

# All-sky search for almost monochromatic gravitational waves using supercomputers

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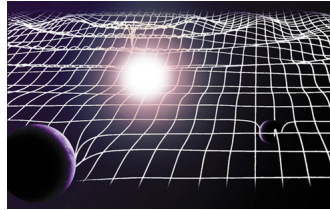
KIT SCC, 17.11.15



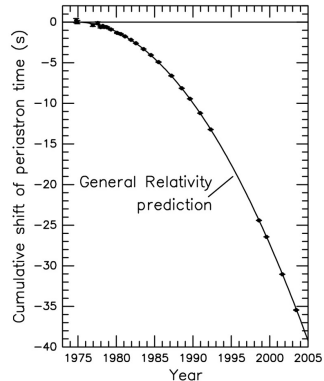
- ★ Gravitation and gravitational waves,
- ★ Sources of gravitational waves,
- ★ Gravitational wave detectors,
- ★ Rotating neutron stars as sources,
  - ★ Gravitational wave data analysis,
  - ★ All-sky search pipeline,
  - ★ Massive parallelization,
- ★ Current and future plans.

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

QUARKS	mass → charge → spin →	$\approx 2.3 \text{ MeV}/c^2$ 2/3 1/2 <b>u</b> up	$\approx 1.275 \text{ GeV}/c^2$ 2/3 1/2 <b>c</b> charm	$\approx 173.07 \text{ GeV}/c^2$ 2/3 1/2 <b>t</b> top	0 0 1 <b>g</b> gluon	$\approx 126 \text{ GeV}/c^2$ 0 0 <b>H</b> Higgs boson
		$\approx 4.8 \text{ MeV}/c^2$ -1/3 1/2 <b>d</b> down	$\approx 95 \text{ MeV}/c^2$ -1/3 1/2 <b>s</b> strange	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2 <b>b</b> bottom	0 0 1 <b><math>\gamma</math></b> photon	
		$0.511 \text{ MeV}/c^2$ -1 1/2 <b>e</b> electron	$105.7 \text{ MeV}/c^2$ -1 1/2 <b><math>\mu</math></b> muon	$1.777 \text{ GeV}/c^2$ -1 1/2 <b><math>\tau</math></b> tau	0 0 1 <b>Z</b> Z boson	
		$< 2.2 \text{ eV}/c^2$ 0 1/2 <b><math>\nu_e</math></b> electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\mu</math></b> muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\tau</math></b> tau neutrino	$\pm 1$ 1 <b>W</b> W boson	
LEPTONS					GAUGE BOSONS	



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



# Gravitational waves

Metric

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

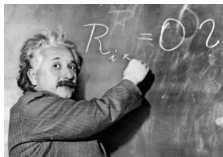
Einstein's equations

$$\longrightarrow G_{\mu\nu} = 8\pi G/c^4 T_{\mu\nu}$$



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

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

Quadrupole moment

GW luminosity

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

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

# How to make a gravitational wave

**Case #1:**

**Try it in your own lab!**

$M = 1000 \text{ kg}$

$R = 1 \text{ m}$

$f = 1000 \text{ Hz}$

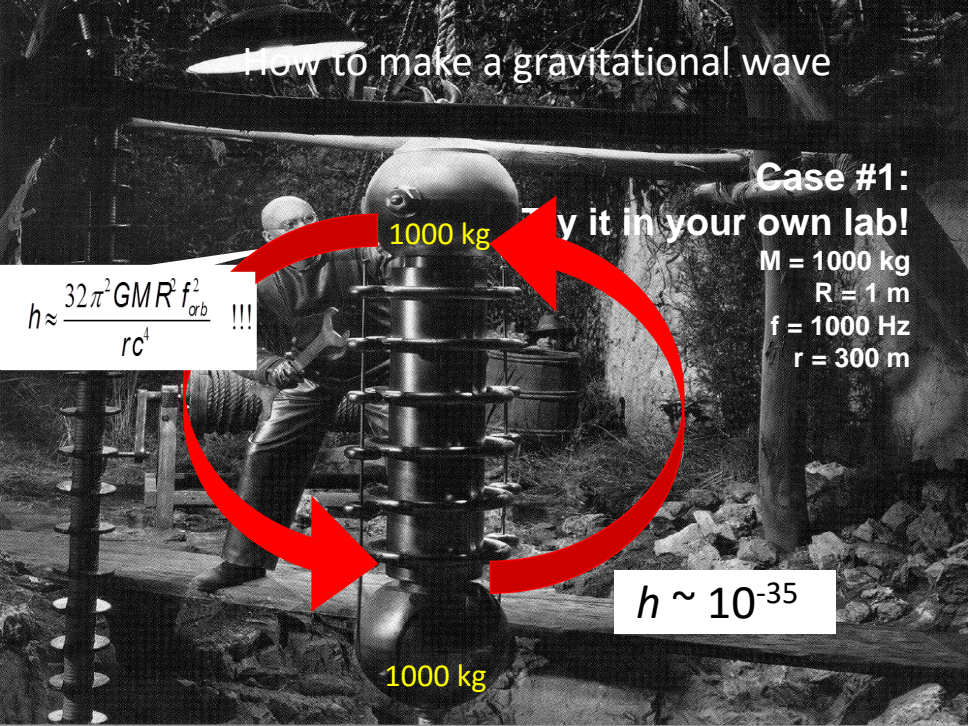
$r = 300 \text{ m}$

$$h \approx \frac{32\pi^2 GMR^3 f_{\text{orb}}^2}{rc^4} \quad !!!$$

$$h \sim 10^{-35}$$

1000 kg

1000 kg



# How to make a gravitational wave that might be detectable!

- Case #2: A 1.4 solar mass  
binary neutron star pair

- $M = 1.4 M_{\odot}$

- $R = 20 \text{ km}$

- $f = 1000 \text{ Hz}$

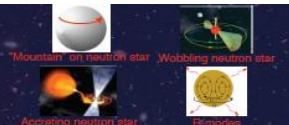
- $r = 10^{23} \text{ m}$

$$h \sim 10^{-20}$$

# Sources of gravitational waves

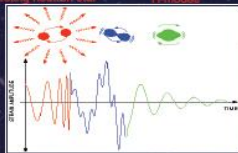
## ■ Periodic sources

- 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



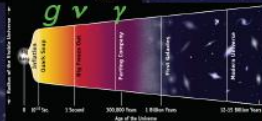
## ■ Burst events

- e.g. Supernovae with asymmetric collapse



## ■ Stochastic background

- Primordial Big Bang ( $t = 10^{-22}$  sec)
- Continuum of sources
- **The Unexpected !**



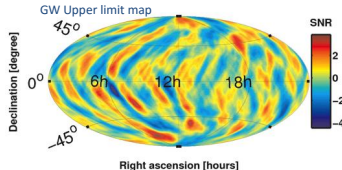
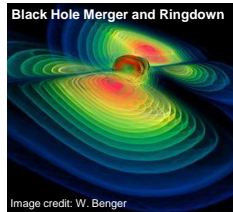
# Some Questions Gravitational Waves May Be Able to Answer

- **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?*



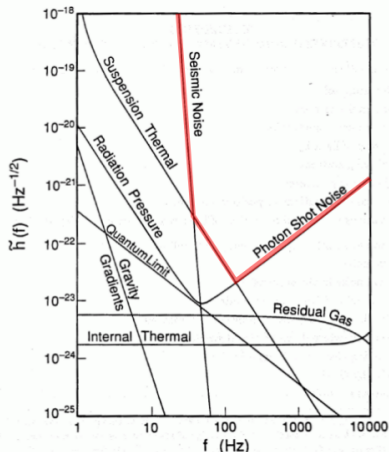
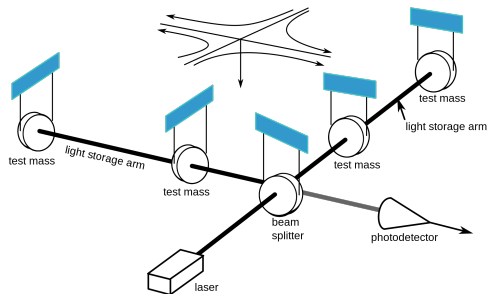


# Michelson-Morley type interferometric detector

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...

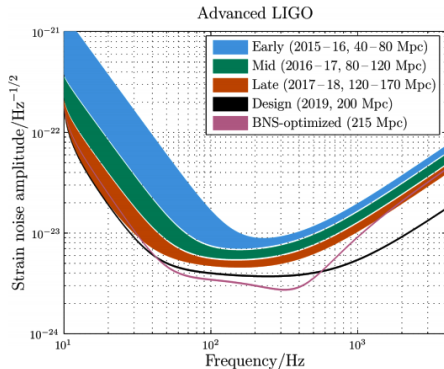
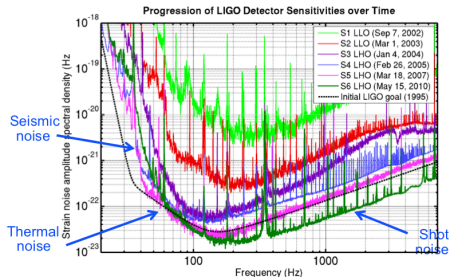


Virgo detector (3km arm length)

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

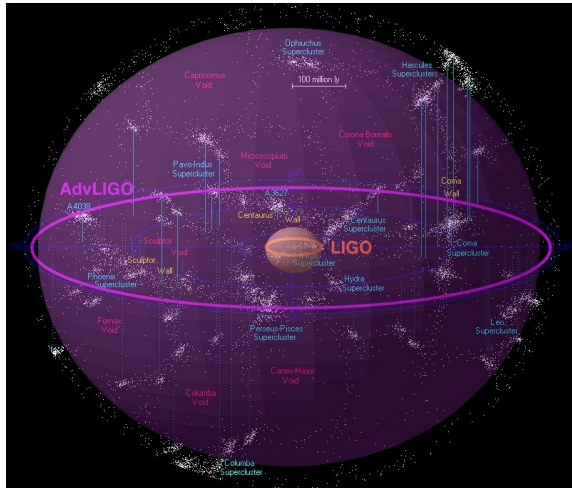


LIGO (US, Hanford & Livingston) and Virgo detectors (FR+IT+NL+HU+PL, Pisa) have reached the desired initial sensitivity (2002-2011).

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

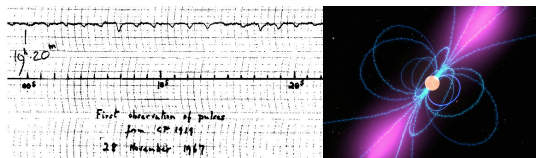
Two LIGO detectors (Livingston & Hanford) began O1 observational run on September 18th 2015 (end of run: January 12th 2016).

## Advanced Detector Era: 2015 - ...

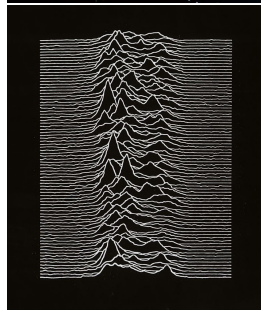
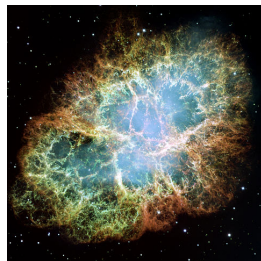
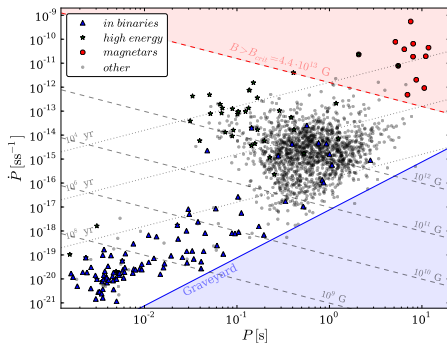


Sensitivity of AdLIGO and AdVirgo increased by an order of magnitude  $\rightarrow$  distance reach  $\times 10$  (sensitivity  $\propto 1/r$  - detection of amplitude, not energy of the wave!)

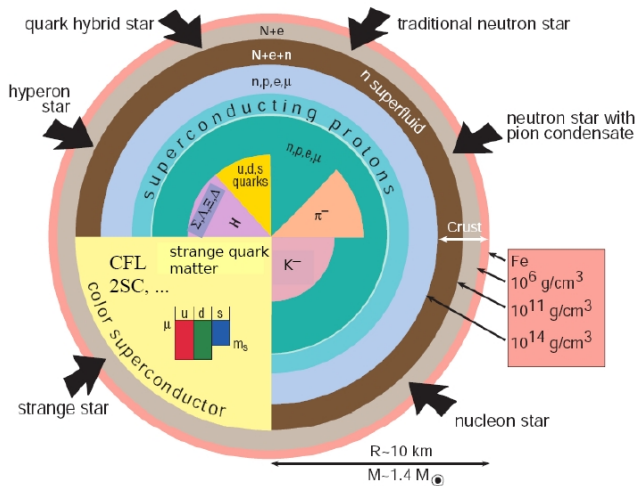
# Neutron stars = very dense, magnetized stars



- ★ 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!

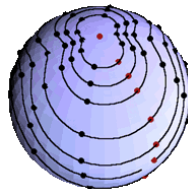
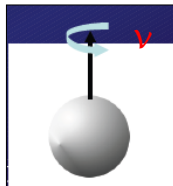
# Continuous GWs from spinning neutron stars

## Characteristics:

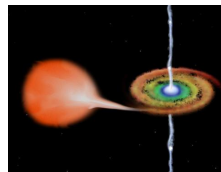
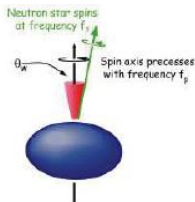
1. Long-lived:  $T > T_{\text{obs}}$
2. Nearly periodic:  $f_{\text{GW}} \sim \nu$

## 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)

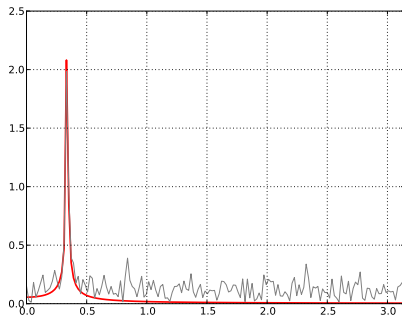
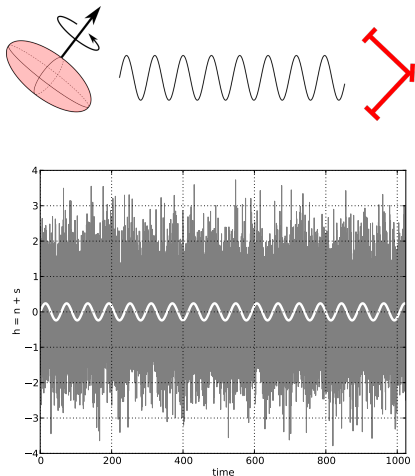


Courtesy: B. J. Owen



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**):

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

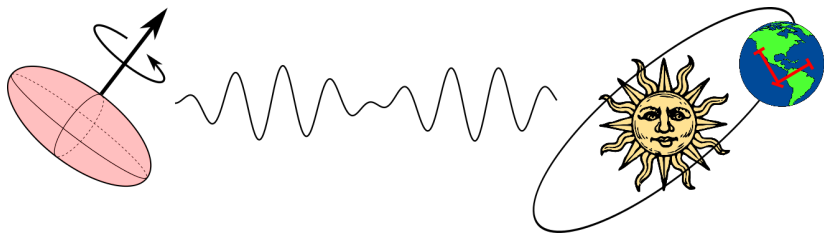
Signal-to-noise

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



## 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

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

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 ( $h_i$ ,  $i = 1, \dots, 4$ )

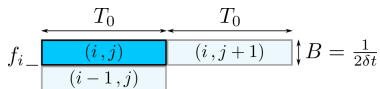
$$h(t) = \sum_{i=1}^4 A_i h_i(t).$$

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

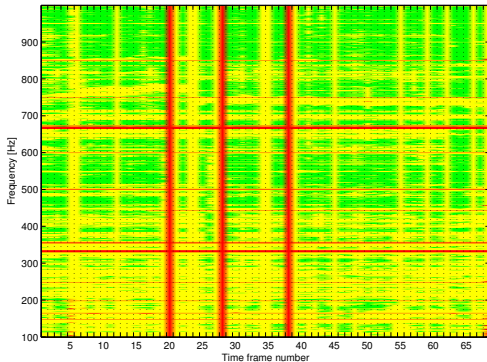
# Methods of data analysis

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 ☹

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.

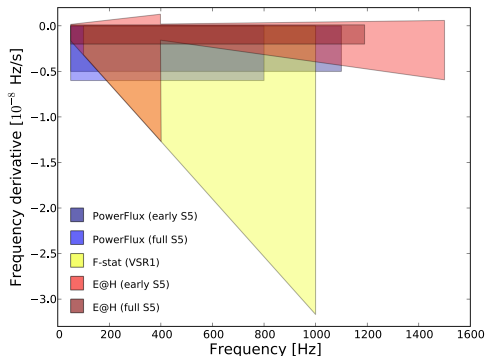
## Typical all-sky search: parameter space

- ★ Narrow (1 Hz) frequency bands  $f$ :  
[100 – 1000] Hz,
- ★ Spin-down  $\dot{f}$  range proportional to  $f$ :

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

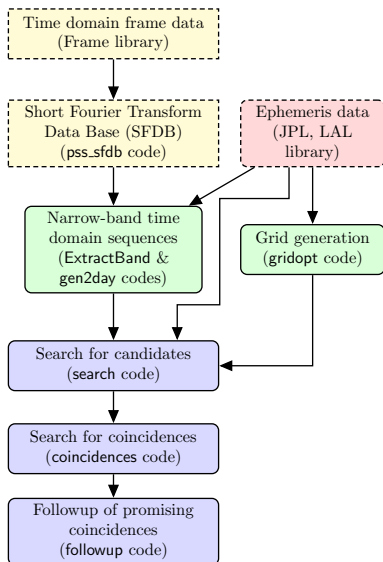
- ★ All-sky search: number of sky positions  $\alpha(f), \delta(f) \propto f$ .

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



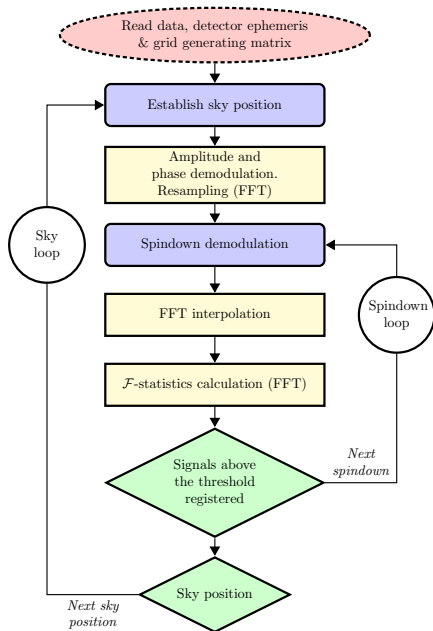
In our astrophysical applications, the 4-dim parameter space  $(f, \dot{f}, \alpha, \delta)$  is big (in VSR1  $\simeq 10^{17}$  F-statistic evaluations)

# All-sky pipeline



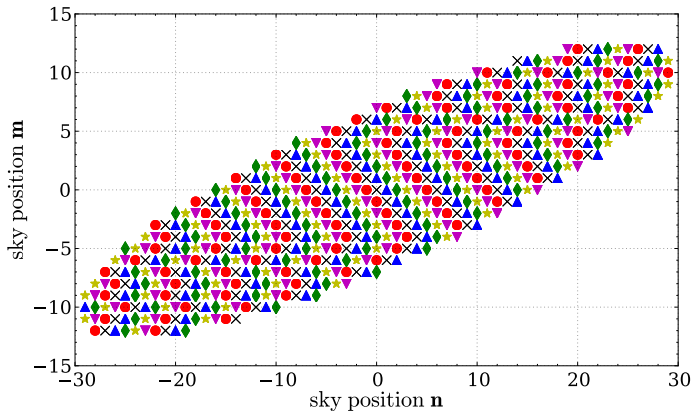
- ★ Input data generation (Raw time domain data  $\sim PB$ )
- ★ Pre-processing  $\rightarrow \sim TB$  (input time series, detector ephemerids and grid of parameters),
- ★ Stage 1: F-statistic **search for candidate GW signals** (the most time-consuming part of the pipeline)  
 $\rightarrow 10^{10}$  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



- ★ 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 independent of each other  
→ "Embarasingly parallel problem"

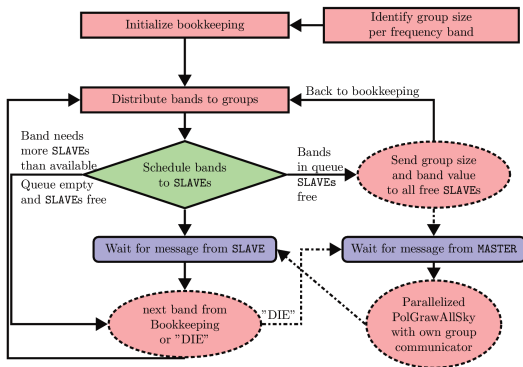
## First level of parallelization: over the sky positions



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

## Second level: massive parallelisation with MPI

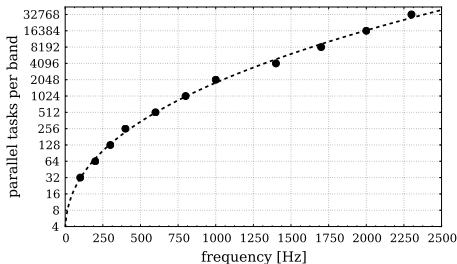
Internal MPI scheduling algorithm to run multiple instances of parallel all-sky search as one massively parallel computation:



- ★ 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.



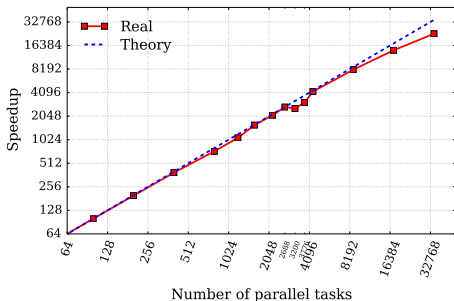
# Scheduling and scalability



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...)