
DELLEMC
SWIN BUR NE
Centre for Astrophysics and Supercomputing

ARC Centre of Excellence for Gravitational Wave Discovery

Gravitational Wave Data (Centre?)

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ARC Laureate Fellow

OzGrav Director

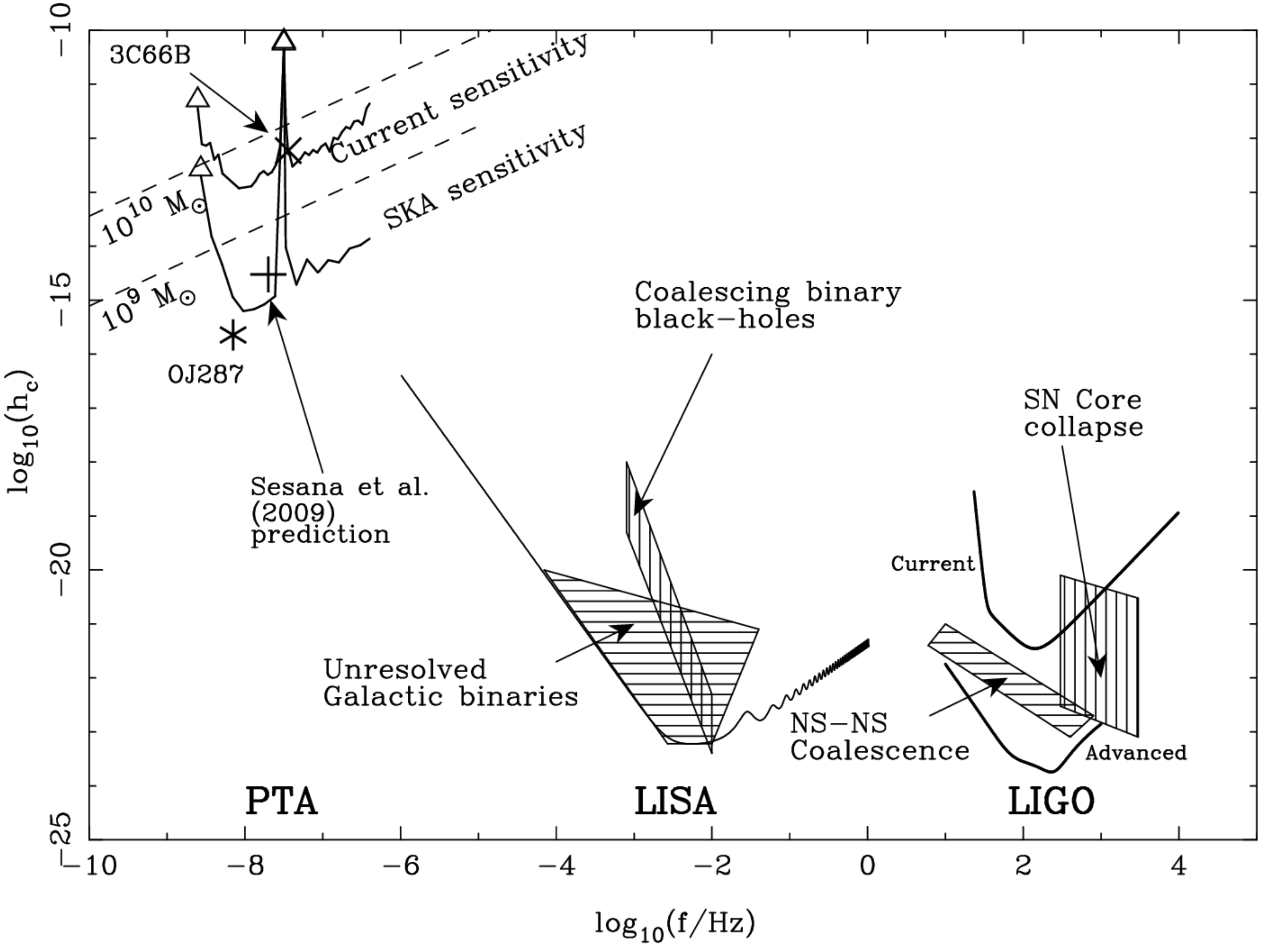
Gravitational Waves

- Astronomy 2016-2025 Decadal Plan:

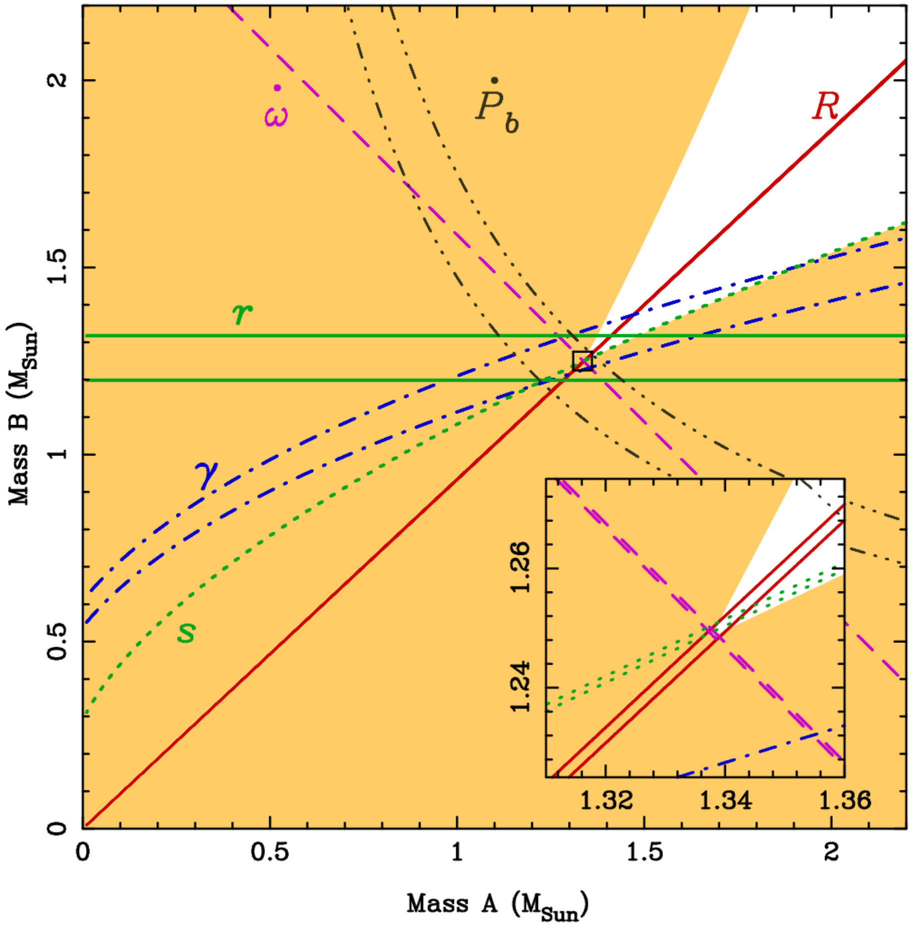
Beyond the traditional strengths of Australian astronomy, a revolution is expected during this Decadal Plan period following the detection of gravitational waves, which, along with next-generation high-energy telescopes and Antarctic astronomy, will open new windows to astrophysics. ***Mid-scale investment in large international facilities will provide the tools for Australian discoveries in these areas.***

GW spectrum

* Pulsars
* LISA – Space
* LIGO-like



Is our understanding of Gravity Correct?



2017: Nobel Prize (GW Discovery)

2017:
Science discovery
of the year
NS merger

OzGrav Launch

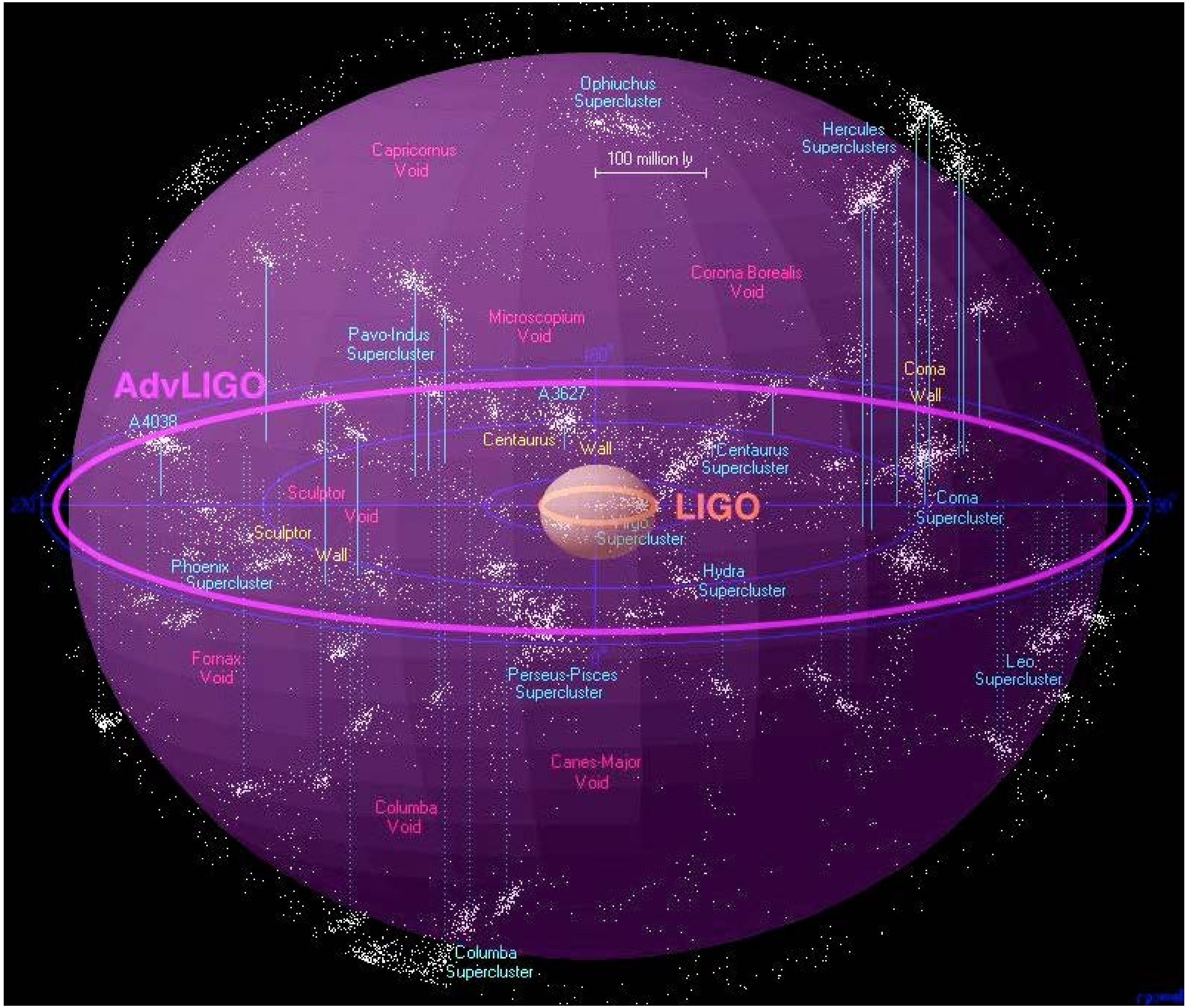
OzGrav Numbers

136 EFT
19 CIs
24 Postdocs
37 PhDs
19 AIs
14 Pre-PhD

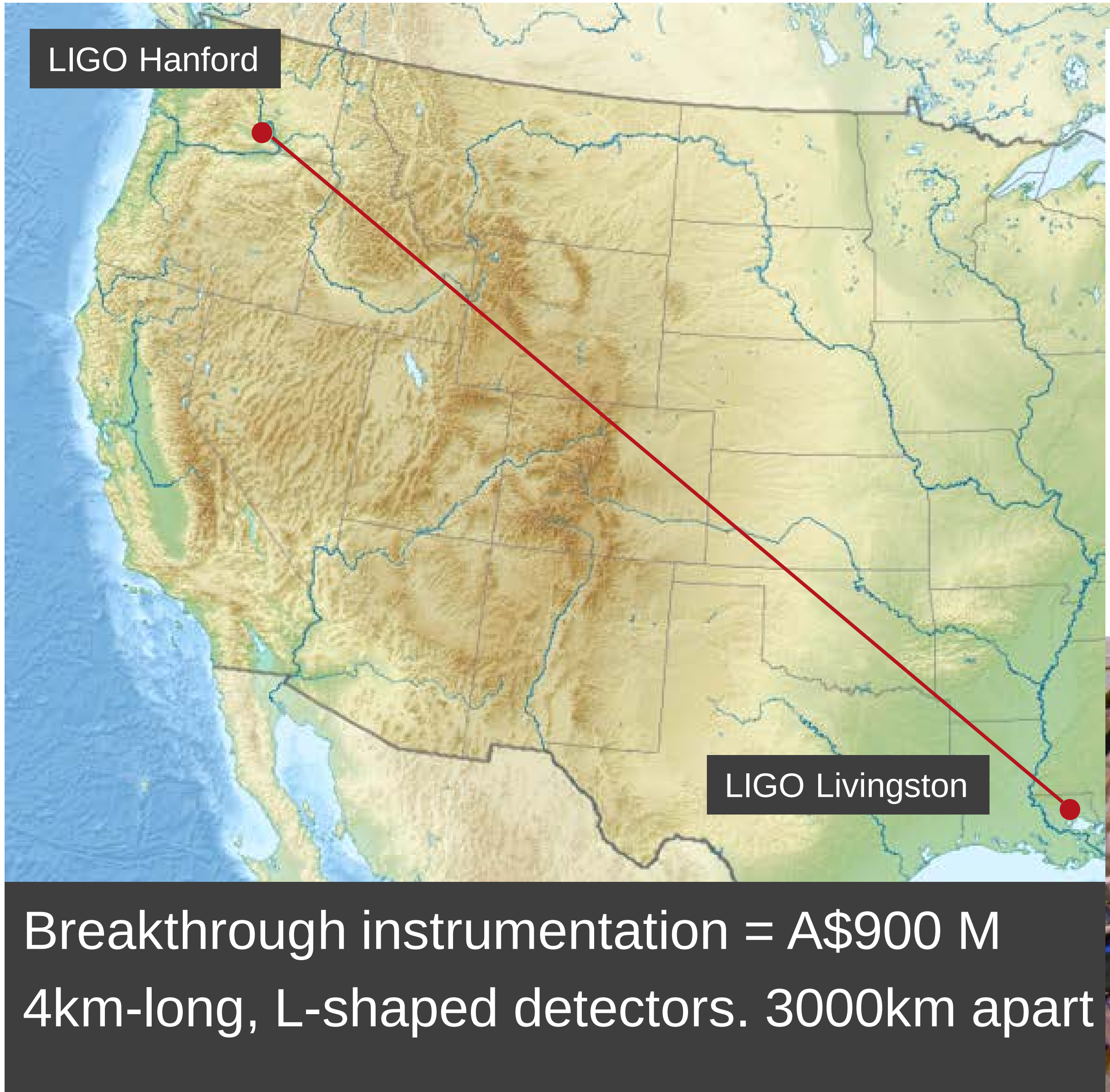
Advanced LIGO:

Design sensitivity 10x iLIGO's range.

1000x merger rate.



Advanced LIGO interferometer



OzGRav CIs provided:

- Lock Acquisition System (ANU)
- Hartmann Cameras (Adelaide)
- Instability Control (UWA)
- Blind injection system

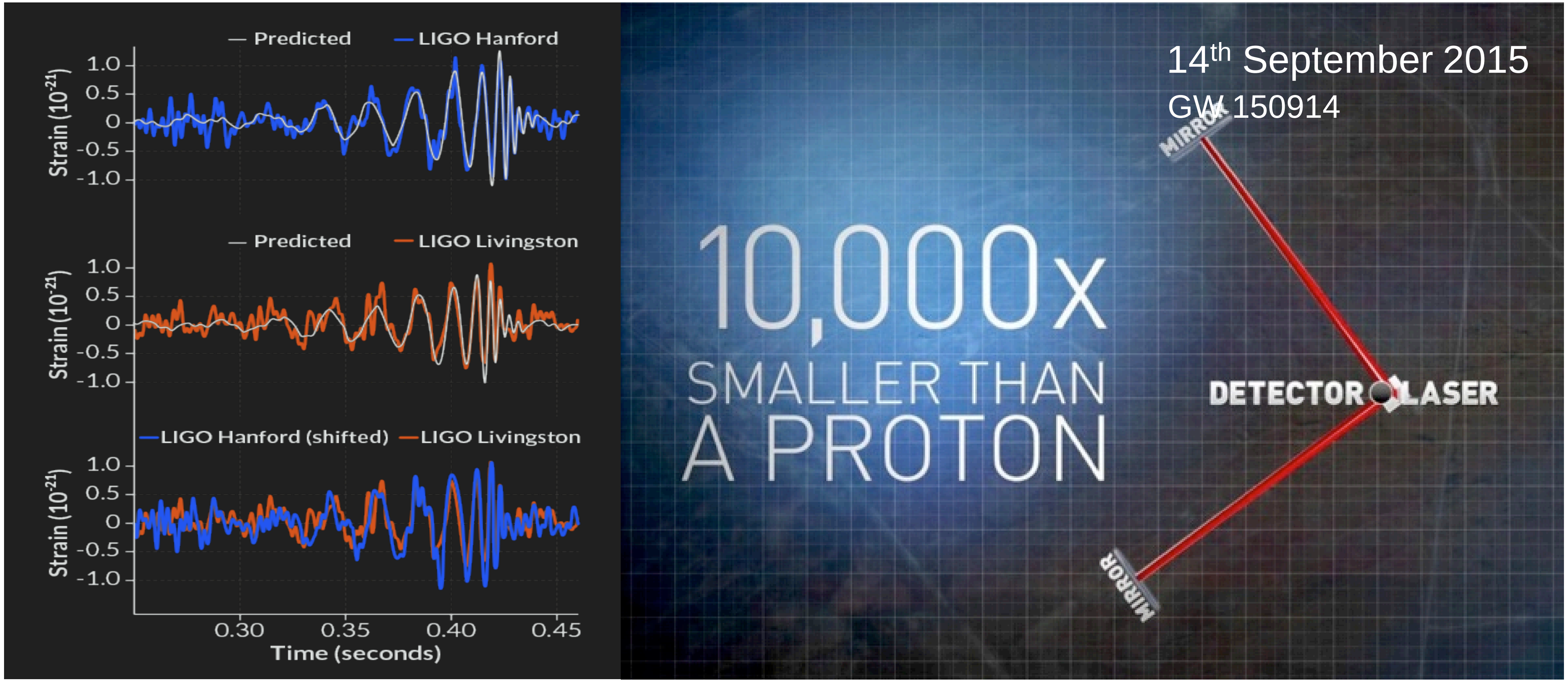
The Gravity Wave Discovery

Ripples in Space-time detected by LIGO*

*Laser Interferometer Gravitational-wave Observatory

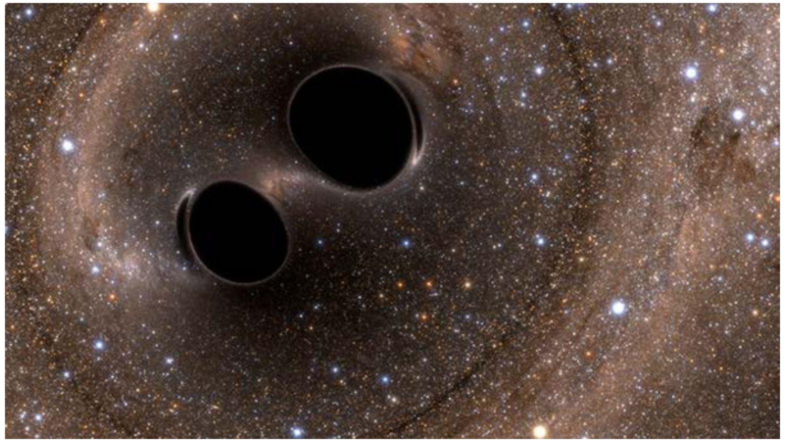
The Gravity Wave Discovery

Most extreme event since the Big Bang



Width of a human hair at alpha centauri!

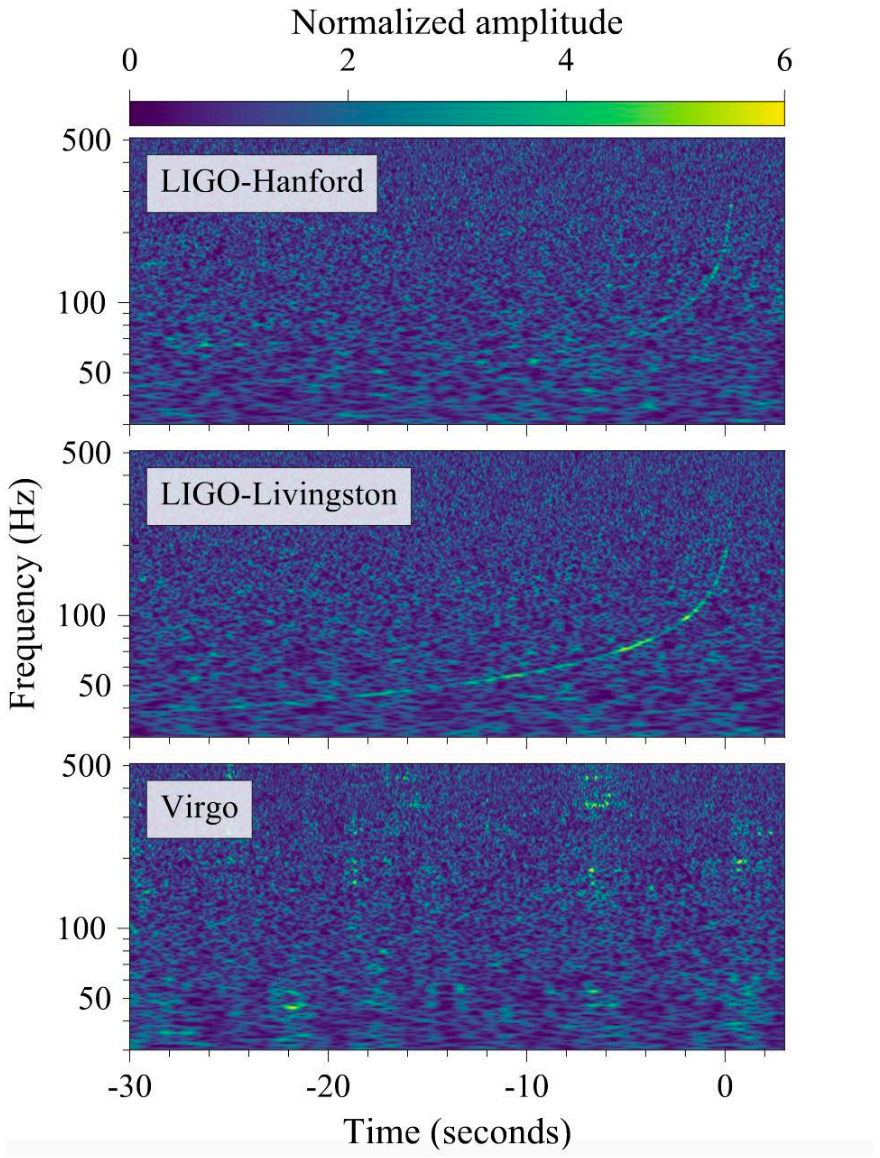
GW150914



- 230-570 Mpc (z=0.054-0.136)
- SNR = 24
- Total Mass 60-70 Mo, 36(4)+29(4) Mo
- Time delay 7 ms
- Likely Sky Position “Southern Hemisphere”!!!
- Strain 10^{-21} !!!
- GW Energy 3Mo – $3.6x10^{56}$ ergs/s
- 250 Hz at coalescence
- Rate 1/(2-400) Gpc^{-3} yr^{-1}

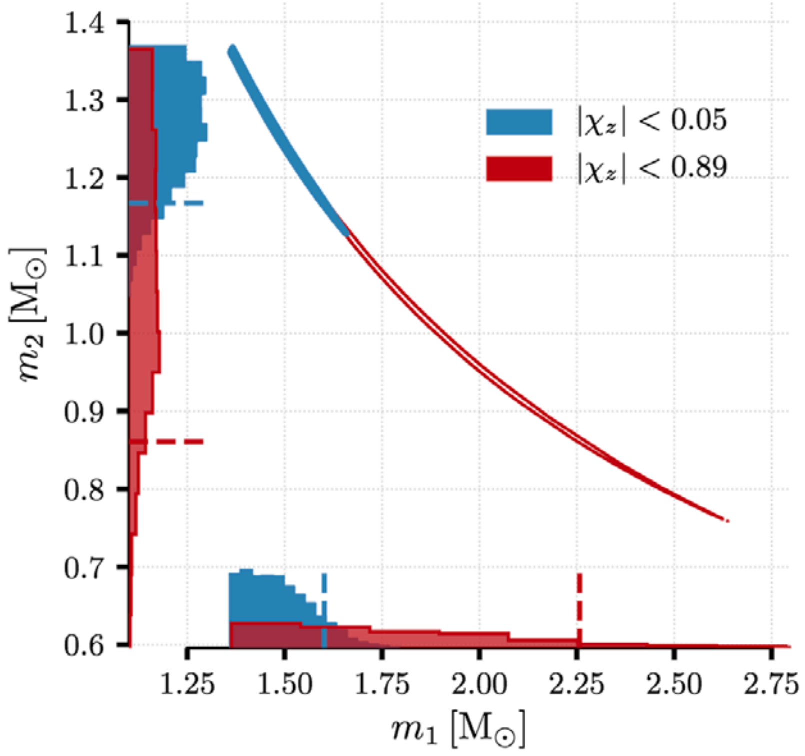
GW170817

- The first LIGO-Virgo detection of the inspiral of two neutron stars.
- Occurred days after the first joint LIGO-Virgo detection GW170814.
- 1.7s after GW signal GRB170817A was detected by Fermi-GBM.
- It is the first GW detection with an EM counterpart.



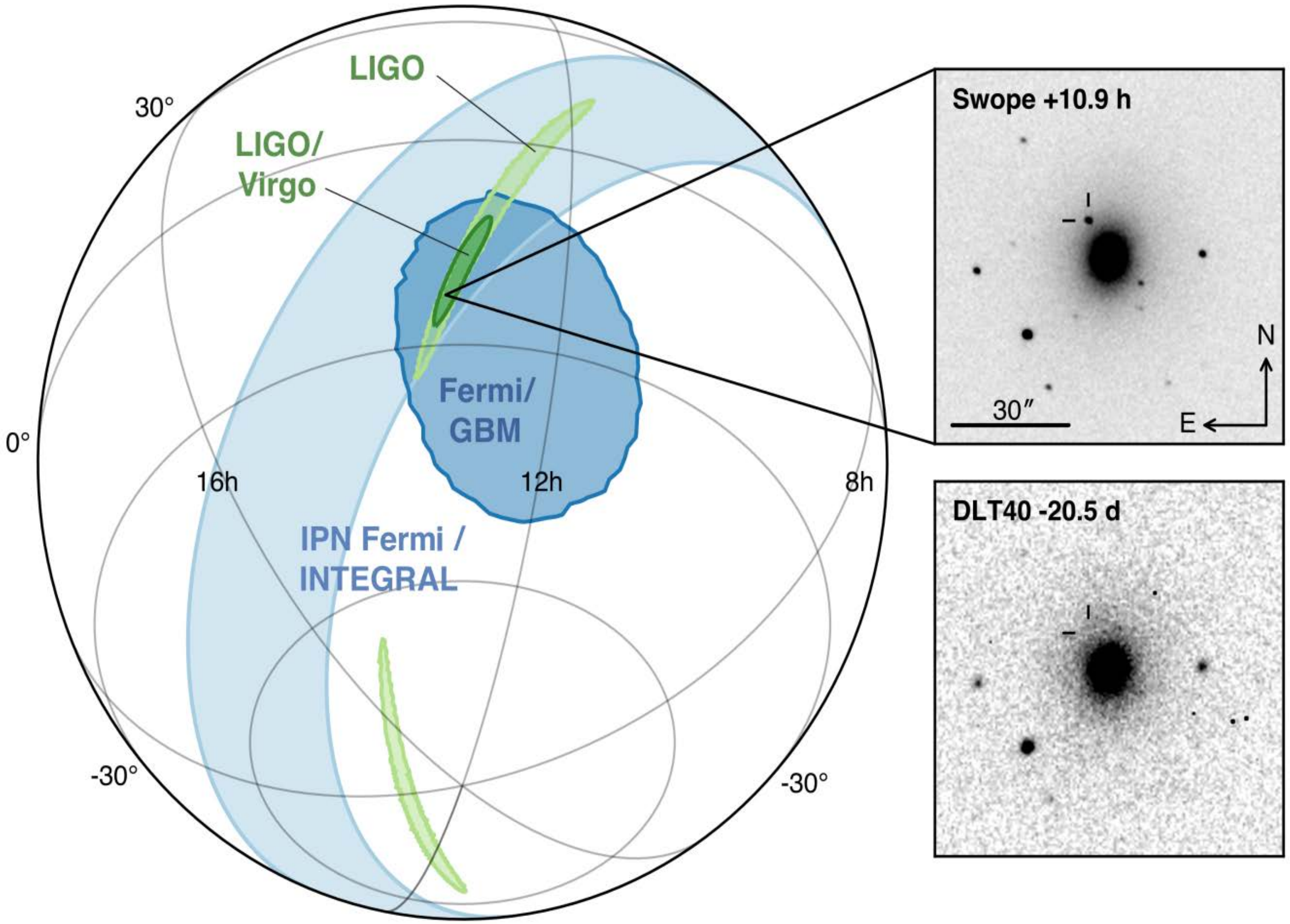
Source Parameters

	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	0.7 – 1.0	0.4 – 1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ M_\odot$	$2.82^{+0.47}_{-0.09}\ M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ M_\odot c^2$	$> 0.025\ M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
using counterpart location	$\lesssim 31°$	$\lesssim 31°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400



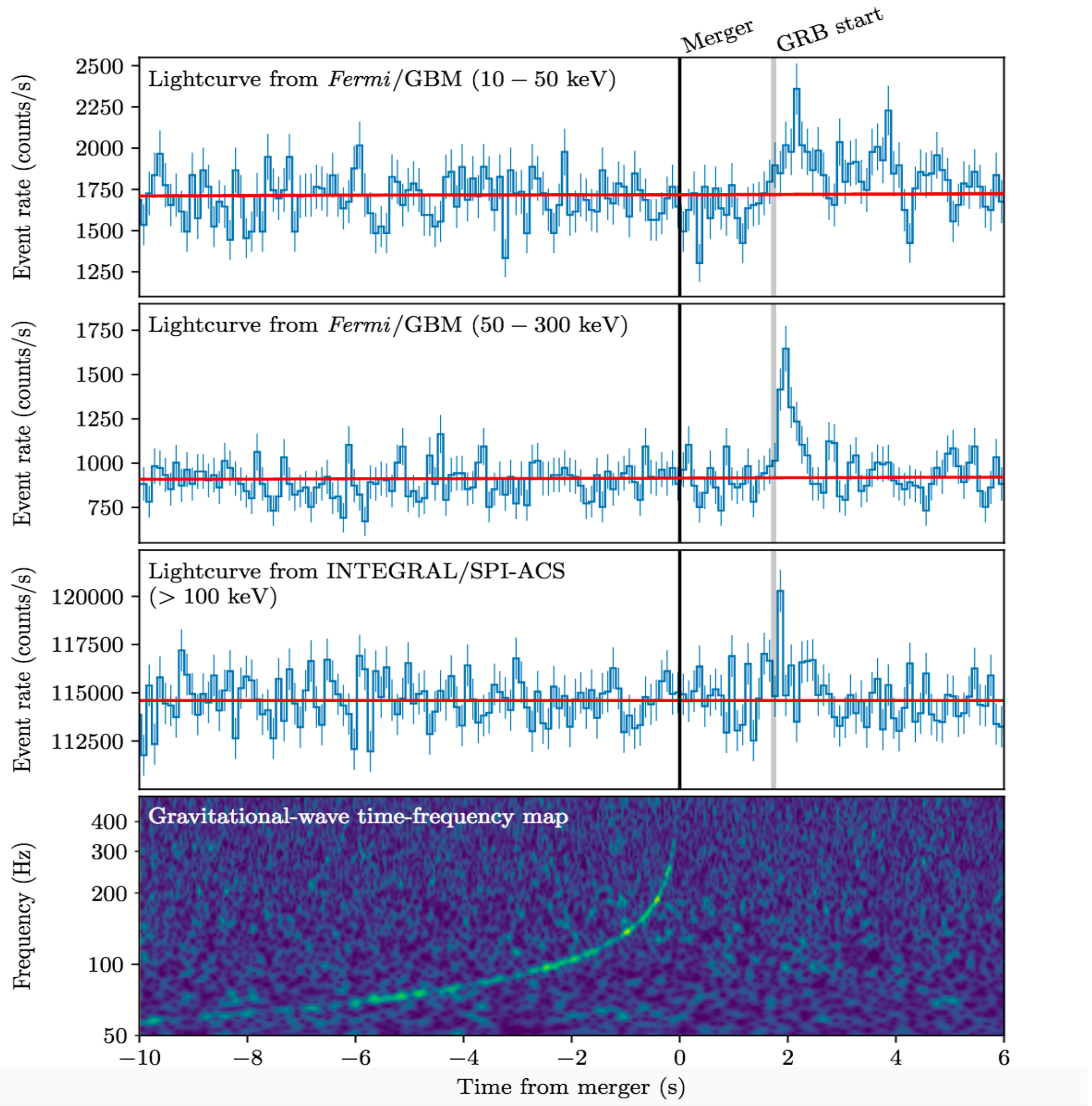
Sky map

- Host Galaxy NGC4993
- Distance 40 Mpc
- Light green is 90% credible region from LIGO. Dark green is LIGO + Virgo. (28 deg^2)
- Andreoni et al. (2017)



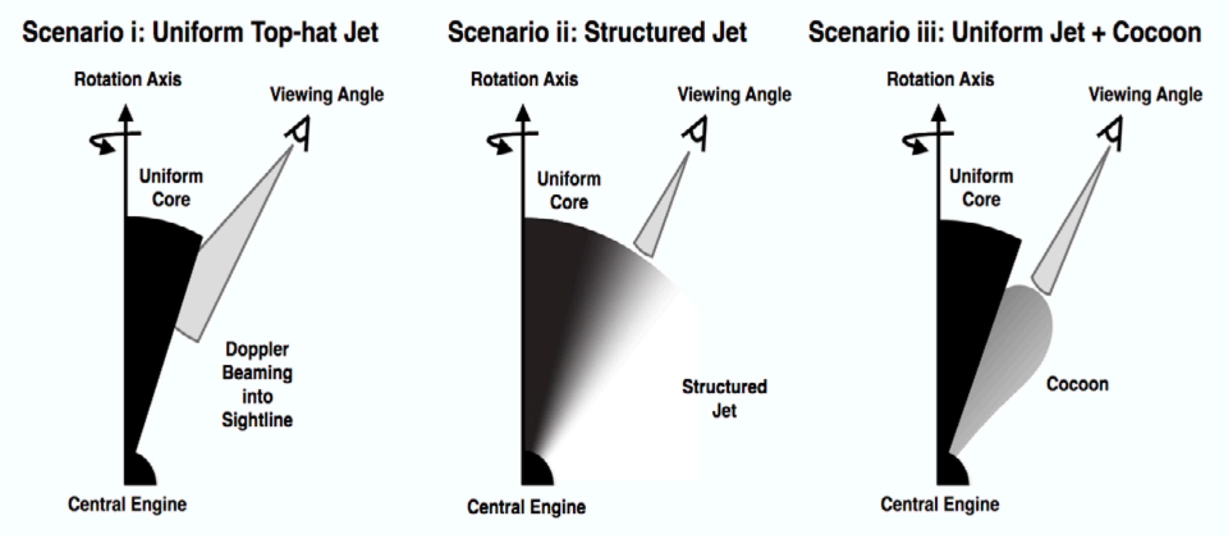
GRB170817A

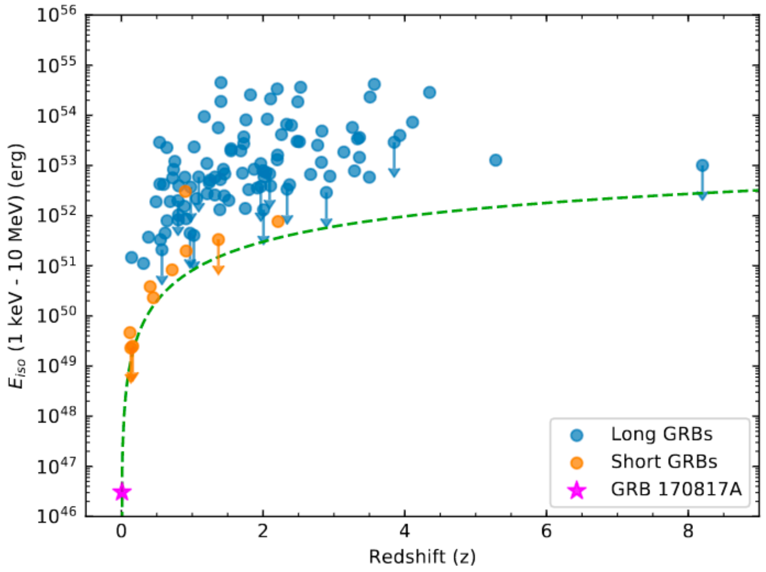
- We confirm binary neutron star mergers as a progenitor of (at least some) short GRBs.
- Time delay of (+1.74±0.05) s between GRB 170817A and GW170817.
- We constrain the difference between the speed of gravity and the speed of light to be between -3×10^{-15} and $+7\times10^{-16}$.

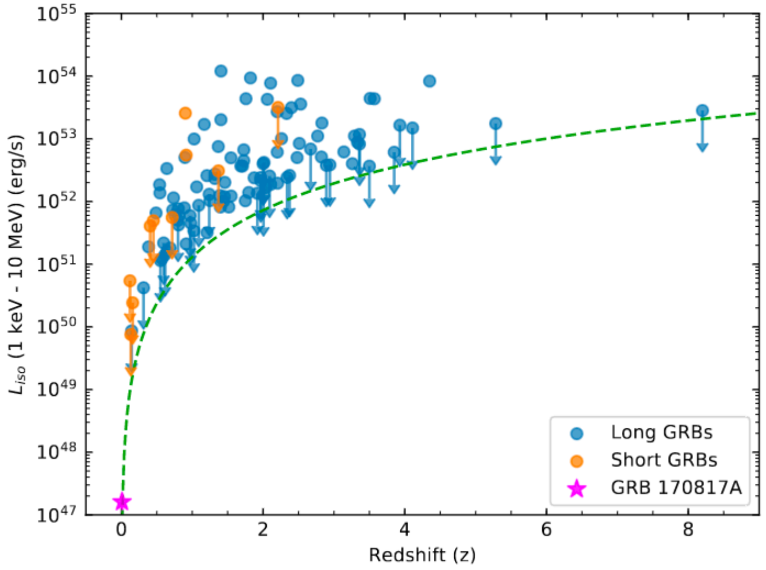


GRB170817A

- GRB 170817A is the closest short GRB with a known distance, but is between 2 and 6 orders of magnitude less energetic than other bursts with measured redshift.



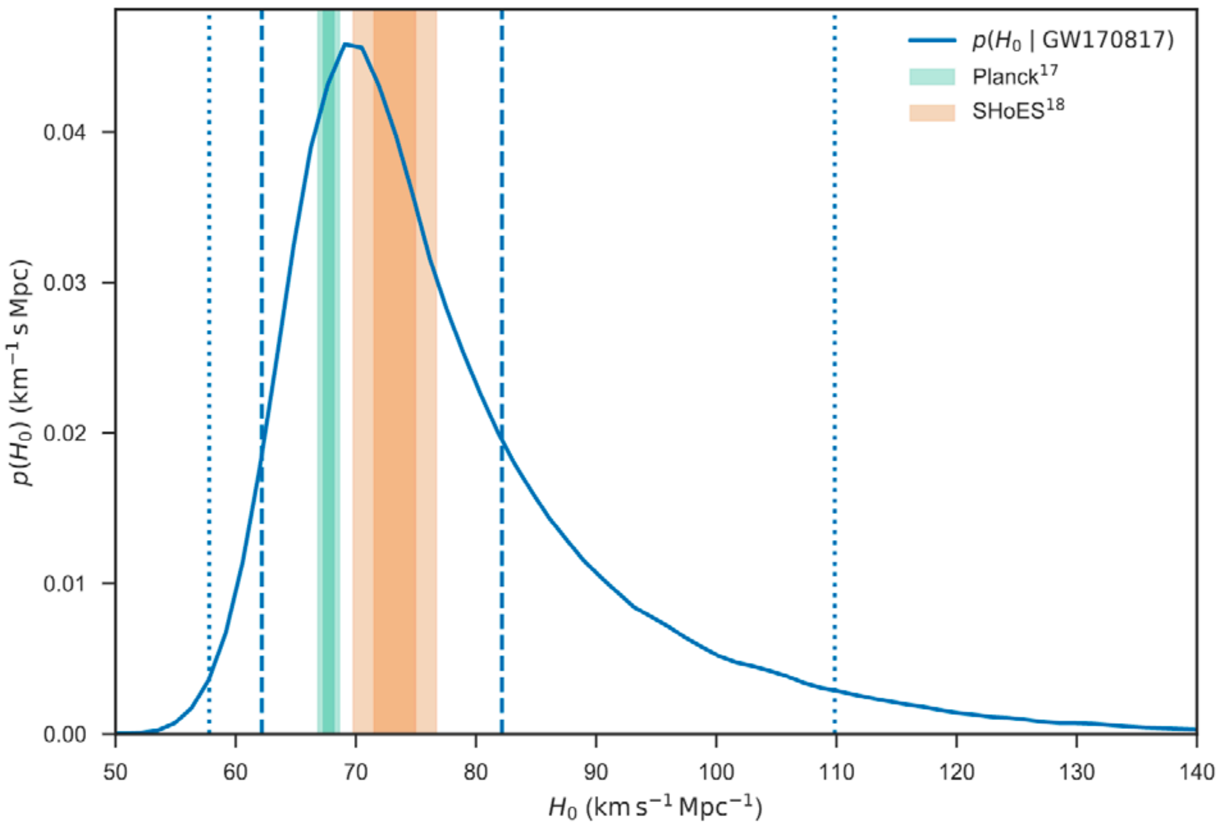




OzGrav

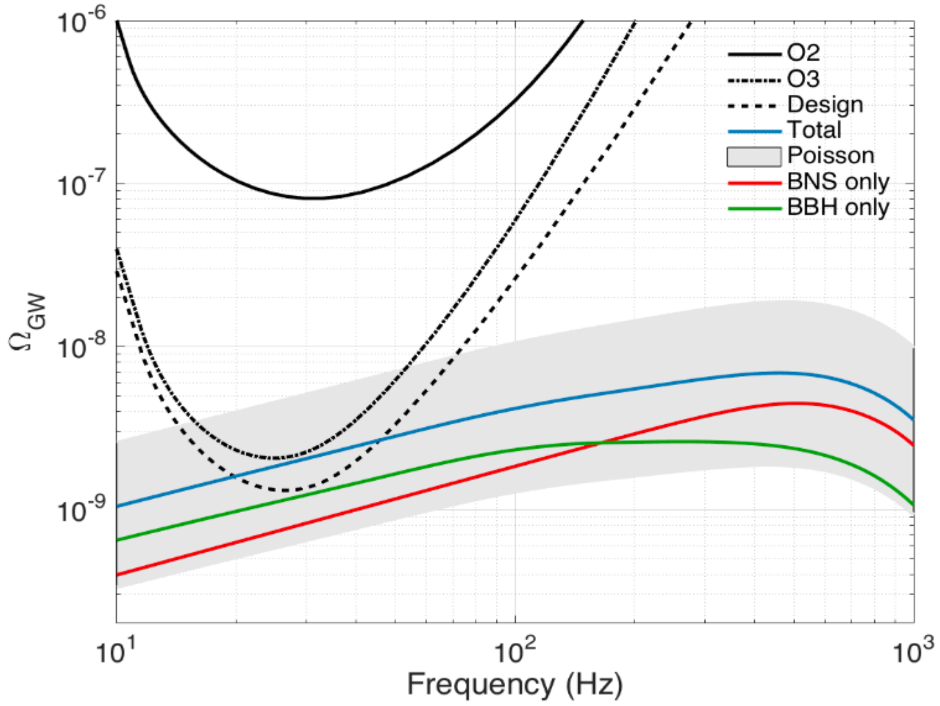
Hubble constant

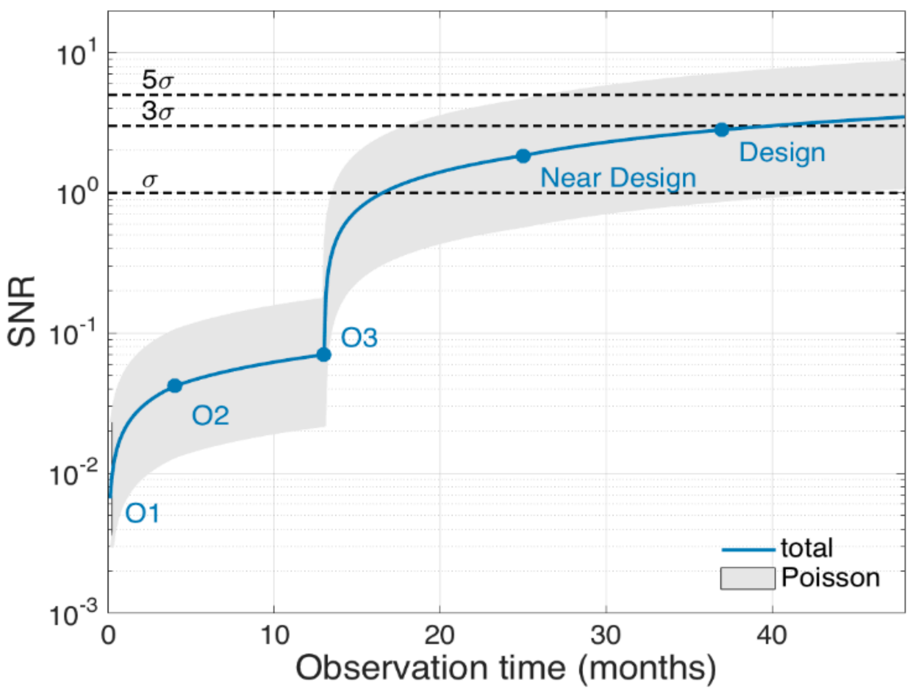
- We use GW170817 as a standard siren to measure the Hubble constant.
- Combines distance measured by GWs with the recession velocity measured by EM.
- We determine the Hubble constant to be $70.0^{+12.0}_{-8.0}$ kms^{-1} Mpc^{-1} (maximum a posteriori and 68% credible interval).
- sin(i) determined via VLBI – large reduction in error



Implications for stochastic background

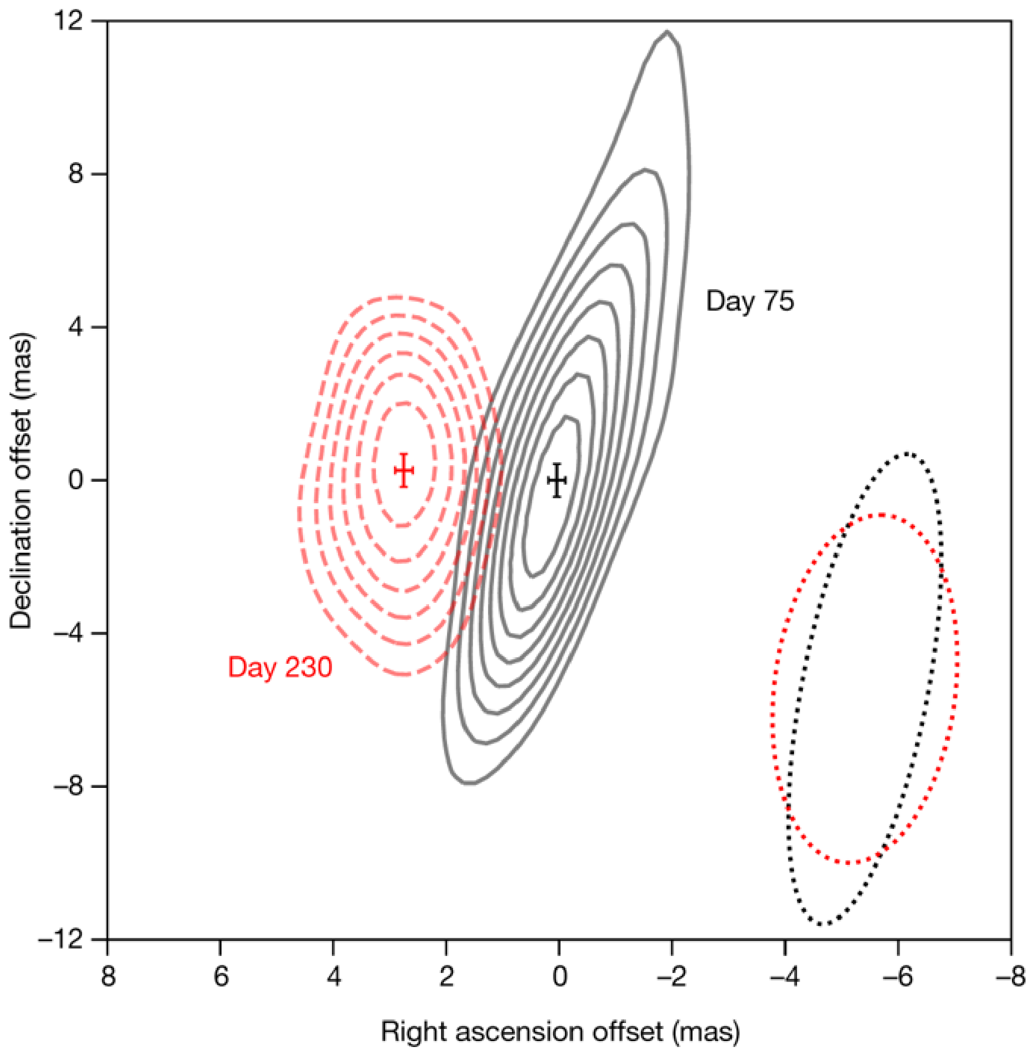
- We find that the background may be detectable with a signal-to-noise-ratio of 3 after 40 months of observation time at design sensitivity.





Radio Follow-up

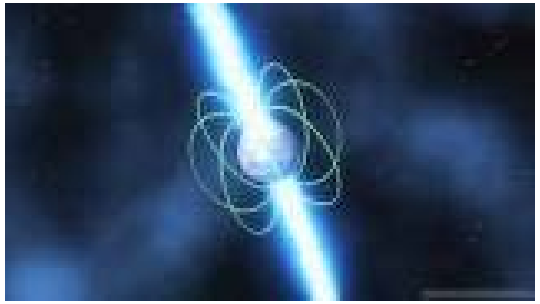
- ATCA – Tara Murphy group et al.
- VLBI – Deller and friends.
- Hubble constant faster.
- Jet physics.

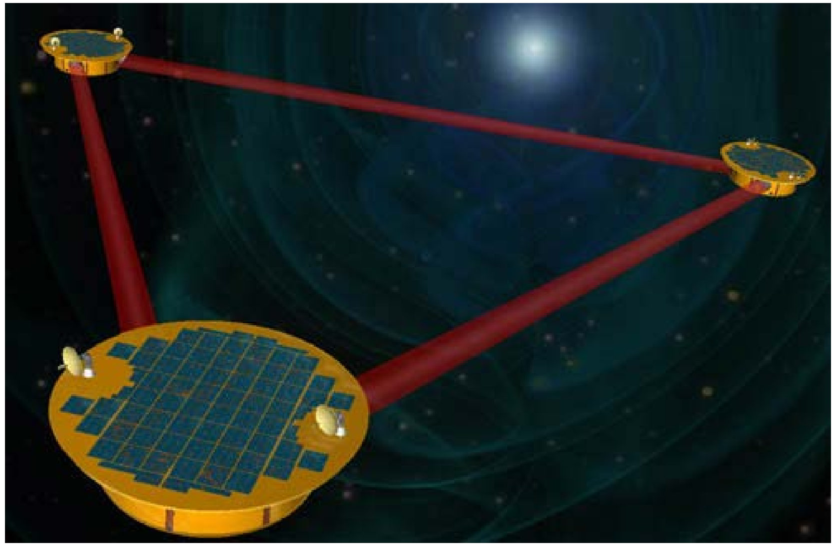



IMPACT
The **merger** of two **Neutron Stars** generated **976 Australian media** items:
436 **radio** references
353 **television** clips
87 **online** articles
10 **print** articles
& 2906 **YouTube** plays
GW170817
Australian Research Council Centre
Gravitational Wave Disc

OzGrav's Instrumentation Program
- Making aLIGO better, and beyond

- Instrumentation Theme (Leader David McClelland)
  - Quantum
    - Quantum Squeezing (sacrifice knowledge of amplitude for phase)
  - Low Frequency
    - Noise elimination
  - Instabilities and Distortions
    - Higher fidelity
  - Space
    - LISA resurrected
  - Radio
    - Pulsar Timing Instrumentation





OzGrav

OzGrav's Data Program

- Data Theme (Leader Eric Thrane)
  - LIGO Pipelines (Melatos/Wen/Thrane/Scott)
    - Rapid Detection
    - CW sources
    - Parameter Estimation
    - Stochastic Background
  - Supercomputing (Hurley)
    - New Supercomputer@swin.edu.au
    - AAL/Swinburne 4M machine (OzSTAR)
    - >1 Petaflops!
  - High-throughput signal processing
  - Machine Learning
  - Advanced Visualisation

Some Immediate Priorities:

- Access to O1, O2, O3 data
  - O3 is imminent!!! Feb 2019….
- GWCloud – GW analysis usable by mere mortals
- Monash’s BILBY parameter estimation code adopted for O3
  - Speed to parameters – like where is it?!
  - User-friendly portals
  - Performance optimisations
- Wen’s (UWA) SPIIR GW detection pipeline
  - Lowest-latency GW detector (GPU-based time domain code)
  - “negative latency” – position before event peaks
- Pulsar timing arrays (CSIRO/Swin/Monash/UWA)
  - Wideband receivers produce 1000’s channels (PKS UWB, MeerKAT, SKA)
    - (really) Poor IO performance with existing codes – needs parallelisation, optimisation, GPUisation
- Continuous wave data analysis (Melbourne/ANU/Monash)
  - Finding GWs from MSPs, x-ray binaries
- Optical pipelines/prioritisation for BNS detection

GW Data Processing

- LIGO Data Processing Centres
  - Tier 1: (US Facilities)
    - Responsible for data acquisition (US)
    - Future (India)
  - Tier 2: ~~(80% in Germany!)~~
    - Responsible for offline processing
    - High availability standards
    - World-wide resource
  - Tier 3:
    - Shared-risk facilities

- >Petabyte Tape Libraries
- High availability PB Storage Arrays
- Supercomputer support staff
- Code Optimisation
- Security patching
- Periodic (4-5 yr) upgrades

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    - World-wid
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    - Shared-risk fa

Goal: Establish an Australian GW Data Processing Centre

- >Petabyte Tape Libraries
- High availability PB Storage Arrays
- Supercomputer support staff
- Code Optimisation
- Security patching
- Periodic (4-5 yr) upgrades

OzSTAR Supercomputing

- Successor to g2/gSTAR

- 4140 Intel SkyLake cores
- 230 NVIDIA P100 GPUs
- 5.1PiB lustre filesystem
- 100 Gbps OmniPath network

- Available now

SWINBURNE UNIVERSITY OF TECHNOLOGY

Astronomy Australia Ltd.

ADACS ASTRONOMY DATA AND COMPUTING SERVICES

OzSTAR

Standard Compute Nodes (107)

Dell R740 14G Server
2 x Intel Xeon Gold 6140 18-core processors
2 x NVIDIA P100 12GB PCI-e GPUs
192 GB DDR4 RAM (12 x 16GB)
400 GB SSD

Data-Crunching Nodes (8)

4 x 384 GB RAM, 4 x 768 GB RAM
2TB NVMe flash SSD

Xeon Phi (KNL) Nodes (4)

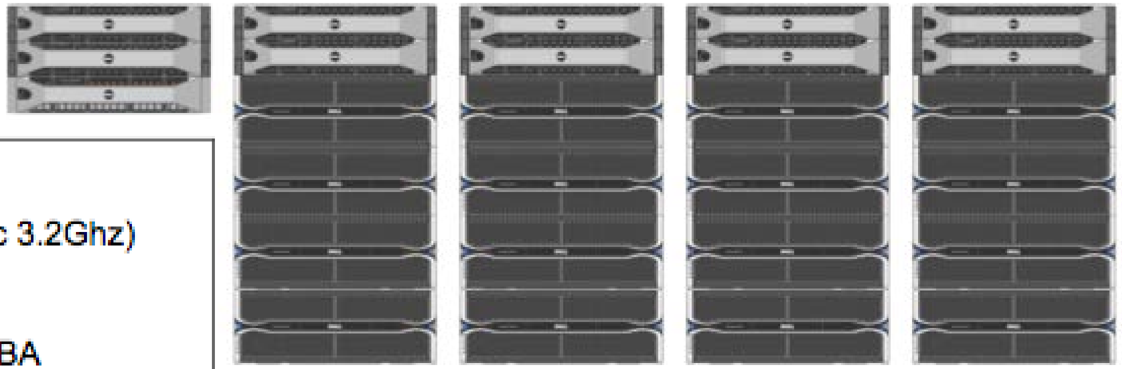
4 x 68-core Xeon Phi PowerEdge C6320p

Management Nodes (2), Login Nodes (2)

	P100	K10
Double-precision	4.7 Tflops	
Single-precision	9.3 Tflops	4.6 Tflops
Half-precision	18.7 Tflops	-
Memory	12 GB	2 x 4 GB
Memory Bandwidth	549 GB/s	160 GB/s
Simpler programming with page migration engine		
High bandwidth memory with 3D stacked DRAM		
Optimised for mixed workload HPC		
ECC protection for reliability		
GPUDirect over RDMA		

OzSTAR

Storage



2 x PowerEdge R740 Servers

- 2 x Intel Xeon 6134 CPUs (8c 3.2Ghz)
- 24 x 32GB DIMMS (768GB)
- 1 x Dual Port 12Gbps SAS HBA
- 2 x 400GB SSD Boot drives

1 x PowerVault MD3420

- 12 x 800GB SAS SSD

2 x PowerEdge R740 Servers

- 2 x Intel Xeon 4114 CPUs (10c 2.2Ghz)
- 12 x 16GB DIMMS (192GB)
- 4 x Dual Port 12Gbps SAS HBA
- 2 x 400GB SSD Boot Drive

4 x PowerVault MD3060E

- 240 x 8TB NL-SAS drives (60 per)

Intel Community Lustre 2.10, OpenZFS

Raid z3

5 PiB (= 5 x 2^{50} bytes ~ 5.6 PB) => 5.2 PB

30 GB/s sustained aggregate r/w
500 MB/s sustained single process/file

OzSTAR

Interconnect

- 100 Gb/s OmniPath non-blocking, low-latency
- 3 core switches, 6 edge switches, 144 ports

Operating System

- CentOS 7.4

Scheduler

- Slurm Workload Manager

Performance

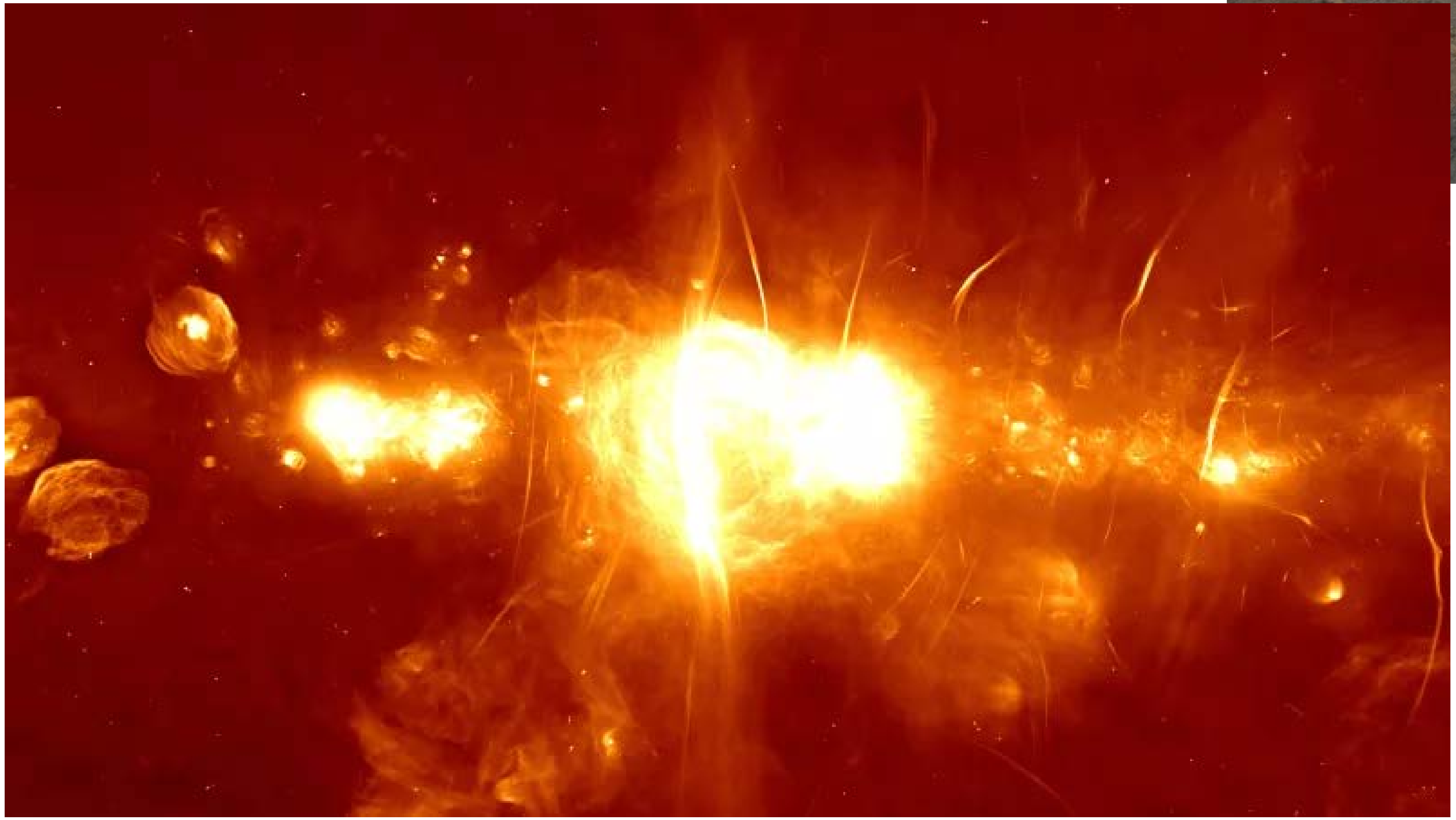
- 1.25 Pflops (DP) ... x2 (SP) ... x4 (half)

Gravitational Wave Astronomy's Future

- Add VIRGO (soon), KAGRA (3y), LIGO-India (6y)
  - Positions "better"
- Beyond 2G Detectors
  - 3G = 10x more sensitive (to *h*) 1000x volume
    - GWIC working group science case
  - 1 event/month – 10^{6+} events/year!
    - EoS of nuclear matter, Ho, Dark Energy, birth/merger rates, ns masses, BH seeds etc
- SKA-mid
  - G/T ~ 25x PKS – 625x as many pulsars/hour at same SNR as PKS
- LISA
  - Space-based GW detectors

OzGrav

SKA and MeerKAT



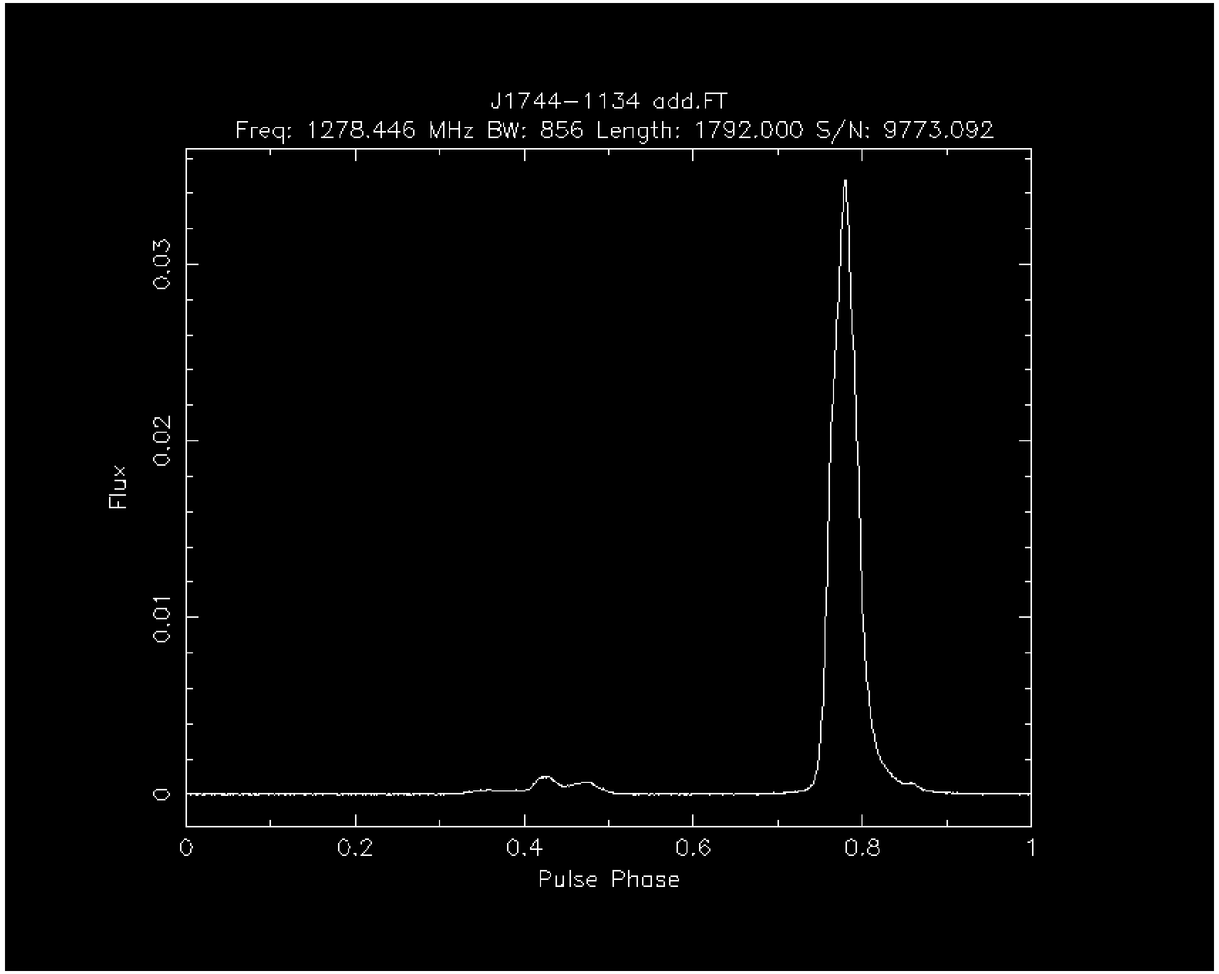
MeerKAT early results:

Dai et. al. 2015 (Parkes)

4,600 in 5.4 day integration

MeerKAT/MeerTime data

9,773 in 30 minutes!



Pulsar Timing with MeerKAT/ MeerTime