Gravitational wave tricks for multi-messenger astronomy

Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Hannover, Germany

Gravitational wave *data analysis* **tricks for** ~~**multi-messenger**~~ *electromagnetic* **astronomy**

Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Hannover, Germany

Basic Idea of Talk

- The Gravitational-wave astronomer is a “starving artist”: the detectors are not yet sensitive enough to make detections
- Huge effort has gone into developing improved or new data analysis methods
- Some of these methods can be used for other purposes (EM astronomy)

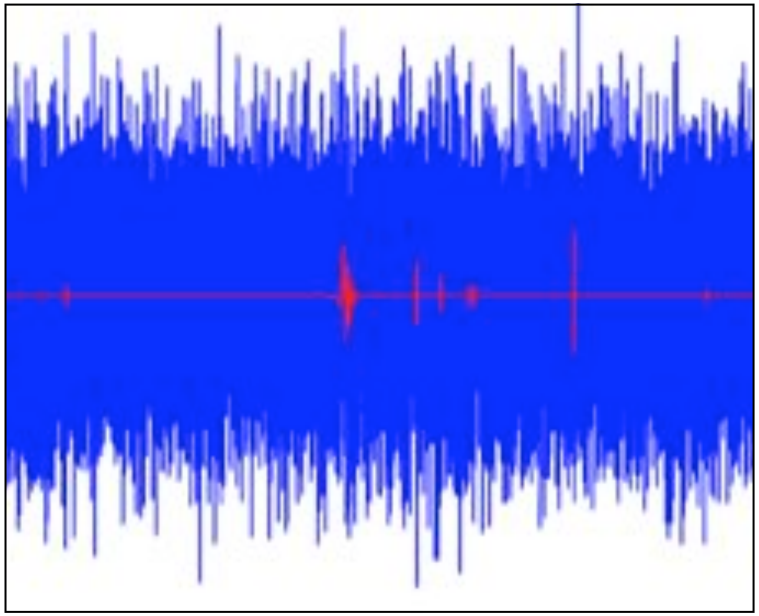
Der arme Poet, Carl Spitzweg, 1839

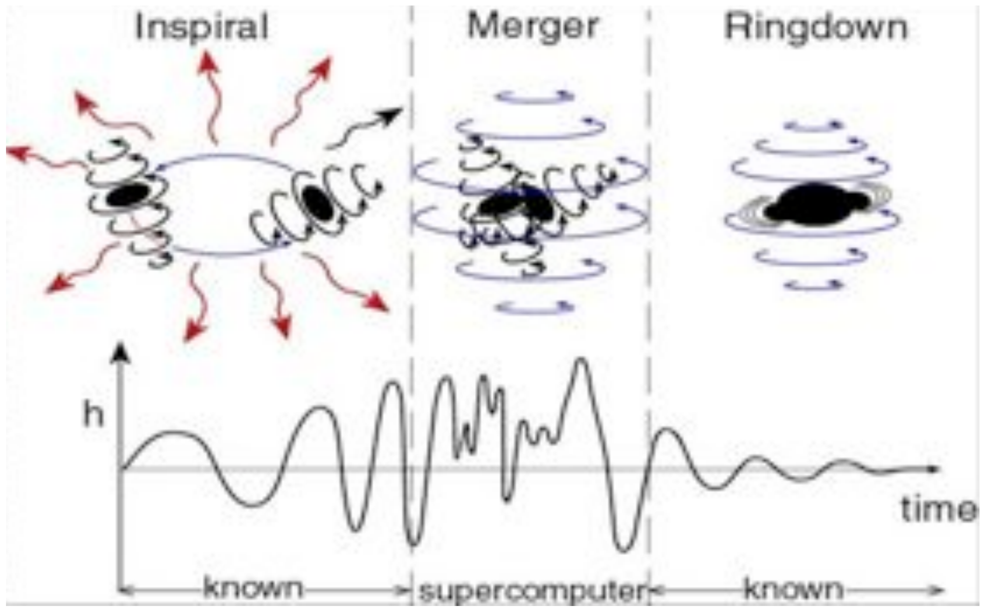
The Electromagnetic Astronomer

Gargantua a son grand couvert, French School circa 1810, Musée Carnavalet, Paris

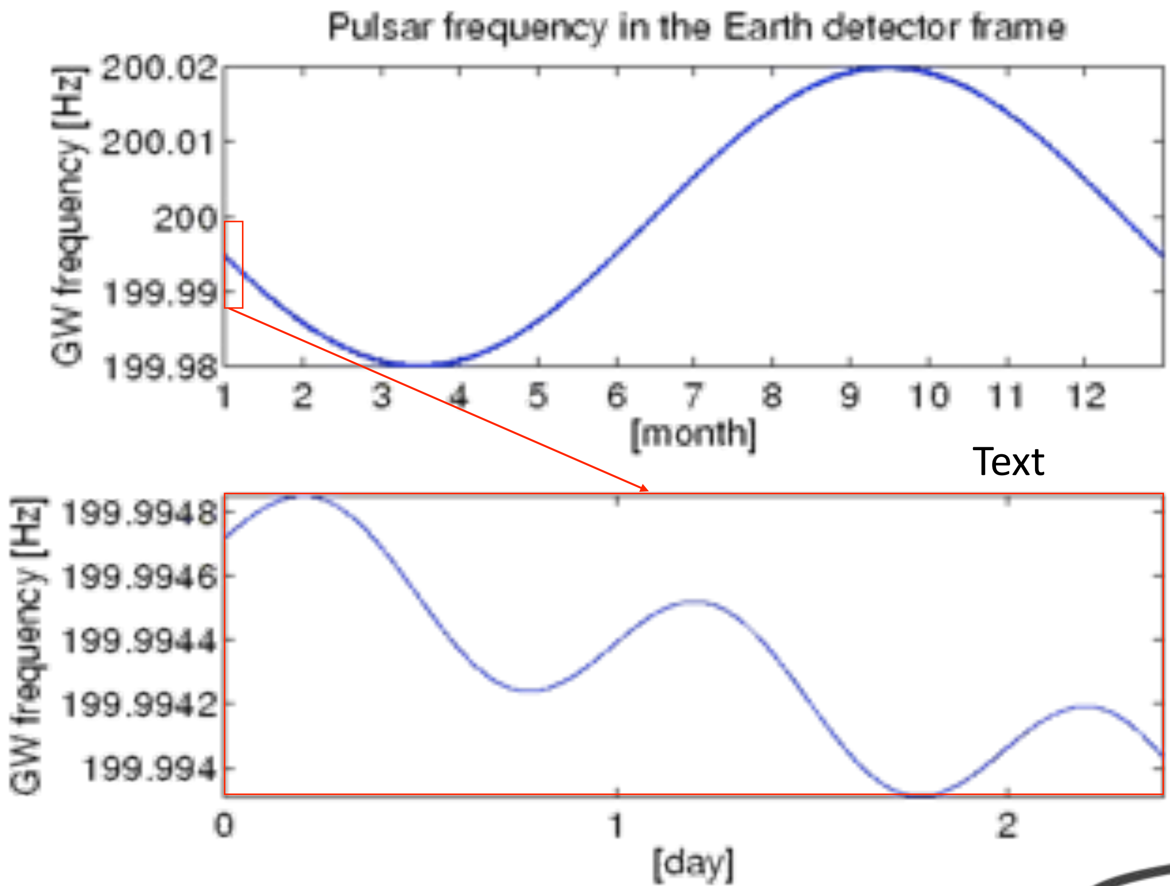
Weak Signals: Binary Inspiral

- Signals hidden in noise
- For given parameters m_1, m_2, α, δ, d, t_0, $\mathbf{s}_1$, $\mathbf{s}_2$, e, ϕ, ι, ... the waveform "templates" can be calculated "precisely".
- But the parameters are **not** know; must hunt through a **huge** parameter space
- Computationally demanding: motivated development of optimal techniques



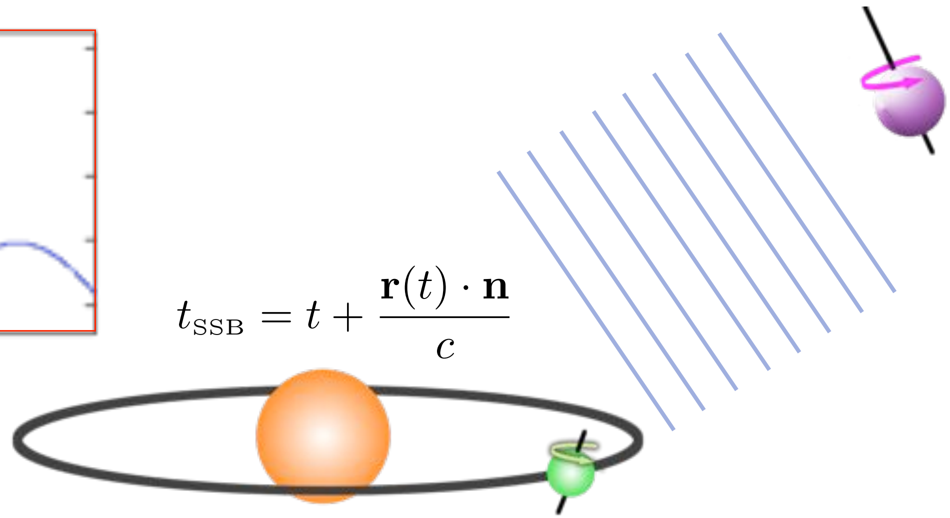


Weak Signals: Spinning Neutron Stars



Search for gravitational waves from unknown spinning neutron stars is a **computational challenge** because the annual Earth's motion around the Sun and daily rotation doppler-modulate the signal.

One must search at least a 4-dimensional parameter space (sky position, frequency, spin-down).



$$t_{\mathrm{SSB}} = t + \frac{\mathbf{r}(t)\cdot\mathbf{n}}{c}$$

Optimal solution: Jaranowski, Królak and Schutz, Phys. Rev. D 58, 063001 (1998)

$$\mathbf{n} = (\cos\delta\ \cos\alpha, \cos\delta\ \sin\alpha, \sin\delta)$$

$$\mathbf{r}(t) = \mathbf{r}_{\mathrm{orb}}(t) + \mathbf{r}_{\mathrm{spin}}(t)$$

1 year period   1 day period

Searching For A Signal

Matched filtering: maximize a "**detection statistic S**"

$$\mathbf{S} = \int \mathbf{o(t)\, w(t)\, dt}$$

DETECTOR OUTPUT   WAVEFORM TEMPLATE

For clean data, **S** has a Gaussian normal distribution.

Key questions:

- How MANY waveform templates **w(t)** to use?
- Where to place them in parameter space (what grid)?

The Computational Challenge

- Ideal world (infinite computing power): pick an enormous and dense grid in parameter-space, then crunch through the data.
- Real world: **computationally limited search sensivitity**
  - Gravitational waves (GWs) from spinning neutron stars
  - Radio pulsars in short-period binary systems
  - Blind searches for gamma-ray pulsars in Fermi Large Area Telescope data
- Example: searches for GWs from spinning neutron stars. Four-dimensional parameter space (f, $\dot{f}$, α, δ). With data set of length T, number of points in the grid scales like (approximately) the fifth power of T:

$$N \propto T \times T^2 \times T \times T = T^5$$

Brady, Creighton, Cutler and Schutz, Phys. Rev. D 57, 2101, 1998

factors: $\Delta f \propto 1/T$, $\Delta \dot{f} \propto 1/T^2$, $\Delta \alpha \propto 1/T$, $\Delta \delta \propto 1/T$

Single computer can do T = 4 hours.
Large cluster can do T = 20 hours.
Einstein@Home can do T = 40 hours.
But we have T = 1 year of data!

The "Starving Artist" Solutions

- Construct an **optimal grid** (or near-optimal) in parameter space
- Use optimal **hierarchical methods** to incoherently combine the results of many coherent searches
- Design a search strategy to **maximize the signal sensitivity at fixed computing cost**
- Use **cost-effective compute farms** such as Einstein@Home

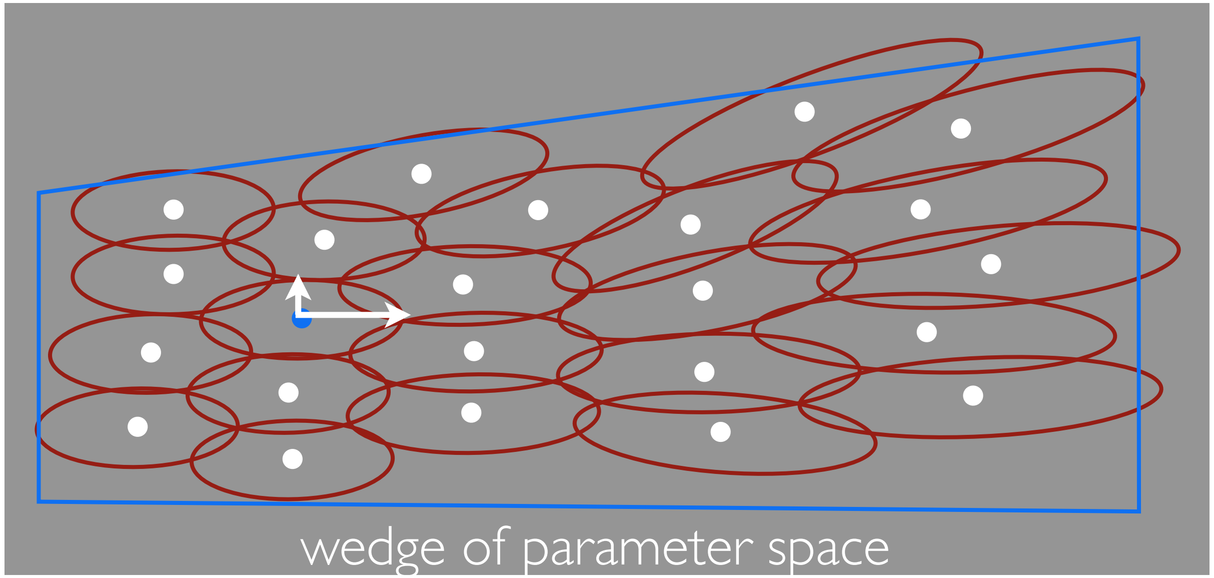
Optimal Grid in Parameter Space

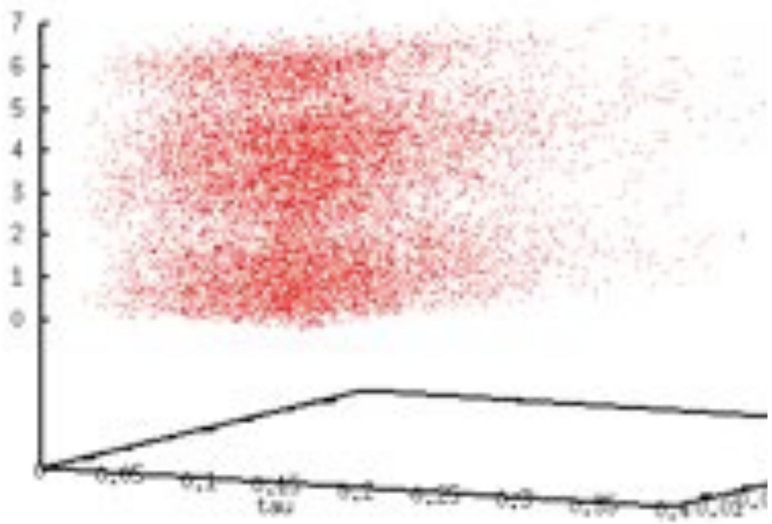
- Define a metric on parameter space to measure fractional-loss of statistic S from parameter-mismatch $\Delta\lambda = \{\Delta f, \Delta\dot{f}, \Delta\alpha, \Delta\delta\}$ (**Owen, Phys. Rev. D 53, 6749, 1996**):

$$ds^2 = -\Delta S/S = g_{ab}\, \Delta\lambda^a\, \Delta\lambda^b$$

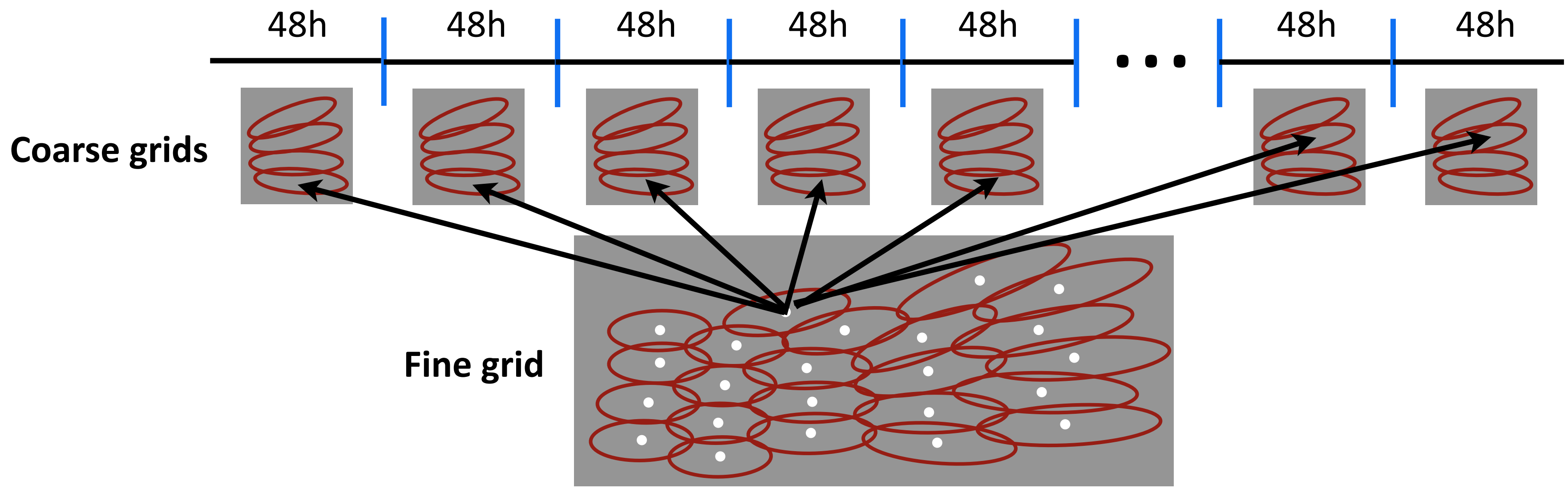
- Use the metric to construct an
  - optimal grid, or without much loss in efficiency, a
  - random grid (**Messenger, Prix, Papa, Phys. Rev. D79, 104017, 2009**), or a
  - stochastic grid (**Harry, Allen, Sathyaprakash, Phys. Rev. D80, 104014, 2009**)

  with a specified maximum loss of the detection statistic S





Optimal Hierarchical Methods



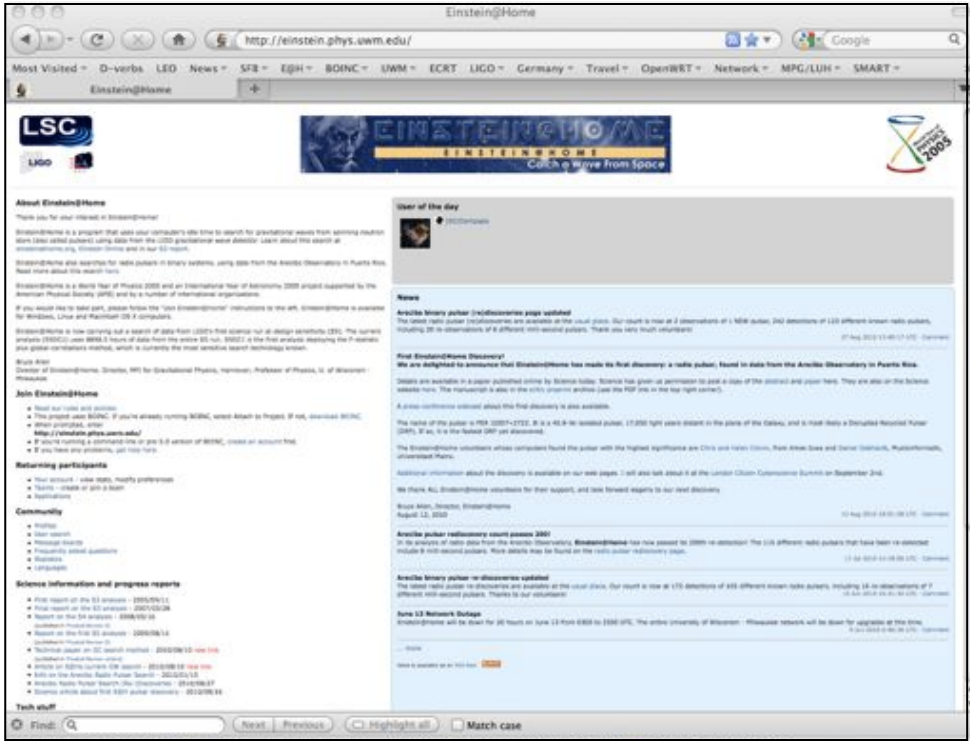
- GW example: can **not** afford to coherently search 360 days of data
- **Can** afford to do 180 x optimal search of T = 48 h
- How to combine these (incoherently)? Many ad-hoc methods used in the past (stack-slide, Hough transform, PowerFlux,...)
- Correct approach was first suggested in **Brady and Creighton, Phys. Rev. D 61, 082001 (2000)**: calculate parameter-space metric “averaged over stacks”
- Optimal solution derived in **Pletsch and Allen, Phys. Rev. Lett. 103, 181102 (2009)**. Trick: find “good coordinates” for parameter space, compute an average metric, use this to (1) construct fine grid and (2) to identify the “closest” point in each coarse grid.
- LIGO S6bucket: 90 x 60 hours / Fermi MSP: 162 x 6 days / HRTU (Parkes) Survey: 14 x 5 min
- Still under development: optimal methods to zoom and follow-up

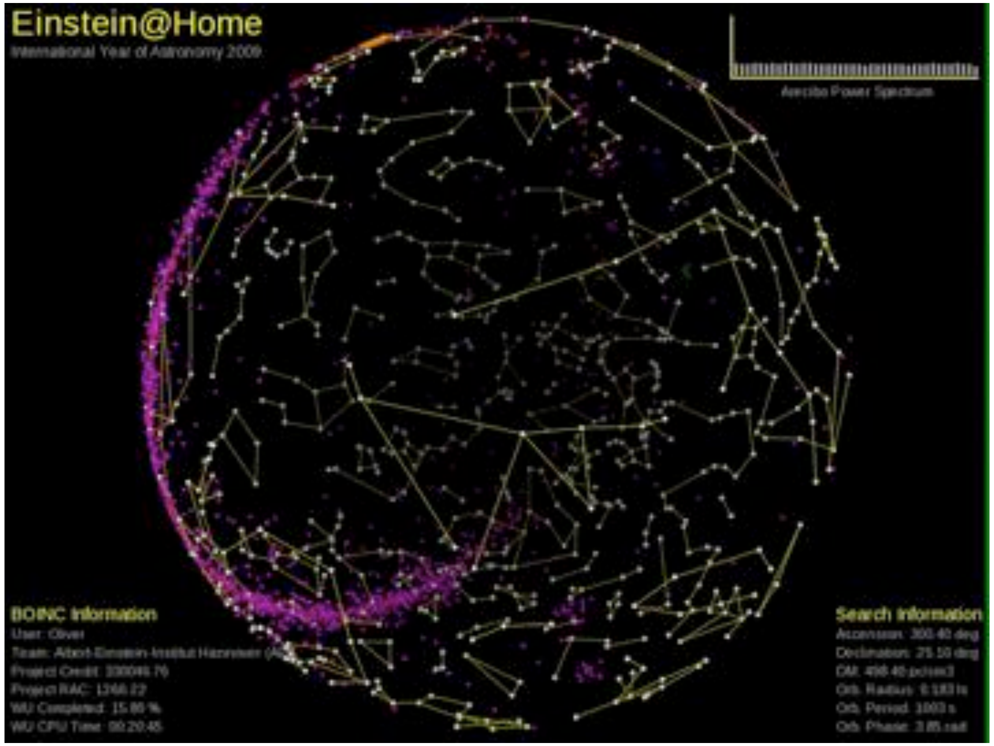
Best Sensitivity at Fixed Computing Cost

- Where to spend the valuable compute cycles?

  Amplitude sensitivity scales as $1/h_{min} \propto T^{1/2} N^{1/4}$
- Should you have a more finely-spaced grid in parameter space (reduce maximum loss of SNR)? Or should you use a coarser grid with a longer coherent integration time T?
- The correct answer depends upon the relative cost of the coherent versus incoherent step.
- Problem solved in **Shaltev and Prix, "Optimizing Stack-Slide sensitivity at Fixed Computing Cost" (manuscript in preparation, 2011)**

Einstein@Home





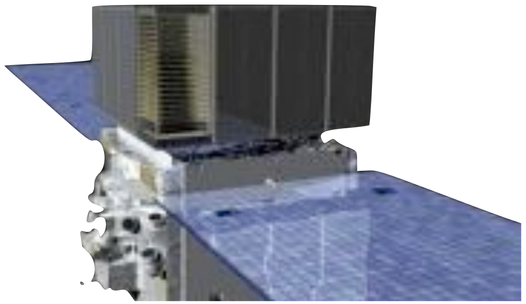
- Launched 2005, now has more than 300k volunteers
- About 65k computers contact servers each week asking for work.
- Many of these have GPU cards, which we exploit
- Currently 456 TFlops, 24 x 7, for details see http://einstein.phys.uwm.edu/server_status.php
- Now searching LIGO S6 data, Arecibo PALFA data, Parkes PMPS data, Fermi-LAT data
- Results include published LIGO S5 and S6 upper limits, 2 exotic pulsars discovered in Arecibo data, and 10 pulsars discovered in PMPS data

Einstein@Home

Knispel, B., et al. Science, 329, 1305 (2010); ApJ Lett 732, 1 (2011)

Ten new pulsars discovered. See **http://einstein.phys.uwm.edu/radiopulsar/html/PMPS_discoveries/** for details.

Abbott, B., et al. Phys. Rev. D, 79, 022001 (2009); Phys. Rev. D, 80, 042003 (2009)



Started a search for gamma-ray milli-second pulsars in Fermi-LAT data about a month ago.

Conclusions

- The methods developed for the “signal poor” field of gravitational wave detection are also applicable to “signal rich” electromagnetic astronomy
- These provide tools for **gridding parameter space**, for **hierarchical searches** (optimally combining the results of many “short” coherent searches) and for **large scale computing**.
- This methods can lead to “factor of two” or “factor of a few” increases in sensitivity, which can significantly increase the number of detections

PS: please sign up <u>your</u> computers to Einstein@Home