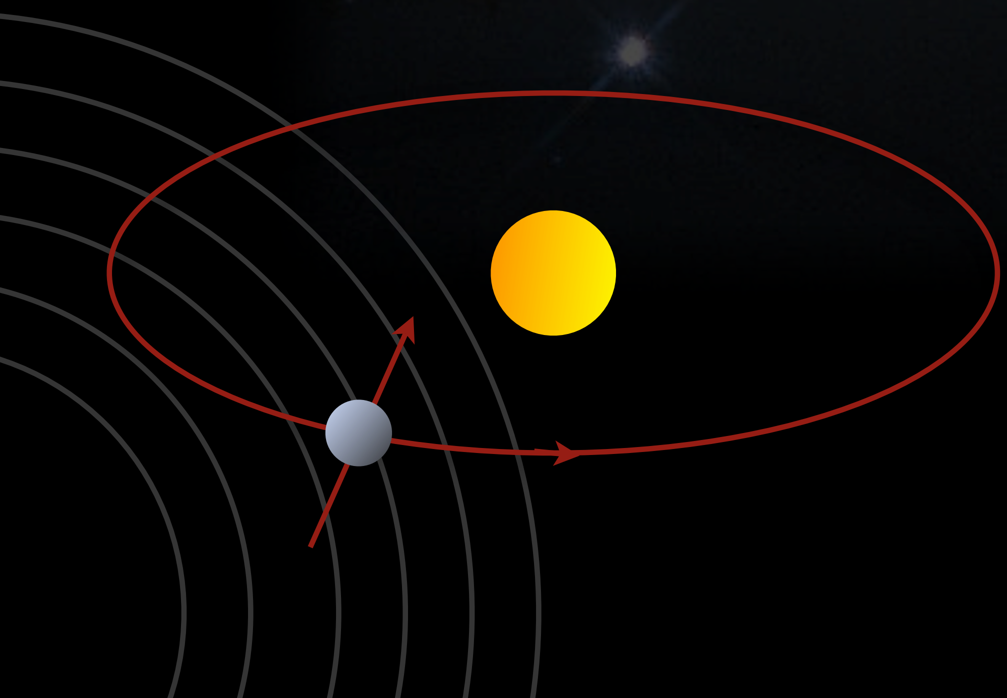


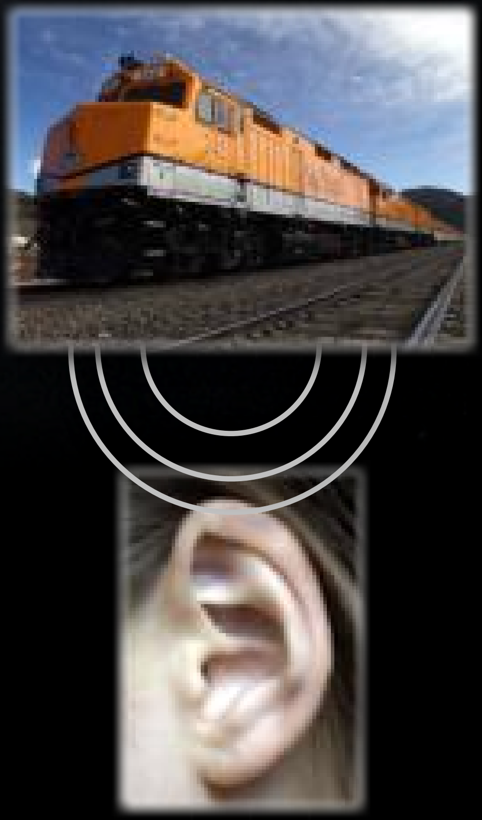
Einstein@Home

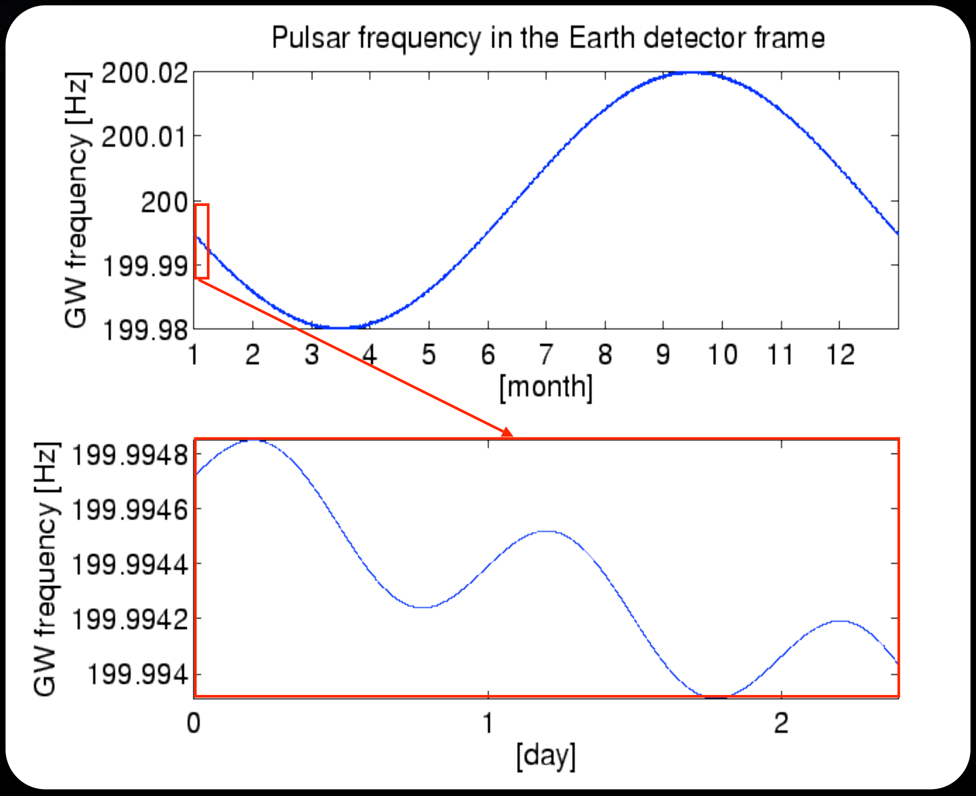
- **Einstein@Home until March 2009:**
  - blind search for GW from rapidly spinning NSs
  - continuous emission at 2x rotation rate
  - weak, but well modeled ➛ matched filtering
  - **computationally difficult:**
    - annual Earth's motion / daily rotation
    - large parameter space (sky position, f, $\dot{f}$)



Mountain on a star







ABP

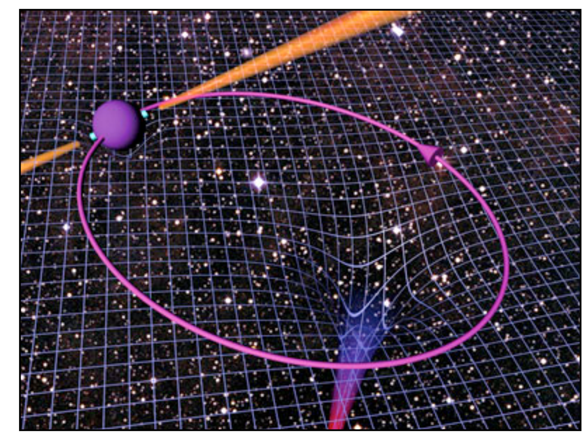
ABP

ASTRONOMICAL NEWSLETTER SOMETIME IN THE NEAR FUTURE...

World record pulsar found

Arecibo & Einstein@Home

discover pulsar in that circles its companion in only 15 minutes



Using new methods developed at the Albert Einstein Institute (AEI) in Hannover, Germany, Einstein@Home will search for radio pulsars that are part of binary star systems with orbital periods as short as 15 minutes. Conventional searches for radio pulsars lose sensitivity if the pulsars are in orbits shorter than about one hour. But the enormous computational capabilities of the Einstein@Home project -- equivalent to a cluster of more than 50,000 computers -- make it possible to search for pulsars in binary systems with significantly shorter periods.

"Discovery of a pulsar orbiting a neutron star or black hole, with a sub-hour orbital period, would provide tremendous opportunities to test general relativity and to estimate how often such binaries merge," said Jim Cordes, professor of astronomy at Cornell and chair of

How they did it

"Combining the sensitivity of the world's largest radio telescope with the distributed computing capabilities of Einstein@Home creates a powerful partnership for discovery," added Dana Lehr, program manager for the Division of Astronomical Sciences at the National Science Foundation (NSF). Cornell's National Astronomy and Ionosphere Center manages Arecibo for the NSF.

All data for PALFA, which began in 2004 and is one of three ongoing sky surveys using the ALFA receiver, are archived and dispensed by the Cornell Center for Advanced Computing.

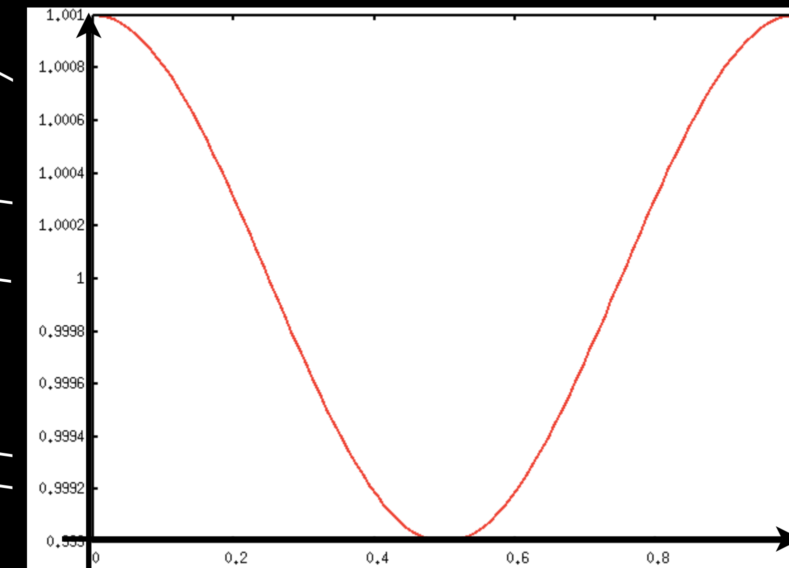
"The Einstein@Home computing resources are a perfect complement to the data management systems at the Cornell Center for Advanced Computing and the other PALFA institutions," Cordes said.

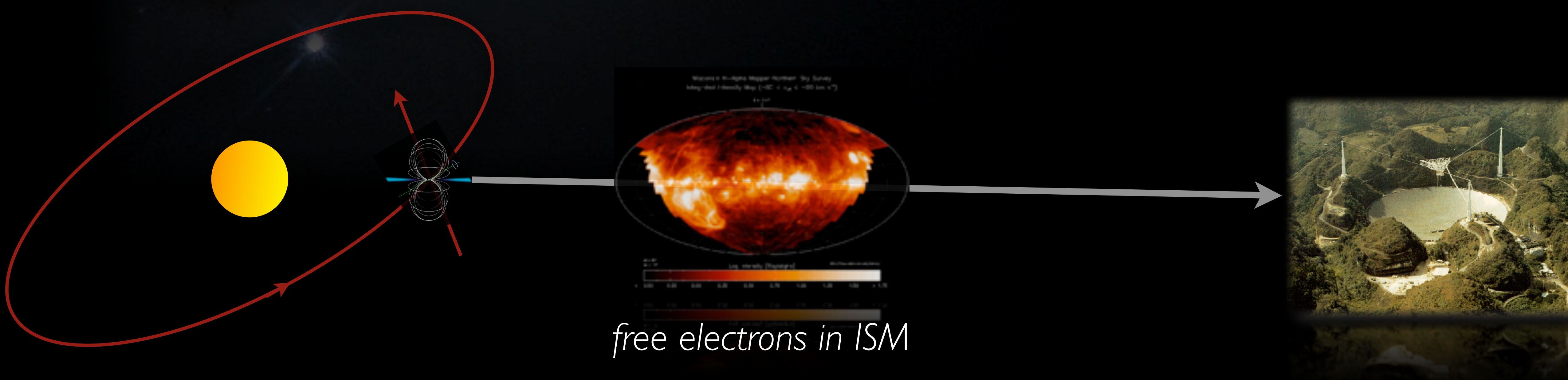
-Lectores Legere

PAGE 1

Pulsar Search Overview

- **March 24, 2009:** *new blind search on Einstein@Home*:
  - looking for pulsed radio signals from binary pulsars
- computationally difficult
  - unknown orbital motion = resulting Doppler effect
  - unknown spin frequency
  - unknown distance to telescope
- must search a large parameter space:
  - DM, f_{spin}, at least 3 orbital parameters





Pulsar Statistics

- **1827 known pulsars in total**
  - 140 known binary pulsars (less than 8%)
  - 45 with orbital Porb<1d
- **64 low-eccentricity (e < 0.027) not in globular clusters (GC)**
  - 1 NS-NS binary
- **19 eccentric binaries not in GC**
  - 9 thereof likely NS-NS binaries
- **shortest orbital period for**
  - NS-NS binary: 147 min (J0737-3039)
  - binaries not in GC: 143 min (J2051-0827)
  - binaries in GC: 96 min
  - (X-ray binaries: 11 min (X1820-303))

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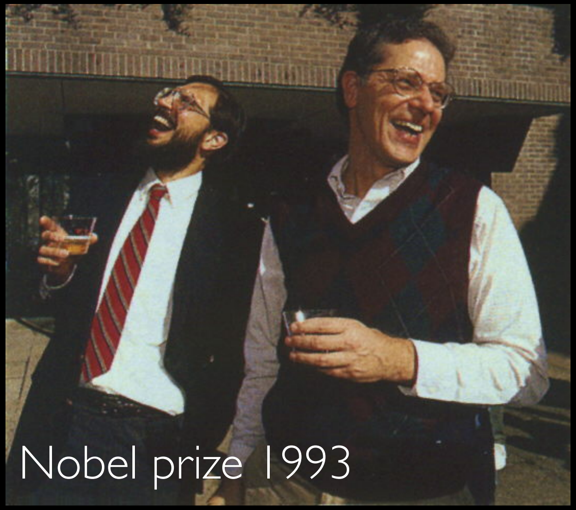
selection effects!

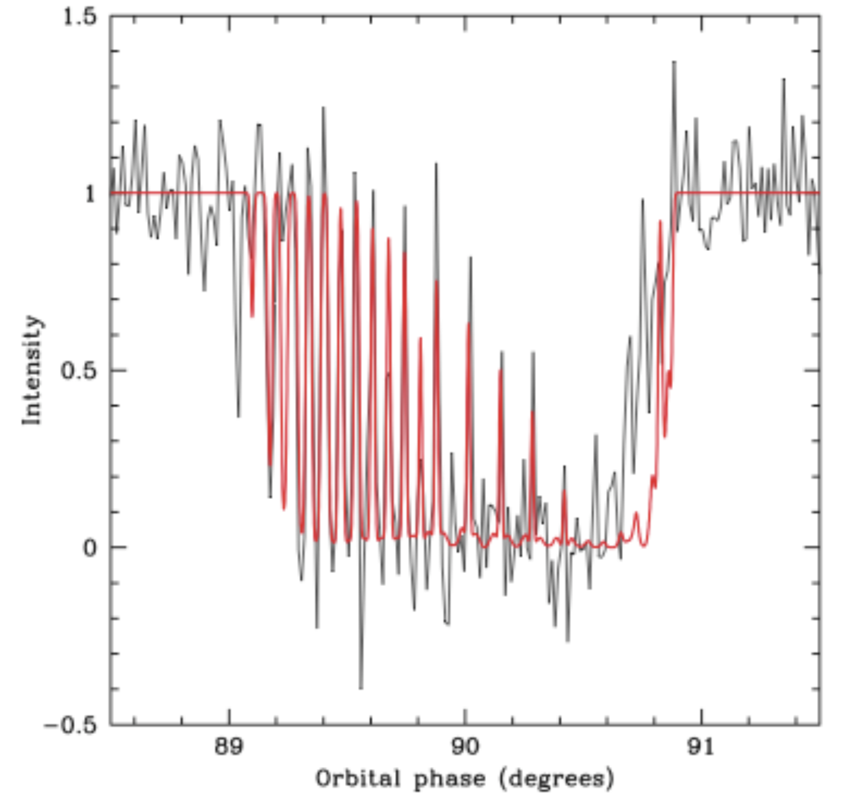
We are hunting for the pulsars with orbital periods from 11 min up.

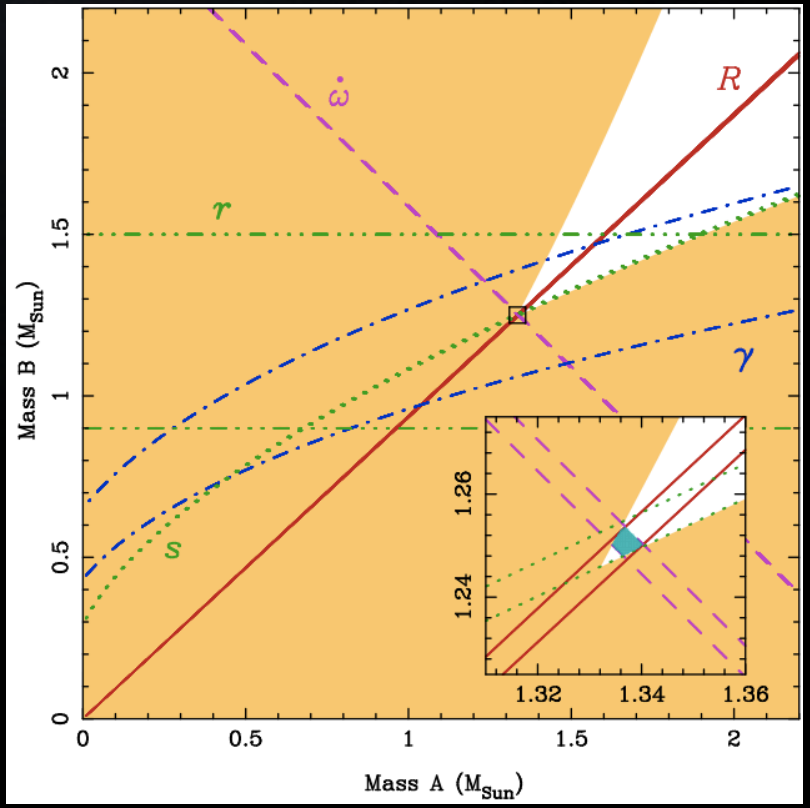
It‘s very likely no search before has seen those!

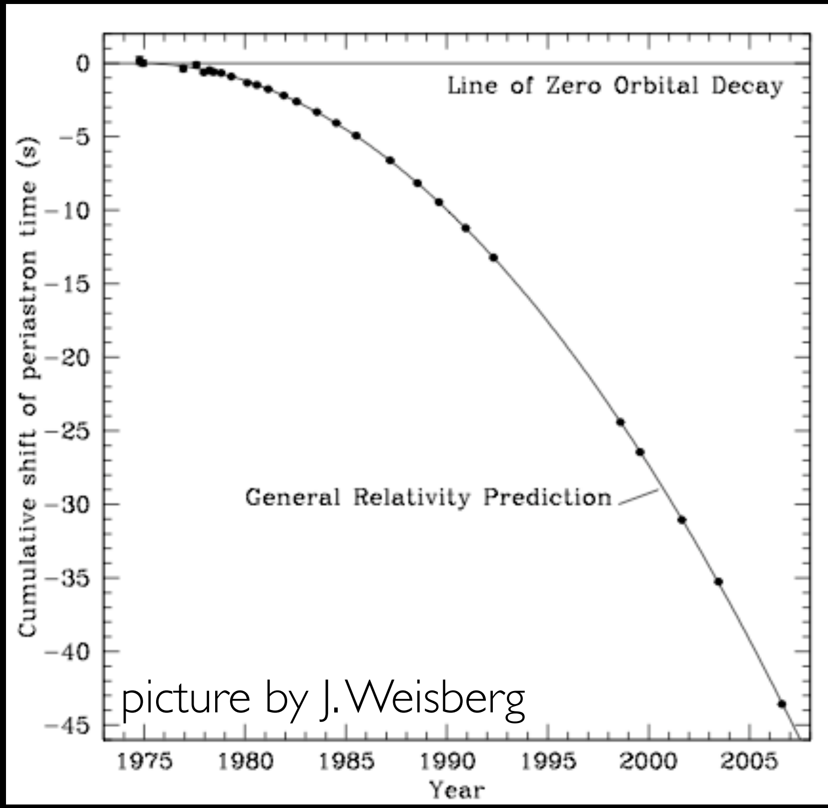
Why binary pulsars?

- Hulse-Taylor binary ➛ **indirect GW detection**
- various GR tests
- measure PK parameters extremely well
- exact mass measurements ➛ probing equation of state
- mapping magnetospheres in eclipsing binaries (J0737–3039)
- NS-NS inspiral rates ➛ **direct GW detection**



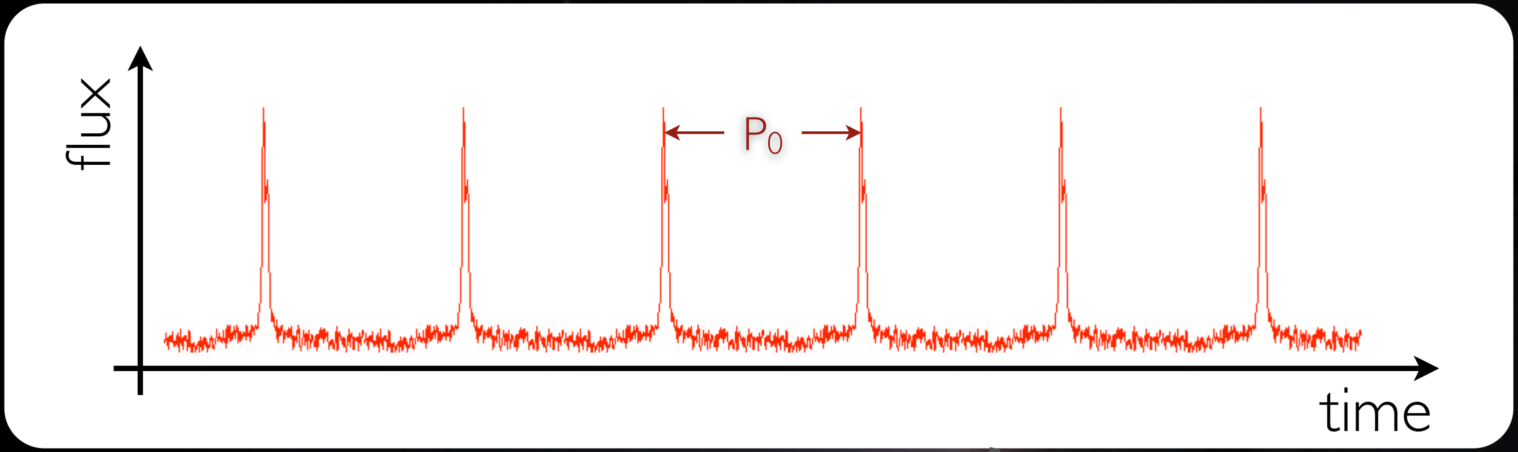




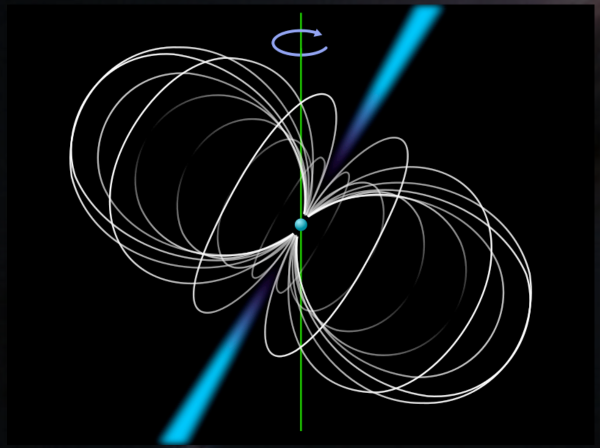


Finding Isolated Pulsars

idealized signal in time domain



- const. time in between pulses
- clean frequency spectrum

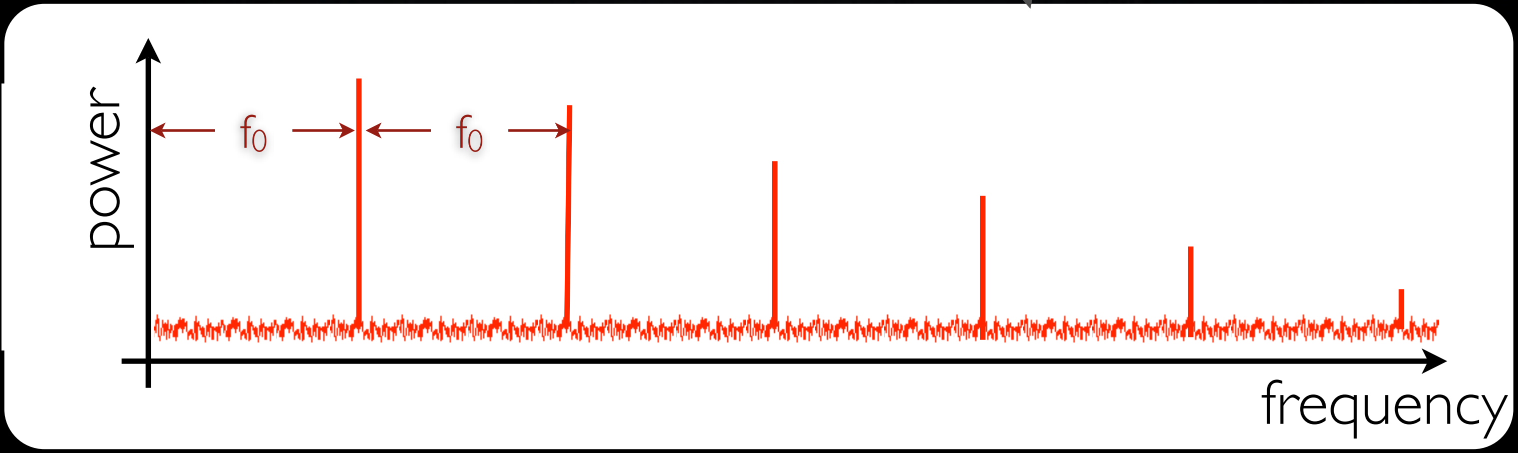


decomposition into harmonics:

$$S(t) = \Sigma_{n=1}^{N_\mathrm{h}} w_n \sin(n\phi(t))$$

$$\phi(t) = 2\pi f_0 t + \phi_0$$

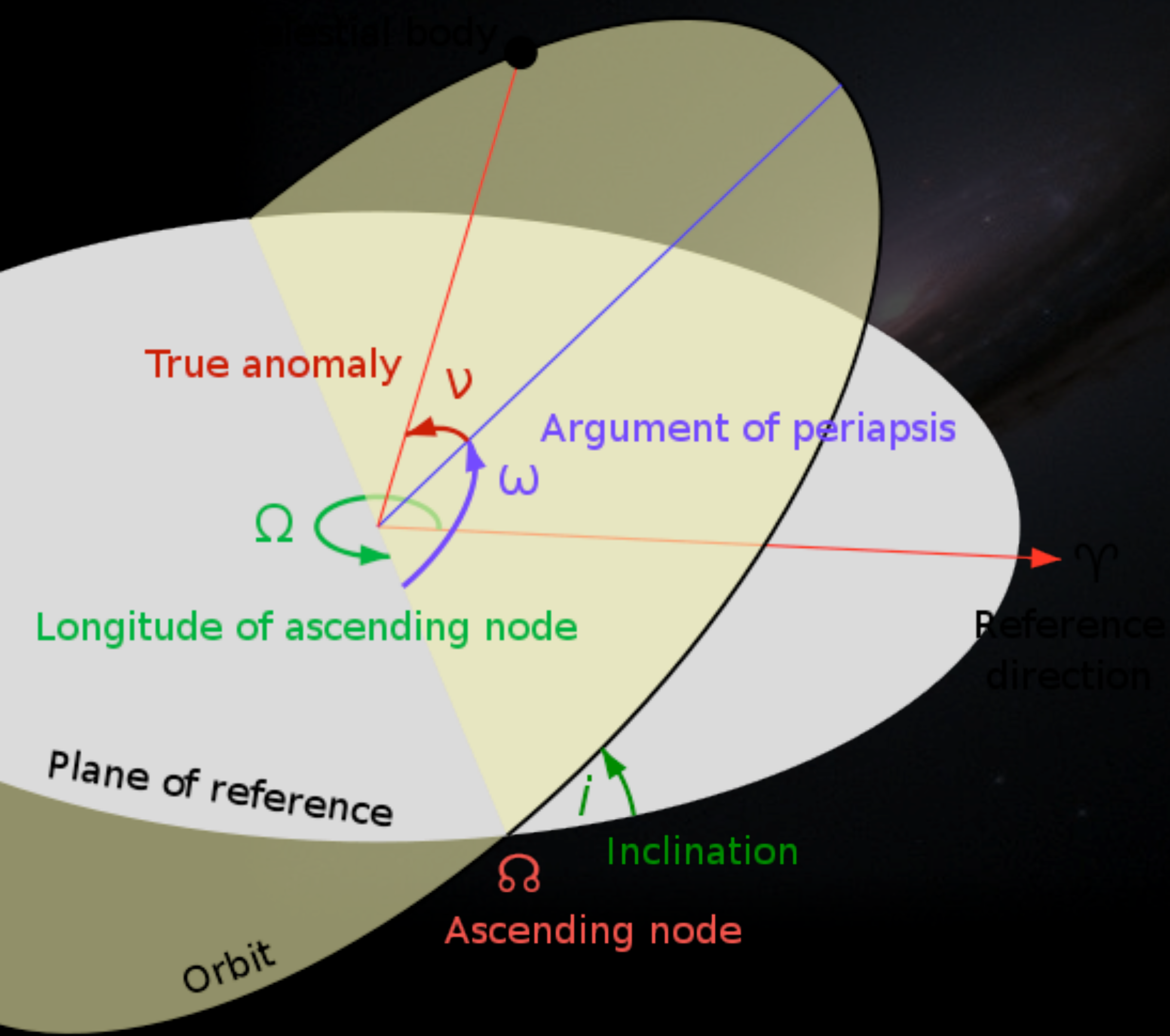
comb of harmonics in Fourier domain



- FFT of timeseries
- sum up harmonics incoherently
- do statistical tests
- find pulsars!

MAX-PLANCK-GESELLSCHAFT

Full Orbital Model

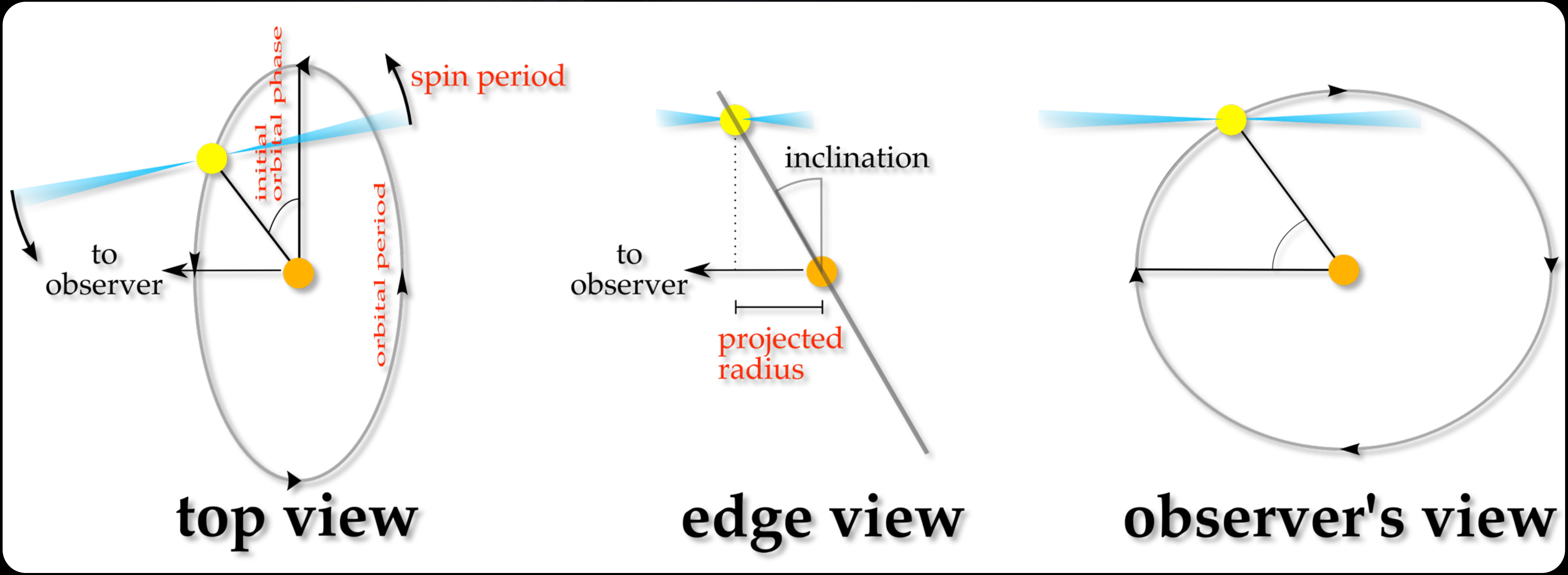


- **Full Keplerian orbit: 5 parameters**
  - time of periastron passage T_0
  - orbital period P_{orb}
  - projected semi-major axis a sin(i)
  - eccentricity e
  - longitude of the periastron ω

Simple Orbital Model

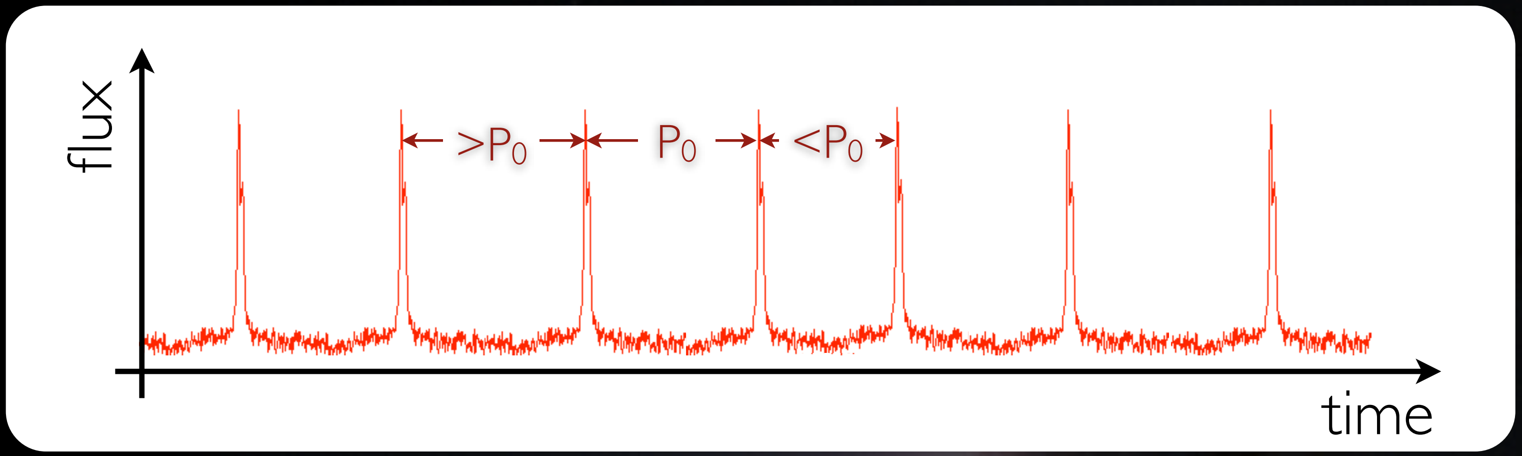
- circular orbits: 3 parameters
  - initial orbital phase ψ_0
  - orbital period P_{orb}
  - projected orbital radius $\tau = a \sin(i)$

- parameter space in this search:
  - $M_{NS} \geqslant 1.2\, M_\odot$, $M_{comp} \leqslant 1.6\, M_\odot$
  - $P_{orb} \geqslant 11$ min
  - $f_{spin} \leqslant 400$ Hz, $N_{harmonics} \leqslant 16$

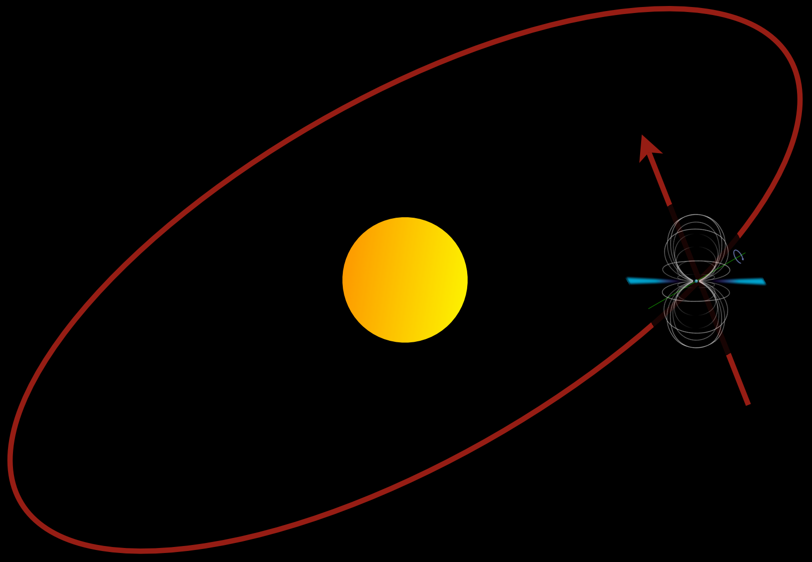


Finding Binary Pulsars

idealized signal in time domain, Doppler-modulated



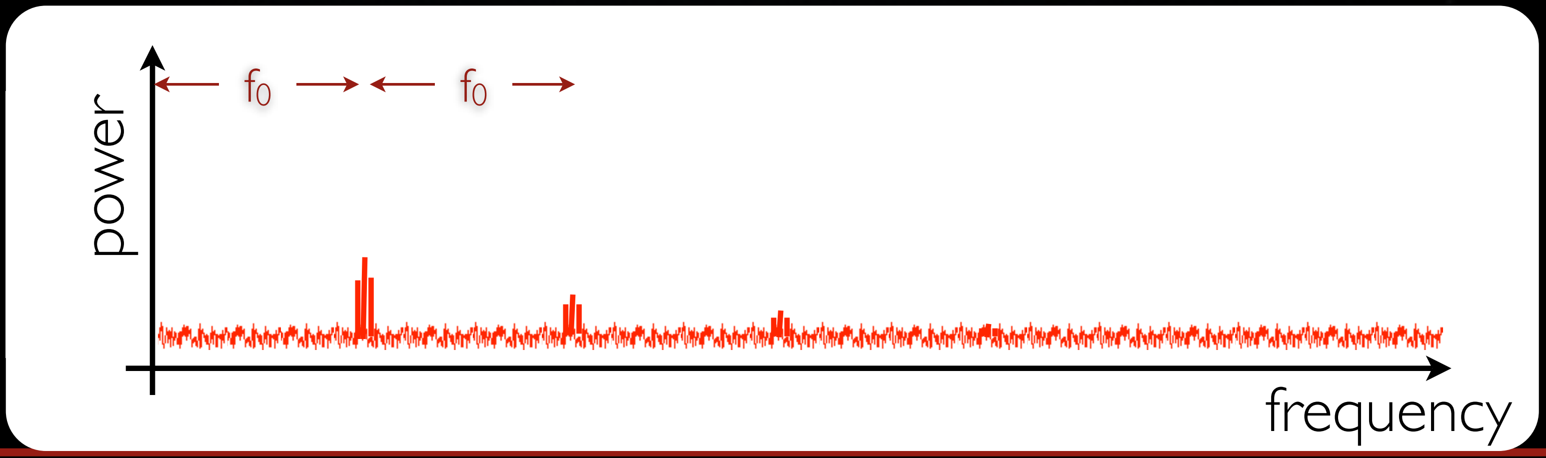
- time between pulses varies due to orbital modulation



$$S(t) = \Sigma_{n=1}^{N_h} w_n \sin(n\phi(t))$$

$$\phi(t) = 2\pi f_0 \left(t + \frac{\tau}{c}\sin(\Omega_{orb} t + \psi_0)\right) + \phi_0$$

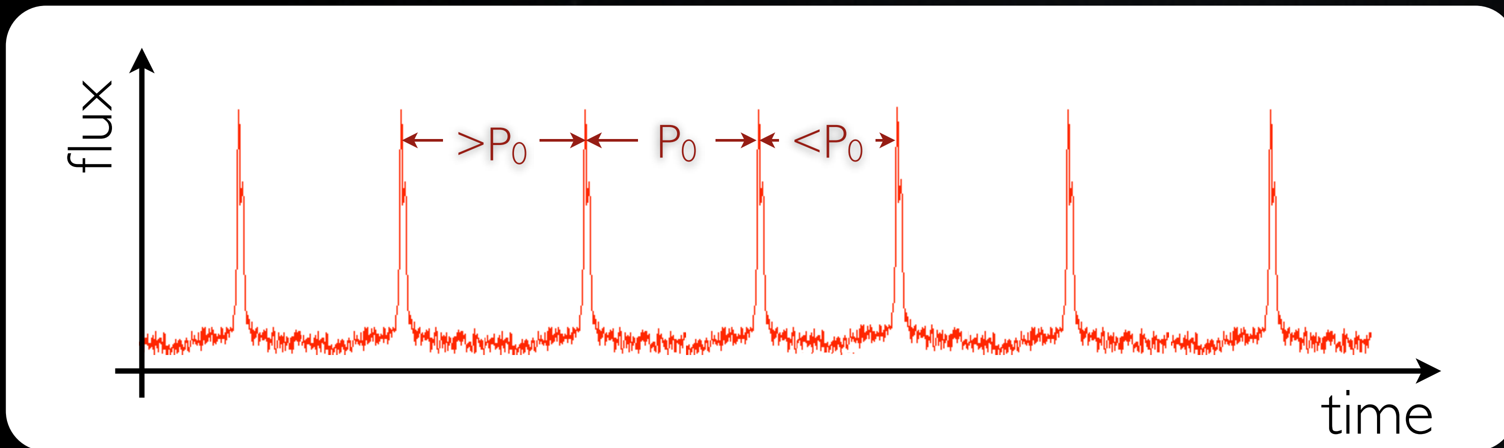
comb of harmonics in Fourier domain



- signal spreads over many neighboring frequency bins
- need to correct for modulation!

Finding Binary Pulsars

idealized signal in time domain, Doppler-modulated



- time between pulses varies due to orbital modulation

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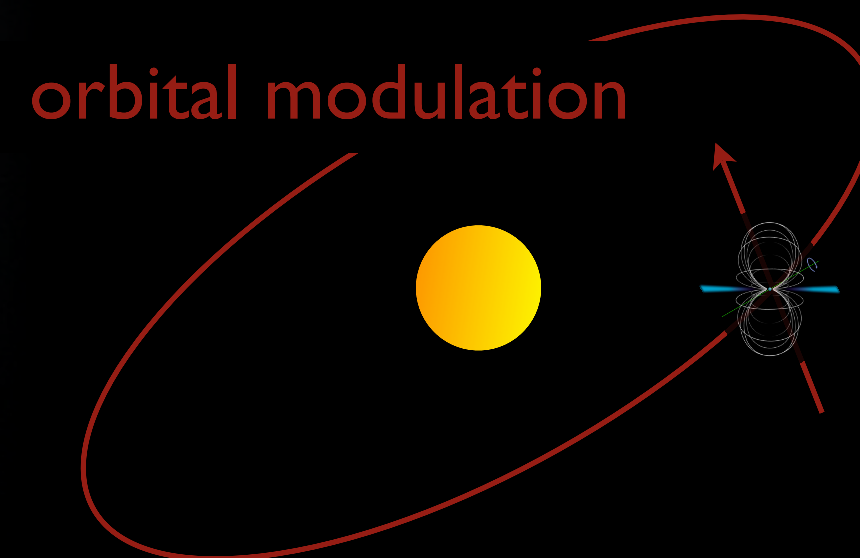

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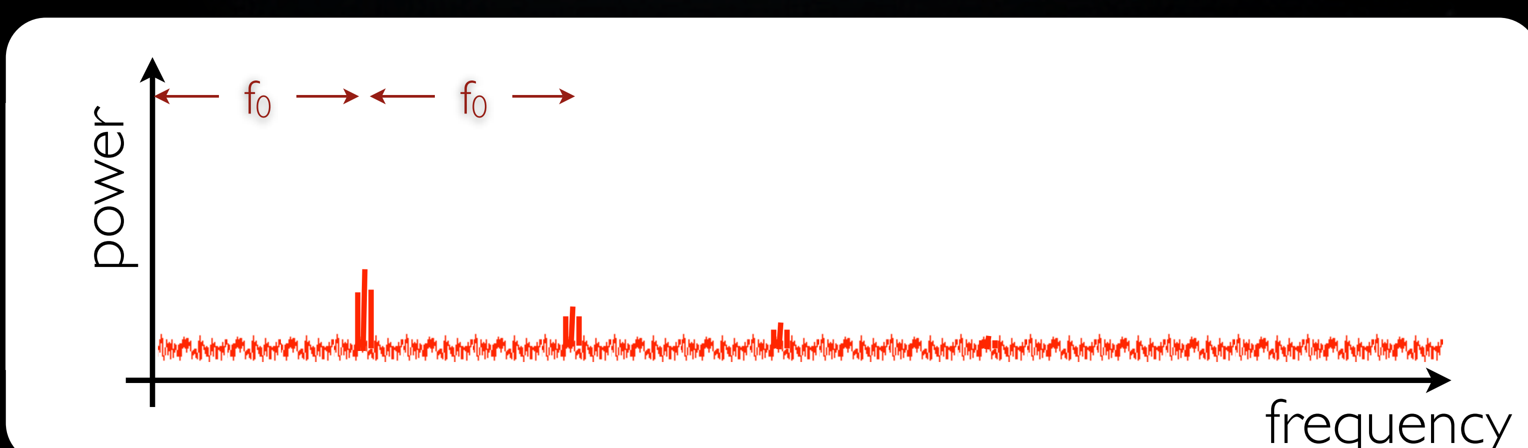

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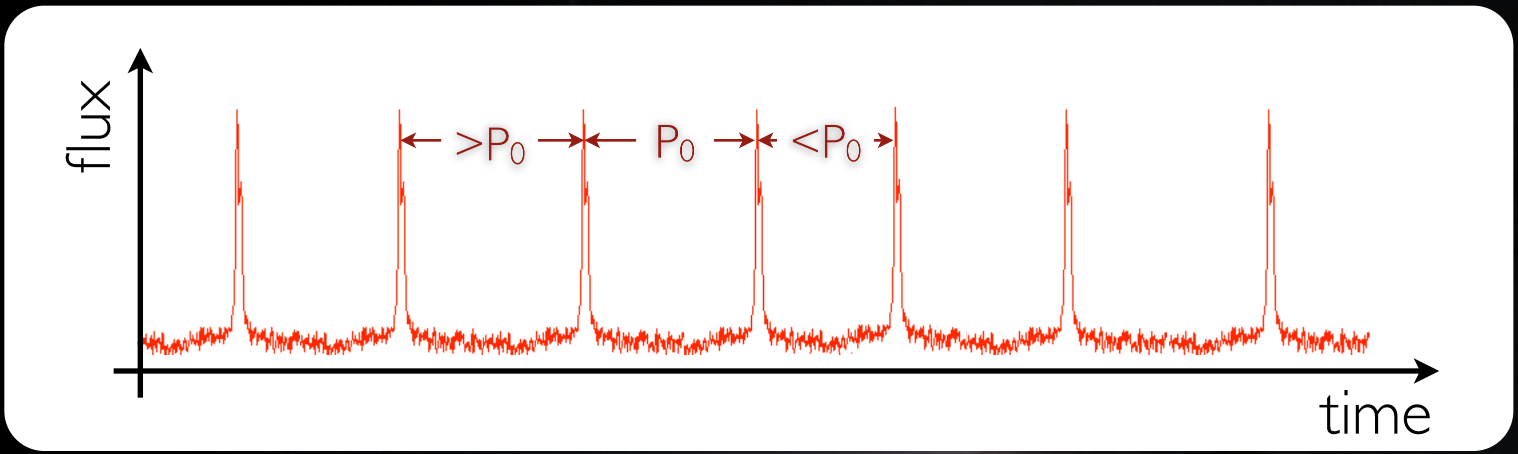

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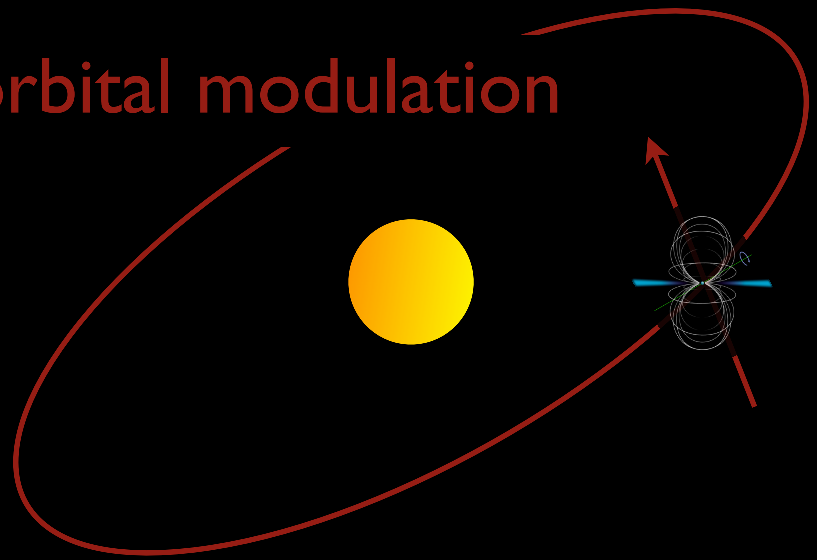
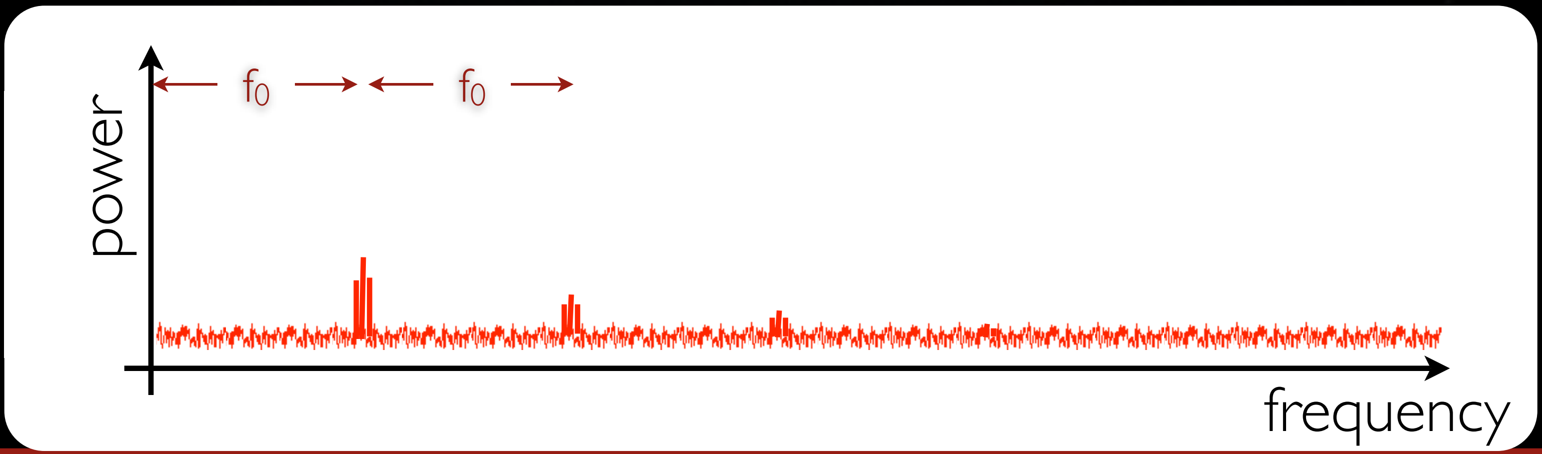
$$t'(t, \mathbf{\Lambda}) = t + \frac{\tau}{c}\sin(\Omega_{orb} t + \psi_0)$$

$$\phi(t', \mathbf{\Lambda}) = 2\pi f_0 t'(t, \mathbf{\Lambda}) + \phi_0$$

orbital modulation



comb of harmonics in Fourier domain



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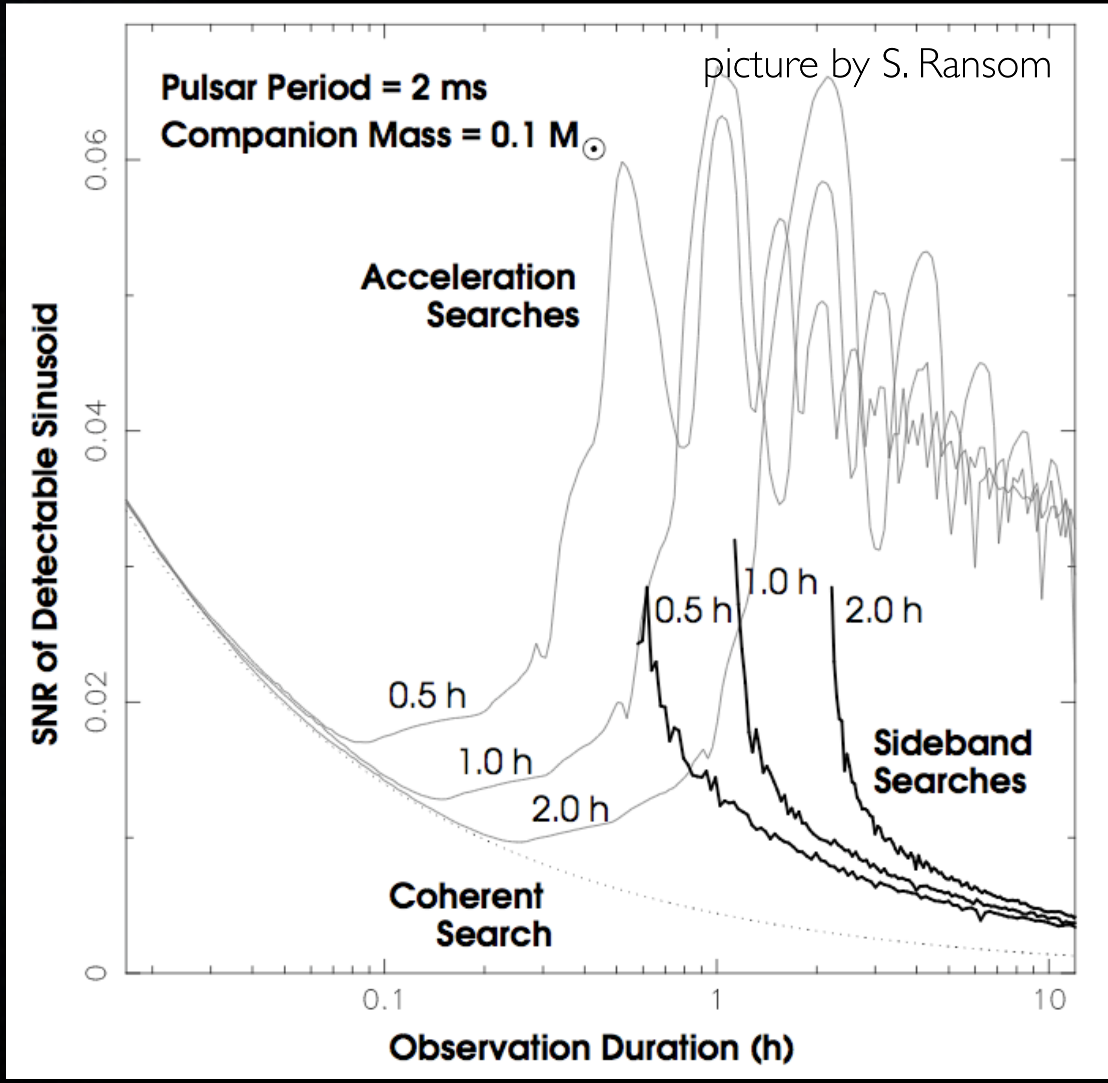
- need to correct for modulation!

Searches for binary pulsars

- **Case 1: $P_{orb} \gg T_{obs}$**
  - fraction of orbit = constant acceleration
  - acceleration searches: standard search
- **Case 2: $T_{obs} \gtrsim P_{orb}$**
  - sideband searches
  - f_{spin} (Hz) modulated by $f_{orbital}$ (0.1mHz)
  - sidebands show up in $|FFT|^2$
  - used for special pulsars
- loss in sensitivity for $T_{obs} \approx P_{orb}$



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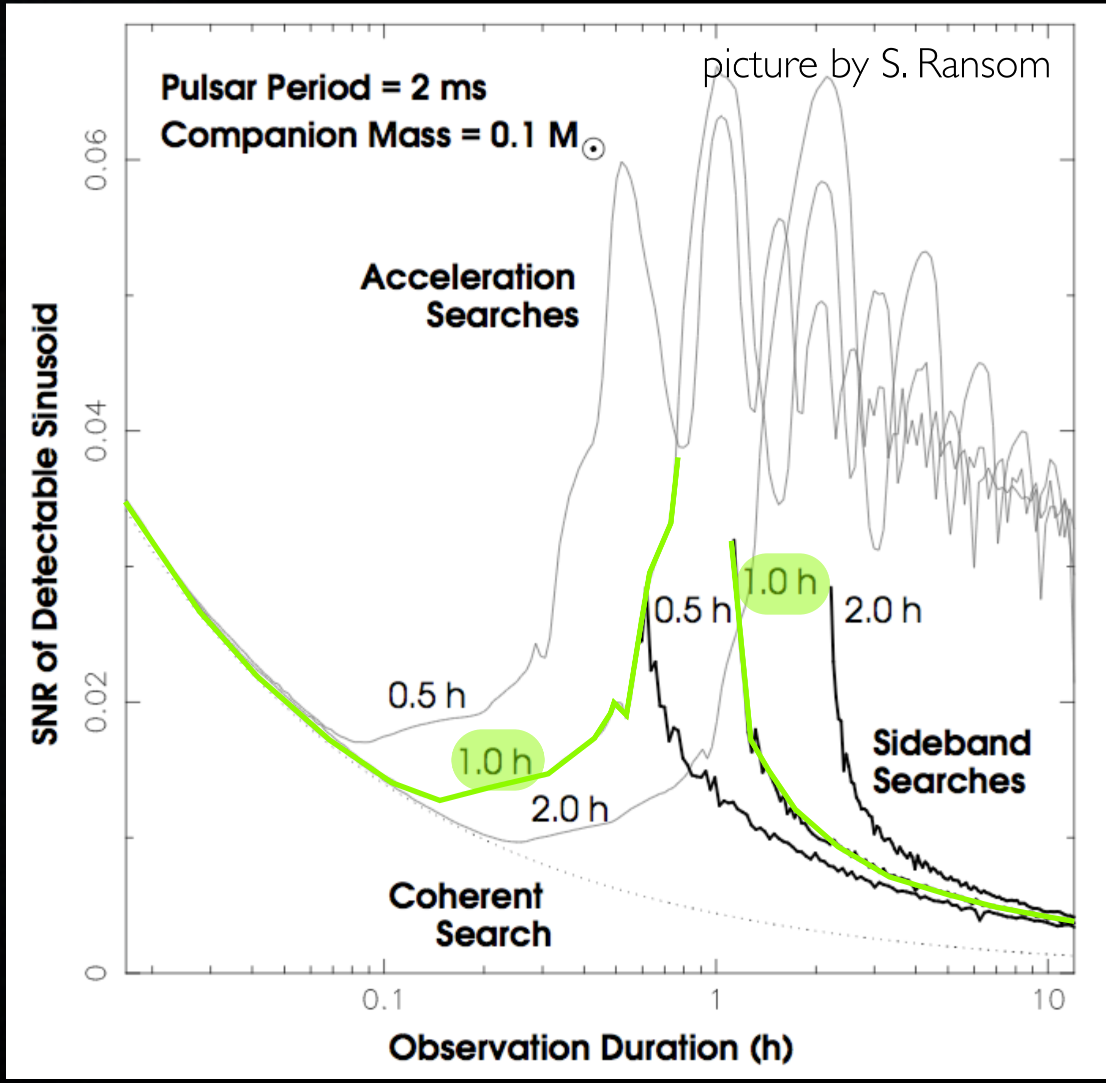

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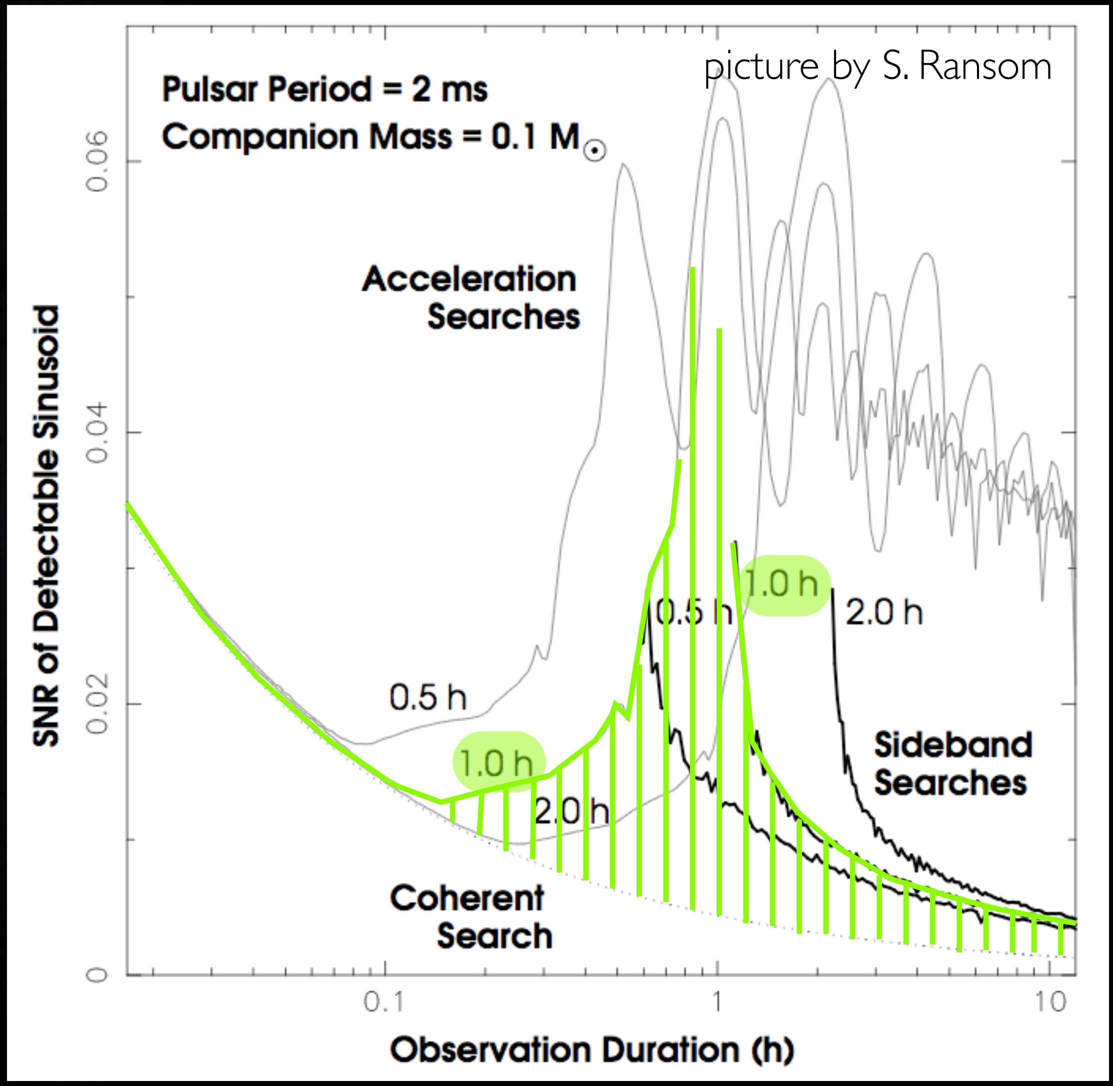

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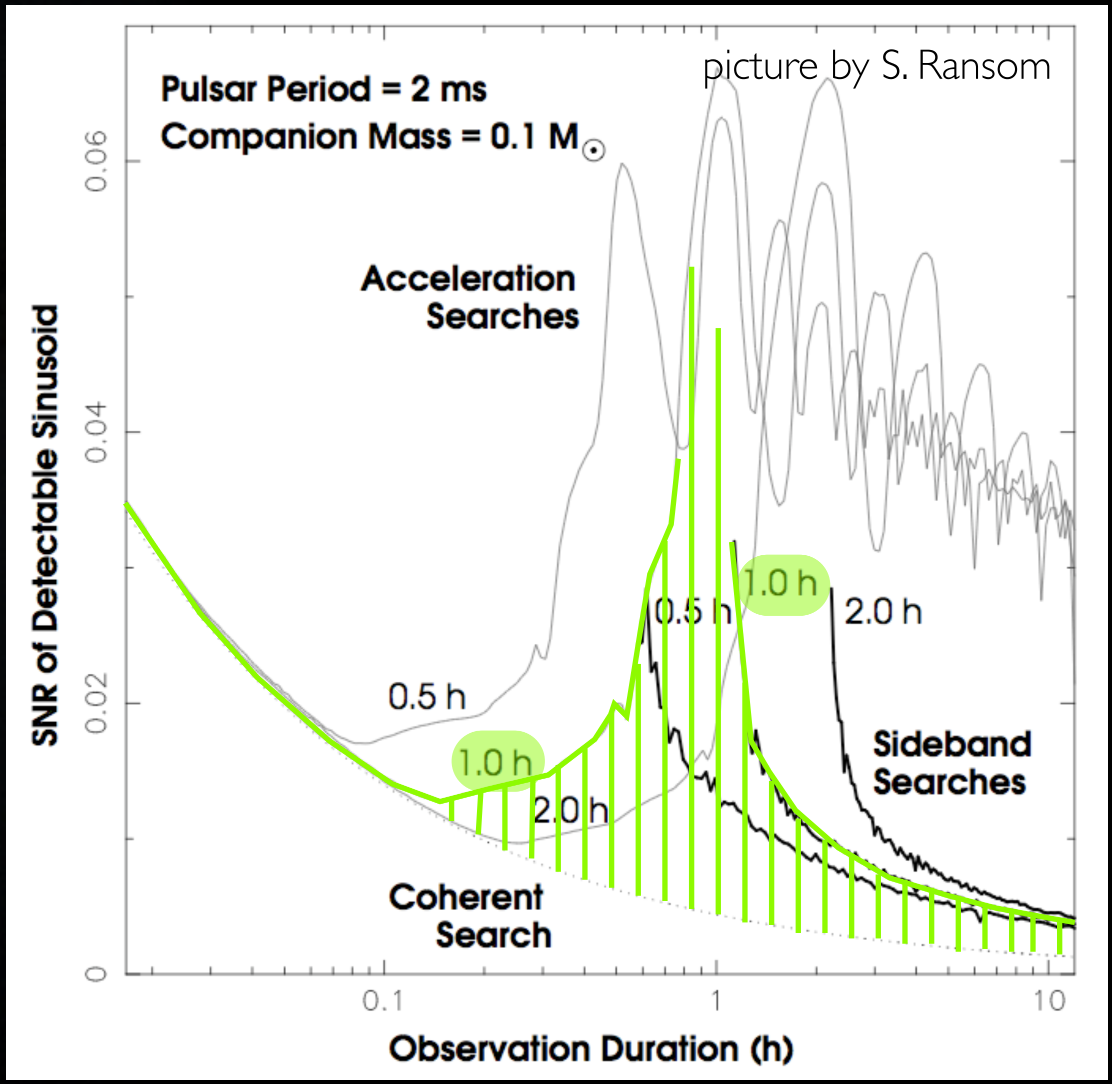

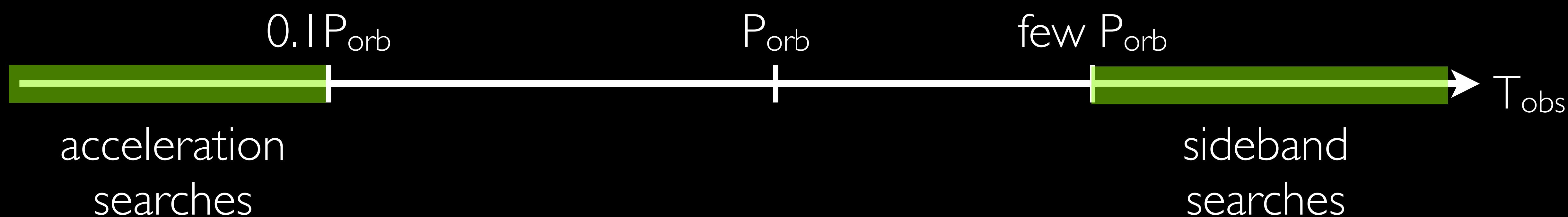

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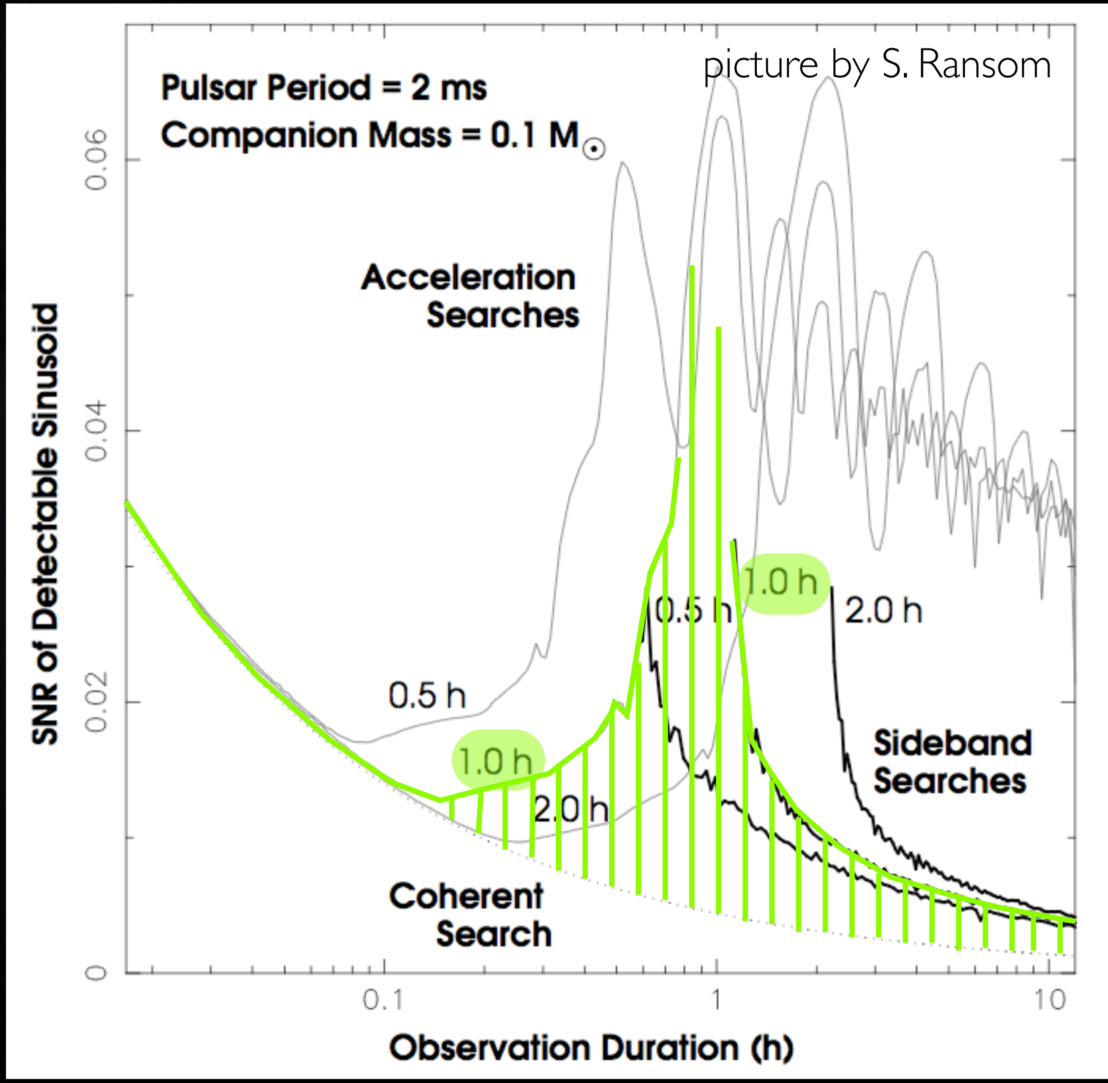
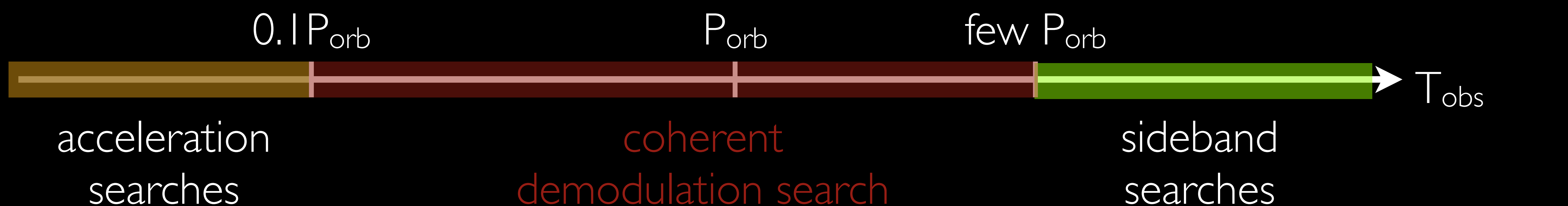
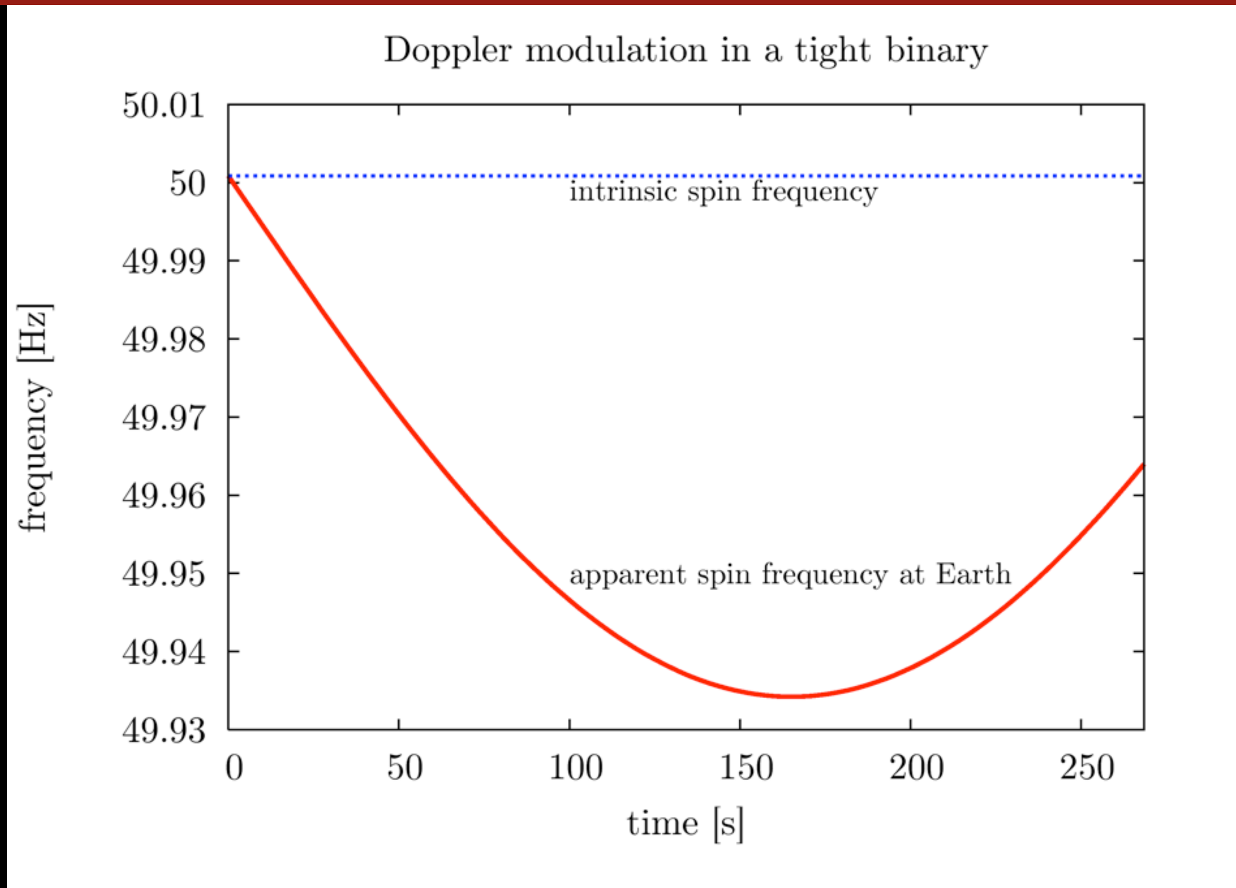


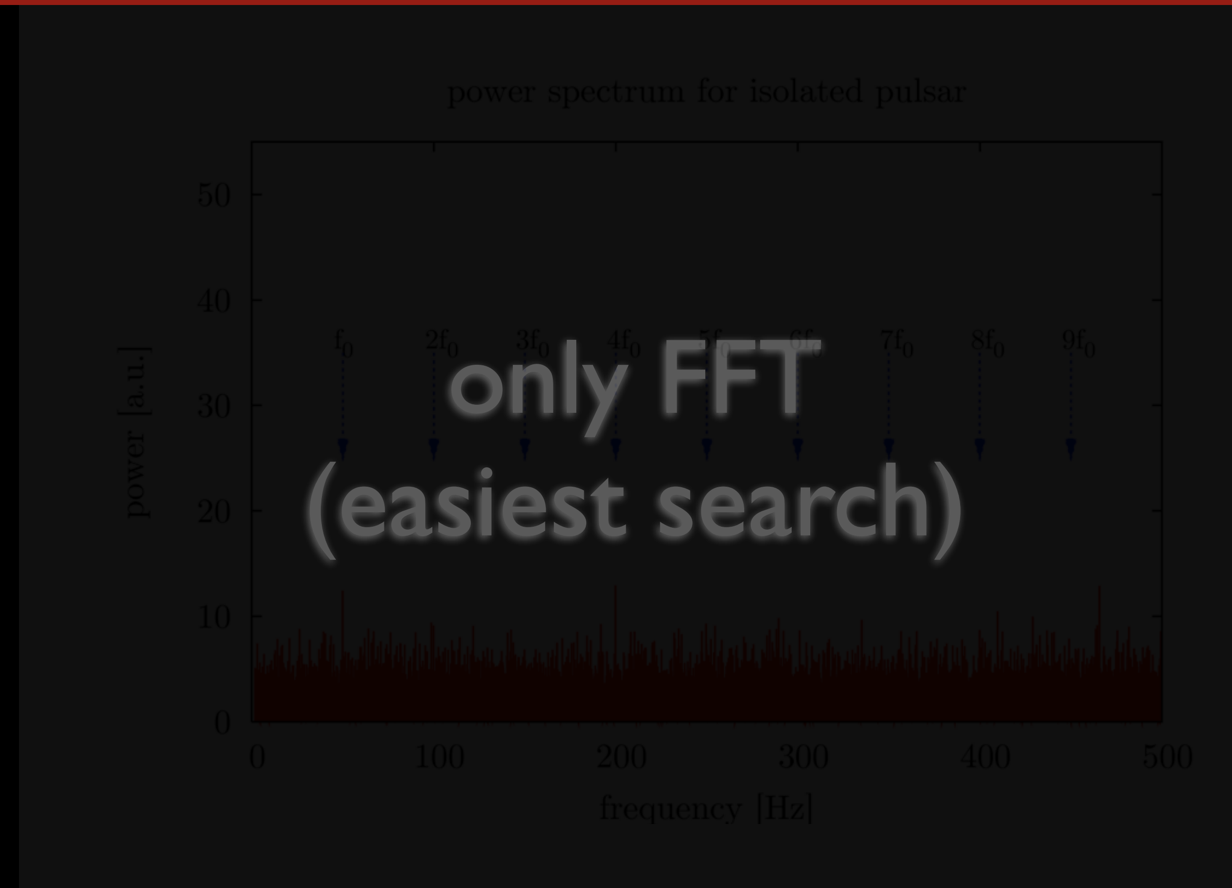
- **loss in sensitivity for $T_{obs} \approx P_{orb}$**

- close the gap (and get acceleration search regime) by brute-force demodulation

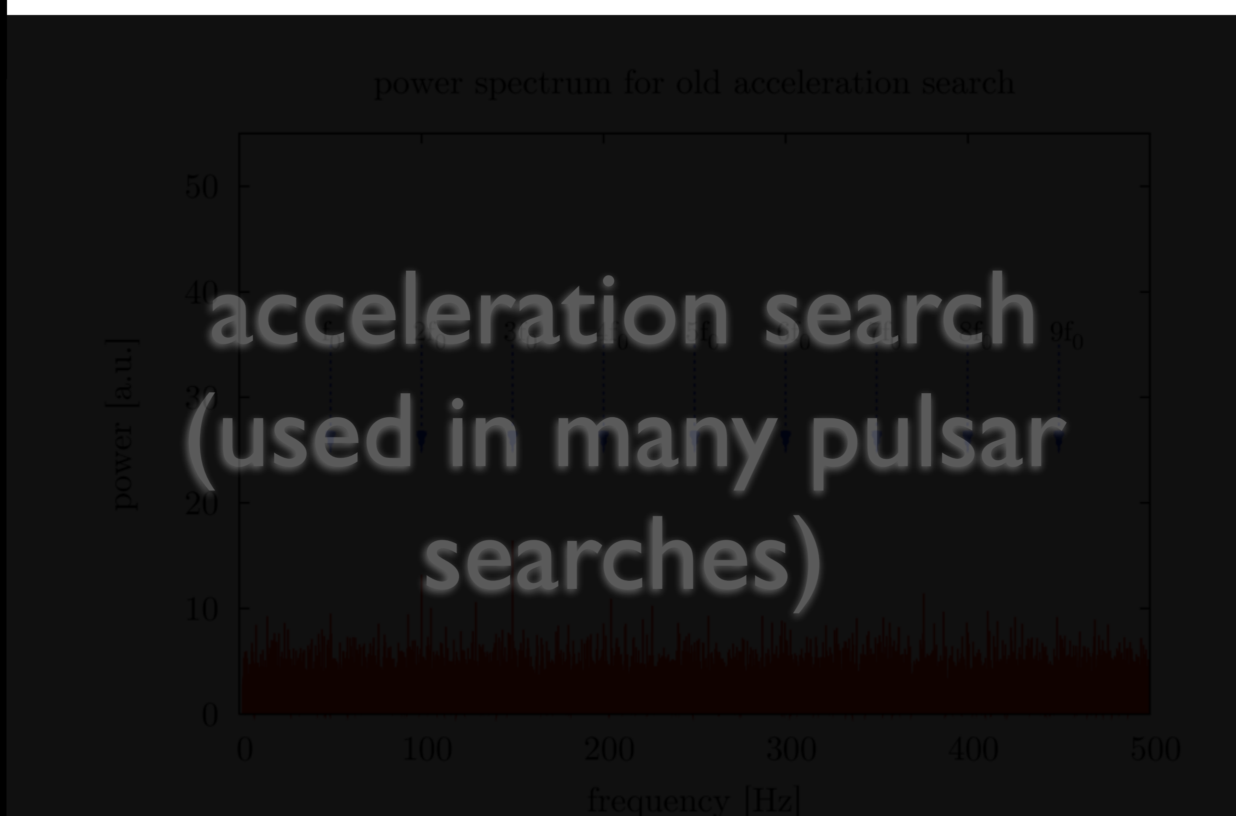


Example

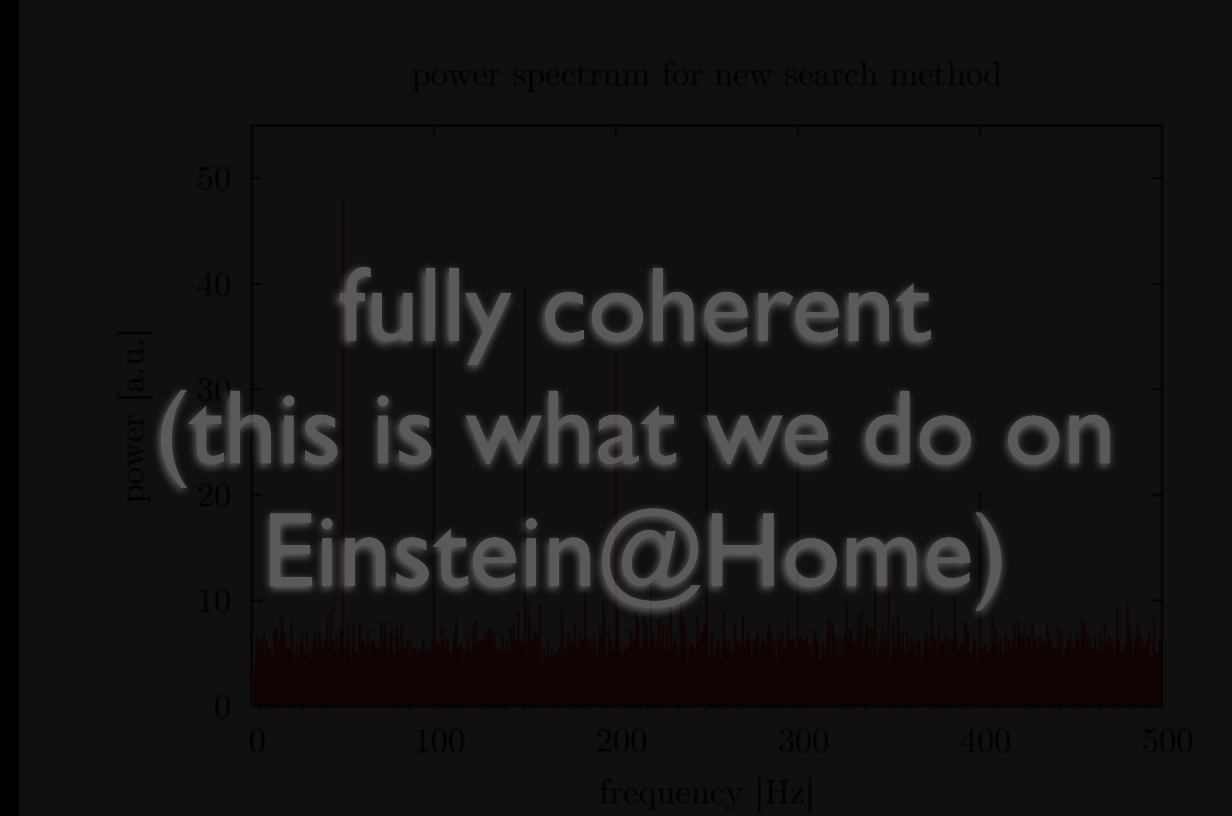




only FFT
(easiest search)

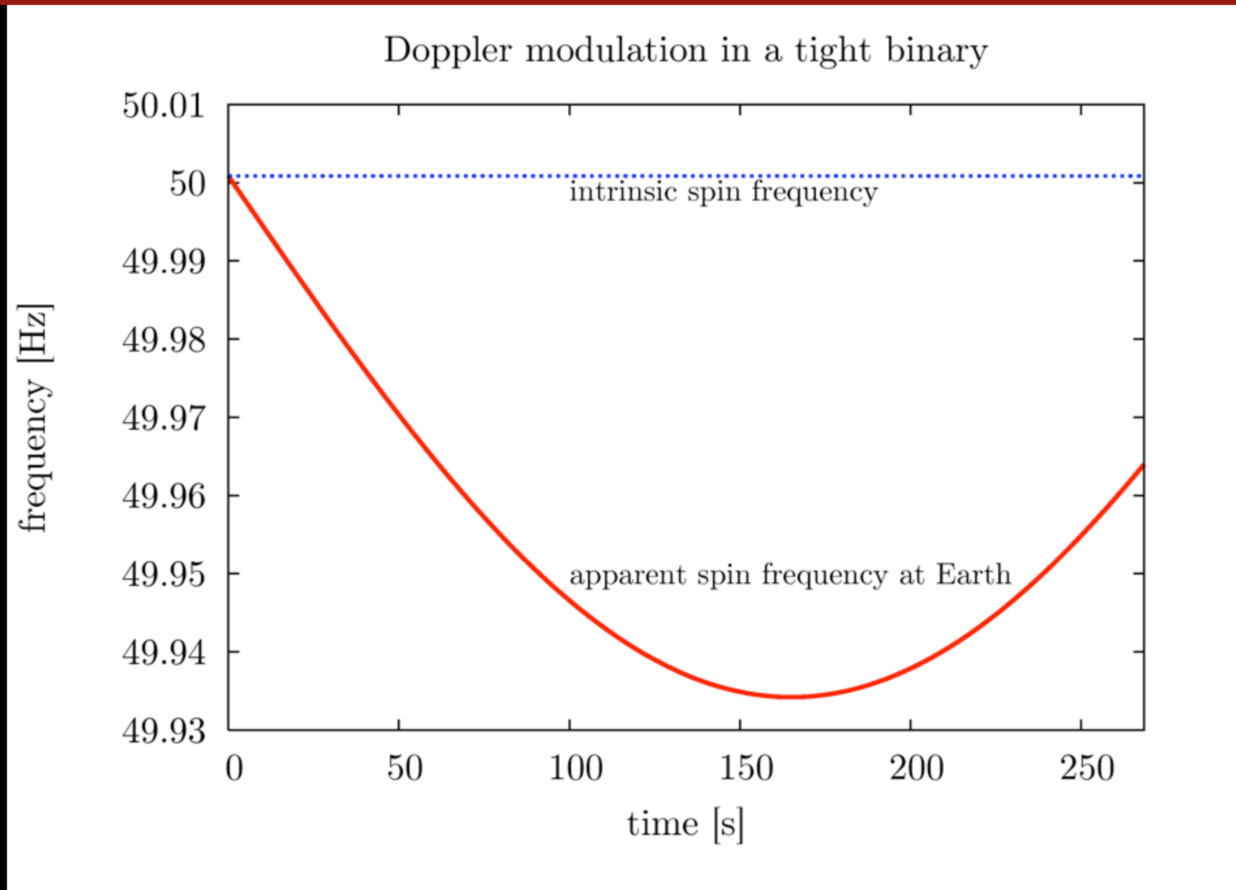


acceleration search
(used in many pulsar searches)

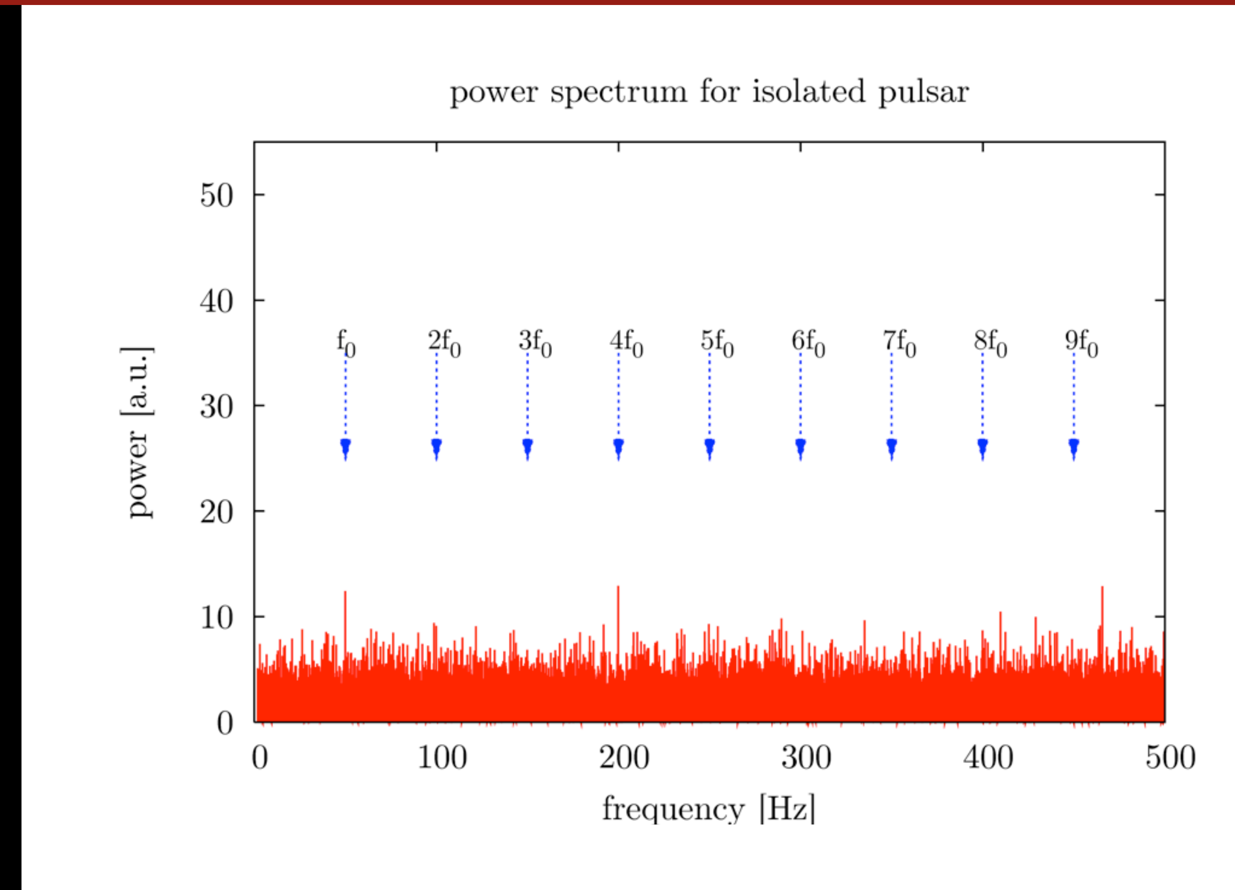


fully coherent
(this is what we do on Einstein@Home)

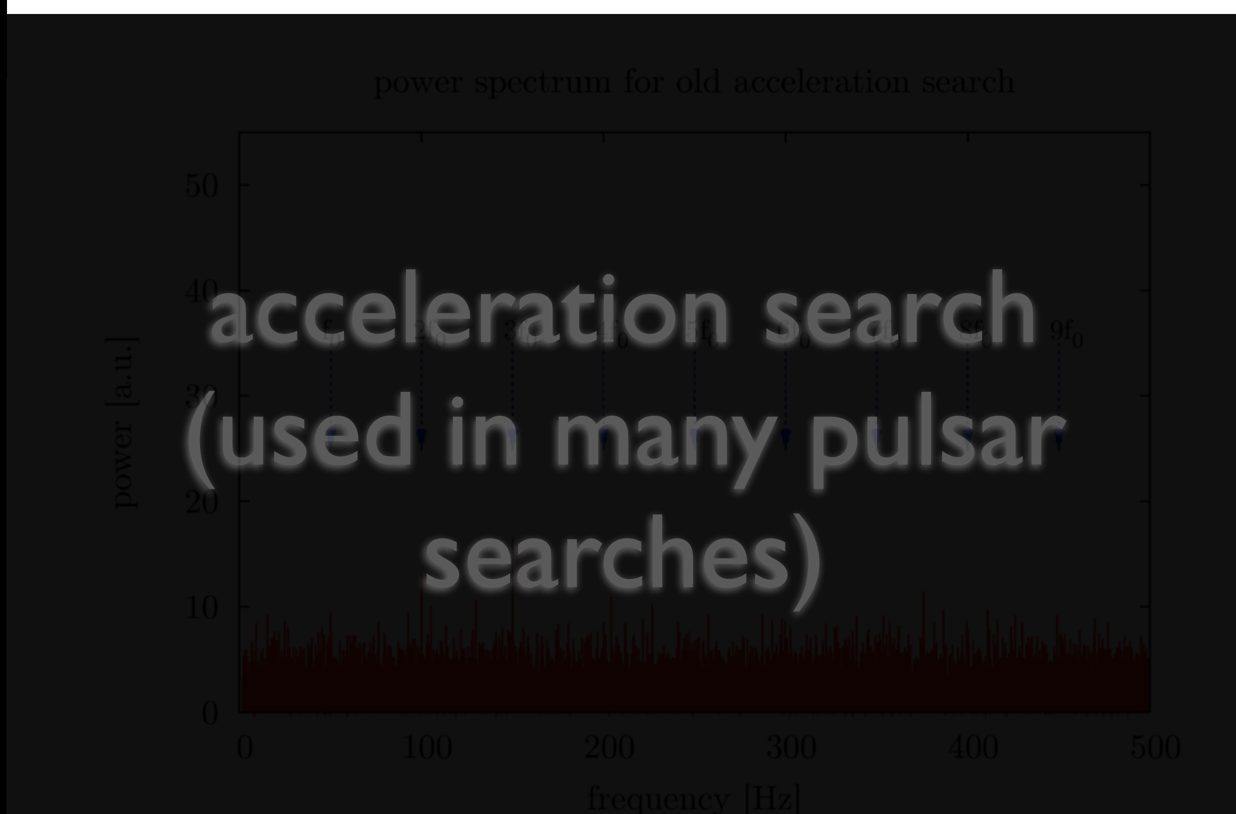
Example



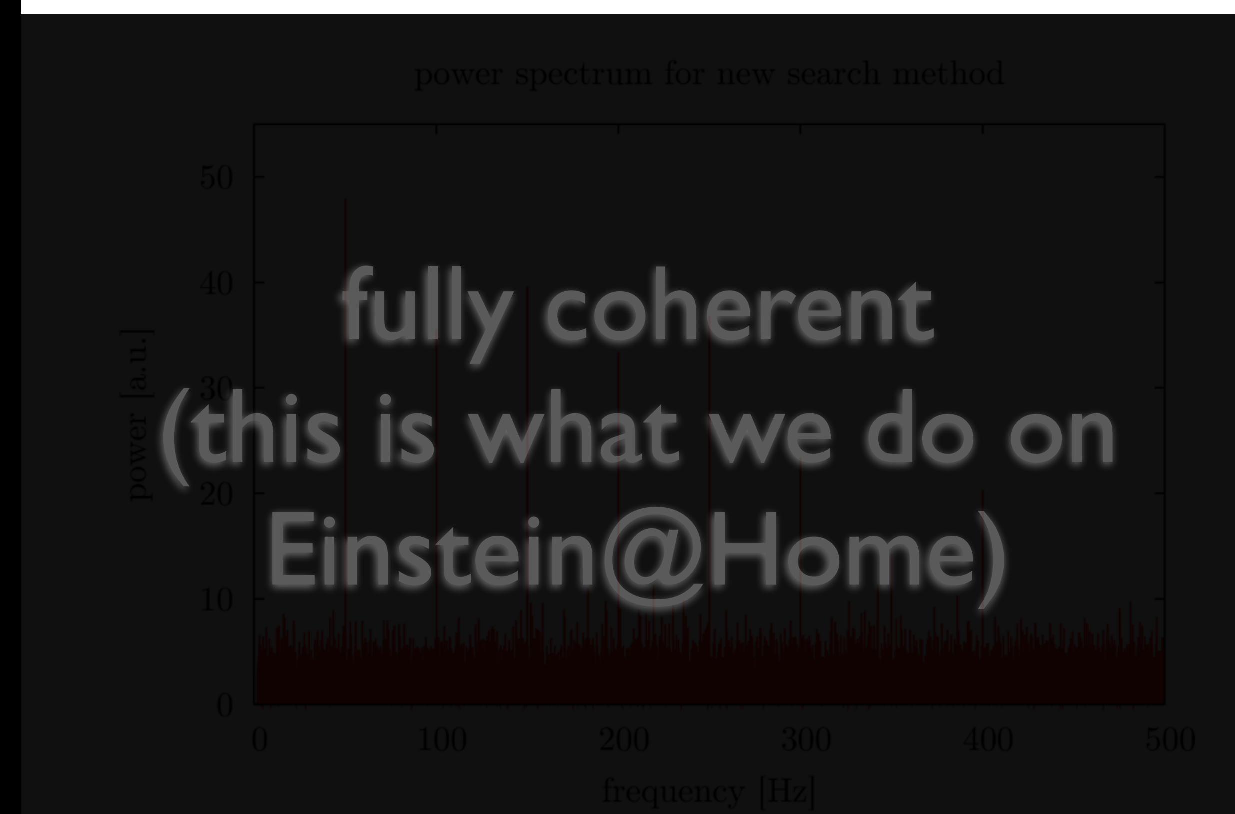
Doppler modulation in a tight binary
intrinsic spin frequency
apparent spin frequency at Earth
frequency [Hz]
time [s]
50.01
50
49.99
49.98
49.97
49.96
49.95
49.94
49.93
0
50
100
150
200
250



power spectrum for isolated pulsar
f_0
$2f_0$
$3f_0$
$4f_0$
$5f_0$
$6f_0$
$7f_0$
$8f_0$
$9f_0$
power [a.u.]
frequency [Hz]
0
10
20
30
40
50
0
100
200
300
400
500

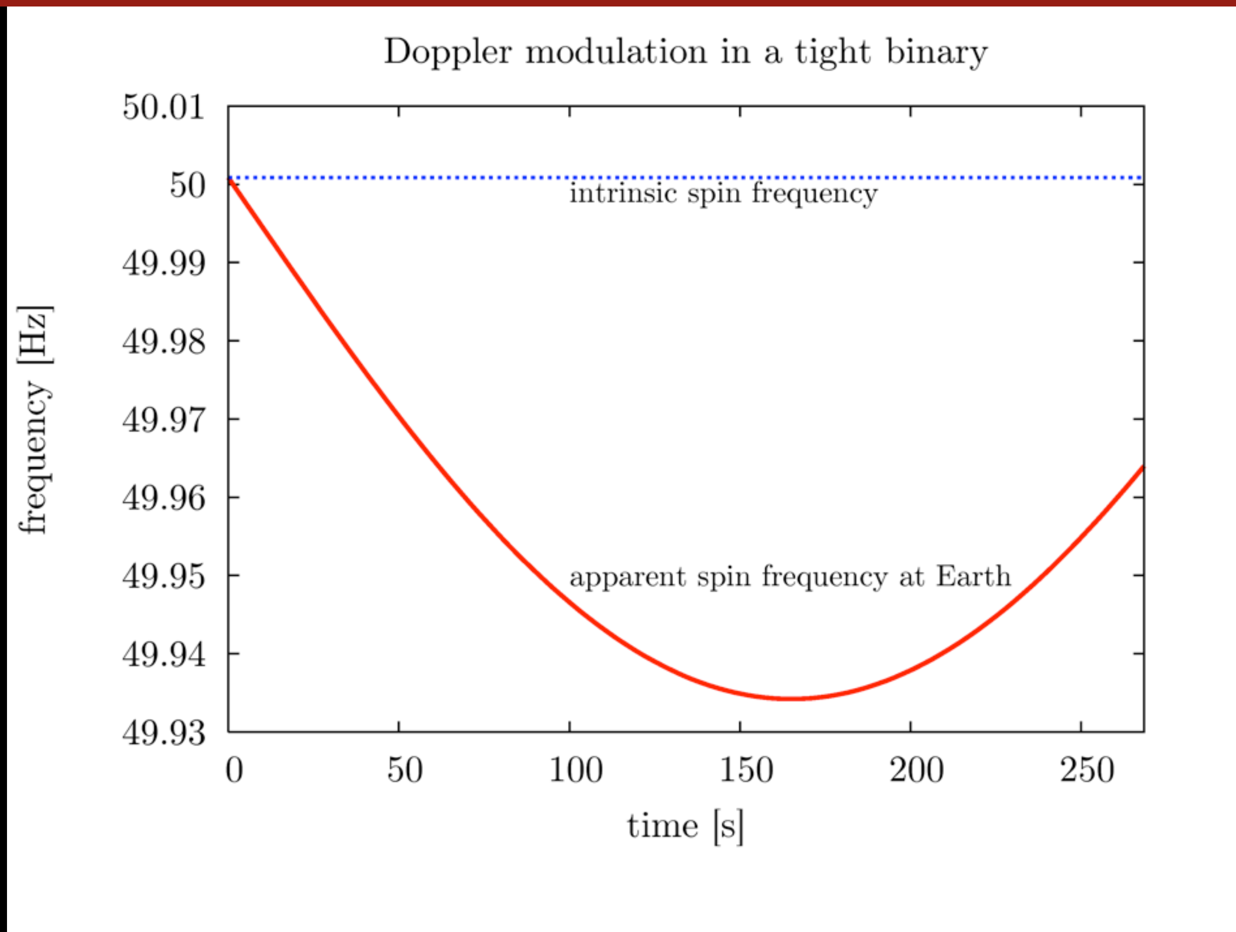


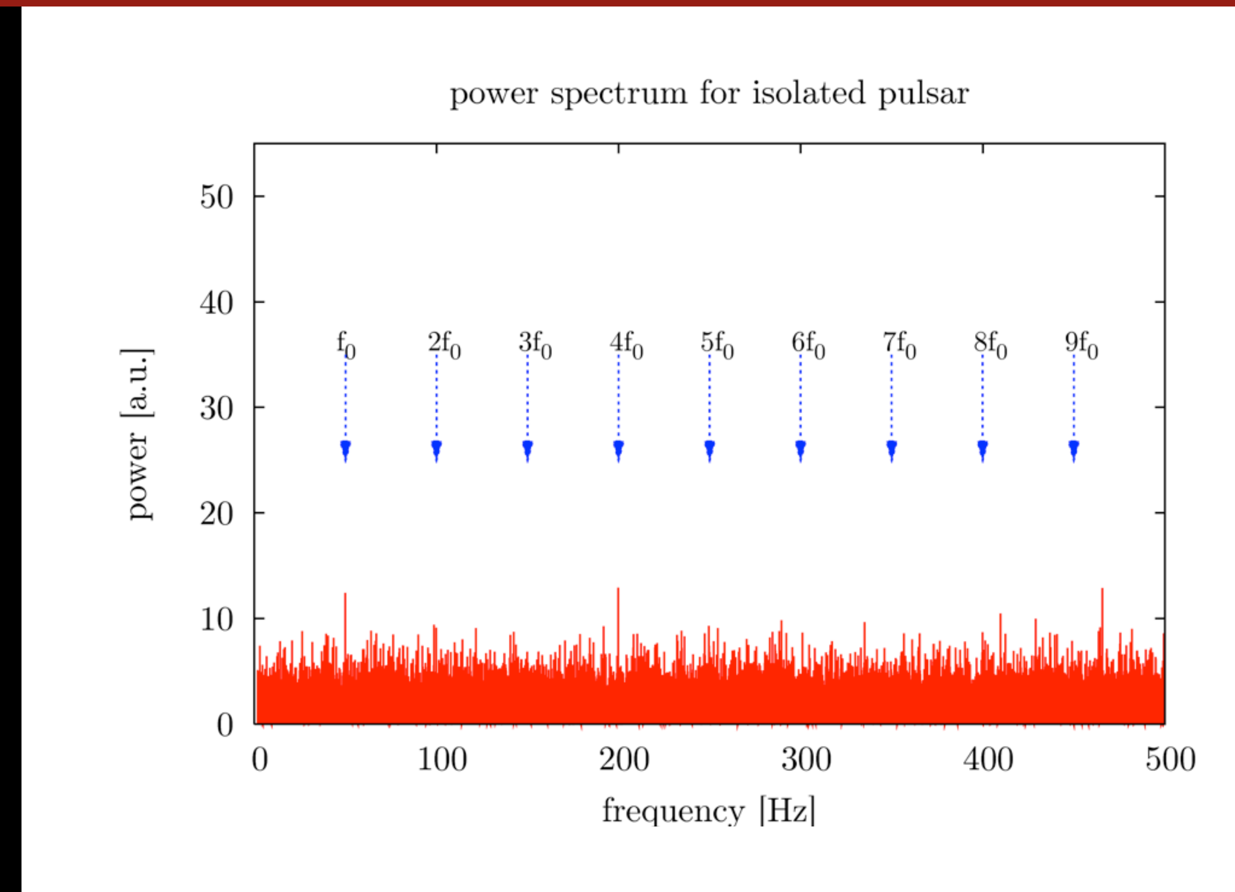
power spectrum for old acceleration search
acceleration search
(used in many pulsar
searches)

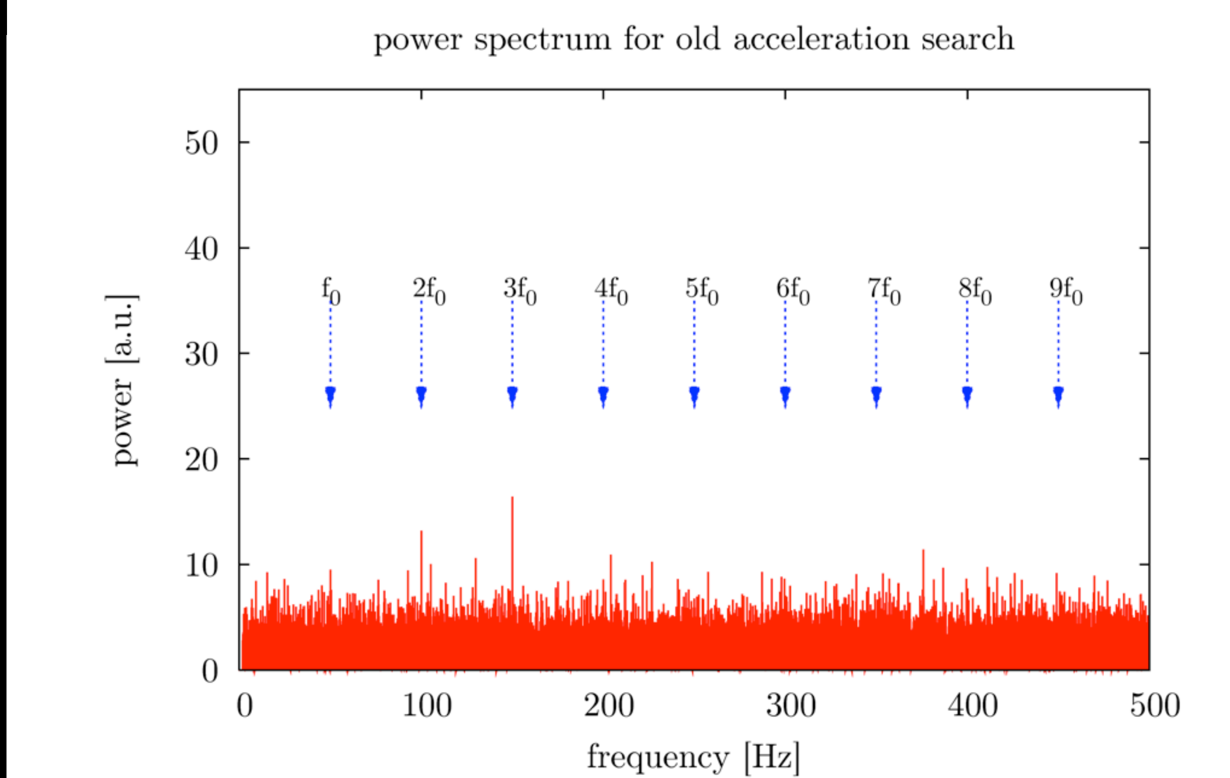


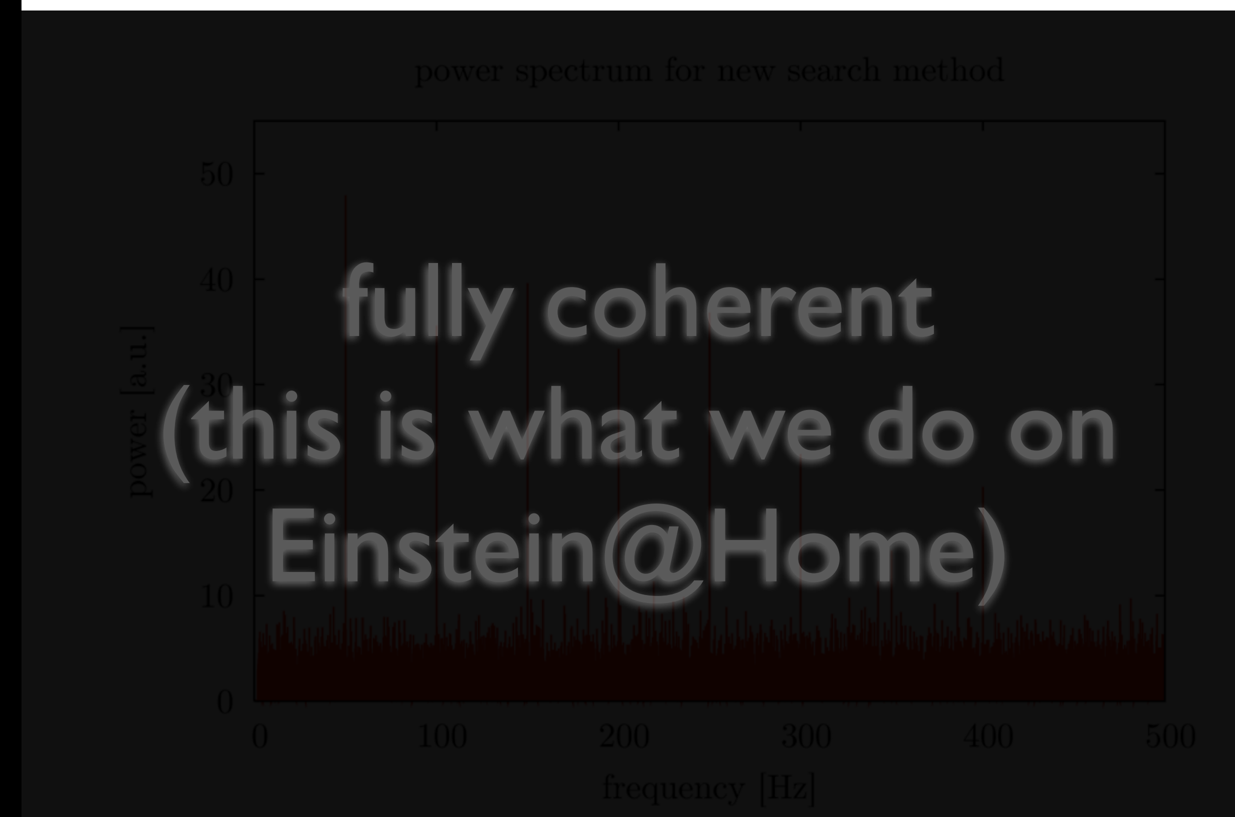
power spectrum for new search method
fully coherent
(this is what we do on
Einstein@Home)

Example









fully coherent
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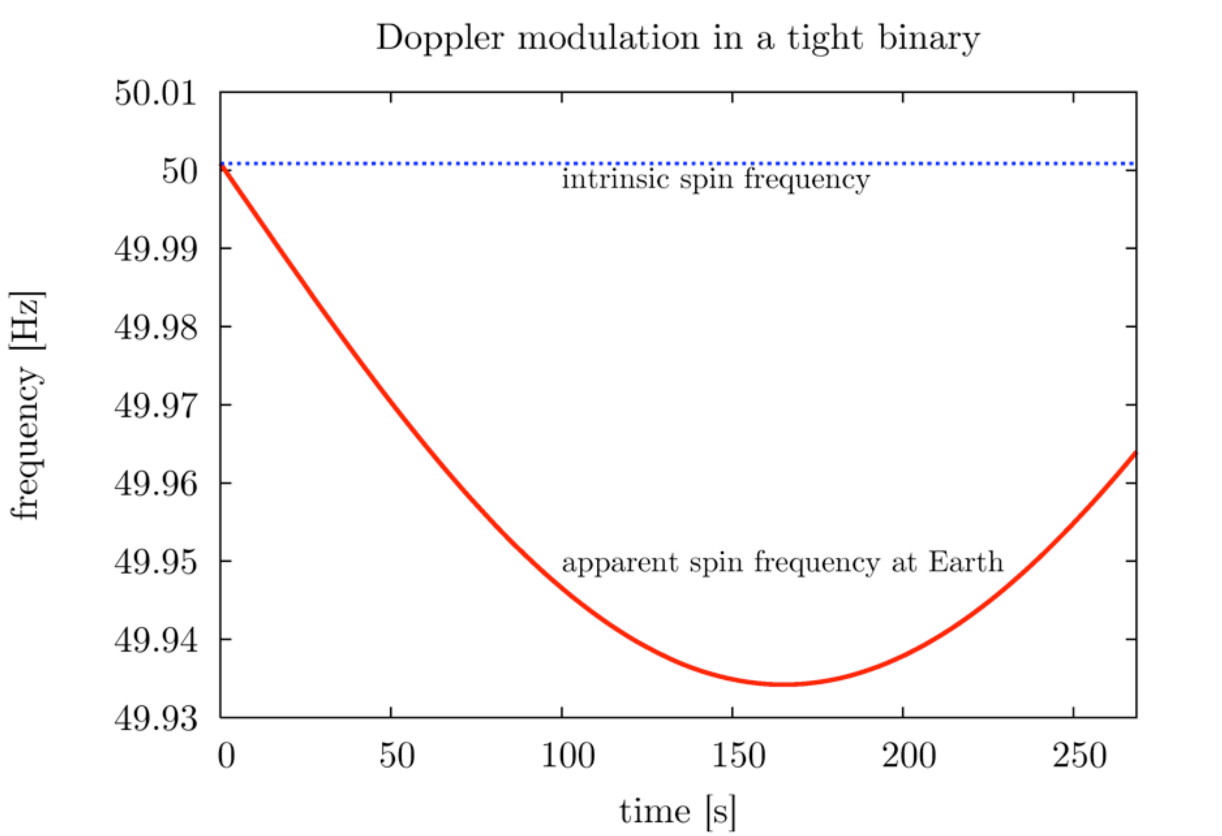
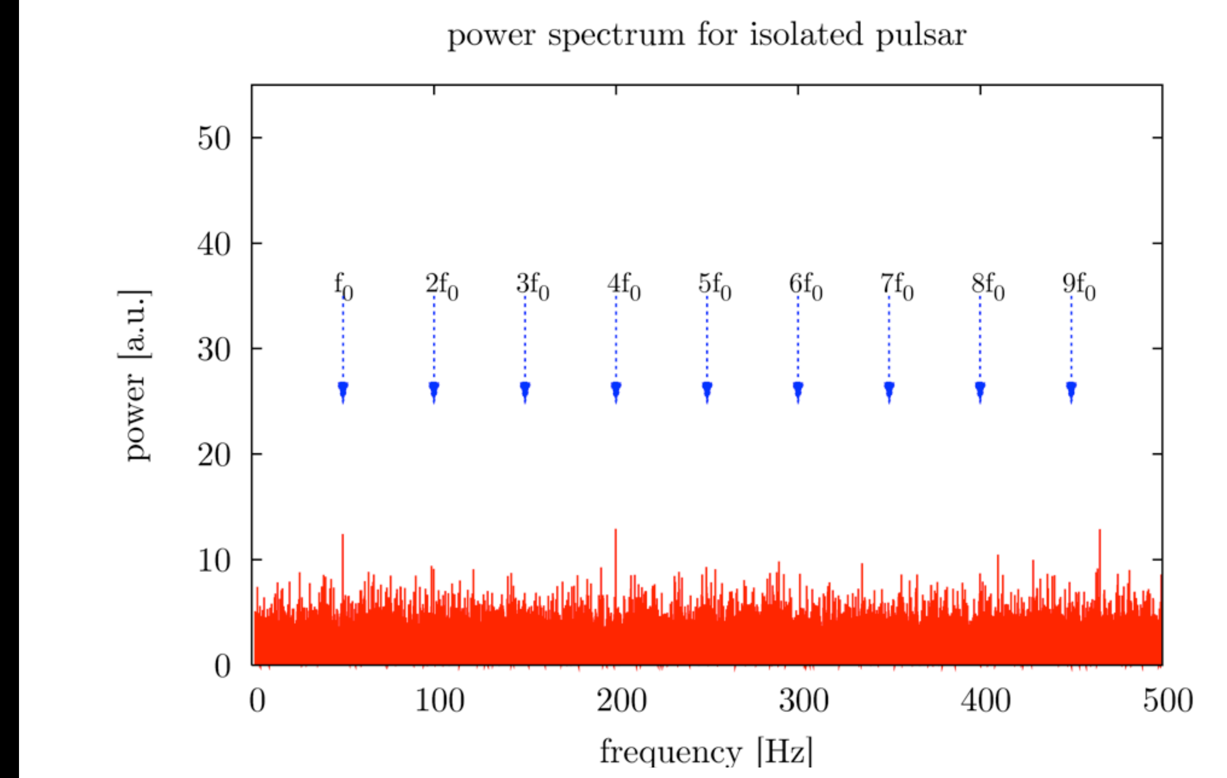
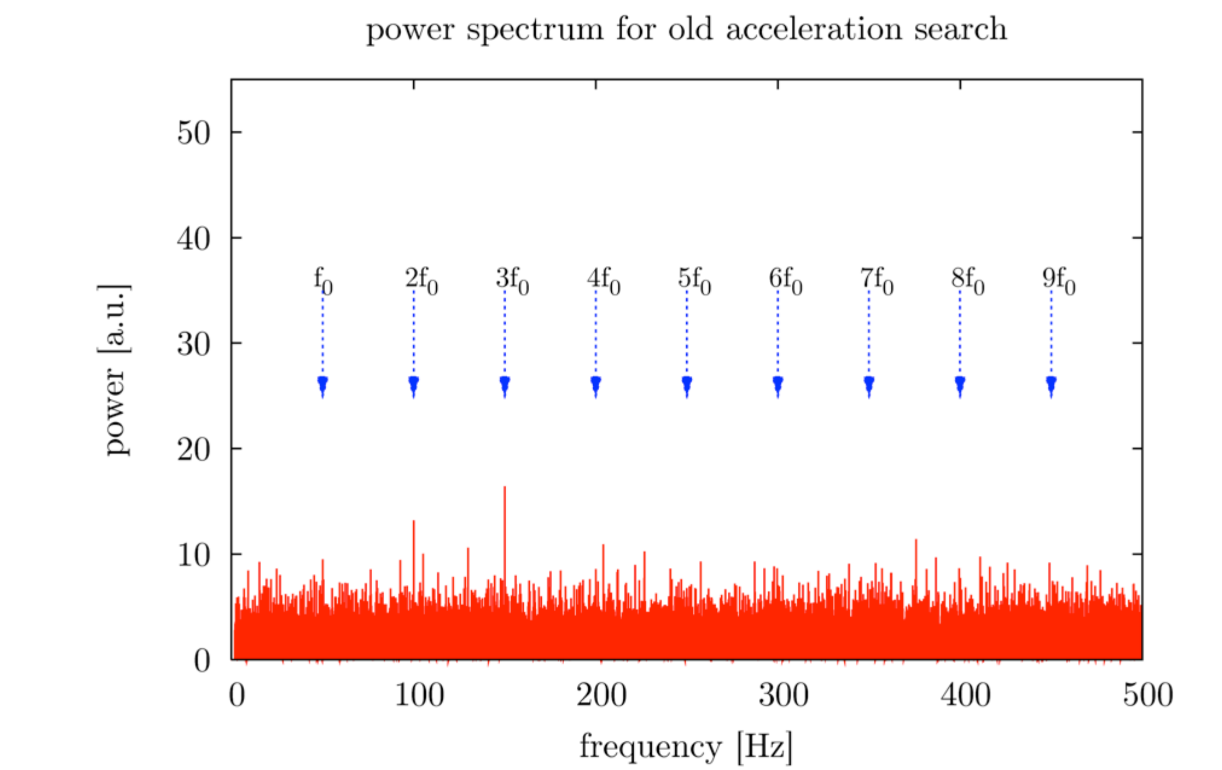
Example



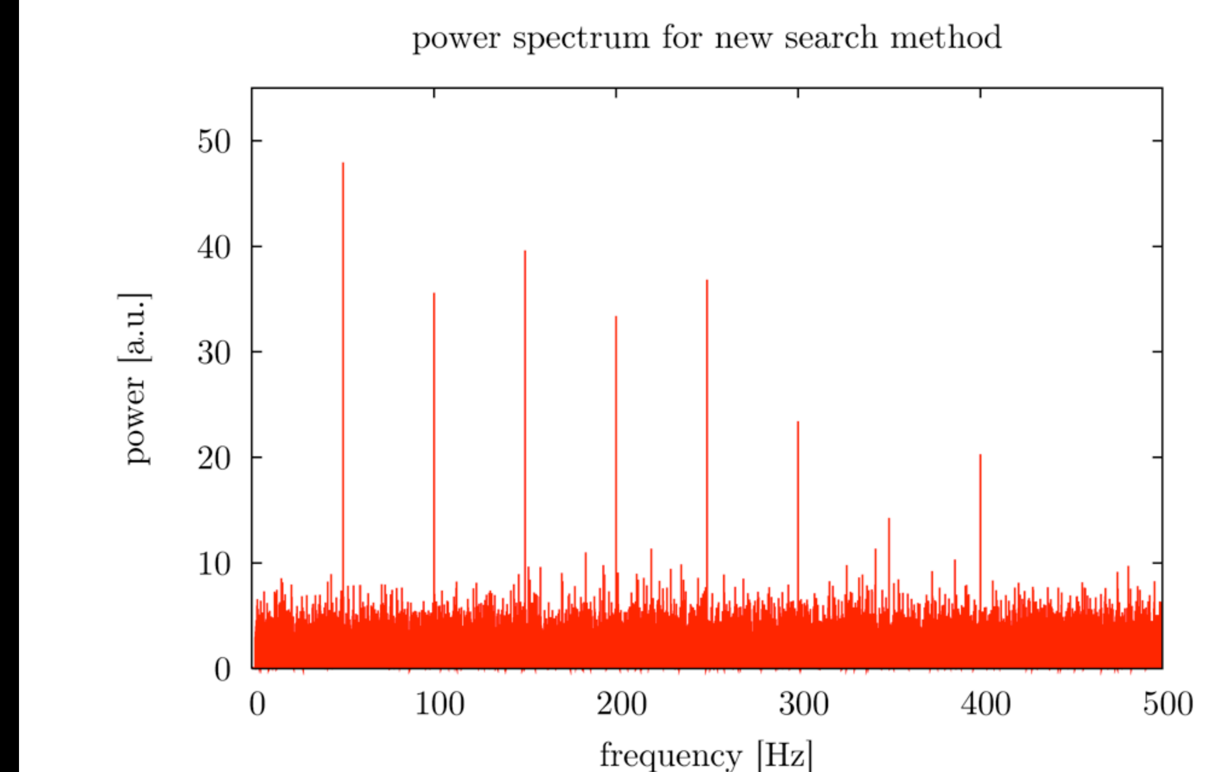
Doppler modulation in a tight binary
frequency [Hz]
50.01
50
49.99
49.98
49.97
49.96
49.95
49.94
49.93
intrinsic spin frequency
apparent spin frequency at Earth
0
50
100
150
200
250
time [s]



power spectrum for isolated pulsar
power [a.u.]
50
40
30
20
10
0
f_0
$2f_0$
$3f_0$
$4f_0$
$5f_0$
$6f_0$
$7f_0$
$8f_0$
$9f_0$
0
100
200
300
400
500
frequency [Hz]



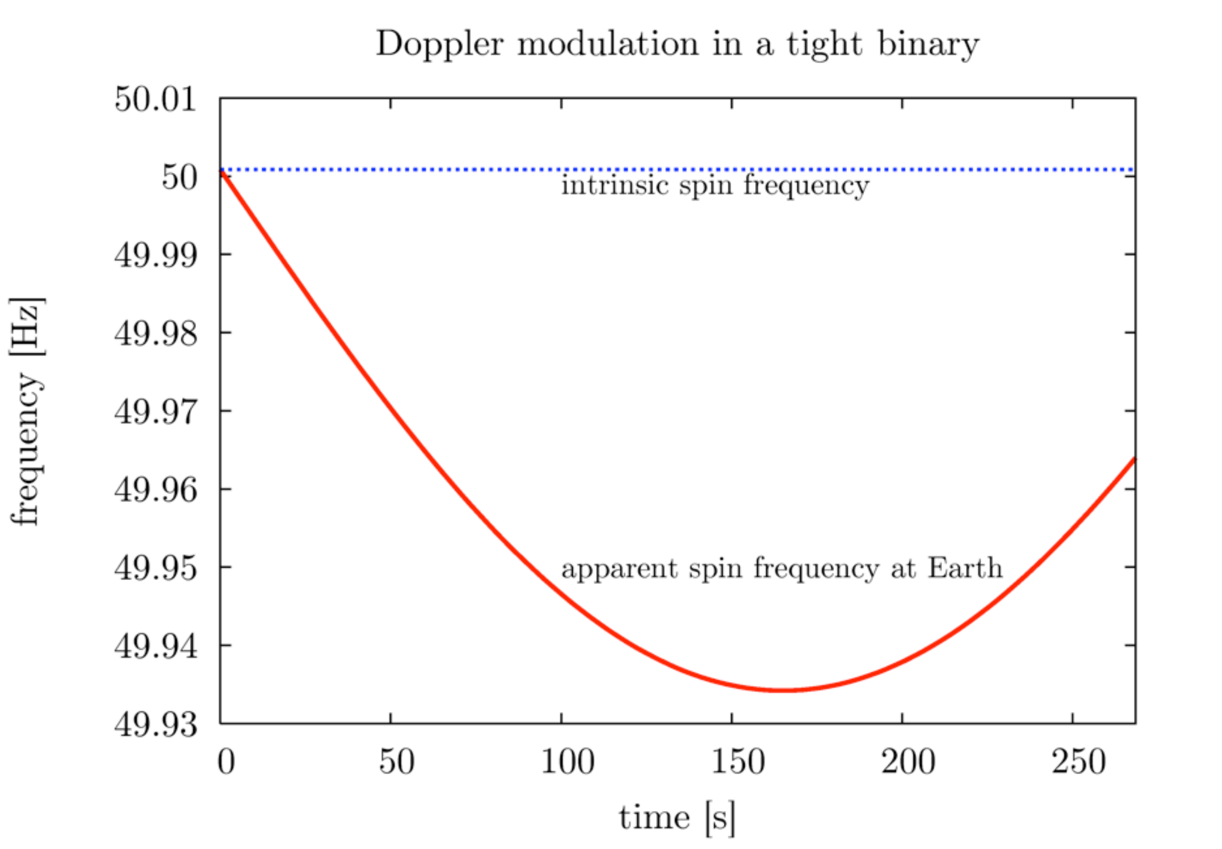
power spectrum for old acceleration search
power [a.u.]
50
40
30
20
10
0
f_0
$2f_0$
$3f_0$
$4f_0$
$5f_0$
$6f_0$
$7f_0$
$8f_0$
$9f_0$
0
100
200
300
400
500
frequency [Hz]

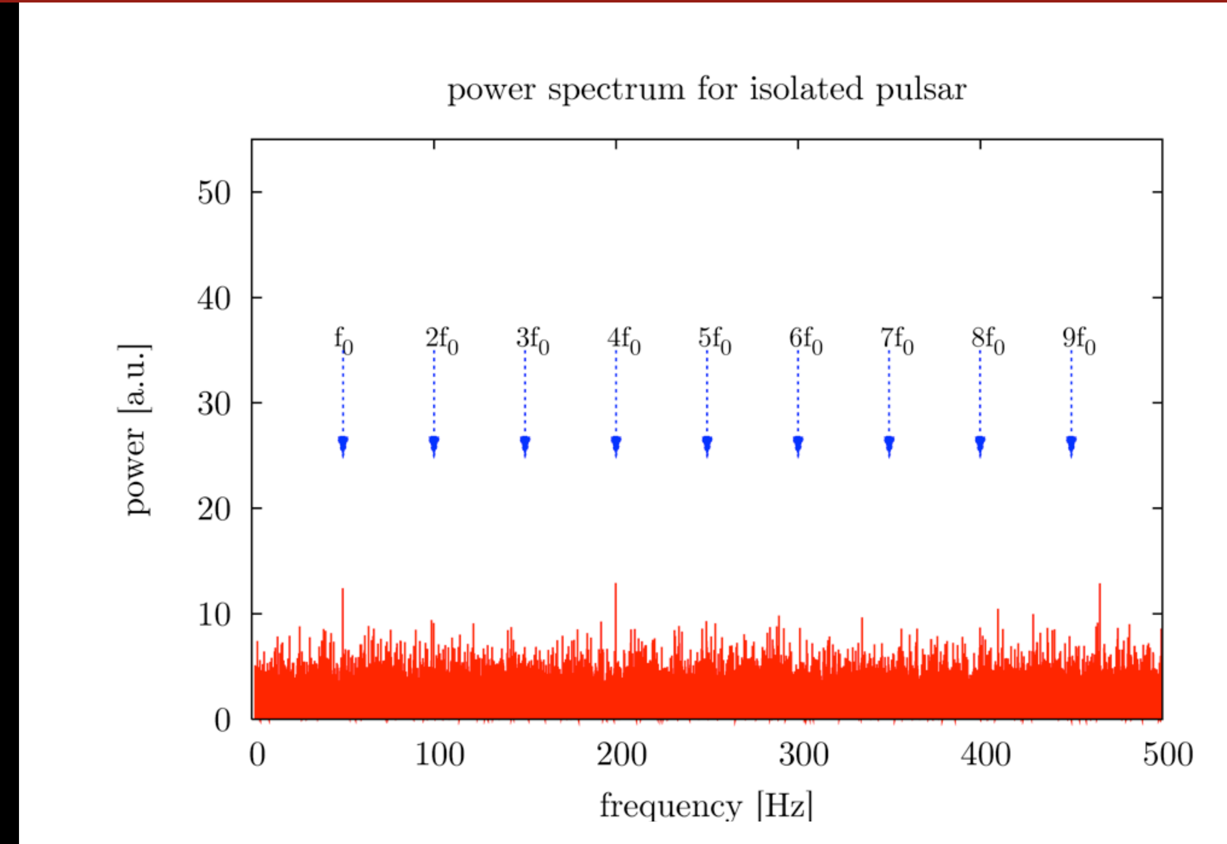


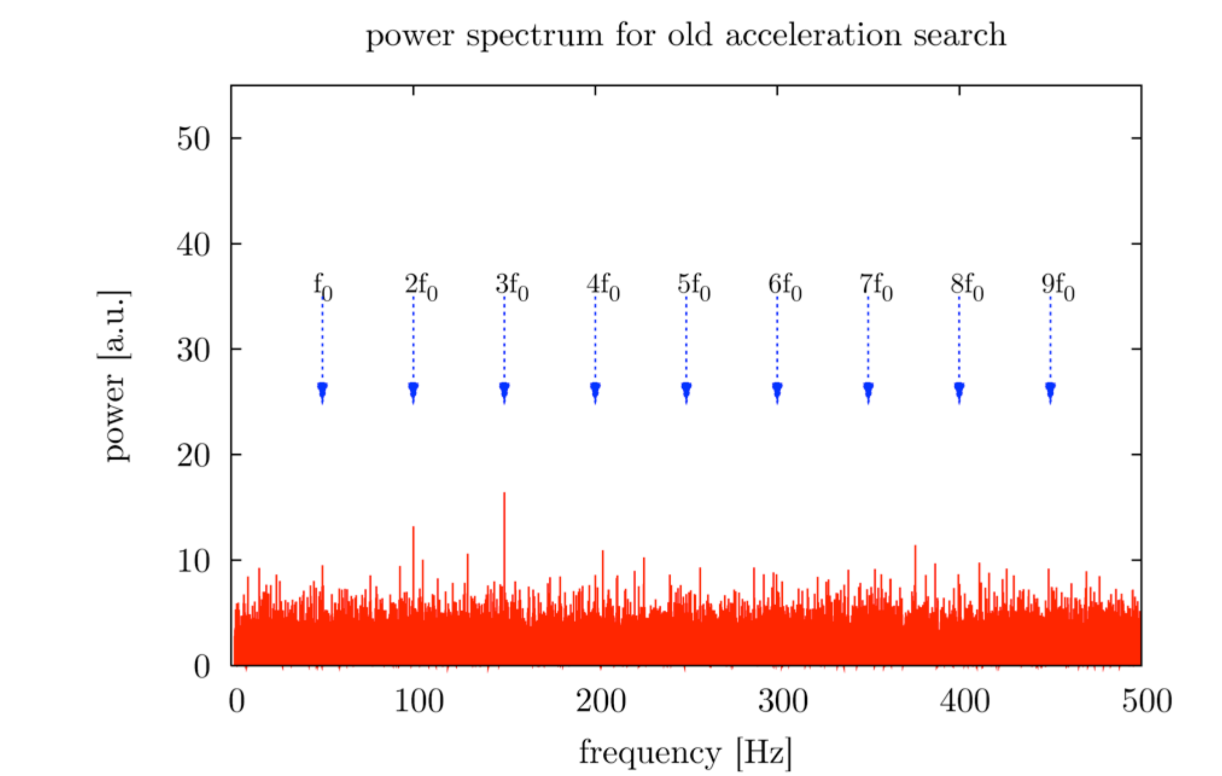
power spectrum for new search method
power [a.u.]
50
40
30
20
10
0
0
100
200
300
400
500
frequency [Hz]

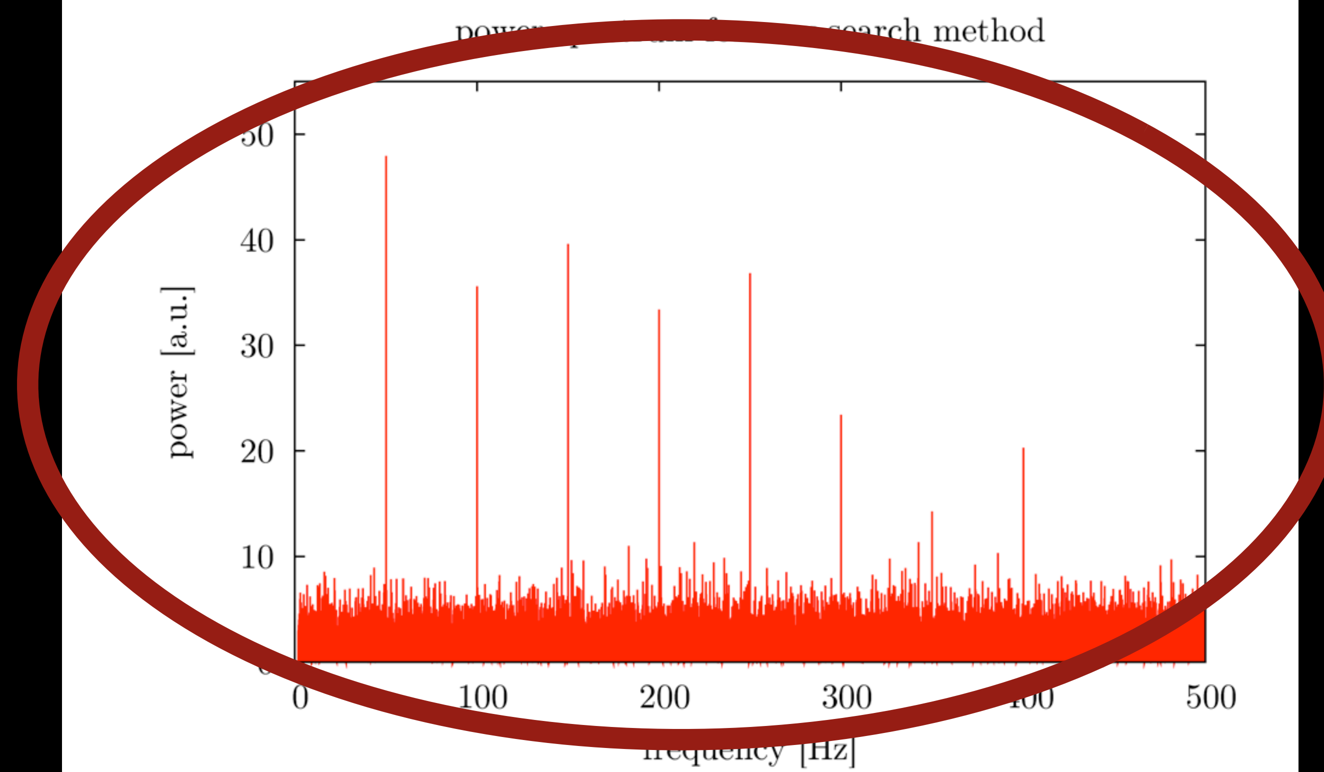
MAX-PLANCK-GESELLSCHAFT

Example



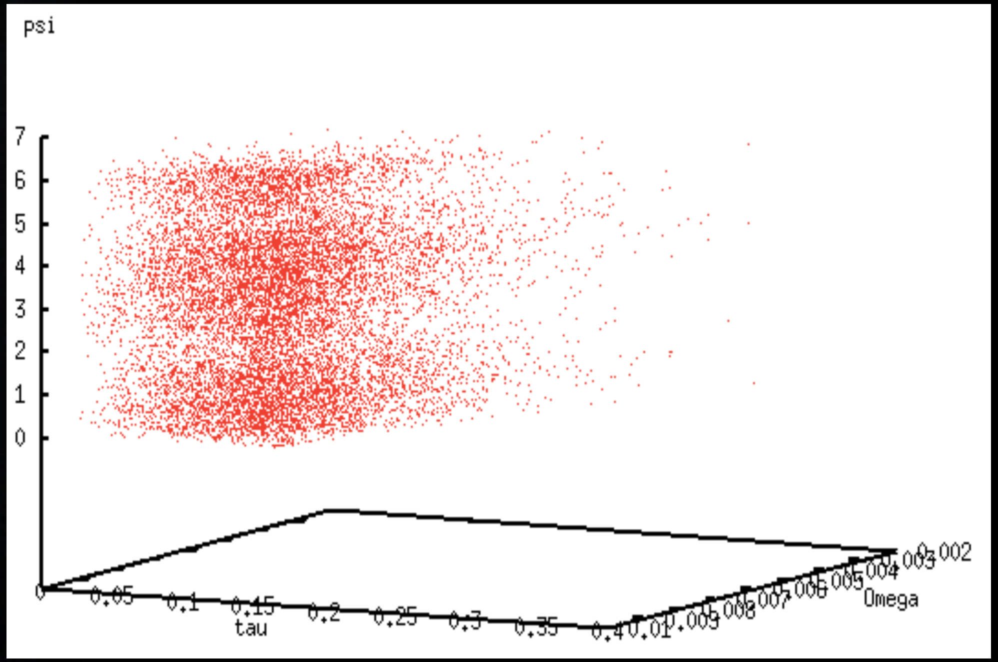






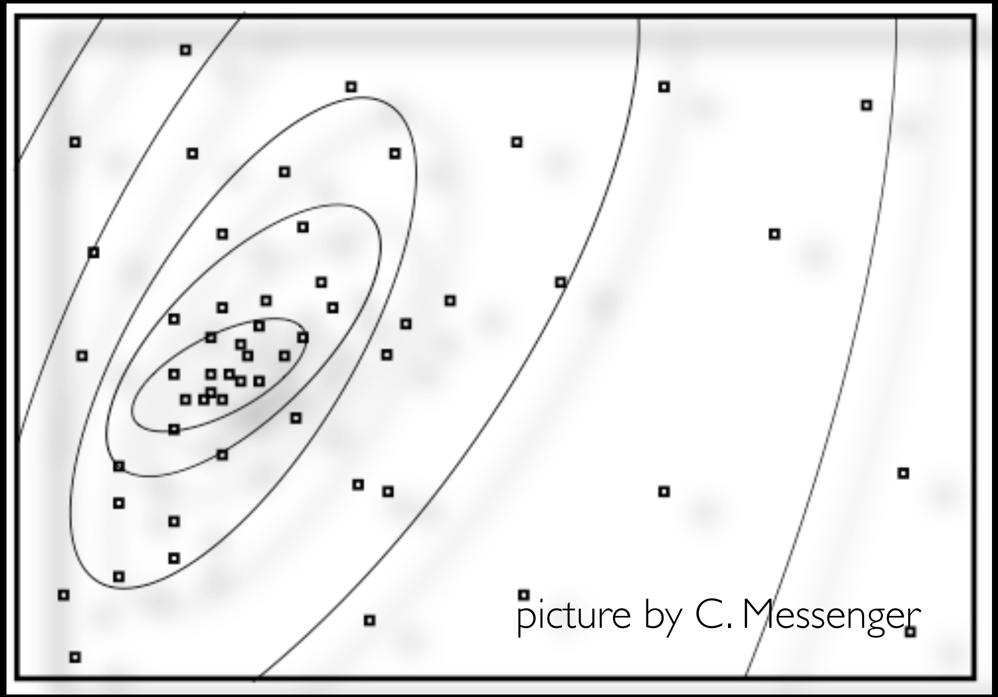
Template Bank

- **metric** = measure of distance on parameter space
- **mismatch**(putative signal, template) < acceptable value



- **lattice-based template bank**
  - find lattice covering (coordinate transformations)
- **random template banks / relaxed lattices**
  - pepper almost all space according to density
- **stochastic template bank**
  - don't add templates overlapping with others

wedge of parameter space



picture by C. Messenger

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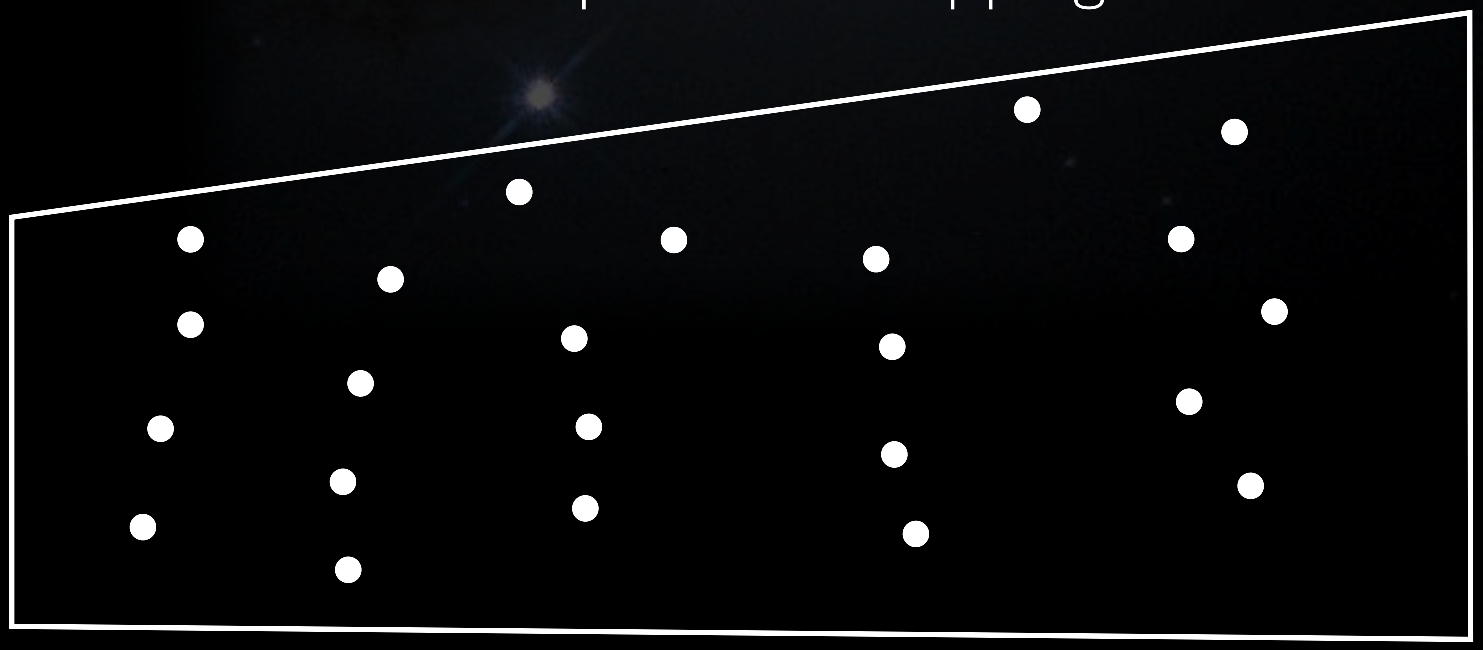
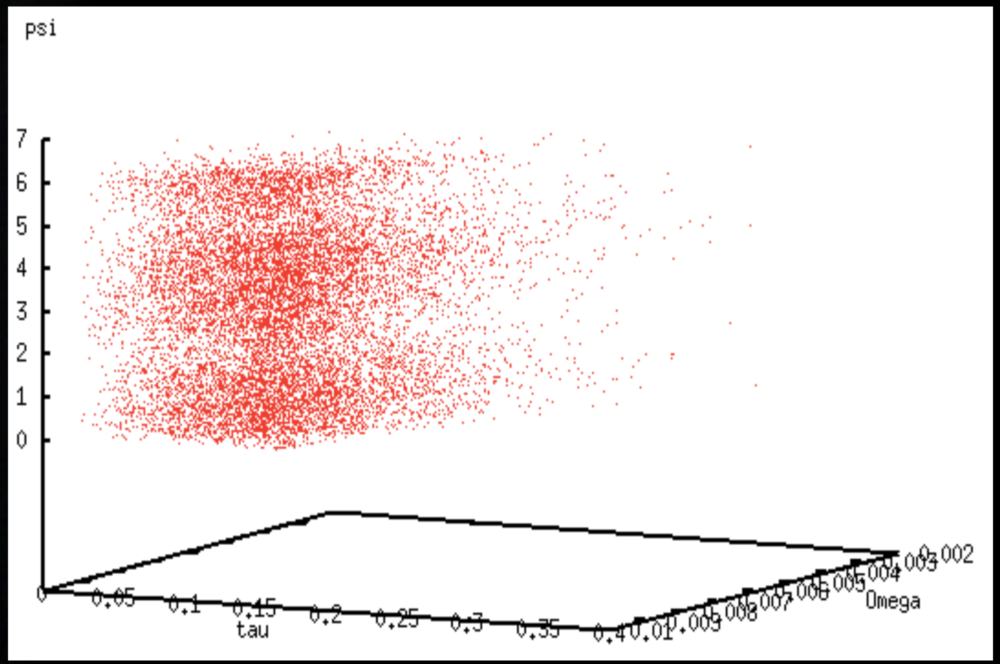
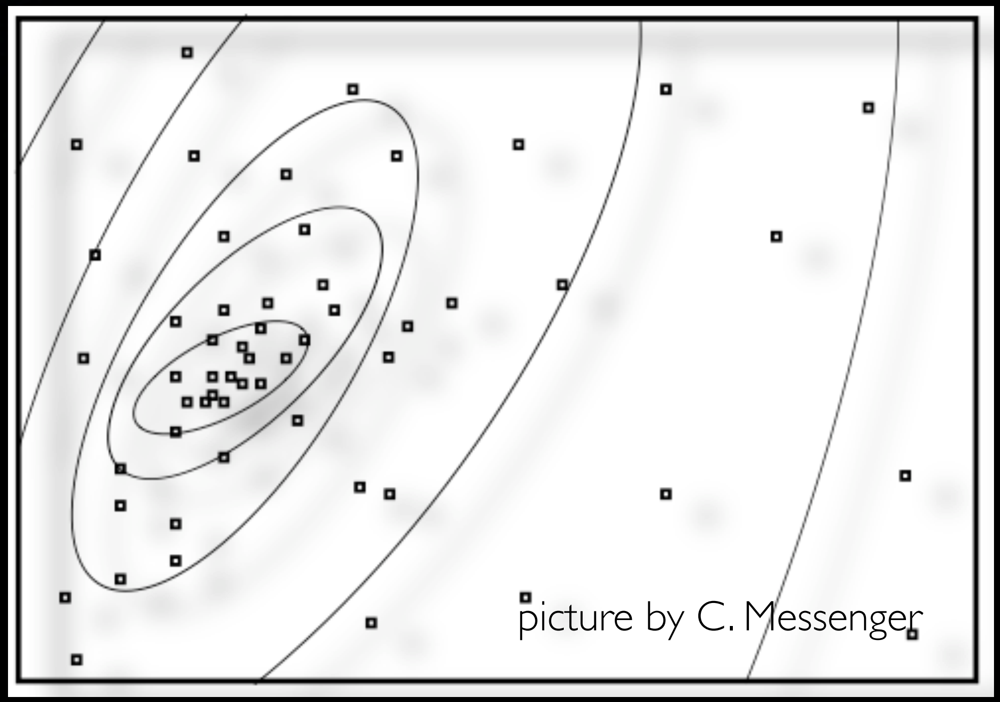


wedge of parameter space





picture by C. Messenger

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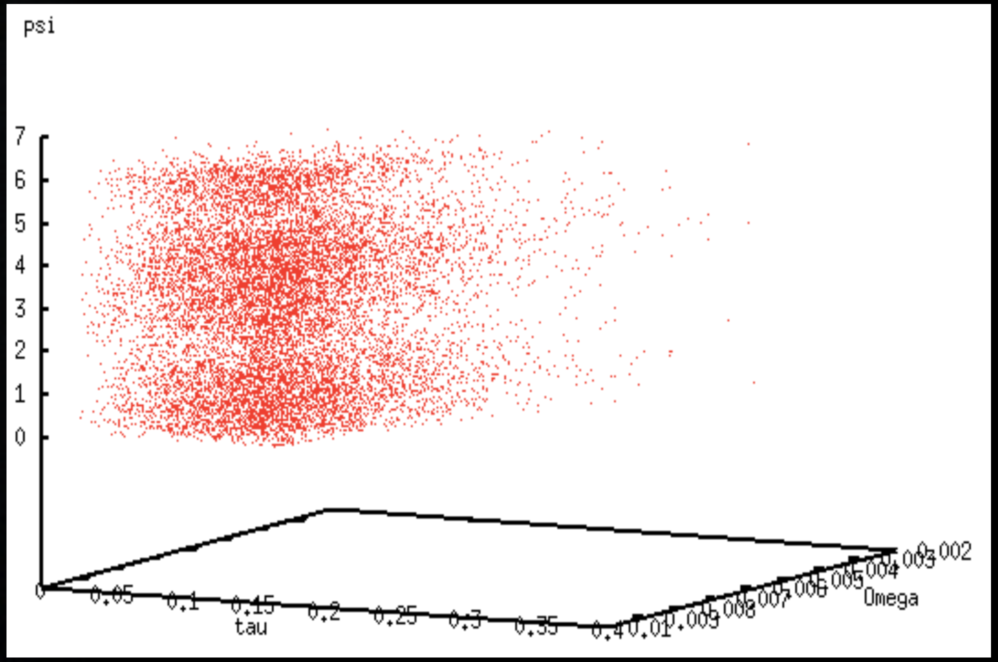

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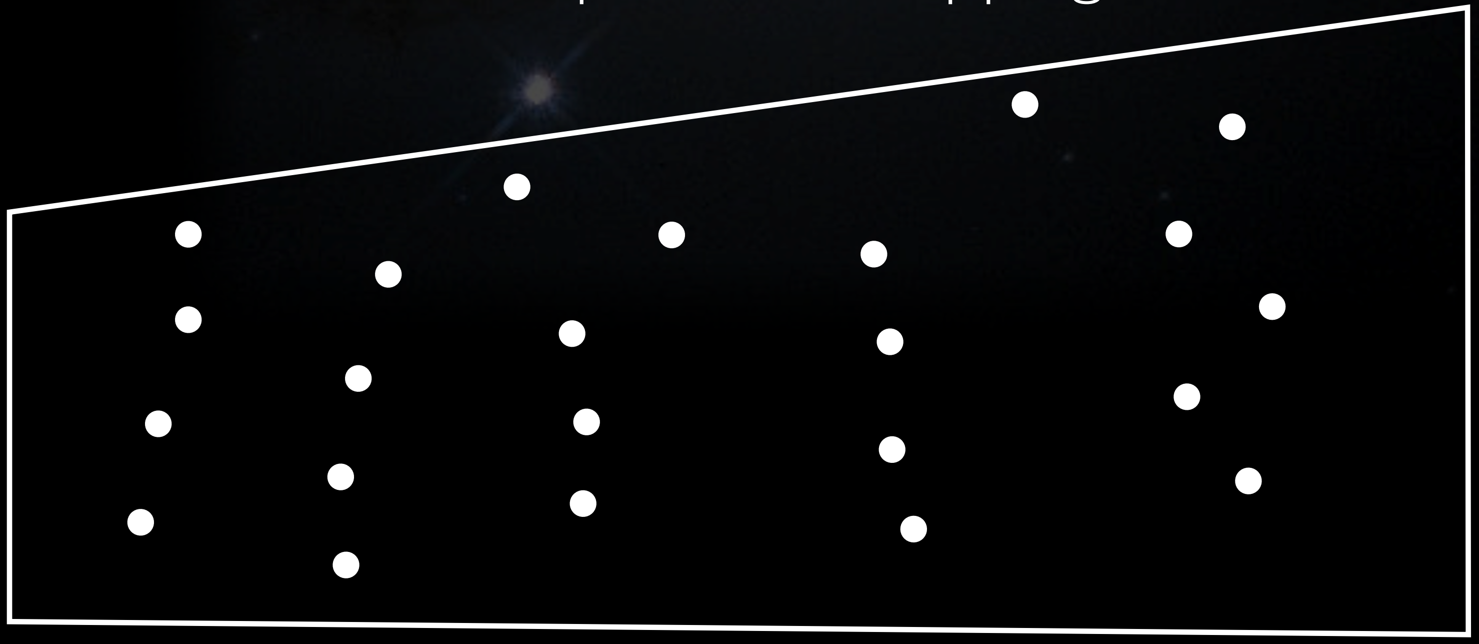
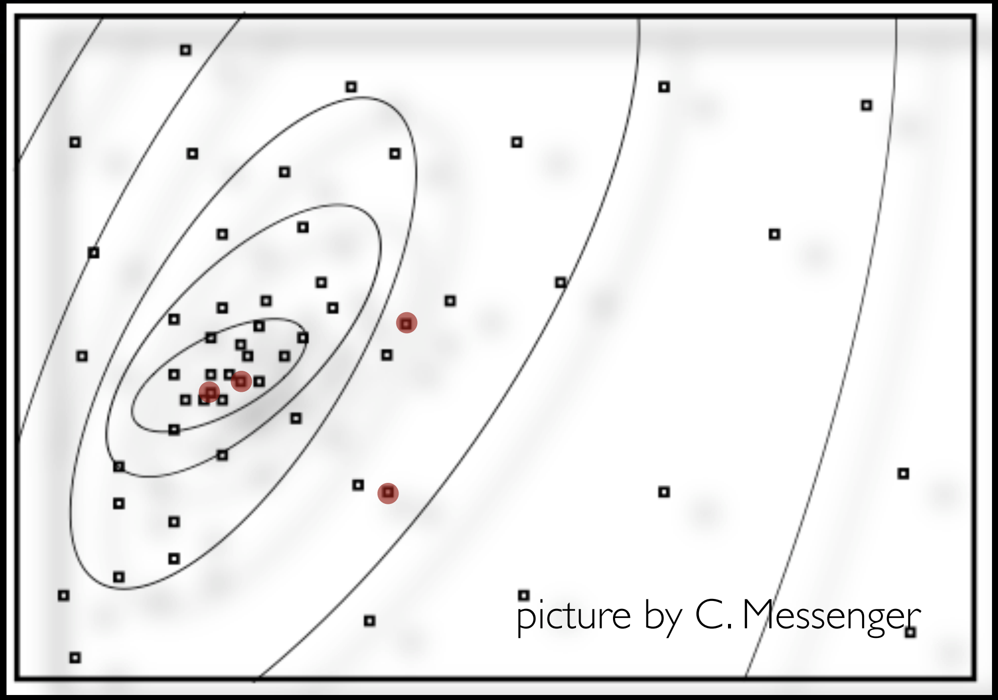
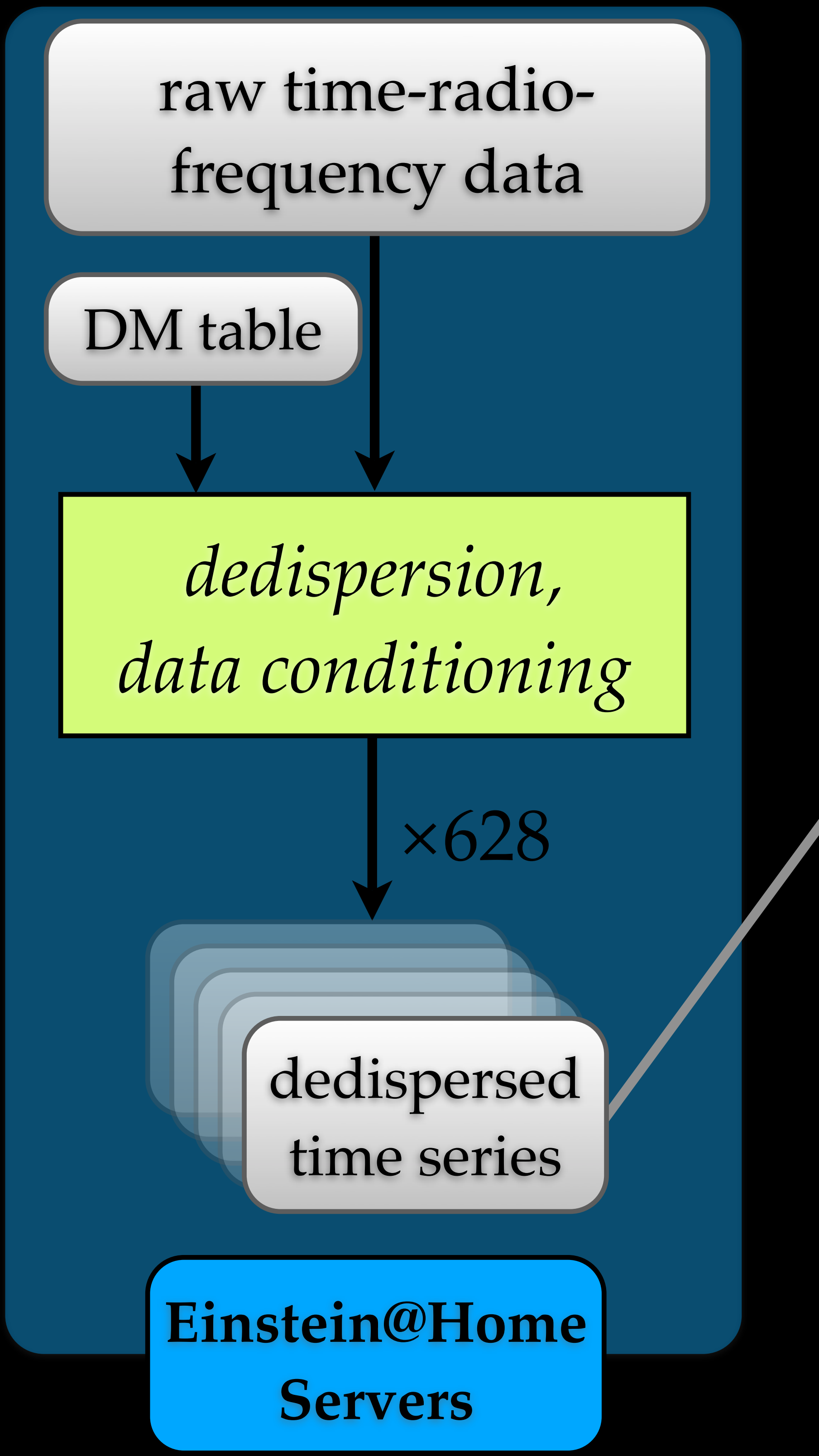


wedge of parameter space



Pipeline

- 305 m dish in carst sinkhole
- spherical + modified Gregorian optics
- 38000 perforated aluminum panels (~2 mm rms)
- 50 m deep, ~900 ton platform 150 m above dish
- **PALFA survey:**
  - 7 beams at the same time, ~5 min dwelling time
  - 430 hrs observation per year, started in 2004

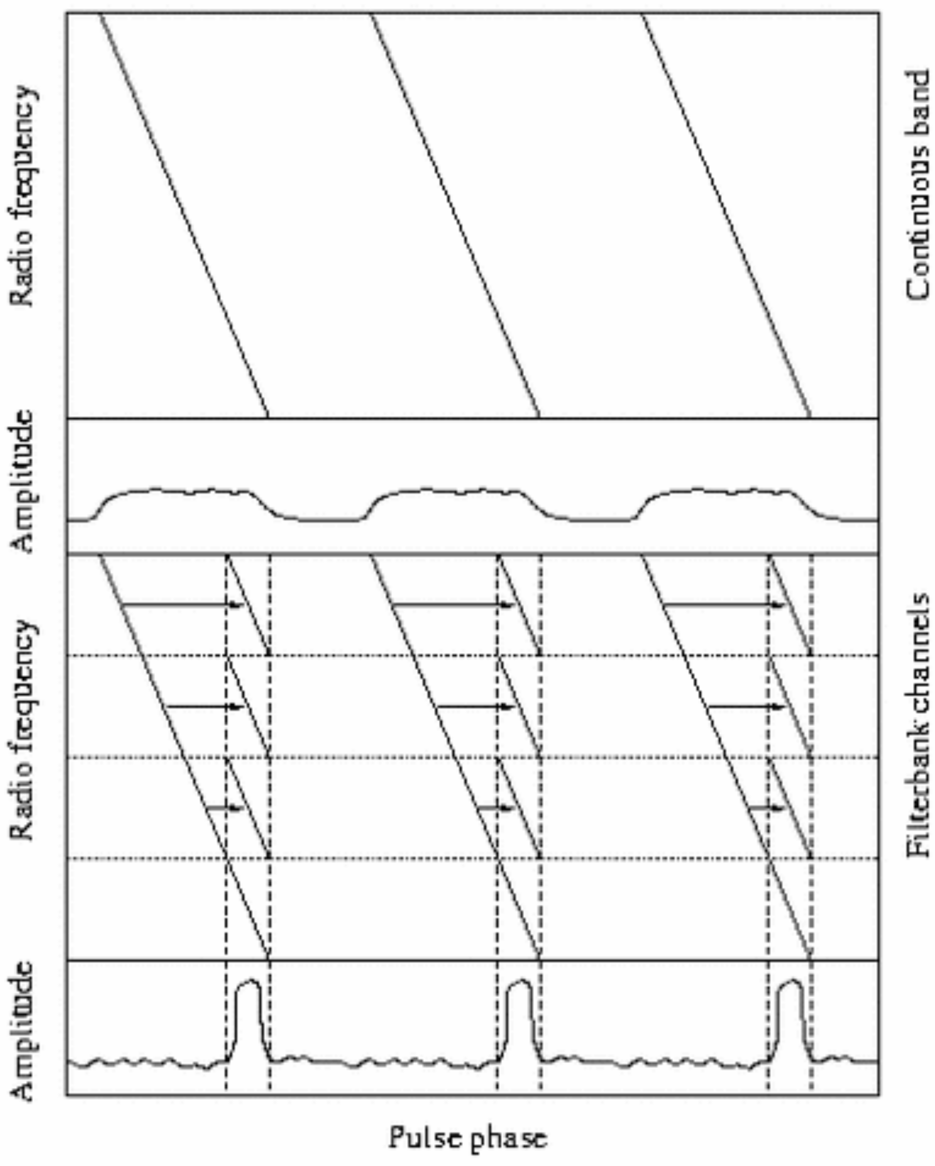


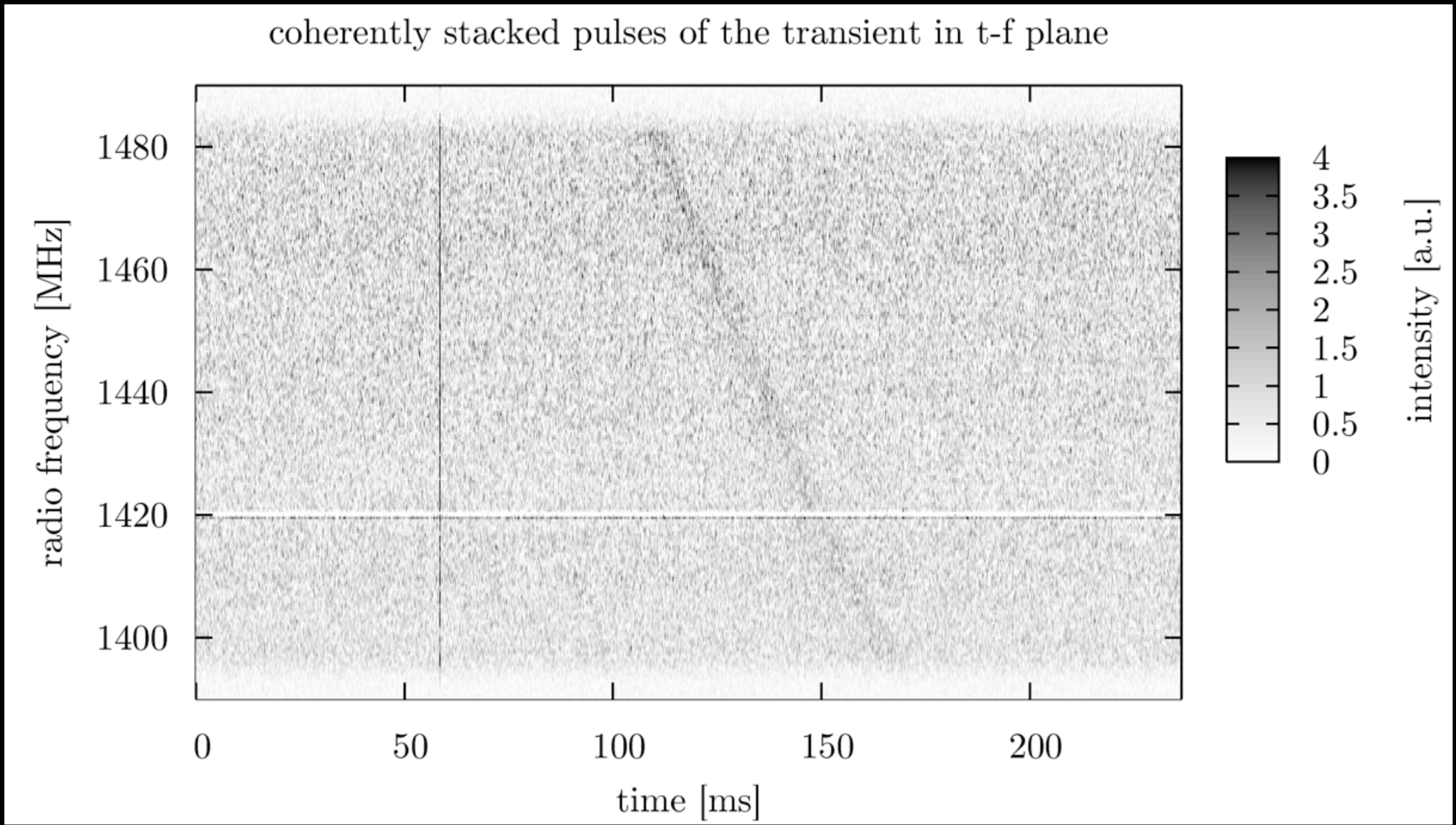
De-dispersion

- free electrons in ISM: radio-frequency dependent delay
- correct for by channel-shifting at 628 trial values

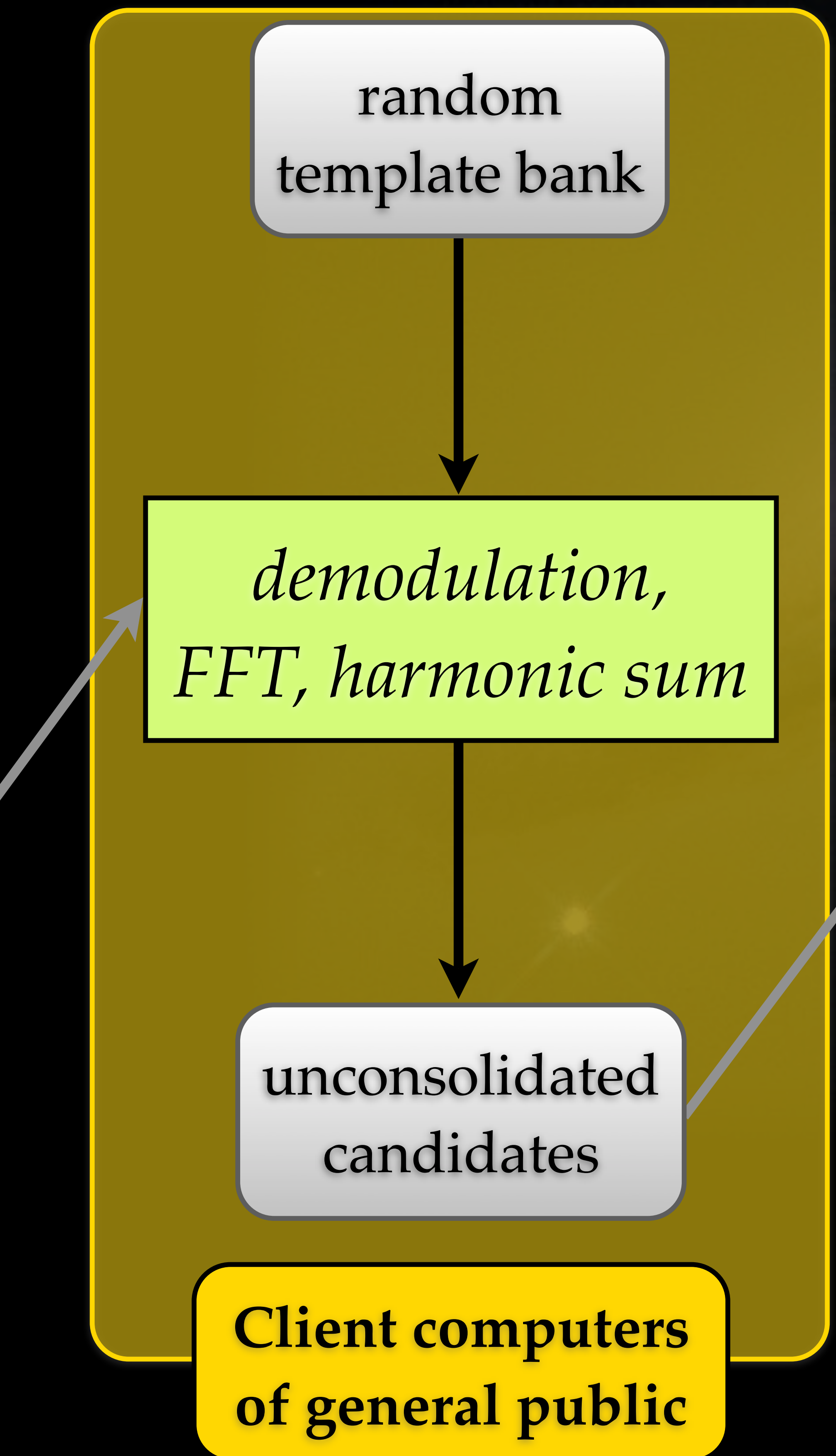
- resulting timeseries are input data for the WUs

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer





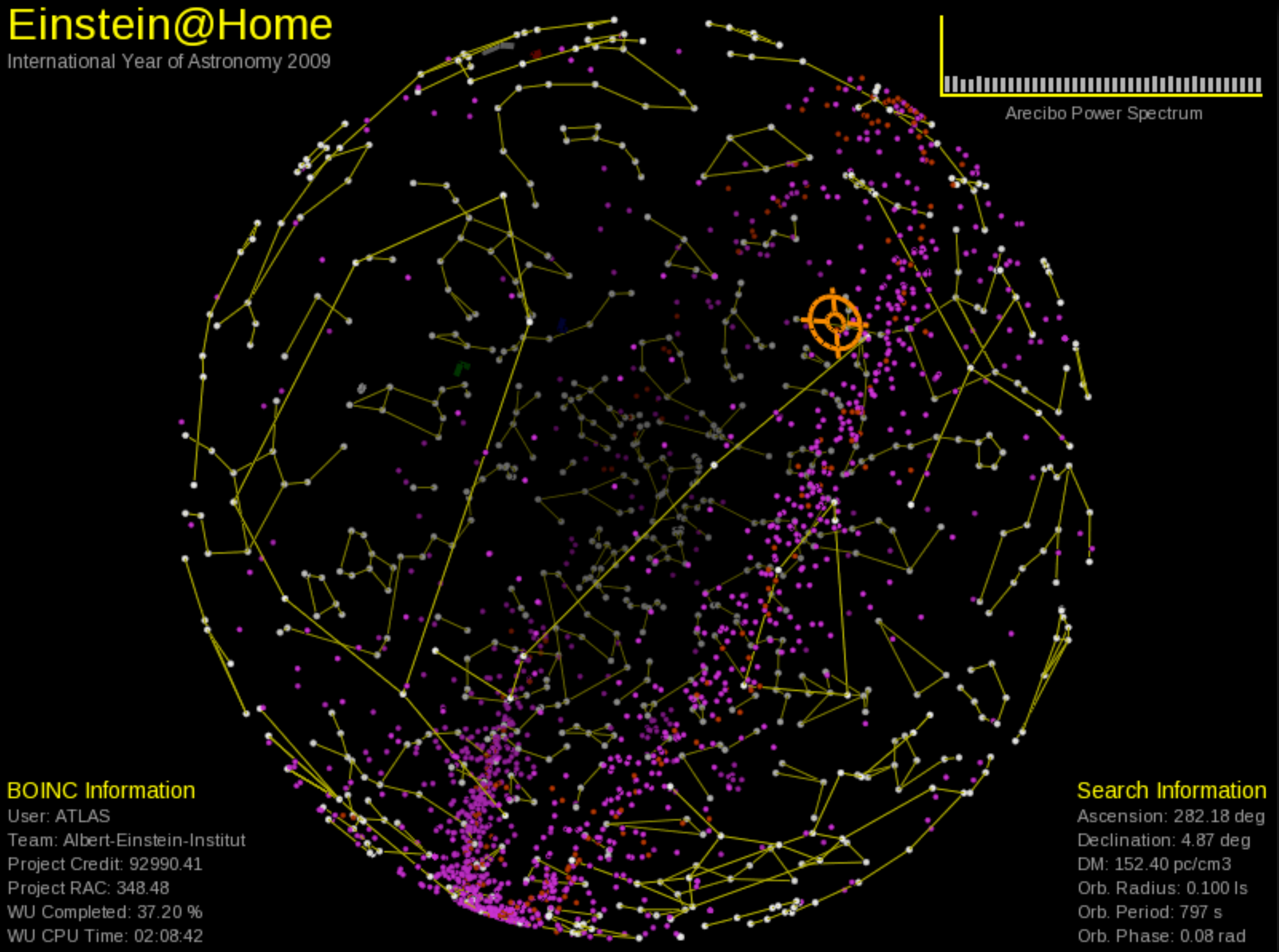
Science Code



- **WU set up**
  - timeseries (2^{21} samples of 1 byte at $t_{samp}=128\ \mu s$)
    - one of seven beams for 268 s long pointing
    - one of the 628 DM trial values
    - quota of 2
  - random /stochastic template bank in orb. param.

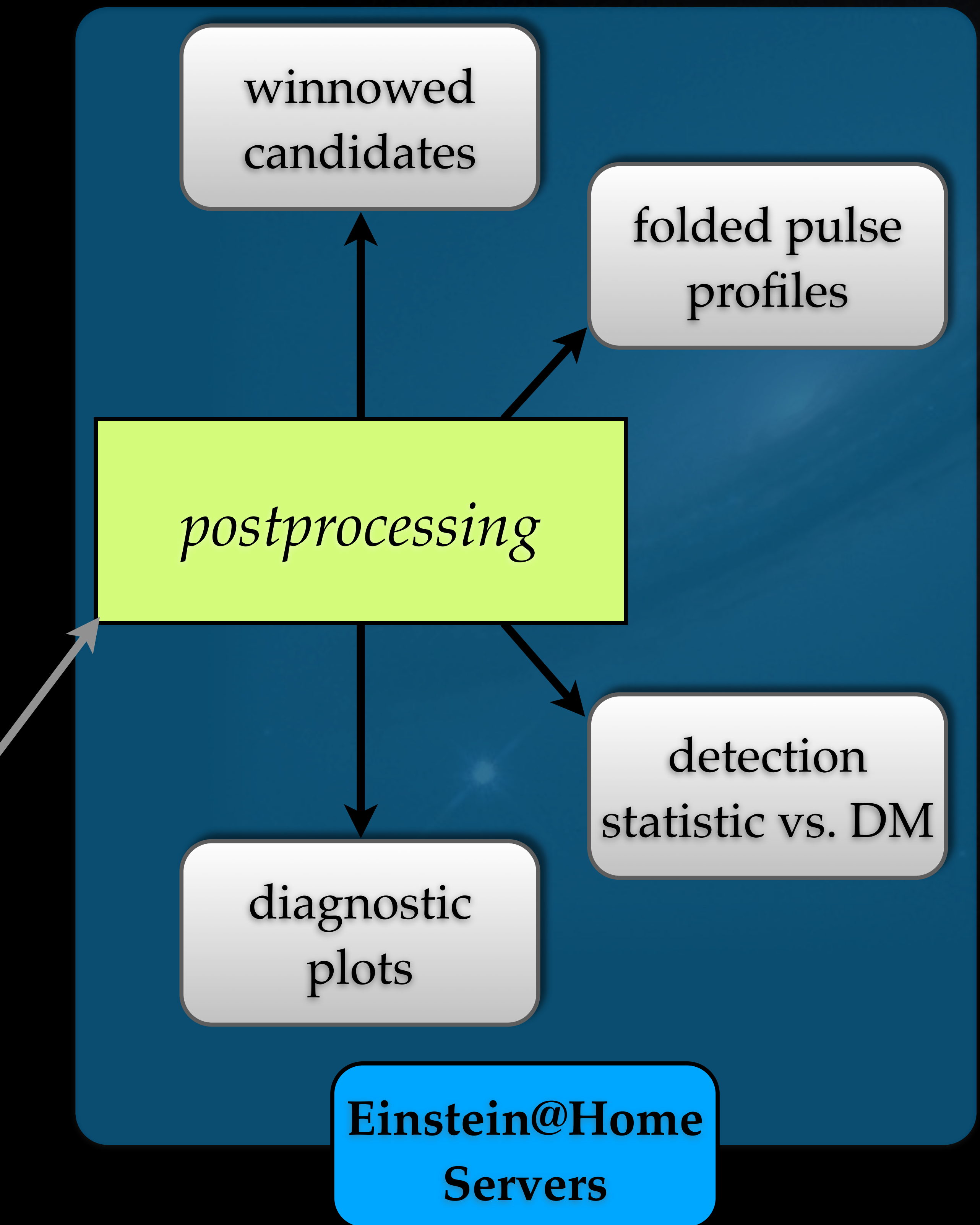
- **Science Code**
  - CPU version for Linux, Windows, Mac
  - GPU beta version for Linux, Windows (speed x2.5)
  - 4 h to 7 h average runtime/WU_{CPU}
  - 1/3 of E@H CPU time used for this search
  - ~20 min observation time equivalent per day
    - this is ~1/3 of data taking real time
  - random ➛ stochastic templatebank (speed x3.3 !)

New Screensaver

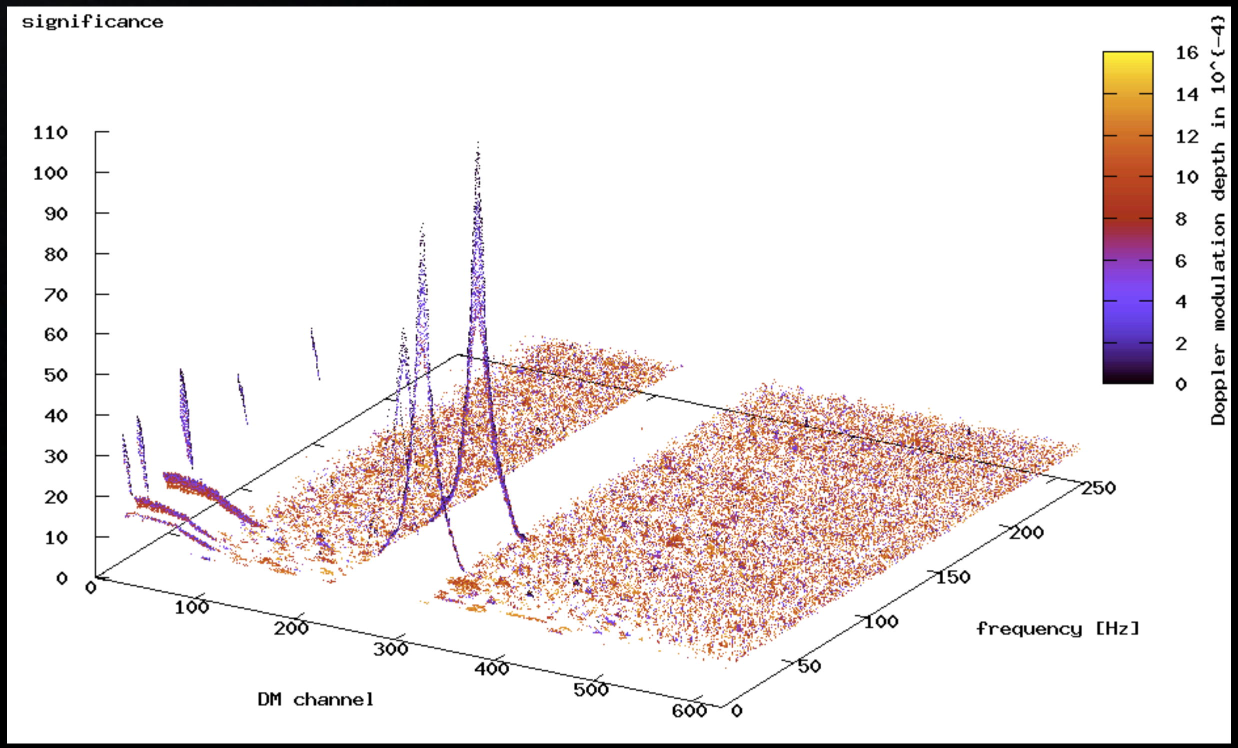


screensaver coding O. Bock

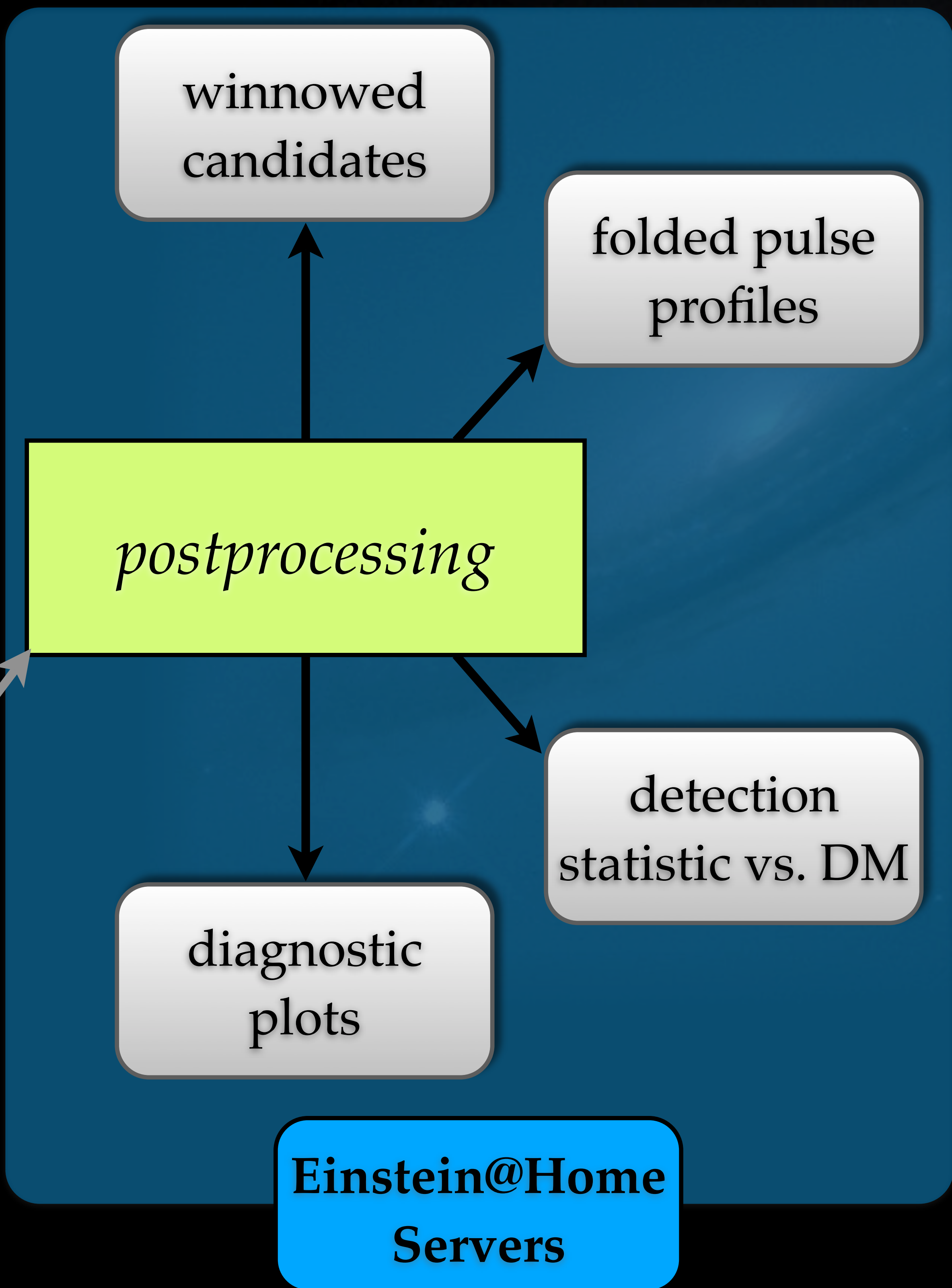
Post-Processing



- visual inspection of diagnostic plots
  - generation of additional diagnostics
  - identification of promising candidates
  - standard software (PRESTO) for control
- automated post-processing in development
- *if need be:* re-observation by AO



Post-Processing



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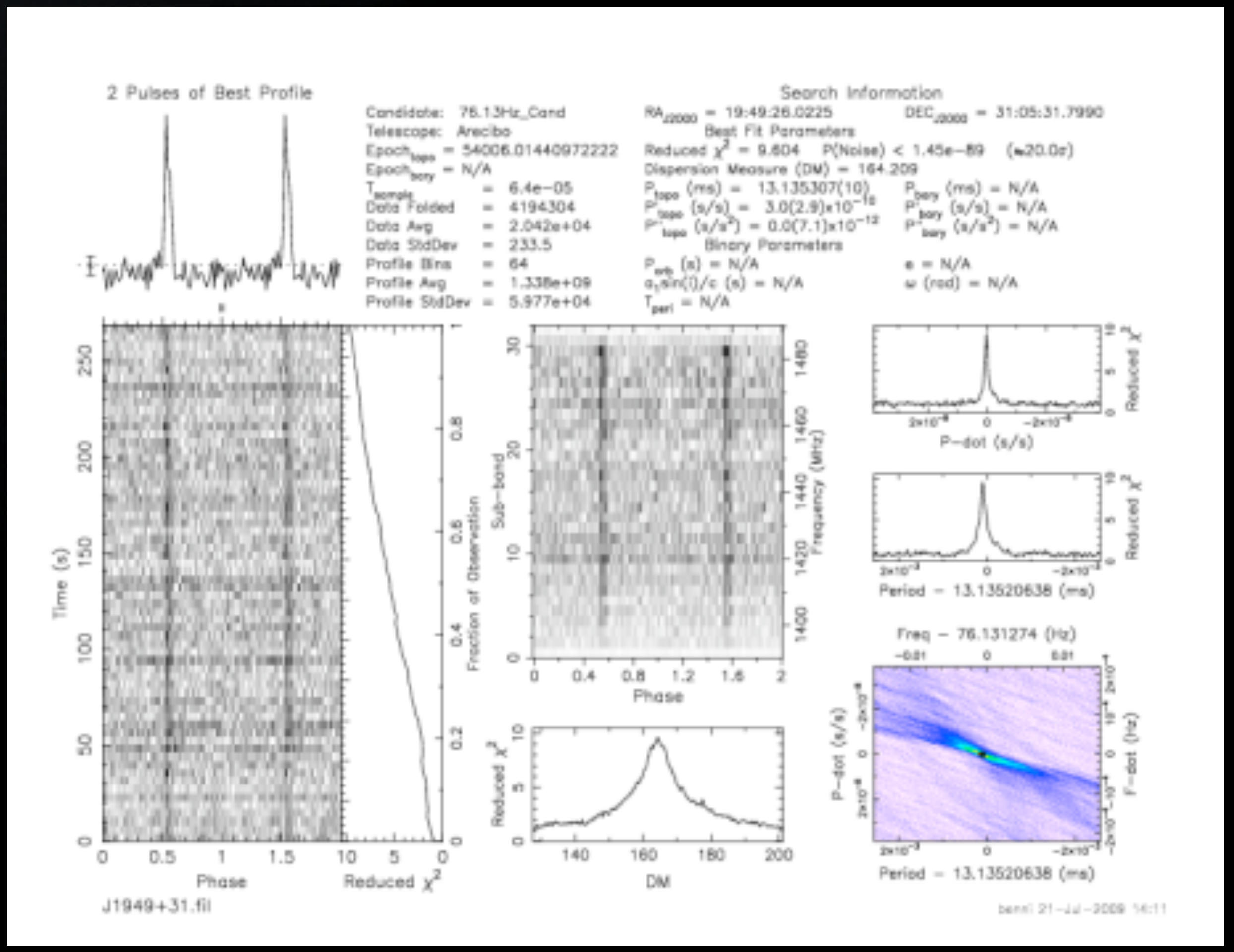


Re-Discoveries

Einstein@Home Arecibo Binary Radio Pulsar Search Detection Page

http://einstein.phys.uwm.edu/radiopulsar/html/rediscovery_page/rediscoveries.html

Wikipedia Fahrplanauskunft Astronomie Firmen Meteorologie Aqua-, Terraristik Uni Kochen Daily GPS/Maps Mikroskopie Sport

Einstein@Home Arecibo Binary Radio Pulsar Search (Re-)Detections

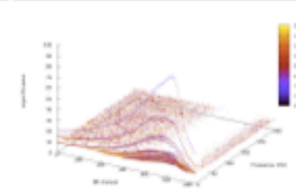
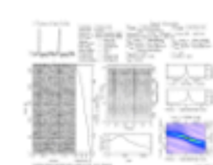
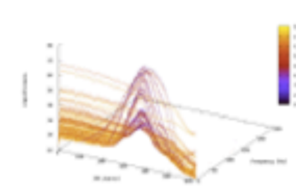
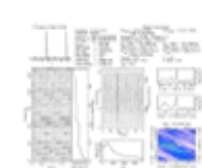
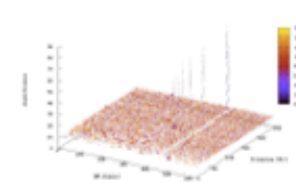
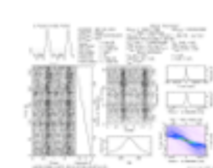
This page contains all (re-)detections of pulsars by the Einstein@Home binary pulsar search on Arecibo radio data.
Each time a pulsar is (re-)discovered it will be added to the list.

The table below displays the following information for each of the pulsars:

- The first column gives the name of the pulsar followed by a link to an entry of this pulsar in a pulsar catalogue (where available).
- The next two columns show topocentric spin freqency (f_{topo}) and dispersion measure (DM) of the pulsar.
- The following column displays the date the last canonical result for this data set was send to the Einstein@Home servers, thereby completing the search on this set.
- The fifth column gives the name of the WU in which the candidate signal was found with the highest significance. It also shows the names of the two users whose computers found the pulsar in this WU and the date (UTC) the result was received from the respective machine (long user names will be truncated).
- The sixth column shows a thumbnail of a pulsar detection plot. Click to see complete plot.
- The last column contains a link to a plot of the confirmation analysis done with the PRESTO software package.

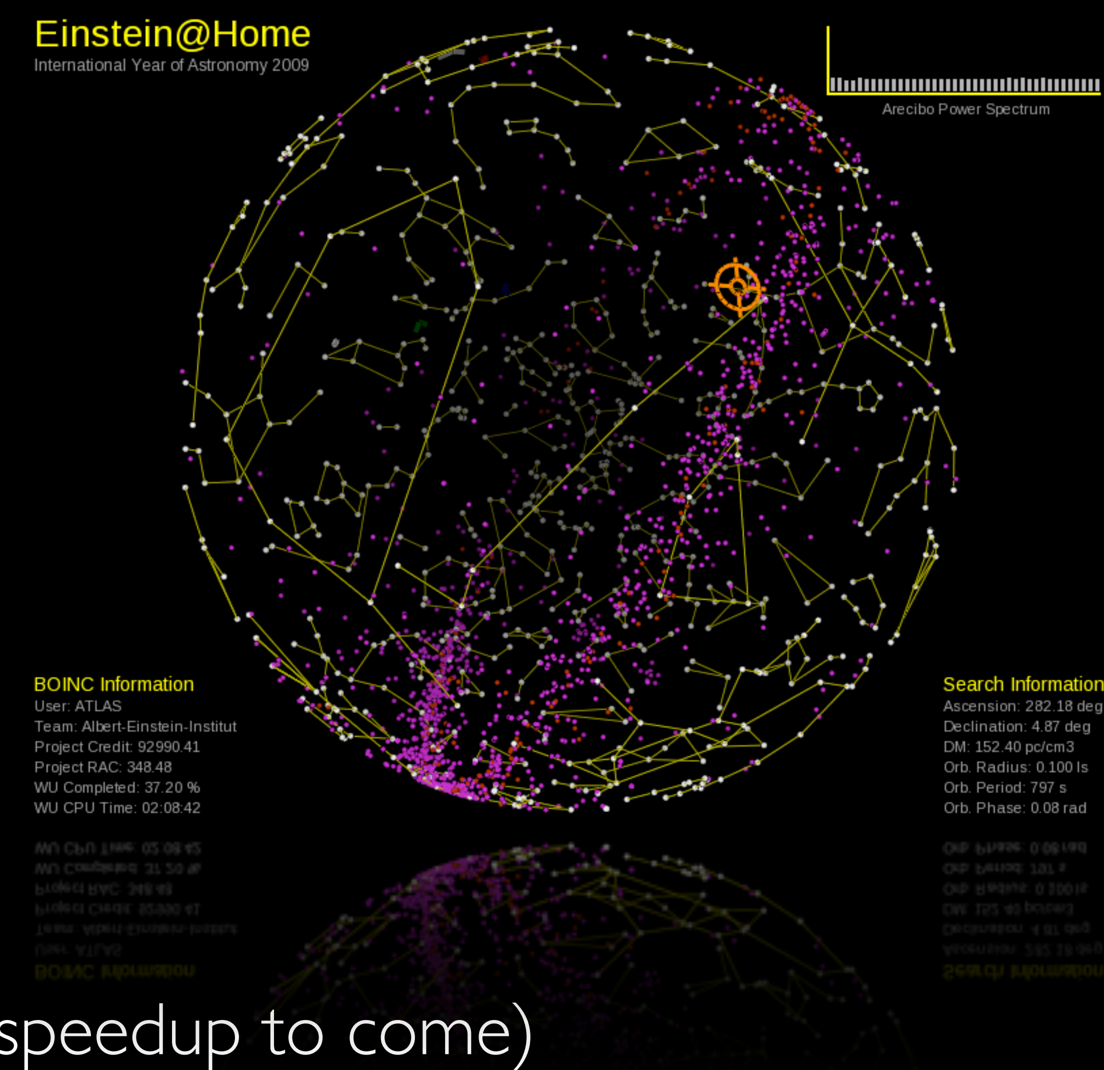
For more information on the Einstein@Home search for binary pulsars in Arecibo data and the results shown here visit the project background / FAQ pages.

Table of Re-Detections

Pulsar	f_{topo} [Hz]	DM [pc cm^{-3}]	finish date	WU name & Users	Detection Plot	Confirmation Plot
J1852+0305 (ATNF psrcat)	0.75414	352.1	03 Oct 2009	p2030_54167_43749_0017_G35.71+01.15.C_6.dm_525 140070 (William D Moates); Tue, 01 Sep 2009 14:25:33 194896 (Andrzej Latanski); Wed, 16 Sep 2009 20:09:19		
B2002+31 (ATNF psrcat)	0.47365	229.2	26 Sep 2009	p2030_53614_06858_0060_G68.94-00.06.N_4.dm_395 39 (Steffen Grunewald,...); Sat, 05 Sep 2009 14:40:39 9896 (supermushroom2go); Fri, 11 Sep 2009 11:08:31		
J1903+0327 (ATNF psrcat)	465.11	297.3	20 Sep 2009	p2030_53991_01873_0015_G37.28-00.97.N_5.dm_439 28646 (Armin Burkhardt,...); Wed, 12 Aug 2009 18:57:36 191534 (Erik A. Espinoza); Mon, 17 Aug 2009 05:11:27		
B1921+17 (ATNF psrcat)	1.8275	121.3	14 Sep 2009	p2030_53618_01978_0014_G51.72+00.82.N_2.dm_297 190685 (Chuck); Fri, 07 Aug 2009 22:12:52		

The Final Slide

- **first ever:**
  - fully coherent search for radio pulsars in tight binaries
  - sensitive to binary pulsars with P_{orb} much less than anything known



- **possible detection very valuable for**
  - tests of General Relativity
  - various GW searches
  - distributed computing

- **progress:**
  - working CPU code for major platforms
  - twice as fast GPU code in beta stage, (more speedup to come)
  - weekly re-detections of known pulsars
  - 3.3x more speed soon (improved template bank)