Continuous Gravitational Waves from Neutron Stars

One of the biggest challenges in gravitational astronomy

Lorenzo Pierini
Università degli Studi di Roma La Sapienza
INFN Roma1
LIGO/Virgo collaboration

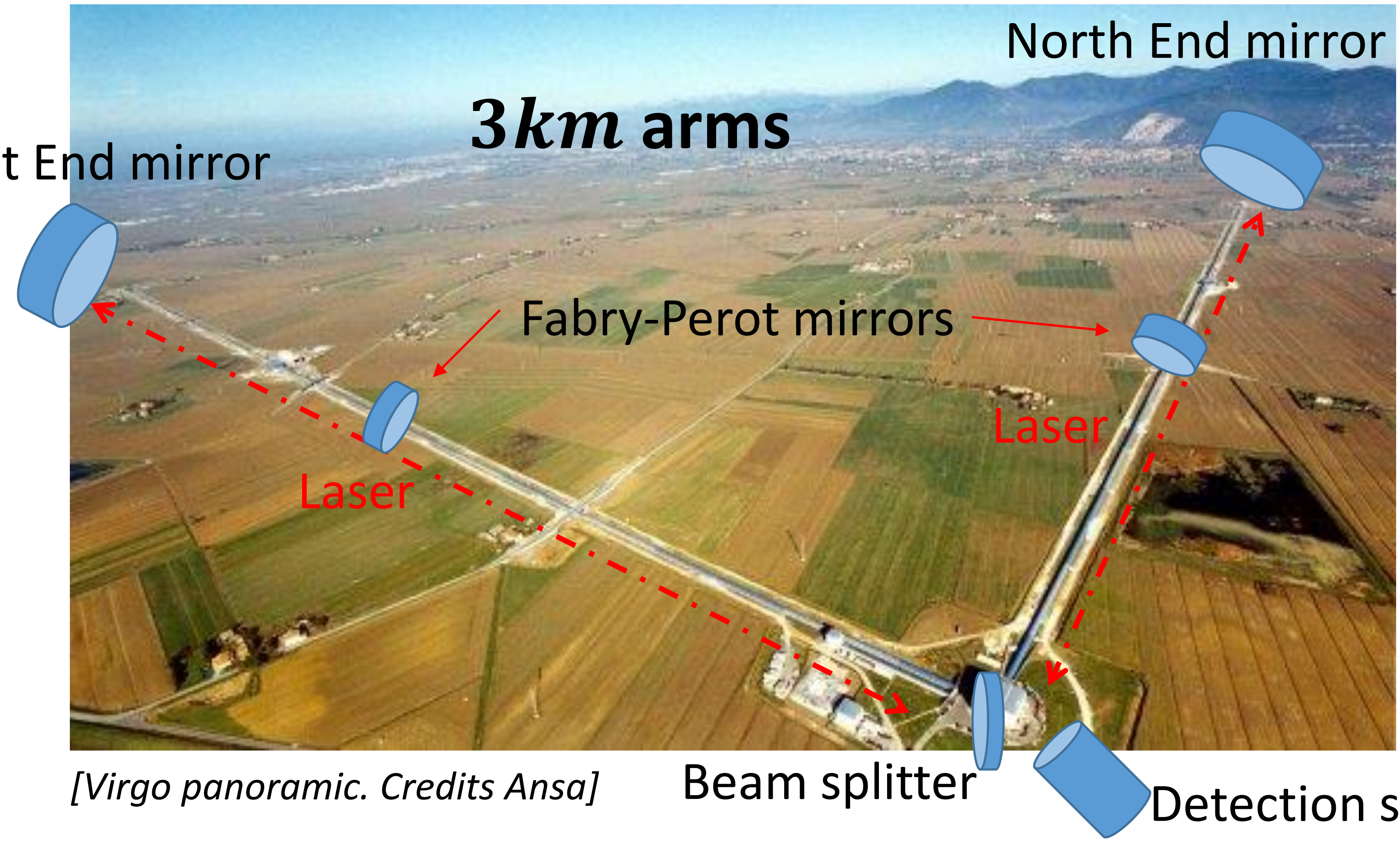
Outline

- ❖Neutron Stars:
  - What they are
  - Why they are so interesting
  - How they emit Gravitational Waves

- ❖ Search for Continuous Waves from known pulsars with an example: the Crab pulsar.

- ❖ All-sky blind searches: how to perform a search when we have no information on the source?

Gravitational Wave detection: interferometers



West End mirror

$3km$ arms

North End mirror

Fabry-Perot mirrors

Laser

Laser

Beam splitter

[Virgo panoramic. Credits Ansa]

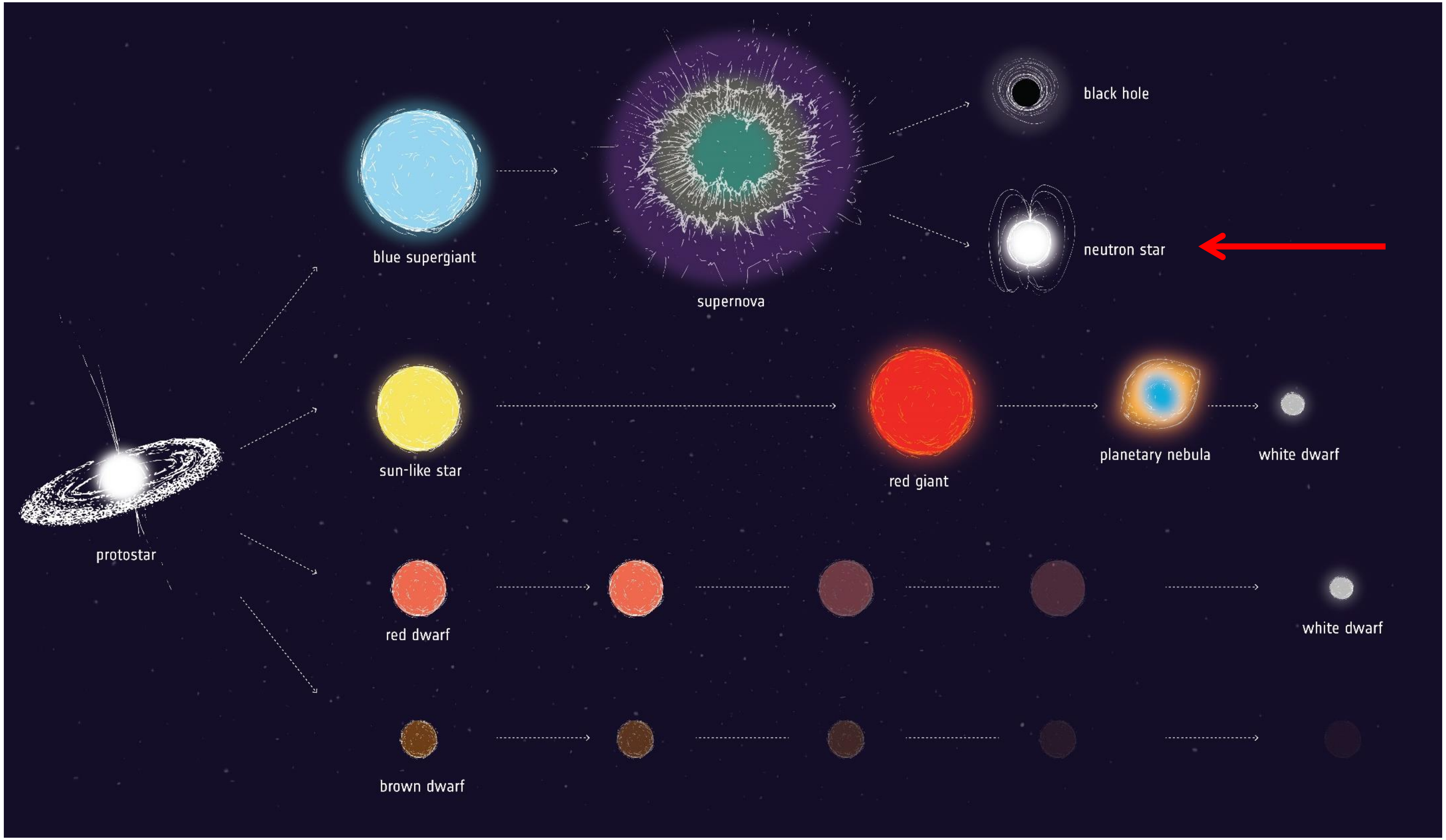
Detection system: photodiode and thousands of other stuff!

Setting:
Michelson +
Fabry-Perot
interferometers

We measure gravitational waves through phase difference between the 2 laser beams.

$$\Delta\varphi(t) = \frac{4\pi L_{\text{eff}}}{\lambda_{\text{laser}}} h_{\text{GW}}(t)$$

What are Neutron Stars?



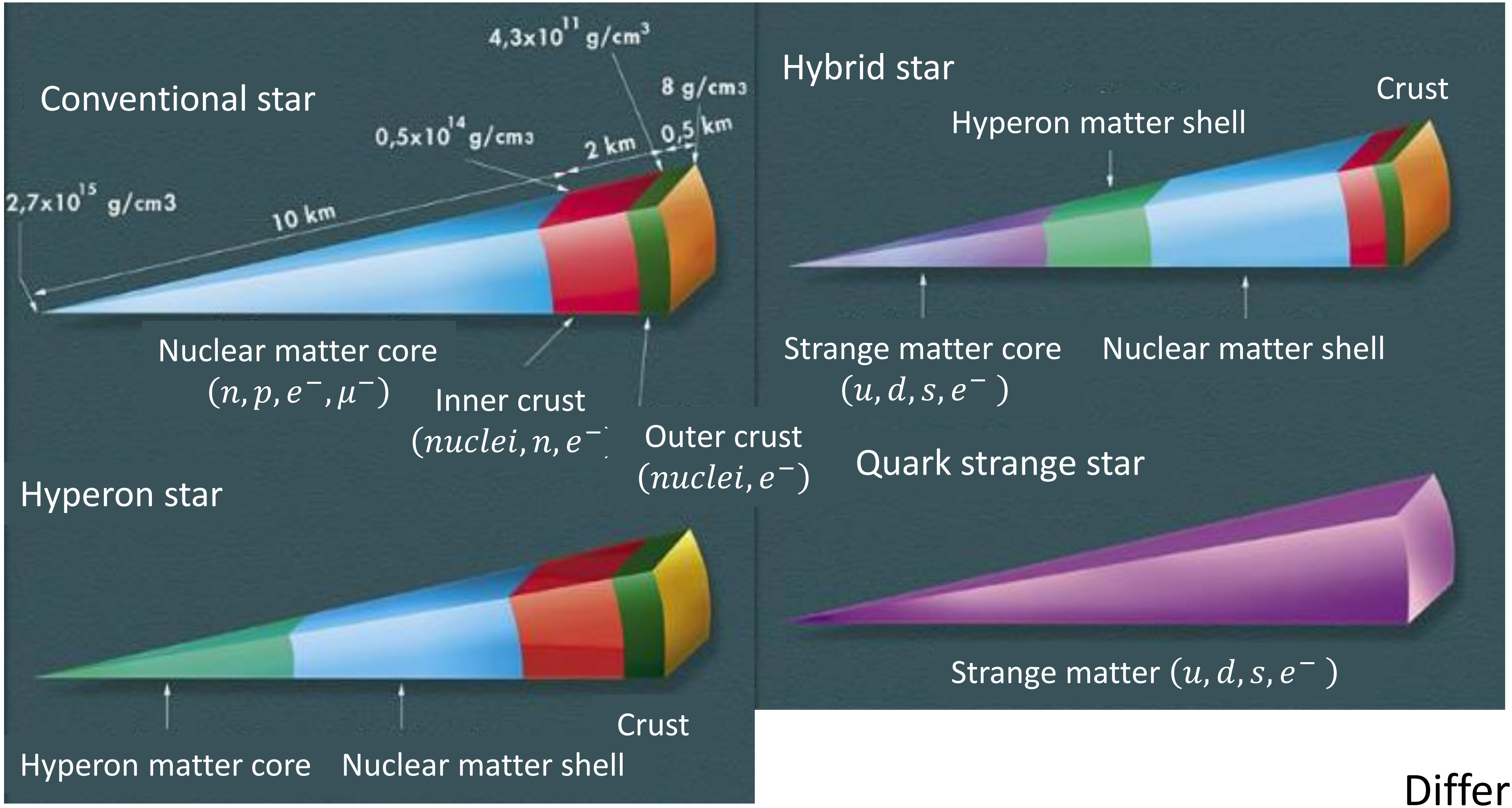
Credits: ESA

They are the remnant of supernovae explosions of stars with masses $\in [\sim 4\,, 30] M_{\odot}$

They are the last stronghold of matter against gravity: Neutron degeneration pressure prevents for gravitational collapse

In the more 'traditional' concept they would be composed mainly by neutrons, but…

How are Neutron Stars composed?



Credits: I. Bombacci, A. Drago, INFN Notizie, n.13, 15(2003)

There is an huge variety of possible compositions…
Which is the right one?
Are we sure the only one of them is possible?
Could Neutron Stars have different compositions depending on their different history?

Different composition

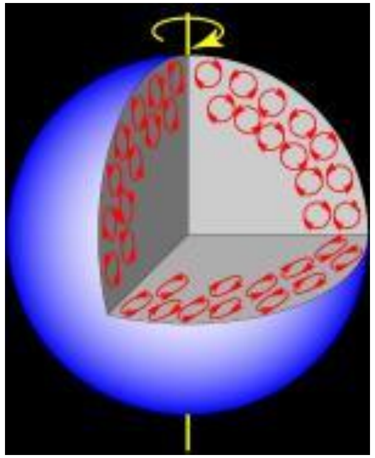
↓

Different Equation of State

↓

Different macroscopic behaviour

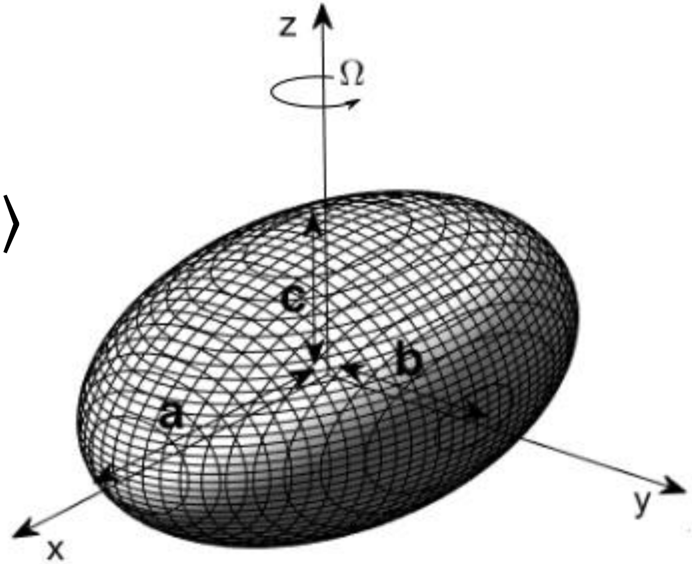
Neutron Stars as Gravitational Wave emitters



Newly born Neutron Stars have very high rotational frequencies $\mathcal{O}(kHz)$: they produce very strong magnetic field through an efficient dynamo

$$B \sim 10^{11} - 10^{13}\text{Gauss}$$

This magnetic field is able to induce a permanent deformation on the star shape, breaking its cylindrical symmetry:



→ Ellipticity/Oblateness: $\varepsilon = 2\dfrac{a-b}{a+b}$ $\qquad$ $\varepsilon = f(M,R;B) \propto \langle B^2 \rangle$

This deformation produces a non-vanishing quadrupole momentum

⇩

Continuous Gravitational Wave emission!

What signal do we expect?

Emitted Gravitational Wave has 2 polarizations: $h_+(t) = h_0 \cos\Phi(t)$ $h_\times(t) = h_0 \sin\Phi(t)$

$$h_0 = 1{,}05 \times 10^{-27} \left(\frac{I_{zz}}{10^{38} kgm^2}\right) \left(\frac{\varepsilon}{10^{-6}}\right) \left(\frac{10kpc}{d}\right) \left(\frac{f_{GW}}{100Hz}\right)^2$$

Phase:

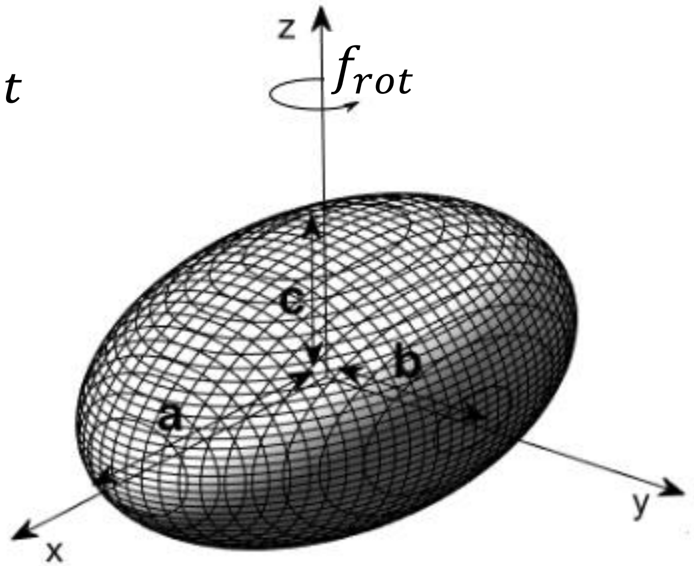
$$\Phi(t) = \int_{t_0}^{t} 2\pi f_{GW}(t')dt'$$

I_{zz}: Inertia momentum with respect to rotation axis

ε: Ellipticity of the Neutron Star

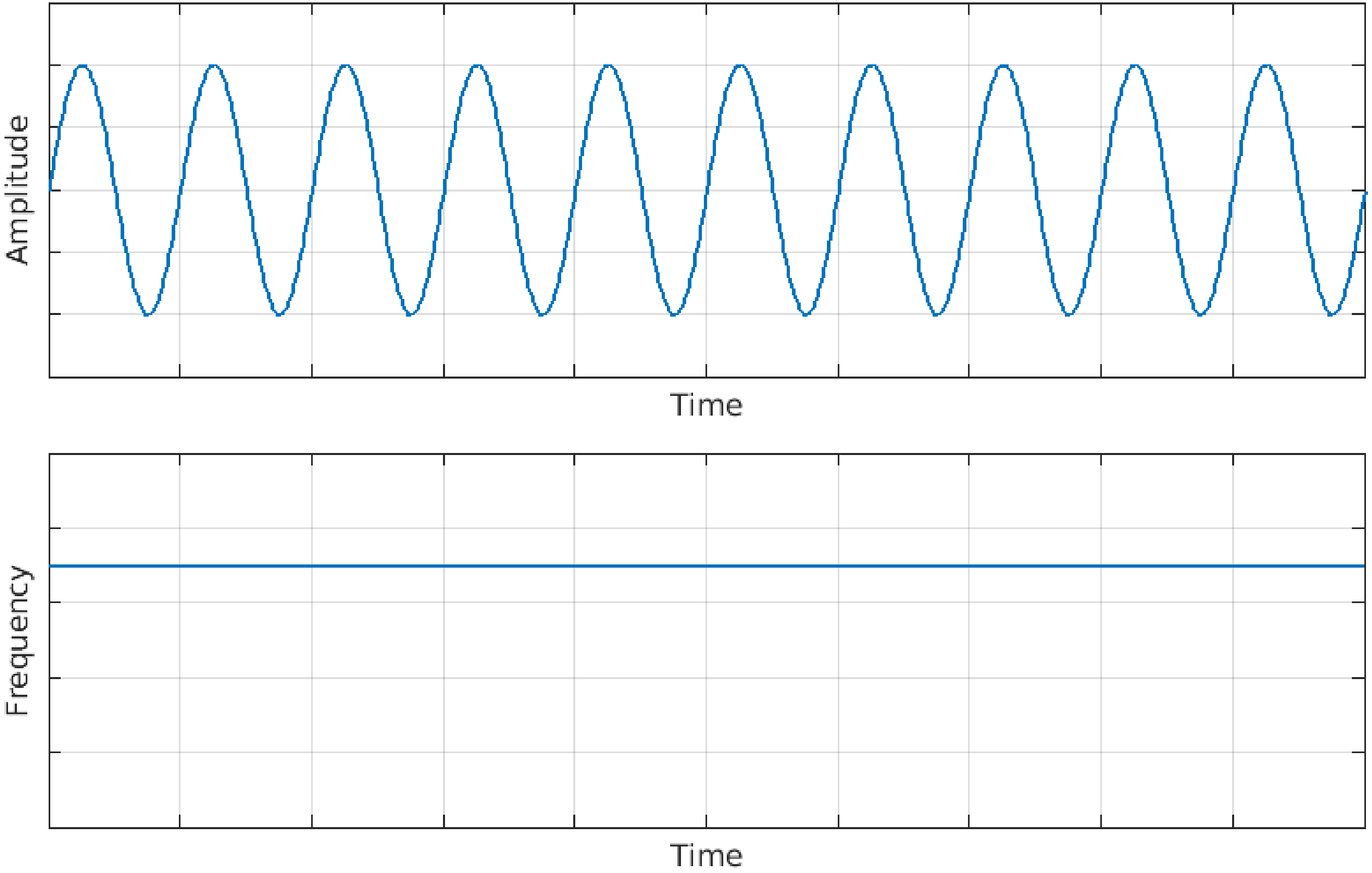
f_{GW}: Frequency of the wave $= 2 \cdot f_{rot}$

d: Distance of the source



So, it seems that we end up with a nearly monochromatic signal..

What signal do we expect?

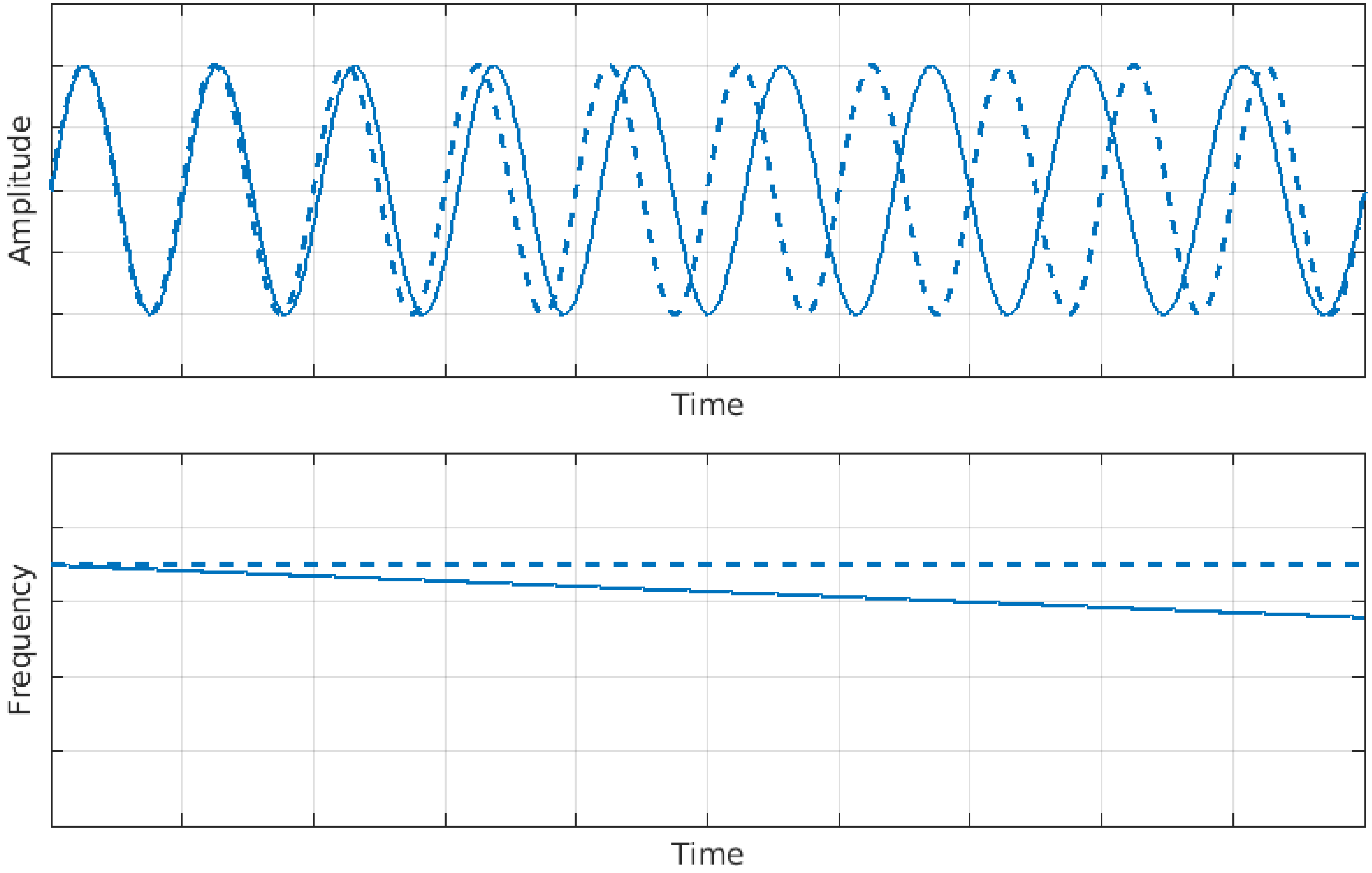


If it were actually monochromatic, that would be great!

Its energy would all accumulate on a single frequency bin! Over a 1 year observation time!

Too good to be true..

What signal do we expect?

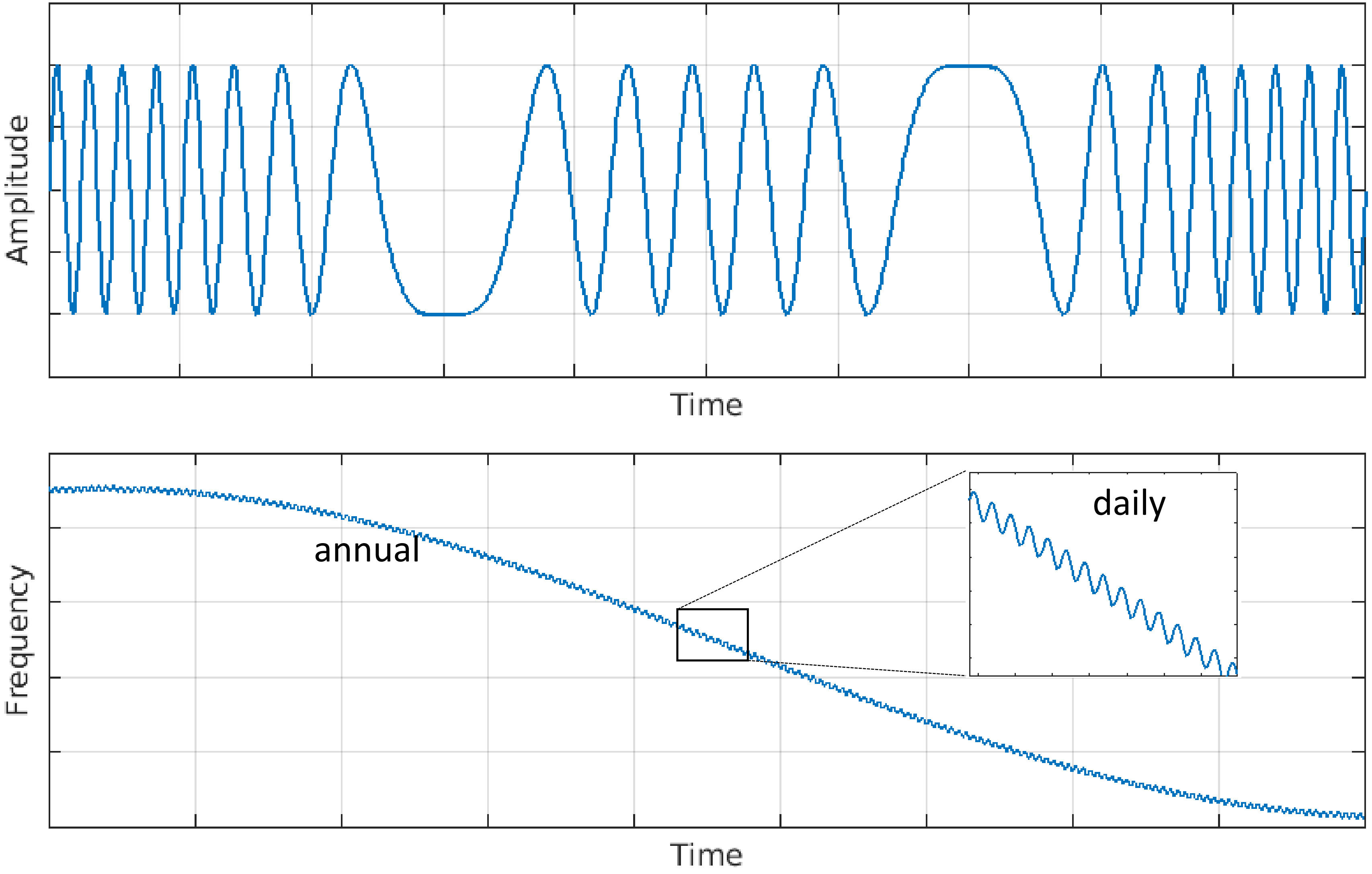


1st complication:

The star loses energy both through electromagnetic and gravitational emission.

$$f_0(t) = f_0 + \dots$$
$$+\dot{f}_0(t - t_0)$$
$$+\frac{1}{2}\ddot{f}_0(t - t_0)^2$$

What signal do we expect?

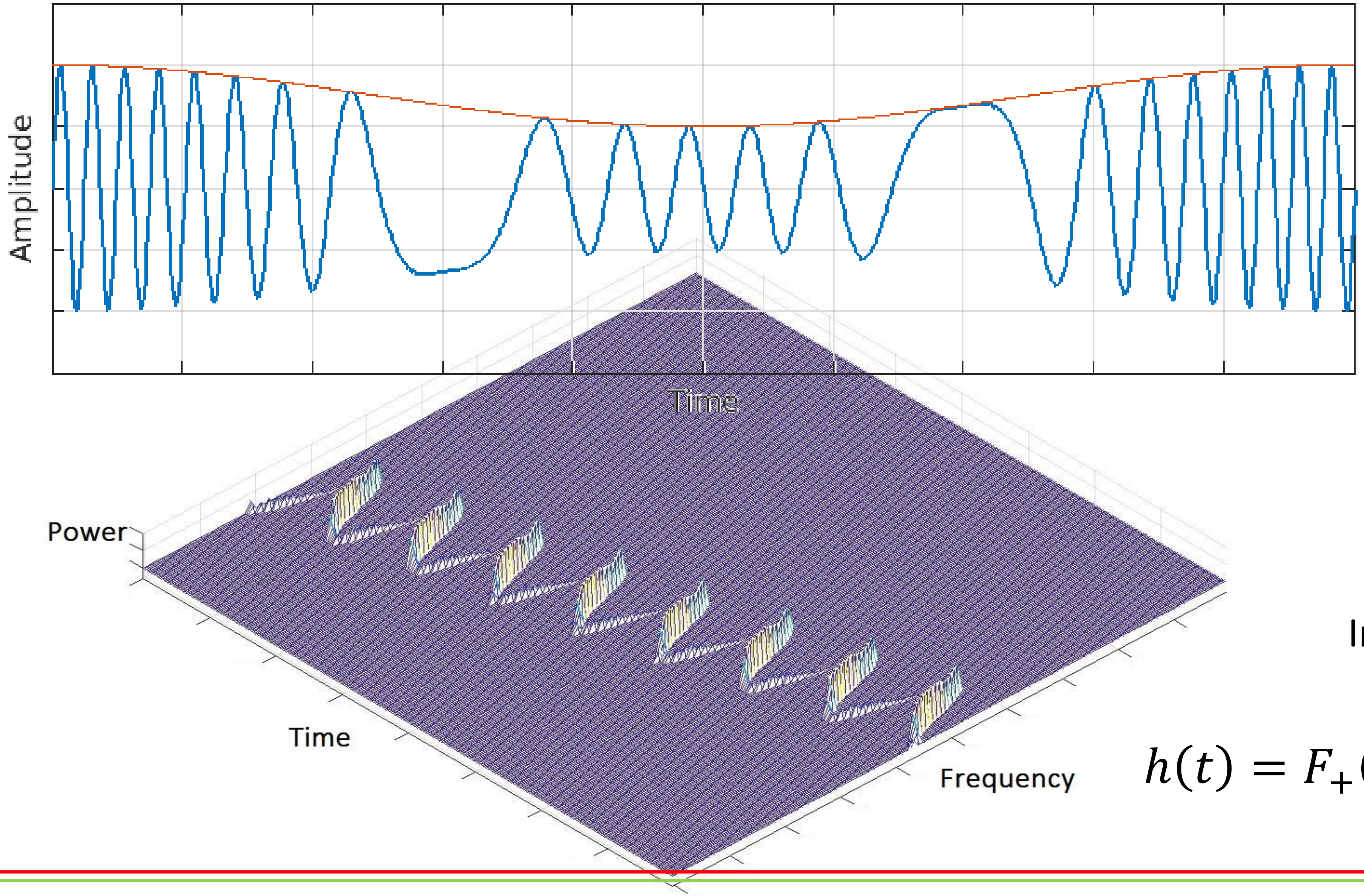


2nd complication:

The observed frequency is distorted by Doppler Effect due to Earth rotation and revolution.
The effect is different for each sky localization.

$$f(t) = f_0\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right)$$

What signal do we expect?



3rd complication:

The signal acquires a sidereal modulation because of the changing angle between the wave and the interferometer.

Interferometer response

$$h(t) = F_{+}(t)h_{+}(t) + F_{\times}(t)h_{\times}(t)$$

How do we search for the expected signal?

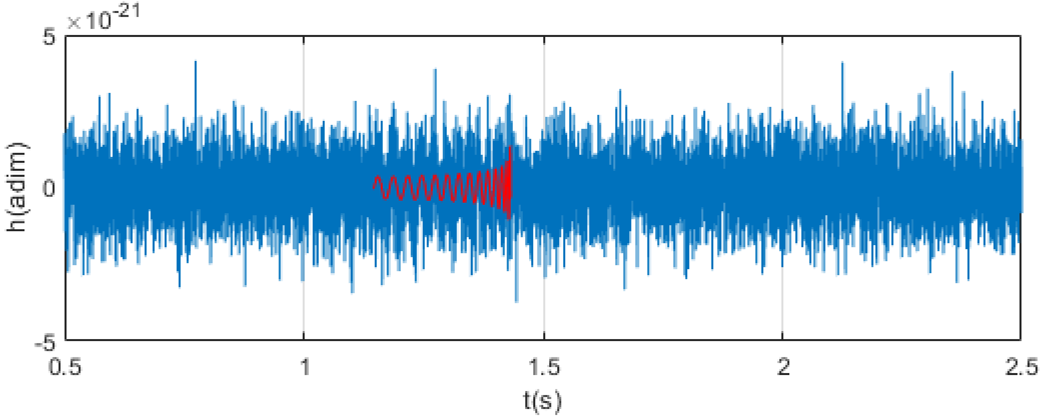
Matched filter: cross-correlation between data and expected signal

$$\rho(t) = \frac{(d \star K)(t)}{\mathrm{Norm}} = \frac{1}{\mathrm{Norm}} \int_{t_0}^{t_0+T} d^*(\tau) K(\tau + t) d\tau$$

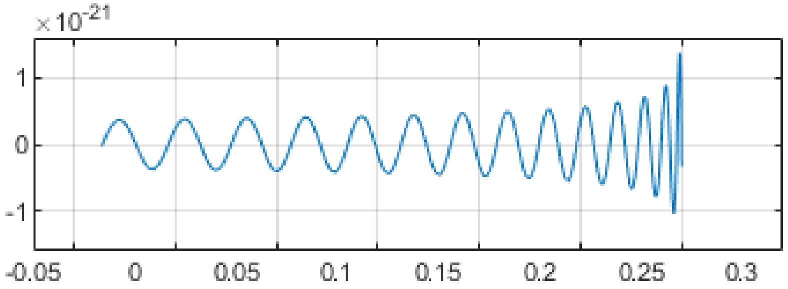
In Fourier domain: $\tilde{K}(f) = c\,\frac{\tilde{h}(f)}{S_n(f)}$

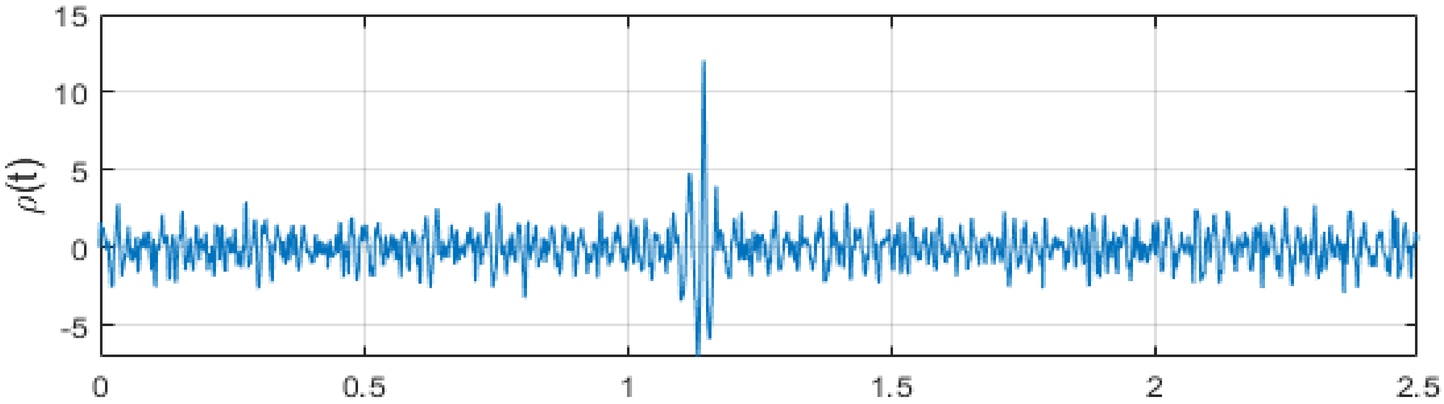
Signal

Noise power spectrum



★





$\rho(t) \sim Gauss(0,1)$

Candidate selection if ρ is over a threshold

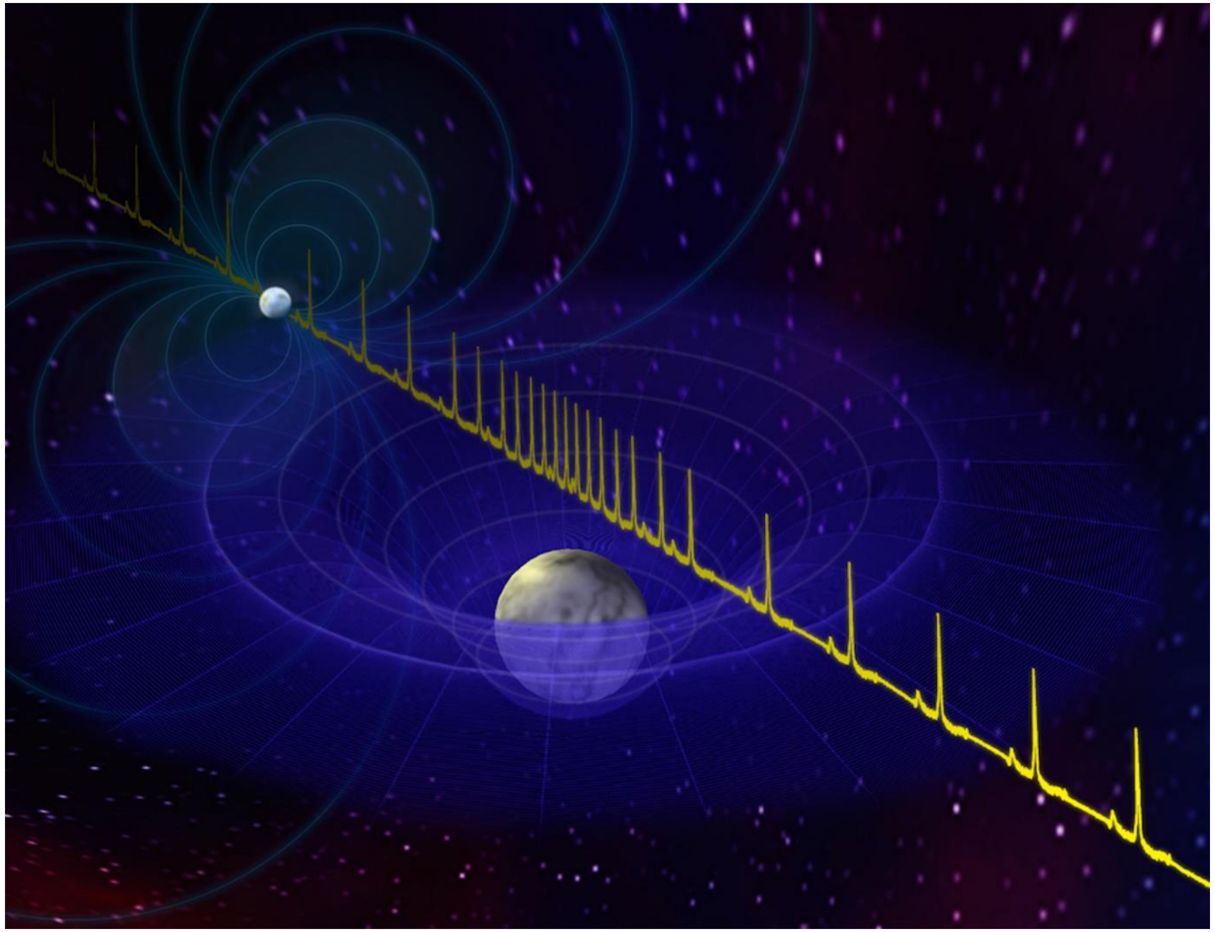
Matched filter for known pulsars

Matched filter: to make it work, we need to know pulsar parameters with extreme precision

Known pulsars: we have almost complete information on parameters (sky localization, rotational frequency) and spin evolution (ephemerides)

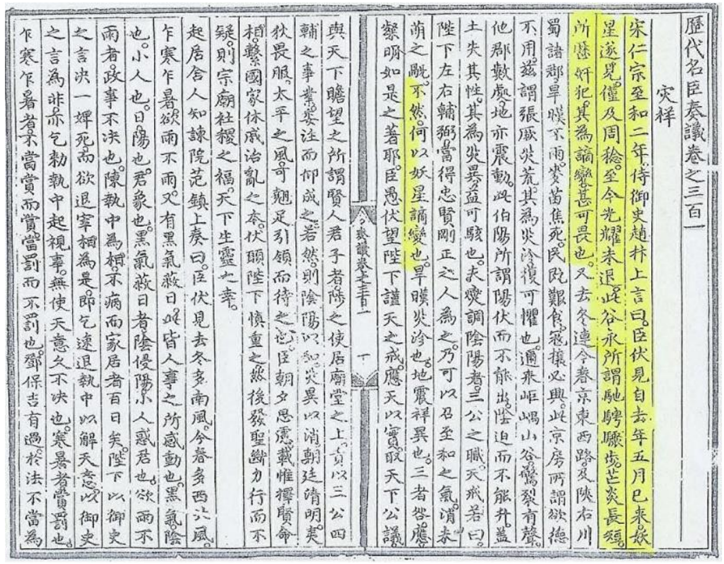
We can reconstruct the expected waveform with the needed precision

We can do matched filtering!



1054: A SuperNova lights up the sky

Recovered by Chinese astronomers in 1054



歷代名臣奏議卷之三百一

災祥

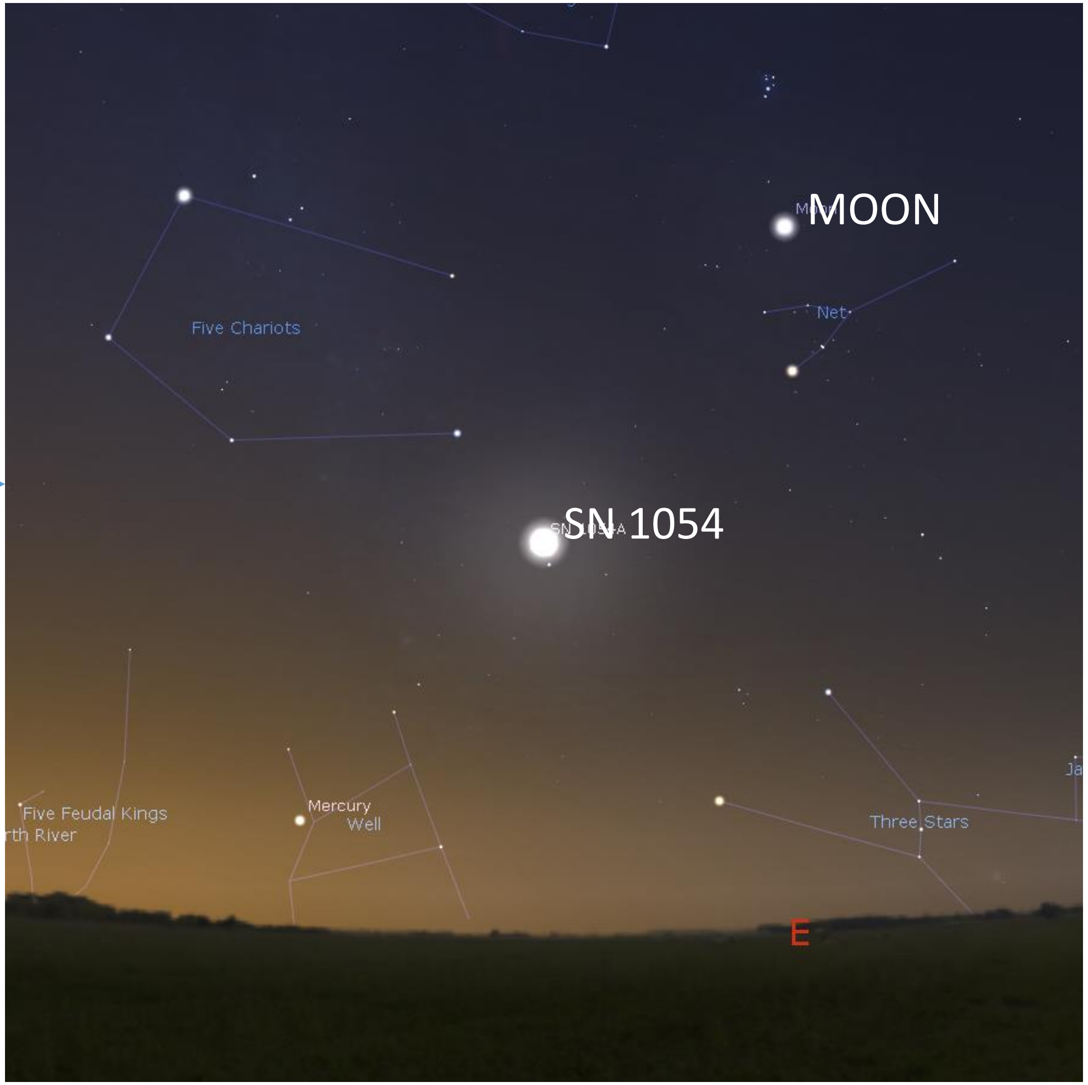
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長短所歷奸犯其為譴變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴復可懼也邇來岠嵎山谷鷩裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未萌之亂不然何以妖星譴變也旱暵災沴也地震祥異也三者咎應粲明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

奏議卷之三百一　十

與天下瞻望之所謂賢人君子者俾之使居廟堂之上責以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明夷狄畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸

起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史之言決一婢死而欲退宰相為是即乞速退執中以解天意以御史之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

How it should have appeared: (simulation based on descriptions)

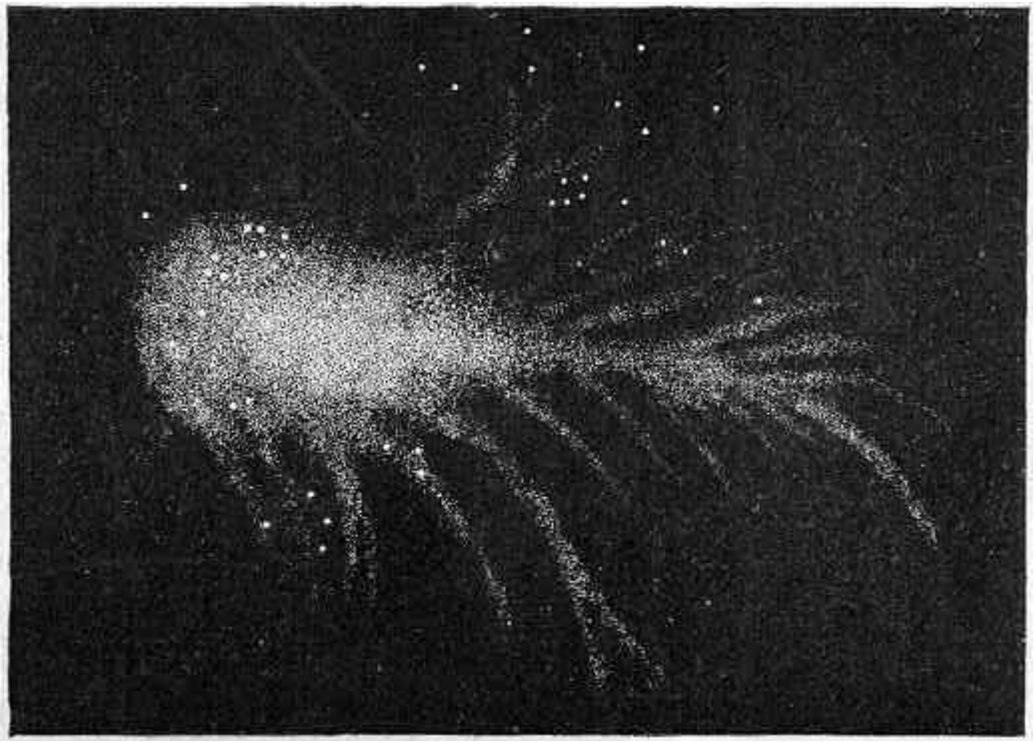


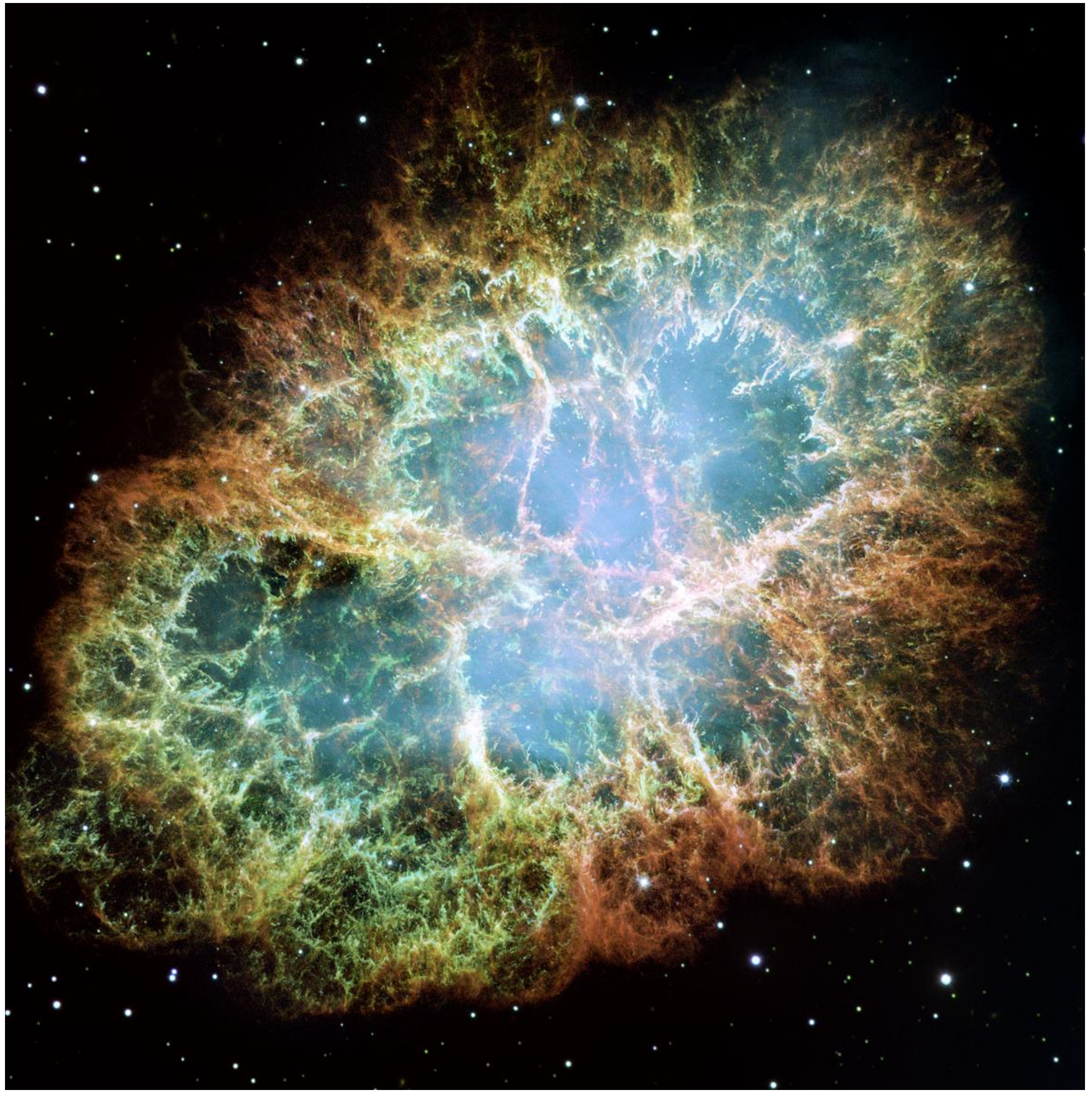
In Europe that year: the Great Schism of 1054
Break between Catholic Church and Eastern Orthodox Church

SN1054 remnant: Crab Nebula

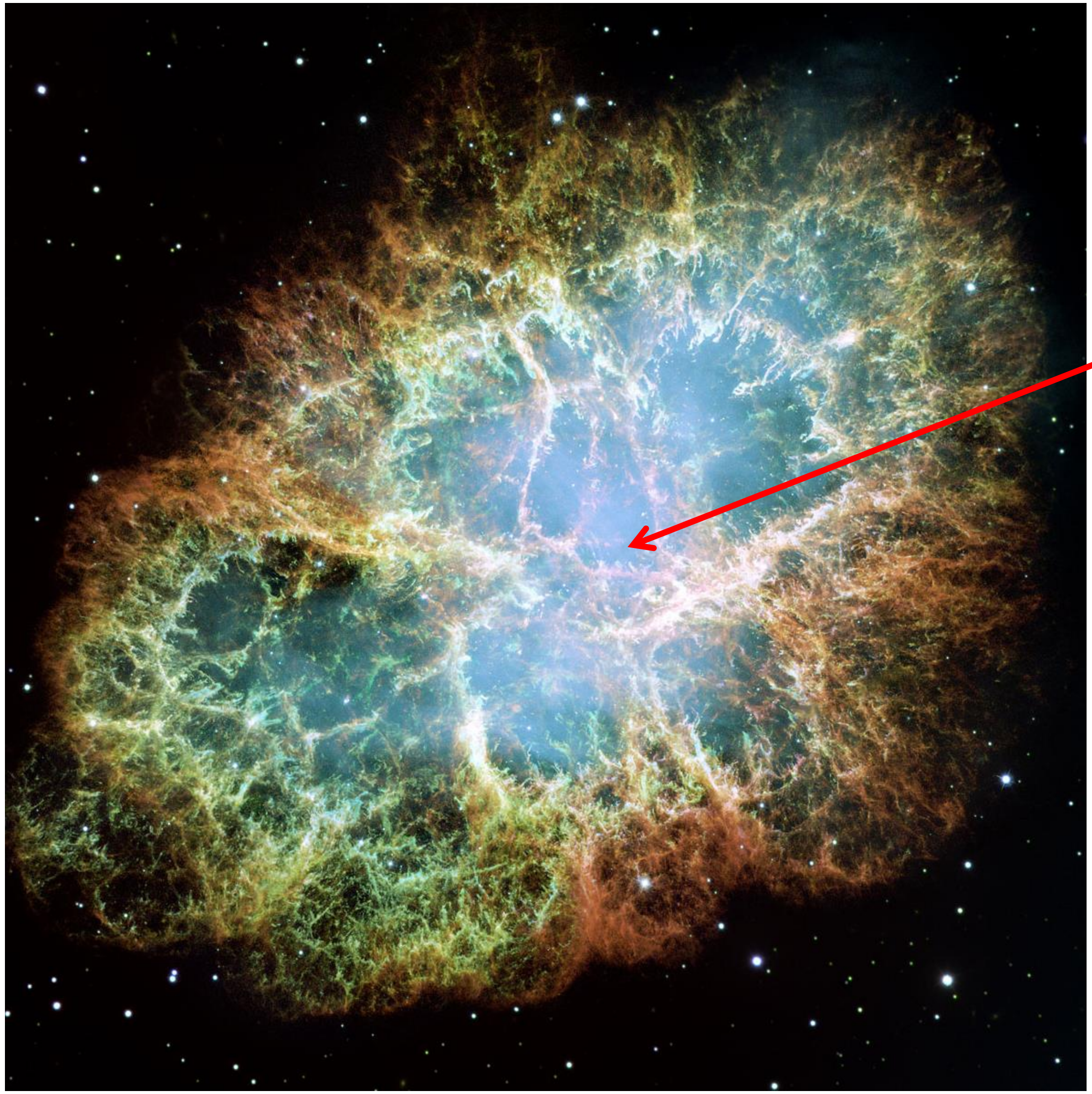
First depiction by Lord Rosse: 1844

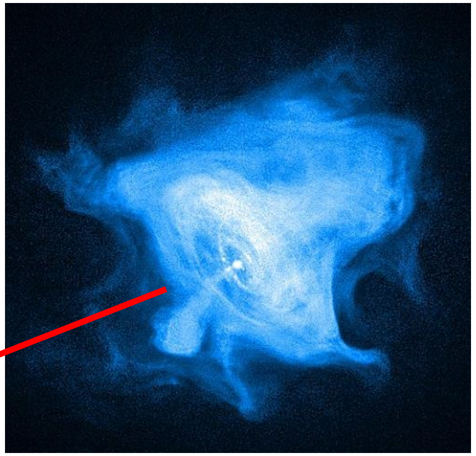
Hubble Space Telescope: 2000





At the Nebula center: Crab Pulsar!





X-ray picture by Chandra

1968: PSR J0534-2200 discovery

Rotational frequency	**29,6 Hz**
Distance	**2 kpc**
Right ascension	05h 34m 31,97s
Declination	+22° 00’ 52,1’’

We know almost everything about this source!

↓

We are able to search for the expected gravitational wave with the required precision

Targeted search: nothing found

Up to now, we did not found any Gravitational Wave signal from Crab Pulsar…
What does it mean? We can put upper limits on its amplitude

Observative Run	Maximum h_0	Maximum ε
O1 (2015)	$5{,}0 \times 10^{-26}$	$2{,}7 \times 10^{-5}$
O2 (2017)	$2{,}9 \times 10^{-26}$	$1{,}6 \times 10^{-5}$
O3 (2019-20)	$8{,}7 \times 10^{-27}$	$\boxed{4{,}9 \times 10^{-6}}$

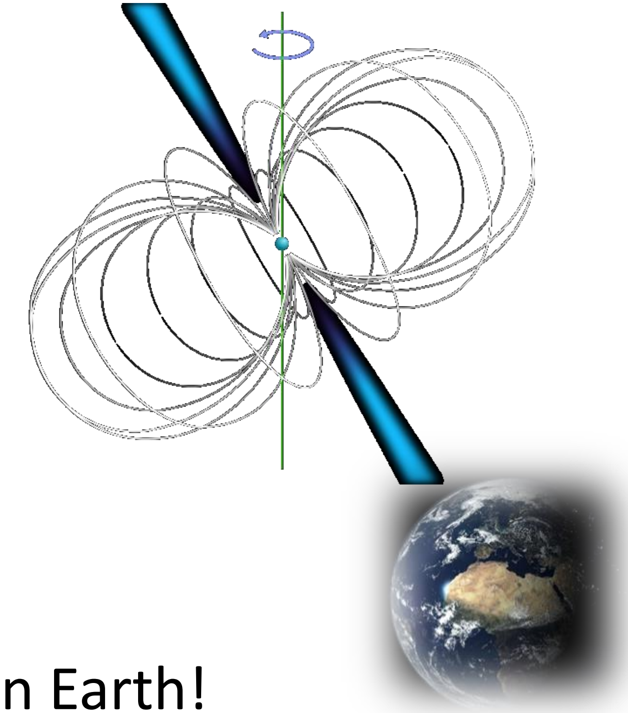
⬇

The deformation on this $\sim 30km$ diameter Neutron Star is $\leq \mathbf{15cm}$

But it doesn’t mean it is the same for all other pulsars!

All-sky blind searches

By now, no Gravitational Waves have been found from known pulsars



BUT known pulsars are just a little fraction of the actual Neutron Stars population in our galaxy: we can see only those emitting and pointing at our direction!

- Observed pulsars by now: ~ 3000+ (still growing)
- Estimated Neutron Stars in Milky Way: $\sim 10^8 - 10^9$

We could have most detectable sources (younger, nearest) without knowing them, just because their beam does not point on Earth!

… Could we search also for them? Can we do blind searches?

All-sky blind searches

Could we do a matched filter for any possible point in the parameter space?

We should scan for:

- All sky localizations (solid angle)
- All frequencies
- All spin-down values
- All orientations

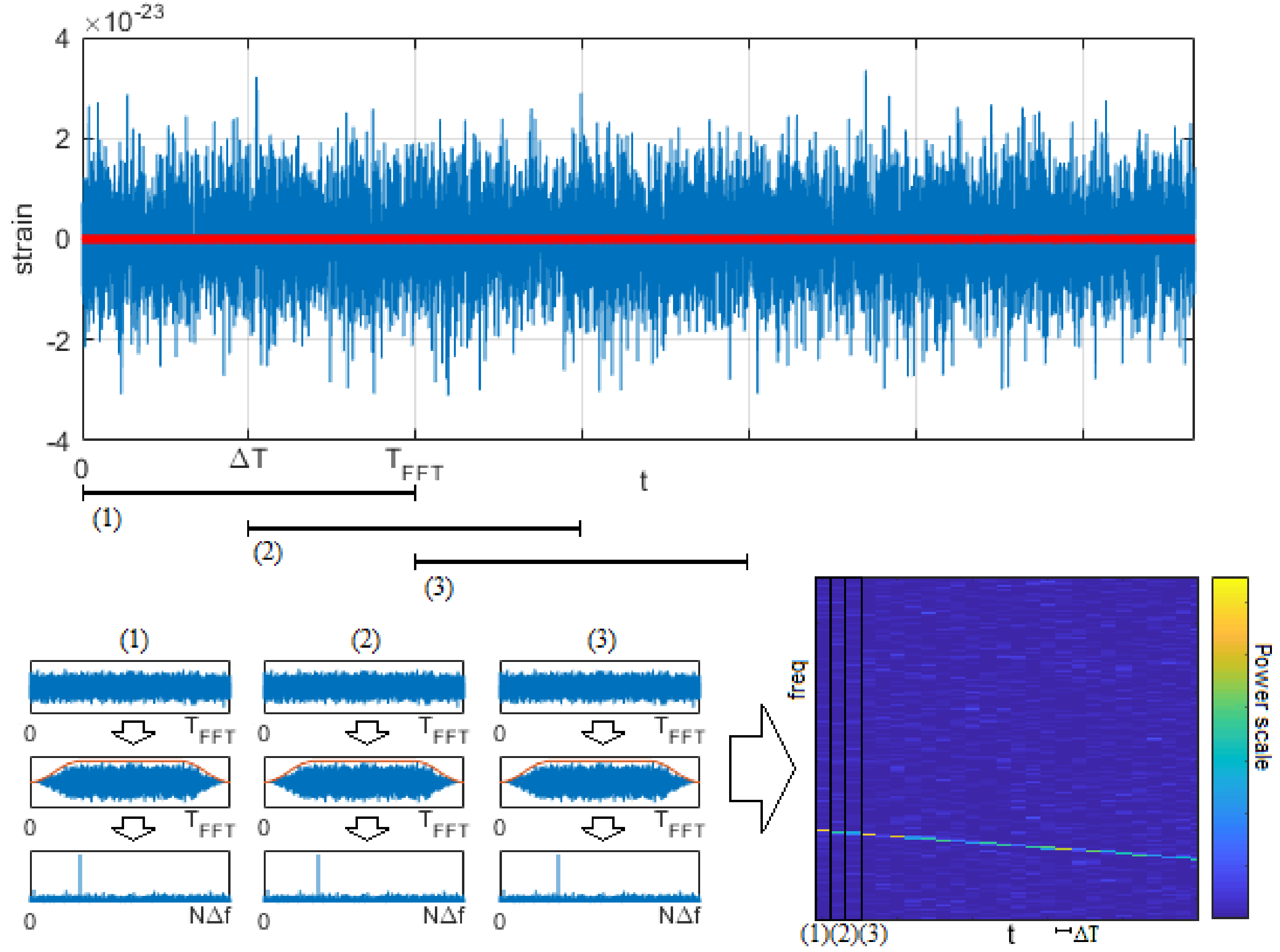
Each one produces a different waveform, which we would use as matched filter on $\mathcal{O}(1year)$ data

Computing time needed: $\boldsymbol{\mathcal{O}\left(10^{n\geq 2}\ \mathbf{years}\right)}$!!

….Not a very interesting scenario for us!

All-sky blind searches

Completely different approach: construction of time-frequency maps



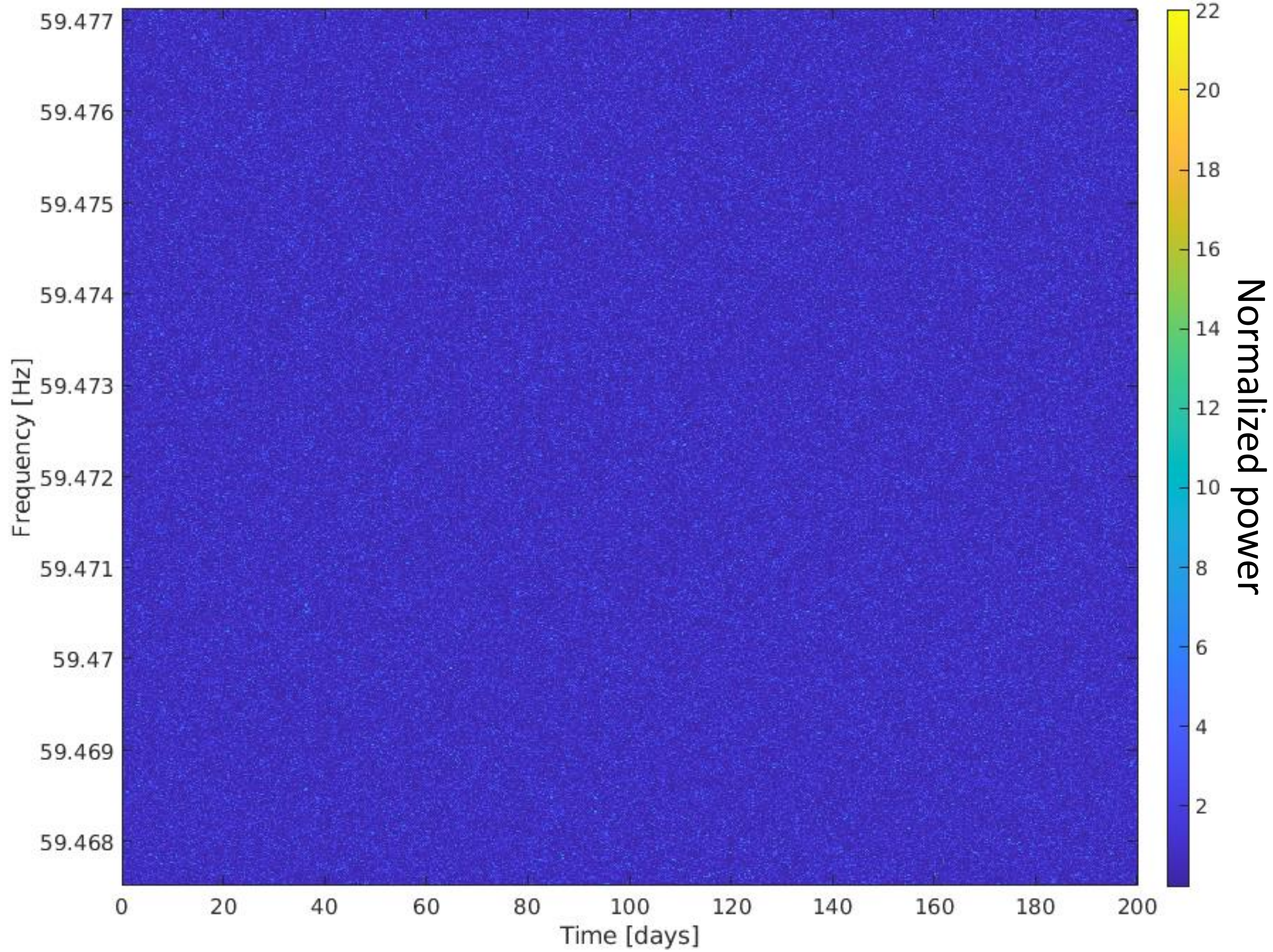
- Original time series is broken in smaller chunks $\mathcal{O}(1000s)$

- Take the normalized power spectrum of these chunks

- Combine these spectra together, to form spectrograms

All-sky blind searches

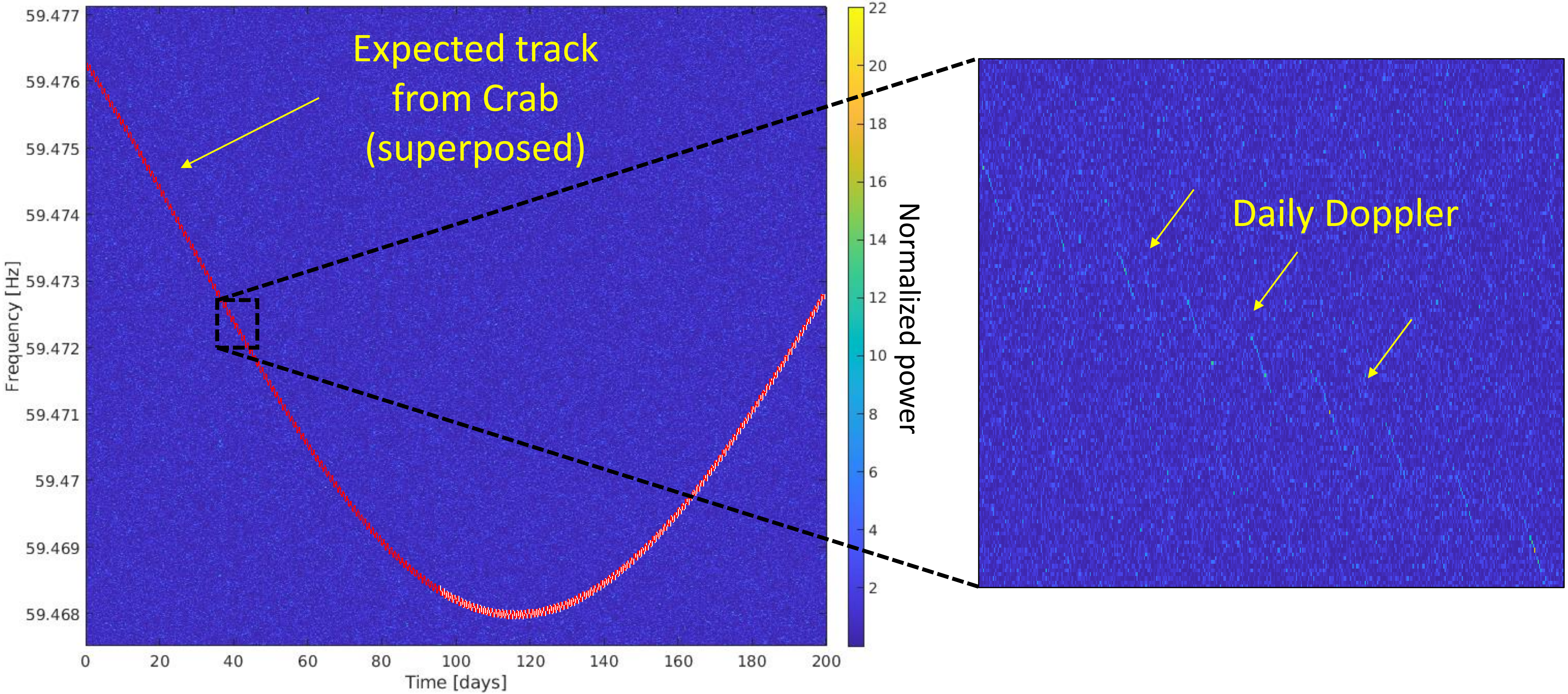
In this way, we obtain a time-frequency representation of data (and signal)



WARNING:
Don’t expect Continuous Wave signals to show up with high contrast: remember that they are extremely weak!

All-sky blind searches

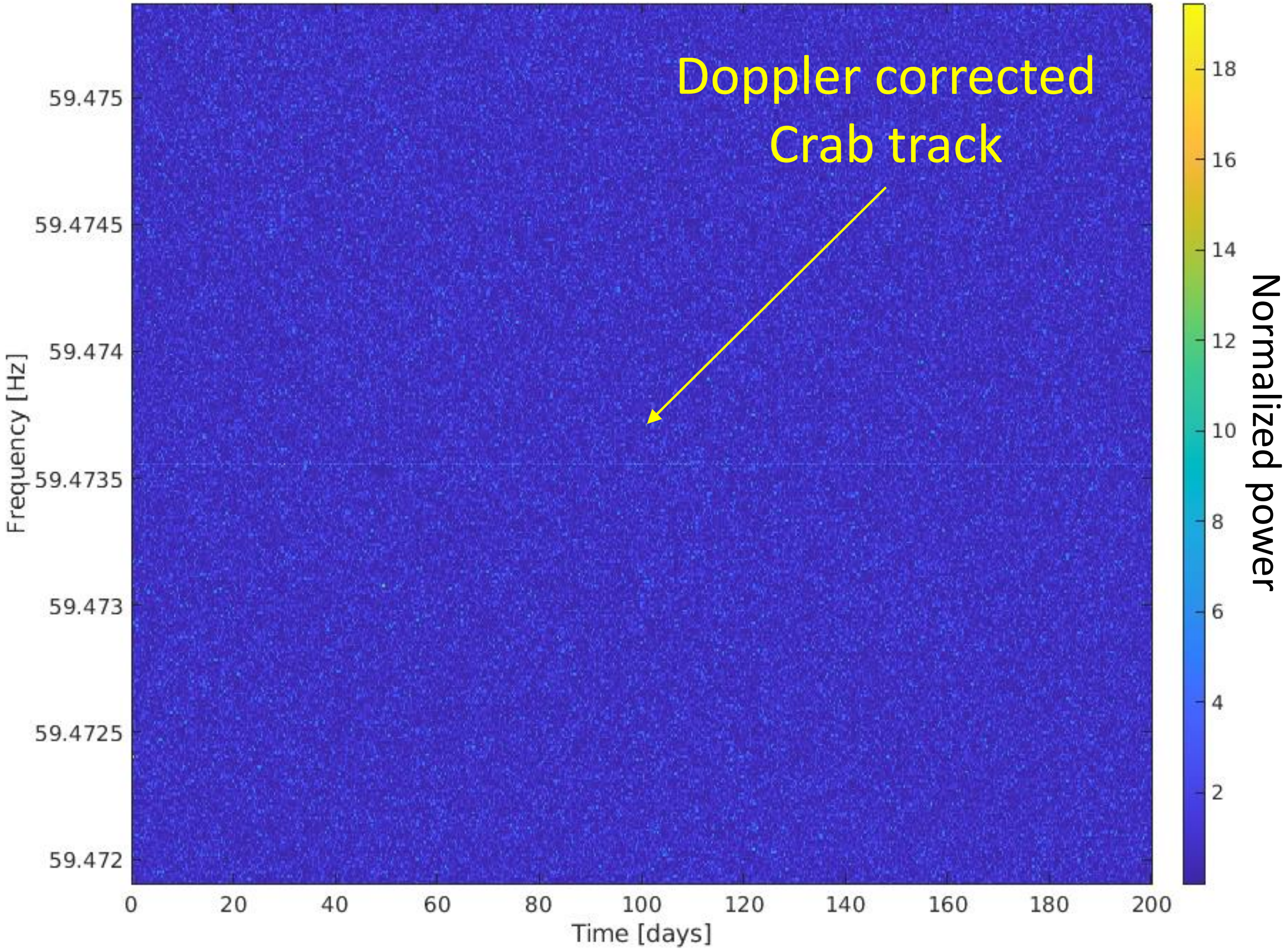
In this way, we obtain a time-frequency representation of data (and signal)


Expected track from Crab (superposed)

Daily Doppler

All-sky blind searches

We then correct for Doppler effect for ALL possible sky localizations



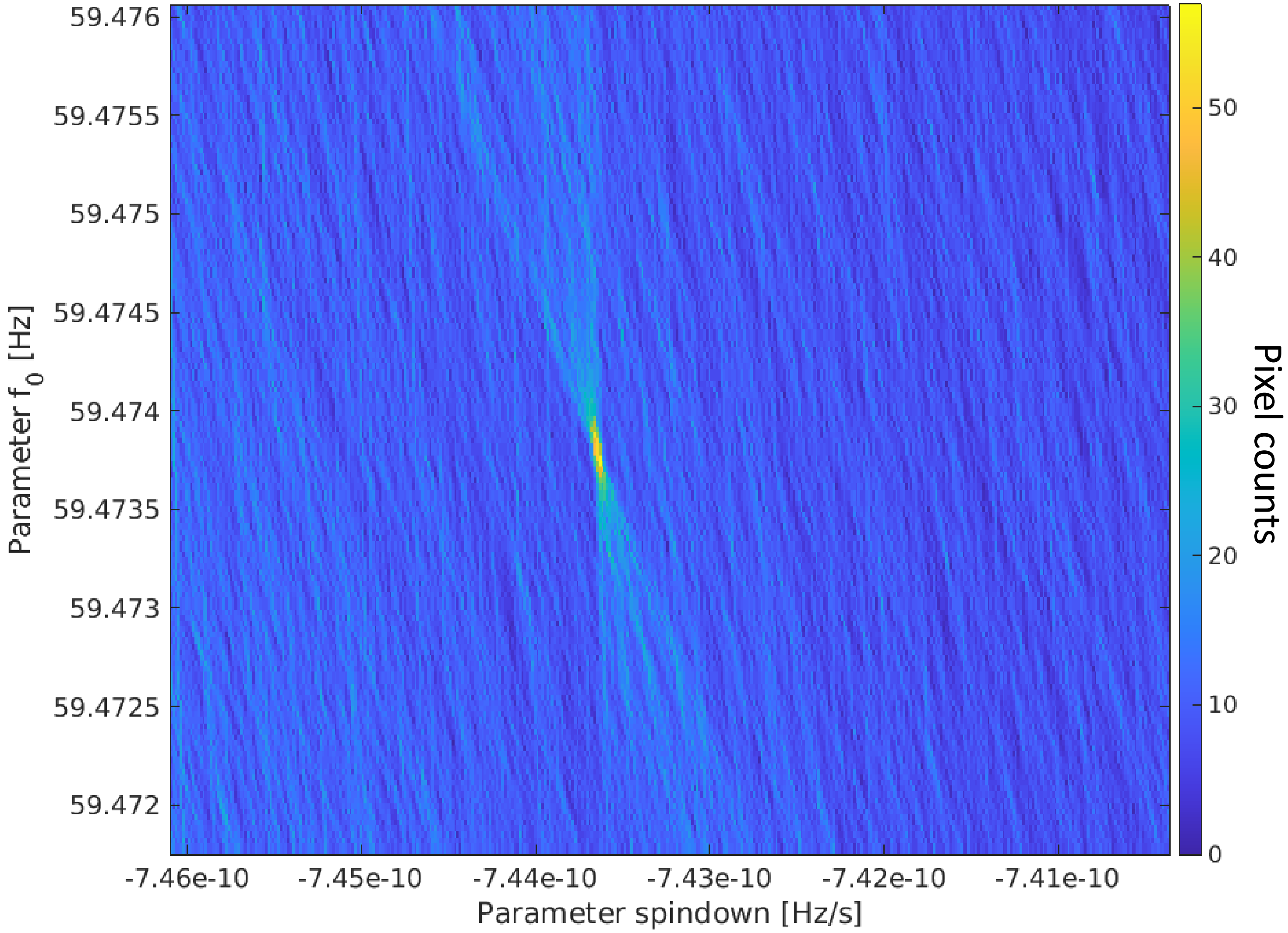
Correction = Frequency shift of pixels

When a Doppler correction matches with the sky direction of a Gravitational Wave present in the map, its time-frequency track becomes a straight line!

Now, we can search for its pattern more easily

All-sky blind searches

Frequency-Hough: a pattern recognition transform to recover straight lines



Frequency-Hough transform maps time-frequency data into the parameter space of the signal

$$f_0(t) = \boxed{f_0} + \boxed{\dot{f}_0}(t - t_0)$$

If a signal is present and is strong enough, it will produce an excess of counts with respect to noise

We can select Gravitational Wave candidates by selecting outliers in the Frequency-Hough map!

All-sky blind searches

What are the most important differences with matched filter searches?

\+ : Computationally cheap: can be completed in few months

\+ : Robustness: we can do detections even with little errors on parameters

\- : Less sensitivity: losses about a $\sim 3 - 4$ factor…

(we have to pay a price in some way!)

Anyway, it is always possible to do better in one or more of these points

We are border line: any improvement could do the difference in order to make the first detection!

Conclusions

Detecting Continuous Gravitational Waves from spinning Neutron Stars is very challenging

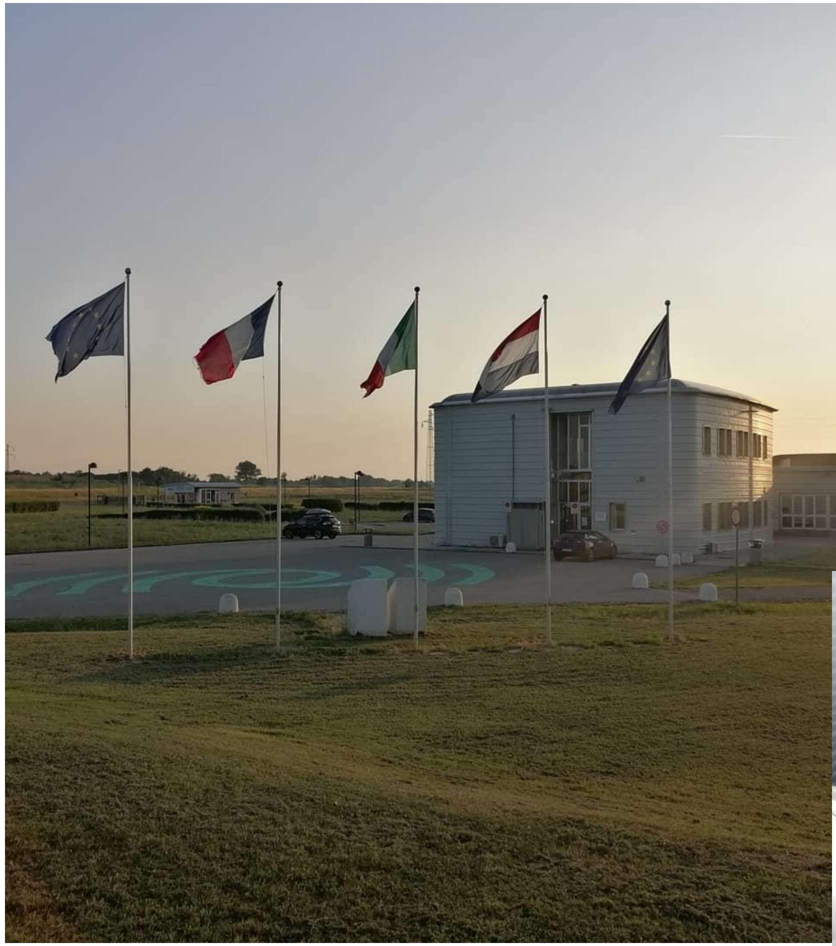
There is a lot of work to be done to increase the detection probability in the future runs!
The Virgo group of Rome is strongly active on various sides:

- Enhance the instrument sensitivity → Cryogenics, Frequency dependent laser squeezing
- Detector characterization/Noise hunting → Searching for environmental disturbances that can reduce the sensitivity and trying to mitigate them

I work on these!

- Development of search procedures → Searching for completely new (and original) search strategies, adapting already existing proceures in order to extend the search also to other astrophysical sources (boson clouds, long transients from magnetars, dark photons…)

Thank you!



Backup slides

Neutron Stars as Nuclear physics laboratories

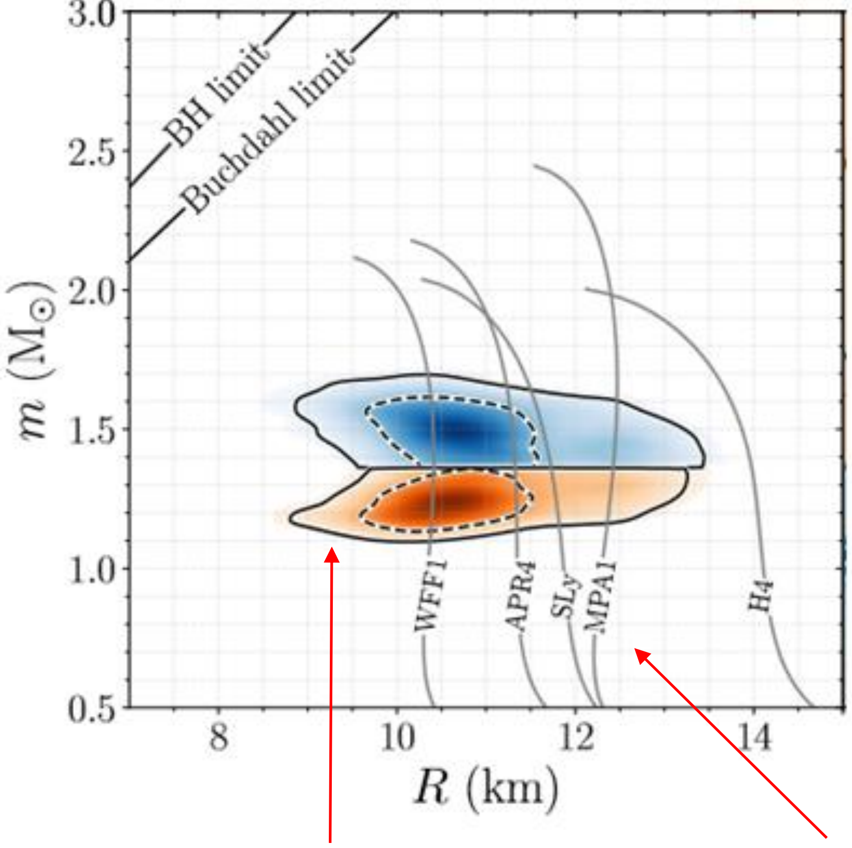
Detecting Gravitational Waves from rotating Neutron Stars, we would obtain a very accurate measure of their ellipticity.

$$\varepsilon = f(M, R; B)$$

It would be a very strong constraint to the star Equation of State!
Determining the Neutron Star EoS will reveal us the behaviour of Nuclear physics at extreme densities

Neutron Stars are a promising laboratory to test Nuclear Physics at energy scales unreachable on Earth

[Credits: PRL, 121, 161101 (2018)]



Constraints from the first Binary Neutron Star coalescence (GW170817)

Some possible EoS curves

Upper limits from All-sky searches

This time, we have a different maximal h_0 for any different search frequency, and the translation in terms of ε is even more complicated! Remember that $h_0 \propto \frac{\varepsilon f^2}{d}$