All-sky search for almost monochromatic gravitational waves using supercomputers

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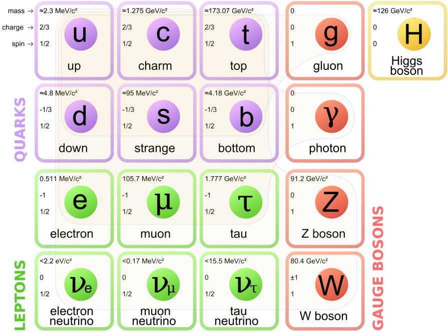
KIT SCC, 17.11.15

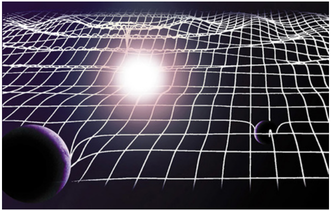
Outline of this talk

- ⋆ Gravitation and gravitational waves,
- ⋆ Sources of gravitational waves,
- ⋆ Gravitational wave detectors,
- ⋆ Rotating neutron stars as sources,
    - ⋆ Gravitational wave data analysis,
    - ⋆ All-sky search pipeline,
    - ⋆ Massive parallelization,
- ⋆ Current and future plans.

4 fundamental interactions, but our knowledge about the Universe is based on EM. Let's directly probe the other long-range interaction: gravitation.

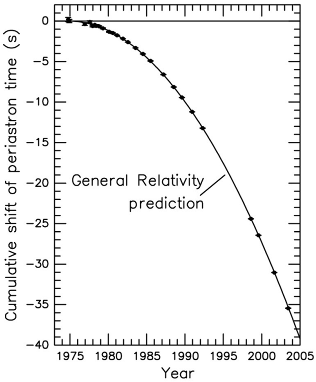


mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	



Gravity.

It's not just a good idea.
It's the Law.



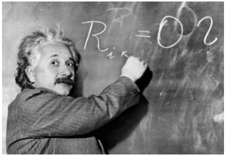
Gravitational waves

Metric → Einstein's equations

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \longrightarrow G_{\mu\nu} = 8\pi G/c^4\, T_{\mu\nu}$$

Einstein 1916:

$$\Delta \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$



$$\Delta = \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x_1^2} - \frac{\partial^2}{\partial x_2^2} - \frac{\partial^2}{\partial x_3^2}$$

GW amplitude

$$h_{ij}(t) = \frac{2G}{c^4 r}\frac{\partial^2}{\partial t^2} I_{ij}\left(t - \frac{r}{c}\right)$$

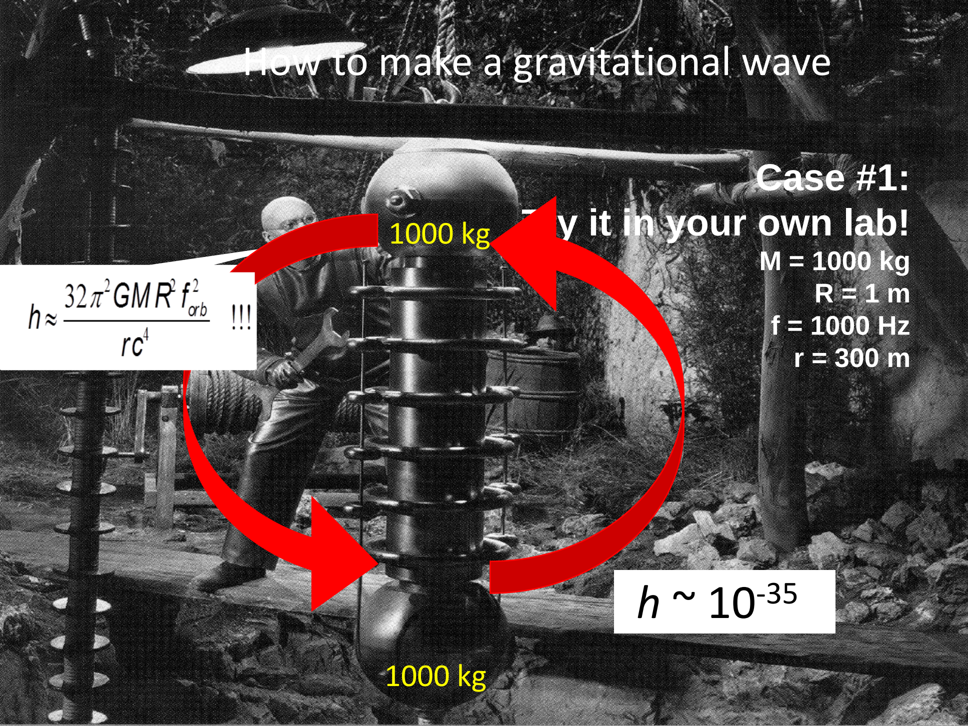
Quadrupole moment

GW luminosity

$$L = \frac{G}{5c^5}\left\langle \frac{\partial^3}{\partial t^3} I_{ij} \frac{\partial^3}{\partial t^3} I^{ij} \right\rangle$$

$G/c^4 = 8{,}3 \cdot 10^{-50}$ [$s^2/(kg\ m)$]

How to make a gravitational wave



Case #1:

Try it in your own lab!

M = 1000 kg

R = 1 m

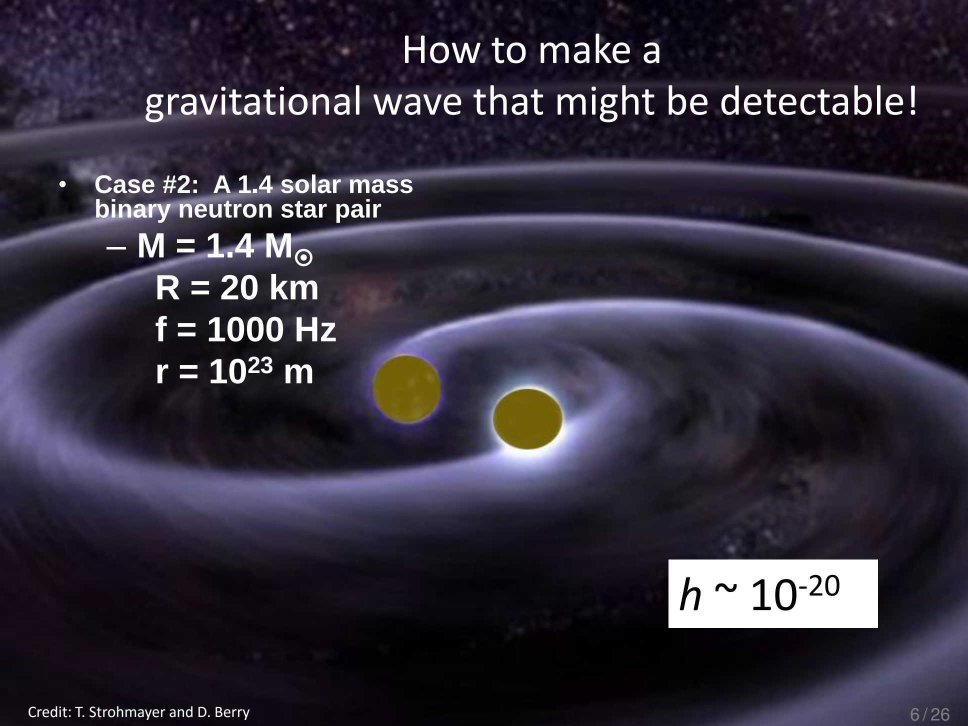
f = 1000 Hz

r = 300 m

$$h \approx \frac{32\pi^2 G M R^2 f_{orb}^2}{r c^4} \quad !!!$$

$h \sim 10^{-35}$

How to make a gravitational wave that might be detectable!

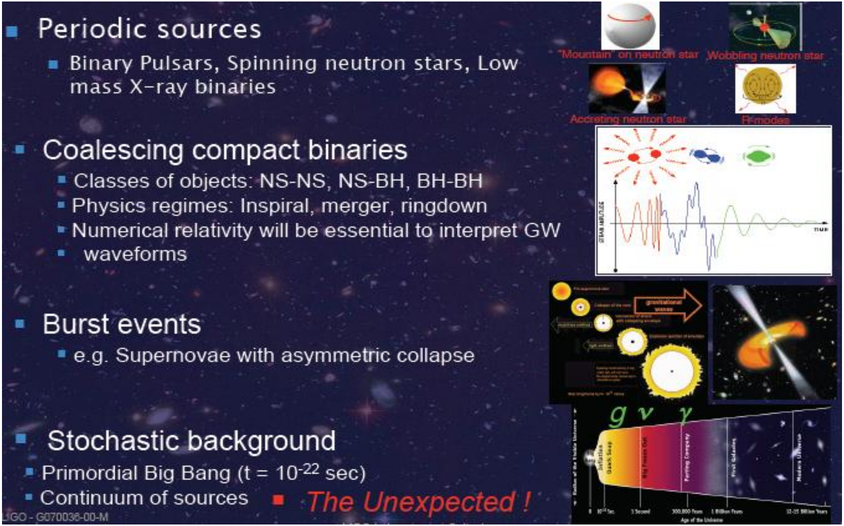


- **Case #2: A 1.4 solar mass binary neutron star pair**
  - **$M = 1.4\,M_{\odot}$**
    $R = 20$ km
    $f = 1000$ Hz
    $r = 10^{23}$ m

$h \sim 10^{-20}$

Credit: T. Strohmayer and D. Berry

Sources of gravitational waves

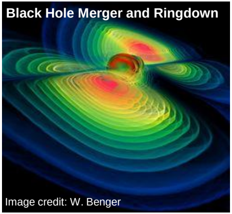


- Periodic sources
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries
- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW
  - waveforms
- Burst events
  - e.g. Supernovae with asymmetric collapse
- Stochastic background
  - Primordial Big Bang ($t = 10^{-22}$ sec)
  - Continuum of sources
- *The Unexpected !*

LIGO - G070036-00-M

Some Questions Gravitational Waves May Be Able to Answer

- **Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme conditions?*
  - *What equation of state describes a neutron star?*
  - *Are black holes truly bald?*
- **Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause GRBs?*
  - *What is the supernova mechanism in core-collapse of massive stars?*
  - *How many low mass black holes are there in the universe?*
  - *Do intermediate mass black holes exist?*
  - *How bumpy are neutron stars?*
  - *Is there a primordial gravitational-wave residue?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can binary inspirals be used as "standard sirens" to measure the local Hubble parameter?*



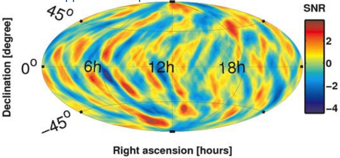
Black Hole Merger and Ringdown

Image credit: W. Benger

Neutron Star Formation

Image credit: NASA

GW Upper limit map

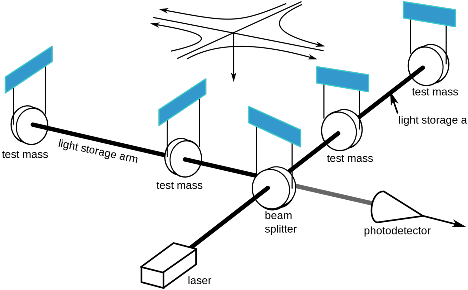


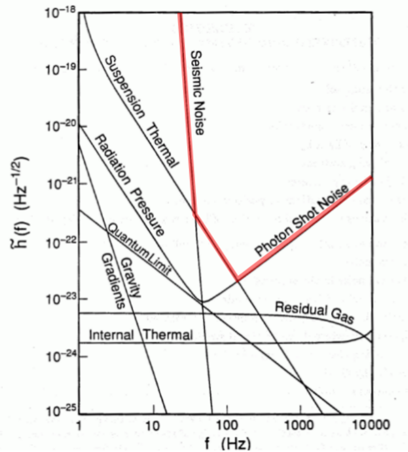
Michelson-Morley type interferometric detector

Gravitational wave is registered by measuring temporal change in arms' length (changes in the interferometric pattern):

$$h(t) = h_+(t) \cdot F_+(t;\psi) + h_\times(t) \cdot F_\times(t;\psi),$$

$$h = \Delta L / L \ll 10^{-18}$$





Main sources of noise (LIGO project, 1989)

Gravitational wave detectors' network

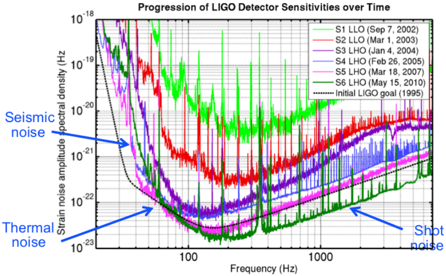
Gravitational wave detectors' network: LIGO (USA), GEO600 (UK, Germany), Virgo (France, Italy, Hungary, Netherlands and Poland), KAGRA (Japan), LIGO India...

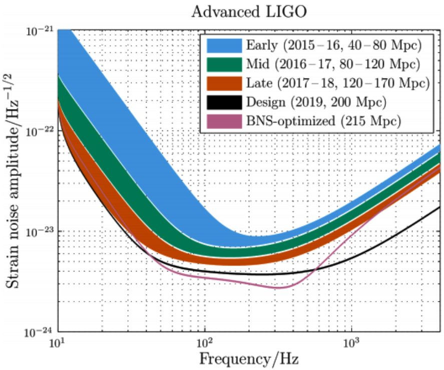
Virgo detector (3km arm length)

Polgraw group in Virgo project and LIGO-Virgo consortium:

- ⋆ IMPAN, CAMK, OAUW, NCBJ, UZg, UwB.
- ⋆ Theory, data analysis, large-scale computation, detector engineering.

LIGO/Virgo sensitivity



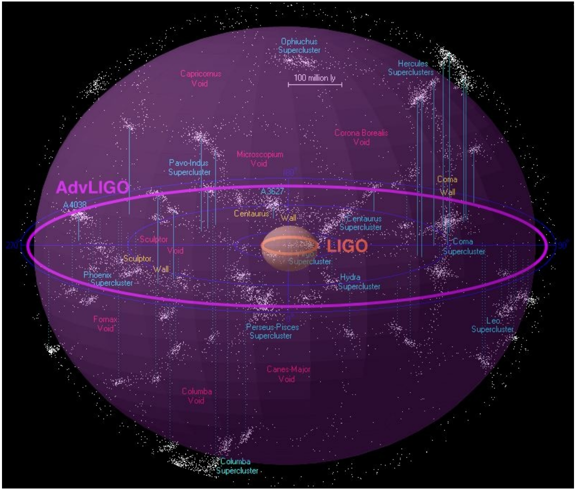


LIGO (US, Hanford & Livingston) and Virgo detectors (FR+IT+NL+HU+PL, Pisa) have reached the desired initial sensitivity (2002-2011).

Currently ongoing - the Advanced Detector Era (2015 - . . .)

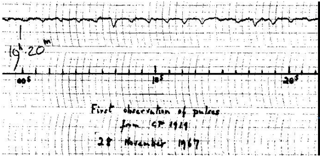
Two LIGO detectors (Livingston & Hanford) began O1 observational run on September 18th 2015 (end of run: January 12th 2016).

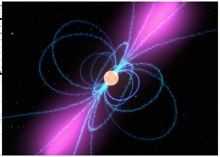
Advanced Detector Era: 2015 - ...



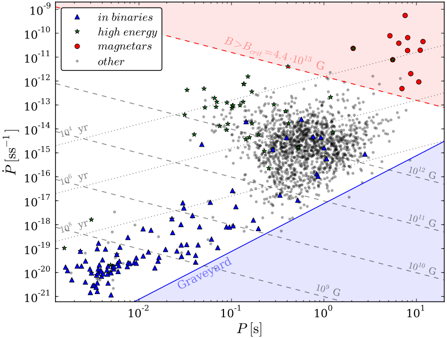
Sensitivity of AdLIGO and AdVirgo increased by an order of magnitude → distance reach ×10 (sensitivity $\propto 1/r$ - detection of amplitude, not energy of the wave!)

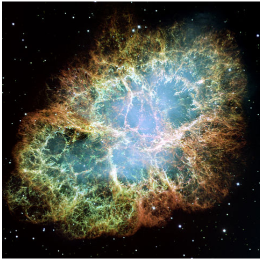
Neutron stars = very dense, magnetized stars

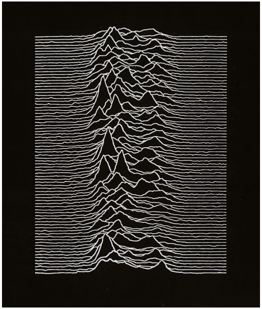




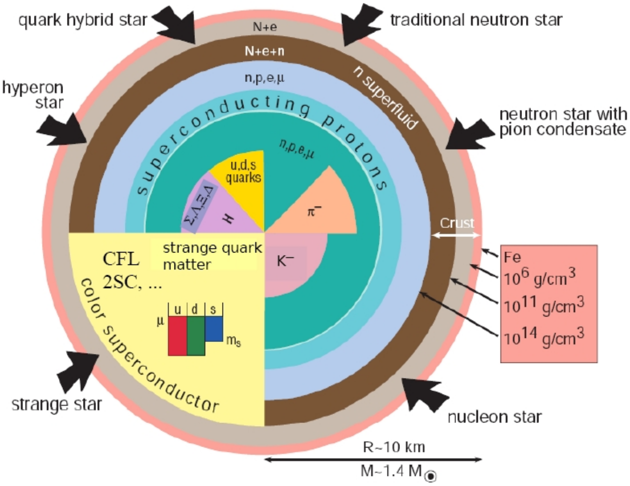
- ⋆ The most relativistic, material objects in the Universe: compactness $M/R \simeq 0.5$.







The mystery of neutron star interiors



(Courtesy: F. Weber)

Dense matter in conditions impossible to obtain on Earth!

Continuous GWs from spinning neutron stars

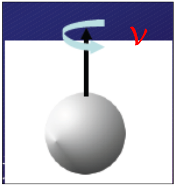
Characteristics:

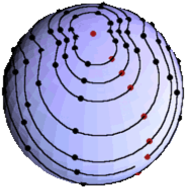
1. Long-lived: $T > T_{obs}$

2. Nearly periodic: $f_{GW} \sim \nu$

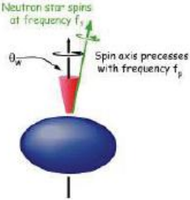
Generation mechanisms (we need a time varying quadrupole moment):

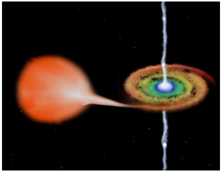
1. *Mountains*
   (elastic stresses, magnetic fields)
2. *Oscillations*
   (r-modes)
3. *Free precession*
   (magnetic field)
4. *Accretion*
   (drives deformations from r-modes, thermal gradients, magnetic fields)





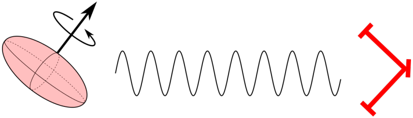
Courtesy: B. J.Owen

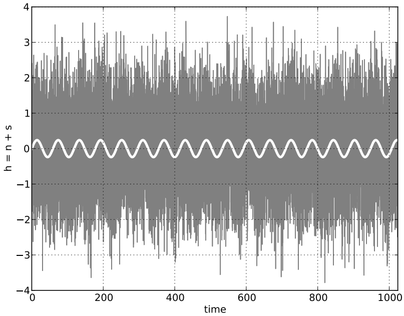


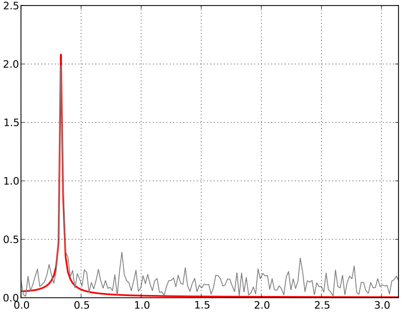


Courtesy: McGill U.

Example: weak monochromatic signals hidden in the noise







In this case Fourier transform is sufficient to detect the signal (a matched filter method):

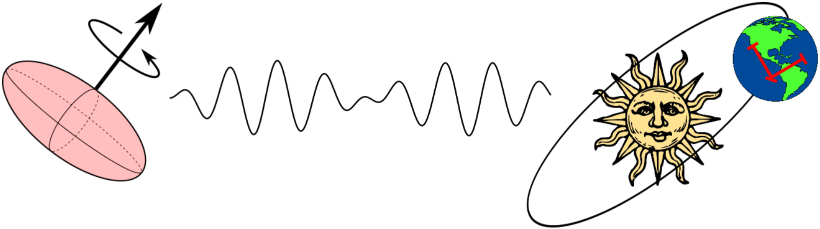
$$F = \int_0^{T_0} x(t)\exp(-i\omega t)dt$$

Signal-to-noise

$$SNR = h_0 \frac{\sqrt{T_0}}{\sigma_{noise}}$$

In reality: signal is modulated

Since the detector is on Earth, influence of planets and Earth's rotation changes the signal's amplitude and phase.



- ⋆ Signal is almost monochromatic: pulsars are slowing down,
- ⋆ To analyze, we have to demodulate the signal (detector is moving),
- → precise ephemerids of the Solar System used.

Calculation of the F-statistic

To estimate how well the model matches with the data $x(t)$, we calculate $\mathcal{F}$,

$$\mathcal{F} = \frac{2}{S_0 T_0} \left(\frac{|F_a|^2}{\langle a^2 \rangle} + \frac{|F_b|^2}{\langle b^2 \rangle} \right)$$

where S_0 is the spectral density, T_0 is the observation time, and

$$F_a = \int_0^{T_0} x(t) a(t) \exp(-i\phi(t)) dt, \, F_b = \ldots$$

and $a(t)$, $b(t)$ are amplitude modulation functions (depend on the detector location and sky position of the source),

$$h_1(t) = a(t) \cos\phi(t), \quad h_2(t) = b(t) \cos\phi(t),$$

$$h_3(t) = a(t) \sin\phi(t), \quad h_4(t) = b(t) \sin\phi(t),$$

related to the model of the signal (h_i, $i = 1, \ldots, 4$)

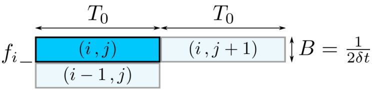
$$h(t) = \sum_{i=1}^{4} A_i \, h_i(t).$$

For triaxial ellipsoid model: dependence on the extrinsic $(h_0, \psi, \iota, \phi_0)$ and intrinsic $(f, \dot{f}, \alpha, \delta)$ parameters.

Methods of data analysis

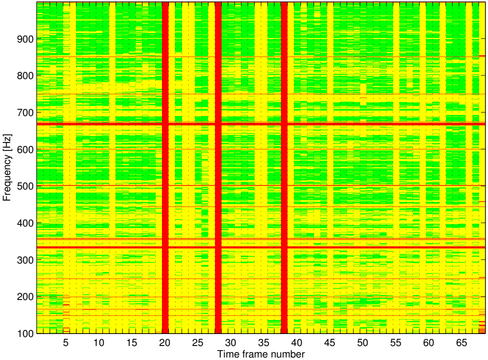
Computing power $\propto T_0^5 \log(T_0)$. Coherent search of $T_0 \simeq 1\,yr$ of data would require zettaFLOPS (10^{21} FLOPS) $\rightarrow$ currently impossible $\ddot{\frown}$

Solution: divide data into shorter length time frames ($T_0 \simeq 2$ days)



- ⋆ narrow frequency bands - sampling time $\delta t = 1/2B$, number of data points $N = T/\delta t \rightarrow N = 2TB$

$\rightarrow$ feasible on a petaFLOP computer.



Example search space (Virgo Science Run 1). Red: no data, yellow: bad data, green: good data.

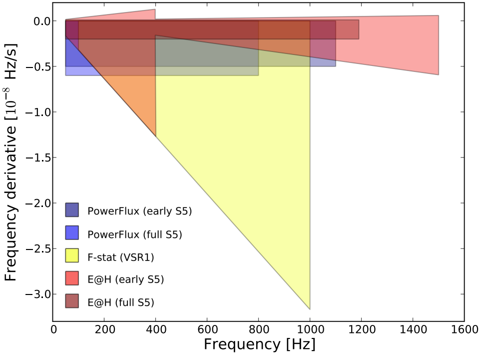
Typical all-sky search: parameter space

- ⋆ Narrow (1 Hz) frequency bands f: $[100 - 1000]$ Hz,
- ⋆ Spin-down f_1 range proportional to f:

$$[-1.6 \times 10^{-9} \frac{f}{100\text{Hz}},\ 0]\ \text{Hz s}^{-1}$$

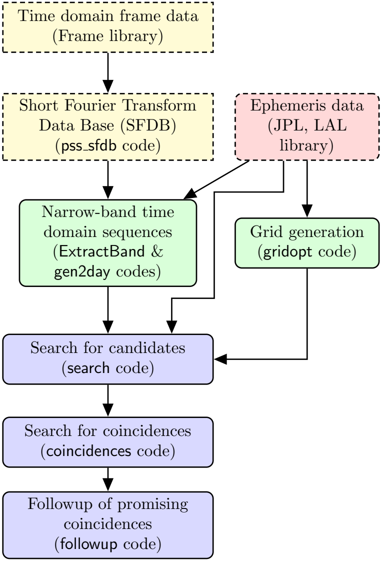
- ⋆ All-sky search: number of sky positions $\alpha(f), \delta(f) \propto f$.

Comparison of the $f - \dot{f}$ plane searched (yellow) with that of other recent all-sky searches:



In our astrophysical applications, the 4-dim parameter space $(f, \dot{f}, \alpha, \delta)$ is big (in VSR1 $\simeq 10^{17}$ F-statistic evaluations)

All-sky pipeline

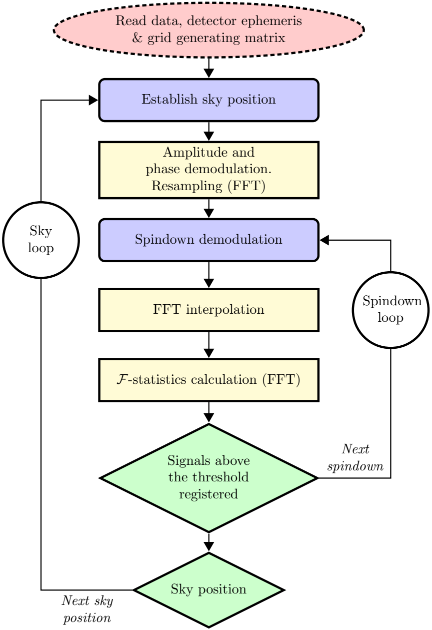


- ⋆ Input data generation (Raw time domain data $\sim$ *PB*)
- ⋆ Pre-processing → $\sim$ *TB* (input time series, detector ephemerids and grid of parameters),
- ⋆ Stage 1: F-statistic search for candidate GW signals (the most time-consuming part of the pipeline)

→ 10^{10} candidates/detector, 100 TB of output.

- ⋆ Stage 2: Coincidences among candidate signals from different time segments,
- ⋆ Stage 3: Followup of interesting coincidences - evaluation of F-statistic along the whole data span.

Most expensive part: search for candidate signals



Read data, detector ephemeris & grid generating matrix

Establish sky position

Amplitude and phase demodulation. Resampling (FFT)

Spindown demodulation

FFT interpolation

$\mathcal{F}$-statistics calculation (FFT)

Signals above the threshold registered

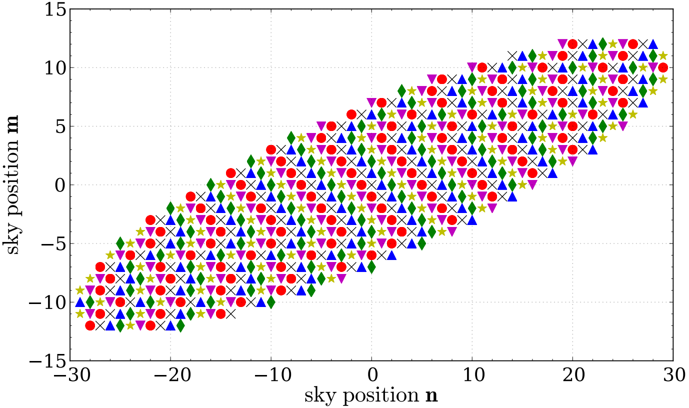
Sky position

- ⋆ Suitable algorithms that allow for Fast Fourier Transforms,
- ⋆ Optimized grid of parameters - minimum number of operation to reach desired sensitivity,

  → partial demodulation before the inner spindown loop (only once per sky position),
- ⋆ Sky positions completely indepedent of each other

  → ”Embarasingly parallel problem”

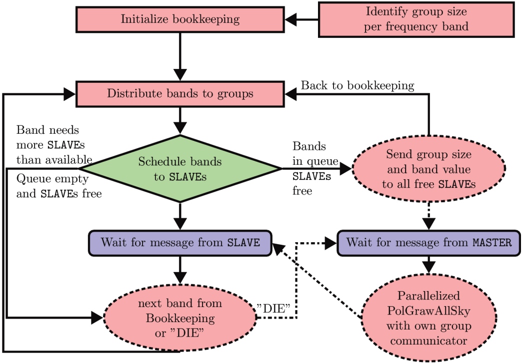
First level of parallelization: over the sky positions



Sky positions (here in parameter grid coordinates) are independent →
Round-robin scheduling.

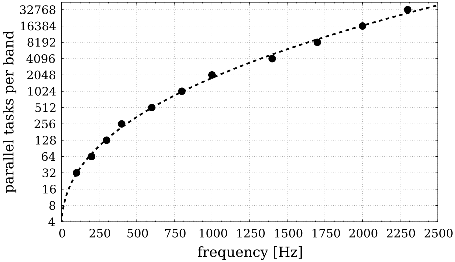
Second level: massive parallelisation with MPI

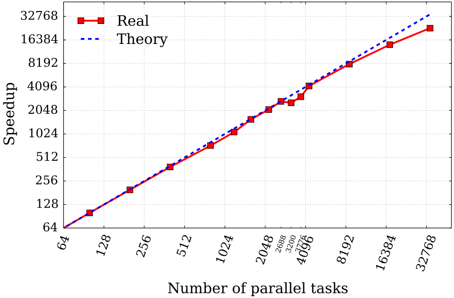
Internal MPI scheduling algorithm to run multiple instances of parallel all-sky search as one massively parallel computation:



- ⋆ Initialization and estimation of the available and necessary parallel resources,
- ⋆ Construction of different tasks as groups for requested frequencies,
- ⋆ Size of Group of tasks estimated using frequency scaling,
- ⋆ Distribution and decomposition of groups,
- ⋆ Bookkeeping.

Scheduling and scalability





Amount of computation scales well with the band frequency.

SkyFarmer was tested up to 50k CPU tasks.

- ⋆ Scalability is good, but not optimal:
  - ⋆ communication per task starts to dominate,
  - ⋆ suboptimal domain decomposition due to simplified scheduling

Current and future plans

- ⋆ CPU SkyFarmer will be used to analyze the incoming O1 data (40 - 2000 Hz, 4 months), using data divided in 2 day segments
- → $\simeq 5 \times 10^6$ CPU-hours needed,
- → For better sensitivity with 6-day segments, we need $\approx 10^8$ CPU-hours.

- ⋆ Scaling higher for future exaFLOP computers - hybrid code with GPU.
- → single-GPU code already exists - `CUDA cuFFT` allowing for considerable speedup ($> 50\times$).

- ⋆ Analysing data from future runs: O2, O3,. . . until 2020 and beyond,
- ⋆ 3 detectors (LIGO + Virgo) or more (+KAGRA, LIGO India...)