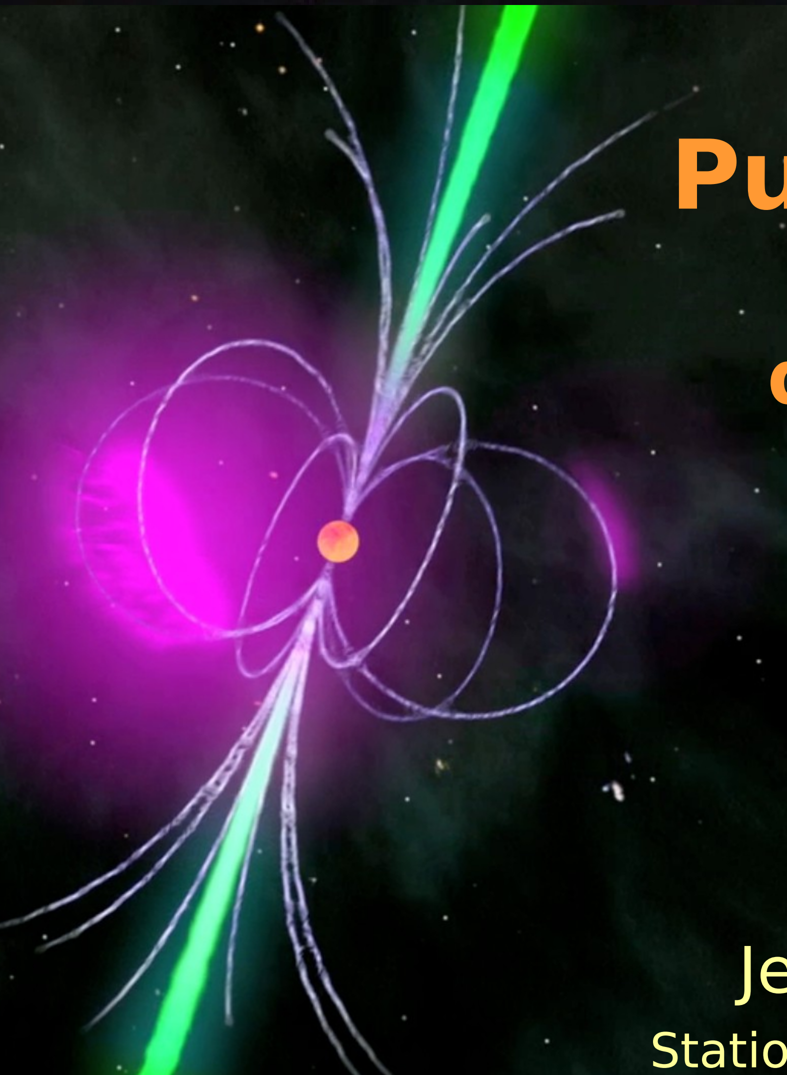
Pulsar timing and the IISM:
dispersion, scattering



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- Pulsar timing
- Dispersion
- Scattering
- Scintillation

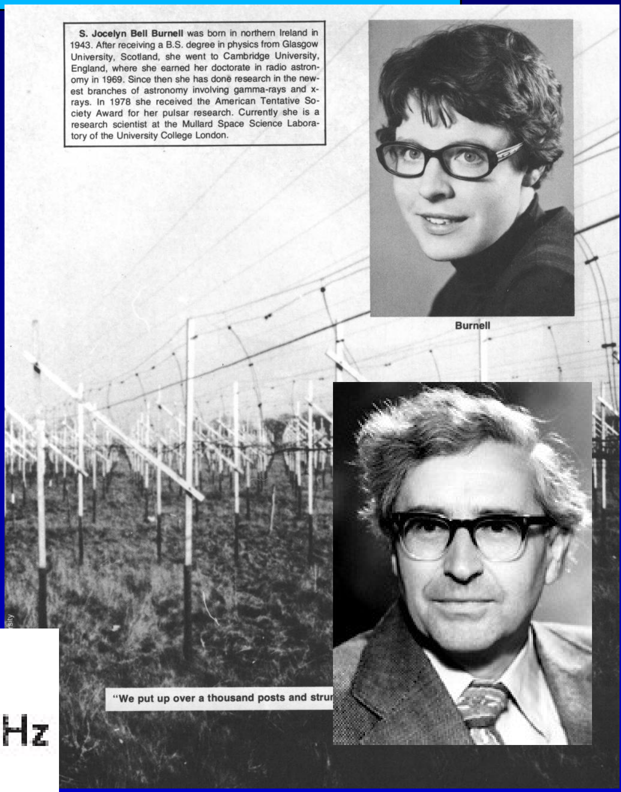
1967: First pulsar detection

radio observation (~81.5 MHz)

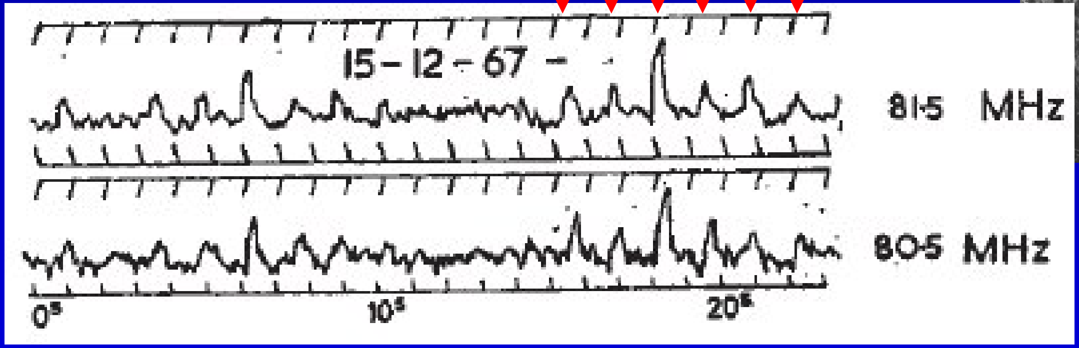
RA: 19h19m

DEC: +21°47'

→ astronomical source

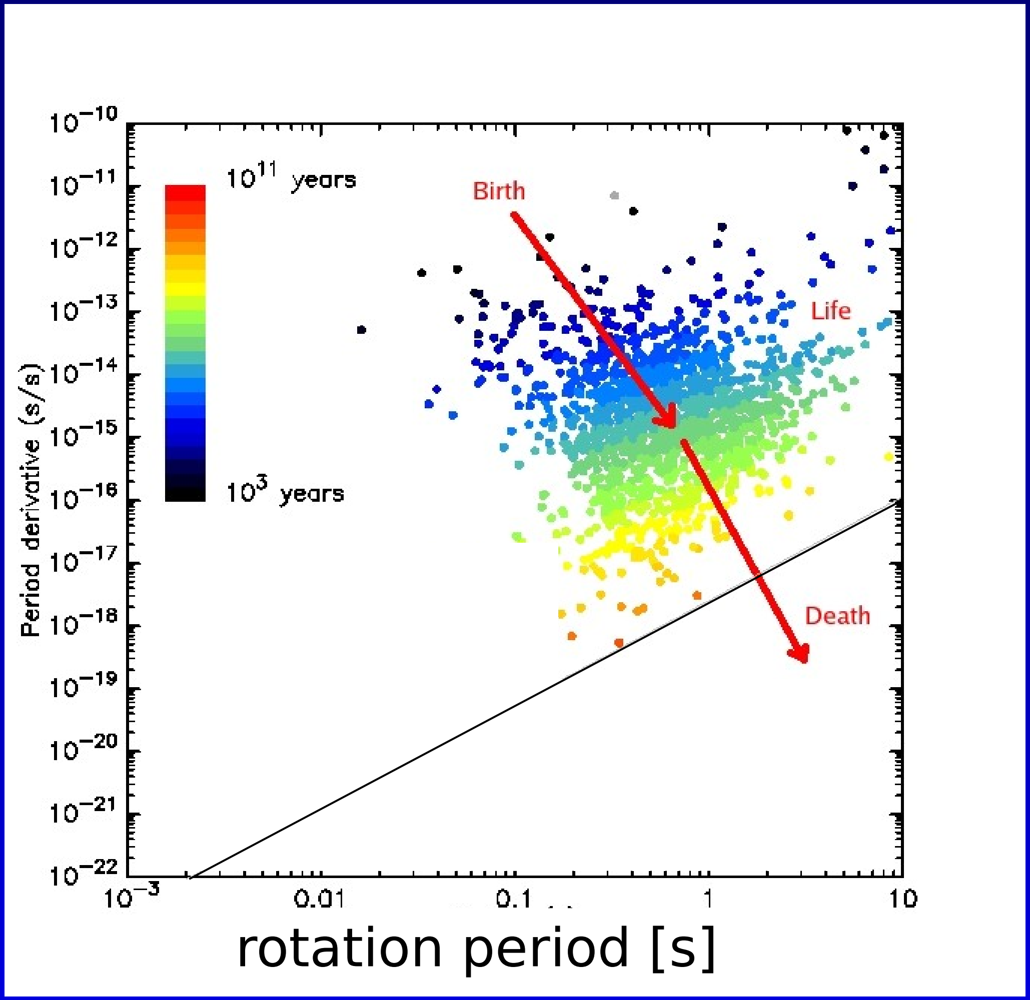


one pulse every 1.337301192269 s!



[Hewish et al. 1968]

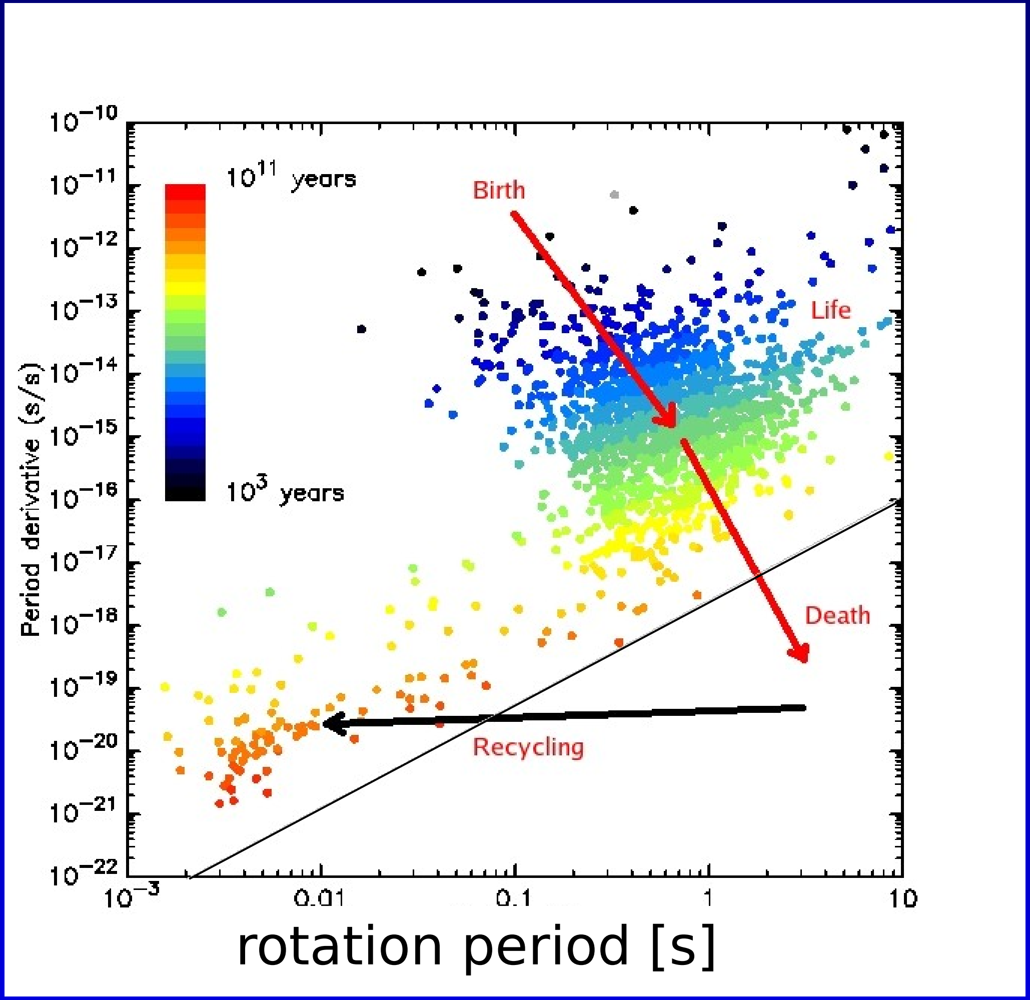
The two lives of pulsars



t=0: P0~30 ms (given by conservation of angular momentum)

rapid slowdown
end of emission after a few 10s of Myr (P0>1s)

The two lives of pulsars

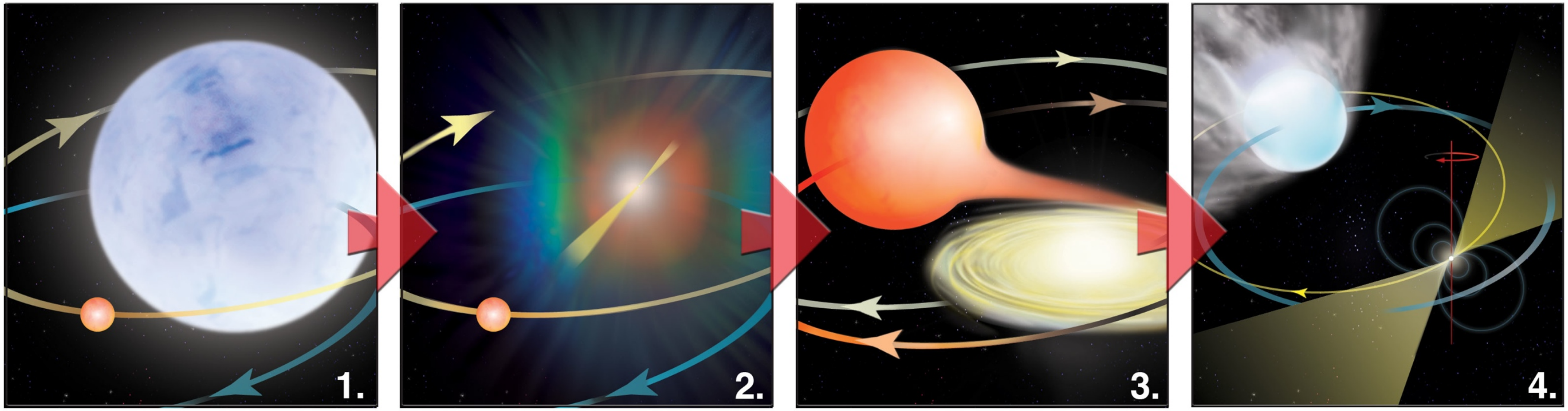


t=0: P0~30 ms (given by conservation of angular momentum)

rapid slowdown
end of emission after a few 10s of Myr (P0>1s)

some pulsars get re-accelerated and emit again in radio
"recycled pulsars"
"millisecond-pulsars"
(P0~3 ms)
(P1~10^{-20}!)
[Alpar et al. 1982]

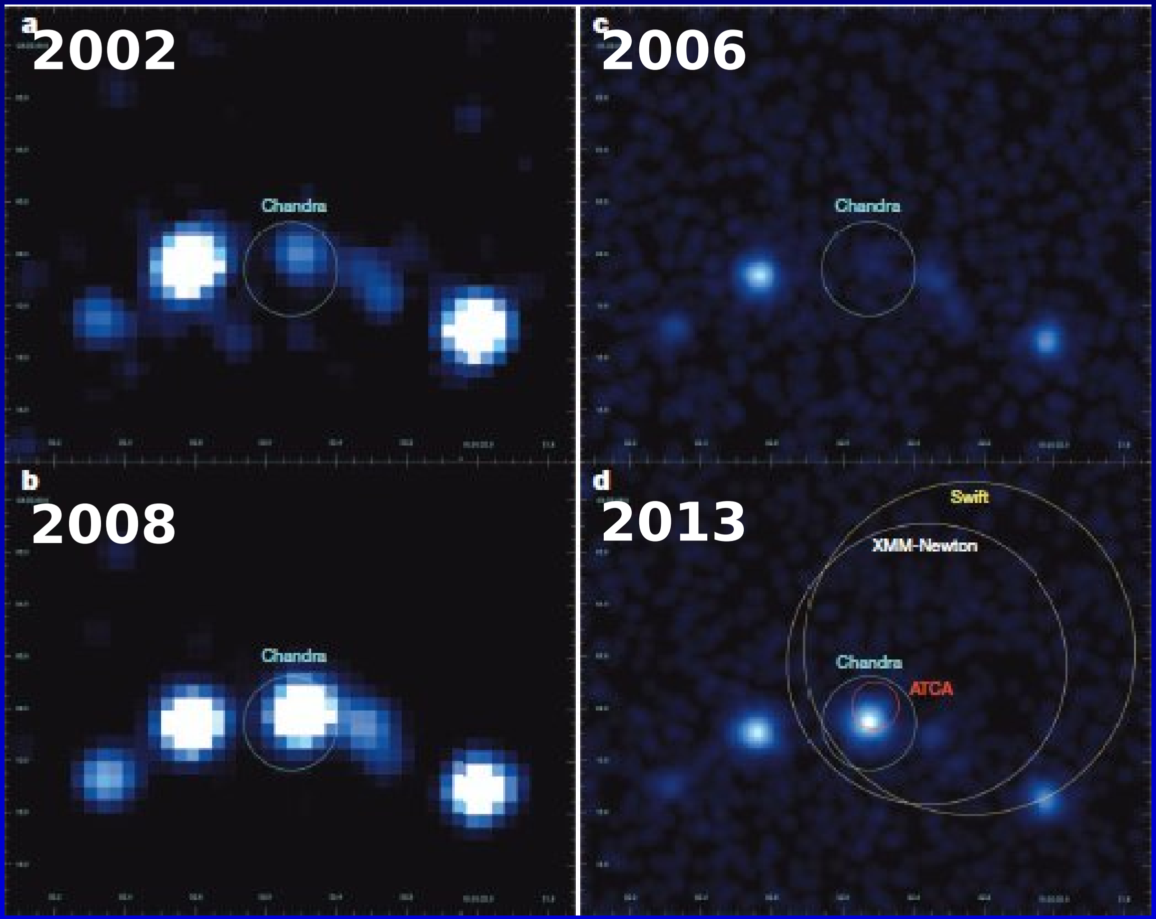
Pulsar recycling

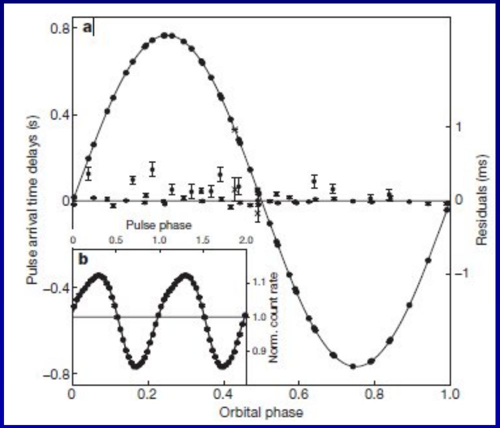


Saxton, NRAO

[Alpar et al. 1982; Rhadakrishnan et al. 1984]

Pulsar recycling

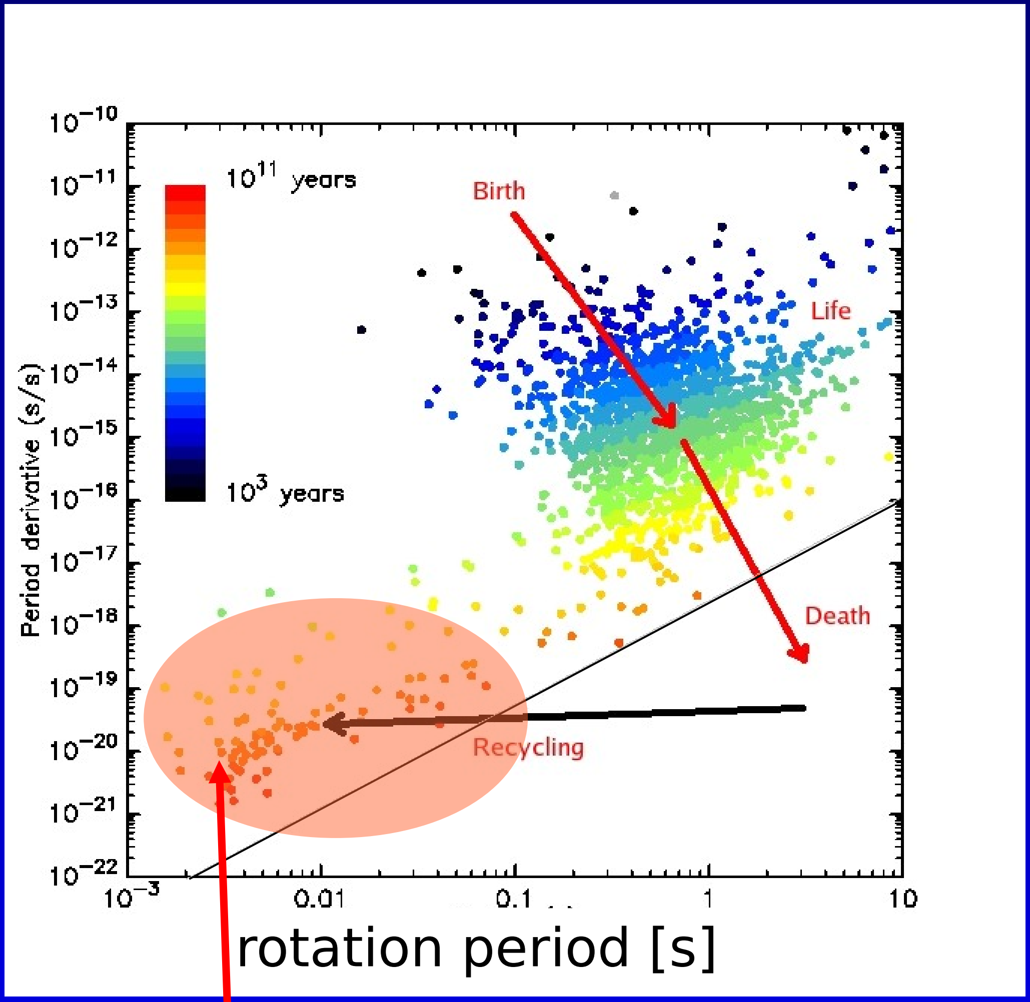




[Papitto et al. 2013]

IGR J18245-2452 = PSR M28I

The two lives of pulsars



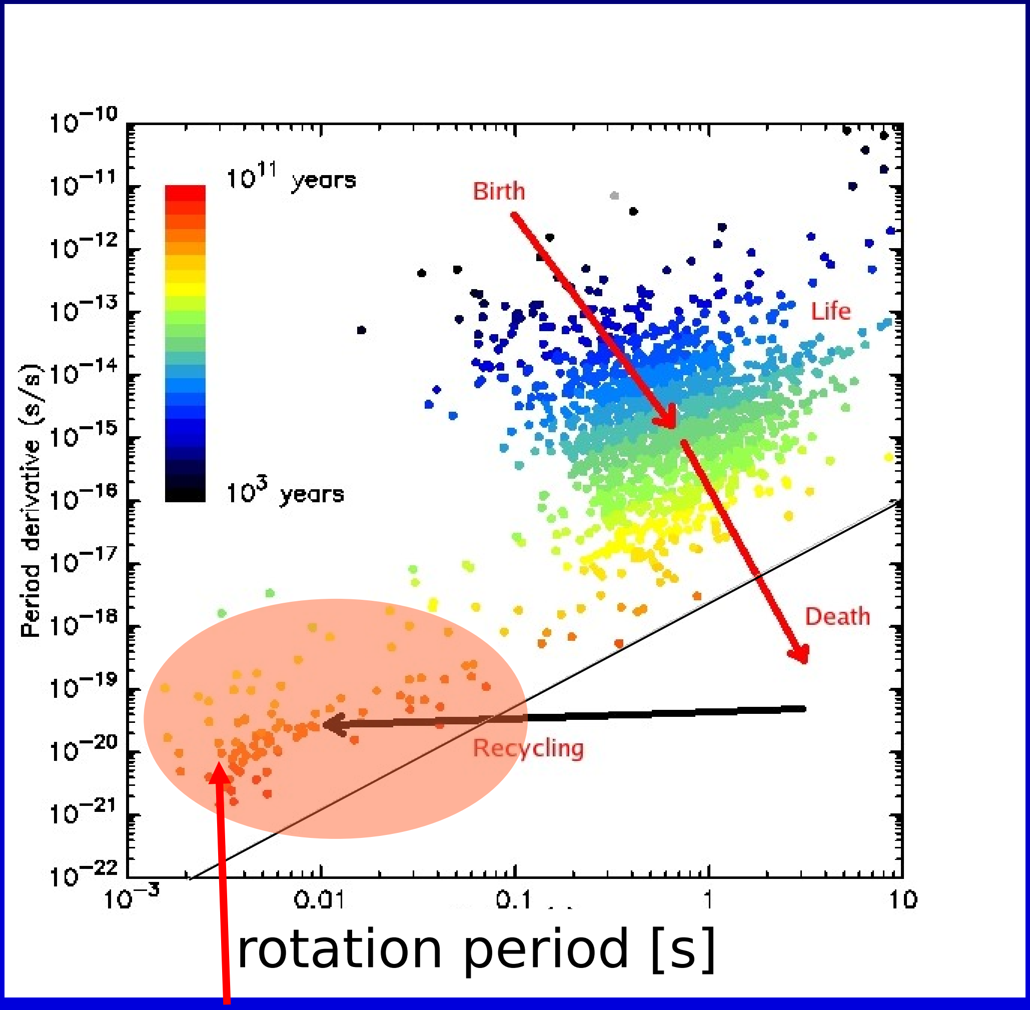
PSR J1909-3744
observation on 2013-03-12, 20h30
P0 = 2.947108068107624(2) ms
P1: 0.00000000000001 in 2 mins

t=0: P0~30 ms (given by conservation of angular momentum)

rapid slowdown
end of emission after a few 10s of Myr (P0>1s)

some pulsars get re-accelerated and emit again in radio
"recycled pulsars"
"millisecond-pulsars"
(P0~3 ms)
(P1~10^{-20}!)
[Alpar et al. 1982]

The two lives of pulsars



t=0: P0~30 ms (given by conservation of angular momentum)

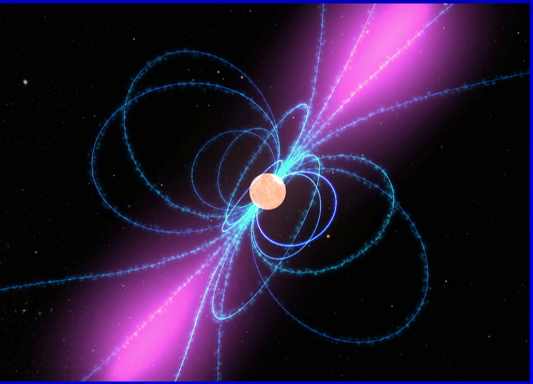
rapid slowdown
end of emission after a few 10s of Myr (P0>1s)

some pulsars get re-accelerated and emit again in radio
“recycled pulsars”
“millisecond-pulsars”
(P0~3 ms)... forever!
(P1~10^{-20}!)
[Alpar et al. 1982]

PSR J1909-3744
observation on 2013-03-12, 20h30
P0 = 2.947108068107624(2) ms
P1: 2.6 ms in 10 Gyr

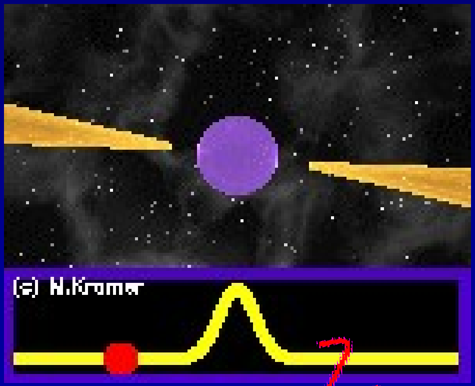
Physics and measurements

- mesuring time = counting clock ticks
  - → can be extremely precise
  - → possible to measure tiny effects
- however: requires a precise clock!
  - → use highly stable MSPs
  - → “pulsar timing”



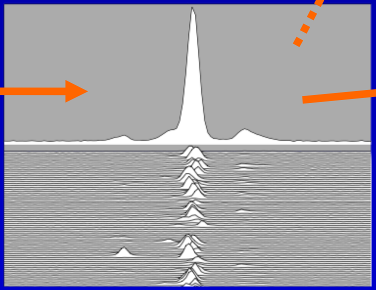
PSR J1909-3744
observation on 2013-03-12, 20h30
P0 = 2.947108068107624(2) ms
P1: 0.000000000000001 in 2 mins

TOAs ("time of arrival")

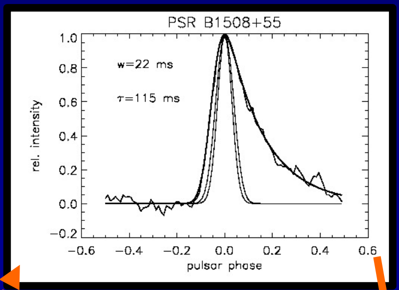


pulsar

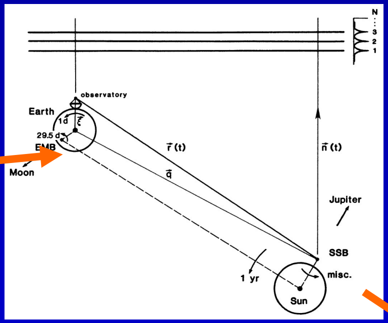
radio telescope



dedispersion
integration



reference profile



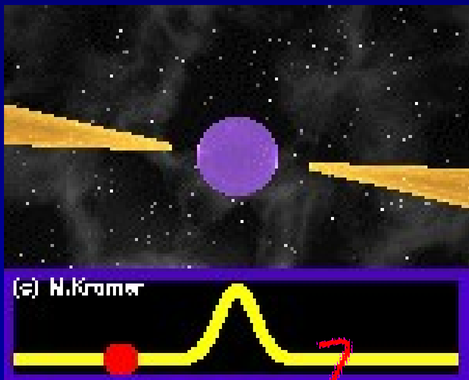
barycentric
correction

Temps d'arrivée du pulsar J1600-3053

Observatory Code	'1'	Pulsar Name	Freq [MHz]	TOA [MJD]	Uncert [μs]
f	1	1600-30	1368.000	54033.5511921591647	0.48
f	1	1600-30	1368.000	54036.5385764225914	0.54
f	1	1600-30	1368.000	54048.5021991052575	0.59
f	1	1600-30	1368.000	54051.5056597667359	0.50
f	1	1600-30	1368.000	54054.4968287444377	0.46
f	1	1600-30	1368.000	54056.4913888998682	0.48
f	1	1600-30	1368.000	54057.4889815273292	0.52
f	1	1600-30	1368.000	54060.4810301095328	0.51
f	1	1600-30	1368.000	54065.4600579101507	0.60
f	1	1600-30	1368.000	54071.4479745723167	0.57
f	1	1600-30	1368.000	54072.4445486474761	0.53
f	1	1600-30	1368.000	54079.4312384526258	0.50

TOAs

TOAs ("time of arrival")



pulsar

radio telescope

Ionized Interstellar medium (IISM)

- Pulsar timing
- Dispersion
- Scattering
- Scintillation

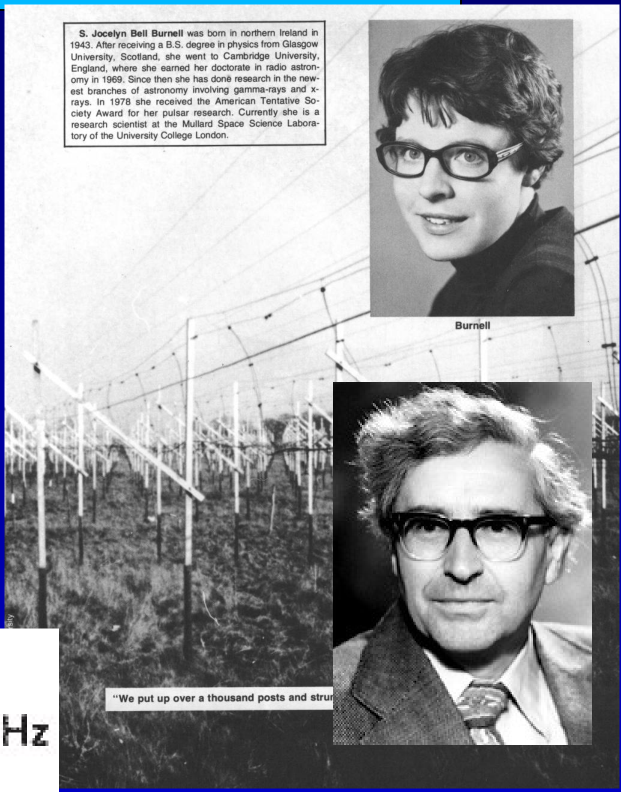
Dispersion

radio observation (~81.5 MHz)

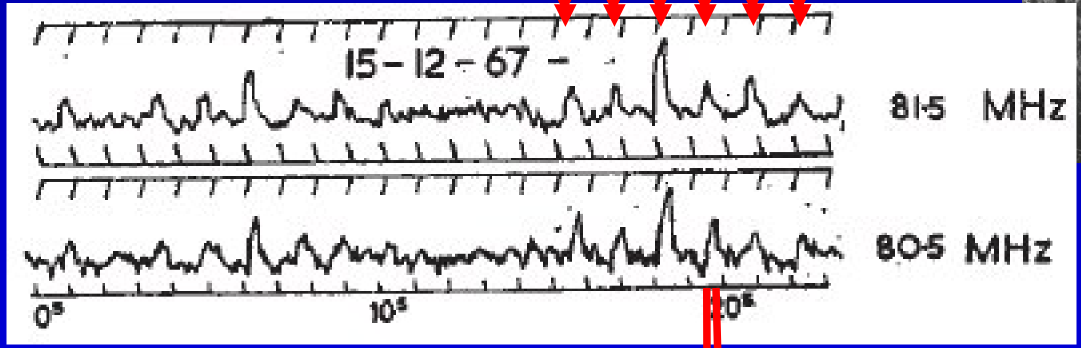
RA: 19h19m

DEC: +21°47'

→ astronomical source



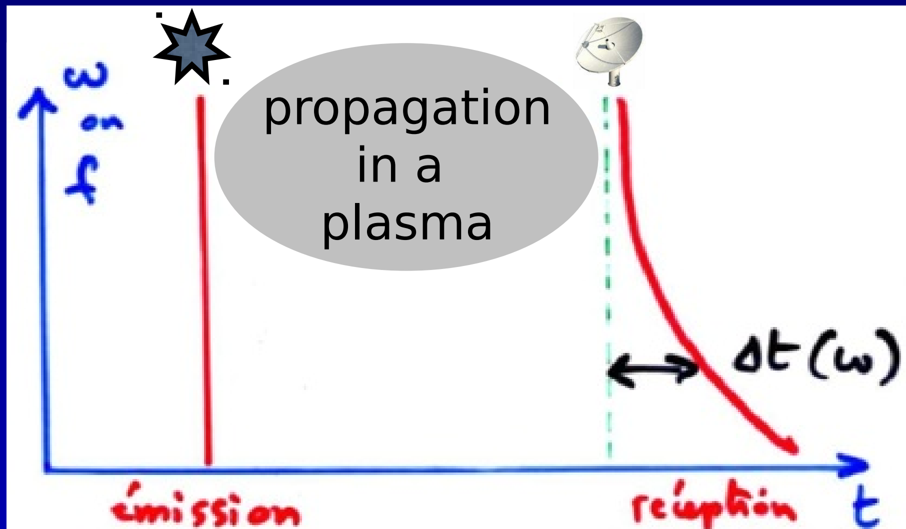
one pulse every 1.337301192269 s!



80.5 and 81.5 MHz : 0.2 s delay!

[Hewish et al. 1968]

Dispersion



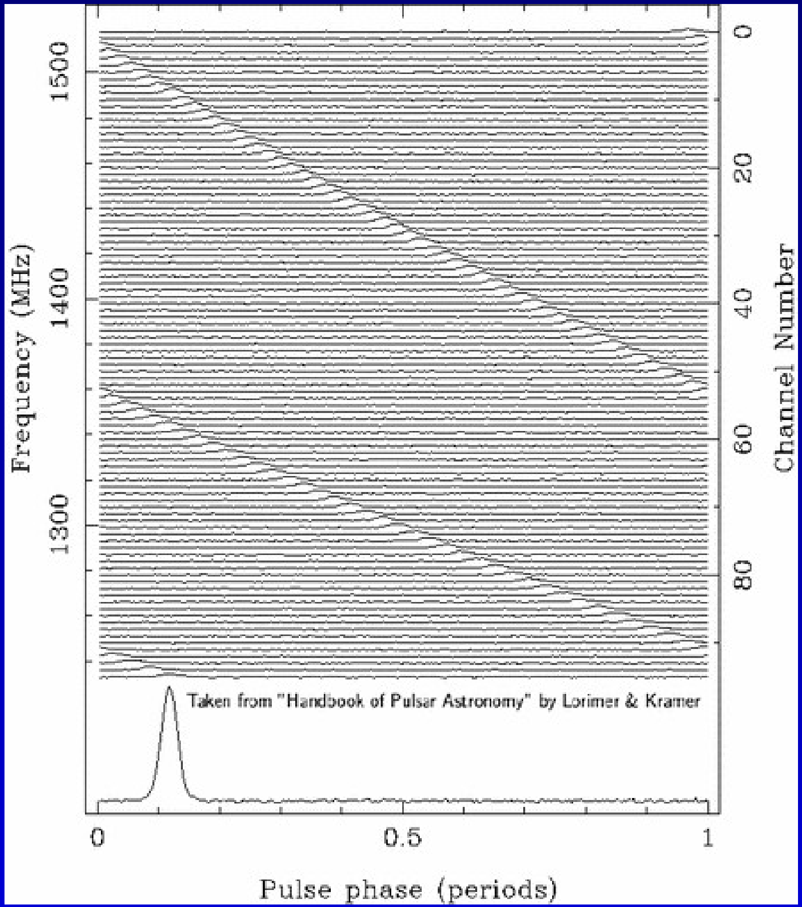
$$n = \sqrt{1 - \frac{f_{plasma}^2}{f^2}}$$

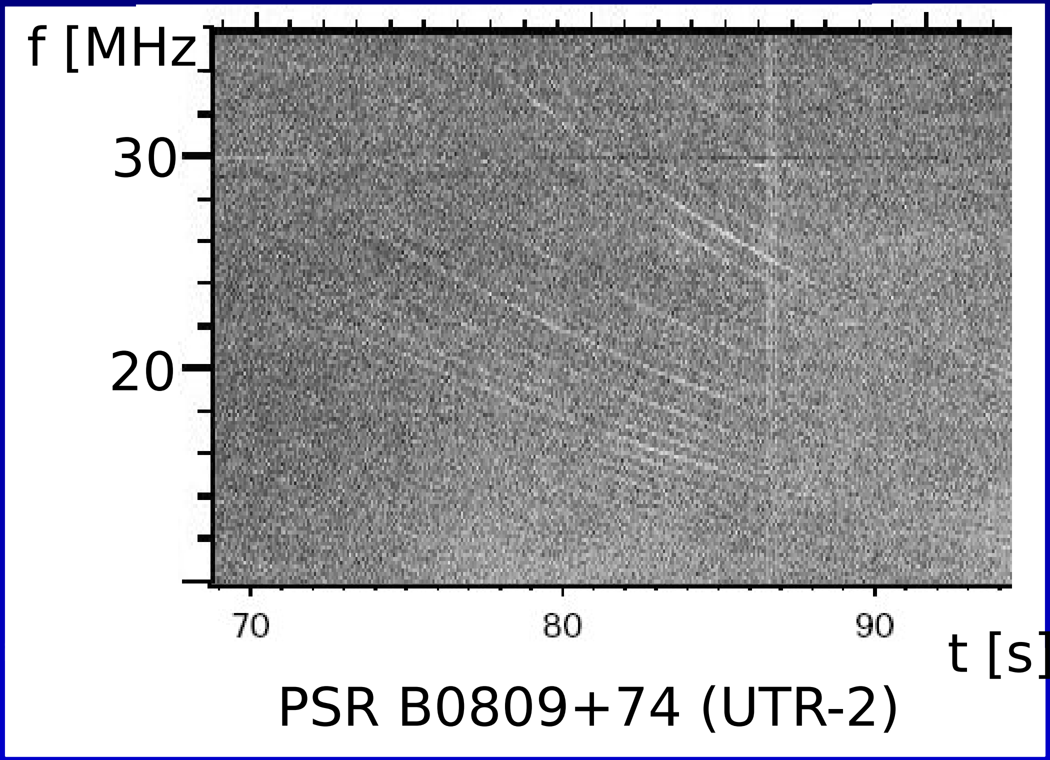
$$f_{plasma} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

- refractive index of interstellar medium: n(ν)
- lower frequencies are delayed

$$t(\nu_2) - t(\nu_1) = \frac{\mathrm{DM}}{a}\left(\frac{1}{\nu_2^2} - \frac{1}{\nu_1^2}\right)$$

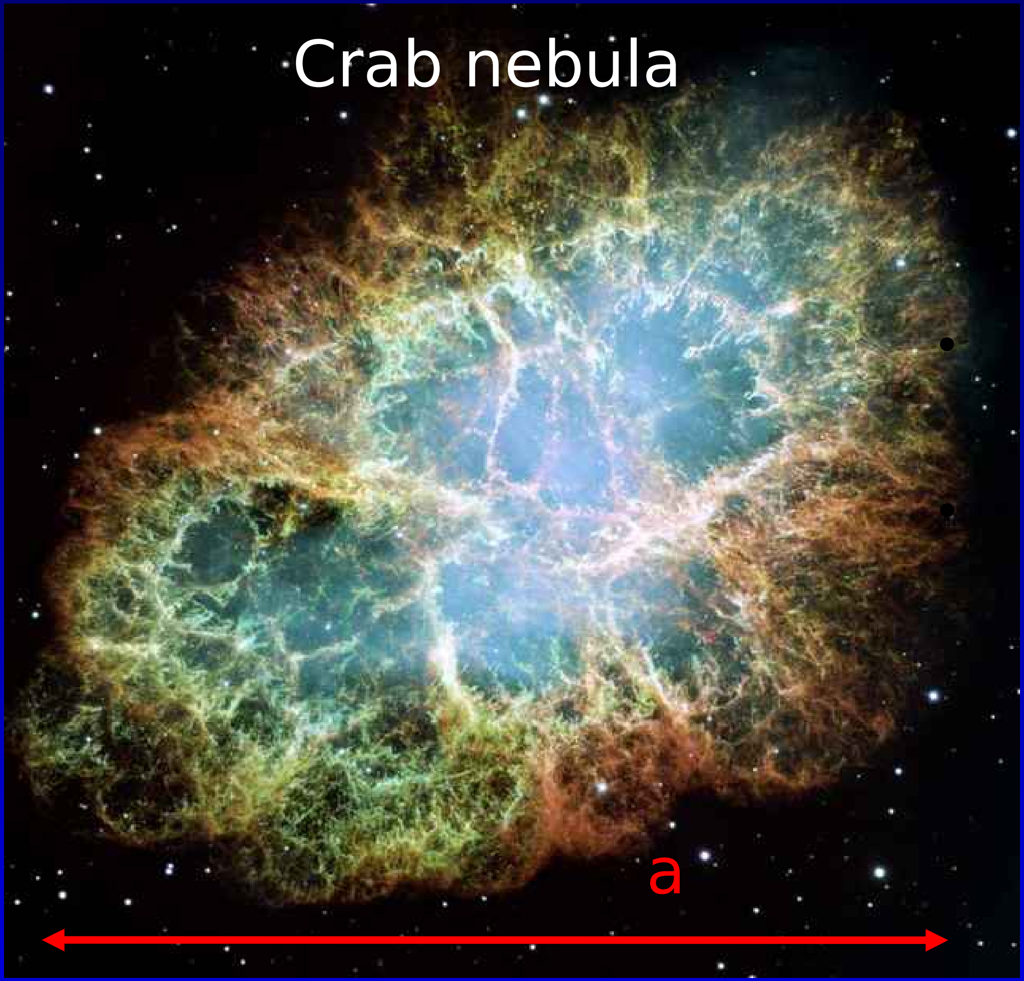
Dispersion : PSR B0809+74





between 1410 & 1400 MHz	(DM=5.8): 0.2 ms
between 150 & 140 MHz	(DM=5.8): 0.2 s
between 24 & 14 MHz	(DM=5.8): 81 s

The dispersion measure



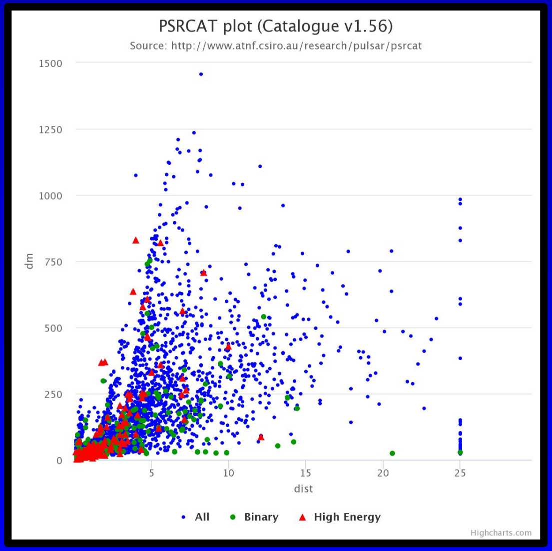
d=2 kpc, a=3 pc

$$\Delta t(f) \approx 4.15\times10^{3}\, DM\, f^{-2}$$

$$\left[DM\right] = \int n_e\, dl$$

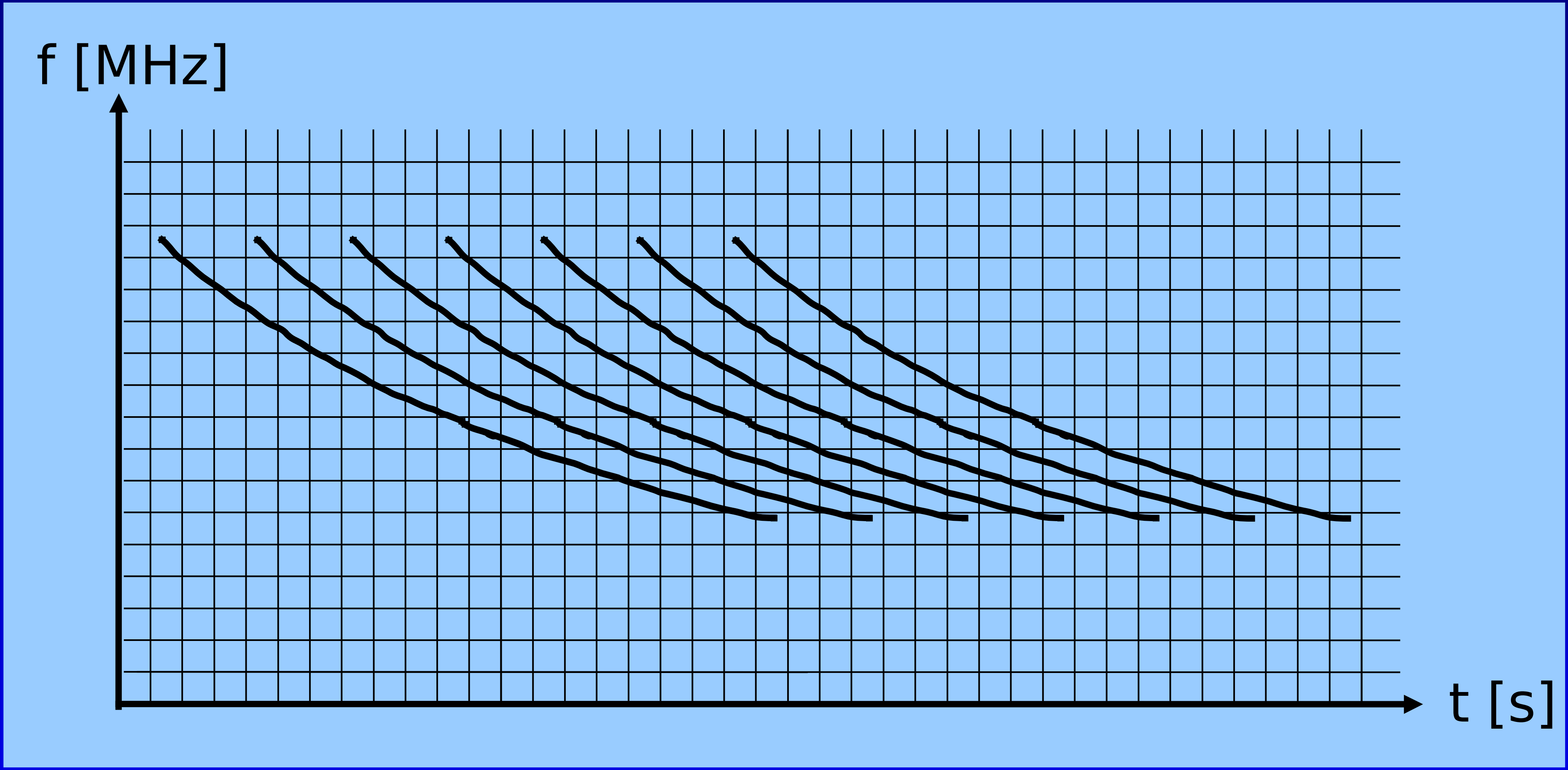
DM is large for distant source

DM is large for pulsars surrounded by ionized medium (SNR)



Incoherent dedispersion

dispersion can be corrected



Incoherent dedispersion

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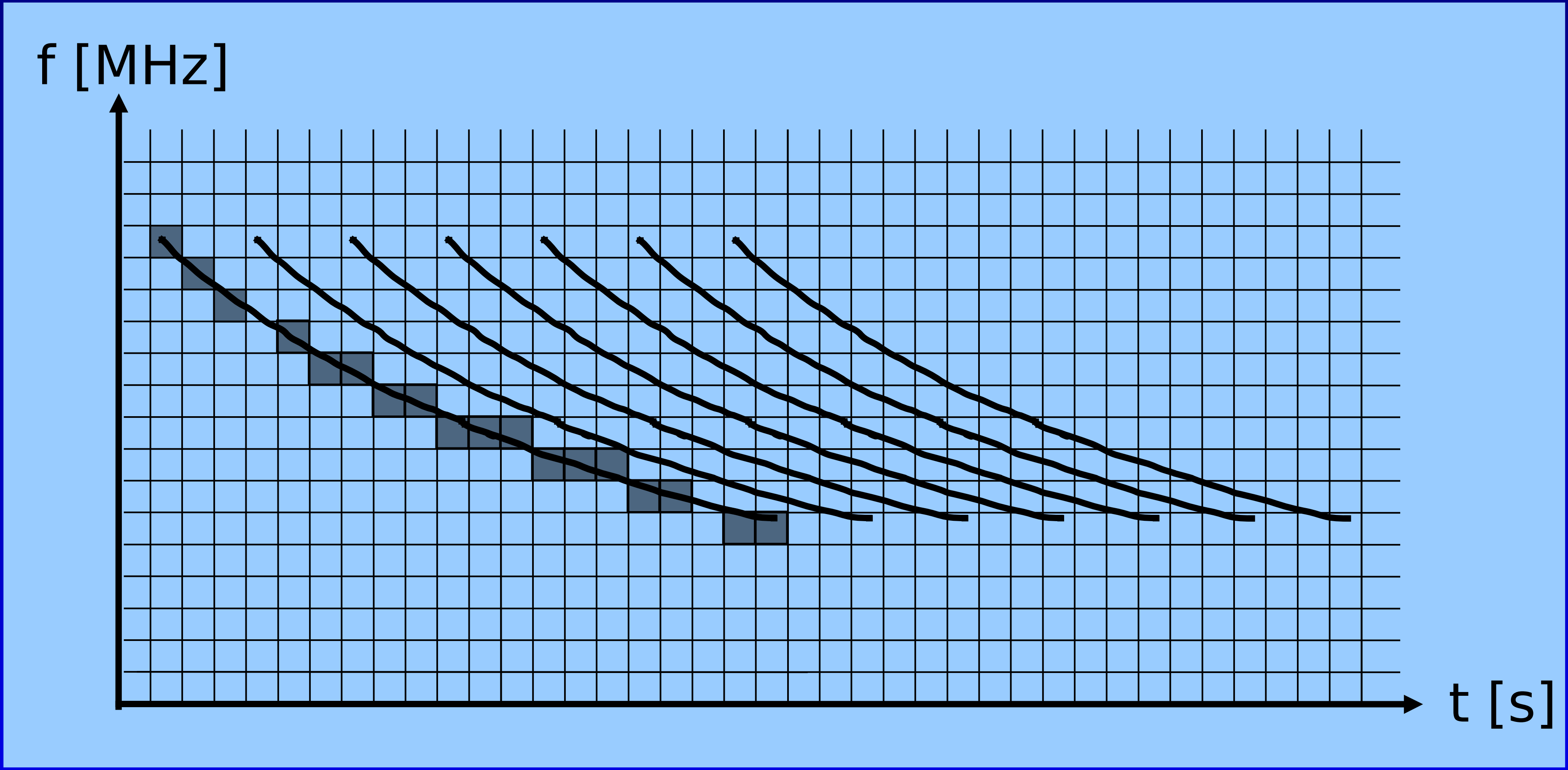
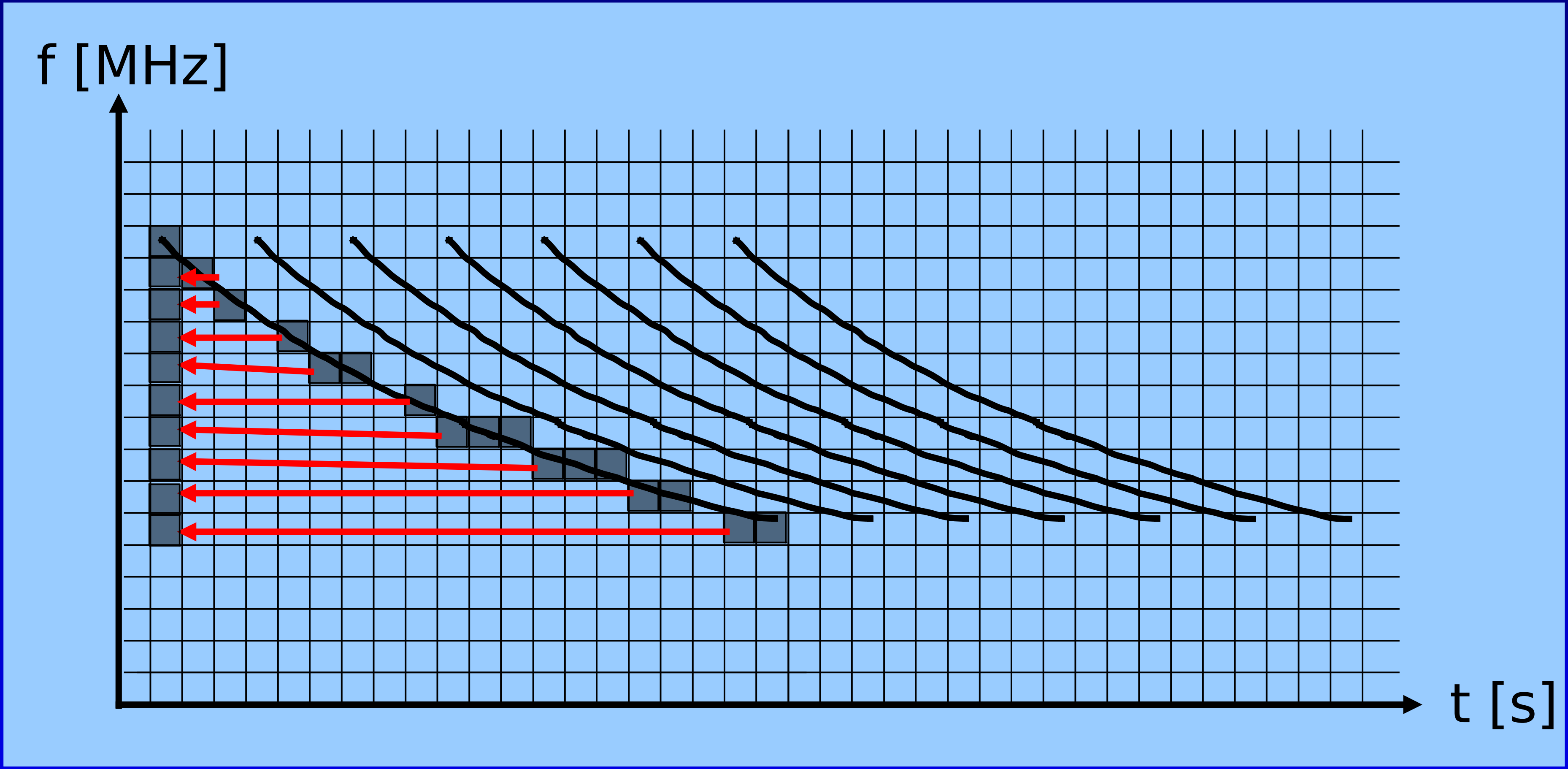
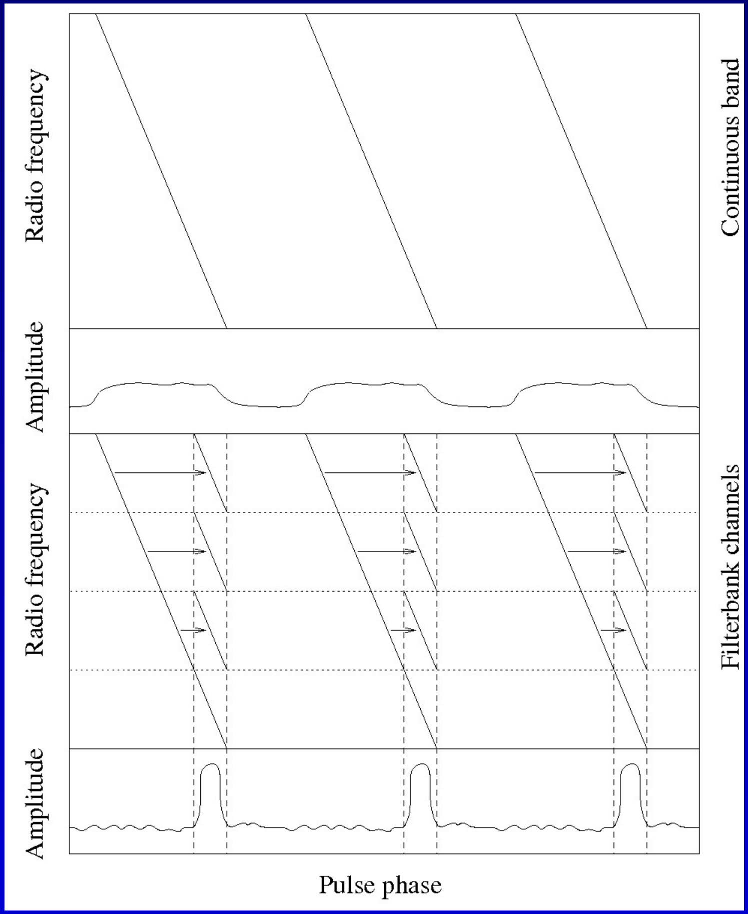


Incoherent dedispersion

dispersion can be corrected

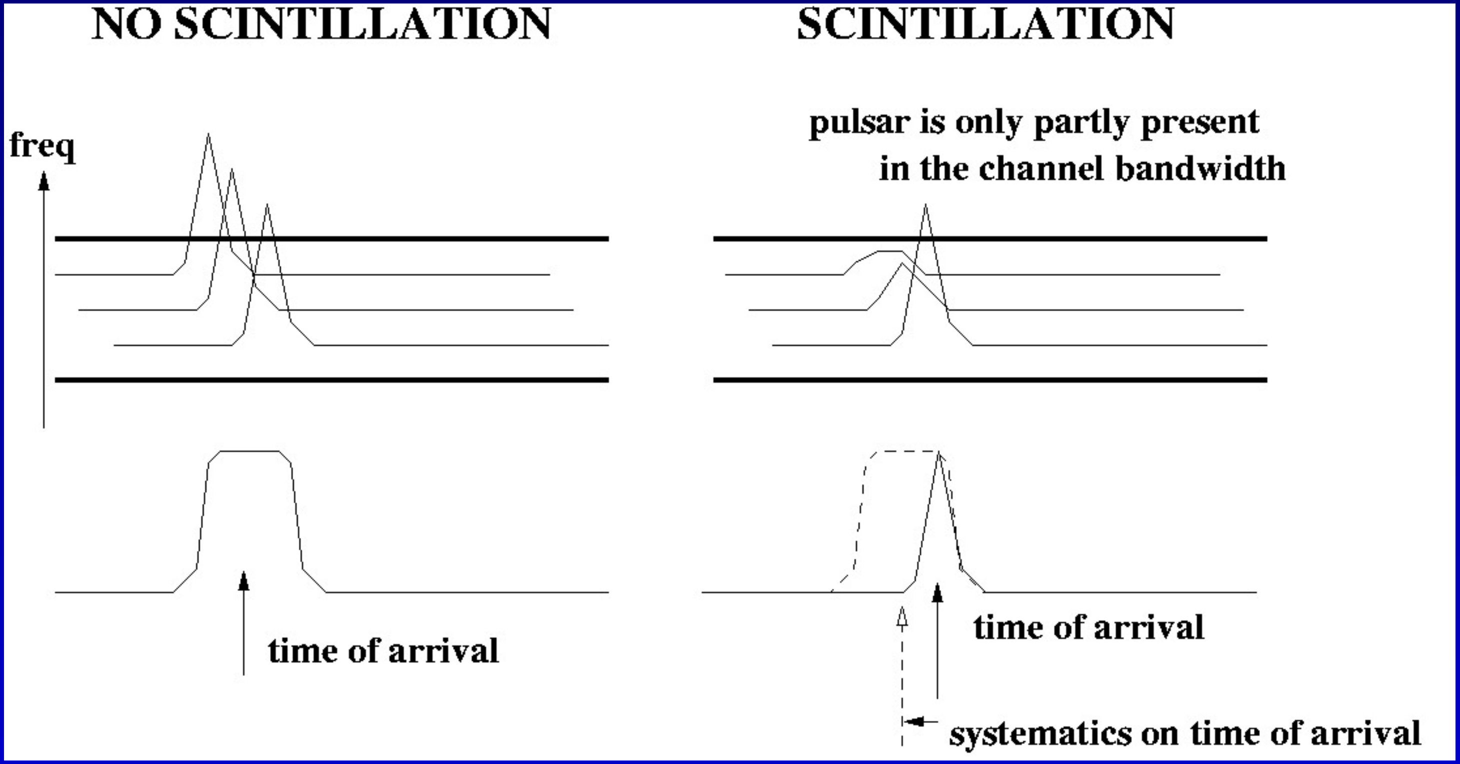


Incoherent dedispersion



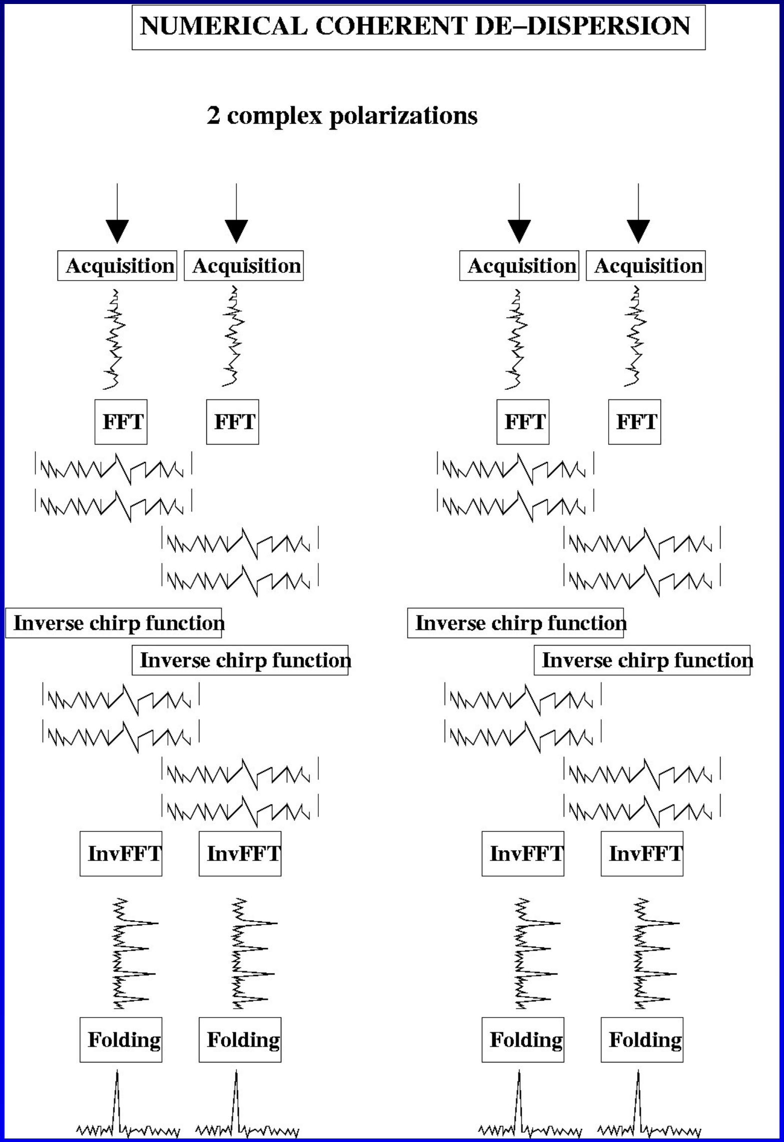
problem 1: integrated profile widens→ less precision for timing

Incoherent dedispersion



problem 2: in the case of scintillation, the integrated profile shifts!

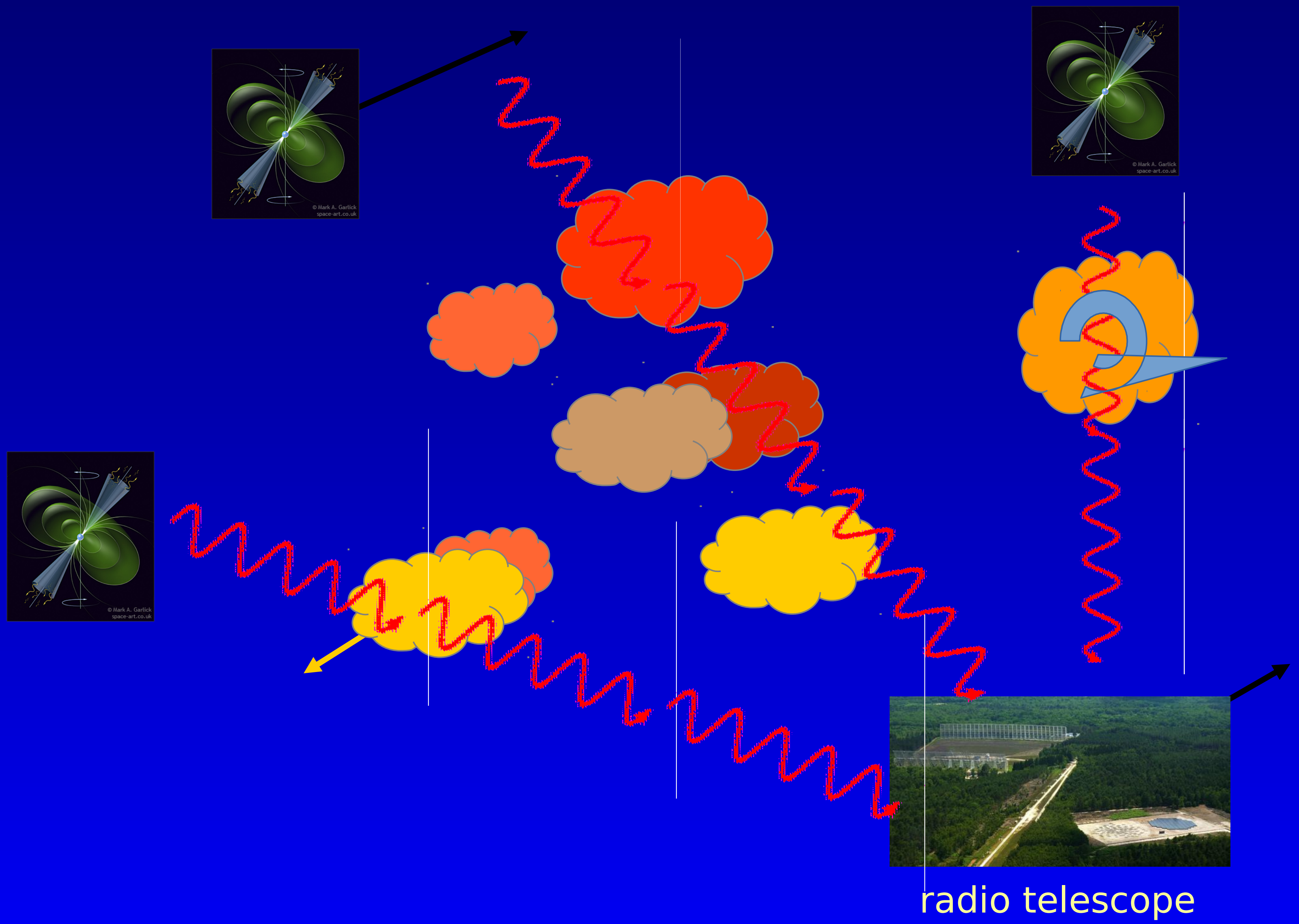
Coherent dedispersion



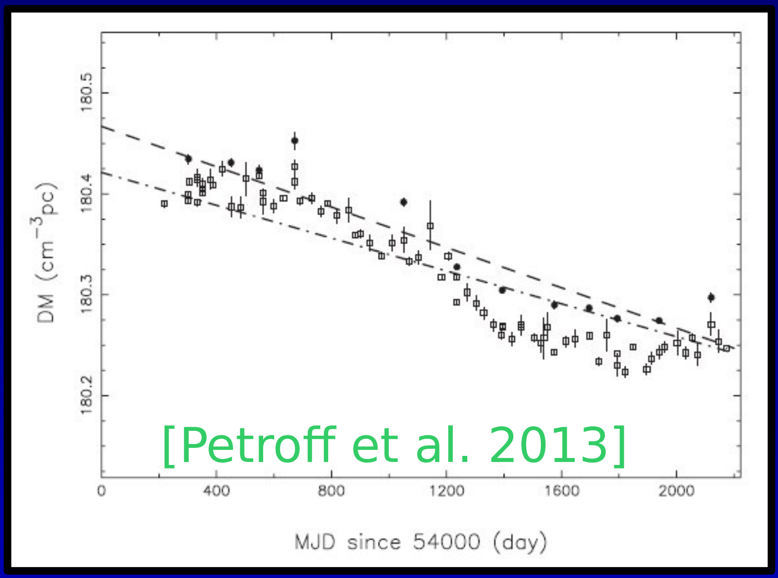
- FFT + inverse filter + FFT^{-1}
- computationally (much!) more expensive
- avoids the problems of incoherent dedispersion
- routinely used since ~2000

→ for pulsar timing, use coherent dedispersion whenever possible!

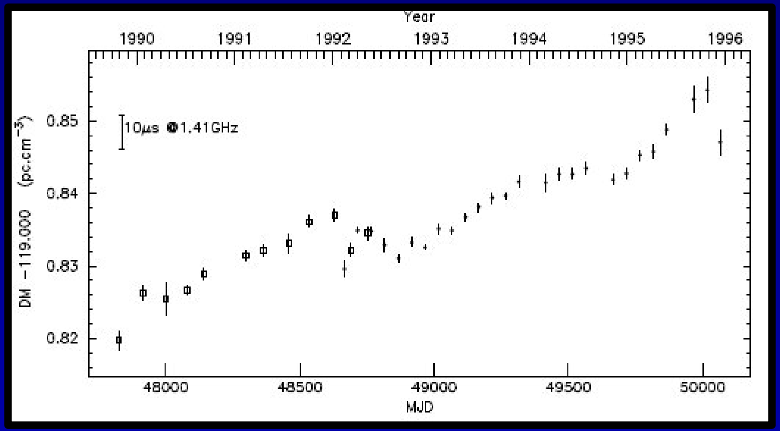
Interstellar medium: variations



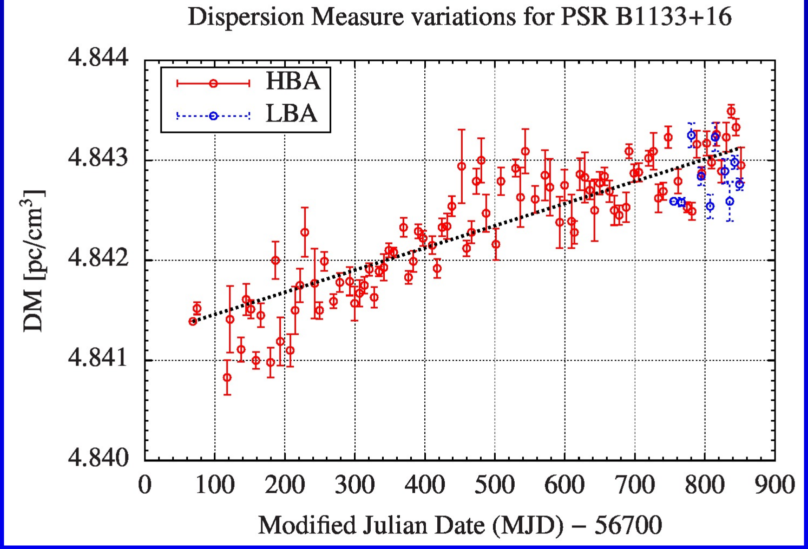
DM variations



[Petroff et al. 2013]



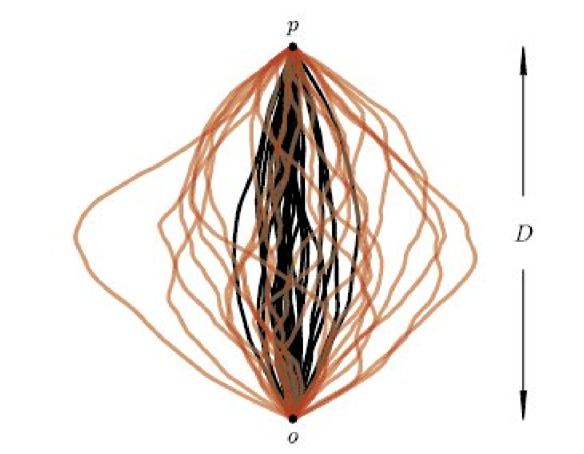
[Cognard et al. 1997]



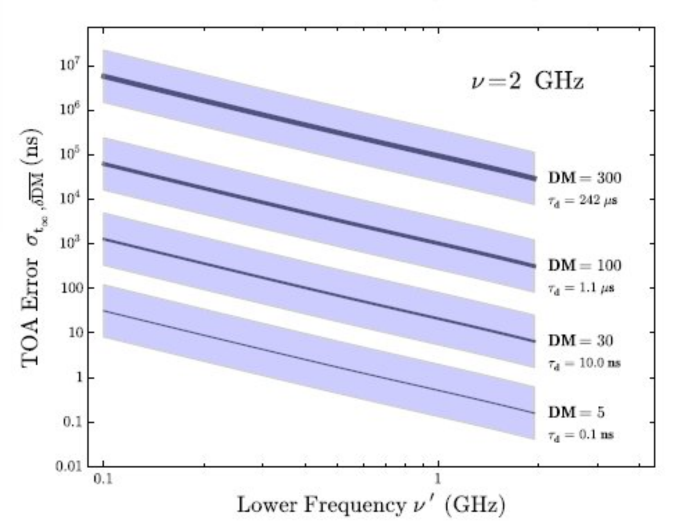
DM variations

- has to be taken into account in timing!
- one DM per observation!
- → less precision on DM and profiles
- → less precision on TOAs

- one possible solution:
- include low-frequency observations (simultaneous!)→ DM
- use this DM to correct high-frequency observations
- but: low- and high-frequency radio waves on the same path? [= frequency-dependent DM?]
- active field of research!



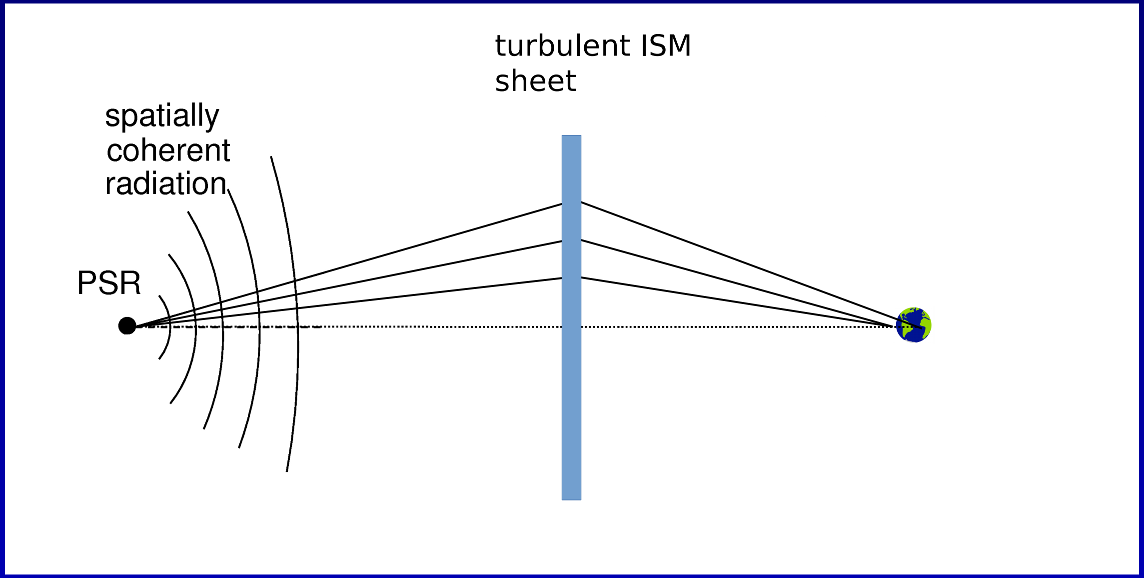
[Cordes et al. 2016]



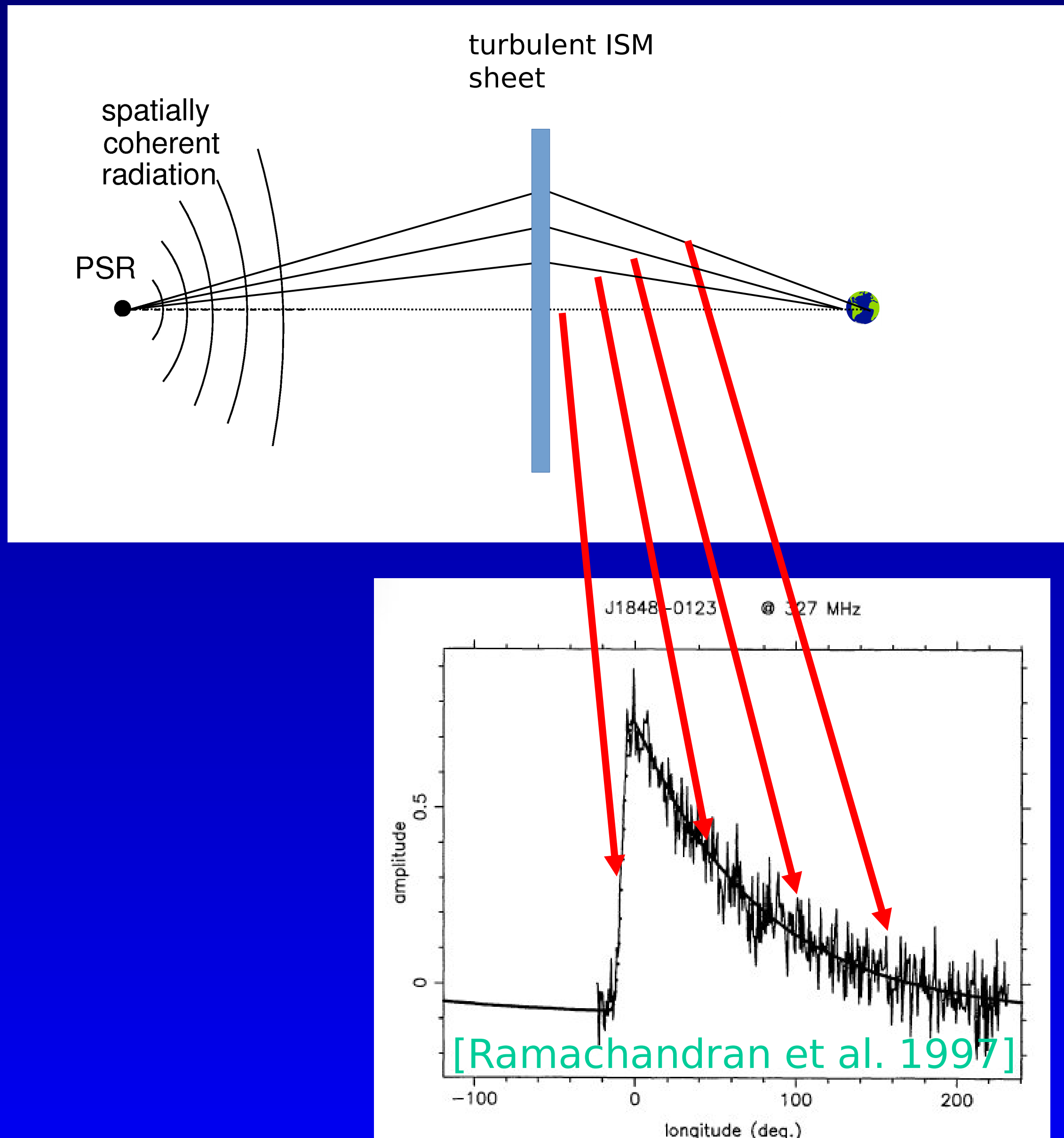
[Cordes et al. 2016]

- Pulsar timing
- Dispersion
- Scattering
- Scintillation

Scattering (scatter broadening)



Scattering (scatter broadening)



Scattering

$$y(t) = x(t) * s(T) * d(t) * i(t)$$

- observed profile
- intrinsic profile
- scatter broadening
- channel dispersion
- instrument

[Ramachandran et al. 1997]

Scattering

$$y(t) = x(t) * s(T) * d(t) * i(t)$$

observed profile

intrinsic profile

scatter broadening

channel dispersion

~~instrument~~

~gaussian

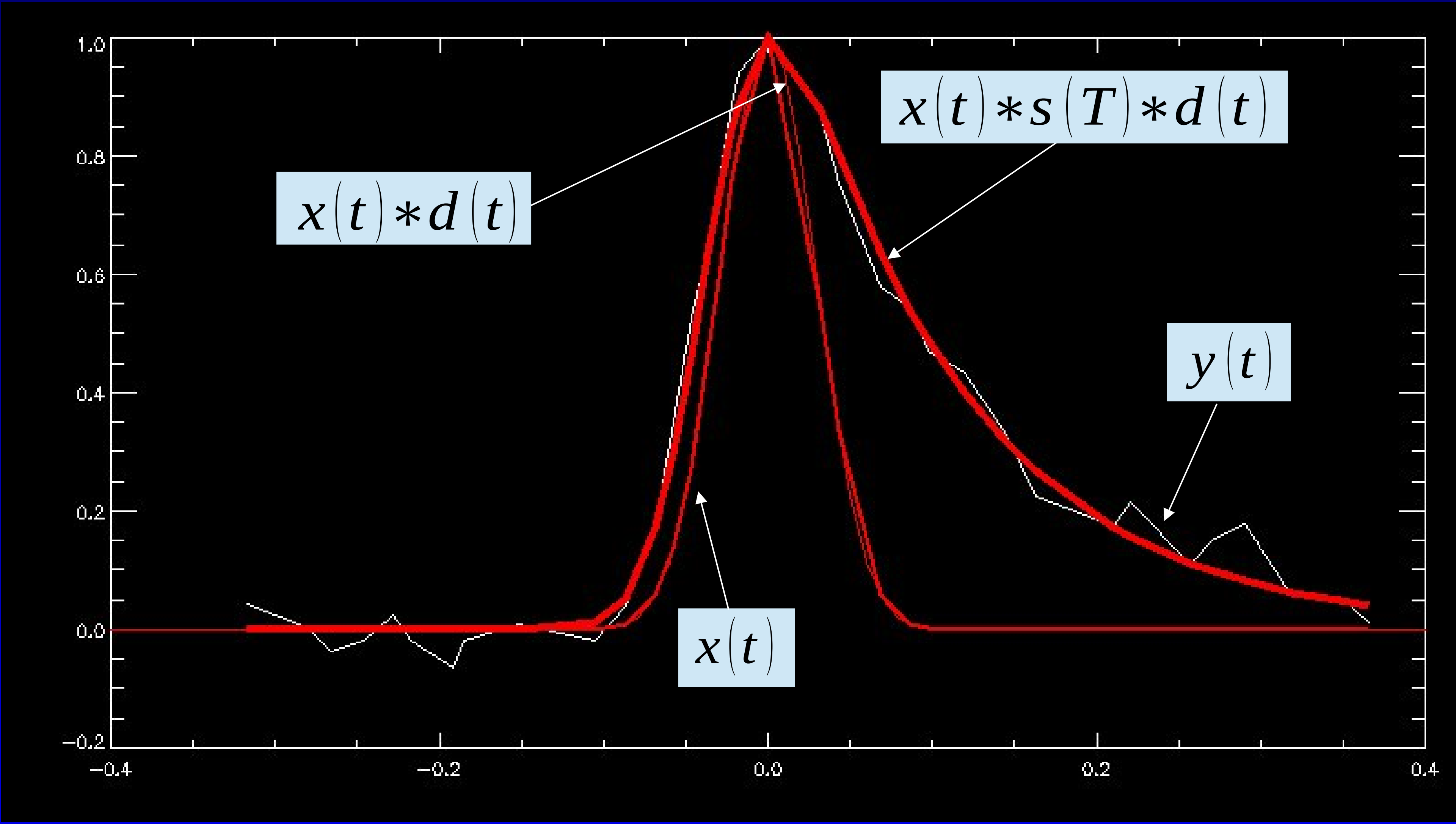
rectangular

$$s(t) = \exp(-t/\tau_{sc})$$

$$\tau_{sc}$$

$$\tau_{sc} \propto f^{-4}$$

Scattering

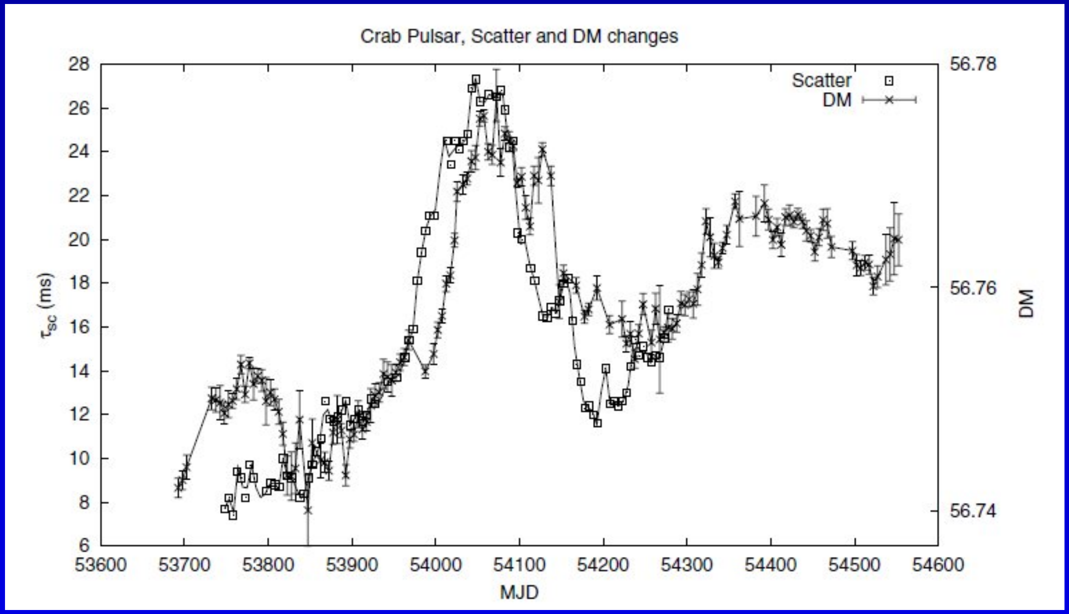


$w = 25\ ms$ $d = 50\ ms$ $\tau = 108\ ms$

Time variable scattering

- time-independent scattering can be (partially) corrected
- broader profiles → less precision on TOAs

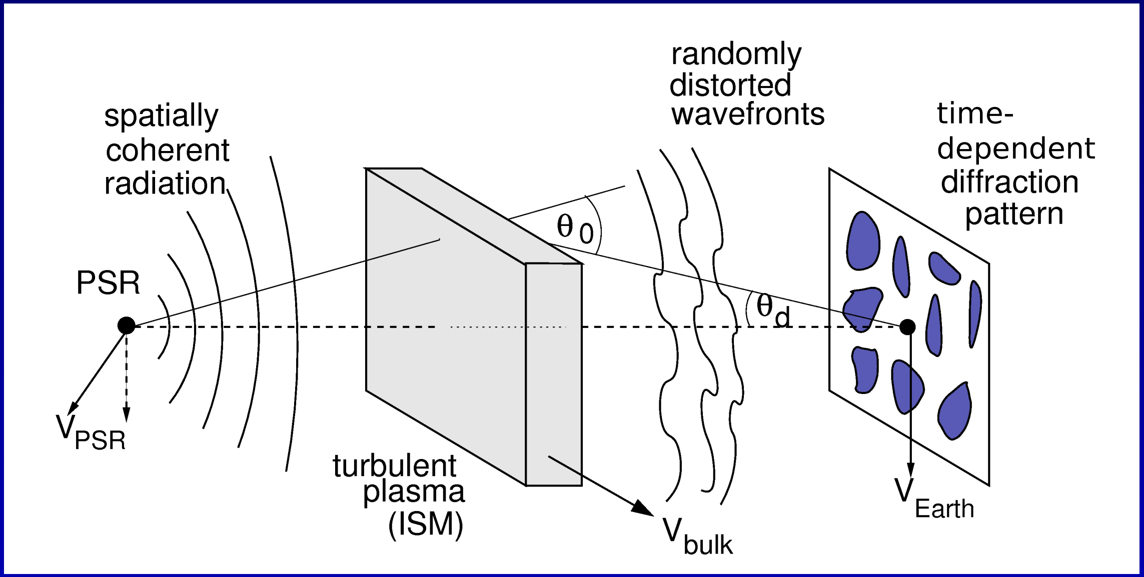
- variations in the ISM → time dependent scatter broadening $\tau_{sc}(t)$
- reduces precision of TOAs



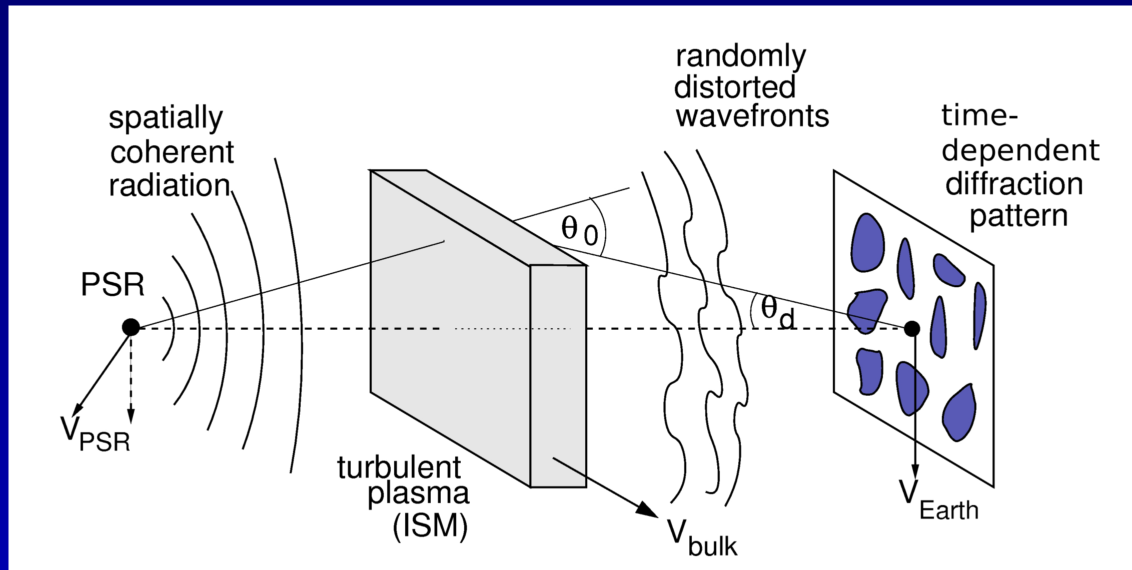
[Kuzmin et al. 2008]

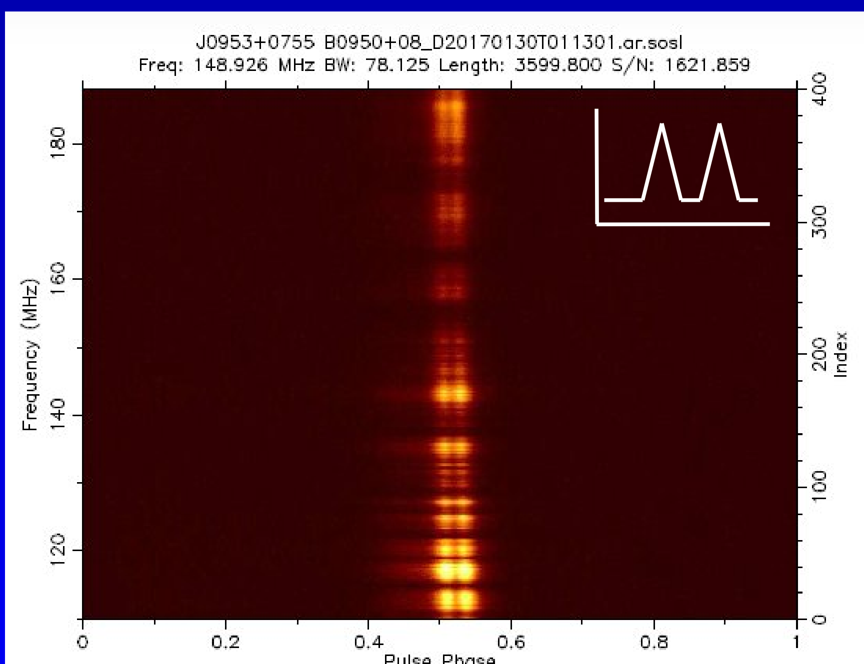
- Pulsar timing
- Dispersion
- Scattering
- Scintillation

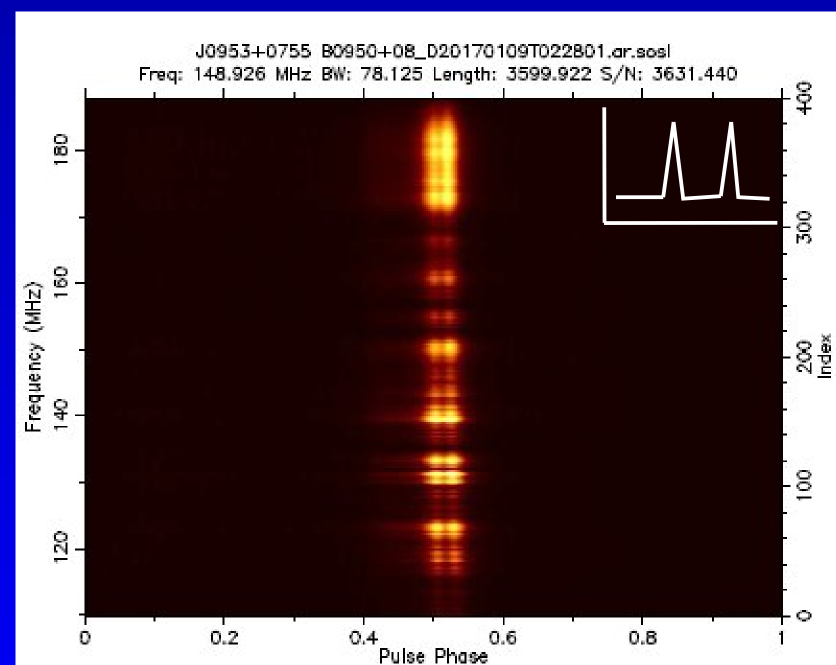
Propagation et turbulence



Propagation et turbulence







Scintiallation

- time-dependent
- time-dependent profiles → less precise TOAs
- scintillation is difficult to correct (cyclic spectroscopy?)

- Pulsar timing
- Dispersion
- Scattering
- Scintillation
- Conclusion

Propagation et turbulence

- some pulsars are more suited for timing than others!
  - sharp profiles
  - small P0, small P1
  - DM(t)=const, τ_{sc}(t)=const

    → know your pulsar!

- IISM will make timing more difficult, but not impossible
- some of the effects can be corrected at least partially

- this also allows to study the IISM!

  “Some people’s noise is other people’s data”!

  (e.g. mapping of the IISM)

    → study the IISM!