INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

LIGO–India Scientific Collaboration

Gravitational Waves: A New Window to the Universe

Bala Iyer

ICTS-TIFR, Bangalore

ICFA School

TIFR, Mumbai

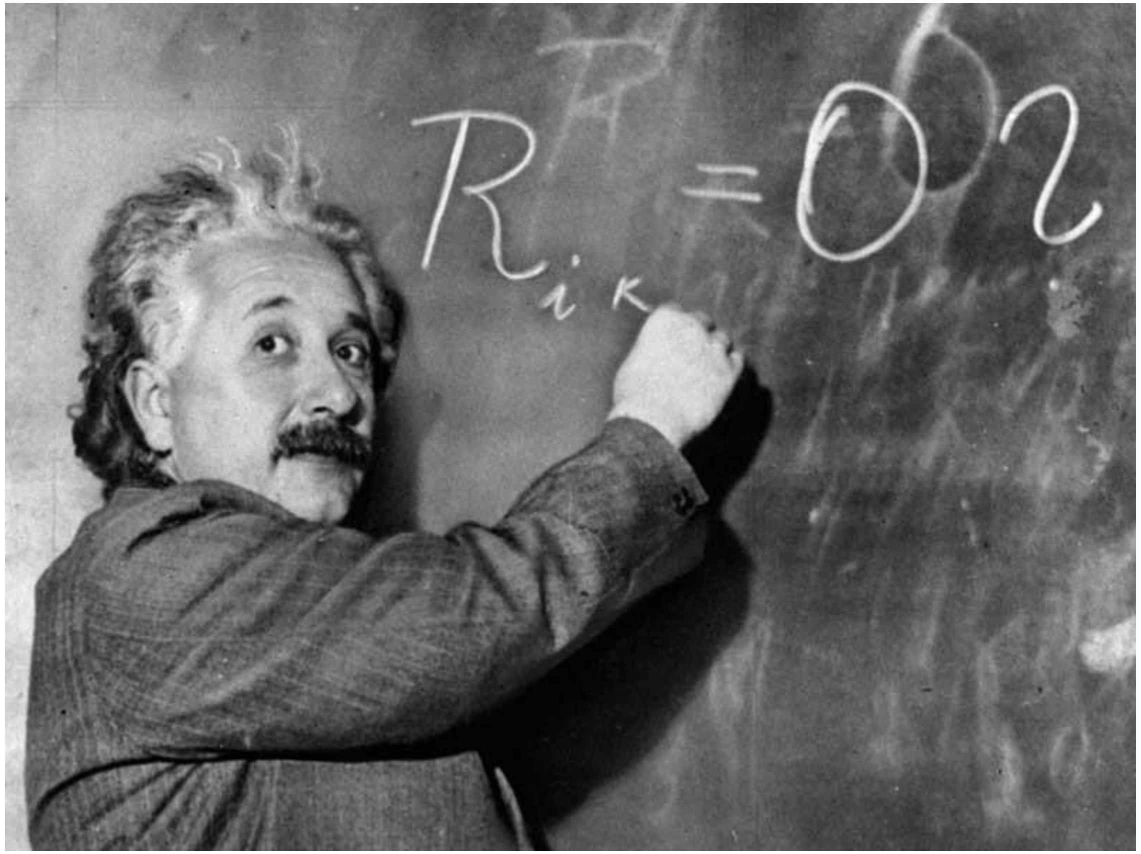
23 Feb 2023

Part I

Gravitational Waves

A Primer

General Relativity (25 Nov 1915)
Einstein's Relativistic Gravity



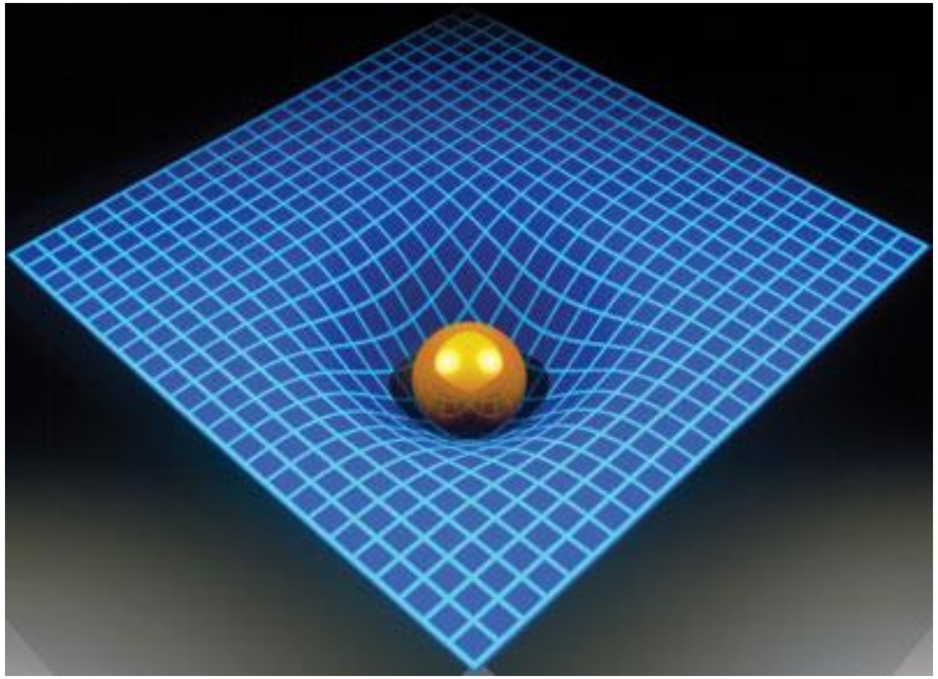
Epitome of

Mathematical elegance,

Conceptual depth,

Observational success

General Relativity (1915)
Einstein's Relativistic Gravity



credit: www.chicagonow.com

Einstein's view ~

Gravitation ~

Spacetime Geometry ~

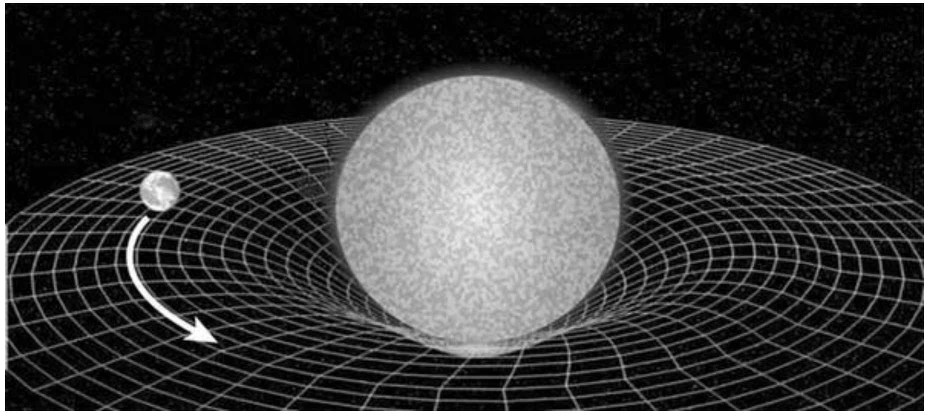
Curvature or

Distortion of Spacetime

Einstein’s Equations

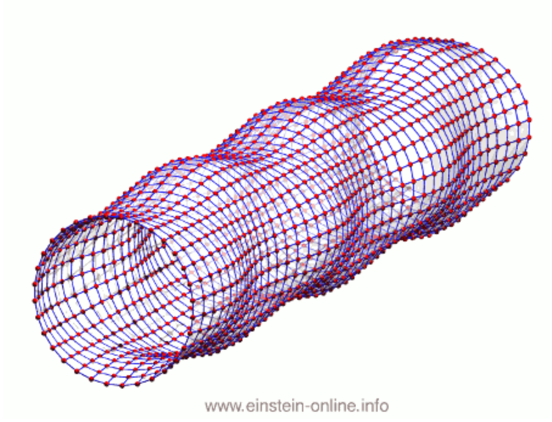
Matter tells spacetime
how to curve,

Spacetime tells matter
how to move



Gravitational Waves

- Gravitational Waves are Freely Propagating oscillations of the Gravitational field
- Physically, gravity manifests as a tidal effect.
- GW are oscillating tidal gravitational fields which propagate out from the source.



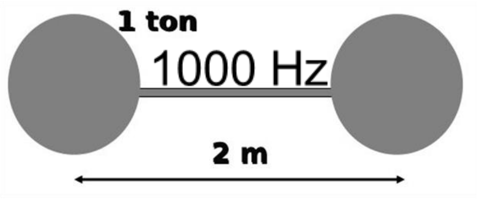
- Do Einstein's equations have GW solutions just as Maxwell's equations have EMW solutions?

Gravitational Waves

- GW predicted by Einstein in 1916 as an important consequence of General Relativity using Linearized gravity.. Quadrupole formula in 1918 (~ dipole formula in EM)

$$\boxed{h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}}$$

$$h \approx \frac{\varphi_{\mathrm{Newton}}}{c^2}\frac{v^2}{c^2} = \frac{Gm}{Rc^2}\frac{v^2}{c^2}$$



$h \approx 10^{-39}$

- "must have a practically vanishing value in all conceivable situations … Such ripples would be vanishingly small and nearly impossible to detect .." Einstein

The Babel

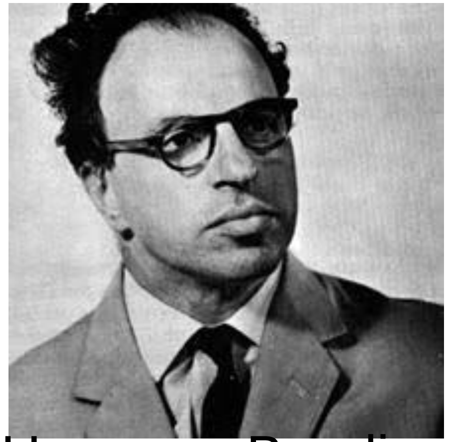
- 40-50 years for a conceptual framework to determine without ambiguity if GW exist in GR and what properties they have

Do GW transfer energy or are merely an illusion due to the choice of wavy-coordinates ?!

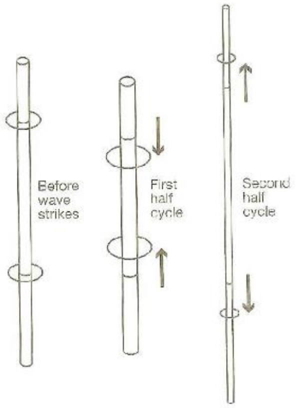
Looking Sideways

The Insight & The Search

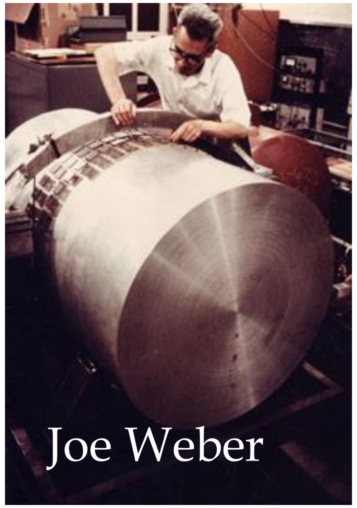
Felix Pirani



Hermann Bondi



Sticky Bead



Joe Weber

Chapel Hill (1957)

Pirani: Tidal effect of GW unambiguous (Geodesic deviation).

Discussions “sticky bead ” with Bondi: Physicality of GW resolved.:

Joe Weber decided to build a Bar detector & Quest for GW detection born

GW in (nonlinear) GR: Bondi, Metzner, Sachs, Chandrasekhar

Chandrasekhar and GW

- 1960s: Chandrasekhar: Radiation Reaction problem.

  How does emission of GW effect a emitting system if it is self gravitating?
- Chandra was first to show conceptually that radiation reaction problem could be solved for continuous physical systems. Following Trautman assembled essential ingredients: Landau-Lifshiftz pseudotensor to include non-linearities of Grav field, retarded potential and near zone expansion to implement outgoing BC.
- Energy and AM radiated as GW was correctly balanced by loss of mechanical energy and AM (Chandra, Esposito)
- Gave astrophysicists confidence that GR was physically reasonable and well behaved.

Resonant Bar detectors

Narrow-band

(1960)

Laser Interferometers

Broad-band,

[2010]

The Tragic Pioneer

1969 claim of GW detection

50 years

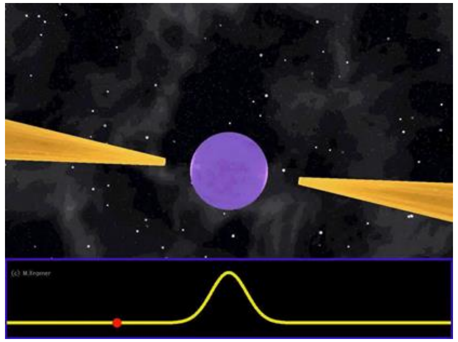
Supernova

Coalescing Compact Binaries

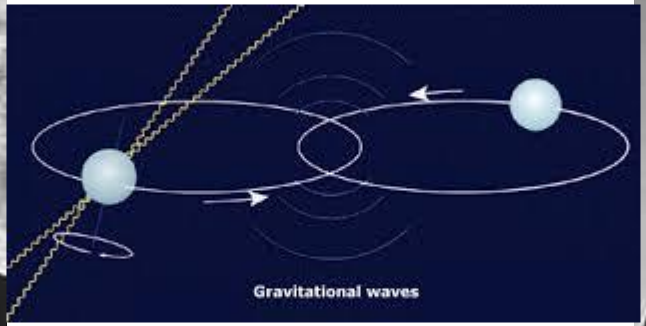
1978, Batelle Conference
Clarke et al

Neutron, Neutron stars,
Pulsars as Celestial Clocks

- 1932: Chadwick discovers Neutron.
- 1931 (?)/ 1932 Neutron Stars: Landau
- 1933: Neutron Stars are end states of SN explosions (Baade, Zwicky).
  Oppenheimer-Volkoff Limit (1939)
- Mass ~ 1-3 Msun, Radius 10-15 km, Nuclear densities
- 1967: Serendipitous discovery of Pulsars by Jocelyn Bell and Tony Hewish. Pulsars are Rotating Neutron stars



Celestial Dumbell of 2 Neutron Stars



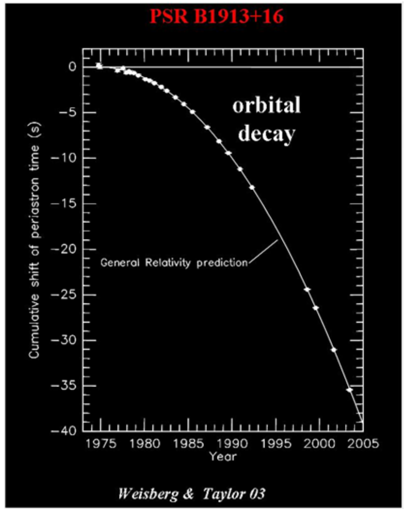
R. Hulse

J. Taylor

- Discovered in 1974 Binary Pulsar 1913+16

- If General Relativity is right, this system must emit GW and spiral inwards (Radio Pulsar Timing)

J. Weisberg and J. Taylor, 1982



"discovery of new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

1993

A watershed event in our story since it demonstrated GW are physical, accurately described by Einstein's General Relativity

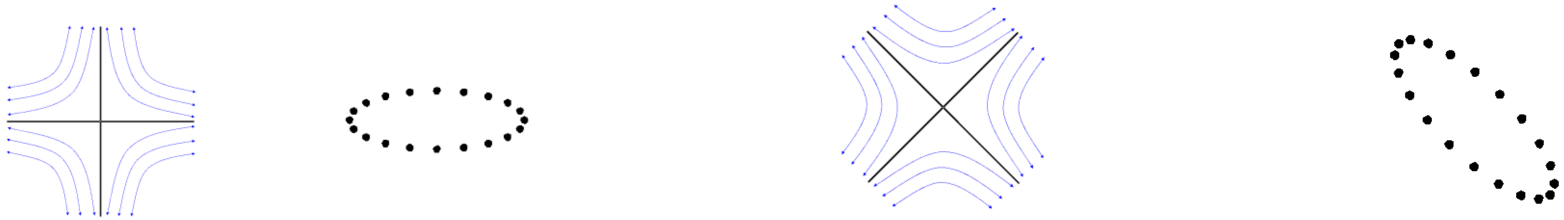
and Coalescing Compact

Neutron Star Binaries could

be Prototypical sources for Laser Interferometer GW Detectors

Effect of GW

- For GW in GR, Tidal Force Field Oriented like Plus or Cross

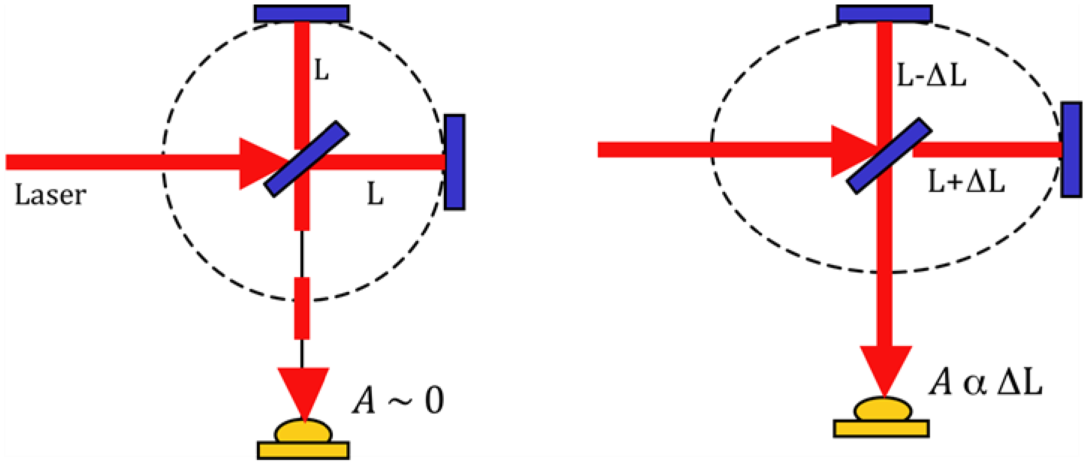


- If GW incident normally on a ring of particles, it would be tidally stretched and squeezed in an oscillatory time dependent manner

- To detect GW we must measure the amount of squeeze

GW Strain

- GW Strain h: If two test particles are initially separated by distance L and if a GW signal passing through changes the separation by ΔL,
- $h = \Delta L / L$



- For a fixed strain, (h), Bigger the device (L) BIGGER the displacement/Squeeze (ΔL)

Strong Sources, Feeble Strains
Twin Challenges

- BNS system of 2 M_{sun} (10^{30} kg) moving at velocities close to light in Virgo cluster (18 Mpc) $h \approx 10^{-21}$.

In km scale Interferometer causes 10^{-18} m displacement (change in path length) affecting the fringe pattern.

The miniscule strain and tiny displacement (1/1000 fermi) must be measured to detect the GW.

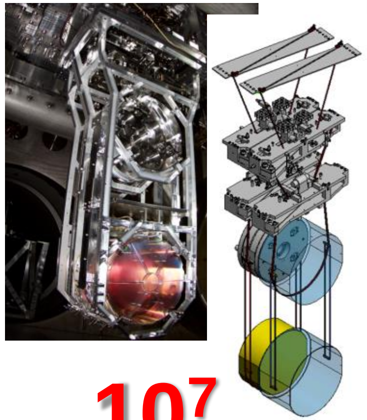
Interferometer acts as a Transducer converting GW to photocurrent proportional to the strain amplitude

- Michelson Morley Special Relativity Expt 5×10^{-9} m
  - Seismic motion ~ Nanometer to be reduced by 10^{10}

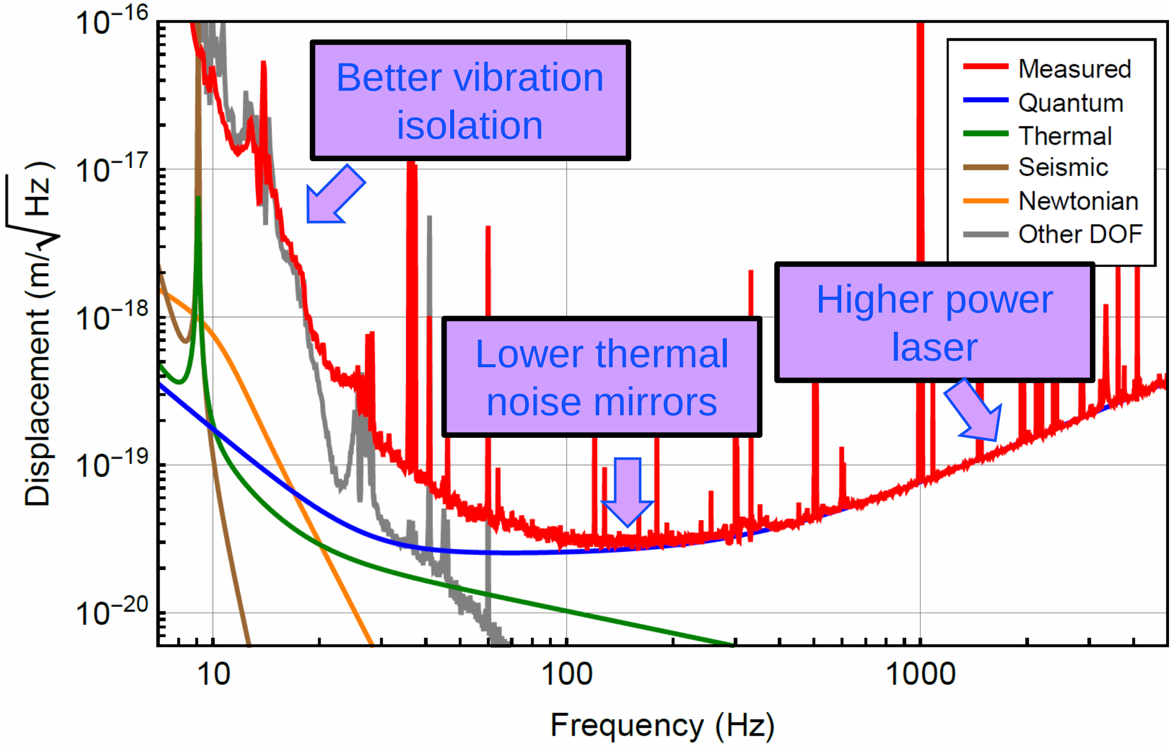
Keys to higher sensitivity in Advanced LIGO

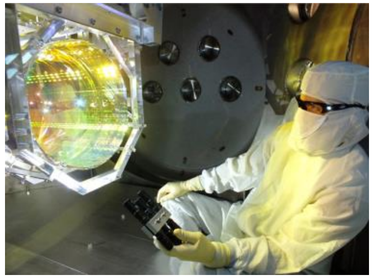
Need to beat number of fundamental and technical noise sources that affect measurement at sub-nuclear length scales.

10^3



10^7





Slide credit:
Stan Whitcomb

10,000 m^3 vacuum at 10^{-9} Torr

> 300 control loops to keep Interferometer optimally running!

Instrument Science at Frontiers of Physics Fundamental Limits

Every single Technology they're Touching they're Pushing &
there's a lots of Technologies they're Touching - Beverly Berger

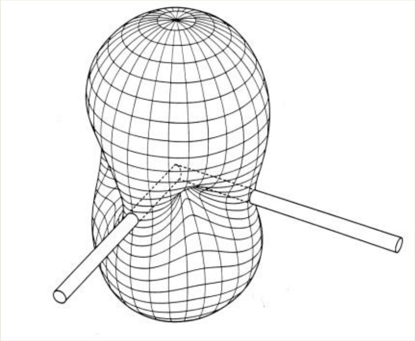
Credit: LIGO-Lab

LIGO: Two sites.
Three Detectors

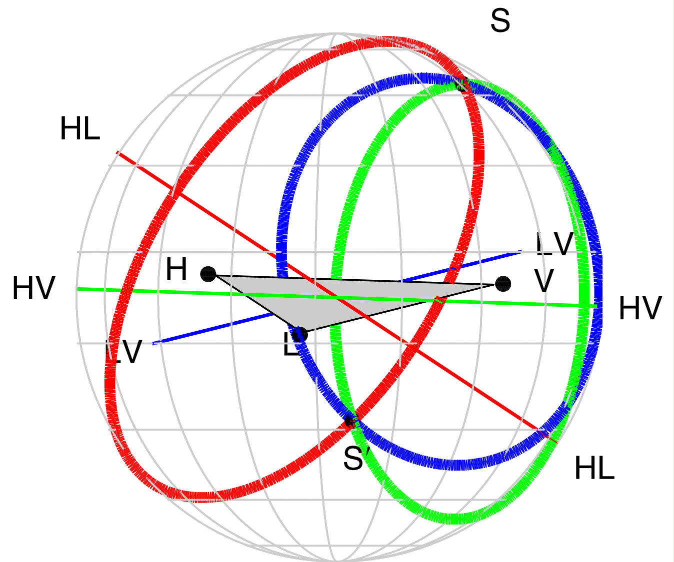
Physical Environmental Monitors:
Observatories deploy seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-powerline monitors, cosmic ray detectors for vetos and characterization of couplings.

Coincident detection between 2 LIGO Observatories used to reject transient environmental disturbances

LOCALIZATION



- Interferometers have broad directional response.
- Like Ears rather than Eyes



[Courtesy: LIGO-G1200972-v3]

✓ **Requires Global Network of GW detectors**

✓ Triangulation using measured Time delays between sites

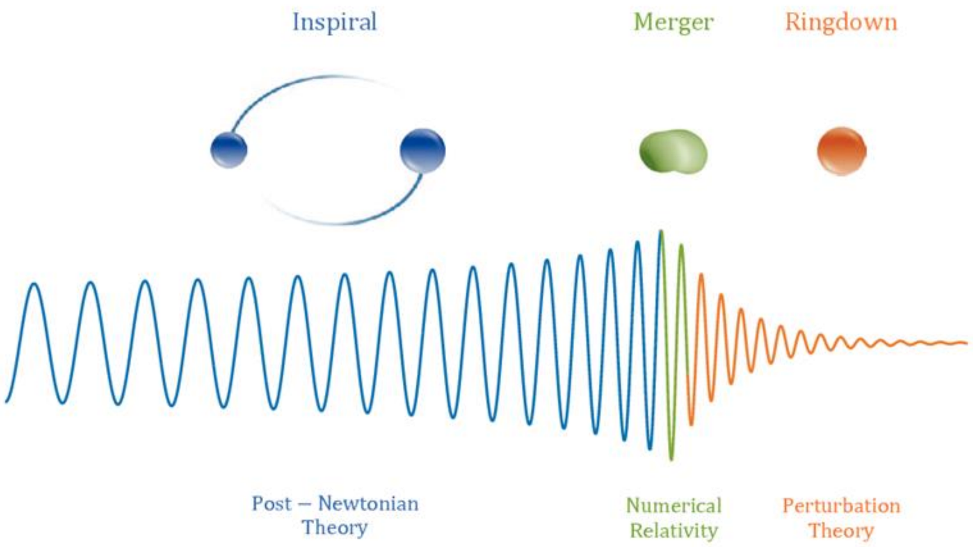
✓ Errors on TOA and Site location determine sky location uncertainty

✓ 2 sites – 1 time delay Localized Ring in Sky

✓ 3 Sites – 2 Time delays – Mirror images in Detector Plane

CHIRP to Coalescing Compact Binary

✓ ***Signal from a compact binary increases in frequency and amplitude (CHIRP) during inspiral until its plunge at its ISCO***



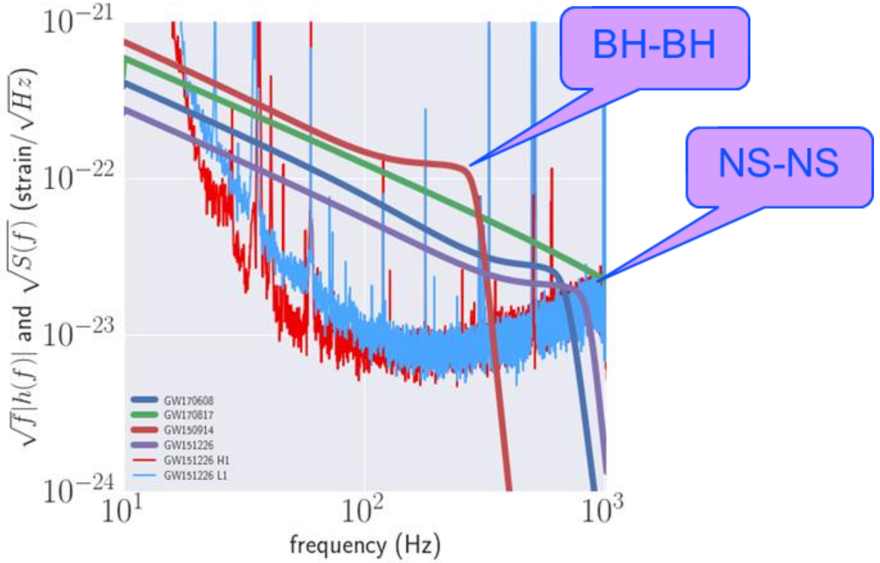


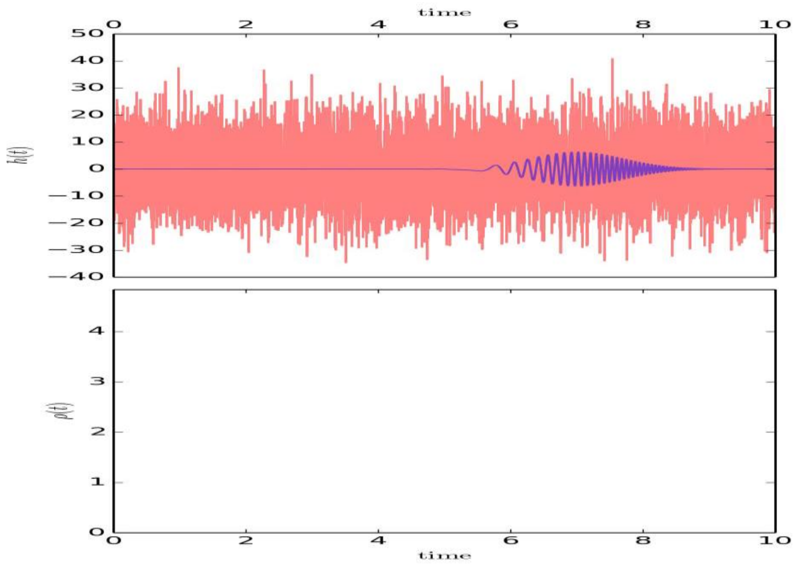
Fig credit
Javier M. Antelis et al, 2017.

$$F_{ISCO} \sim 220 \; \frac{20\, M_0}{M} \;\; \text{Hz}$$

Last Three Minutes: Issues in Gravitational wave measurements of Coalescing Compact Binaries; Cutler et al Phys. Rev.Lett 70 2984, (1993)

Source Modelling, Data Analyses

- GW are WEAK SIGNALS buried in LARGE NOISE of detector. Require Matched Filtering (MF) both for their Detection or Extraction and Parameter Estimation or Characterization.



Correlating a KNOWN SIGNAL with the NOISY DATA

✓Success of MF requires Accurate model of signal using GR.

✓Since Parameters of source unknown need a template Bank

Last Three Minutes: Issues in Gravitational wave measurements of Coalescing Compact Binaries; Cutler et al Phys. Rev.Lett 70 2984, (1993) For self-gravitating bodies ($GM/R \sim v^2$; Virial Theorem)

higher order Post Newtonian (v^2/c^2) calculations requires dealing with higher order non-linearities (G) of Einstein's Equations

$\nu = m_1 m_2/(m_1+m_2)^2$

$x = (G\, m\, \omega/c^3)^{2/3}$

Perturbative expansion in v/c

$$\begin{aligned}\phi = -\frac{x^{-5/2}}{32\nu}\Bigg\{ & 1 + \left(\frac{3715}{1008} + \frac{55}{12}\nu\right)x - 10\pi x^{3/2} \\ & + \left(\frac{15293365}{1016064} + \frac{27145}{1008}\nu + \frac{3085}{144}\nu^2\right)x^2 + \left(\frac{38645}{1344} - \frac{65}{16}\nu\right)\pi x^{5/2}\ln\left(\frac{x}{x_0}\right) \\ & + \left[\frac{12348611926451}{18776862720} - \frac{160}{3}\pi^2 - \frac{1712}{21}\gamma_E - \frac{856}{21}\ln(16\,x)\right. \\ & \left. + \left(-\frac{15737765635}{12192768} + \frac{2255}{48}\pi^2\right)\nu + \frac{76055}{6912}\nu^2 - \frac{127825}{5184}\nu^3\right]x^3 \\ & + \left(\frac{77096675}{2032128} + \frac{378515}{12096}\nu - \frac{74045}{6048}\nu^2\right)\pi x^{7/2} + \mathcal{O}\left(\frac{1}{c^8}\right)\Bigg\},\end{aligned}$$

Blanchet, Damour, Esposito-Farese, Faye, Iyer, Joguet…

See E.g. Blanchet, Living Rev. Relativity 17, 2 (2014)

1990 +

Source Modelling
Bala Iyer
RRI

GWDA
IUCAA
Sanjeev
Dhurandhar

Resummation, Effective one body, Numerical Relativity, IMR Phenomenological, Surrogates..

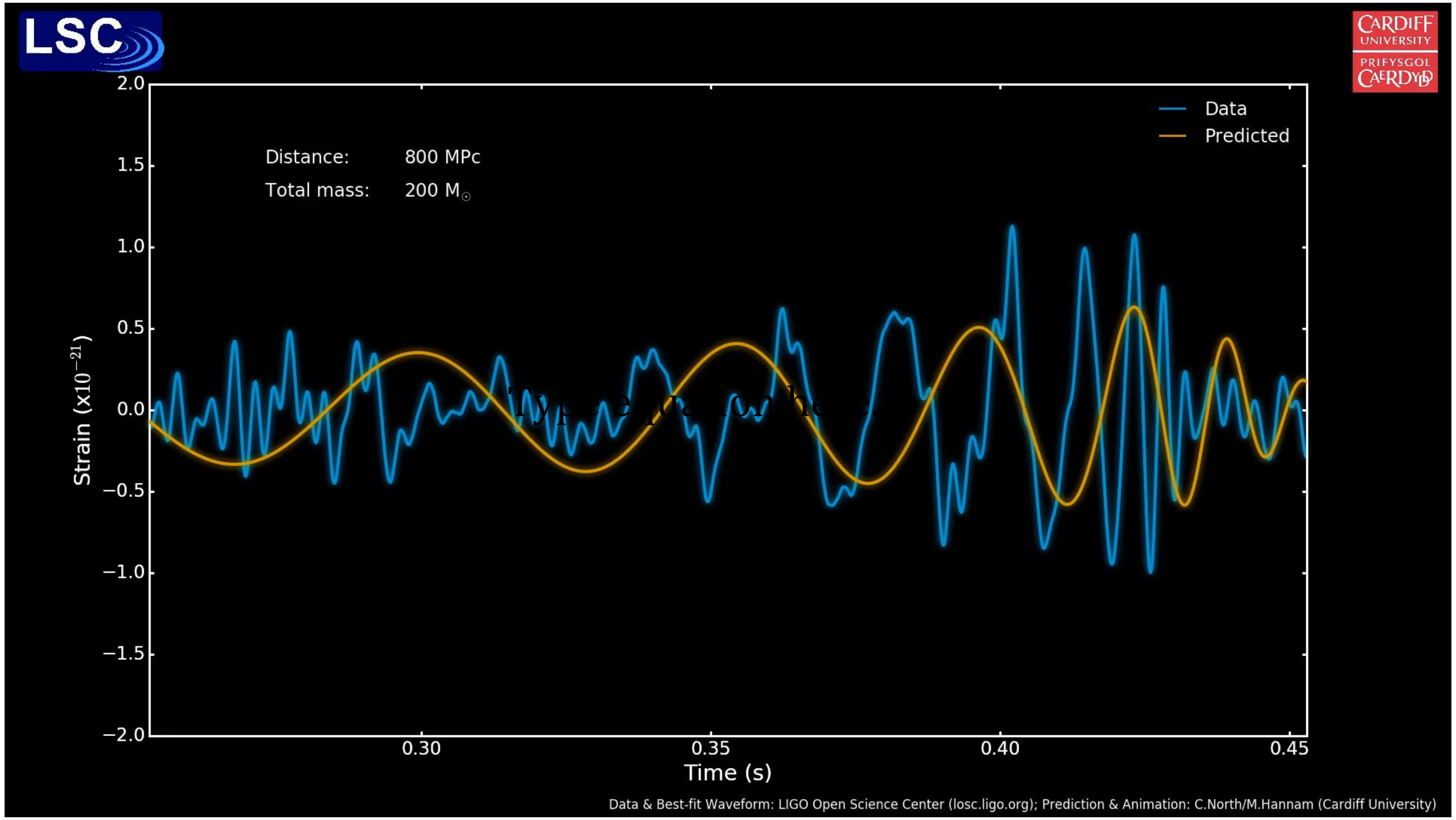
Damour, Buonanno, Nagar, Pretorius, Ajith …

Challenging Detector Calibration and Characterization

Raw Data → GW Signal →→Bayesian Parameter estimation

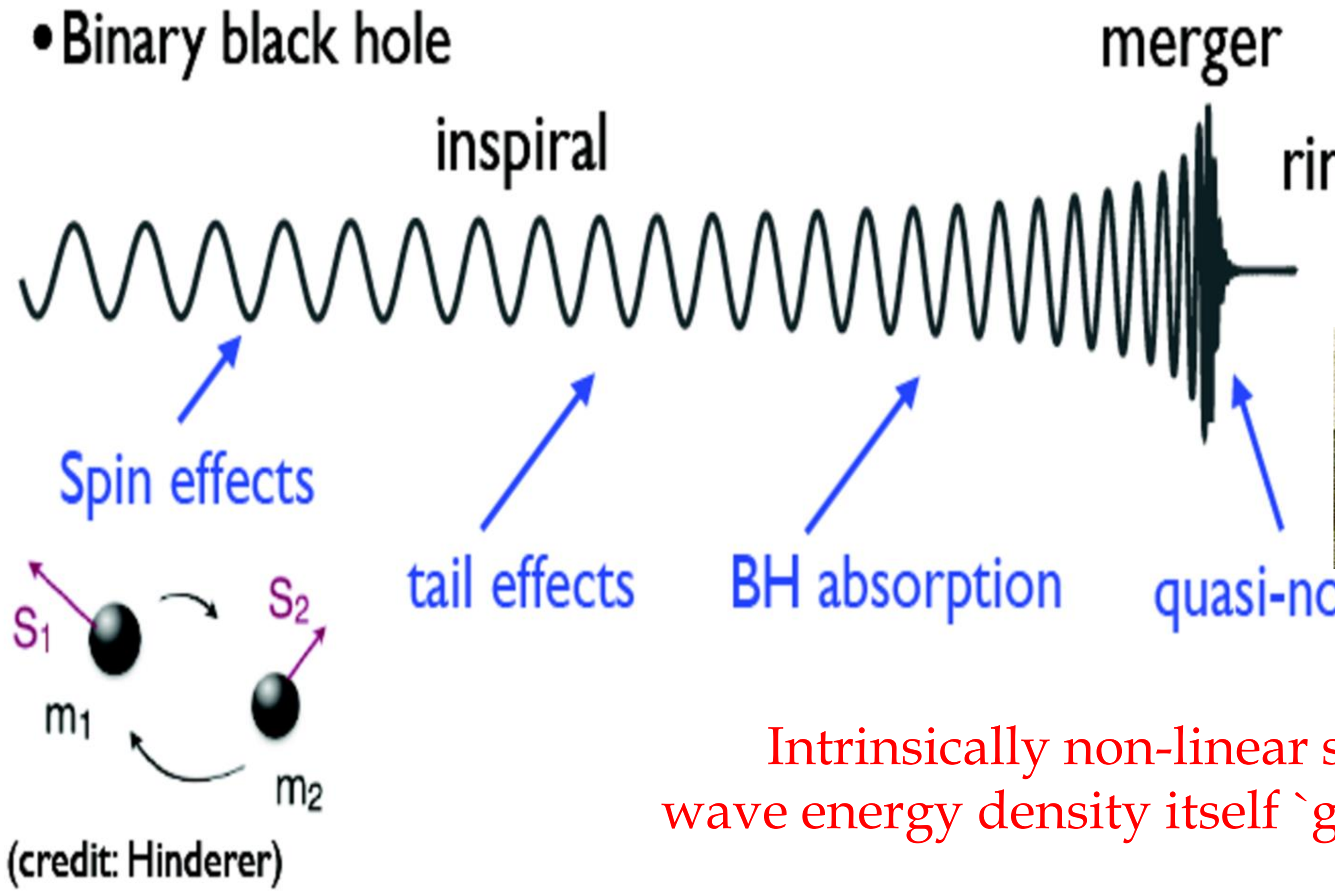
Challenging Detector Calibration and Characterization

Raw Data →
GW Signal →
Bayesian Parameter estimation



15 Parameters:
Masses (2) , Angular Momenta (6)
Distance(1) , Sky Location(2) , Relative location of Source and Detector (2)
Coalescence Time (1) and Coalescence Phase (1)

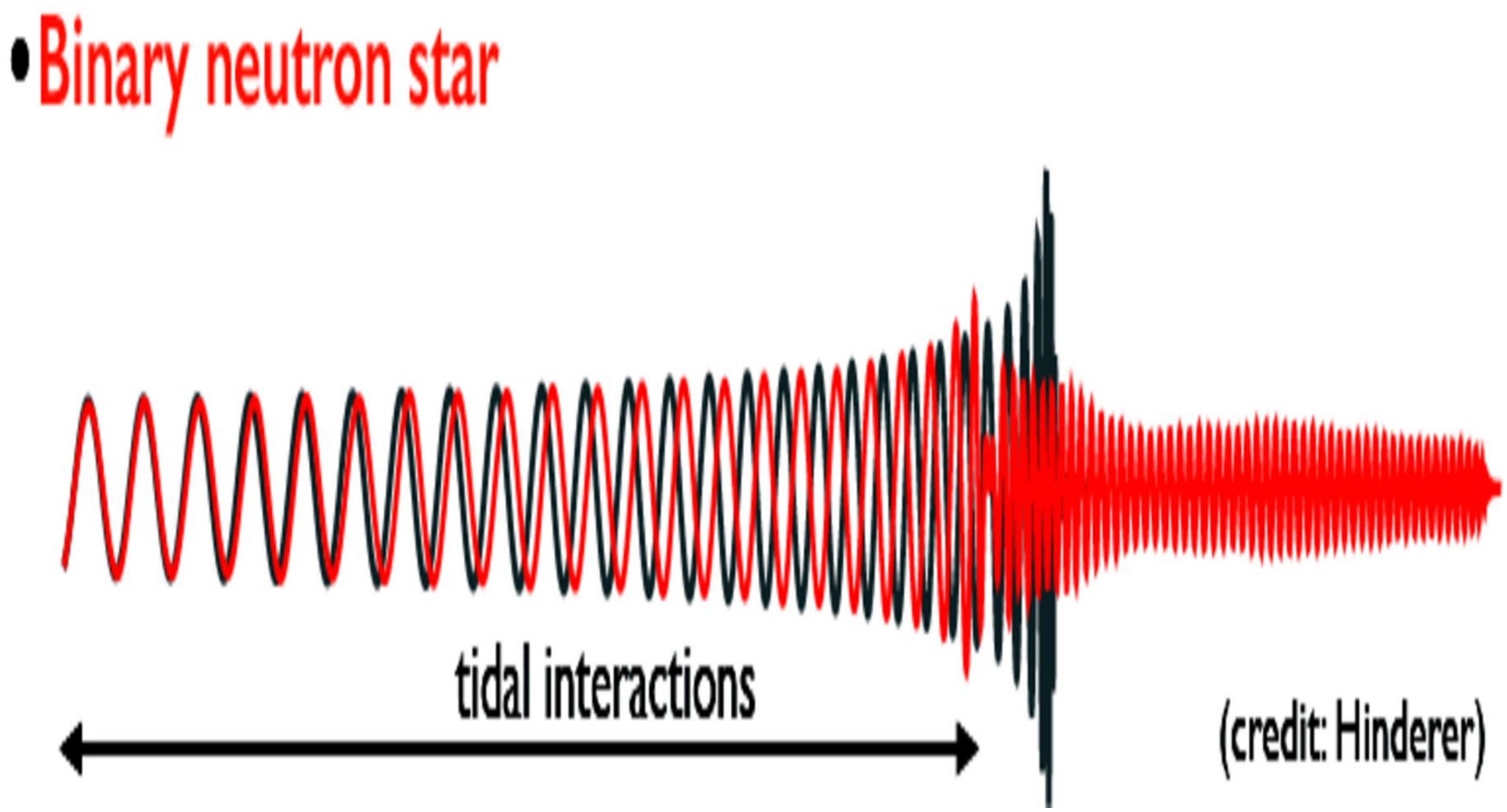
Binary black Hole



Vishveshwara

Intrinsically non-linear since
wave energy density itself `gravitates'

Binary Neutron Star



Tidal
Deformation
Depends on
Equation of
State of
NS matter

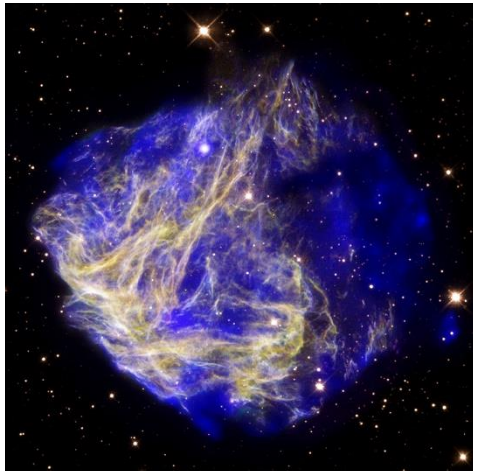
GW in Einstein's GR

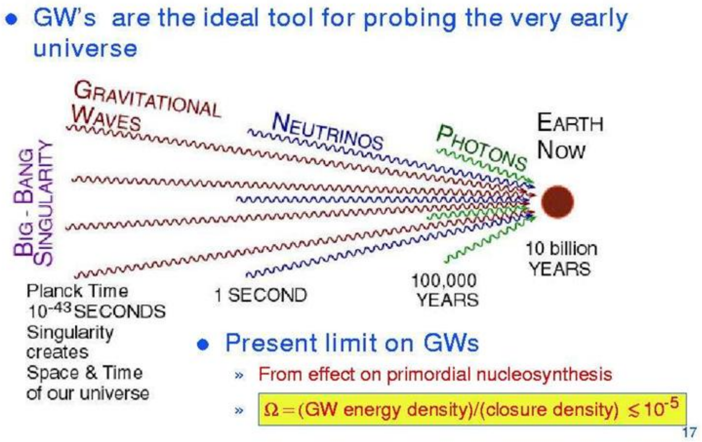
- In GR, as in EM,
  - GW travel with speed of light,
  - are transverse
  - have two states of polarization (+, x)
  - No Monopole or dipole radiation because of conservation laws of energy, linear and angular momentum

But, unlike EMW…

- GW propagate essentially unperturbed thro space as they interact weakly with matter.
- Observe GW from inside of Supernova or much closer to the Big Bang than EM (CMBR)

X-ray: (NASA/CXC/Penn State/S.Park et al.); Optical: NASA/STScI/UIUC/Y.H.Chu & R.Williams et al





- Properties of the GW can be different in different theories of gravity..
- Possibility to Test Einstein's General Relativity

PART II

The First Direct Detection of Gravitational Waves GW150914

O1

Sept 12 2015 - 4 months

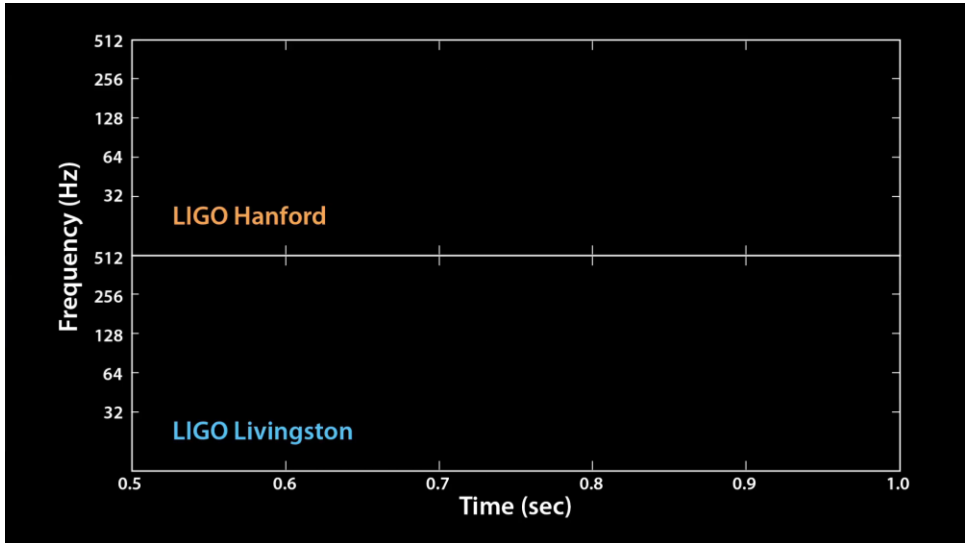
LIGO Scientific Collaboration

Acknowledgement

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

On Sept 14 2015 at 09:50:45 UTC

- Two LIGO observatories in Hanford and Livingston (USA)detected a coincident gravitational-wave signal.



- Signals arrived in the two detectors within ~7 milliseconds.

Combined signal-to-noise ratio 24.

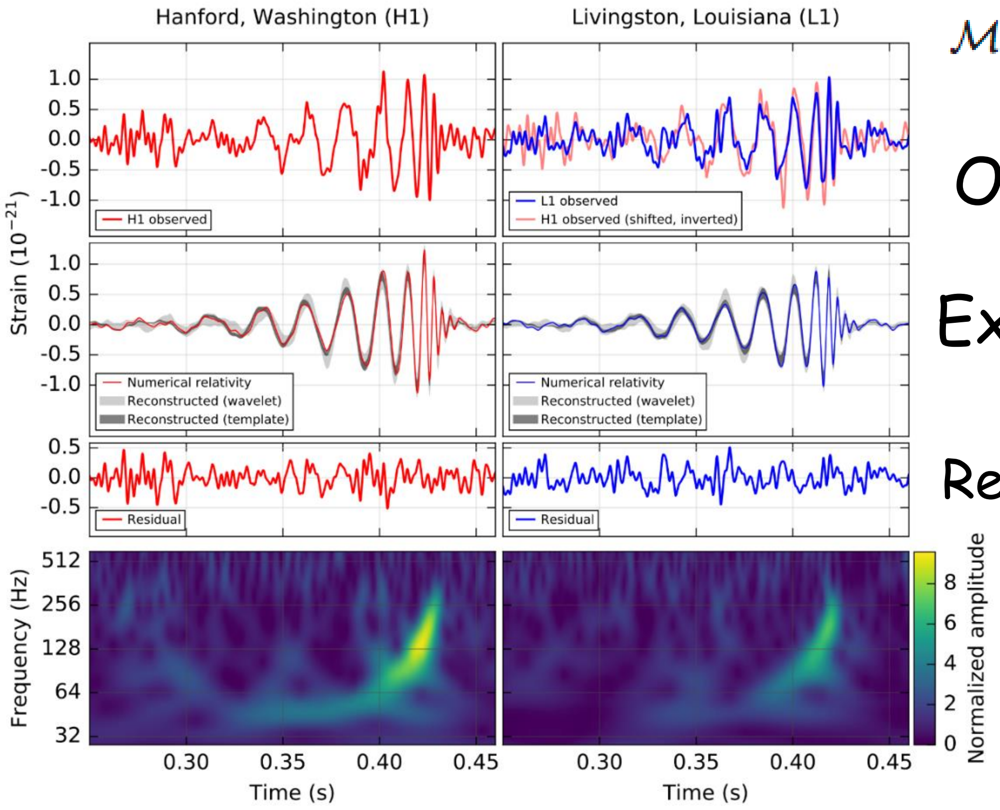
[Phys. Rev. Lett. 116, 061102 (2016)]

Estimated Parameters
GW150914

Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Phys. Rev. Lett. 116, 061102 (2016)

The Observed Signal



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

Observed Data

Expected Signals

Residuals Consistent with noise

GW150914:
SNR=24 (very loud!),
~8 GW cycles, ~0.2 sec.

Consistent with a signal expected from the coalescence of two black holes
Source information uniquely encoded in Phase/amplitude evolution

Phys. Rev. Lett. 116, 061102 (2016)

First discovery
Astrophysical Implications

- First Direct Detection of GW (Phys. Rev. Lett. 116, 061102 (2016))
- First detection of a binary black hole, that merges within the age of the Universe
- First observation of stellar-mass black holes with mass $\gtrsim 25 M_{\odot}$
- Points to an environment of weak massive-star winds

  $\rightarrow$ low metallicity.
- Test of GR in dynamic strong field regime

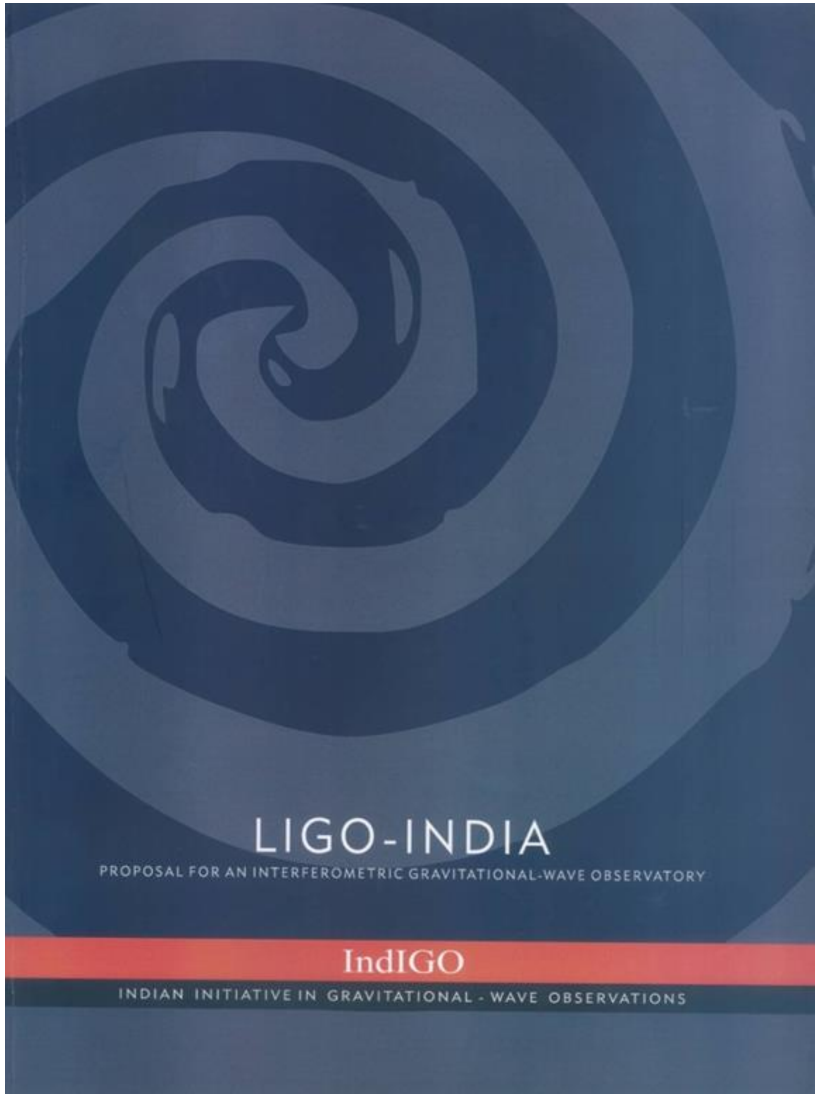
  [PRL 116, 221101 (2016)]

First discovery
Implications

- GW came from a Binary BH system at cosmological distance.
- Emitted 1.3b yrs ago when on earth transition was happening from single cell to multicellular forms of life!!
- Discovery Paper (11 Feb 2016)

had 37 Authors from Indian Institutions

and Citations to Seminal papers including Indian Researchers



In Principle approval of LIGO-India
Feb 17, 2016

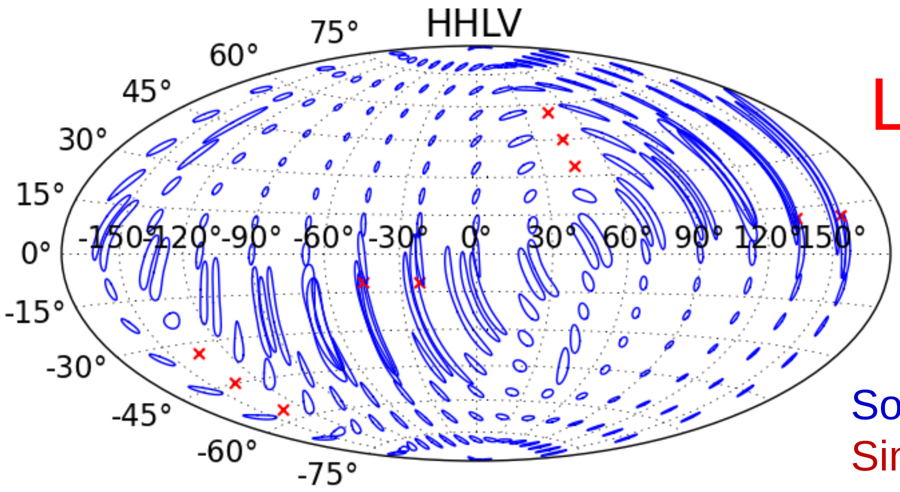
IndIGO Consortium (2009)

Extend Indian footprint in GW Source Modelling at RRI and GW Data Analyses at IUCAA over 2 decades to Pan Indian GW Expt

LIGO-India Proposal (2011)

LIGO-India (2030)

RRCAT, IPR, IUCAA, DCSCEM

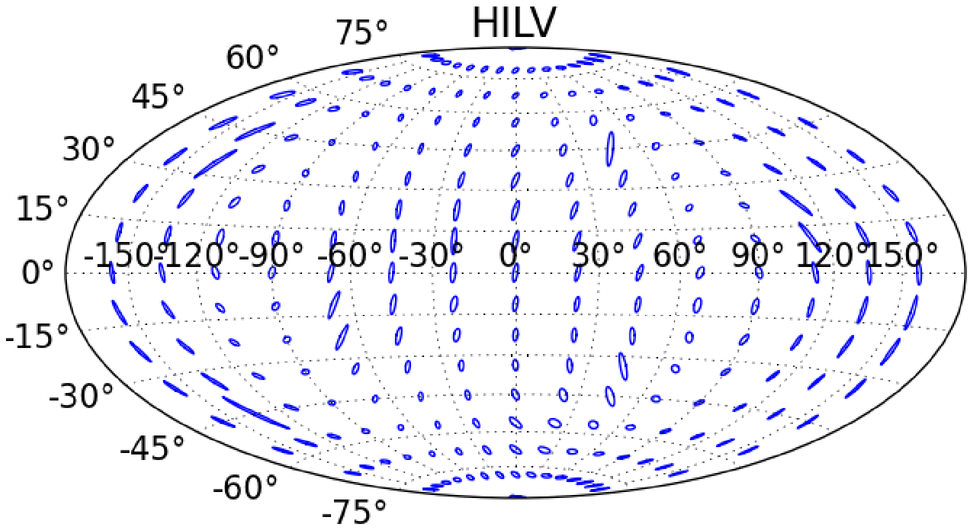


Localization poor for sources in and close to plane with LIGO-Virgo network

Source localization error – Courtesy Steve Fairhurst

Similar results: Sathyaprakash; Klimenko & Vedovato

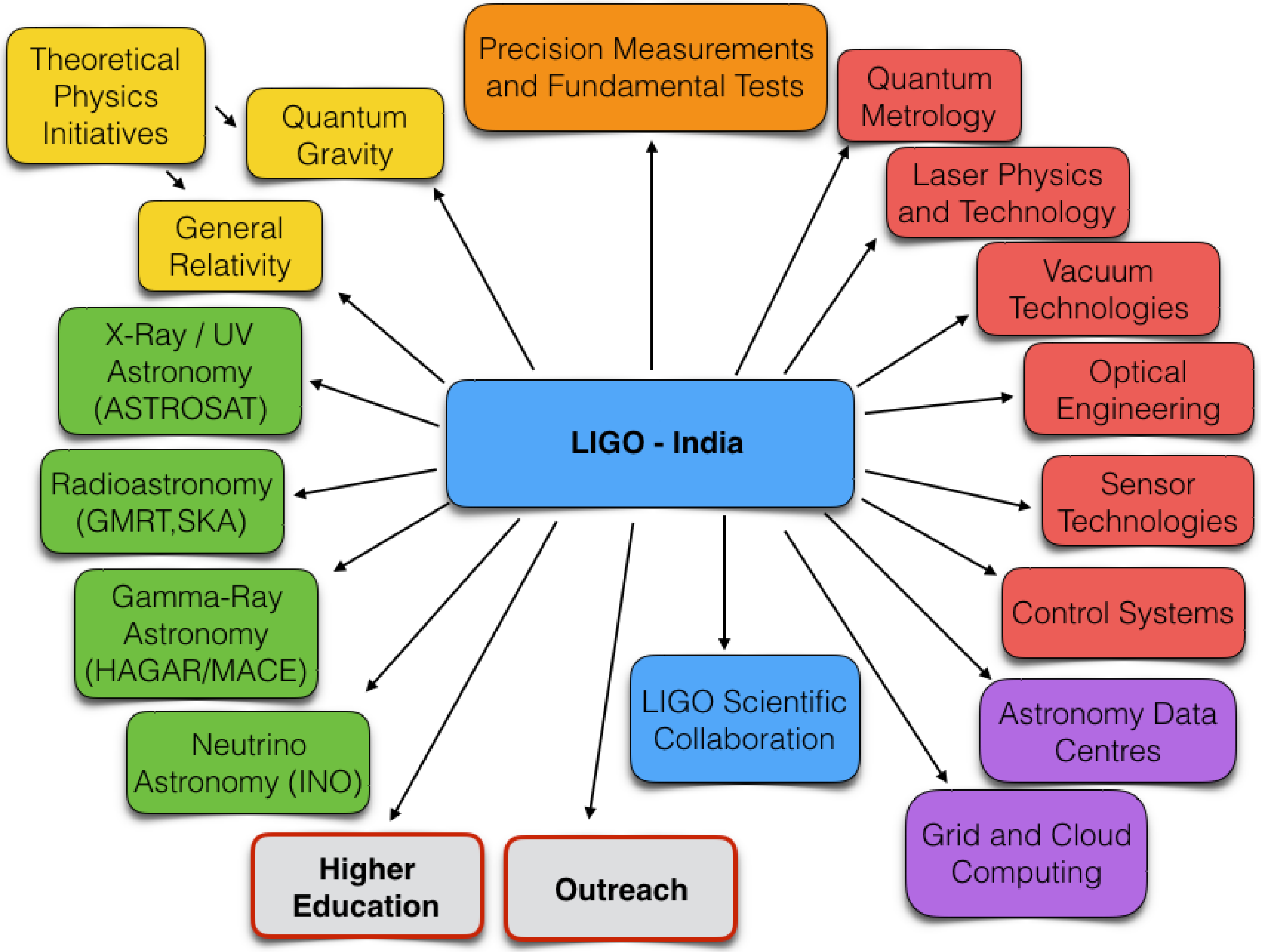
Source Localization if the second Hanford detector Is moved to a location in India (LIGO-India)



The Science Case for LIGO-India
arXiv:2105.01716
Class. Quantum Grav. 39 025004 (2022)

✓**Inclusion of LIGO-India would improve angular resolution on average by four times and in some directions by a factor of 10-20**

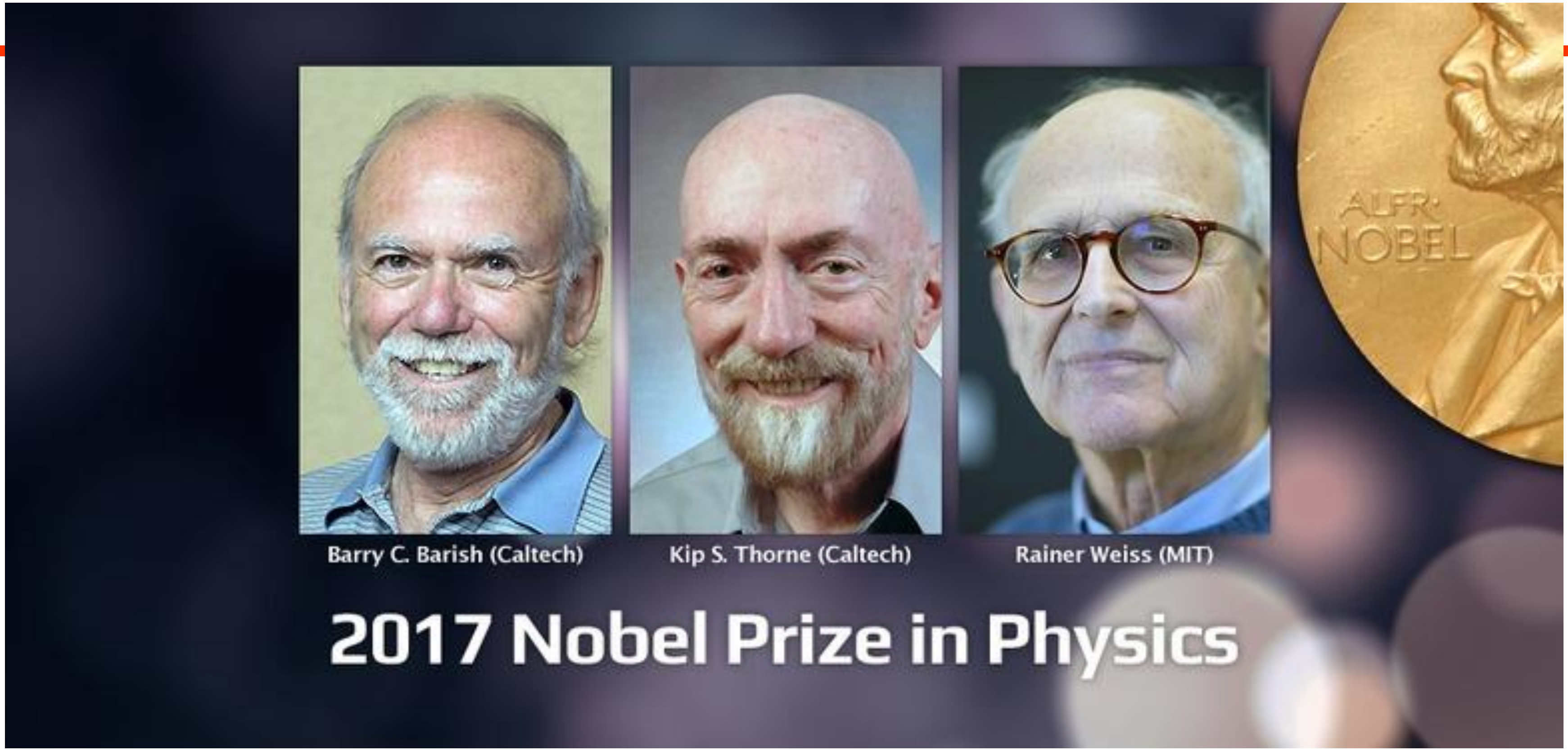
Highly Multi-disciplinary Astro^{++}



Every Technology they are Touching, they are Pushing
and there are a lot of Technologies they are touching. – Beverly Berger

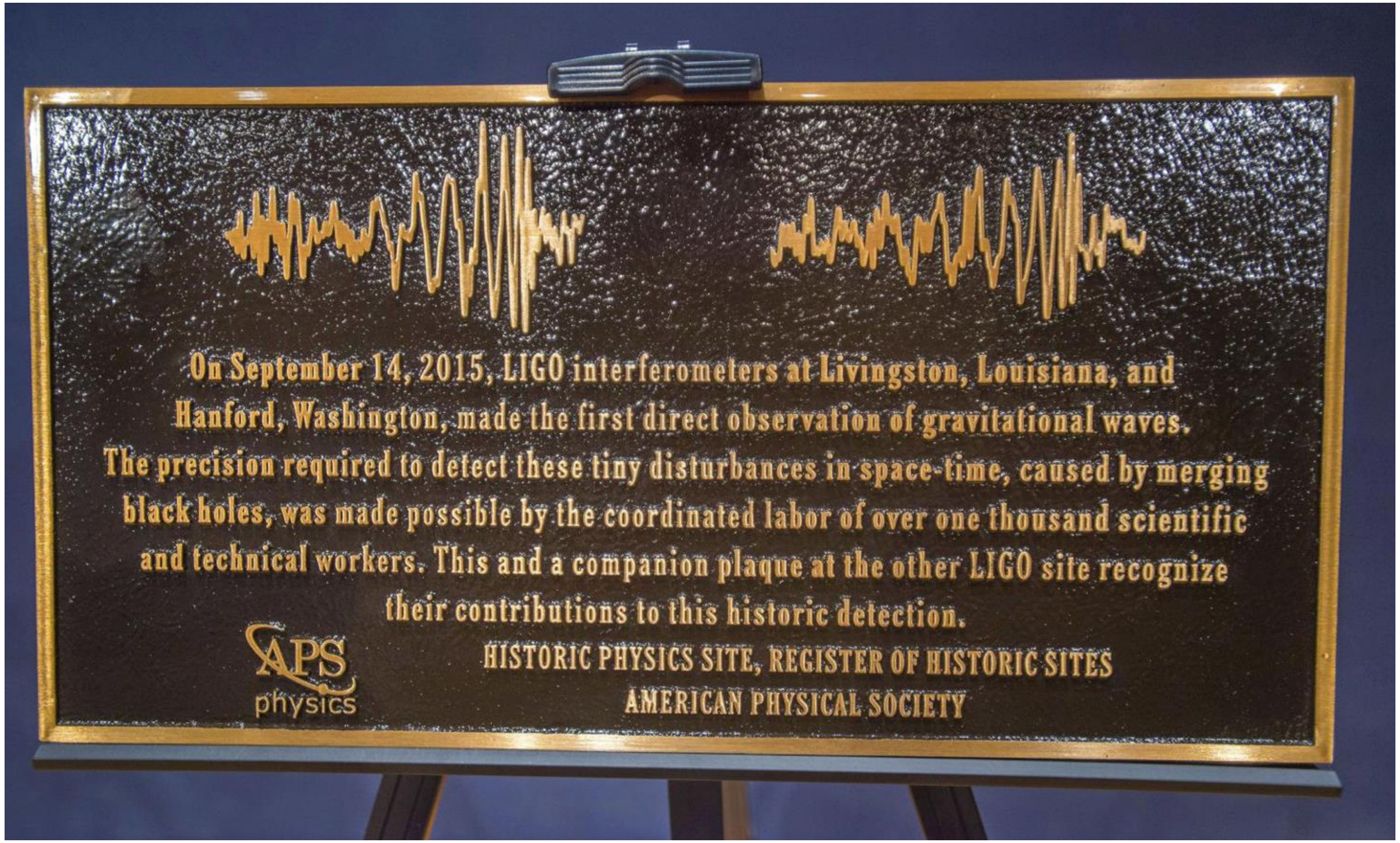
(Oct 3 2017)

Barry Barish, Kip Thorne, Rainer Weiss



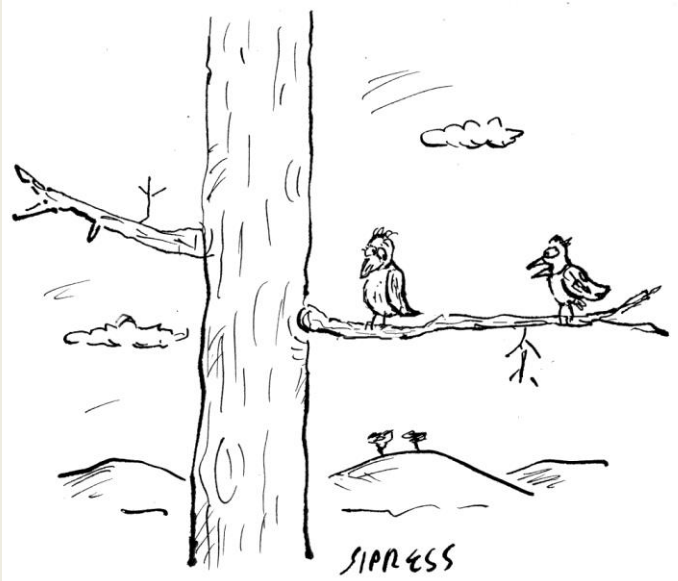
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Detection of GRAVITATIONAL WAVES celebrated as one of the GREATEST SCIENTIFIC ACHIEVEMENTS of All Time

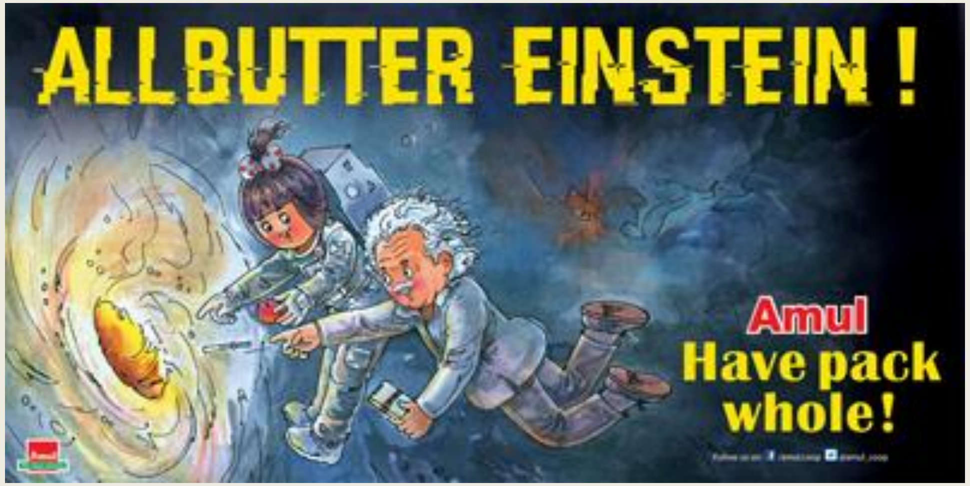


LIGO Livingston Observatory and LIGO Hanford Observatory declared HISTORIC PHYSICS SITES

Feb 11 2016 was the Nov 7 1919 of our generation.

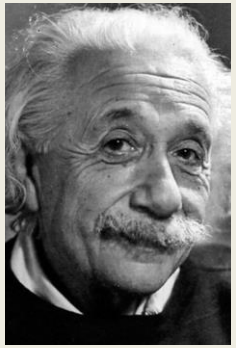


Feb 11 2016
Was the
Nov 7 1919
of our
Generation



"Was that you I heard just now,
or was it two black holes colliding?

What more would Einstein want at the
Centenary of GR and GW ??



O2

Nov 30 2016 - 25 Aug 2017

Virgo joined 1 Aug 2017

GW170814 (60 sq.deg)

Fireworks Even Overshadowing the Nobel (Oct 3 2017)

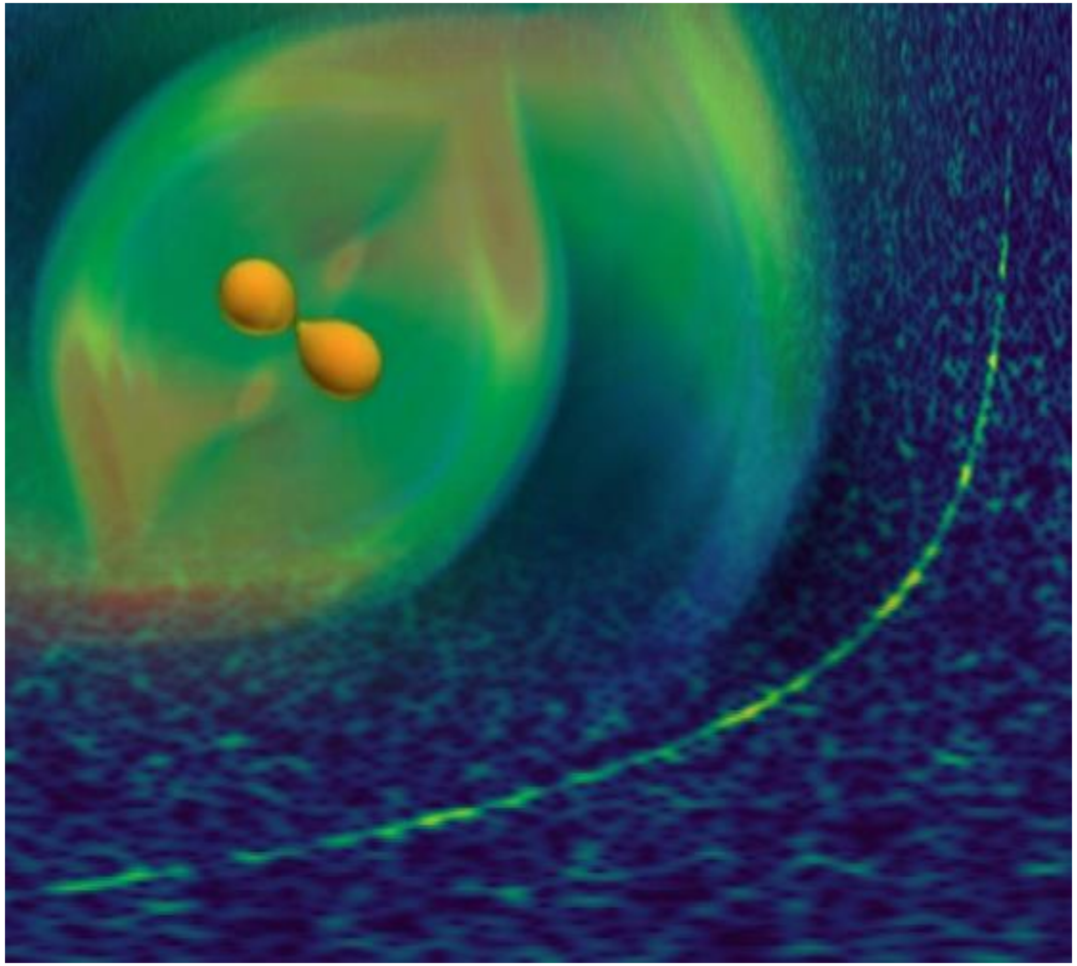
The Spectacular Launch of Multi Messenger Astronomy

GW170817, GRB170817A, AT2017gfo

Oct 16 2017

On

17 August 2017 at 12:41:04 UTC LIGO and Virgo made their first observation of binary neutron star inspiral (GW170817)



(PRL 119 161101 (2017))

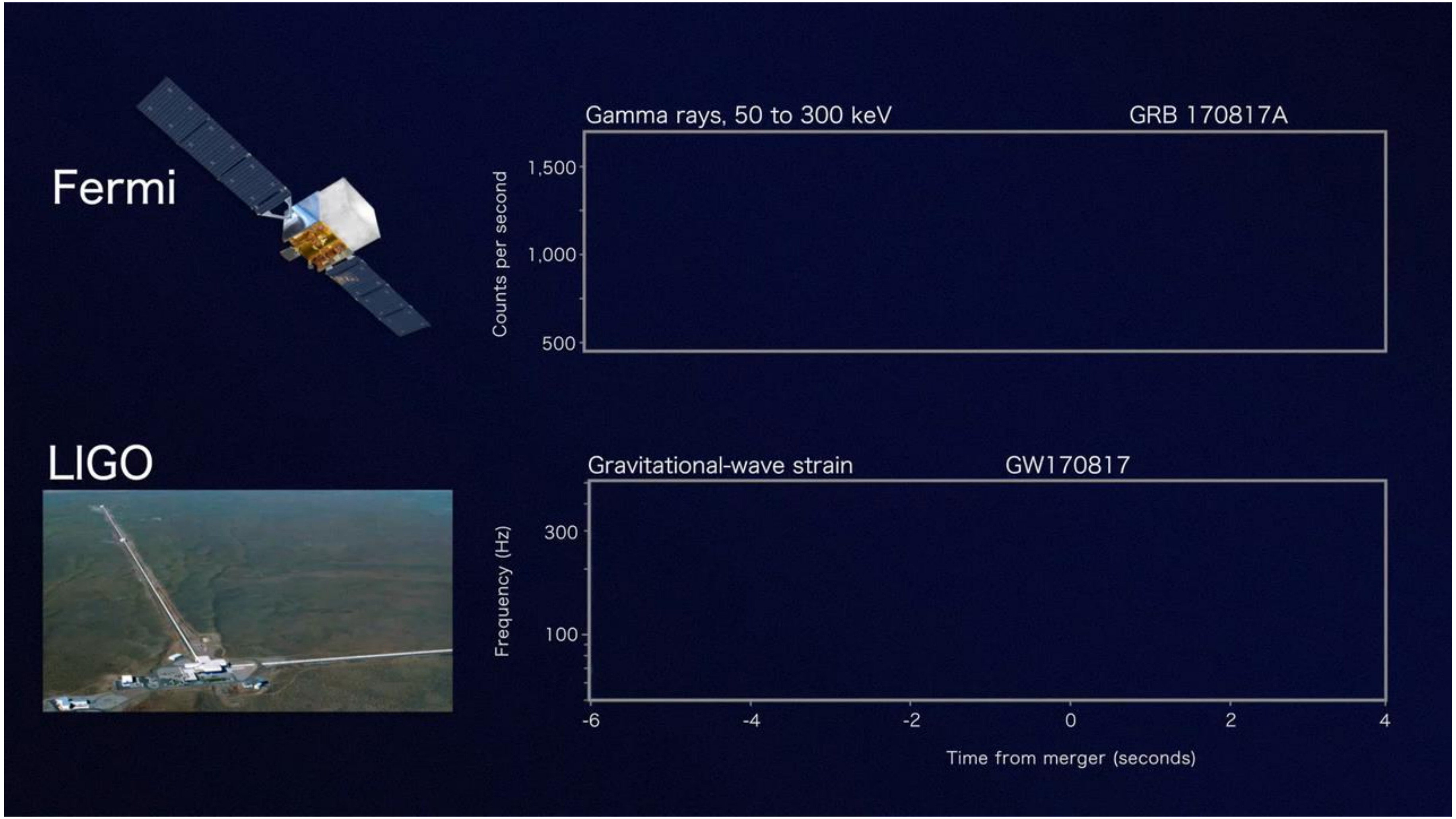
Image credit : LIGO/Virgo/T. Dietrich (FSU/AEI); BAM Collaboration.

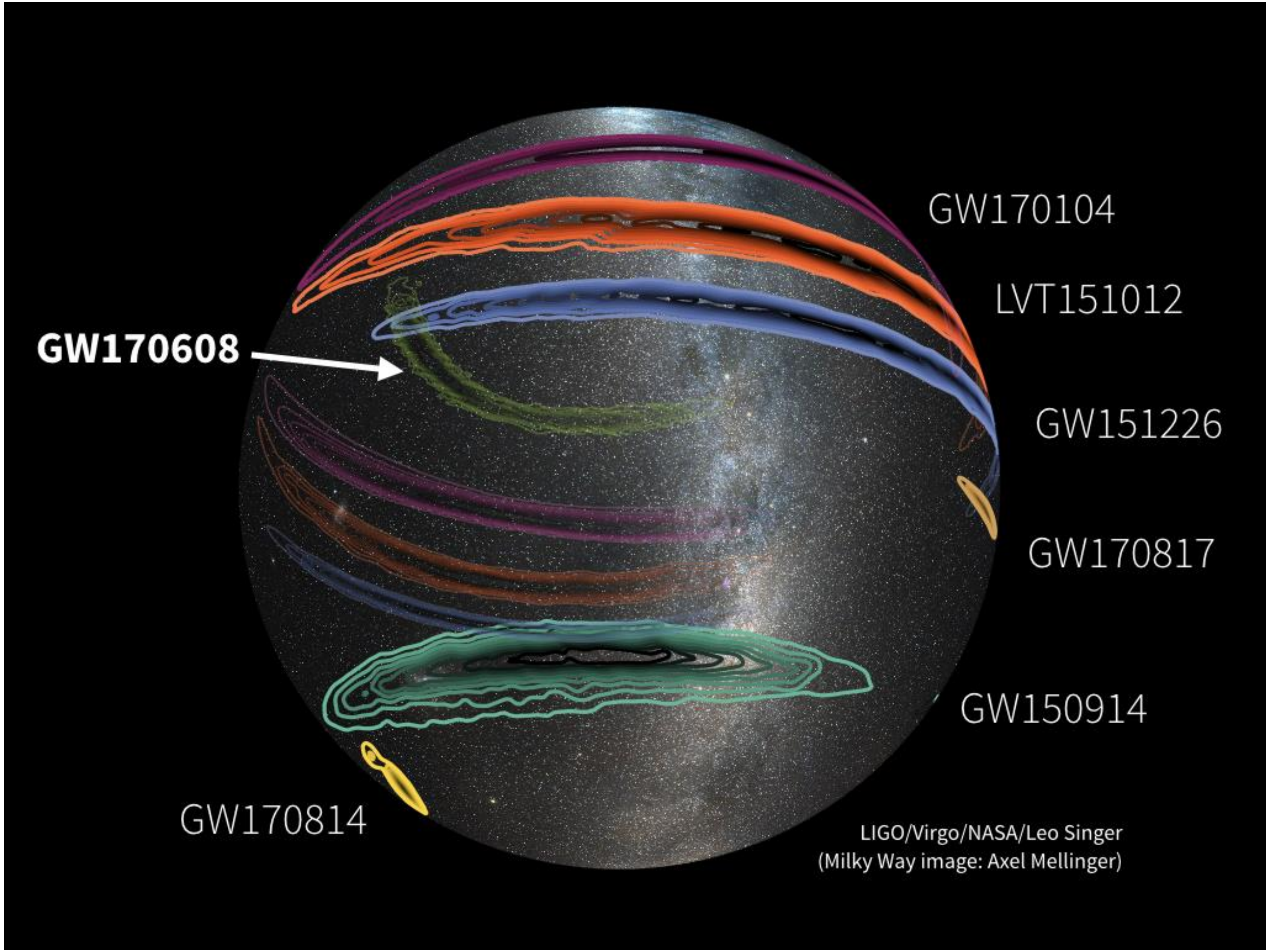
Detected by Matched Filter based pipelines using post-Newtonian models of expected signals

~4200 cycles in 23-2048Hz

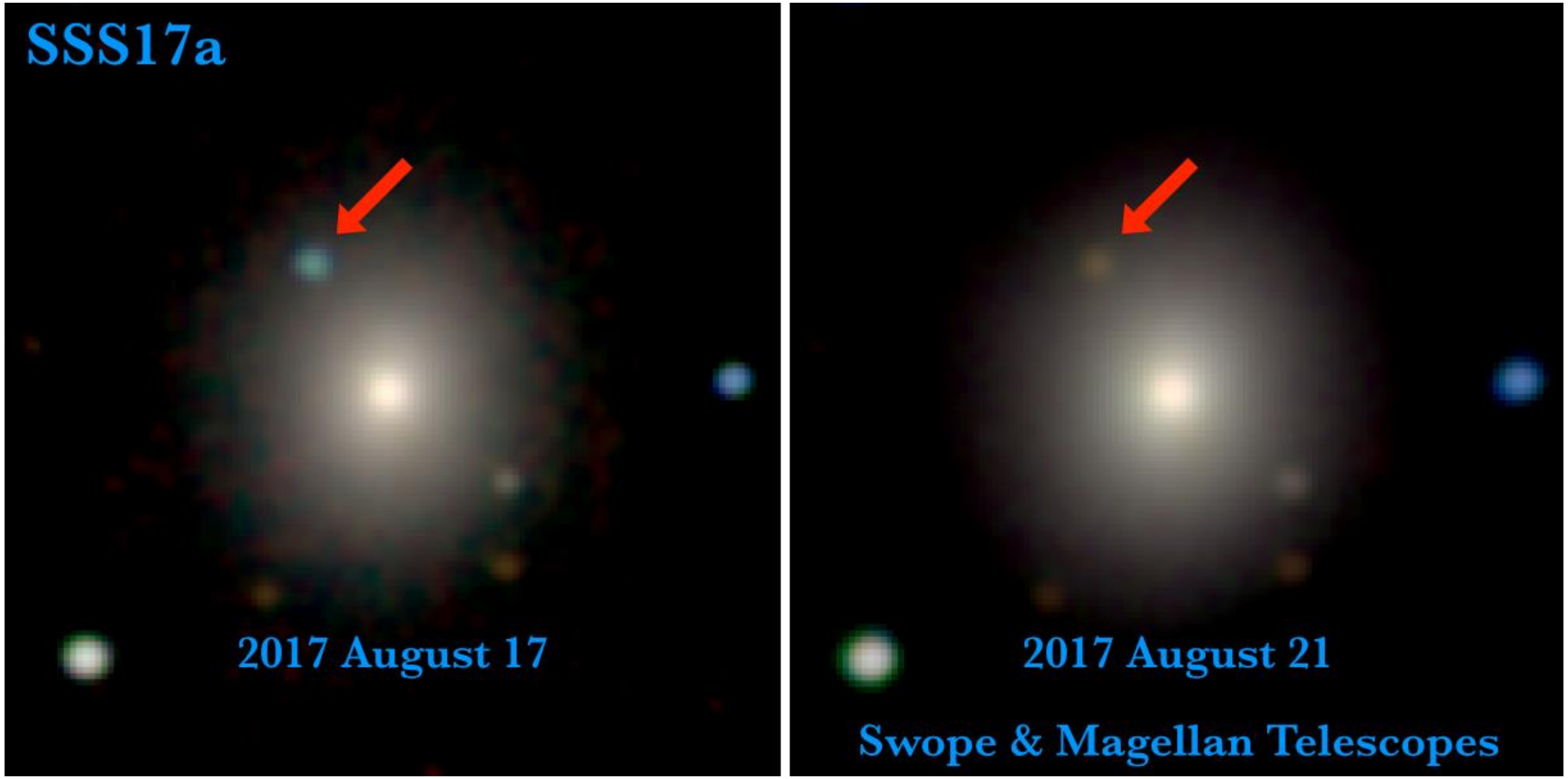
Duration of observed signal ~ 100 s (starting 24 Hz)

Combined SNR ~ 32.4. Estimated False Alarm rate < 1 in 80,000 years


Fermi
LIGO
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)


GW170104
LVT151012
GW170608
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Science 358, 1556 (2017)



About 10 hours later SWOPE Telescope in Chile spotted an optical counterpart

5 other observatories chimed in within next hour

70 observatories ; >100 instruments

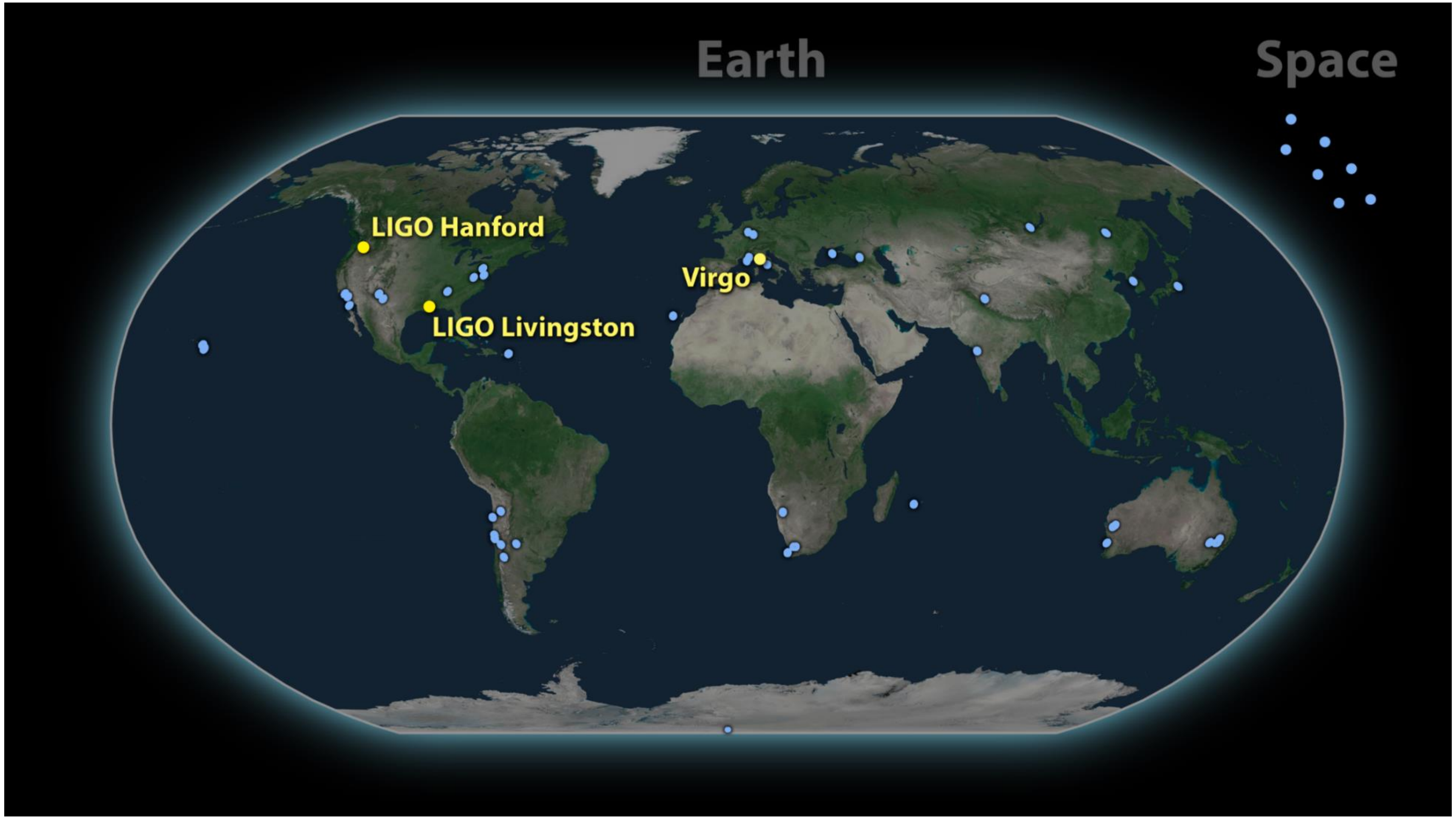
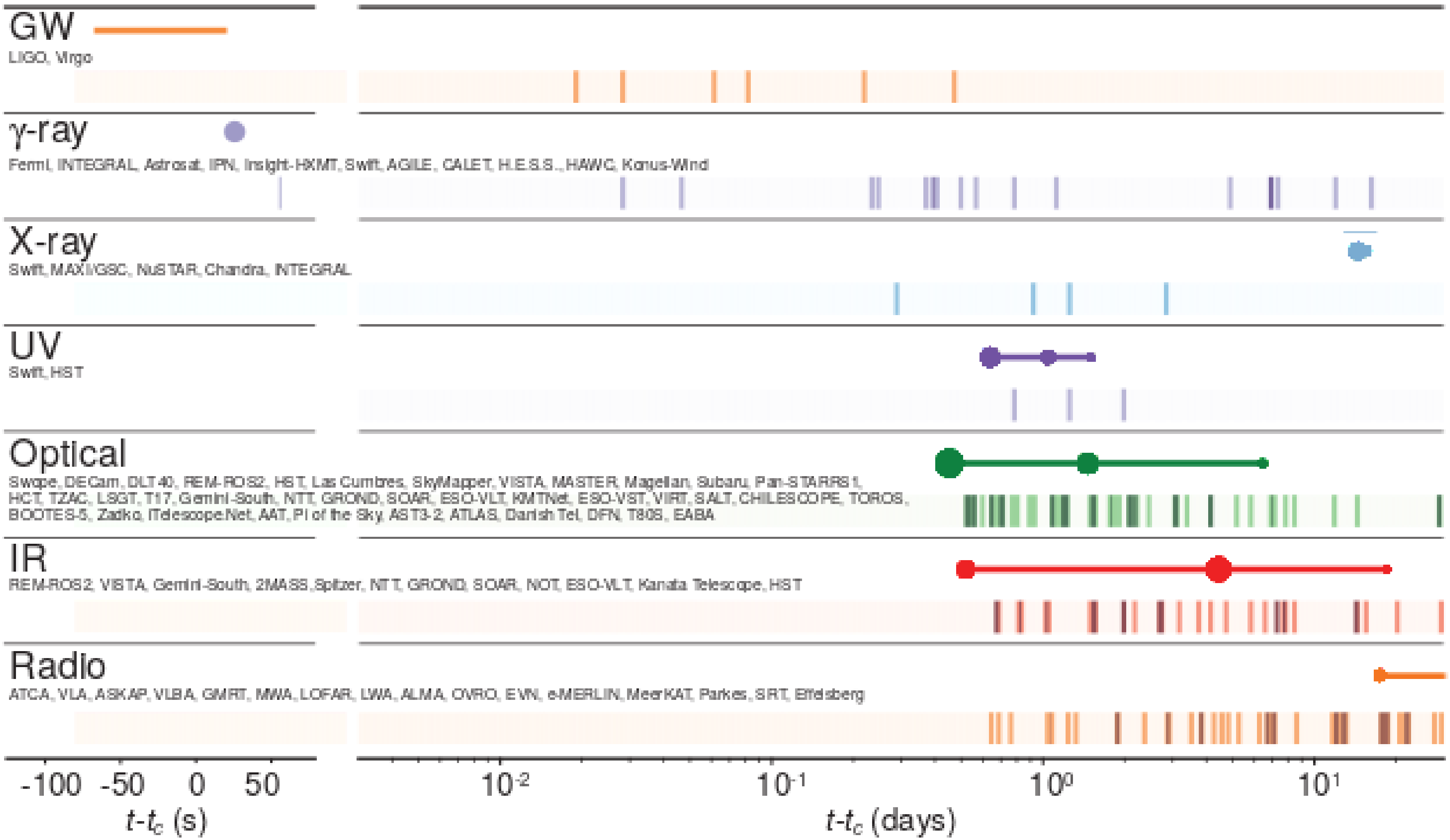


Image credit: LIGO/Virgo AstroSat, GMRT, HCT

Ap. J. Lett 848 L12 (2017)



Delayed x-ray (9 days) and radio (16 days)

Multi-Messenger Observations of a Binary Neutron Star Merger

Ap. J. Lett 848 L12 (2017)

3500 authors ; ~ 950 institutes ;
~48 follow-up groups; 70 observatories ;
>100 instruments

Most ambitious and emotionally charged EM campaign in history, probably, for any transient (short lived event).. Metzger

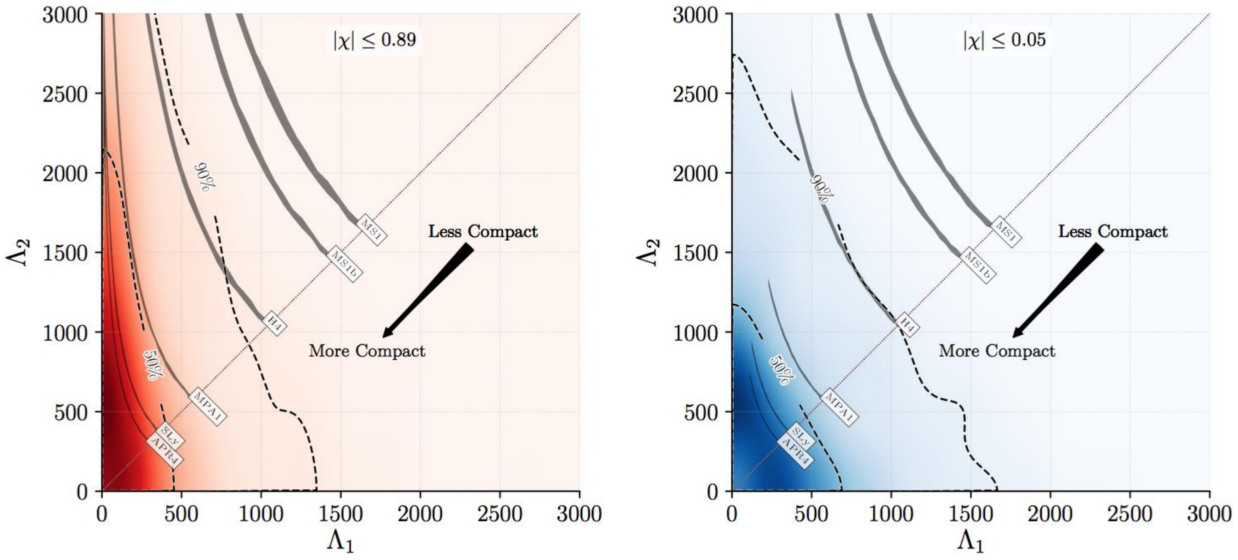
If GW150914 was like the advent of Talkies in the Silent Movie Era,
GW170817 was like the advent of IMAX

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
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_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

(PRL 119 161101 (2017)

GW from Binary Neutron Stars to Eq. of State of NS matter

- Details of the internal structure of the objects becomes important at close separations
- Tidal deformability Λ: Ratio of the induced quadruple moment to the external tidal field. Qij = - Λ Eij
- Constraints on Λ disfavor EoSs that predict less compact stars.



[LVC+, PRL 119, 161101 (2017)
]

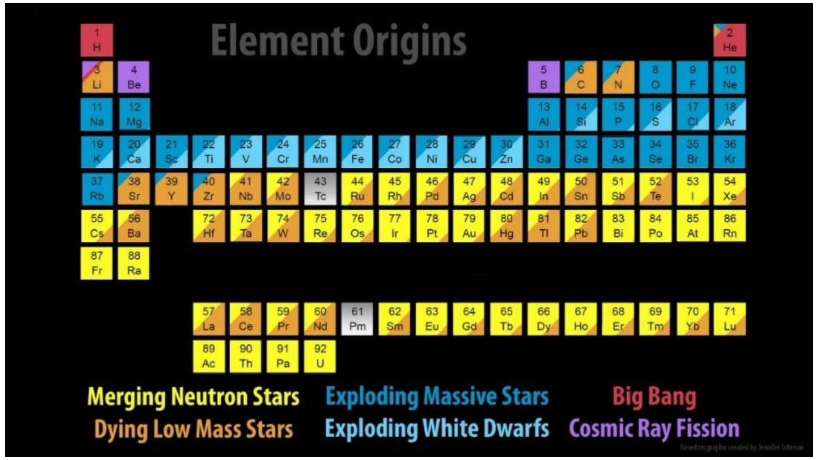
New Firsts

- First observation of GW from a NS-NS system
- First obsvn of GW and EMW from a single source
- Support hypothesis that GW170817 was produced by the merger of two neutron stars in NGC4993
- Followed by a Short Gamma-ray Burst (GRB170817A) and
- A (blue → red) Kilonova powered by the radioactive decay of r-process nuclei synthesized by the ejecta.

- PRL 119 161101 (2017); Ap. J. Lett 848 L12 (2017)

New Firsts

- Much of universe's gold and platinum and nearly all uranium can be produced in neutron star mergers.



50 Earth Mass Silver
100 Earth Mass Gold
500 Earth Mass Platinum

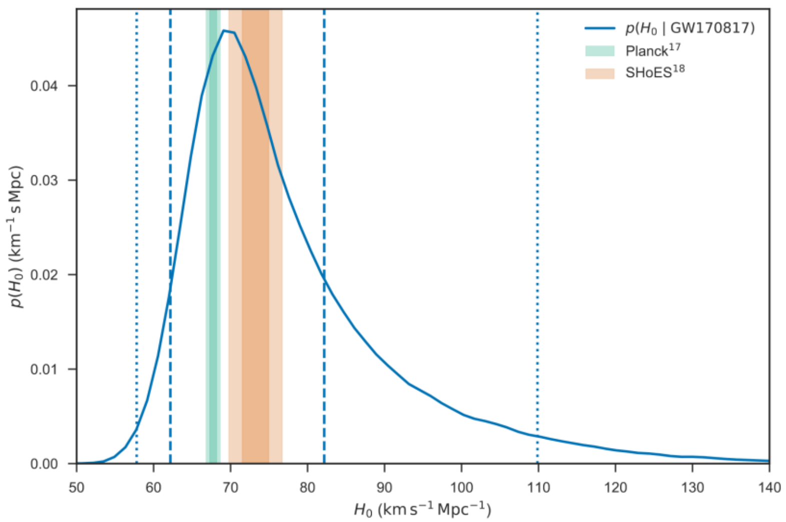
1768 Papers on GW170817
Observations, Interpretation, Models
Beamed relativistic jet or cocoon
Proofs of r-process (2018)
Kilonova afterglow (2021)
Sph Symm Kilonova (2023)

- New Era in Multi-Messenger, time domain astronomy
- Importance of Collaborative GW, EM, Neutrino observations

Cosmology

A gravitational-wave standard siren measurement of the Hubble Lemaitre constant

- Compact binaries are self calibrated standard candles
- GW observations of CBC provide an absolute measurement of luminosity distance (without use of the usual hierarchy of distance ladders)
- EM observations provide the cosmological redshift
- Constraints on the cosmic expansion history from the third LIGO-Virgo-KAGRA Gravitational-Wave Transient Catalog
arXiv: 2111:03604



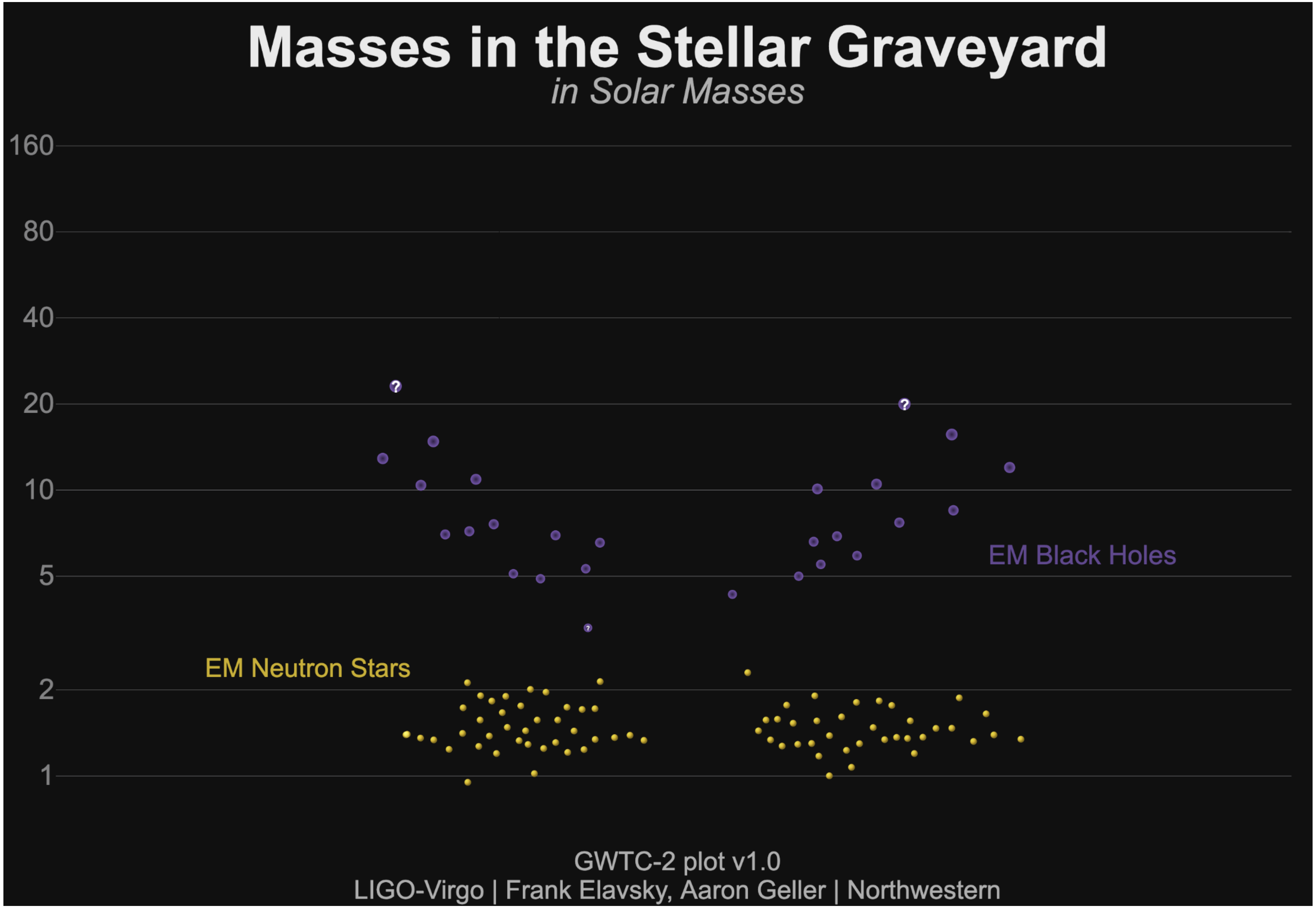
LSC, Virgo, 1M2H, DECam GW-EM and DES, DLT40, LCO, VINROUGE and MASTER) Nature 551, 81 (2017)

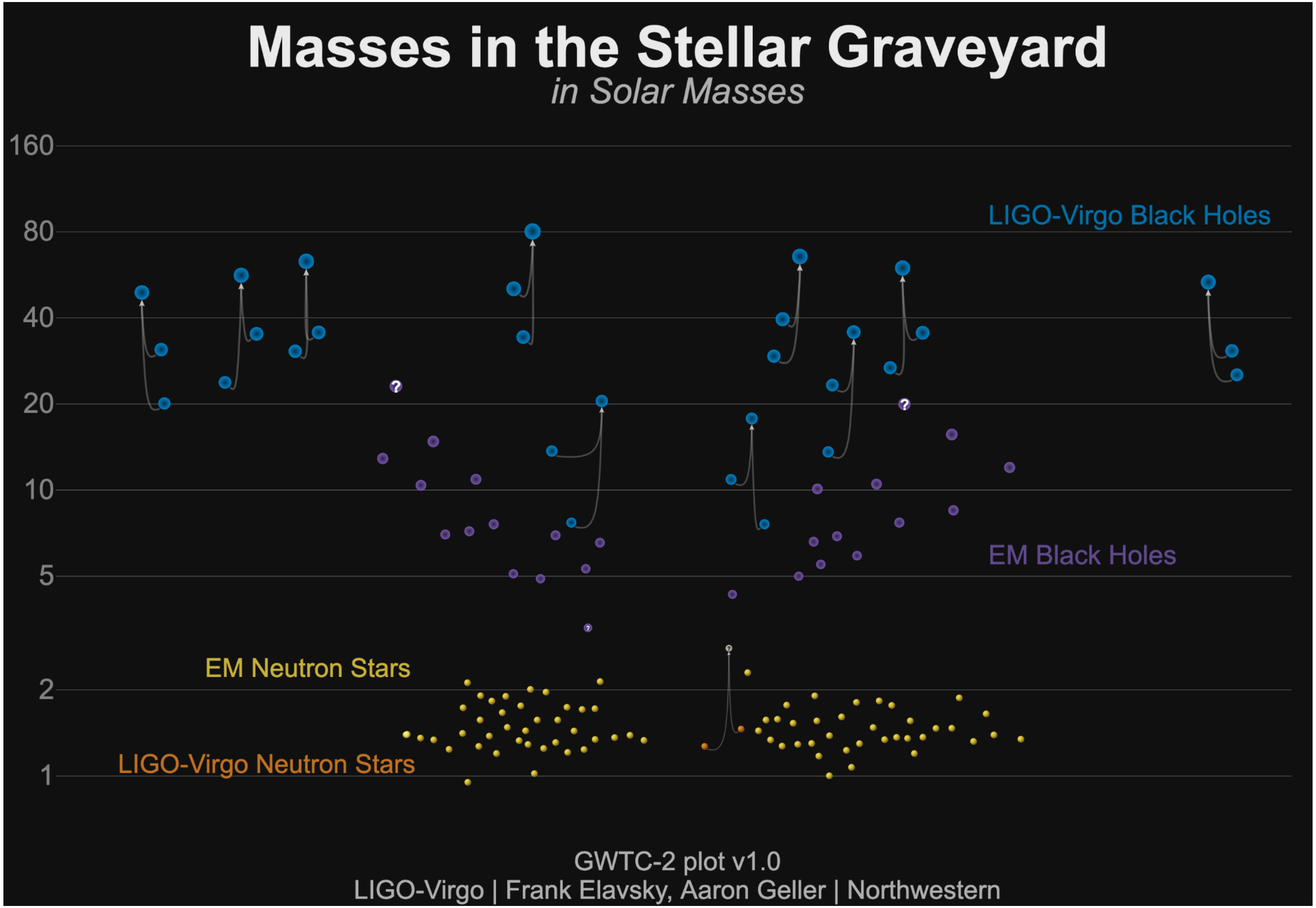
Tests of GR with GW170817

in the Dynamical Strong field regime

- Diff in Speed of GW and light
- Test of the equivalence principle (Shapiro)
- Tests of Lorentz Invariance violation
- Constrain Alternate Theories for DM, DE
- Constrain Dipole Radn in strong field and radiative regimes.. Constrain PN inspiral
- Constrain Anomalous dispersion
- Constrain Large extra spatial dimensions
- Alternative Polarization states (EM counterpart available)

LVC, Phys. Rev. Lett. **123**, 011102 (2019)


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
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160
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LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

LIGO

Laser Interferometer Gravitational-wave Observatory

O in LIGO earned twice over in a couple of years:
GW150914 and GW170817
A new class of heavy BH & sub-luminous sGRB

O1: 3 BBH; O2: 7 BBH+1 BNS

TRANSFORMATIVE

GWTC-1 Catalog

10BBH+ 1 BNS

LVC, Phys. Rev. X **9**, 031040 (2019)

+

8 BBH of the IAS Group

(Phys. Rev. D 101, 083030 (2020))

PART III

Current Status

O3

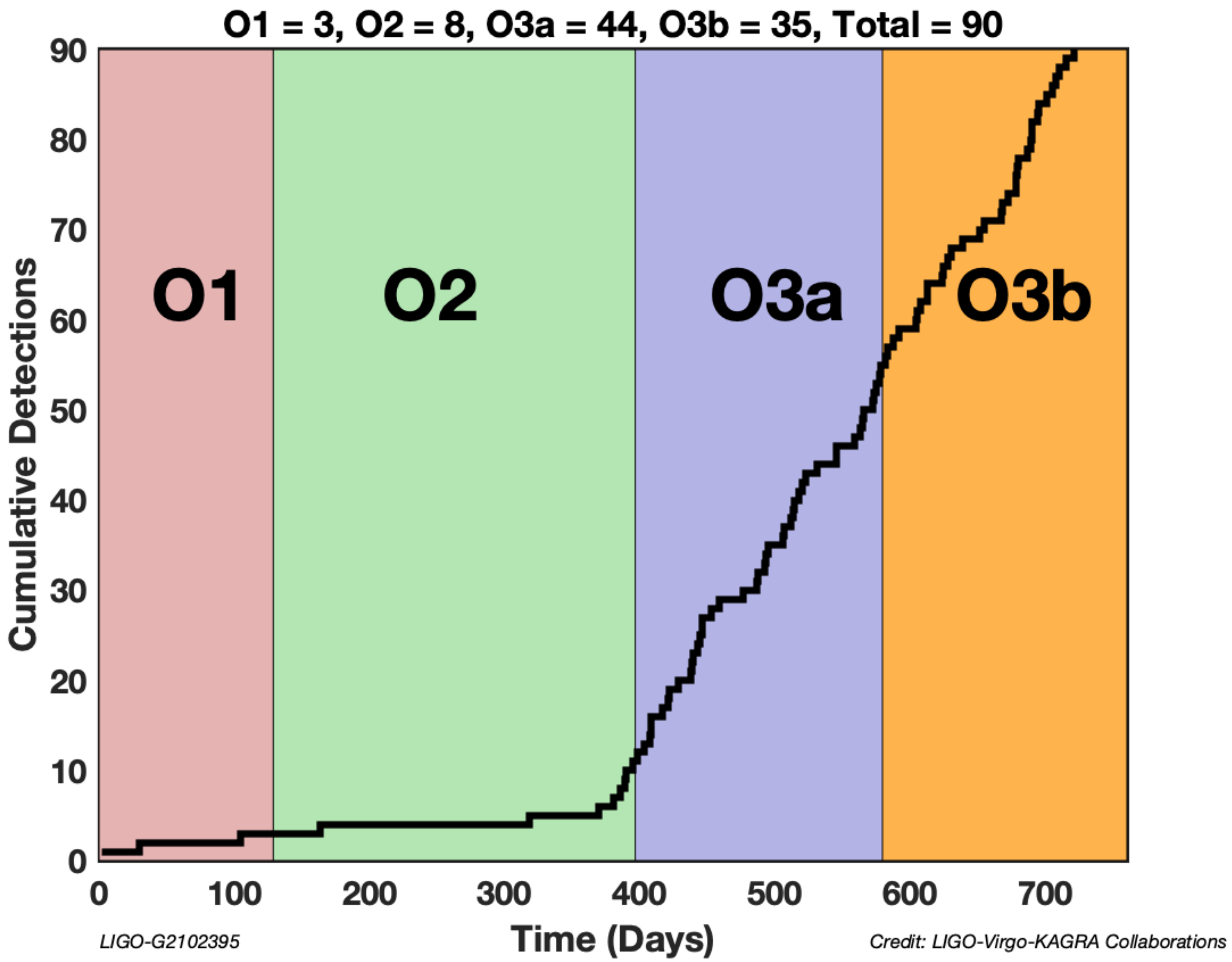
O3a: 1 April – 30 Sept 2019

O3b: 1 Nov 2019 – March 27 ~~(April 30)~~ 2020

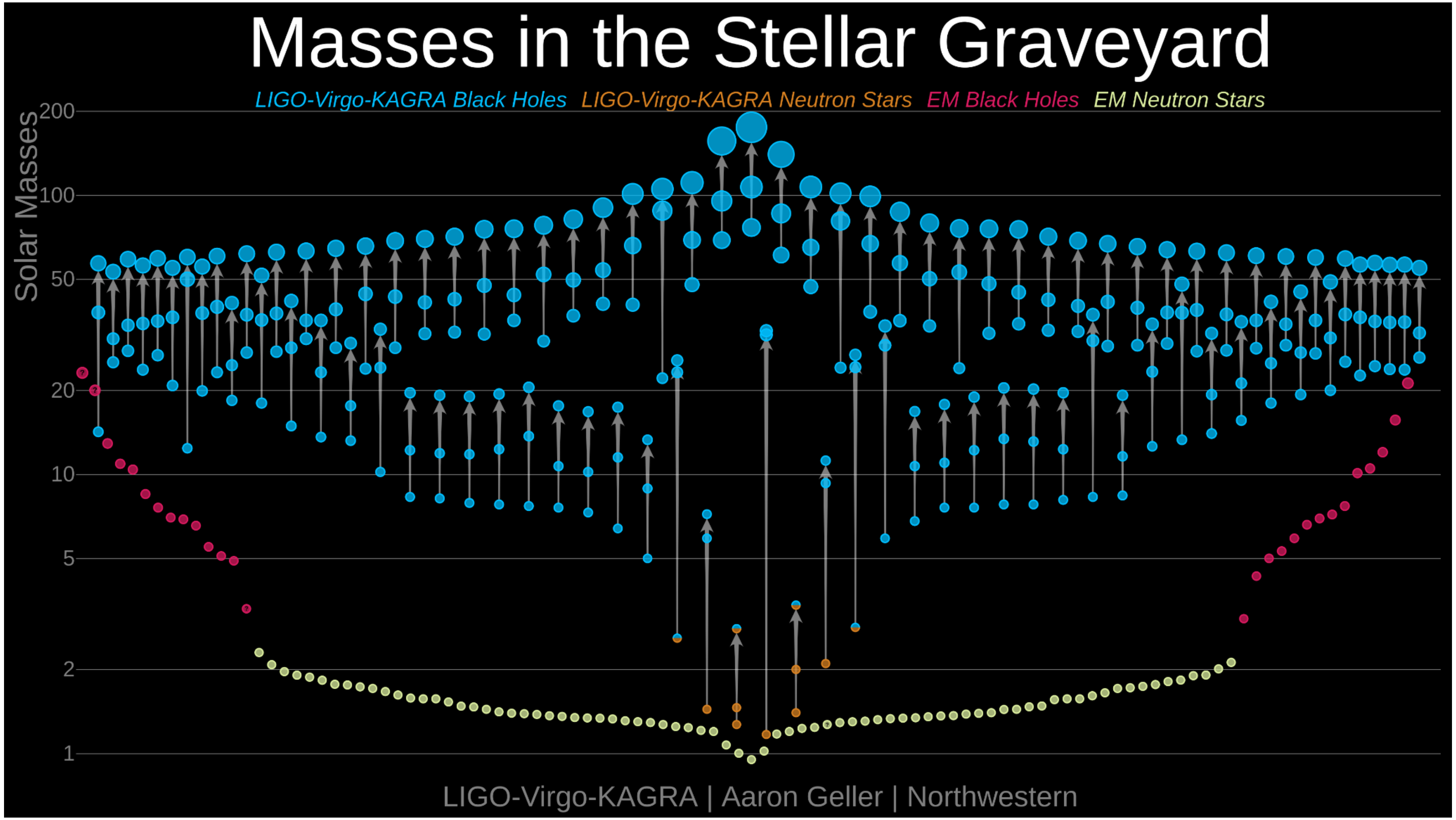
KAGRA was to join by end of 2019

KAGRA-GEO: 7 April – 20 April 2020

O3b Data Release: 5 Nov 2021


O1 = 3, O2 = 8, O3a = 44, O3b = 35, Total = 90
O1
O2
O3a
O3b
Cumulative Detections
0
10
20
30
40
50
60
70
80
90
0
100
200
300
400
500
600
700
Time (Days)
LIGO-G2102395
Credit: LIGO-Virgo-KAGRA Collaborations

35 O3b GWTC-3 Events
Total 90 CBC GW Events (Transients)



2nd BNS

NSBH

IMBH

Asymmetric BBH

Subdominant modes
Systems in Mass gaps
Lower, PPI
Antialigned spins
GR precession
Kick
Eccentric
Exotic

LVK PRX (2021) (submitted)

LVK, arXiv: 2111:03606

O3 GW data used for

- Open Alerts: Look for EM , Neutrino counterparts
- Identify Exceptional Events
- Create Catalog of GW transients with parameter values
- Infer CCB Rates, Population properties; Formation channels
- Test of GR
- Cosmology with GW
- Look for GW Lensing
- Searches for other Burst sources, Persistent Sources, Exotica

LIGO India Scientific Collaboration (LISC)

PI: Archana Pai, co-PI: BI

- Chennai Mathematical Institute, Chennai
- DCSCEM, Mumbai
- ICTS-TIFR, Bangalore
- IISER-Pune, Pune
- IISER-Kolkata, Kolkata
- IIT, Bombay, Mumbai
- IIT Madras, Chennai
- IIT, Hyderabad
- IIT, Gandhinagar
- IPR, Bhatt
- IUCAA, Pune
- RRCAT, Indore
- SINP, Kolkata
- TIFR, Mumbai

LISC
LIGO–India Scientific Collaboration

14 Institutions, 112 Members

Some LISC research
Burst, CBC, Stochastic, CW, Detector characterization

- Sanjeev Dhurandhar, Sanjit Mitra , Anand Sengupta: Template Bank
- Archana Pai: Burst, IMBH
- Sukanta Bose: BNS EOS, Detector characterization,
- Debarti Chatterjee: BNS EoS..
- Anupreeta More: Lensing, Detector characterisation
- Sanjit Mitra: Stochastic
- Sheelu Abraham, Ninan Sajeeth Phillip, Sanjit Mitra: Machine learning
- Arun, Mishra: TOG
- Ajith: TOG, Lensing
- Rajesh Nayak: PSO, Seismic studies for LI
- Surhud More: GW Cosmology
- Arunava: CW, BH mimickers,
- Shivraj K: Stochastic, Detector characterization
- Surendra: Seismic studies for LI
- Varun Bhalerao: EM followup..
- Prayush Kumar: Numerical relativity
- *EM followup outside LISC; eg Resmi, Poonam Chandra , Kuntal Mishra, Varun …*

CBC Rates post O3

BBH Rate Per Gpc^3 per year:

17.9 - 44

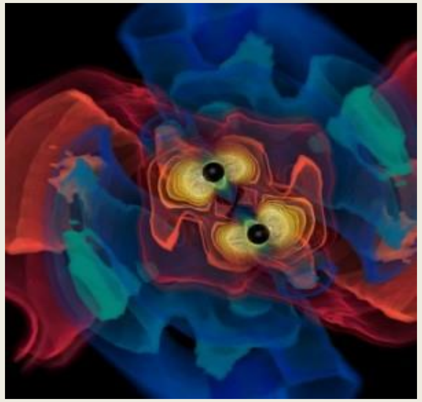
BNS Rate Per Gpc^3 per year:

10 - 1700

NSBH Rate Per Gpc^3 per year:

7.8 - 140

Astrophysical Sources of Gravitational Waves



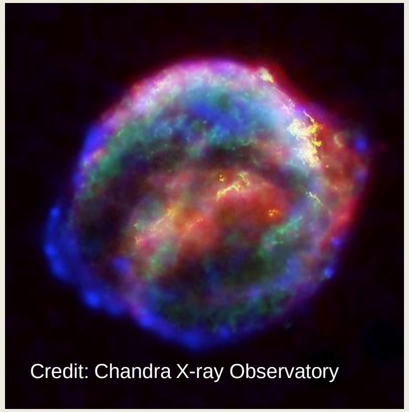
Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems:

Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

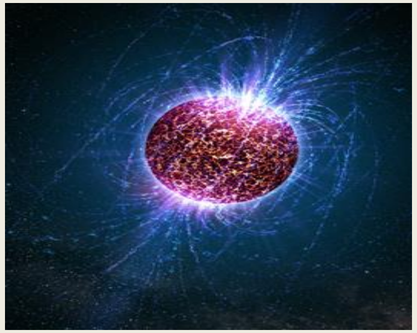
- (effectively) transient



Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient



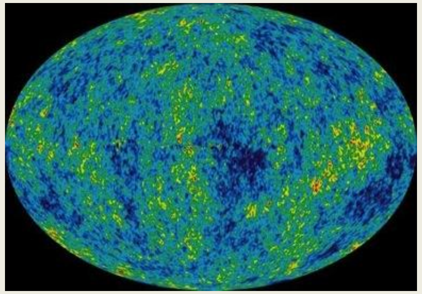
Casey Reed, Penn State

Spinning neutron stars

- (nearly) monochromatic waveform

- Long duration

Persistent
(Targetted, Directed, All Sky)
$h < 5\times 10^{-27}, 10^{-26}, 10^{-25}$



NASA/WMAP Science Team

Stochastic Gravitational-wave Background

- Cosmic: Residue of the Big Bang

- Astrophysical stochastic background

Persistent
All Sky, All Frequency

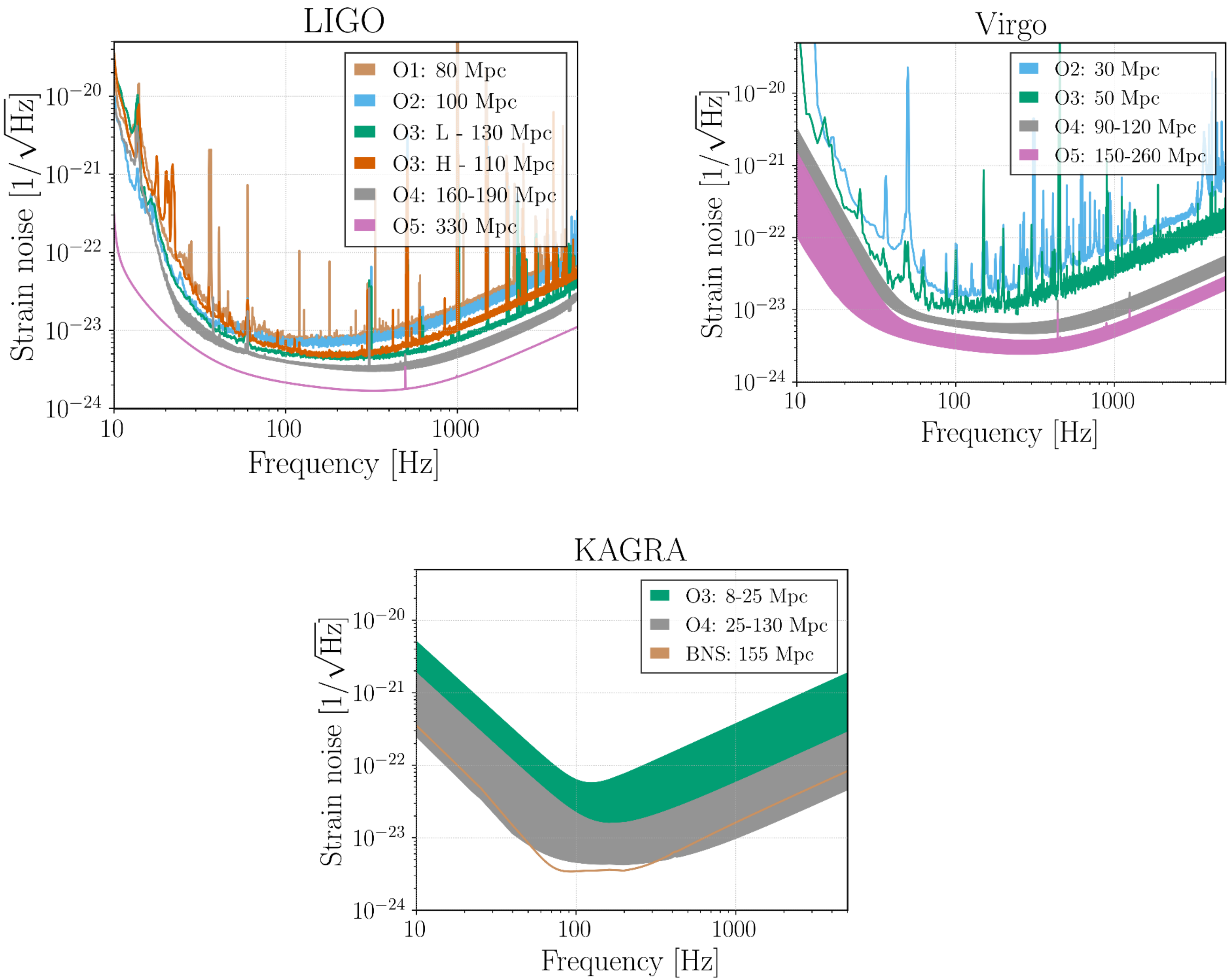
Part IV

Future Prospects

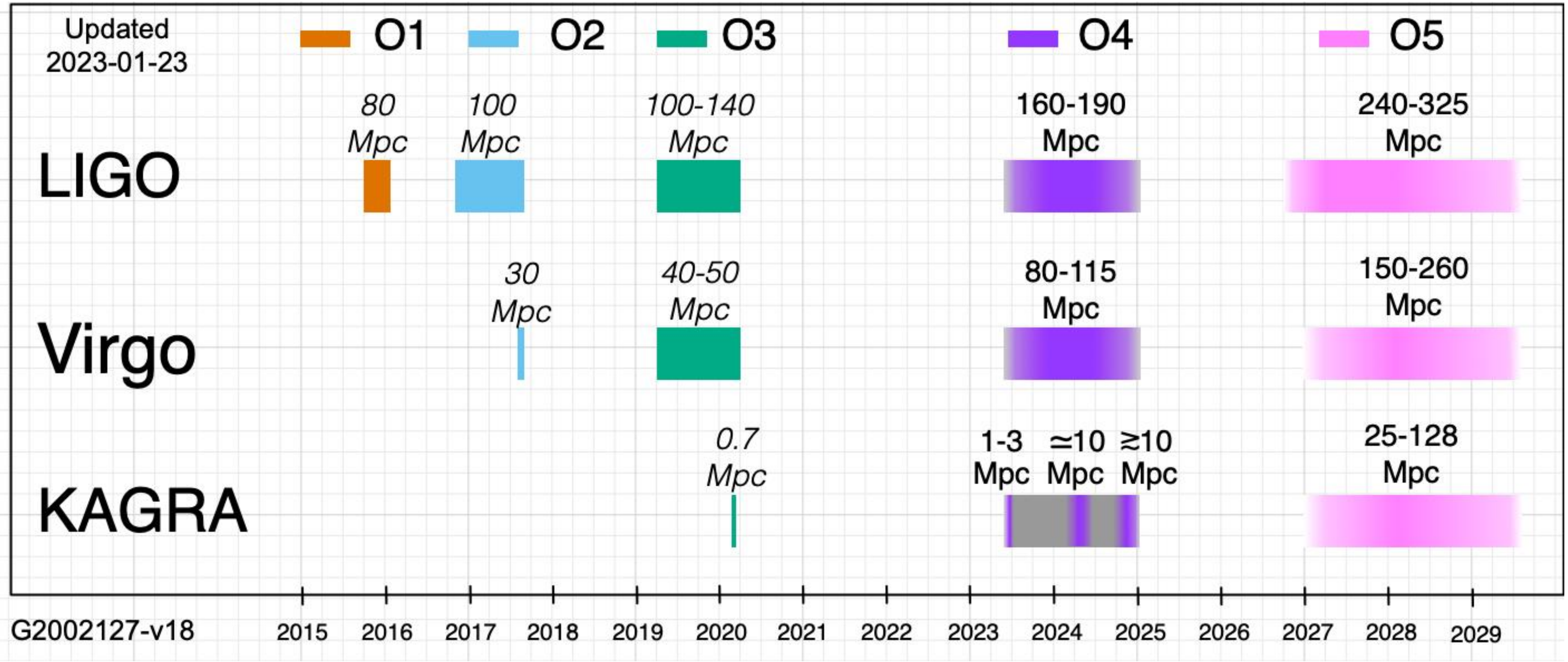
LSC Program

Document Type	LIGO-M2200183-v2	Spetember 2022
LIGO Scientific Collaboration Program (2022 Edition)		
The LSC Program Committee: Stefan Ballmer, Vuk Mandic, Lisa Barsotti, Christopher Berry, Sukanta Bose, David Keitel, Zsuzsanna Marka, David Ottaway, Jocelyn Read, Stuart Reid, Joseph Romano, Janeen Romie, Jax Sanders, Patrick J. Sutton, David Reitze, Albert Lazzarini, Patrick Brady		

https://dcc.ligo.org/LIGO-M2200183/public



LIGO
O1: 80 Mpc
O2: 100 Mpc
O3: L - 130 Mpc
O3: H - 110 Mpc
O4: 160-190 Mpc
O5: 330 Mpc
Strain noise [1/√Hz]
Frequency [Hz]
Virgo
O2: 30 Mpc
O3: 50 Mpc
O4: 90-120 Mpc
O5: 150-260 Mpc
Strain noise [1/√Hz]
Frequency [Hz]
KAGRA
O3: 8-25 Mpc
O4: 25-130 Mpc
BNS: 155 Mpc
Strain noise [1/√Hz]
Frequency [Hz]



O4: Starting 24 May 2023
18 months long + 2 one month breaks

O4 (one year) projections

Network	BNS	NSBH	BBH
LVK O4	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}
LVK O4	29 – 48 sq deg	48 -69 sq deg	33 –47 sq deg
LV O3	250-310 sq deg	310-390 sq deg	250-340 sq deg

(O4: 24 May 2023; 18 months long)

Beyond Advanced LIGO/Virgo

A+ (2025)
A# (2029)
Voyager

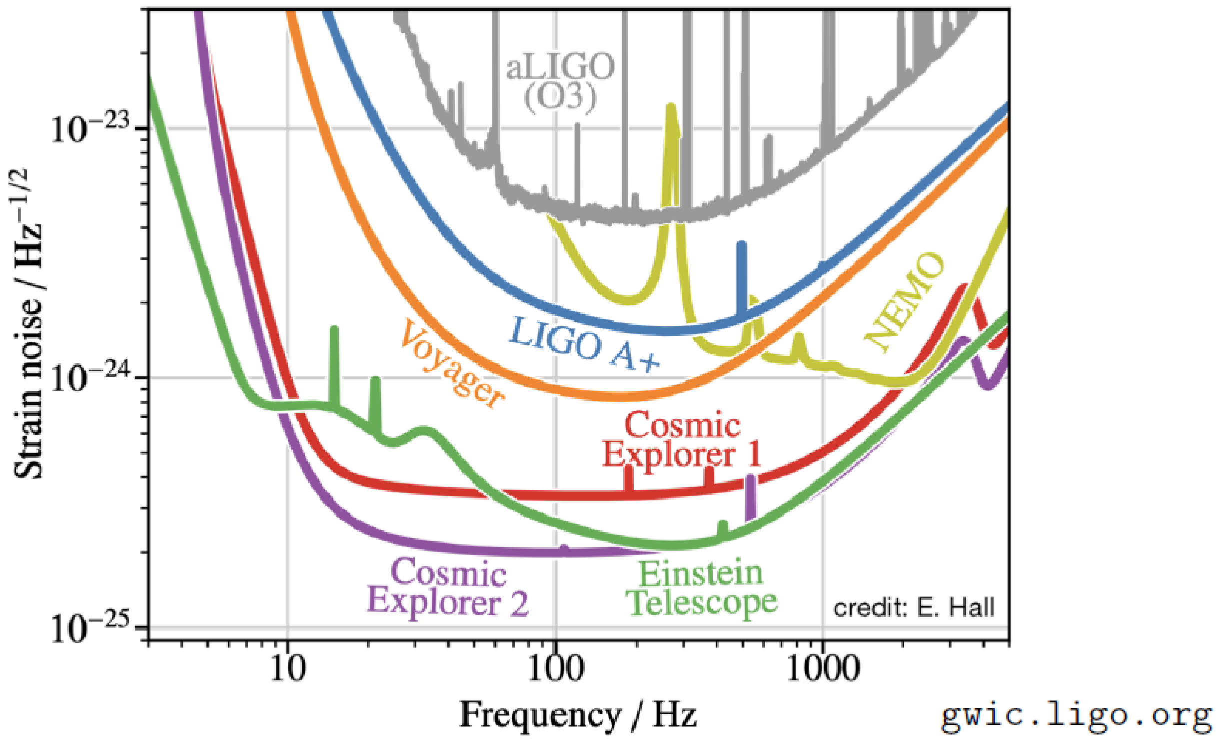
LISA (2034) [Space, 2.5 million km]

3G
Einstein Telescope (2030's) [10 km, triangular, underground]
Cosmic Explorer (CE) (2035) [40 km, 20 km]

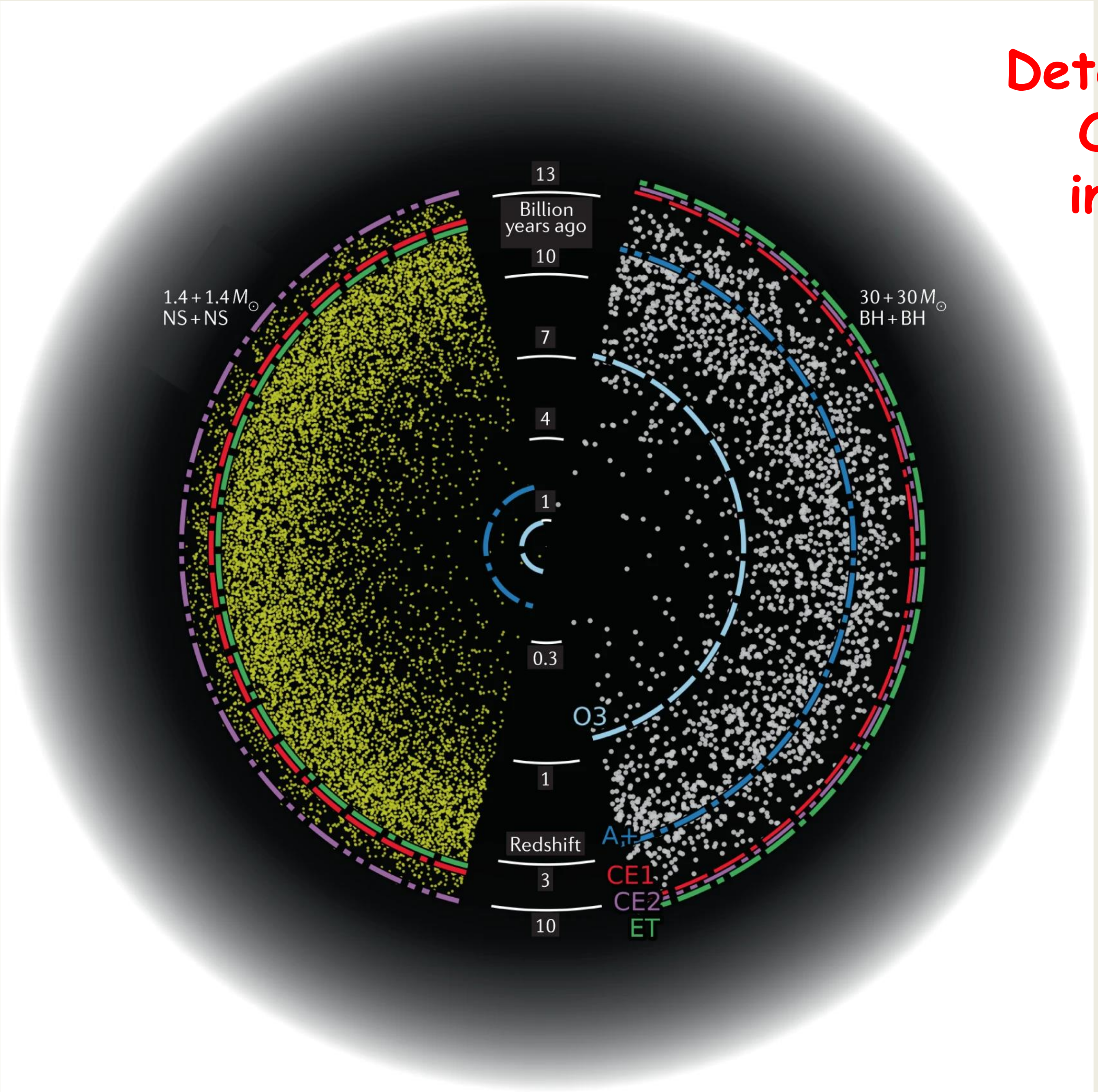
3G Science drivers

Extreme gravity; Extreme Matter; Cosmic history

Towards 3G



aLIGO (O3)
LIGO A+
Voyager
NEMO
Cosmic Explorer 1
Cosmic Explorer 2
Einstein Telescope
credit: E. Hall
Strain noise / Hz$^{-1/2}$
10^{-23}
10^{-24}
10^{-25}
10
100
1000
Frequency / Hz
gwic.ligo.org



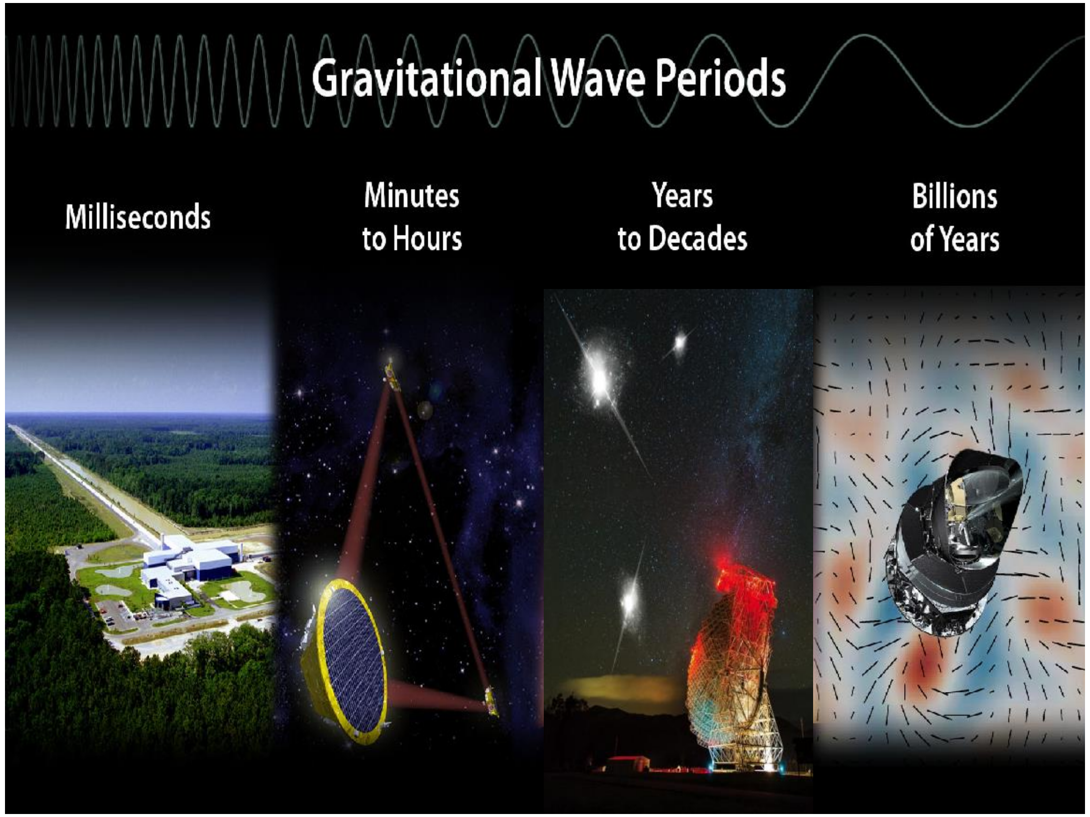
Detect significant fraction
Of ALL CBC mergers
in the Visible Universe

Detect mergers
Before first stars formed
Due to primordial
Black holes

Two Decades in Frequency

KiloHz, MilliHz, NanoHz, AttoHz

LIGO India



GW in NanoHz Band

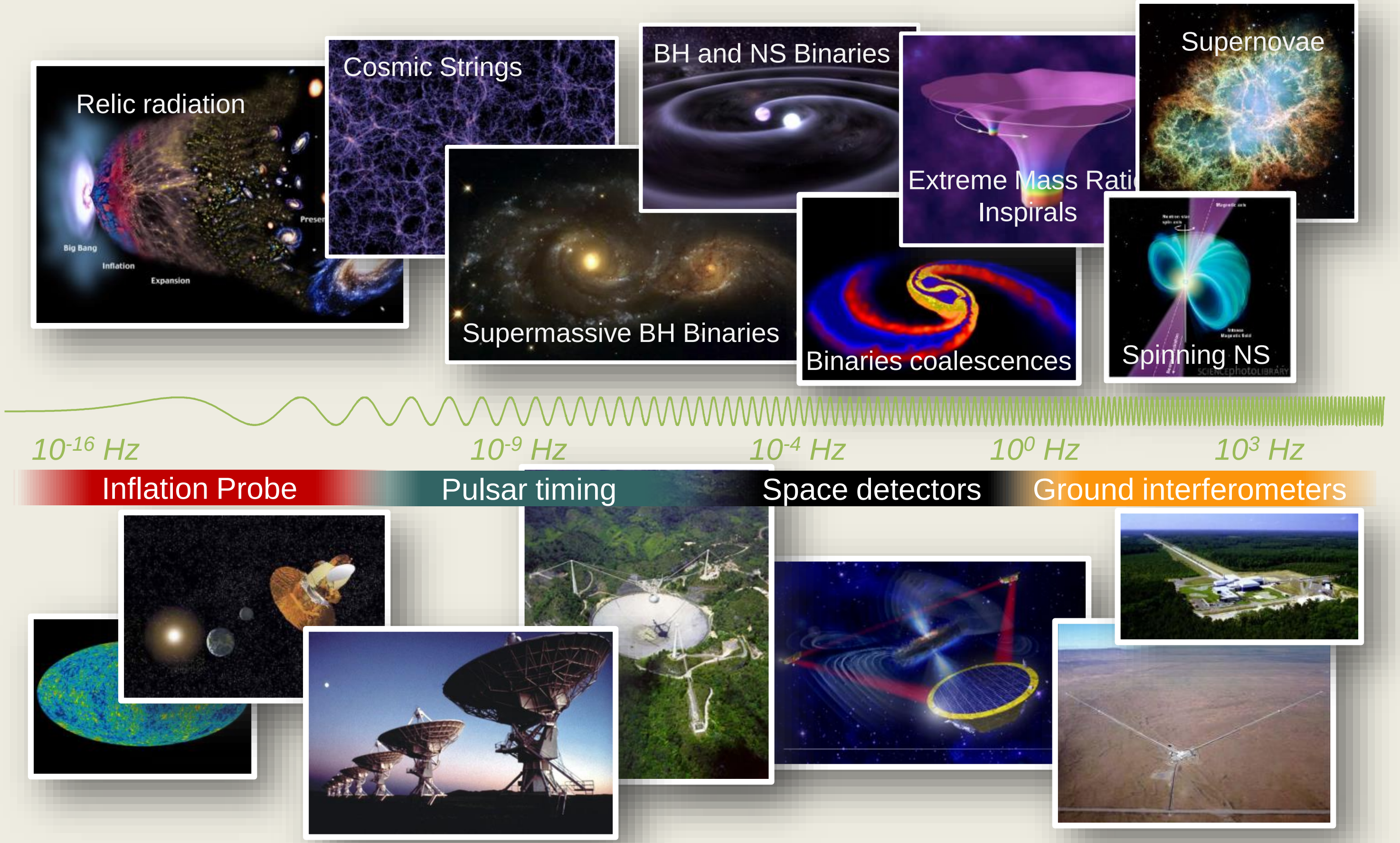
InPTA

uGMRT

LVK, LISA, PTA, BBO

MULTI-BAND GW ASTRONOMY

The GW Spectrum



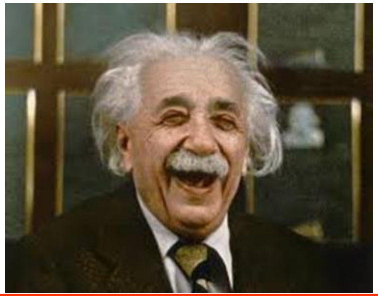
From Known-Knowns and Known-Unknowns to Unknown-Unknowns

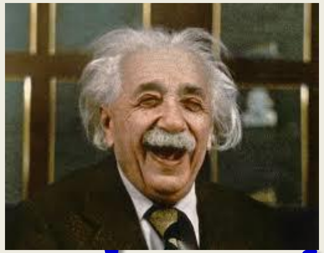
Gravitational-wave physics and astronomy in the 2020s and 2030s

Nat Rev Phys **3,** 344–366 (2021)

To Conclude

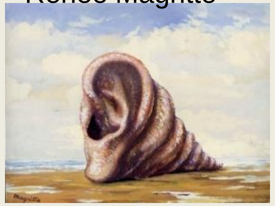
- Black Hole Astronomy was ushered in with GW150814 and
GW triggered Multi Messenger Astronomy with GW170817 .
- The gamechanger was the network of LIGO and Virgo GW detectors and their ability to localize a GW source to a small enough region and
send alerts to realistically facilitate EM follow up.
Future network brings in KAGRA and LIGO-India
- O3 consolidated new insights into Astrophysics, Cosmology, and Fundamental Physics assessed feasible earlier that remarkably emerged with the first discovery of GW from a BBH & BNS system. O3b analysis just completing. Preparing for O4.
- First Faint Strains of the GW Symphony are Whispers of a New Astronomy. A New Window with New emerging interfaces/synergies of GR, QFT methods and HEP





Come Decipher the universe using Gravitational Wave Observations And Multi-Messenger Astronomy

Renee Magritte



??? Hubble Constant, BH, Naked singularity, QNM, Gravastars, Boson Stars, Echoes, FuzzBalls !!!

GW from Big Bang

Multi-band GW Astronomy

Join Einstein@Home

Join GravitySpy

Explore GWOSC

Amateur Followup of GW Alerts

LISA

LSC PROGRAM

LIGO-India

InPTA

Daksha

PTA SKA

3G CE,ET, NEMO

GW Lensing

Eccentric CBC

GW from Supernovae

GW from Pulsars

SGWB

GW Cosmic strings

BH-BH

NS-NS

IMBH

NS-BH

EM, Neutrino Followup

THANK YOU FOR YOUR ATTENTION