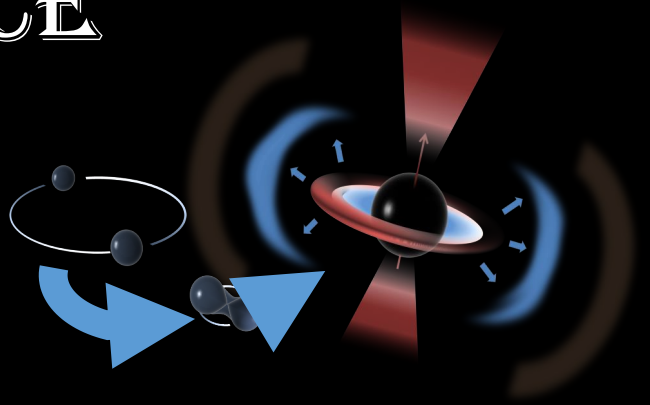
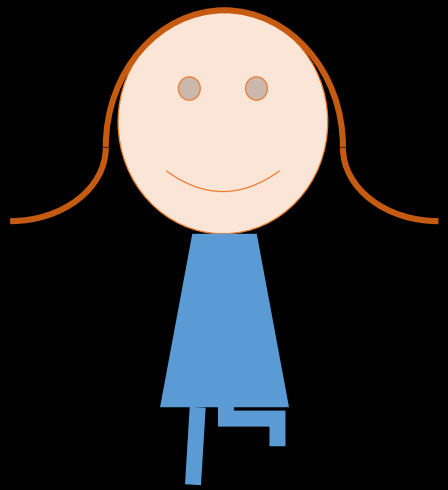
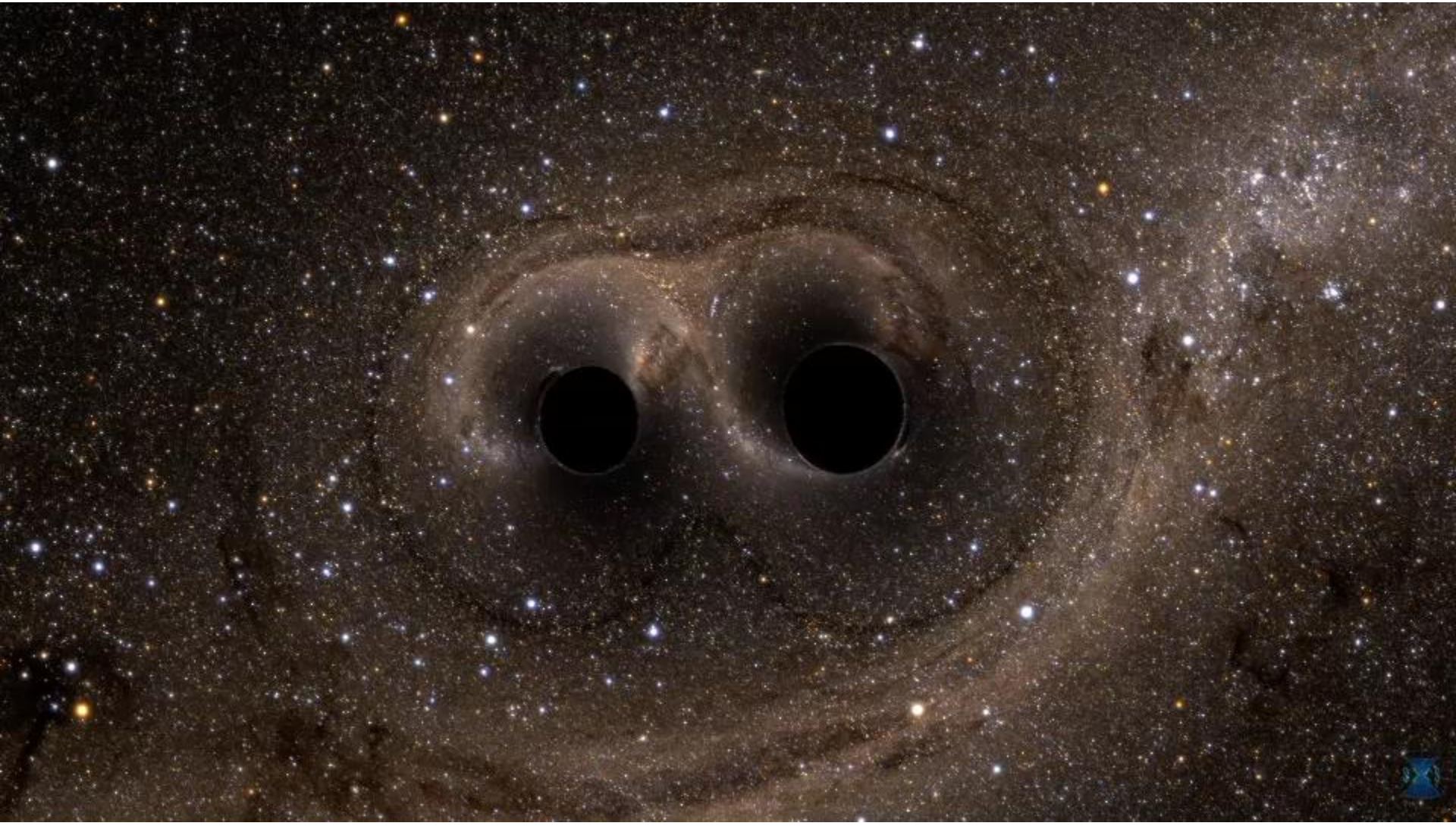
From Instrumentation to Astrophysics: A Journey in Collaborative Science





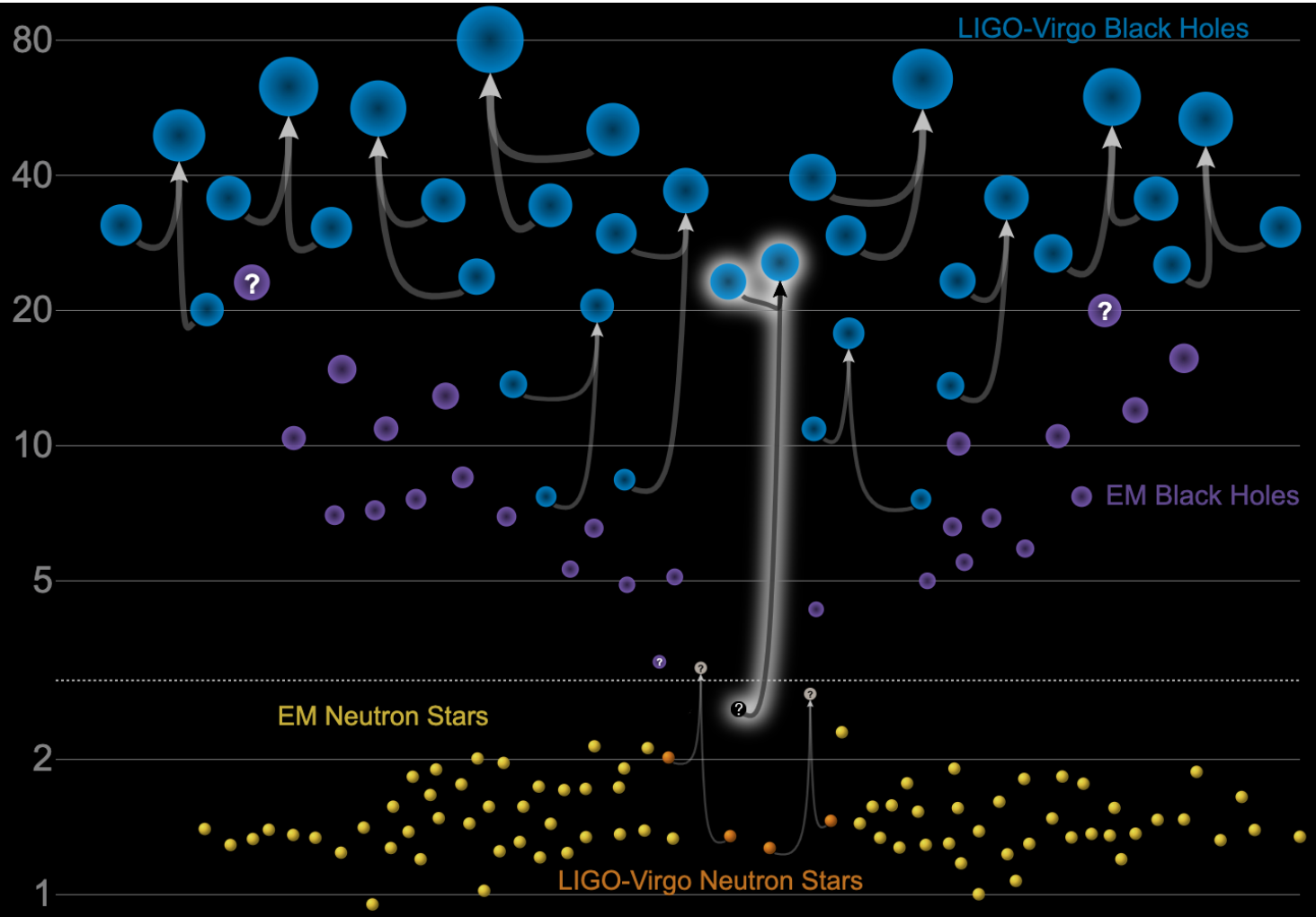
Zsuzsa Marka
Columbia University

23 June 2020
Summer Colloquium Series



The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20
https://doi.org/10.3847/2041-8213/ab960f

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object



Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

My personal journey stared two decades ago

Image credit: LIGO Laboratory

Courtesy of LIGO and LSC

Surprise in LIGO Document Control Center ☺

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-CALIFORNIA
INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type LIGO-T000131-00-H	26 March 2001
Accessing the Quanterra 4128 Datalogger Via Its Web Interface	
Szabolcs Márka and Zsuzsa Márka	

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LIGO

California Institute of Technology
LIGO Project - MS 18-34
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

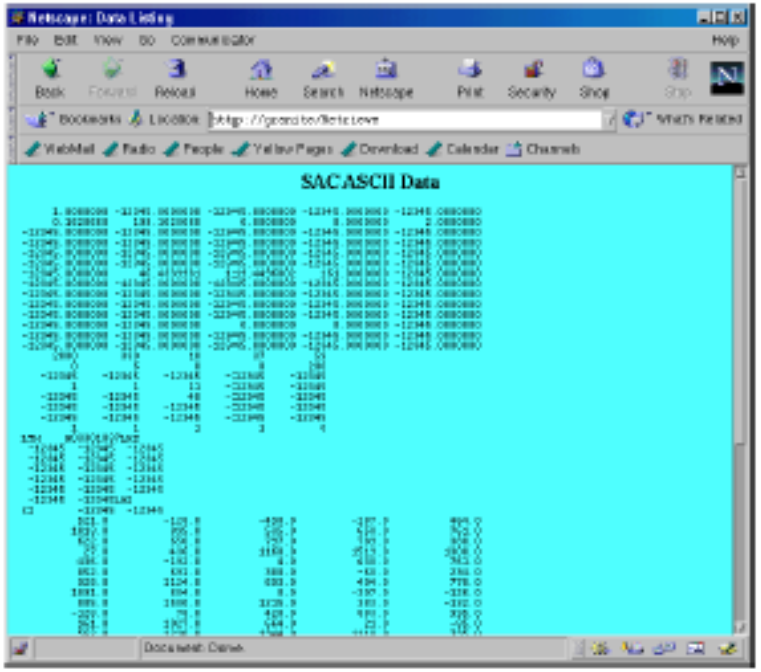
Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

The first line gives the channel, start time, spacing and the number of data points. The next lines contain the data. You can use the following Unix script to produce a single column of data:

```
"cat <datafile.name> | awk '{n++;if(n>1){for(i=1;i<=NF;i++){print $i}}}' > <new.file>"
```

Choosing the SAC ASCII option writes a file-format usually provided by USGS stations, with the header giving the detailed station information (e.g. latitude, longitude etc.).



Acknowledgement: I would like to thank my wife Zsuzsa Márka for her help to prepare this document.

Contact: Please do not hesitate to contact me if you have any comments or questions regarding this document! (Szabi Márka, smarka@ligo.caltech.edu)

Magdolna Hargittai
István Hargittai

Symmetry through the Eyes of a Chemist

3rd Edition

Springer

Women Scientists

Reflections, Challenges, and Breaking Boundaries

Magdolna Hargittai

On Switching Fields..

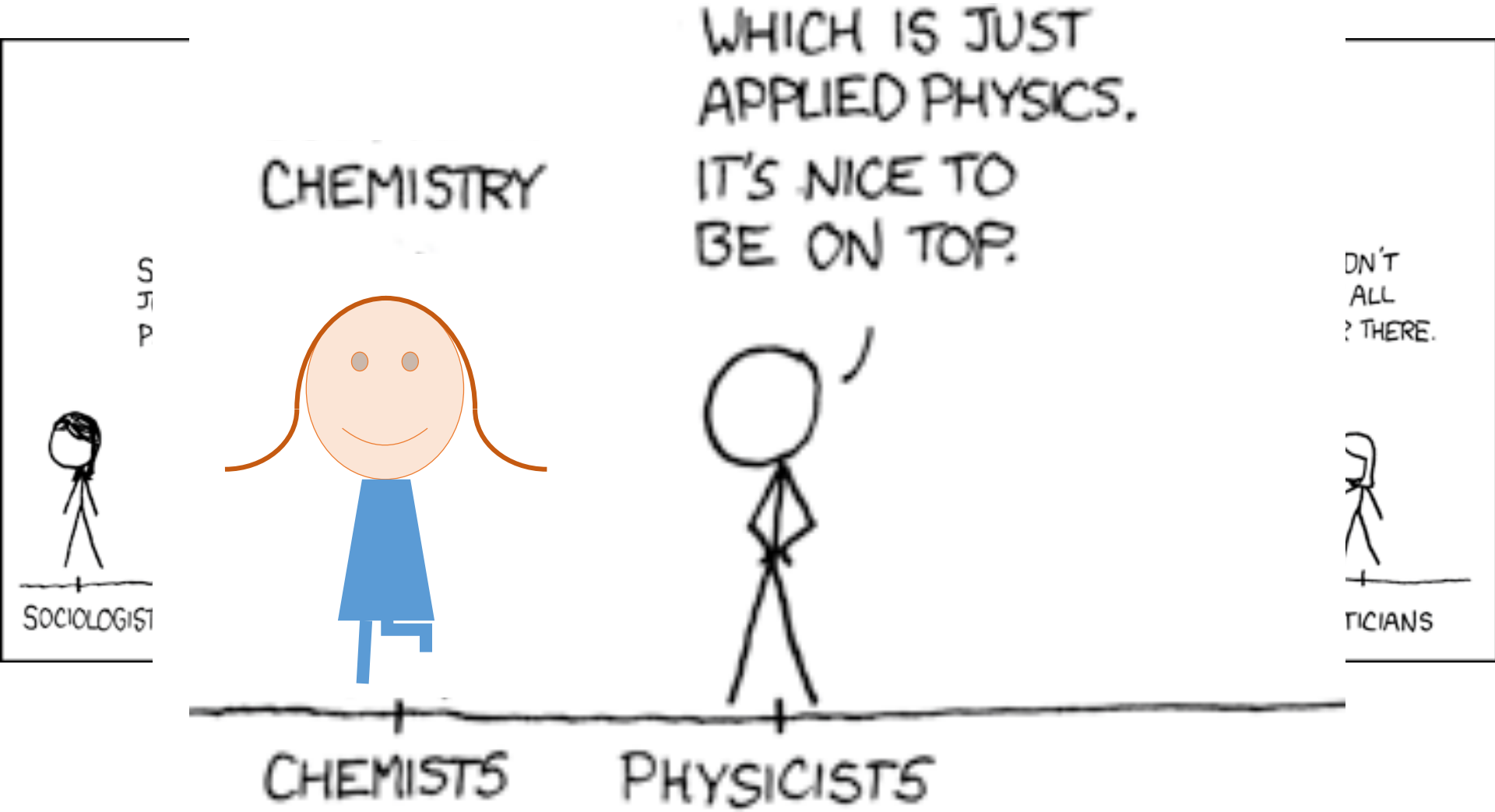
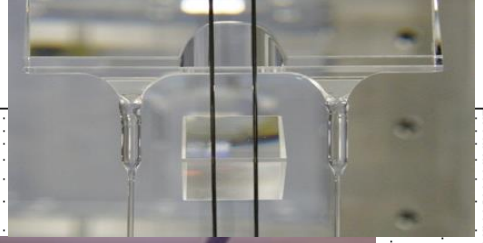
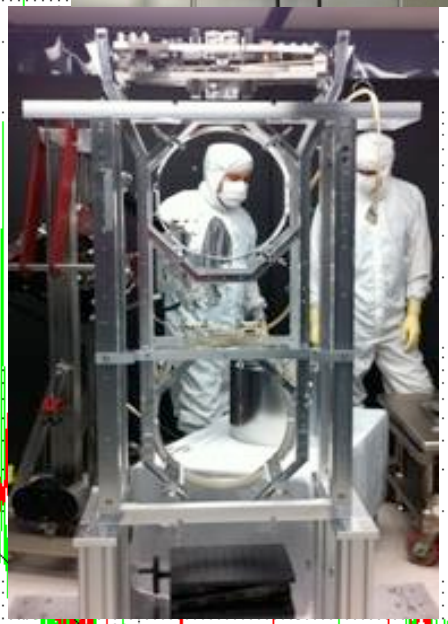


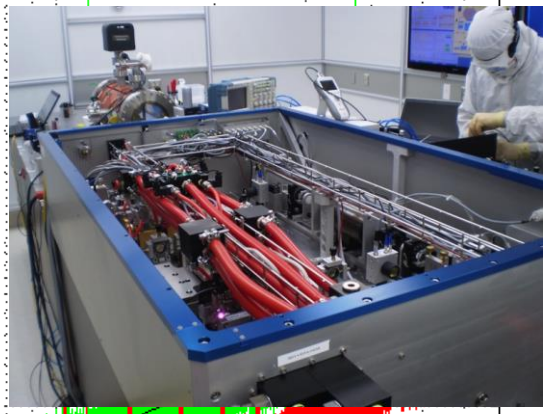
Image from https://xkcd.com/435/

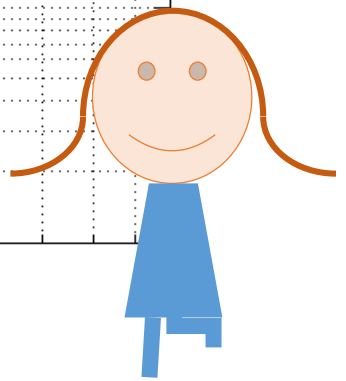
Why GW physics?

A VERSATILE FIELD



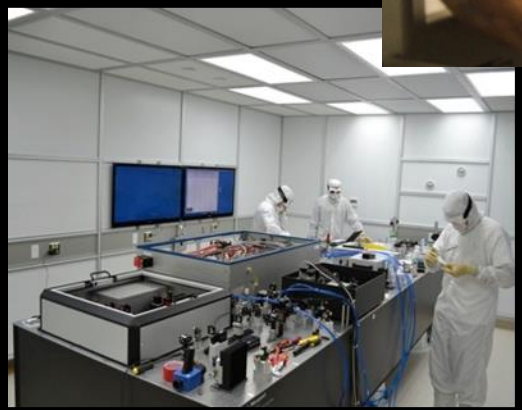




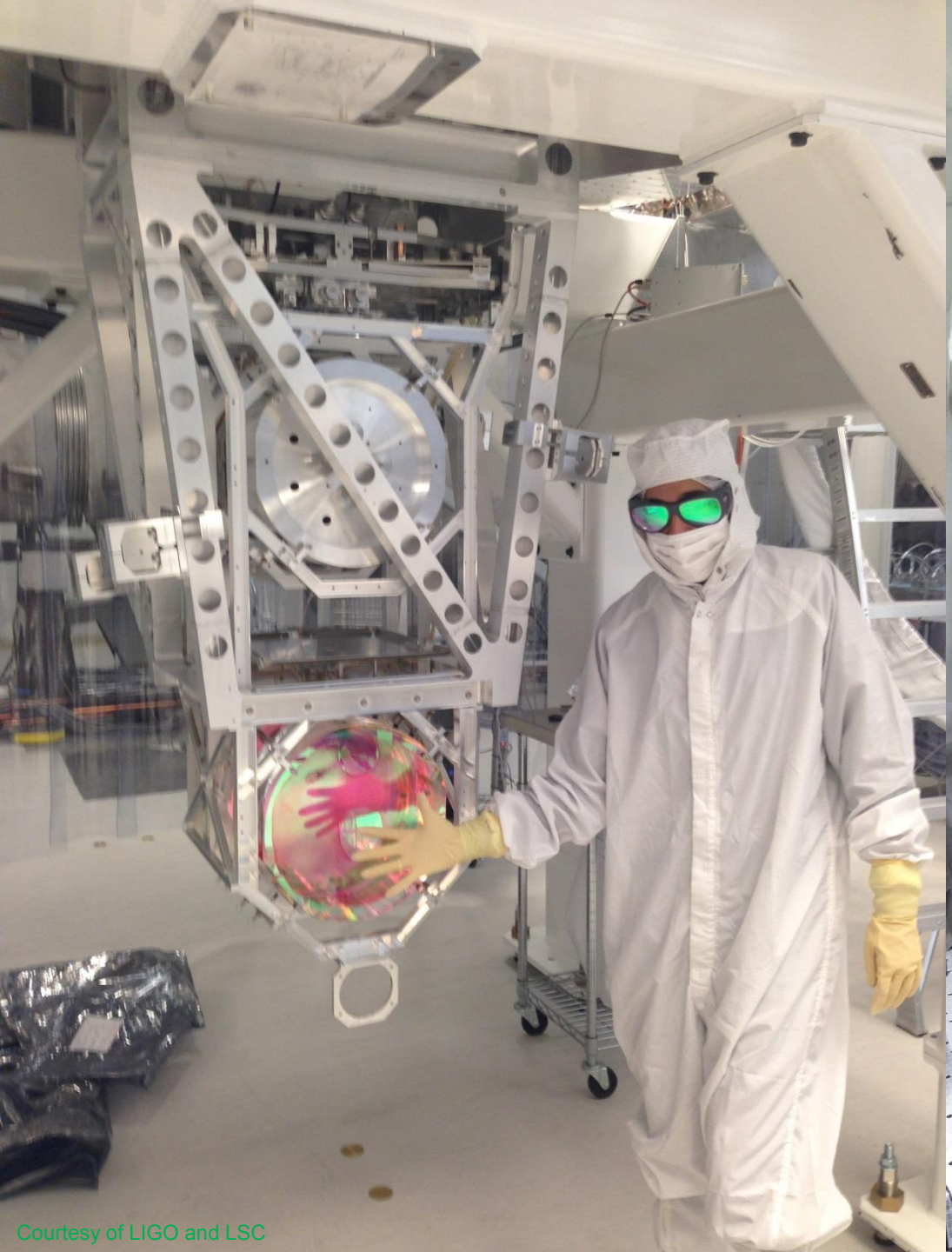


Courtesy of LIGO and LSC

Advanced LIGO



Thanks to D.Shoemaker, S.Larson, and LSC



Courtesy of LIGO and LSC

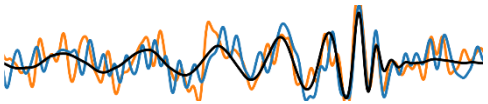
Courtesy of LIGO and LSC and Kai Staats

Collaboration!

Collaboration!

Pushing the limits in measuring the smallest ever possible displacement **FUN, FUN, FUN**

Data Analysis Challenges

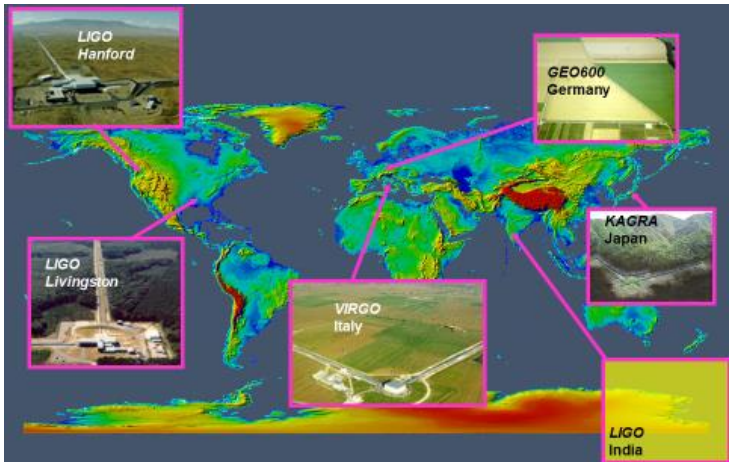


Opening a new window to the Universe

International factor! Diversity

Travel

Long telecons



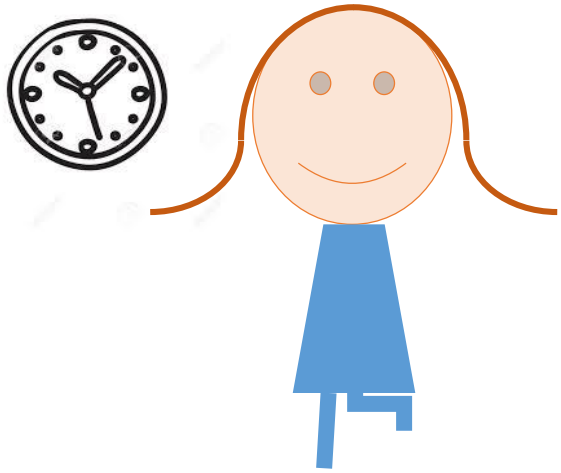
Human nature, unfair competitions, harassment

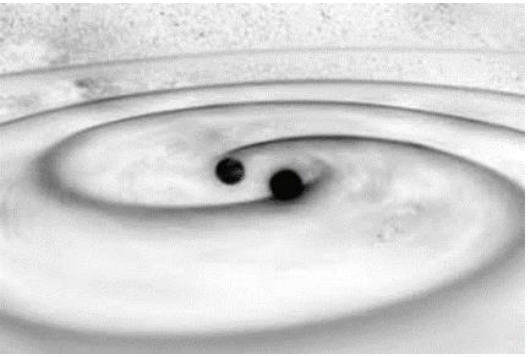
Email load

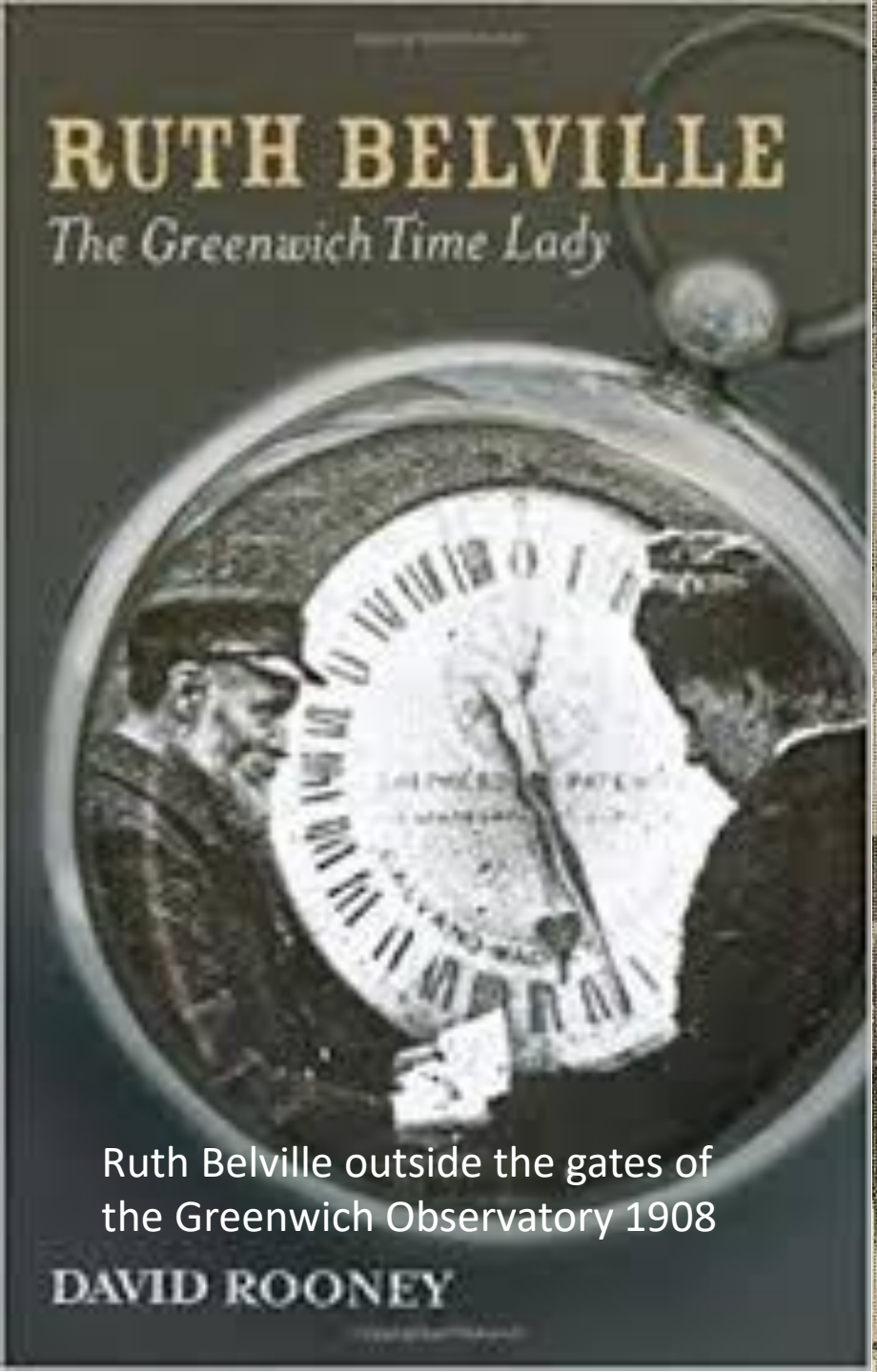
Wonderful students

Excitement of the Public including the Young Generation!

How Can I Serve?

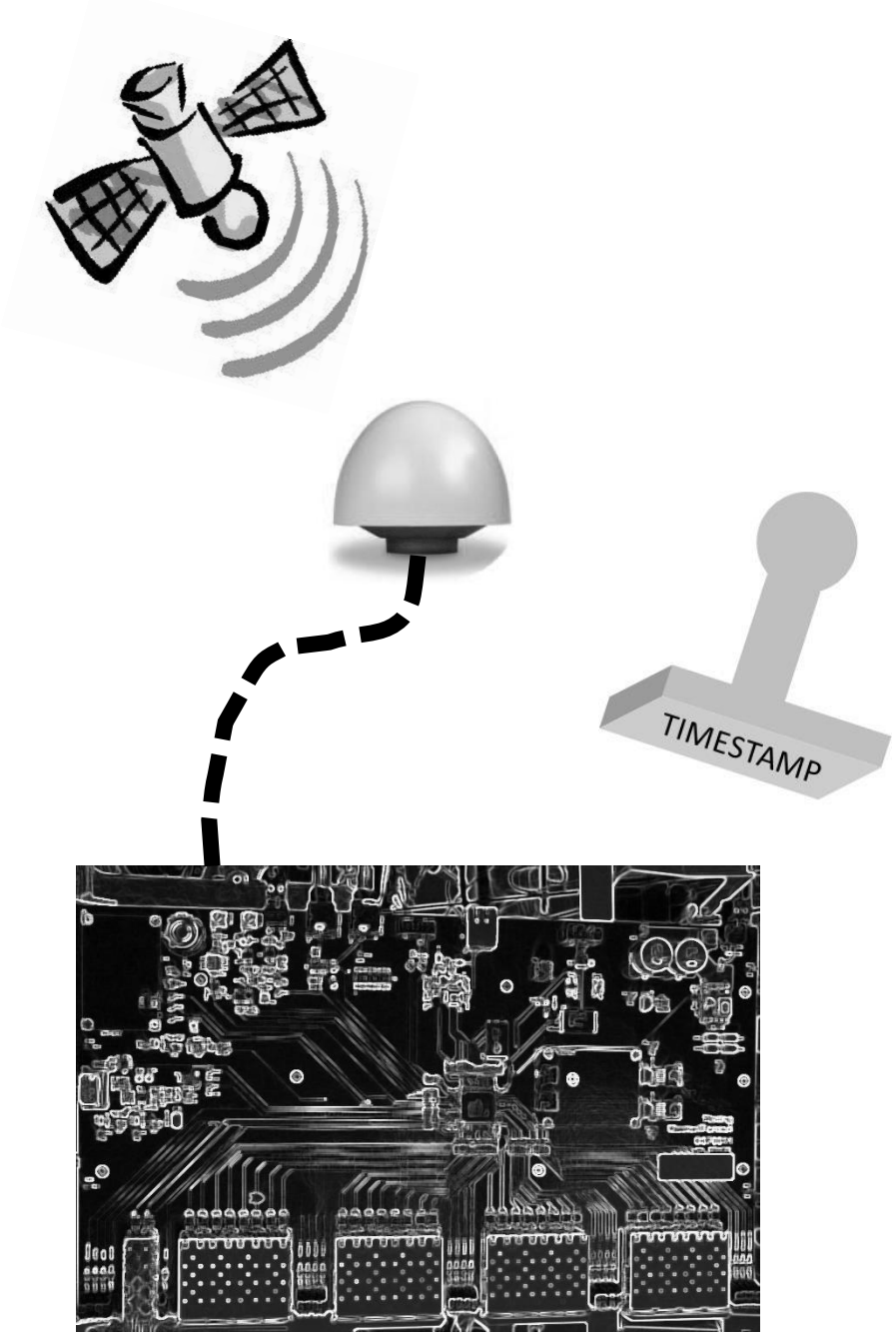




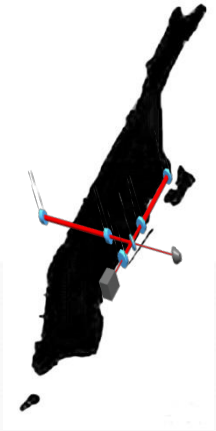


Ruth Belville outside the gates of the Greenwich Observatory 1908

Ruth's mother, Maria in 1892, Inherited the business from her husband, John Henry


TIMESTAMP

Suspensions



End mirror

Fabry-Perot arm cavity

Input mirror

Beam splitter

Fabry-Perot arm cavity

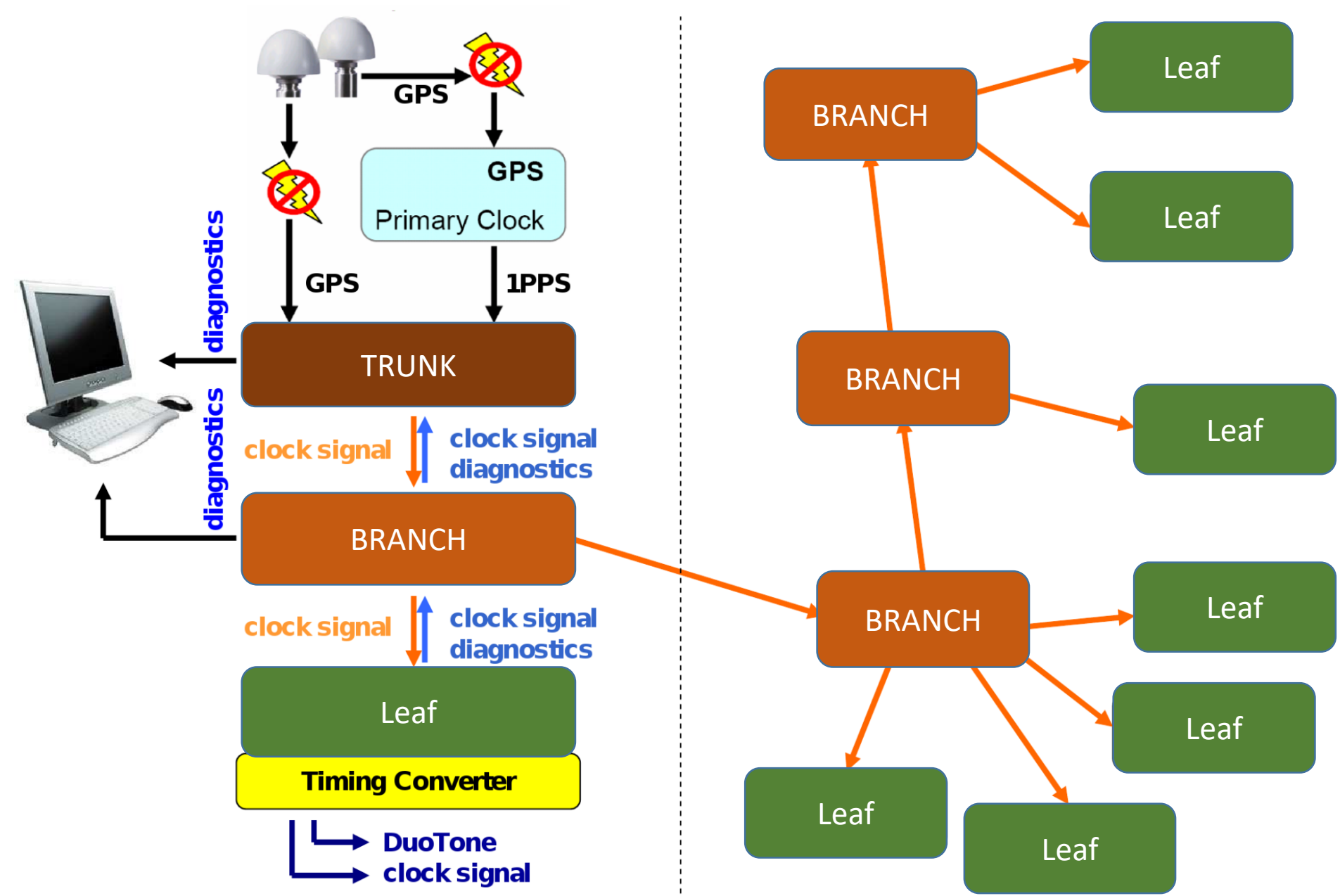
Input mirror

End mirror

"Recycling" mirror

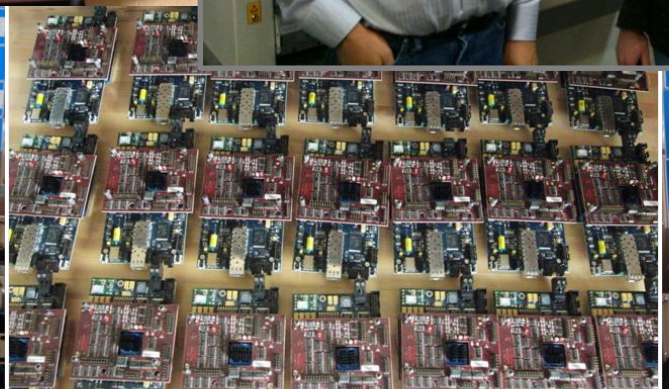
"Antisymmetric" photodiode

Yoichi Aso
Columbia University



Bartos et al, CQG 2010

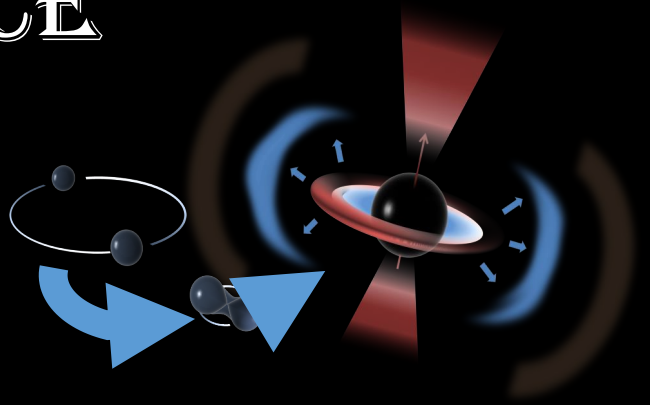

Timing
Master
INPUT

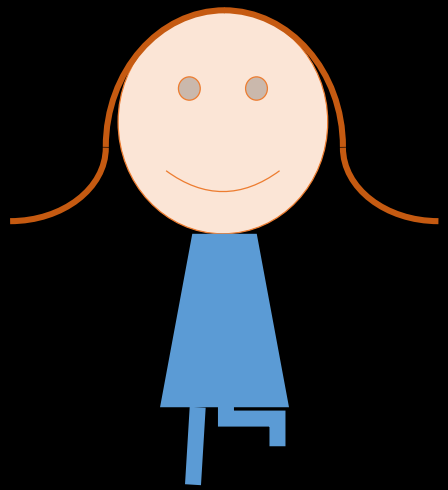



Timing IRIG-B
D0900301


EXIT

From Instrumentation to Astrophysics: A Journey in Collaborative Science





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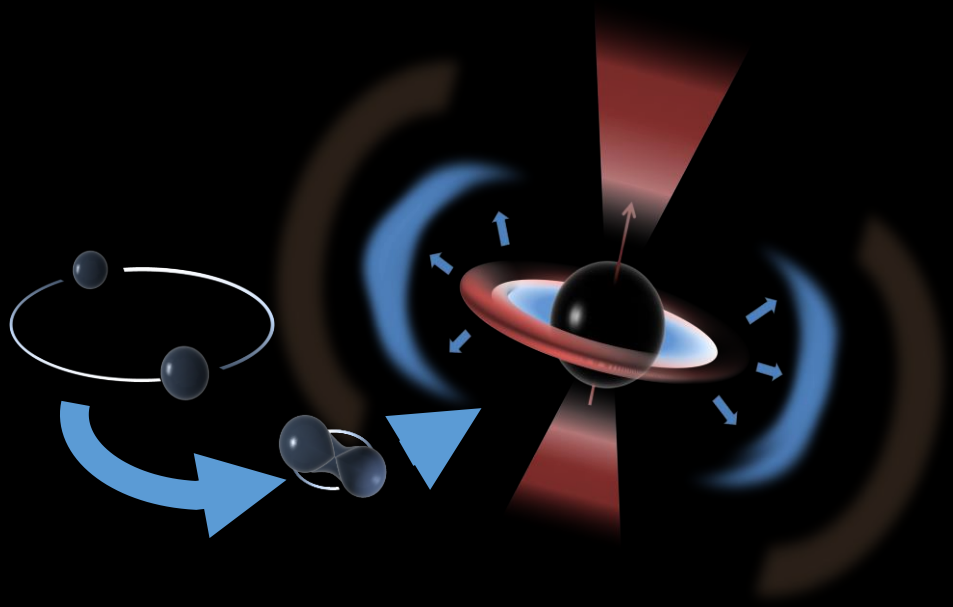
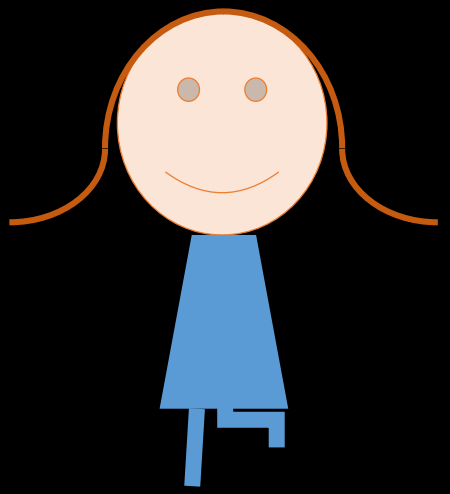
23 June 2020
Summer Colloquium Series





Multimessenger Astronomy *Immediately!*

LIGO Magazine: https://www.ligo.org/magazine/LIGO-magazine-issue13.pdf

The Early Years:
The Multi-Messenger Effort in LIGO

Zsuzsa Márka

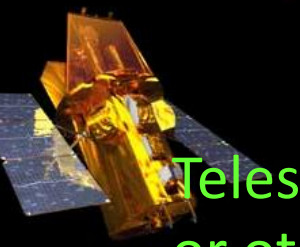
is a long time LIGO member in the Columbia Experimental Gravity group, and works on timing diagnostics and multimessenger searches. She has 4 children, who are what she is the most proud of in her life.

The first multimessenger astronomy discussion I remember took place during a dinner in Louisiana, and the topic was SN1987A. Soon after, Szabi Márka proposed LIGO multimessenger efforts to Barry Barish, who enthusiastically supported them. The LSC joined SNEWS, the SuperNova Early Warning System, and initiated multimessenger search related code development with vigor and enthusiasm.

A joint detection from a supernova is still a long shot with current detector sensitivities, but definitely it is worth waiting for. On the other hand, gamma ray bursts (GRBs), especially the short kind, were excellent candidates. LIGO started to receive GCN circulars originally on an old Sun workstation that to be. Except for some innovative faculty, mostly postdocs and graduate students were the driving forces behind the vision. Virgo members also joined the effort. I vividly remember hearing Alessandra Corsi's voice over the phone as she talked about the hallmark Virgo-GRB analysis. Beyond GRB related submitted an abstract, with Yoichi Aso joining the team, for a poster for the upcoming Gravitational Wave Data Analysis Workshop. It was clear that a correlation analysis of gravitational wave data and IceCube events was promising and should be pursued further. As of writing, the latest news from IceCube was just announced: On September 22, 2017 the IceCube Neutrino Observatory detected its first multimessenger event, a high-energy neutrino associated with a flaring blazar. I was especially pleased to see that the so far missing 'holy grail', a GW/high-energy neutrino event (maybe with an electromagnetic counterpart) was highlighted as an ultimate goal at the press conference. Only nature can tell, we must keep searching.

Basic Glossary: Multimessenger Approaches

"Multi-messenger astrophysics": connecting different kinds of observations of the same astrophysical event or system



"ExtTrig" strategy:

Telescopes, Satellites or other external entities → Flow of trigger information → GW Search

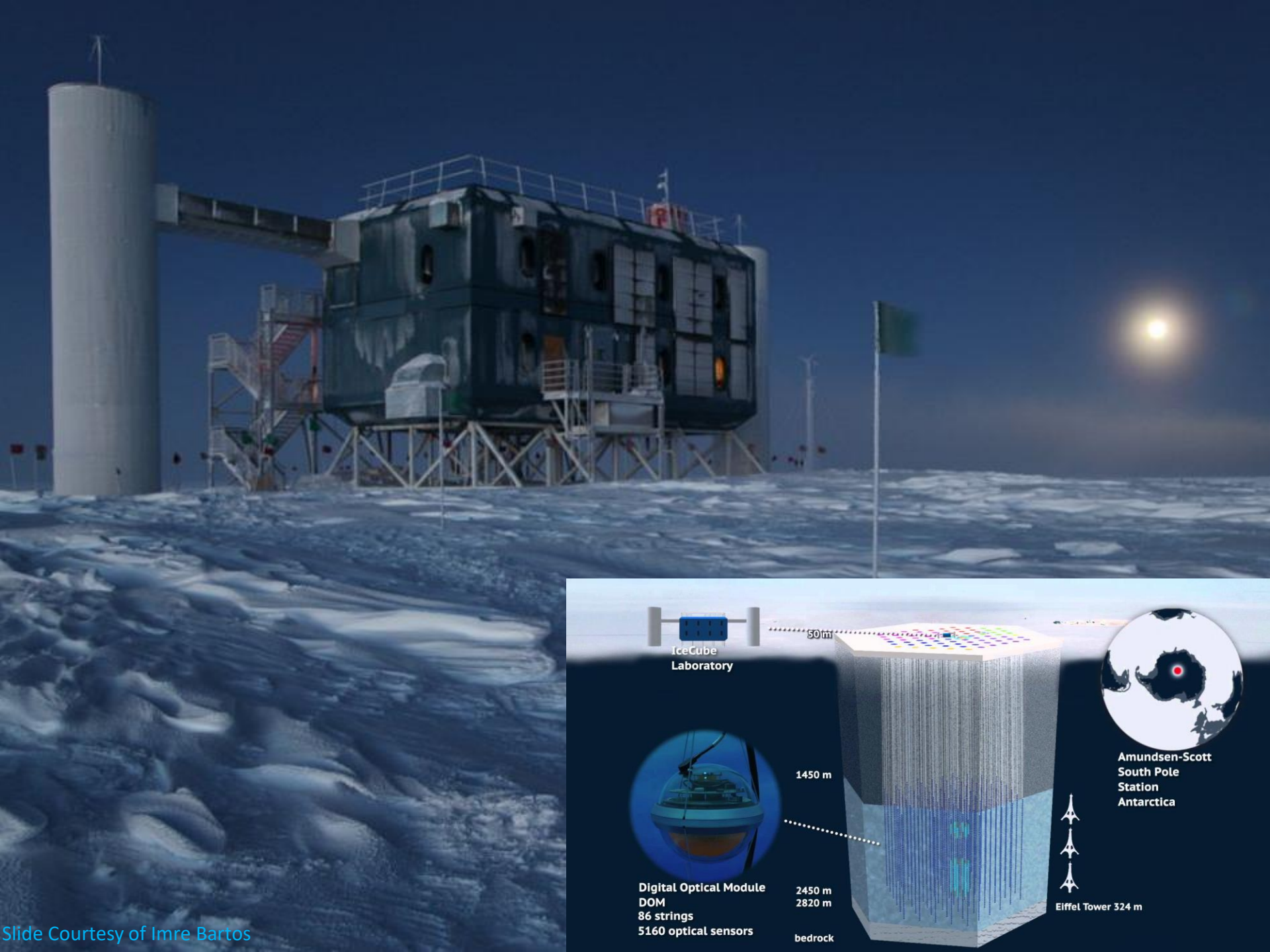
"Follow-Up" strategy:

GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

"Low-latency joint search" strategy:

GW detector →
GRB detector →
HEN detector →
++ →

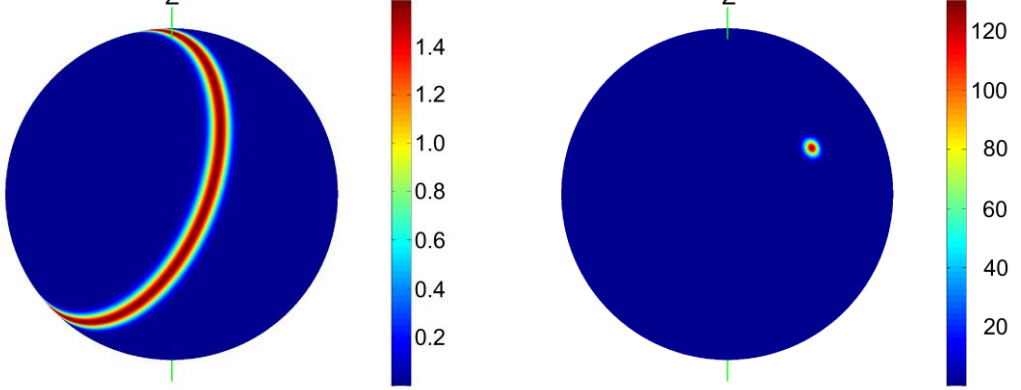
Low
Latency
Algorithm for
Multimessenger
Astrophysics



Slide Courtesy of Imre Bartos

Multimessenger searches for GWs with LIGO: HENs

High-energy neutrino – GW multimessenger studies since 2006



"Search method for coincident events from LIGO and IceCube detectors" Class. Quantum Gravity, 25, 114039, 2008

Astrophysics, Theory development, Method and Team building: GWHEN <= LIGO, Virgo, Icecube, ANTARES

Y. Aso, Z. Marka, C. Finley, J. Dwyer, K. Kotake, S. Marka, *"Search method for coincident events from LIGO and IceCube detectors"* Class. Quantum Gravity, 25, 114039, 2008

Baret et al., *"Bounding the **time delay** between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts"*, Astroparticle Physics, 35,

Ando et al., *"Colloquium: Multimessenger astronomy with gravitational waves and high-energy neutrinos"*, Rev. Mod. Phys. 85, 1401-1420, 2013

Bartos et al., *"**Observational Constraints on Multimessenger Sources of Gravitational Waves and High-Energy Neutrinos**"*, Physical Review Letters, 107, 251101, 2011

Baret et al., *"Multimessenger Science Reach and Analysis Method for Common Sources of Gravitational Waves and High-energy Neutrinos"*, Physical Review D, 85, 103004, 2012

Aartsen et al., *"Multimessenger search for sources of gravitational waves and high-energy neutrinos: Initial results for LIGO-Virgo and IceCube"*, Physical Review D, 90, 102002, 2014 (Initial LIGO/Virgo era search)

Observational Result from O1/O2

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube, Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, Virgo Collaboration, arXiv:1602.05411, 2016

Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube, Albert et al., Physical Review D, 96, 022005, 2017

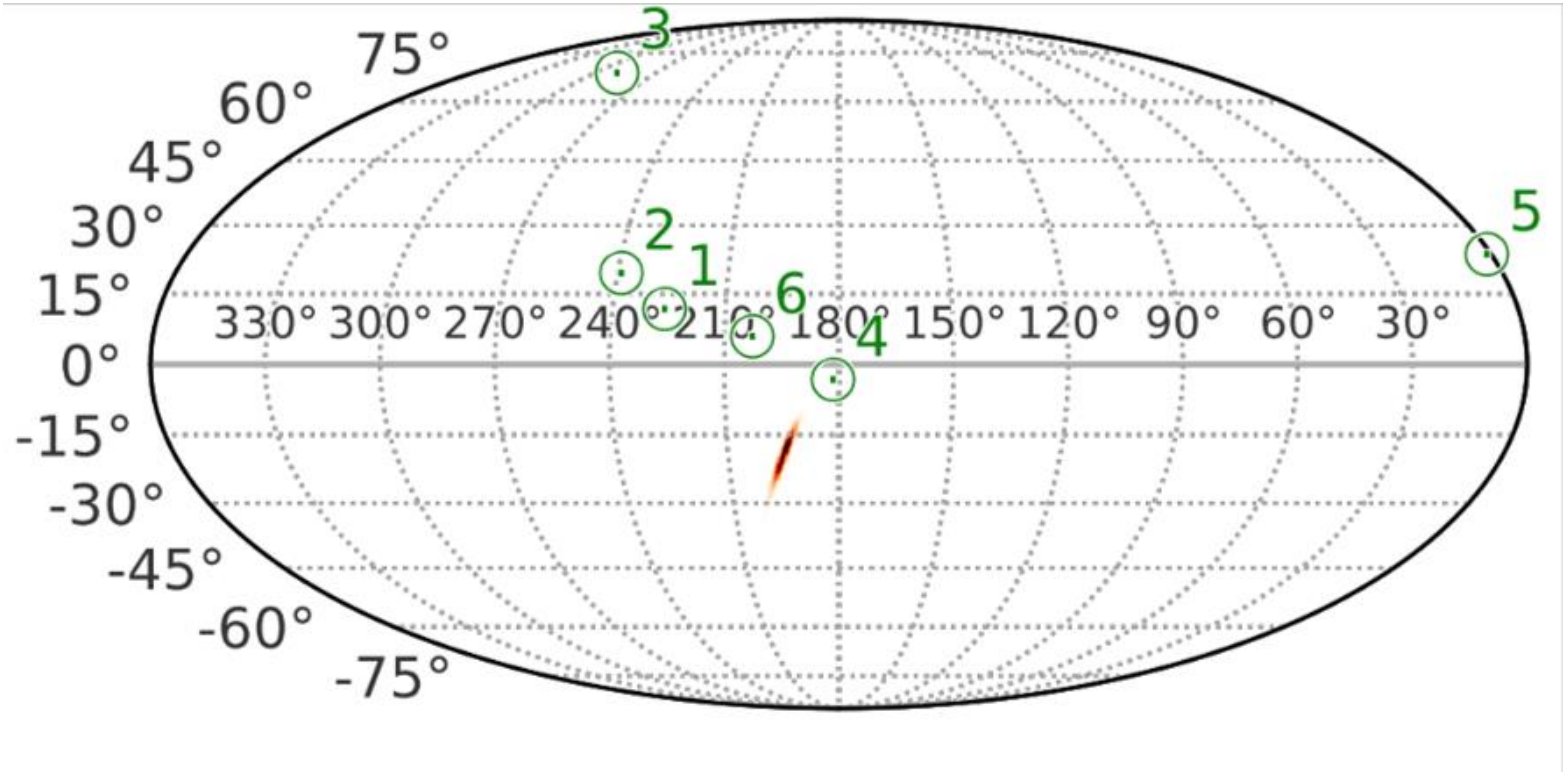
Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory, Albert et al., The Astrophysical Journal, 850, L35, 2017

Search for Multi-messenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during its first Observing Run, ANTARES and IceCube, ANTARES, IceCube,LIGO, Virgo Collaborations, Astrophys.J. 870, 134, 2019

Aartsen M. G., et al.; *IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-Wave Transient Catalog*; arXiv e-prints, arXiv:2004.02910, 2020

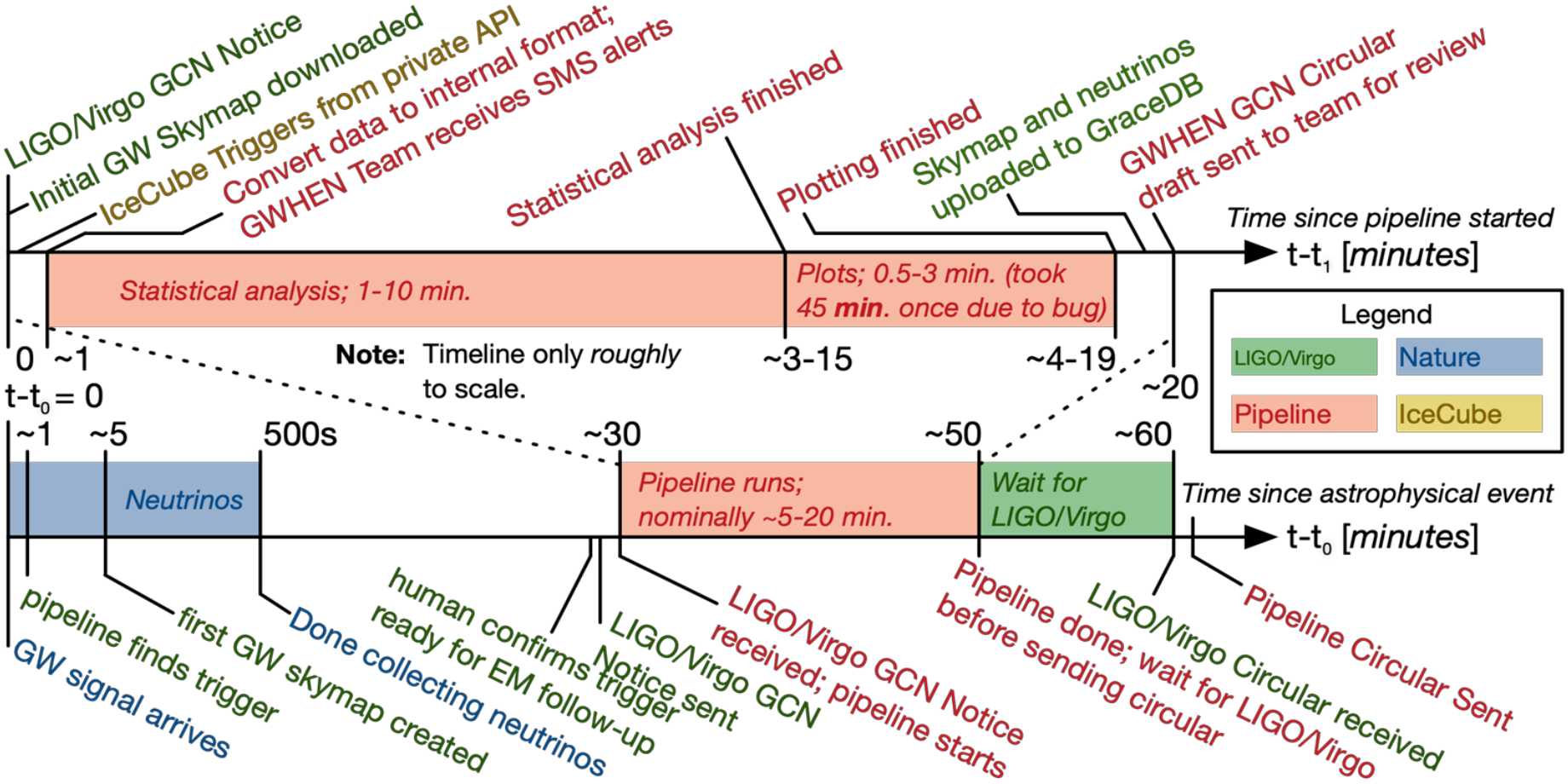
O2 Low-latency Analysis Pipeline

- Working low-latency GW+HEN analysis during O2
- Interface with IceCube, LIGO via GraceDB
- results via GCN Circulars *(Can add Notices)*



Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) with Gravitational-Wave and High-Energy Neutrino Candidates

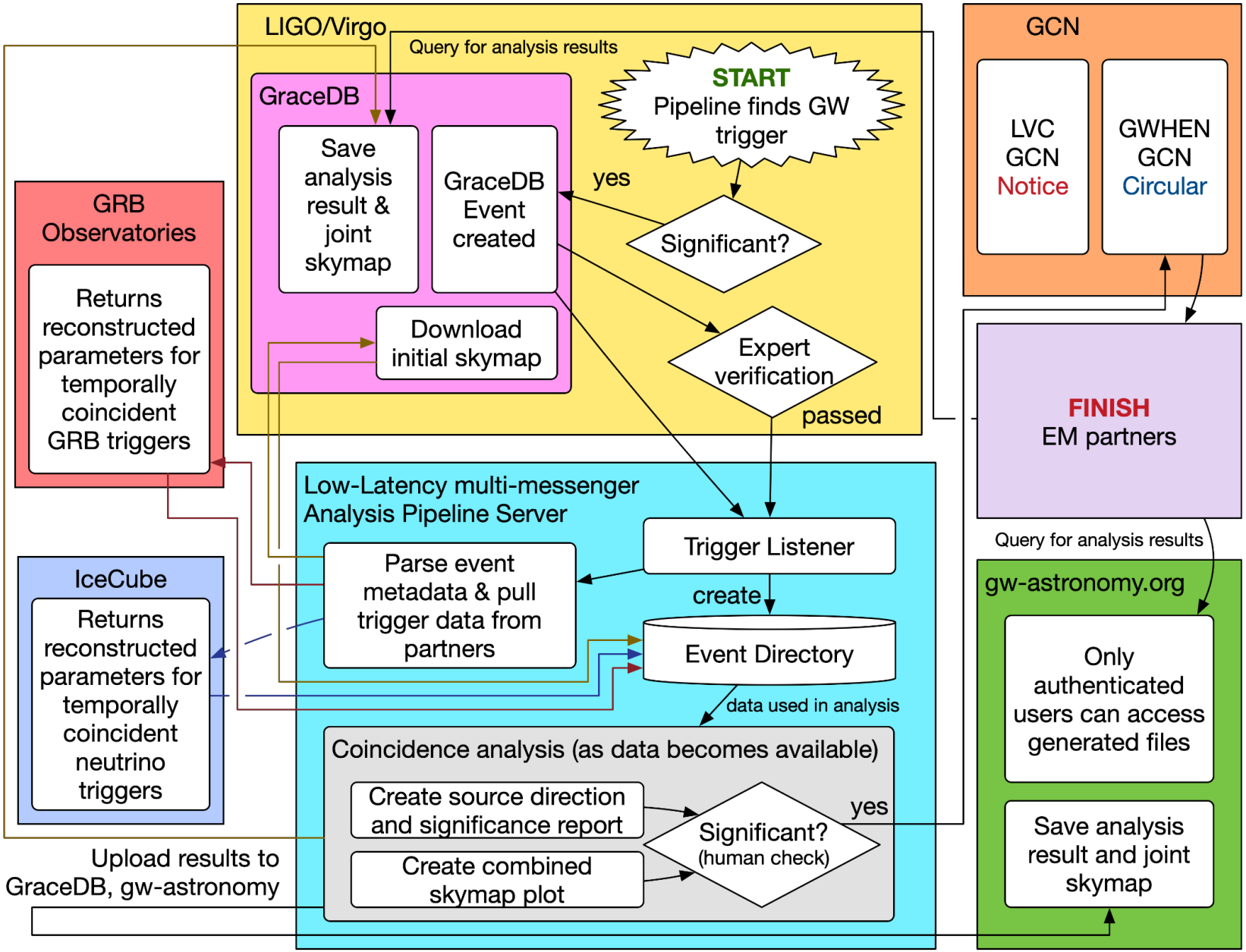
Fastest and most mature Low-Latency method with long history, standard in O2



Countryman et al. arXiv:1901.05486v1

Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA)

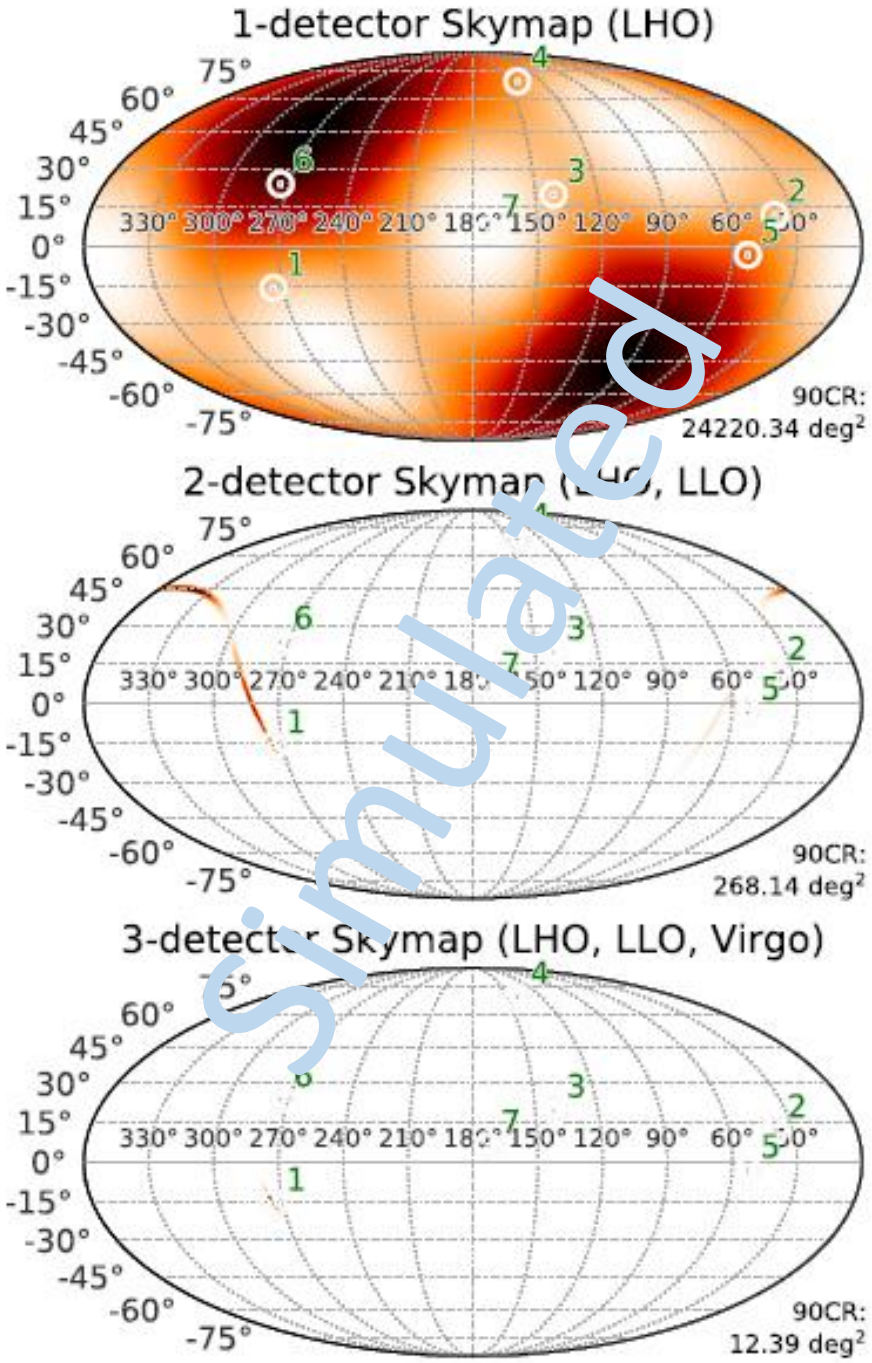
EXTENDABLE The multimessenger analysis method/tool used with other messengers.



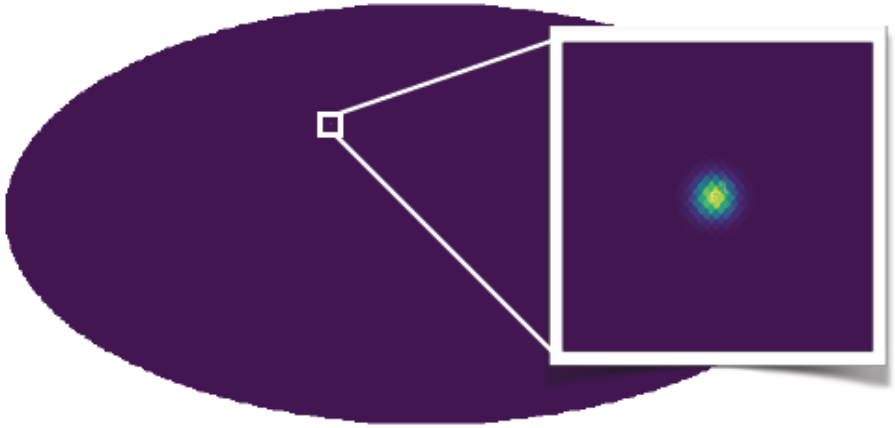
- Is it a real event?
- A chance coincidence of two background events?
- A chance coincidence of an astrophysical signal and a background event?

Bartos, Veske, et al. *Bayesian Multi-Messenger Search Method for Common Sources of Gravitational Waves and High-Energy Neutrinos*
arXiv:1810.11467v2

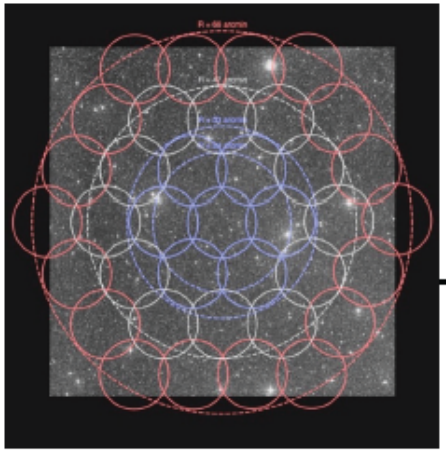
incorporation of **astrophysical priors** and **detector characteristics** following a Bayesian approach

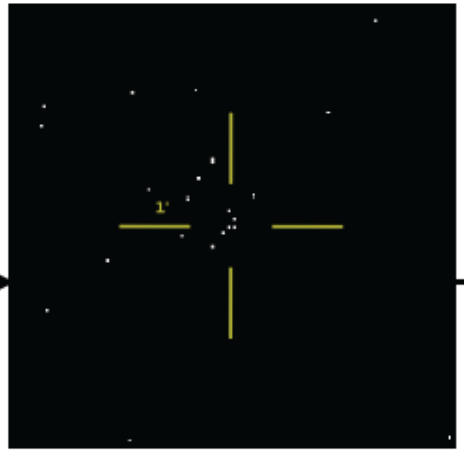


S200213t-3-Initial GW+v+Swift-XRT



- GW+v enables fast follow-up
- 3rd Swift ToO pointing under Azadeh's proposal
- Good event localization, used Swift's tiling algorithm
- Nothing found in Swift-XRT





NUMBER: 27121
SUBJECT: LIGO/Virgo (S200213t/IceCube neutrino candidate: No counterpart candidates in the Swift-XRT Observations

S. Countryman (Columbia U.), P. A. Evans (U. Leicester), A. Tohuvavohu (PSU), A. Keivani (Columbia U.), J. A. Kennea (PSU), Z. Marka (Columbia U.), S. Marka (Columbia U.), I. Bartos (U. Florida), D. B. Fox (PSU), N.J. Klingler (PSU)

...

In total we found 3 "good" X-ray sources, all of which were classified as "rank 3", i.e. uncatalogued in X-rays, but with fluxes below historical upper limits. 2 further rank 3 sources were found with detection flag of "poor", indicating that they are likely spurious. Details of the good sources are:

Source ID	RA	Dec	Err90	Flux*
S200213t_X2	03h 01m 23.65s	+31d 42' 02.3"	5.8"	7.9e-13
S200213t_X4	02h 59m 58.48s	+31d 28' 17.1"	7.1"	2.2e-13
S200213t_X6	03h 00m 16.09s	+31d 58' 48.9"	4.7"	2.3e-13

Full details of all sources are available at:
https://www.swift.ac.uk/LVC/S200213t/

Doğa Veske, Azadeh Keivani, Stefan Countryman,
Zsuzsa Marka, Imre Bartos, Szabi Marka

Will the Universe be kind to us?

SEARCH *(different for each)*

GW
1 GW trigger

- Skymap (Ω)
- Mean distanc
- SNR (ρ)
- Time

line 860
```
gw_skymap =
    LVCInitialSky
    .get_healpix(
```

PARAMETERS
(for many triggers)

BACKGROU

Adjust neutrino energy window so that it matches enough background triggers

lines 668-678
```
if (enu > maxenu): enu = maxenu
if (enu < minenu): enu = minenu
```

Find similar neutrinos in empirical background data

lines 685-705
```
while (Pempnu<5): ...
```

Calculate background (BG) rate

line 709
```
Rbg = ratebggw*ratebgnu
```

Real neutrinos, BG

$$\int A_{eff}\Omega_\nu d\Omega \times$$

$$\int r^2 Poiss.(n, \langle n_\nu(E_\nu, r)\rangle) dr dE_\nu$$

lines 726, 741
```
fourtyeight=2.0*ratebggw*...
fourtyone=p_xgw_given_h0*integral...
```

Calculate chance coincidence likelihood

line 785
```
p_h_c = p_xgw_xnu_given_hgw_c * ...
```

real neutrino**s** with overlap**ping** get signal lik

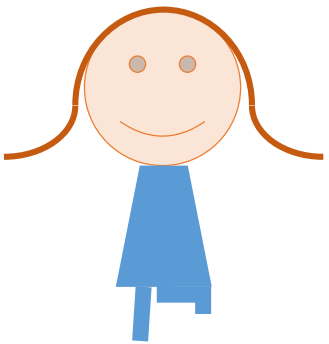
$$\int Poiss.(n, \langle n_\nu(E_\nu)\rangle) dE_\nu \times$$

$$P_{E_{GW}}\left(\frac{r_{GW}^2\rho^2}{k_0^2}\right) r_{GW}^2 \times$$

$$(t_\nu, t_{GW}\ overlap\ integral) \times$$

$$(spatial\ overlap)$$

lines 780, 782
```
p_h_s1 = (five(...))*ndotgwnu/fb
p_h_s2 = fiveresult2*ndotgwnu/fb
```



ODDS RATIO *For any GW+HEN detection on this GW trigger (decomposed into partial fractions)*

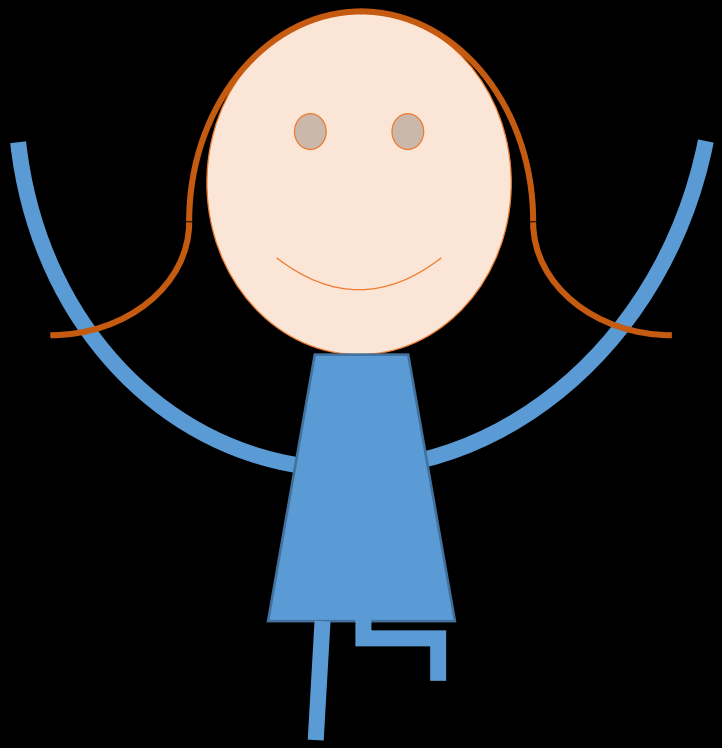

CAUTION!
BLACK
HOLES


LIGO

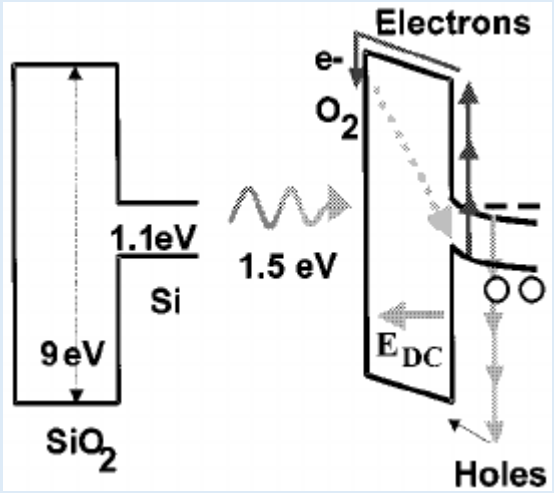

LATE
SHOW

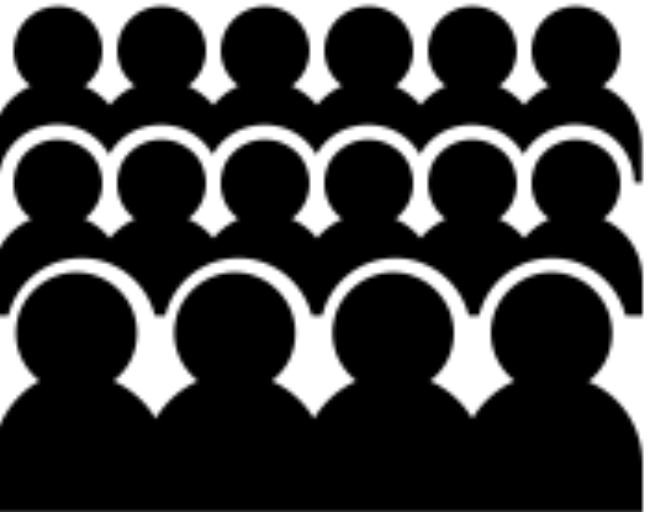
WORK

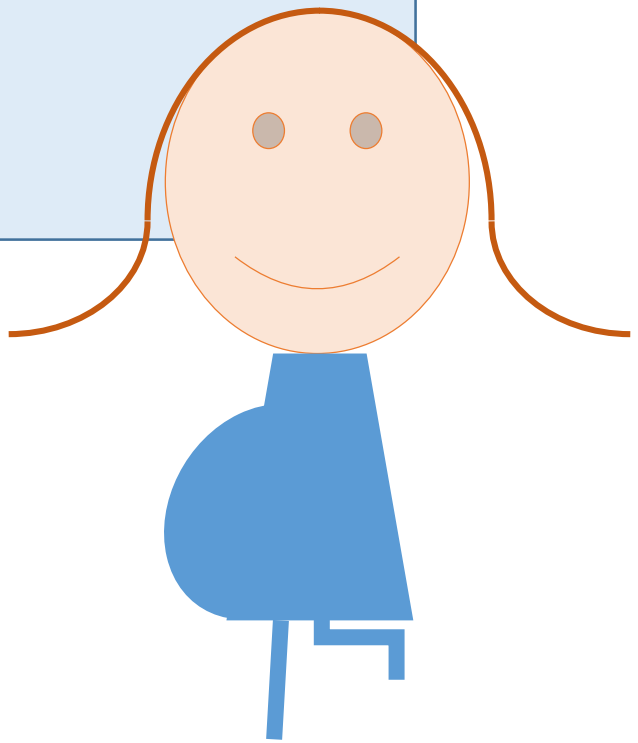
LIFE



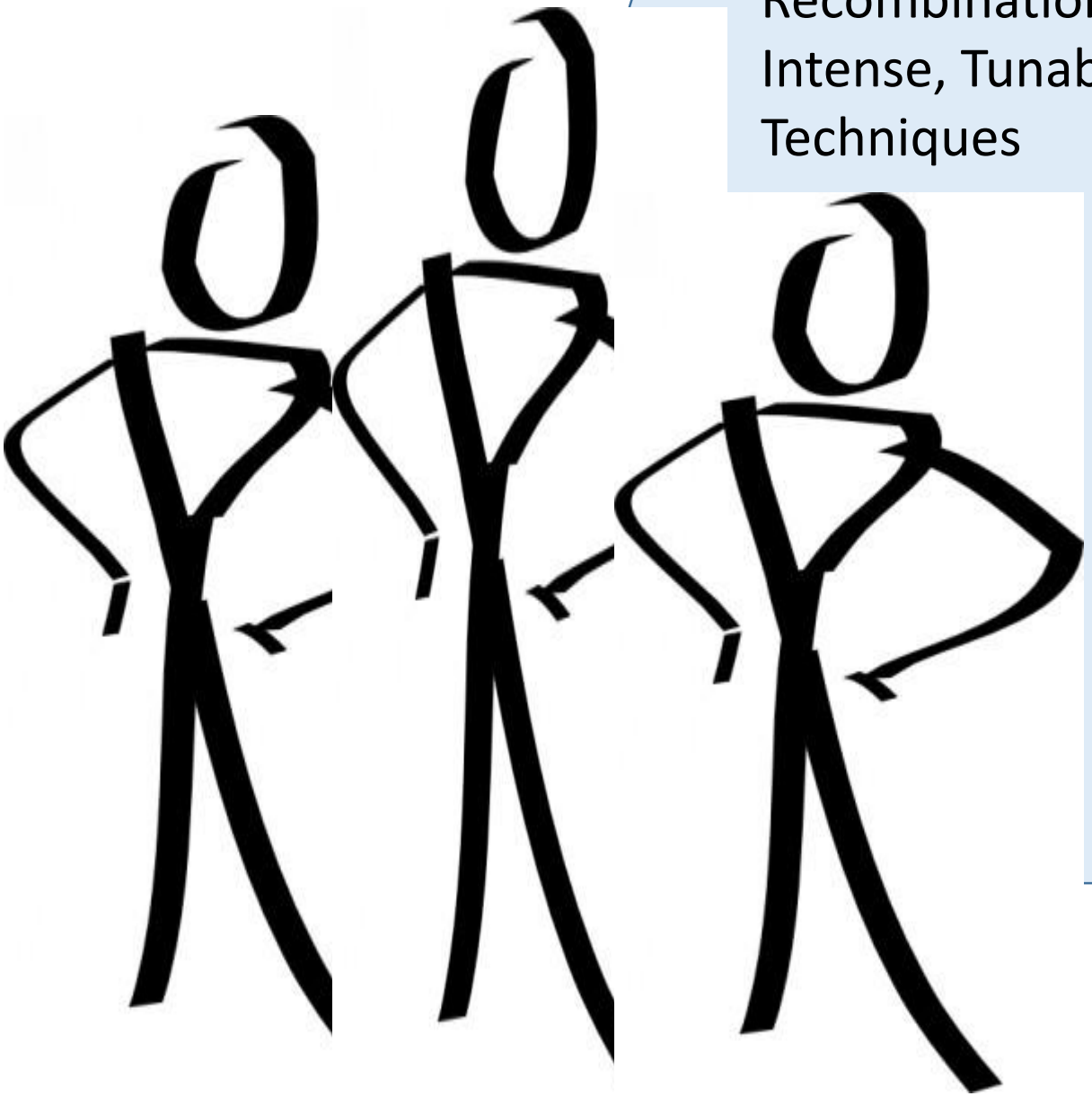
Characterization of X-Ray Radiation Damage in Si/SiO_2 Structures Using Second-Harmonic Generation

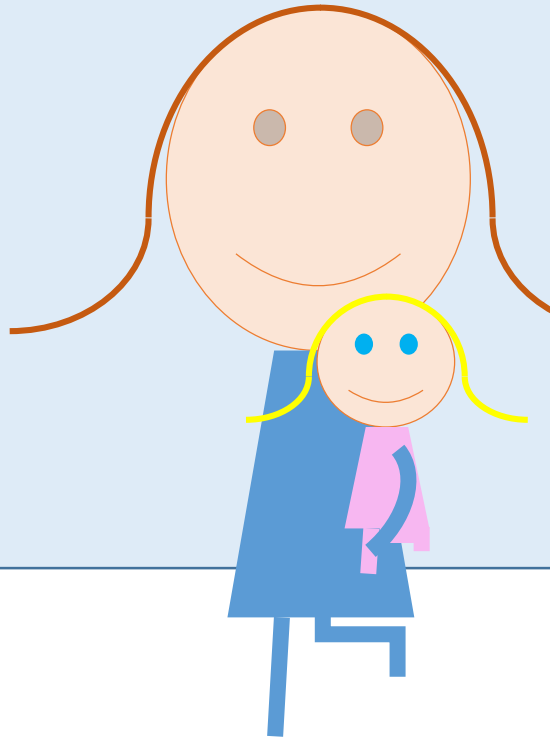




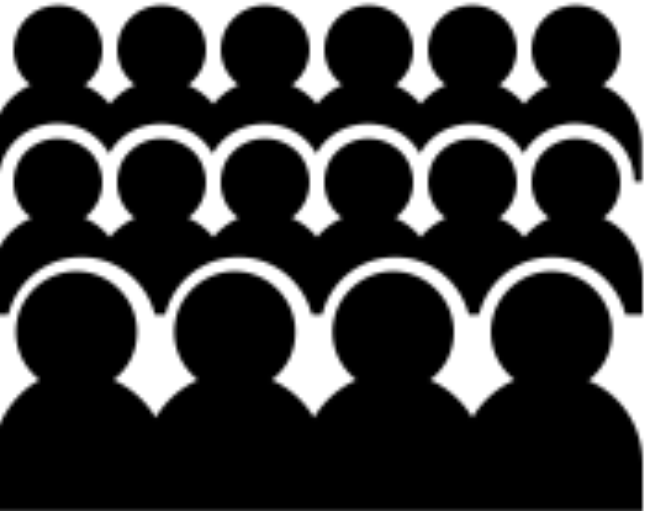


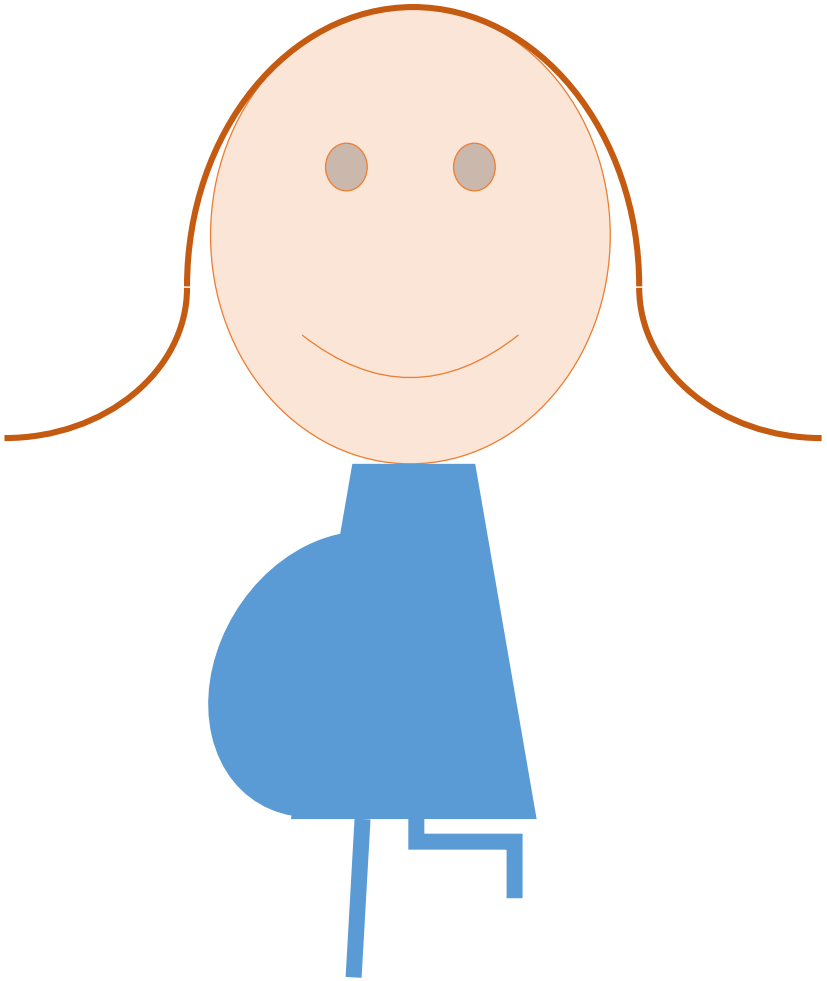
Characterization of Carrier Injection and Recombination Processes at Si/SiO_2 Interf Intense, Tunable, Ultra-Fast Laser Pump-P Techniques

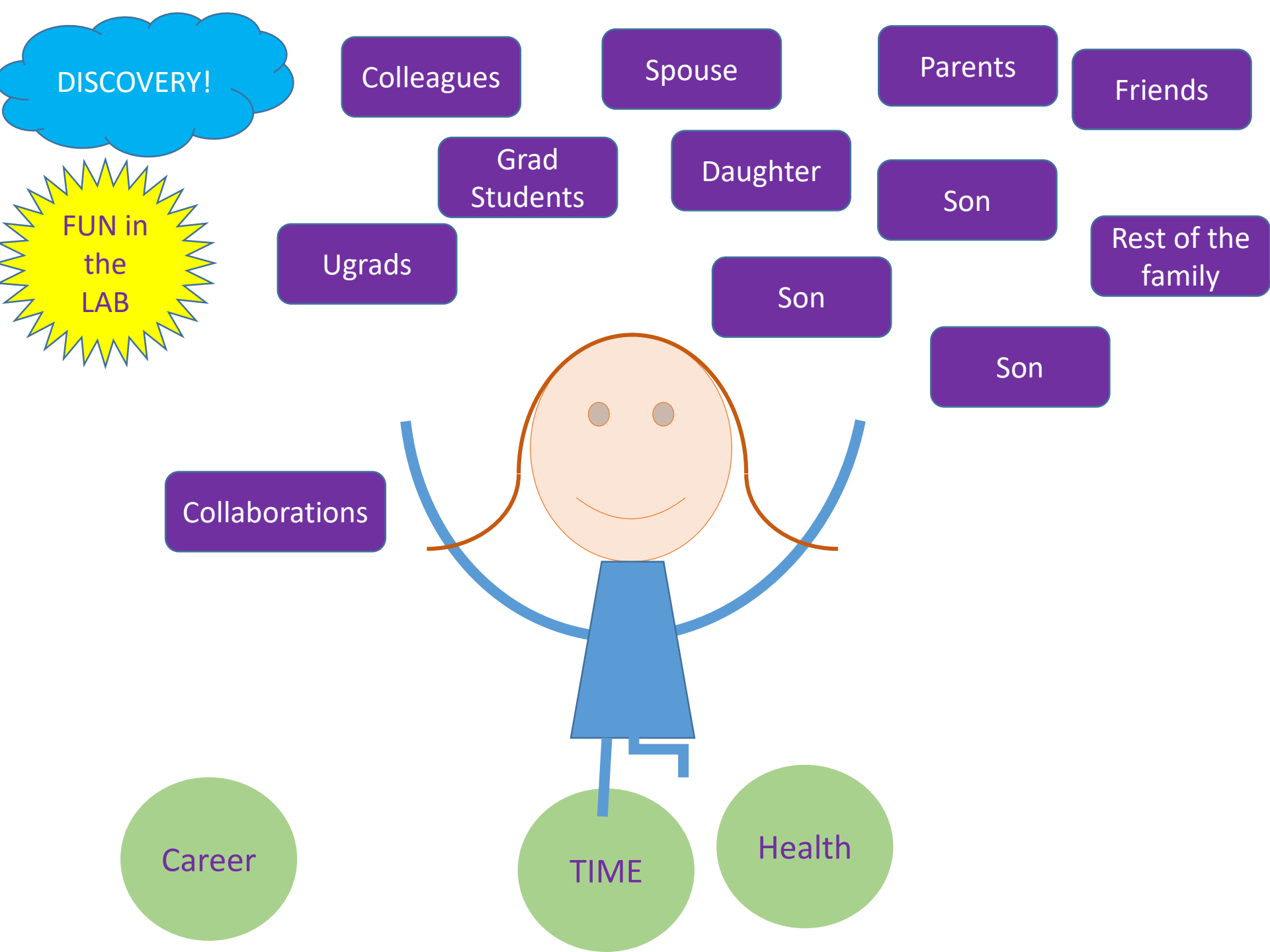




Thesis Defense






DISCOVERY!
FUN in the LAB
Colleagues
Spouse
Parents
Friends
Grad Students
Daughter
Son
Ugrads
Rest of the family
Son
Son
Collaborations
Career
TIME
Health


We Can Do It!
J. Howard Miller
POST FEB. 15 TO FEB. 28
WAR PRODUCTION CO-ORDINATING COMMITTEE

SUPPORT STRUCTURE IS
PART OF OUR STRENGTH

AND GIVES OUR PURPOSE