GPUs in gravitational wave research

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Virgo Experiment

Content

- Wigner GPU laboratory
- The Virgo experiment
- The way we work with GPUs
  - The Compute Wrapper , CUDA/OpenCL compute backends
- Analysis examples
  - Coalescing Compact Binaries
    - The matched-filter
  - Continous Waves
    - The frequency Hough algorithm
- Plans with Tegra K1
- Conclusion

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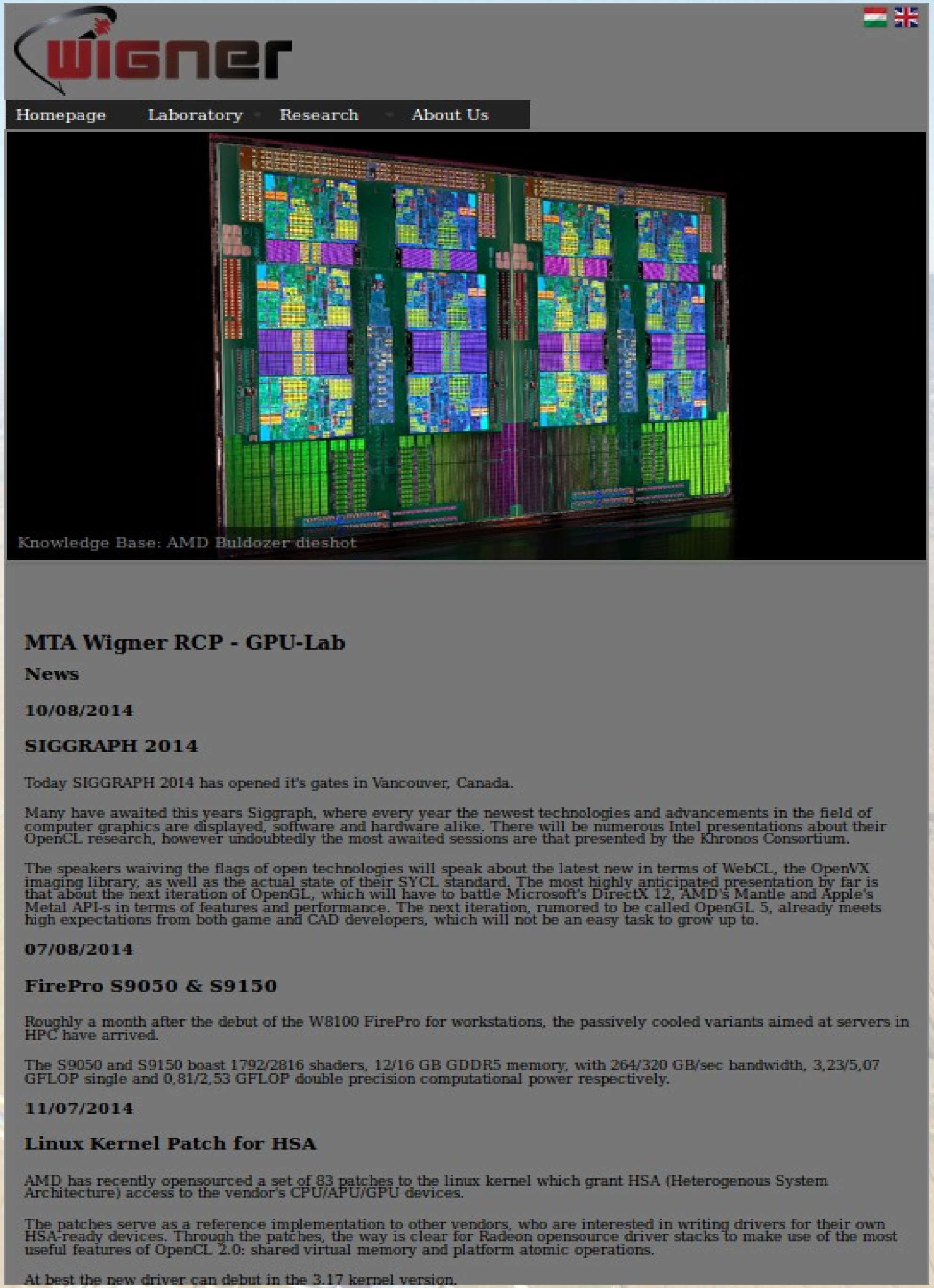
The Wigner GPU laboratory

http://gpu.wigner.mta.hu

- Small scale heterogenous cluster
- Serves as a playing ground for researchers in the Institute
- Support by experts:

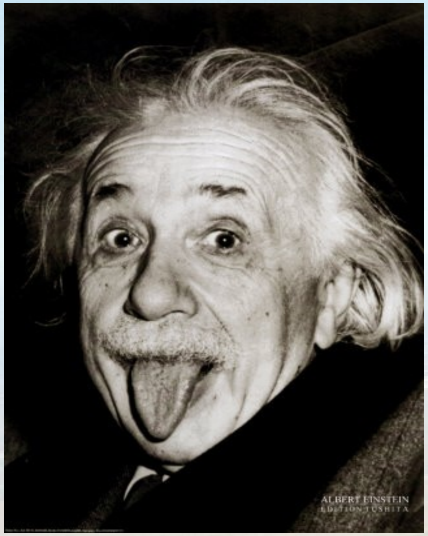
  Nagy-Egri Mate Ferenc

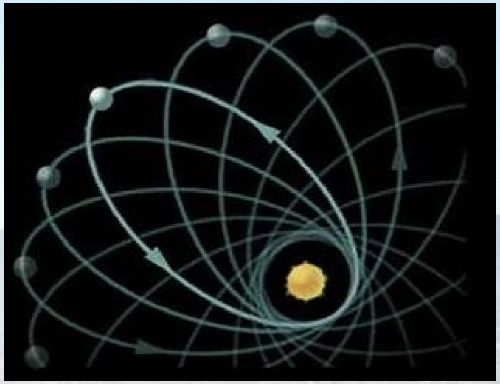
- Various cards: Nvidias, AMDs, Phis



General Relativity

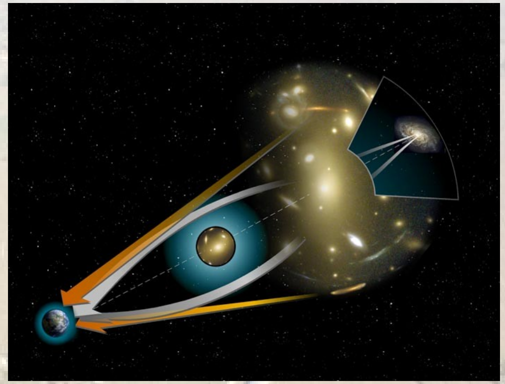
Observables





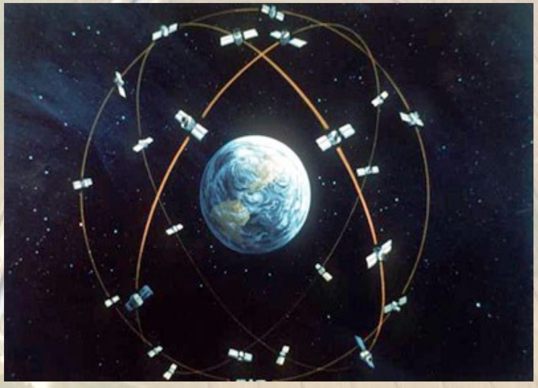
Experimentally prooved:

1. Perihelium shift of planets
2. Gravitational lensing
3. Time dilatation/contraction in strong/weak gravitational fields



4.… and the existence of gtavitational waves…

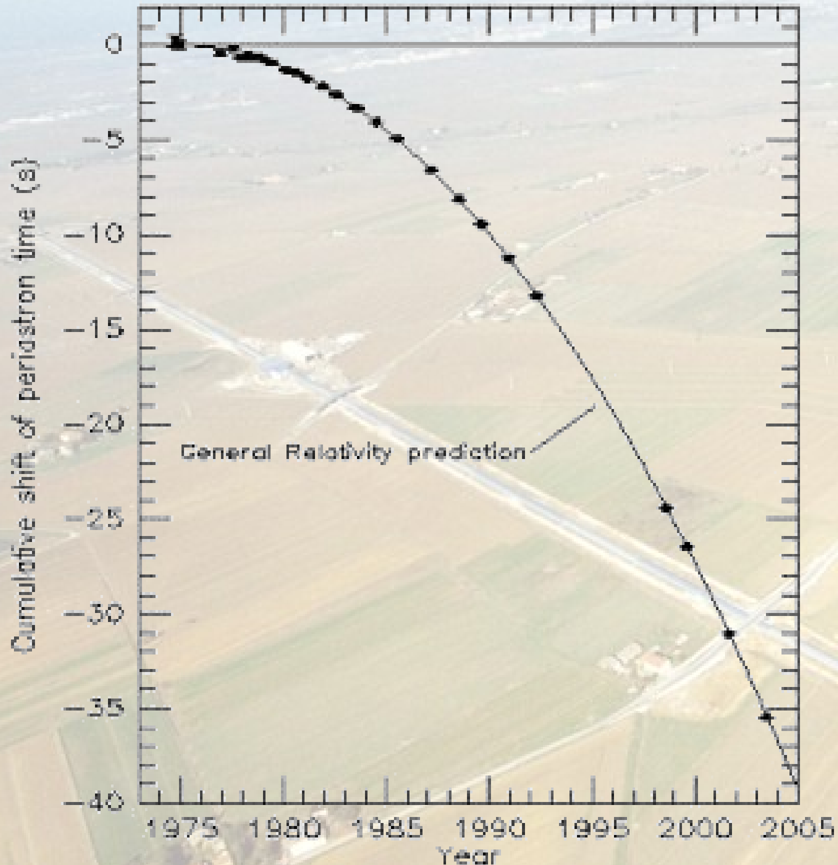
- Gravitational waves are ripples/waves of space-time itself created by certain energetic acceleration of huge masses.
- As of today, we have only indirect – but quite convincing – proof of their existence

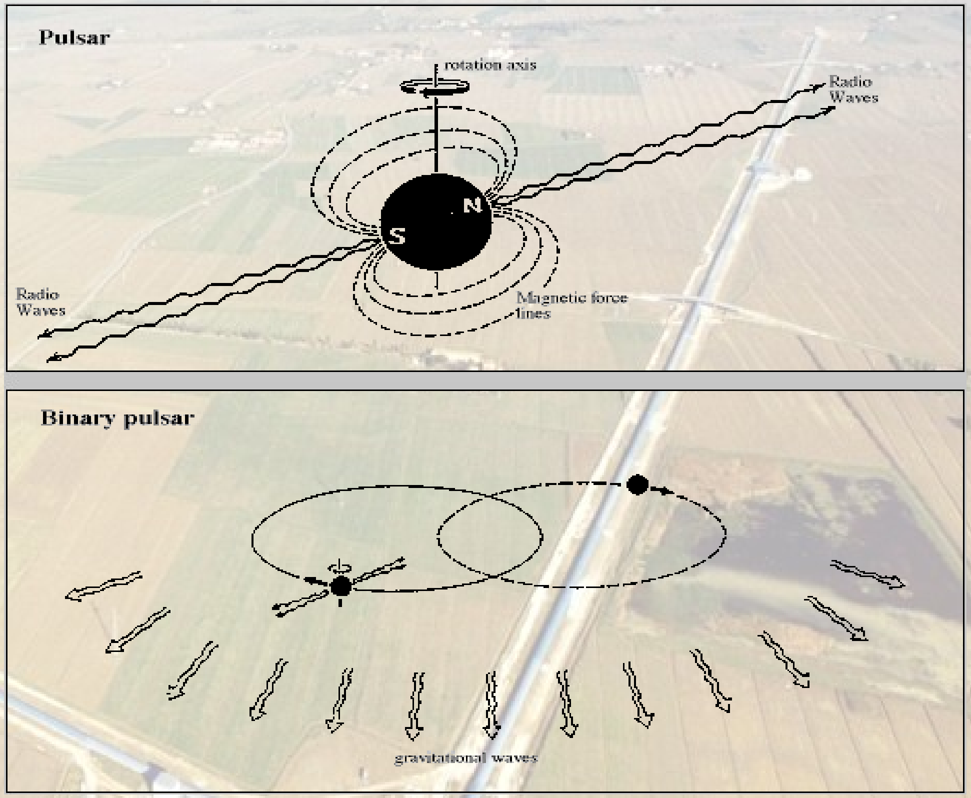


A Hulse- Taylor pulsar

- The „Holy Grail" of gravitational wave researchers
- Discovered in 1974 (Russel Hulse, Joseph Taylor)
- 1993 Shared Nobel-prize

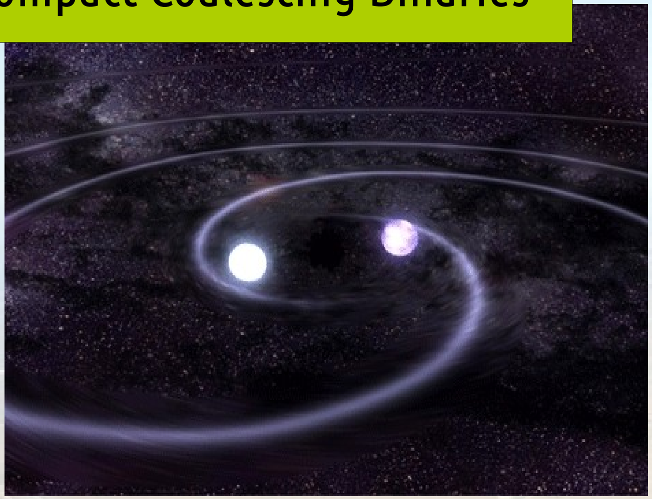
- Probably two neutron star
- 3,1 mm shrink for every orbit cycle
- 59 ms-os pulsating period
- 7,75 hour orbital period



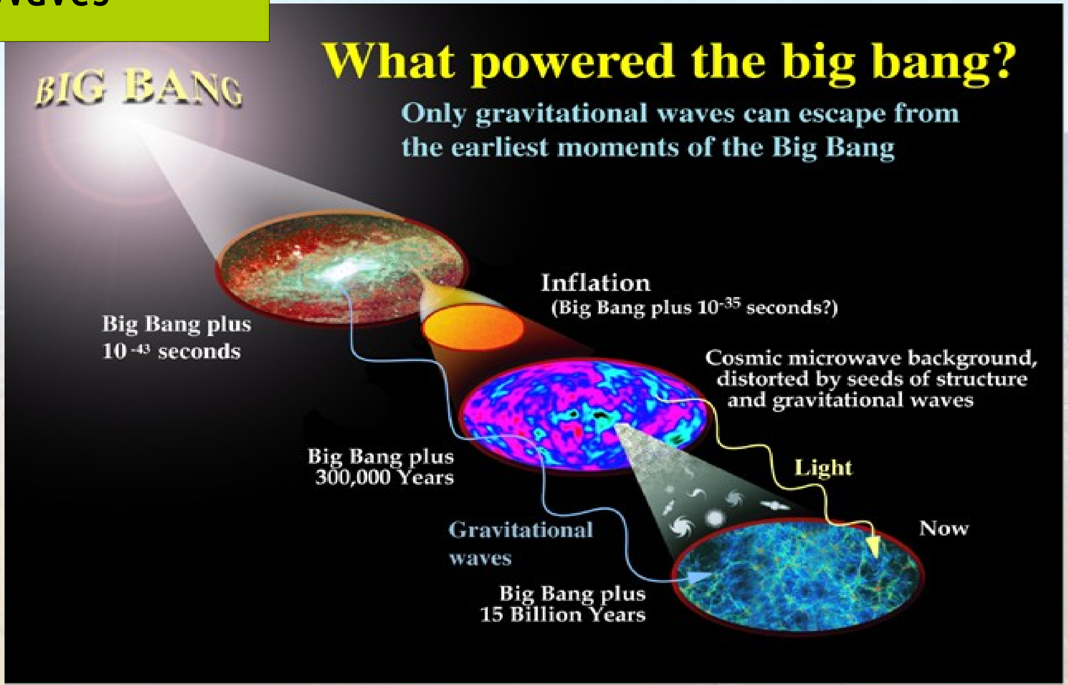


Possible GW sources

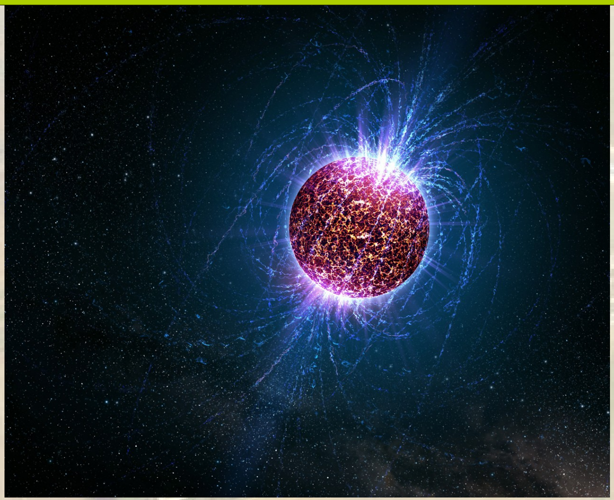
Compact Coalescing Binaries



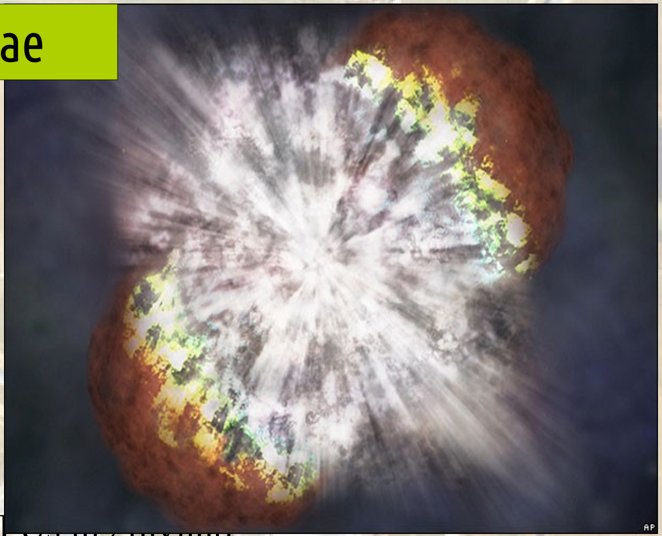
Stochastic Waves



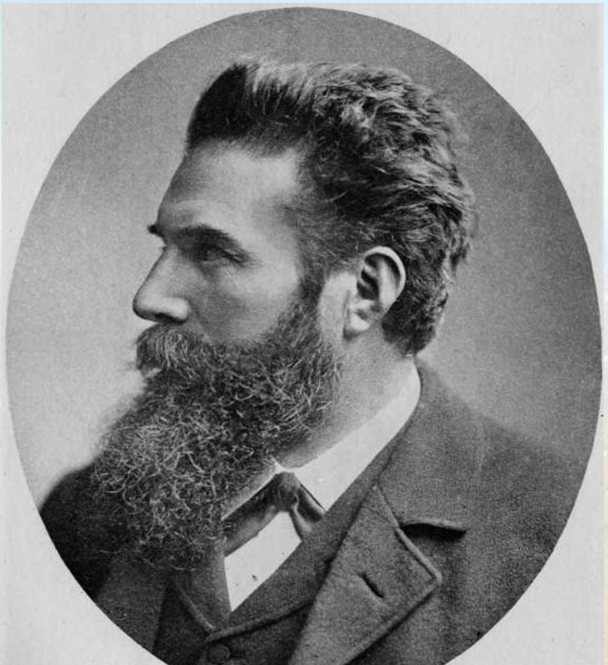
Pulsars



Supernovae



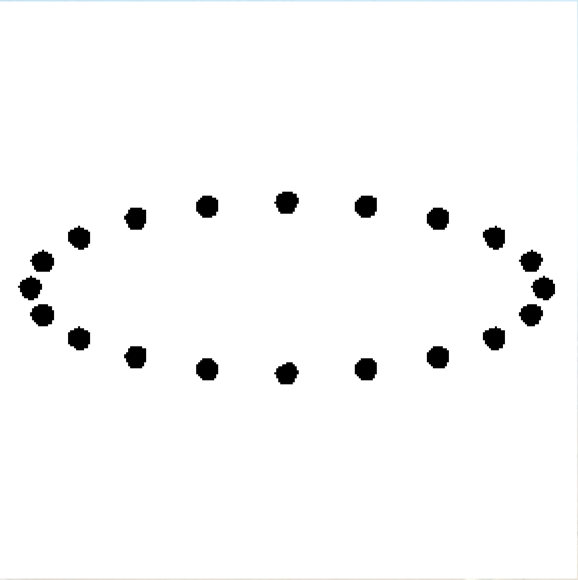
Why interesting ?

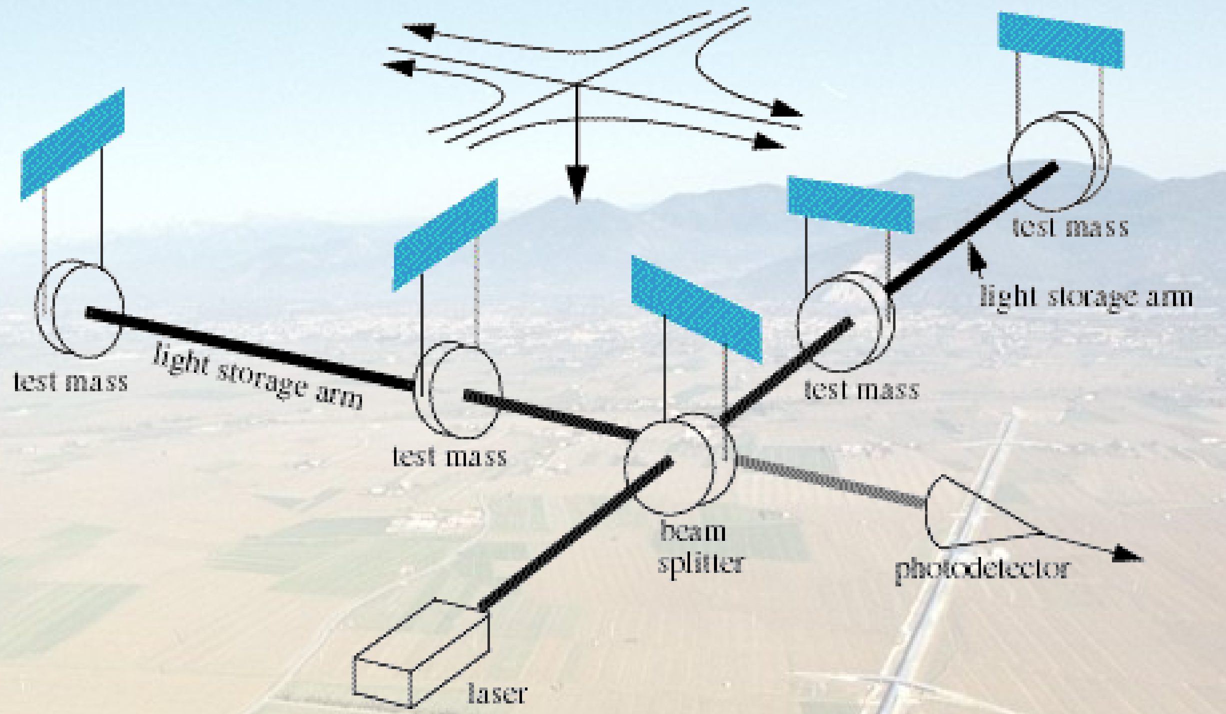


Wilheim Conrad Roentgen
1845 - 1923

- Completely new face of astrophysisal objects, of Universe
- One can observe so far hidden phenomenae
- Would be the new „sense-organ” of Humanity
- Testing theories

Interferometers





- Incident GW changes the arm length
- Light intensity changes in the interference point
- The outcome of the measurement is the difference of arm lengths

- The worlds most precise relative measurement with a precision of 10^{-18} .
- Huge collection of environmental noise have to be cancelled
- Isolated detectors are needed for coincidence detection of same event (see LIGO).

The Virgo experiment

VIRGO

• A Virgo detektor az EGO (European Gravitational Observatory) telephelyén az Arno folyó sikságán Pisa melletti Cascina-ban található

• Az építkezés 2003-ban fejeződött be

• A Wigner FK Rácz István vezetésével 2008-ban csatlakozott a kísérlethez

• A francia - olasz együttműködésként induló kollaborációnak ma már magyar és lengyel tagjai is vannak.

The GWTools project

The GWtools project

http://gwtools.org

GWTools - the C++/OpenCL [1] based Gravitational Wave data analysis Toolkit - is an algorithm library aimed to bring the immense computing power of emerging many-core architectures - such as GPUs, APUs and many-core CPUs - to the service of gravitational wave research. GWTools is a general algorithm library intended to provide modular building blocksfor various application targeting the computationally challenging components of GW data analysis pipelines.

The Compute Wrapper - features

- Forever ongoing discussion about cards and programing languages
- We created a Compute Wrapper (CW) and using mutiple backend (CUDA / OpenCL / CPU / etc..)
- Development and testing happens in OpenCL, than the code ported to the appropriate backend.
- OpenCL → CUDA kernel translation is trivial (almost semi-automatic)
- CUDA → OpenCL can be problematic in some cases and requires special attention
- Built-in GL interop
- The Compute Wrapper also provides a
  - thread pool
  - a host side scheduler with
  - relational workflow handling
  - for CPU side optimisation for optimal load balancing.

The Compute Wrapper – code example

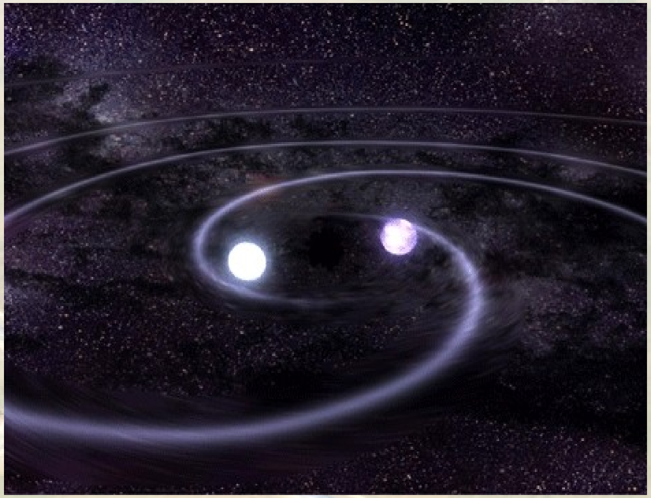
```
#include <ComputeWrapper/include/ProgramManager.h>
#include <ComputeWrapper/include/Factory.h>
#include <ComputeWrapper/include/IBuffer.h>
#include <System/include/ModulParameterFactory.h>
#include <Utils/include/ImageTypes.h>

int main() {

 // Host side objects and problem size
 math::Size m_size(1024,2048);
 float * h_buffer = new float[m_size.getCount()];

 // Create device objects
 cw::IBuffer * m_buffer = cw::Factory::createImage2D(m_size, IMAGE_UCHAR_C4, MEM_READ_WRITE);
 cw::IImage  * m_image  = cw::Factory::createBuffer(m_size.getCount() * sizeof(flot), MEM_READ_ONLY | MEM_COPY_HOST_PTR, h_buffer);

 // Create a program
 m_program_id = FIND_PROGRAM_ID("hough_transform");

 // Kernel arguments
 cw::cwInt arg1(10);
 cw::cwInt arg2(20);

 // Call the kernel
 PROGRAM_BY_ID(m_program_id)("integral_map", cw::Range(global_size_x, global_size_y), cw::Range(32,23), 4,  m_buffer, m_image, &arg1, &arg2);

 // Finish every kernel execution
 cw::ContextManager::FinishQueue();

 // Read back the results
 m_buffer->readBuffer(h_buffer);

 // Exiting
 return 0;
}
```

About gravitational wave data

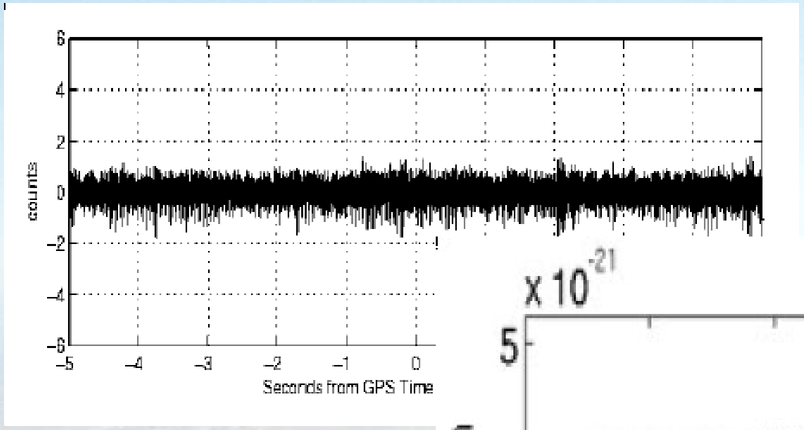
- GW data analysis is compute intensive not data intensive
- By quantity it is much less than LHC data: O(100-300 TB / detector / year)
- However, it's arithmetic density is much higher
- Available computing power directly tanslates to detector sensitivity !
    - For CW searches sensitivity goes as ~1.0 /sqrt(T), while necessary computing power is ~exp(T)
    - For CBC ~ number of background estimation and lowering clustering thresholds ~N
- In contrast to HEP experiments, events cannot be regenerated
- Qucik, low latency analysis are necessary for externally triggered searches
- Order of CPU cores ~20K
- Order of GPUs ~ 300

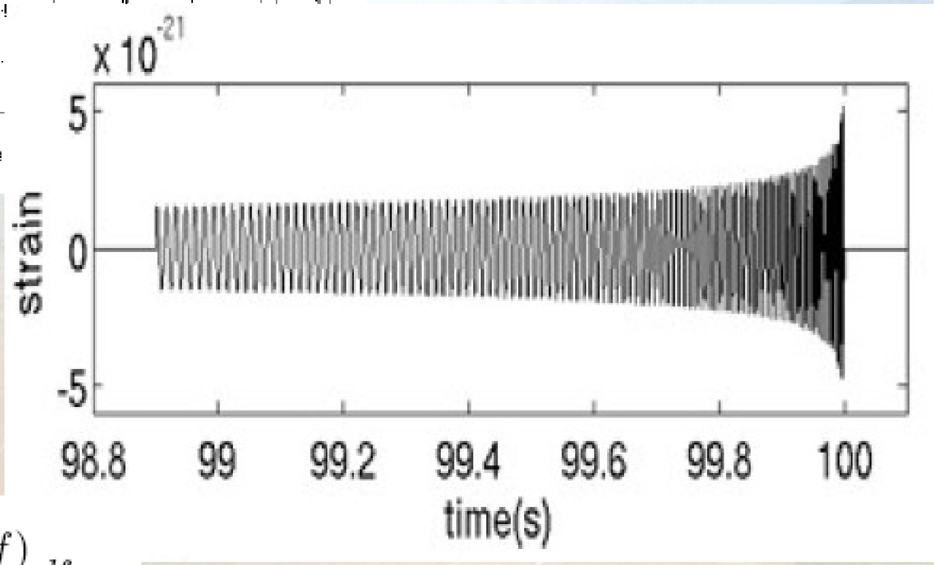
Analysis example I:

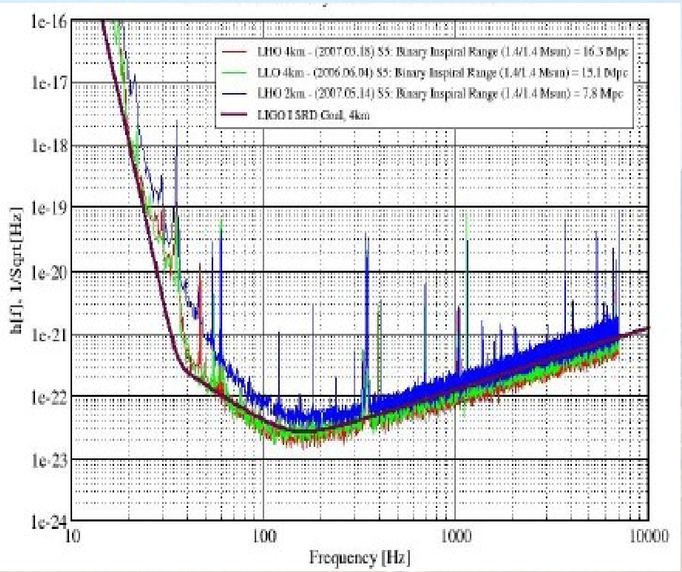
Compact Binary Coalescence



Compact Binary Coalescence

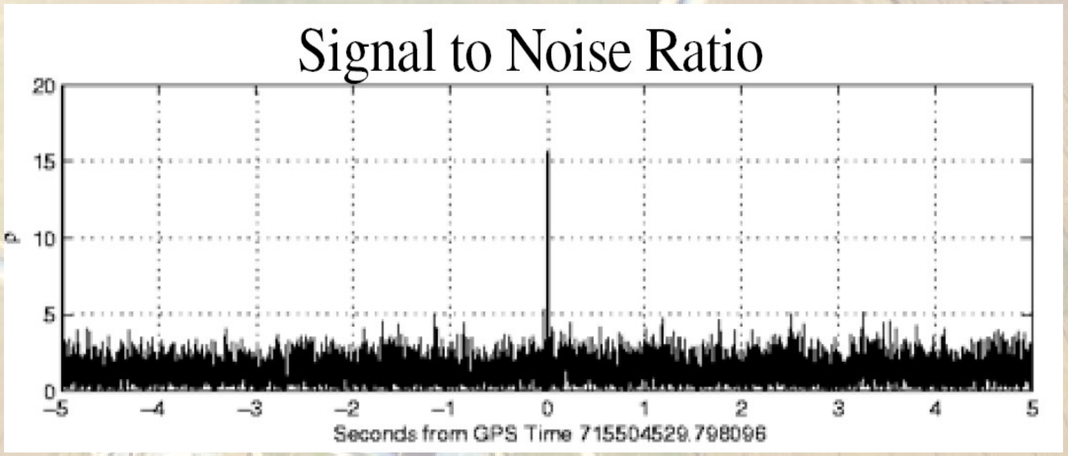






$$(A, B) = \int \frac{A^*(f)B(f)}{S_n(f)} df,$$

$$\mathrm{SNR} = \frac{z}{\sqrt{\langle(\delta z)^2\rangle}} = \frac{(\tilde{Q}, \tilde{s})}{\sqrt{(\tilde{Q}, \tilde{Q})}},$$



Compact Binary Coalescence

Algorithmic steps of the analysis:

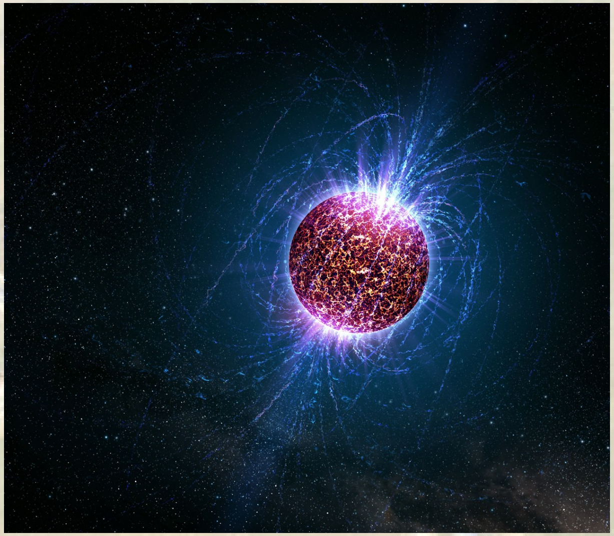
- Spectral density calculation (OK)
- Theoretical template generation (OK)
- Template filtering
  - vector multiplication (OK)
  - Inverse FFT (OK)
  - Maximum finding (OK)
  - Clustering (can be challenging depending on thresholds)
- Post-processing (on CPU)

- Golden application of GW searches
- Runs on AMD and Nvidia
- CUDA FFT is superior
- Typical data segment length $10^{20} – 10^{24}$
- Runs mainly on Teslas and cheap GTX cards

Almost optimal in all sense (occupancy, throughput, CPU/GPU balance, etc)!

Analysis example II:

Continous Waves: Pulsars



CW: The Hough search I

- Searching for **neutron stars with unknown frequency** evolution on the sky
- Nor the frequency neither its time derivatives (spin down parameters) are known -> has to be scanned
- Basic steps of the method:
  - Segment the data (T_{total}) into coherent segments (T_{coh}), where the frequency can be approximated to be constant (order of 30 min, but depend on the actual frequency bin).
  - Calculate the power spectra of the entire data and normalize the Fourier Transformed segments with it. The normalized FFT domain segments are then thresholded -> converted to 0s and 1s -> the peakmap is obtained in the time observed - frequency plane
  - For each position in the sky the peakmap is doppler de-modulated to obtain the (time - real frequency) peakmap. The happens on-the-fly, no need to store them.

CW: The Hough search II

- Taking into account only the first spindown parameter d, (i.e. assuming linear relationship) one can write up the following equation:

$$f_{instantaneous} = f_0 - d * (t - t_0)$$

that is a straight line in the f_0 - d plane.

- Since we have a finite frequency resolution (df) this equation becomes

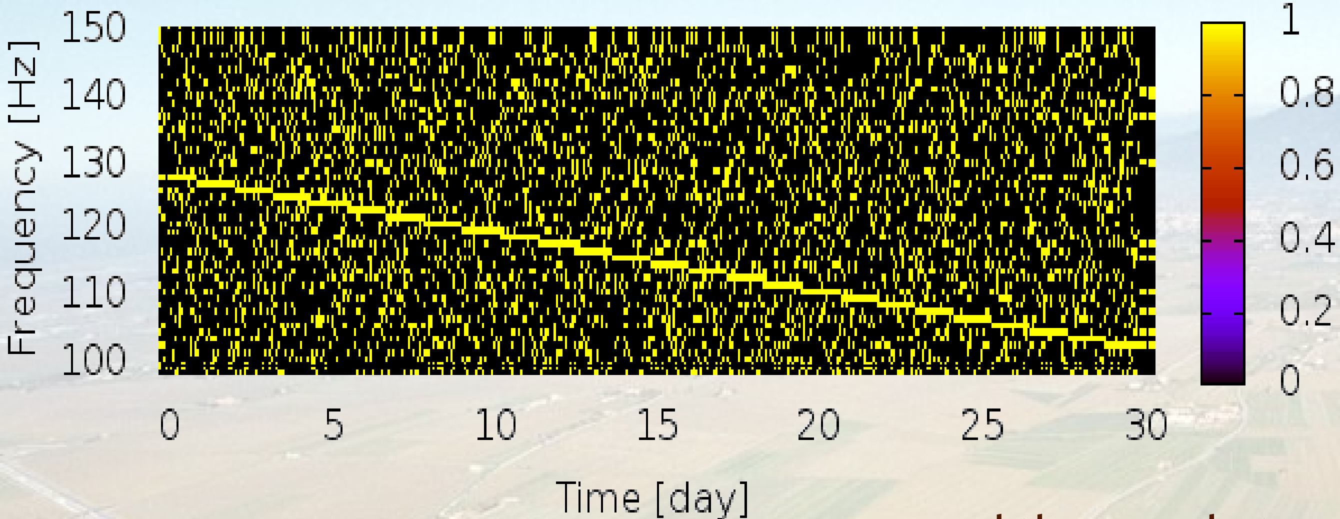
$$-f_0 / (t - t_0) + (f - df / 2) / (t - t_0) < d < -f_0 / (t - t_0) + (f + df / 2) / (t - t_0)$$

i.e, two straight line on the plane

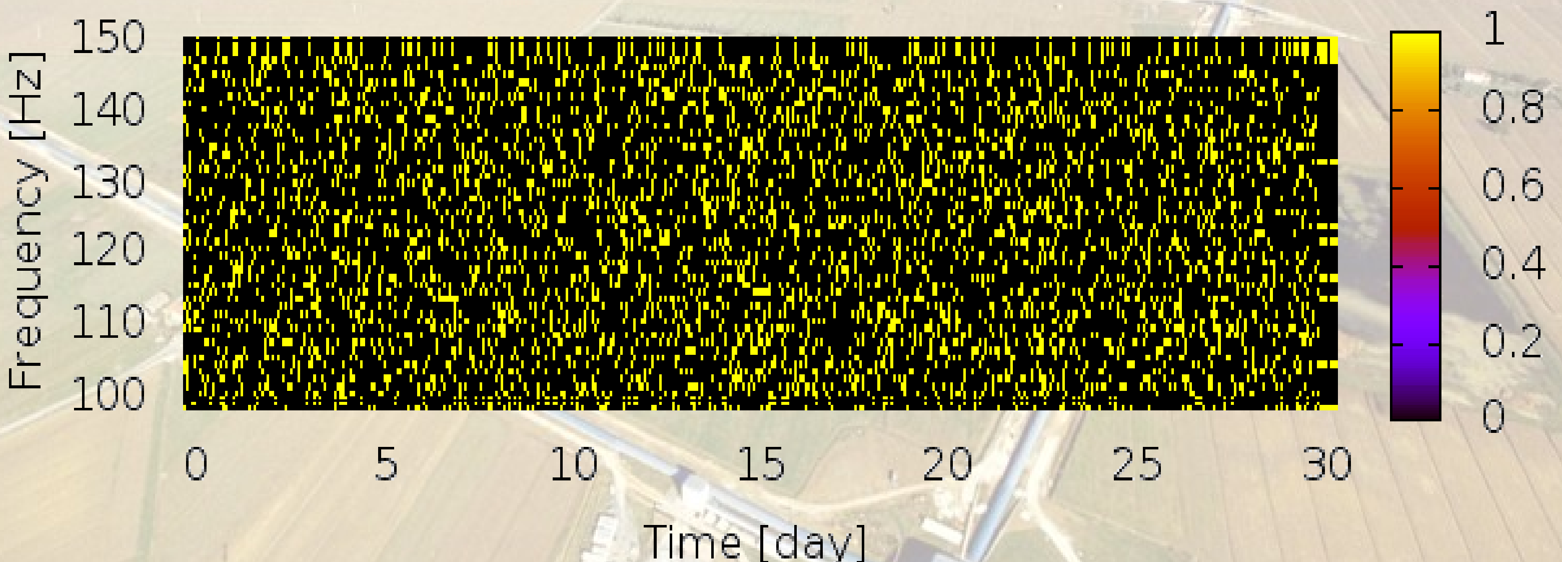
- For every point in the peak map (every t, $f_{instantaneous}$ value) draw a line in the f_0, d plane and increase the value of each bin by 1 which is intersected by the line, i.e. a 2D histogram.
- There are tricks
  - to increase the resolution one uses oversampled frequency bins
  - and to decrease computational cost one uses differential Hough maps when drawing lines with 1s and -1s and integrating only at the very end. This save significant computational cost, since it not necessary to shade / fill large areas in memory.

CW: The Hough algorithm: The peakmap

- A peakmap example with strong signal

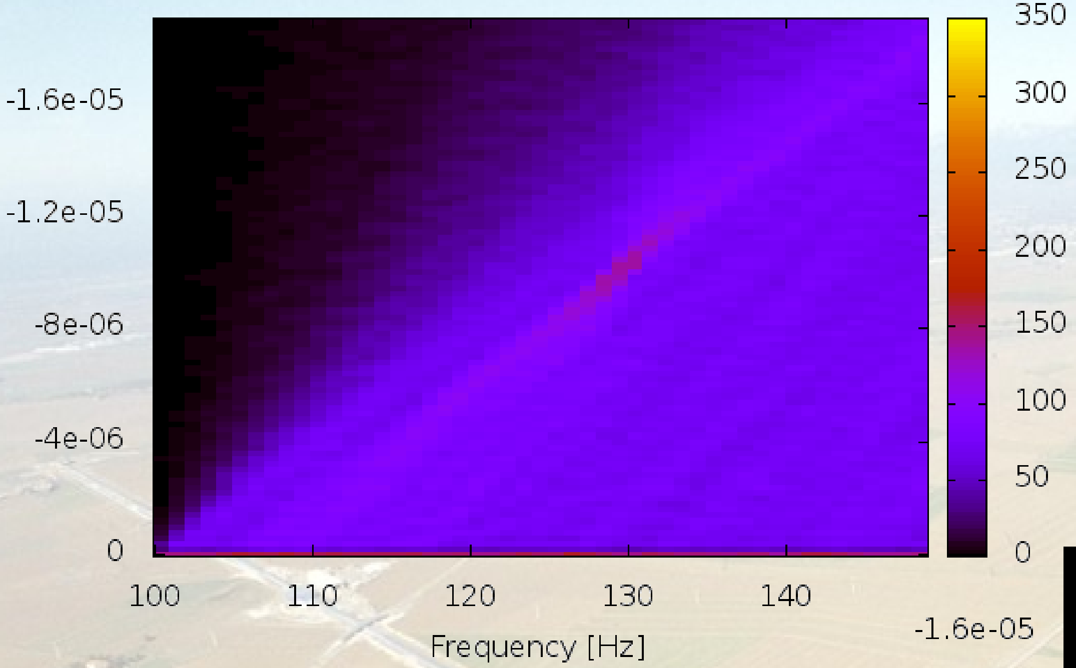


... and the same but weaker signal

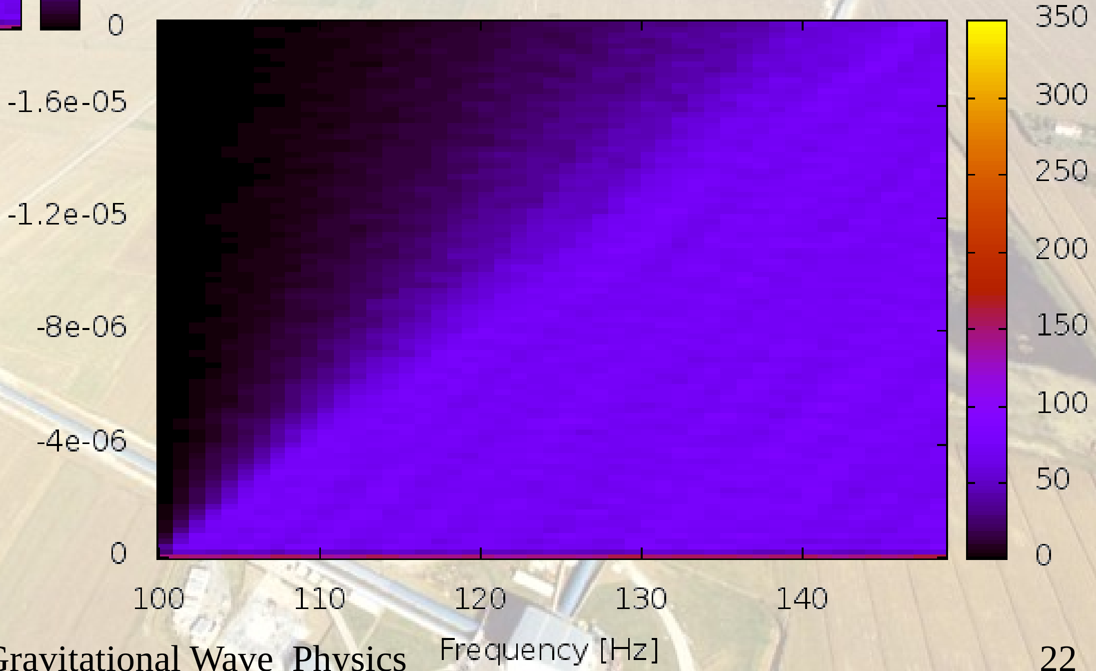


CW: The Hough algorithm: The Hough - map

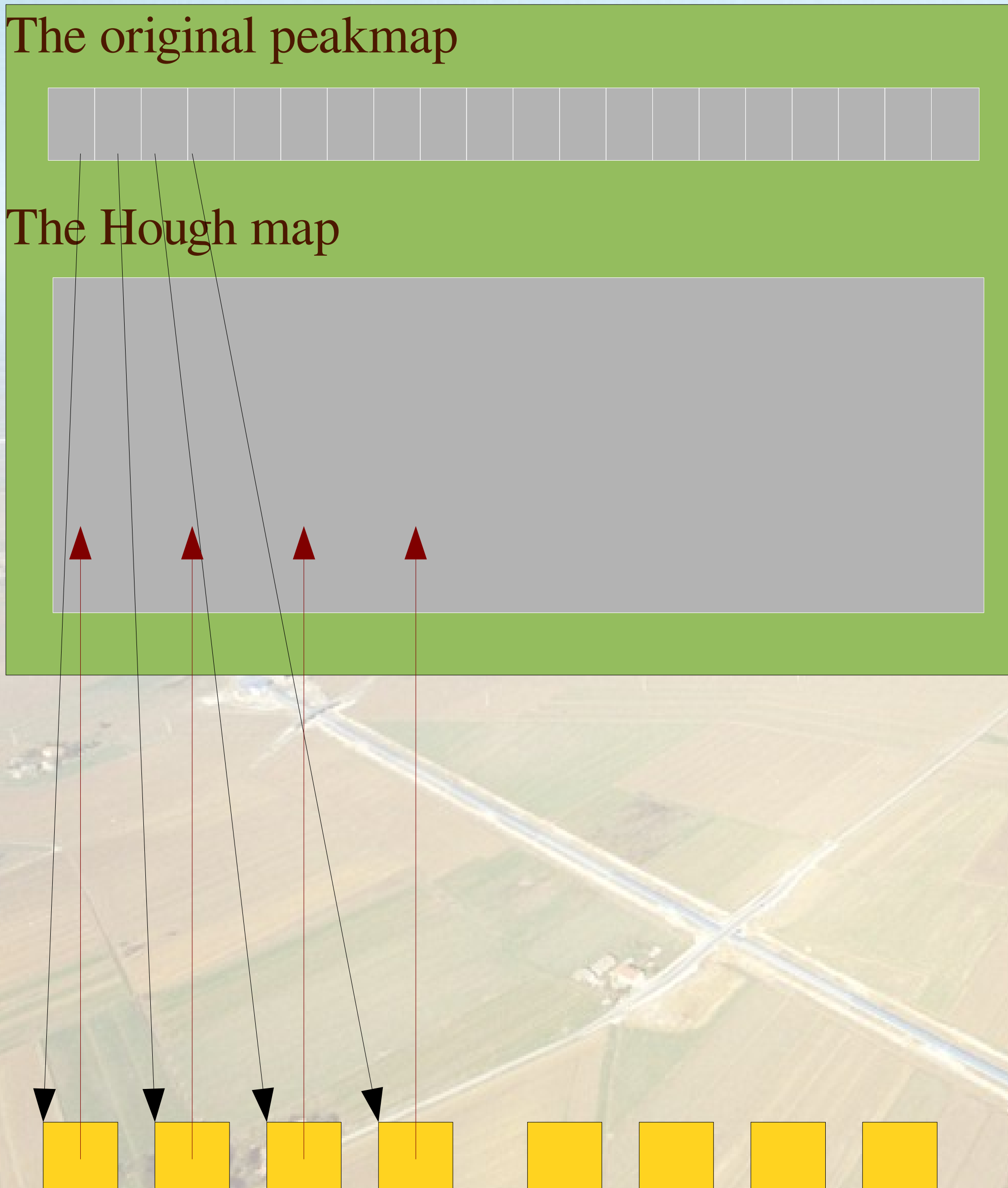
- The Hough map of the previous peakmap with with the weak signal

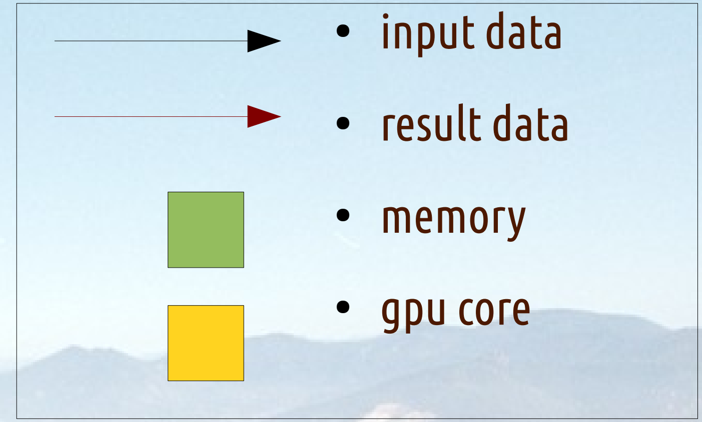


... and the same without signal



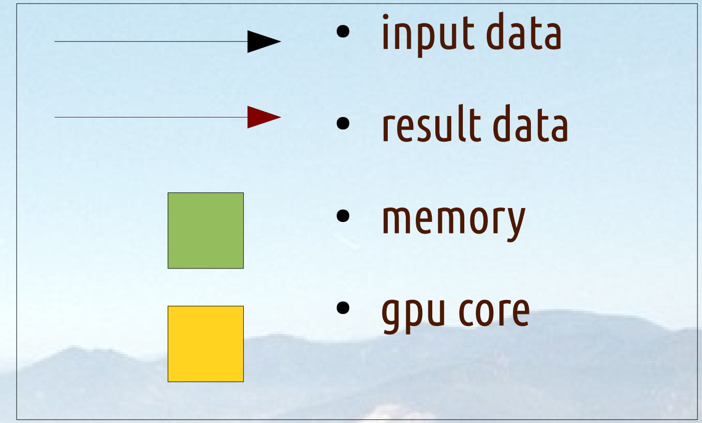
A possible implementation

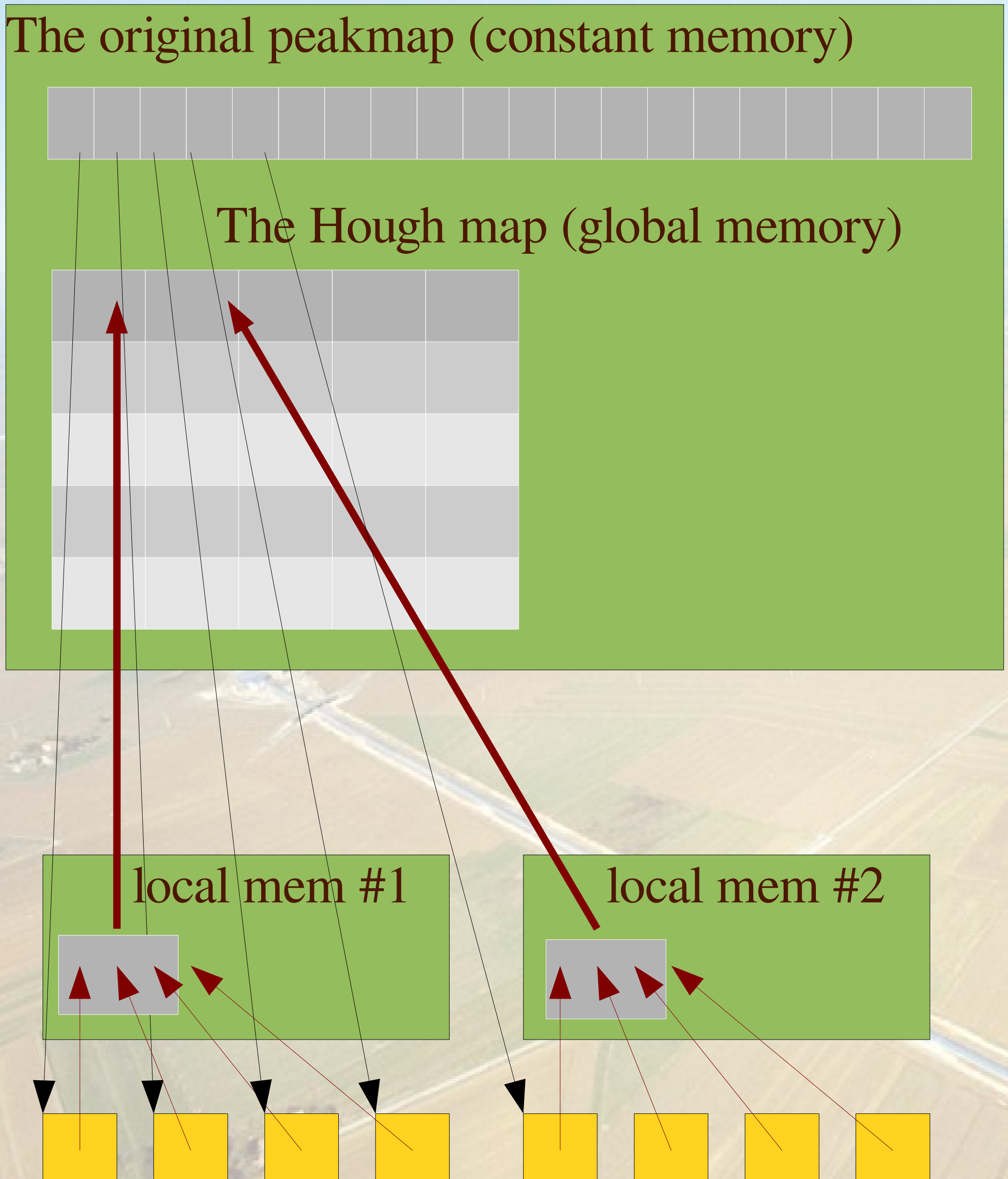




- Each core reads a (some) peak
- Draws the corresponding line on the Hough map
- Problems
  - looping through on global memory is slow
  - intersection of lines requires atomic operations

A better implementation





- Hough map is partitioned
- Partitions are filled in local memory and copied back to global and the end
- All the line which instersects the given partition are drawn
  - much faster
  - no atomic operations involved

Continous Waves: Algorithmic steps

Algorithmic steps of the analysis:

- FFT coherent segments (OK)
- Thresholding (OK)
- Differential Hough-map (OK)
- Integral Houg-map (OK)
- Maximum finding, clustering (can be tricky)

By now also very much optimized

Future (?) and testing: Tegra K1

- Good experiences with Tegra K1
  - Enables for unified memory access
    - (framework handles it)
  - 192 compute core
  - 4 ARM cores with NEON
  - Ubuntu Linux on devboard
- Low power consumption
- CUDA compiles quite OK, profiling, debuging sometime difficult
- Considering for future use

Conclusions

- GPUs are optimal for GW analysis
- With proper framework multi-language, multi-platform development does not require additional manpower
- GW analysis is kind of prepared for the challenges of forthcoming years