Jan. 30, 2015 at Joint Winter Conference on
Particle, String and Cosmology in High1, Korea

Gravitational wave detection experiments; Current status and Korean activities

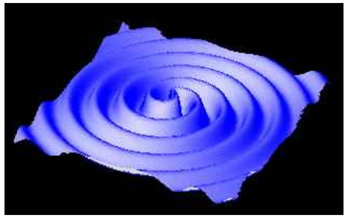
Gungwon Kang (KISTI)

Outline

I. Introduction
II. Detection experiments for GWs
III. Korean activities
IV. Conclusion

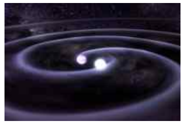
I. Introduction

1. Gravitational waves:



- Ripples in the spacetime curvature that propagate with the speed of light
- Emitted by “accelerated” matter as in the case of EM waves by an accelerated charge

– In weak gravitational fields, one may have



$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}\ , \quad \text{with} \ \ |h_{\alpha\beta}| \ll 1$$

– Defining $\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} h\, \eta_{\mu\nu}\ , \quad h \equiv \eta^{\alpha\beta} h_{\alpha\beta}$ with the Lorenz guage $\bar{h}_{\mu\nu}{}^{,\nu} = 0$, the linearized Einstein gravity gives

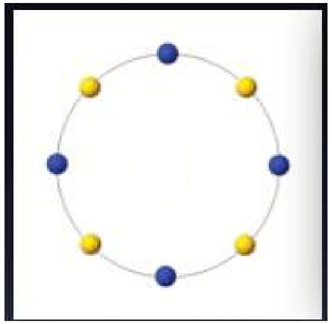
$$\boxed{\bar{h}_{\mu\nu,\alpha}{}^{\alpha} = h_{\mu\nu,\alpha}{}^{\alpha} = 0}\ . \qquad \partial^2 \bar{h}_{ab} = \left(-\frac{\partial^2}{\partial t^2} + \vec{\nabla}^2\right) \bar{h}_{ab} = 0$$

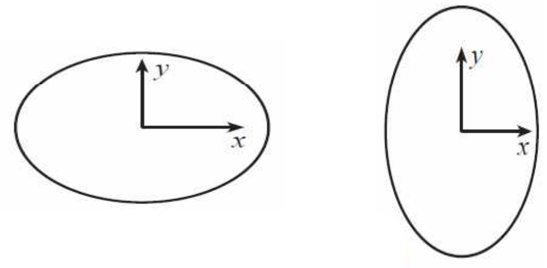
➔ Wave eq.: Massless, propagating at the speed of light, spin-2 fields, only two-degrees of freedom, etc.

- Plane waves propagating in the z-direction, in TT (Transverse-Traceless) gauge,:

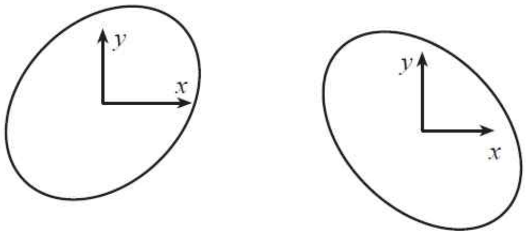
$$h^{TT}_{\alpha\beta} = h_+(t-z)\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + h_\times(t-z)\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\begin{aligned} L'_x &= \int \sqrt{1+h_{xx}}dx \\ &\sim \int (1+\frac{1}{2}h_{xx})dx \\ &= (1+\frac{1}{2}h\sin(\omega t))\int dx \\ &= L+\frac{1}{2}Lh\sin(\omega t) \end{aligned}$$





"Plus" (+) polarization

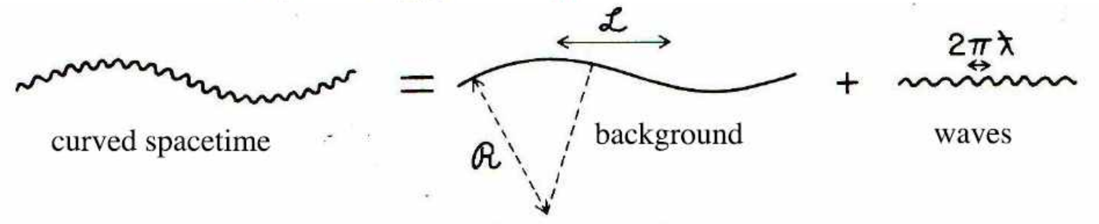


"Cross" (x) polarization

- In a more general context, e.g., GWs propagating through curved ST,

Isaacson ('68)

$$g_{\alpha\beta} = g^{\rm B}_{\alpha\beta} + h_{\alpha\beta}$$



$$\boxed{\lambda\!\!\!^{-} \ll \{\mathcal{R}, \mathcal{L}\}}$$

⇨

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} h\, g^{\rm B}_{\mu\nu}\,, \qquad h \equiv g_{\rm B}^{\alpha\beta} h_{\alpha\beta}\,.$$

$$\bar{h}_{\mu\nu}{}^{|\nu} = 0$$

$$\boxed{\bar{h}_{\mu\nu|\alpha}{}^{\alpha} = 0}$$

- GWs carry energy, angular momentum and momentum:

$$\boxed{\frac{dM}{dt} = -\frac{1}{5}\left\langle \frac{\partial^3 \mathcal{I}_{jk}}{\partial t^3}\frac{\partial^3 \mathcal{I}_{jk}}{\partial t^3}\right\rangle},$$

$$\boxed{\frac{dJ_i}{dt} = -\frac{2}{5}\epsilon_{ijk}\left\langle \frac{\partial^2 \mathcal{I}_{jm}}{\partial t^2}\frac{\partial^3 \mathcal{I}_{km}}{\partial t^3}\right\rangle}, \qquad \boxed{dP_j/dt = 0.}$$

$$\boxed{\frac{dP_i}{dt} = -\frac{2}{63}\left\langle \frac{\partial^3 \mathcal{I}_{jk}}{\partial t^3}\frac{\partial^4 \mathcal{I}_{jki}}{\partial t^4}\right\rangle - \frac{16}{45}\epsilon_{ijk}\left\langle \frac{\partial^3 \mathcal{I}_{jp}}{\partial t^3}\frac{\partial^3 \mathcal{S}_{kp}}{\partial t^3}\right\rangle}.$$

2. GW sources:

$1.6 \times 10^{-44}\ \mathrm{sec^2 kg^{-1} m^{-1}}$

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu},$$

So, extremely weak for most cases!

- <u>Laboratory generation of GWs:</u>

Ex). A rotating dumbbell consisting of two masses (1ton, 2m & 1kHz) produces

$$h_{lab} = 2.6 \times 10^{-33}\mathrm{m} \times \frac{1}{R}.$$

R ~ λ = 300km ➔ $h_{lab} = 9 \times 10^{-39}$

Ex). From particle accelerators, e.g., LHC,

$$h_{\mu\nu} \sim 4.94 \times 10^{-54} \frac{\frac{m}{m_p}\left(\frac{v}{v_0}\right)^2}{r}$$

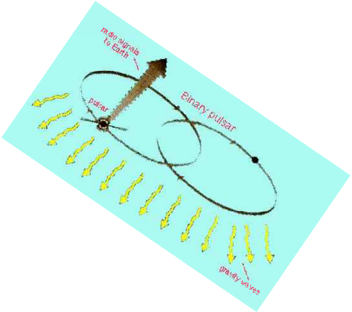
where $v_0 = 0.9$

$$\sim 10^{-30} \frac{(v/v_0)^2}{r}$$

for $m = 1.67g = 10^{24} m_p$

In the LHC, v~0.999999991 and 10^11 protons per bunch ➔ h ~ 10^-43 !!

- <u>Astrophysical sources of GWs, e.g., binary,:</u>

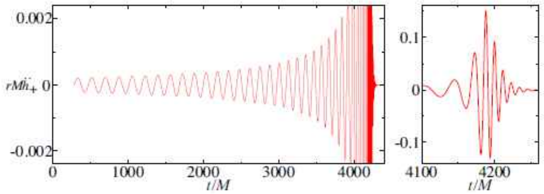


$$h_{\mu\nu} \sim 10^{-20} \left(\frac{M}{M_{\rm SUN}}\right) \left(\frac{M/M_{\rm SUN}}{f/{\rm kHz}}\right)^{2/3} \frac{\rm Mpc}{r}$$

Ex). Neutron star binary $h_{ns} = R_{s1} R_{s2} / rR$

$R_s = 2GM/c^2$ ~ 4km (~ $1.4\,\mathrm{M}_\odot$),

r ~ 200km & R ~ 200Mpc ➔ h ~ 10^{-23}



Ex). Black hole binary $h_{bh} \sim R_s / R$

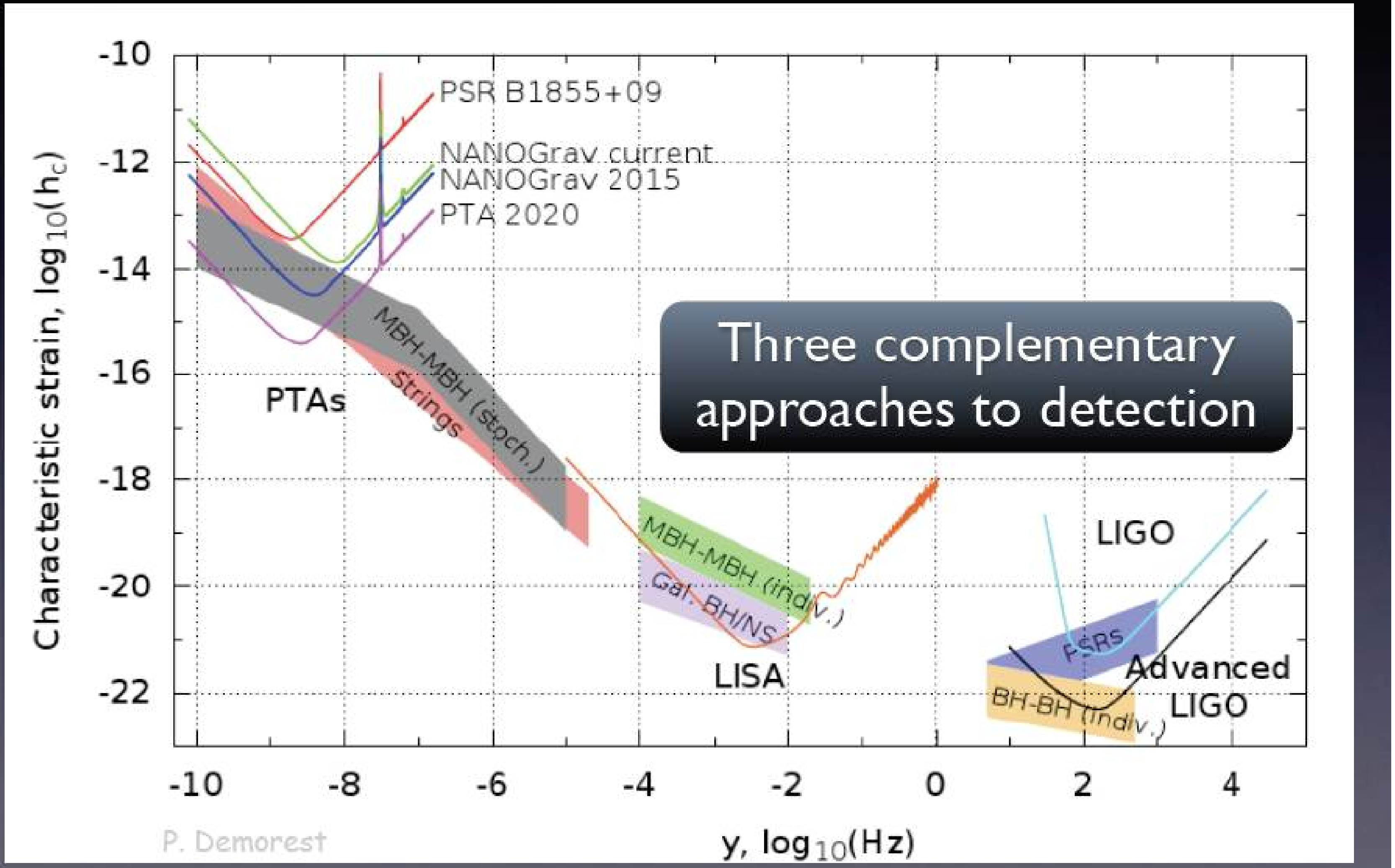
$10\,\mathrm{M}_\odot$ ➔ $h \sim 5 \times 10^{-21}$ (≫ ~10^-40)

$L \sim L_0 + 1/2\ h\ L_0$

$\Delta L \sim h\ L_0 \sim$ 10^-21 x 6400km x 2 ~ 10^-14m ~ size of nucleon

Much better, but still extremely hard to detect even for ASs!!

Gravitational-Wave Spectrum



Three complementary approaches to detection

Courtesy: NanoGrav, M. McLaughlin, P. Demorest

Credit courtesy: Patrick Brady

- Bandwidths and significances of sources: (Cutler & Thorne '02)
  - Extremely Low Freq. band (ELF, 10^-15~10^-18Hz):
    - Primordial GWs
    - Imprint on the polarization of CMB radiations
    - Quantum origin at big bang subsequently amplified by inflation
    - Great potential for probing the physics of inflation

- VLF band (10^-7~10^-9Hz):
  - Emitted by pulsars (e.g., Hulse-Taylor ‘75)
  - via pulsar timing array, or indirectly by pulses at earth
  - Extremely massive BH binary or violent processes in 0.1 second of the early universe

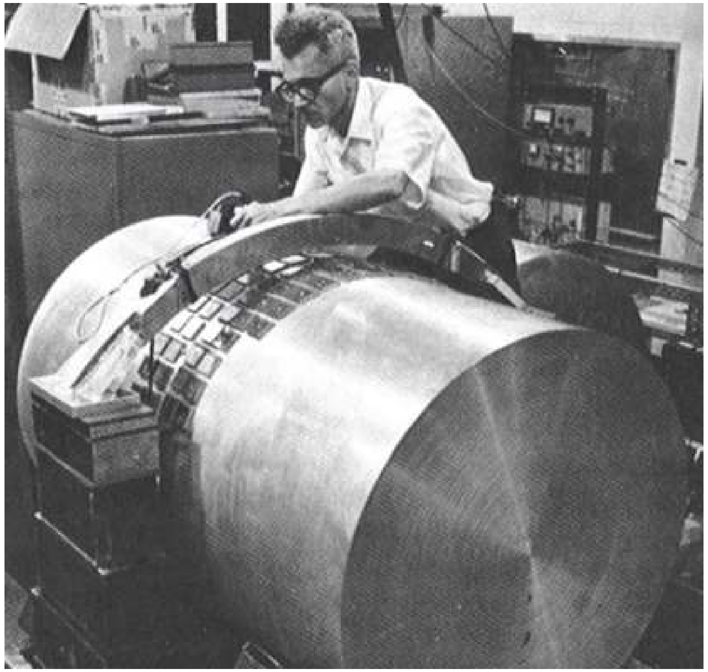
- LF band (10^-4~0.1Hz):
  - From massive (10^5~10^7M☉) BH binaries out to cosmological distances (CD)
  - From small BHs, NSs and WDs spiraling into massive BHs out to CDs
  - From orbital motions of WDB, NSB, and stellar-mass BHB in our own galaxy
  - And possibly from violent processes in the very early universe
  - To be observed by the space-based detector, LISA

- HF band (10~10^3Hz):
  - From a spinning slightly deformed NS in our Milky Way galaxy
  - From a variety of sources in the more distance:
    - Final inspiral and collisions of NSB and stellar-mass BHB (up to ~100M⊙)
    - Tearing apart of a NS by a companion BH
    - Supernovae, Triggers of GRBs, etc.
  - To be measured by earth-based detectors such as LIGO, Virgo, KAGRA, and resonant-mass bar

II. Detection experiments for GWs

1. Brief history:

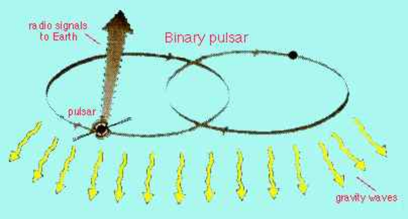
- GW is predicted even before the full formulation of GR.
- It was J. Weber ('63) who tried for the first time the detection experiment by using a resonant-mass cylindrical bar at 1660Hz.
- It was very sensitive h~10^-16, but still far from ~10^-22.

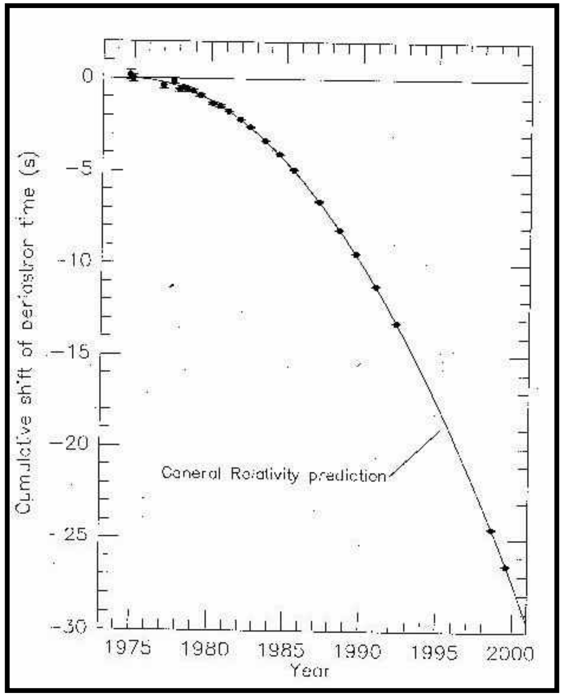


- To overcome this gap (~10^6) interferometric detectors have been developed since '70.
- LIGO (Laser Interferometer Gravitational-wave Observatory) performed its first operation, S1, in 2002, and achieved its designed sensitivity at S6 in 2010.
- Other GW detectors: Virgo, GEO, KAGRA (in construction), InLIGO (in plan).
- There has been no GW signal detected so far.
- LIGO has been upgraded to have a better sensitivity of ~10 times, and this advanced one (aLIGO) will be in operation in 2015.

2. Indirect detections:

- Ex) Period change in a binary pulsar

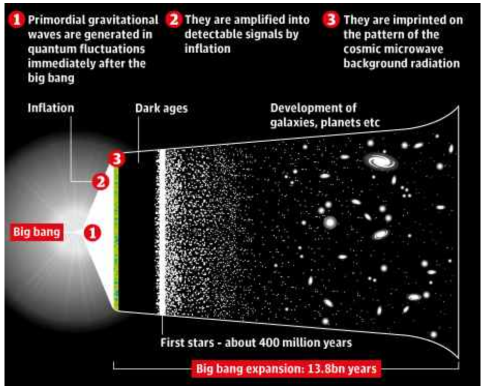




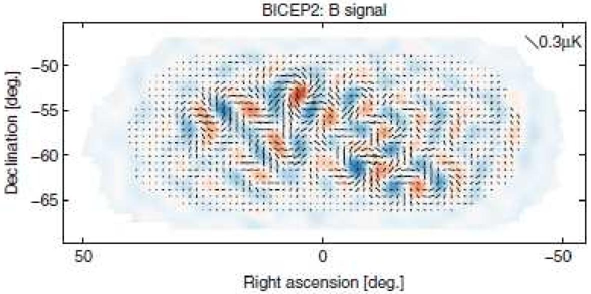
PSR1913+16 Hulse & Taylor (1974)

- P ~ 8hr and e ~ 0.6
- Effect of Gravitational Wave Radiation
- 1993 Nobel Prize

– Ex) Imprints of primordial GWs

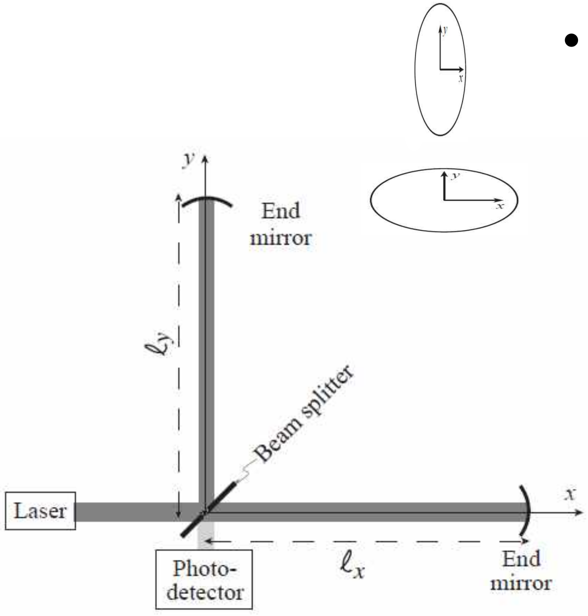


BICEP2 (2014)



“PRL (’14)”

3. Interferometric detector:



- <u>Principles:</u>
  - Measure the change of lengths by using a Michelson-type interferometer:

$$\delta x = \tfrac{1}{2} h_+ \ell_x \ , \quad \delta y = -\tfrac{1}{2} h_+ \ell_y$$

$$\rightarrow \quad \Delta\varphi(t) = \omega_o(2\delta y - 2\delta x) = \omega_o(\ell_x + \ell_y) h_+(t)$$

  - Isn’t the light itself stretched as well due to passages of GWs?

    ➔ Co-expansion of the arms and of the light wave!

    ➔ The interferometer really works?

- In the TT gauge and geometric optics,

$$\boxed{ds^2 = -dt^2 + [1 + h_+(t - z)]dx^2 + [1 - h_+(t - z)]dy^2 + dz^2}$$

$A^\alpha = \Re(\mathsf{A}^\alpha e^{i\varphi})$ A^α: slowly varying amplitude, φ : rapidly varying phase

Note that mirrors and BS do not move!

- How does light interact with GWs?

$$A^{\alpha;\mu}{}_{\mu} = 0$$

$$\vec{k} \cdot \vec{k} = \varphi_{,\alpha}\varphi_{,\beta}g^{\alpha\beta} = 0$$

w/ $\vec{k} \equiv \vec{\nabla}\varphi$

➔

$$-\left(\frac{\partial\varphi_{x\ \mathrm{arm}}}{\partial t}\right)^2 + [1 - h(t)]\left(\frac{\partial\varphi_{x\ \mathrm{arm}}}{\partial x}\right)^2 = 0\ ,$$

$$-\left(\frac{\partial\varphi_{y\ \mathrm{arm}}}{\partial t}\right)^2 + [1 + h(t)]\left(\frac{\partial\varphi_{y\ \mathrm{arm}}}{\partial y}\right)^2 = 0\ .$$

- The solutions for the outwards and backwards from the beam splitter are, respectively,

$$\begin{aligned}
\varphi^{\rm out}_{x\ {\rm arm}} &= -\omega_o\left[t - x + \frac{1}{2}H(t-x) - \frac{1}{2}H(t)\right] \ , \\
\varphi^{\rm out}_{y\ {\rm arm}} &= -\omega_o\left[t - y - \frac{1}{2}H(t-y) + \frac{1}{2}H(t)\right] \ , \\
\varphi^{\rm back}_{x\ {\rm arm}} &= -\omega_o\left[t + x - 2\ell_x + \frac{1}{2}H(t+x-2\ell_x) - \frac{1}{2}H(t)\right] \ , \\
\varphi^{\rm back}_{y\ {\rm arm}} &= -\omega_o\left[t + y - 2\ell_y - \frac{1}{2}H(t+y-2\ell_y) + \frac{1}{2}H(t)\right] \ .
\end{aligned}$$

$$H(t) \equiv \int_0^t h(t')dt'$$

➡
$$\begin{aligned}
\Delta\varphi \ \equiv\ \varphi^{\rm back}_{x\ {\rm arm}} - \varphi^{\rm back}_{y\ {\rm arm}} &= -\omega_o[-2(\ell_x - \ell_y) + \frac{1}{2}H(t-2\ell_x) + \frac{1}{2}H(t-2\ell_y) - H(t)] \\
&\simeq\ +2\omega_o[\ell_x - \ell_y + \ell h(t)]
\end{aligned}$$

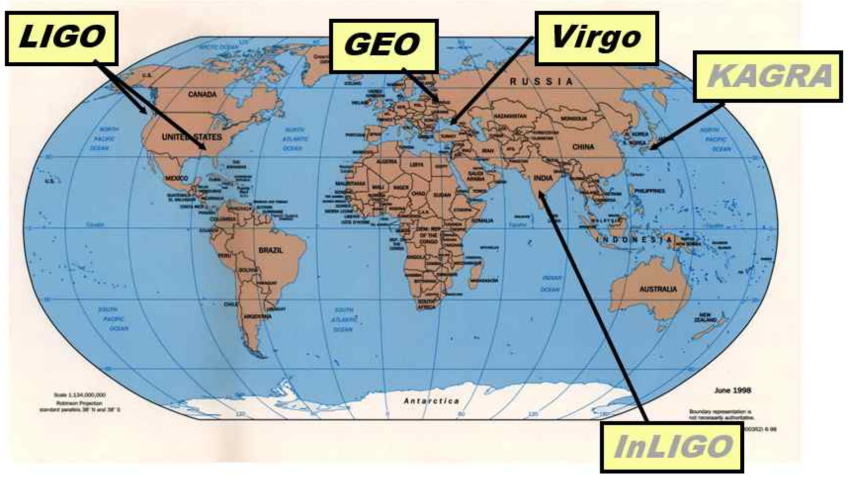
➡
$$\boxed{I_{\rm PD} \propto |e^{i\Delta\varphi} - 1|^2 \simeq |\Delta\varphi|^2 \simeq 4\omega_o^2(\ell_x - \ell_y)^2 + 8\omega_o^2(\ell_x - \ell_y)\ell h_+(t)} \ .$$

✓ **Therefore, we see an intensity modulation directly proportional to the GW perturbation!!**

- Detector networks: LIGO, Virgo, GEO, KAGRA, InLIGO

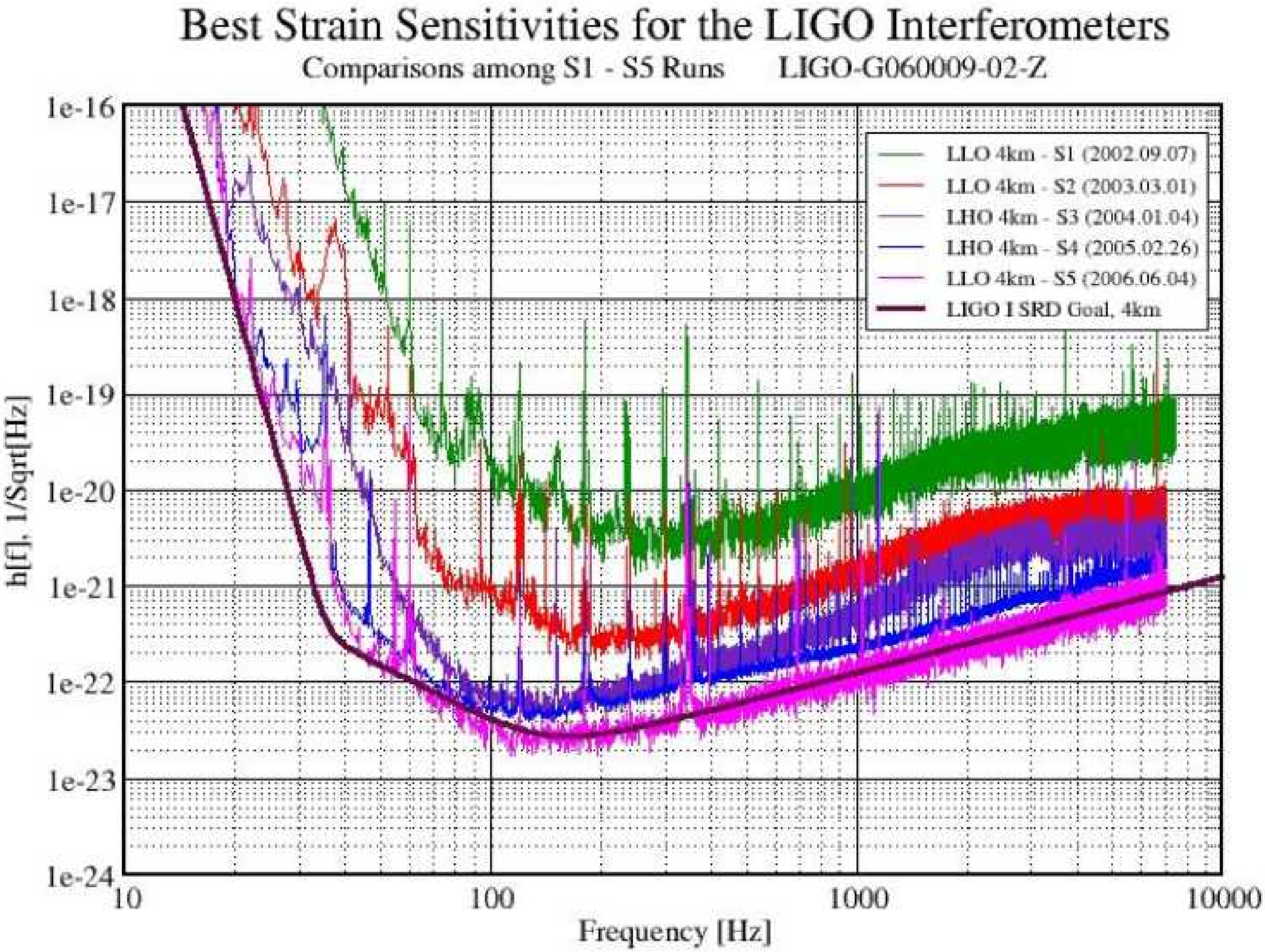
4km

LIGO Livingston Obs. (LLO)



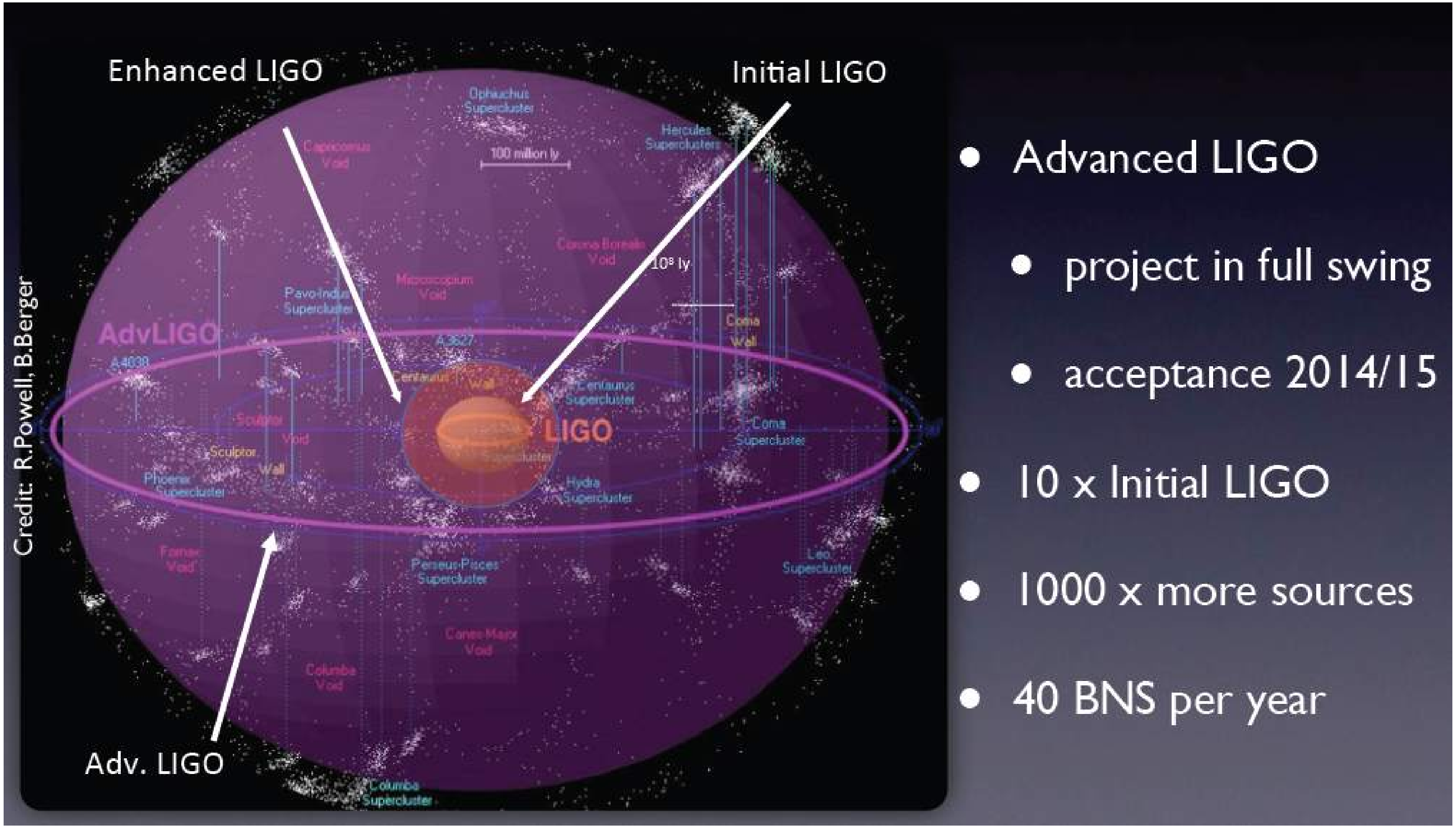
- The initial LIGO performed 6 science runs: S1 (2002) ~ S6 (2010)
- It has been upgraded since then: Advanced LIGO (aLIGO)
- aLIGO will have 10 times better sensitivity, and start to run in 2015 or 2016.

- <u>Sensitivities and event rates :</u>
  - Achieved the designed sensitivity in S5, 2009



Source: https://www.advancedligo.mit.edu/summary.html

- Event rate of the initial LIGO: ~ 1 per 100 years for NS binaries



- Advanced LIGO
  - project in full swing
  - acceptance 2014/15
- 10 x Initial LIGO
- 1000 x more sources
- 40 BNS per year

Credit courtesy: Patrick Brady

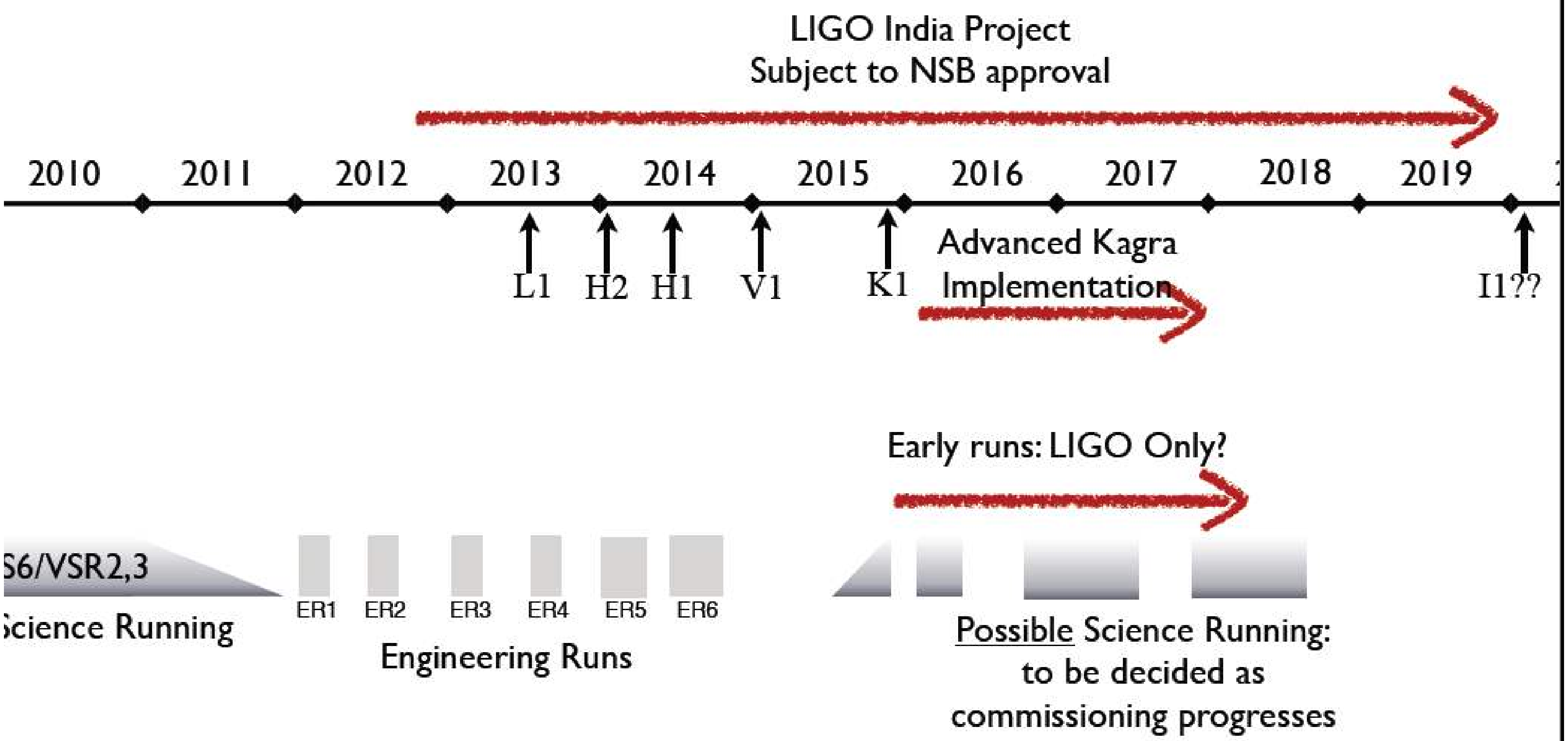
- Current status of aLIGO:

Commissioning focus for the first Observational Run

- ❑ Target sensitivity
    - ➢ Binary neutron star coalescence range of 40-80 Mpc, each detector
    - ➢ Important frequency band: 20—300 Hz
    - ➢ Input laser power: 25 W
- ❑ Nominal duration
    - ➢ 3 months
- ❑ Run start
    - ➢ Some time in 2015, perhaps mid-2015

Credit courtesy: Peter Fritschel, Stanford LVC (2014.08.27)

Tentative Timing



LIGO India Project
Subject to NSB approval

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

L1 H2 H1 V1 K1

Advanced Kagra
Implementation

I1??

Early runs: LIGO Only?

S6/VSR2,3
Science Running

ER1 ER2 ER3 ER4 ER5 ER6
Engineering Runs

Possible Science Running:
to be decided as
commissioning progresses

Credit courtesy: Patrick Brady

LOSC S5 data release

- The LIGO S5 strain data is now in public release : losc.ligo.org
- LOSC = LIGO Open Science Center

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the National Science Foundation of the United States.

- Getting Started
- Data & Catalogs
- Timelines
- Tutorials
- Software
- My Sources
- GPS ↔ UTC
- About LIGO
- Student Projects
- Acknowledgement

Welcome to the LIGO Open Science Center

This site provides access to data from the LIGO observatories and associated software tools. Please click below to join the email list, so that we can inform you of updates and data releases from this site.

Click to join the email list

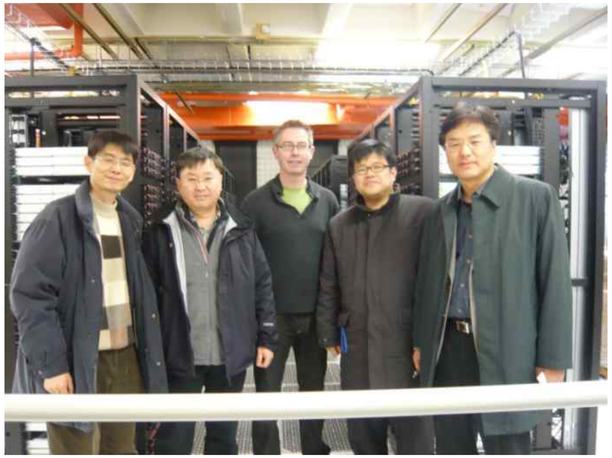
If this is your first visit to the site, we suggest you START HERE.

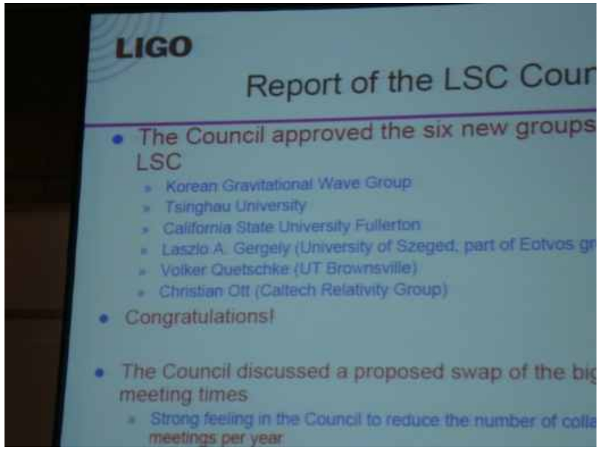
For general information on LIGO, please visit ligo.org.
If you have LSC credentials, you may go to the development site.

LIGO Hanford Observatory, Washington (image: C.Gray) LIGO Livingston Observatory, Louisiana (image: J.Giaime)

III. Korean activities on GW physics

- **Brief history:**
  - Some activities such as workshops and summer schools on numerical relativity and GWs starting from 2003
  - 2008.09: Korean Gravitational Wave Group (KGWG) founded
  - 2009: Visit to LSU and UWM and series of meetings
  - 2010: Joined LSC (LIGO Scientific Collaboration)
  - 2012: Collaborations with KAGRA began
  - 2013: Bidding to host 11th Amaldi Conference on GWs approved (2015.06.21~26 at Gwangju). 1st paper and 1st PhD in GW data analysis appeared





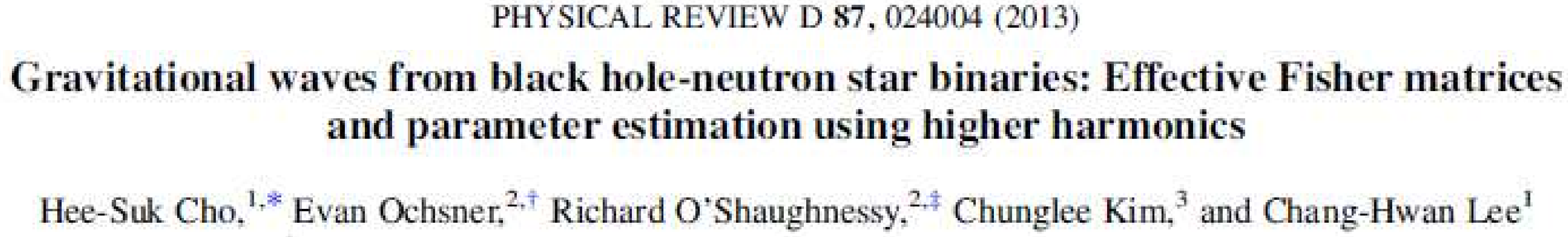
LIGO

Report of the LSC Cour

- The Council approved the six new groups LSC
  - Korean Gravitational Wave Group
  - Tsinghau University
  - California State University Fullerton
  - Laszlo A. Gergely (University of Szeged; part of Eotvos gr
  - Volker Quetschke (UT Brownsville)
  - Christian Ott (Caltech Relativity Group)
- Congratulations!
- The Council discussed a proposed swap of the big meeting times
  - Strong feeling in the Council to reduce the number of colla meetings per year

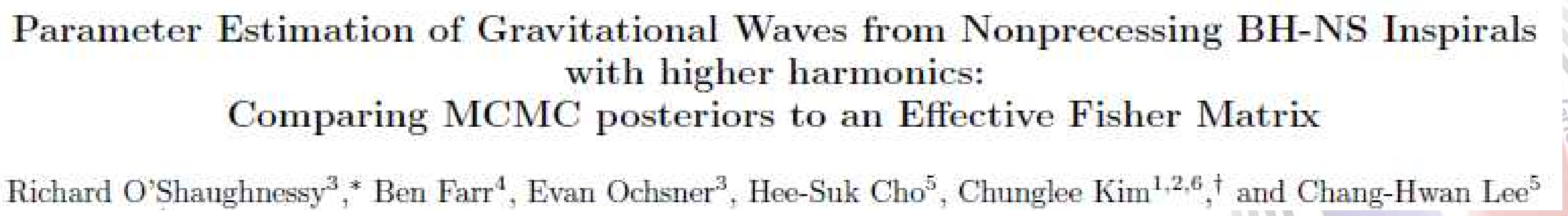
- **<u>KGWG organization:</u>**
  - Members from 2 National insts and 9 Universities
  - LIGO: Four (6) faculty/staff, 3 postdocs, 4 PhD students, 5 technical staff, and supporting members.
  - KAGRA: ~17 members (7 co-members of LSC)
  - Group leader: Hyung Mok Lee at SNU

- **KGWG activities:**
  - LIGO: Data analyses. KAGRA: Data analysis + Instrumentation
  - CBC, AuxMVC, PE (Markov-Chain Monte Carlo Analysis of GW signals), G-ray burst search, ANN, etc
  - Teleconferences per week and F2F meetings per month
  - Summer school on NR and GWs


PHYSICAL REVIEW D 87, 024004 (2013)

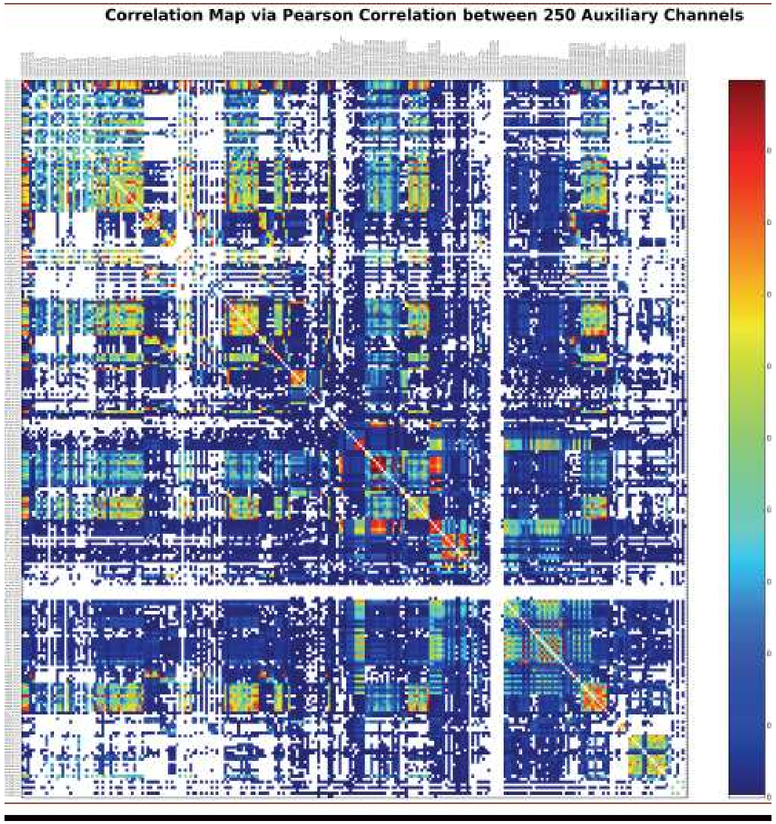
Gravitational waves from black hole-neutron star binaries: Effective Fisher matrices and parameter estimation using higher harmonics

Hee-Suk Cho,[1,*] Evan Ochsner,[2,†] Richard O'Shaughnessy,[2,‡] Chunglee Kim,[3] and Chang-Hwan Lee[1]


Parameter Estimation of Gravitational Waves from Nonprecessing BH-NS Inspirals with higher harmonics: Comparing MCMC posteriors to an Effective Fisher Matrix

Richard O'Shaughnessy[3],* Ben Farr[4], Evan Ochsner[3], Hee-Suk Cho[5], Chunglee Kim[1,2,6],[†] and Chang-Hwan Lee[5]

And several more papers

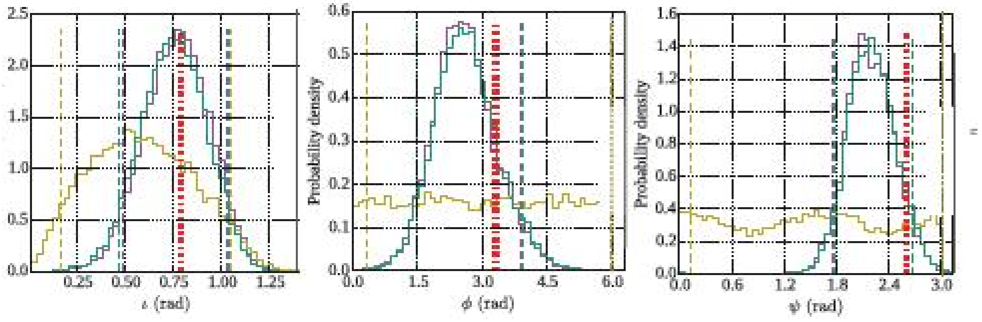


Correlation Map Analysis of Auxiliary Channels using Pearson's Correlation Coefficient

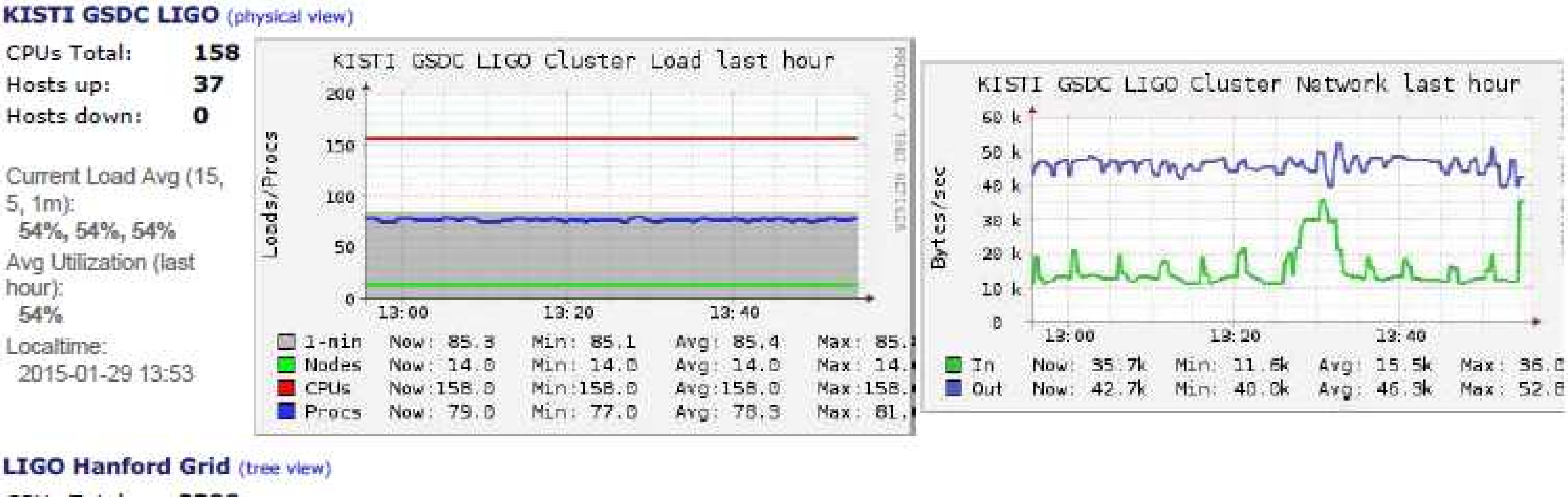
John J. Oh, Sang Hoon Oh and Edwin J. Son

MCMC parameter estimation of CBC inspirals with TaylorF2Amp

Chunglee Kim[1,2], Jeongcho Kim[3], and Hyung Won Lee[3]



- **KISTI GSDC LDG (LIGO Data Grid):**
  - Computing environment for GW data analyses
  - KISTI established a Tier 3 center for it.
  - 35 nodes (420CPUs) and 152TBs
  - LIGO & Virgo data stored and analysis pipeline softwares installed
  - 124TBs of LIGO/Virgo data stored



KISTI GSDC LIGO (physical view)

CPUs Total: **158**
Hosts up: **37**
Hosts down: **0**

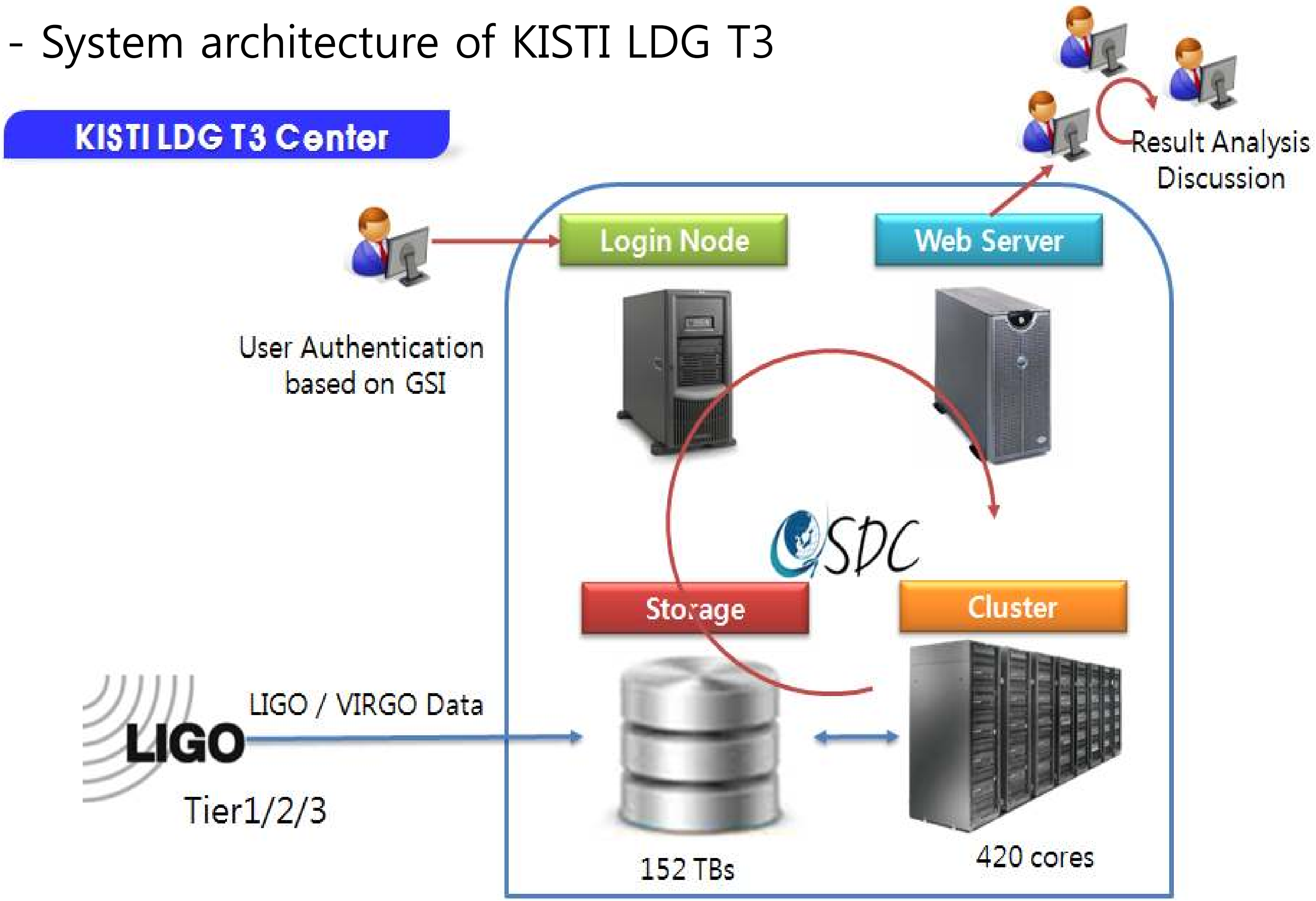
Current Load Avg (15, 5, 1m):
54%, 54%, 54%
Avg Utilization (last hour):
54%
Localtime:
2015-01-29 13:53

```
KISTI GSDC LIGO Cluster Load last hour
1-min   Now: 85.3   Min: 85.1   Avg: 85.4   Max: 85.
Nodes   Now: 14.0   Min: 14.0   Avg: 14.0   Max: 14.
CPUs    Now:158.0   Min:158.0   Avg:158.0   Max:158.
Procs   Now: 79.0   Min: 77.0   Avg: 78.3   Max: 81.
```

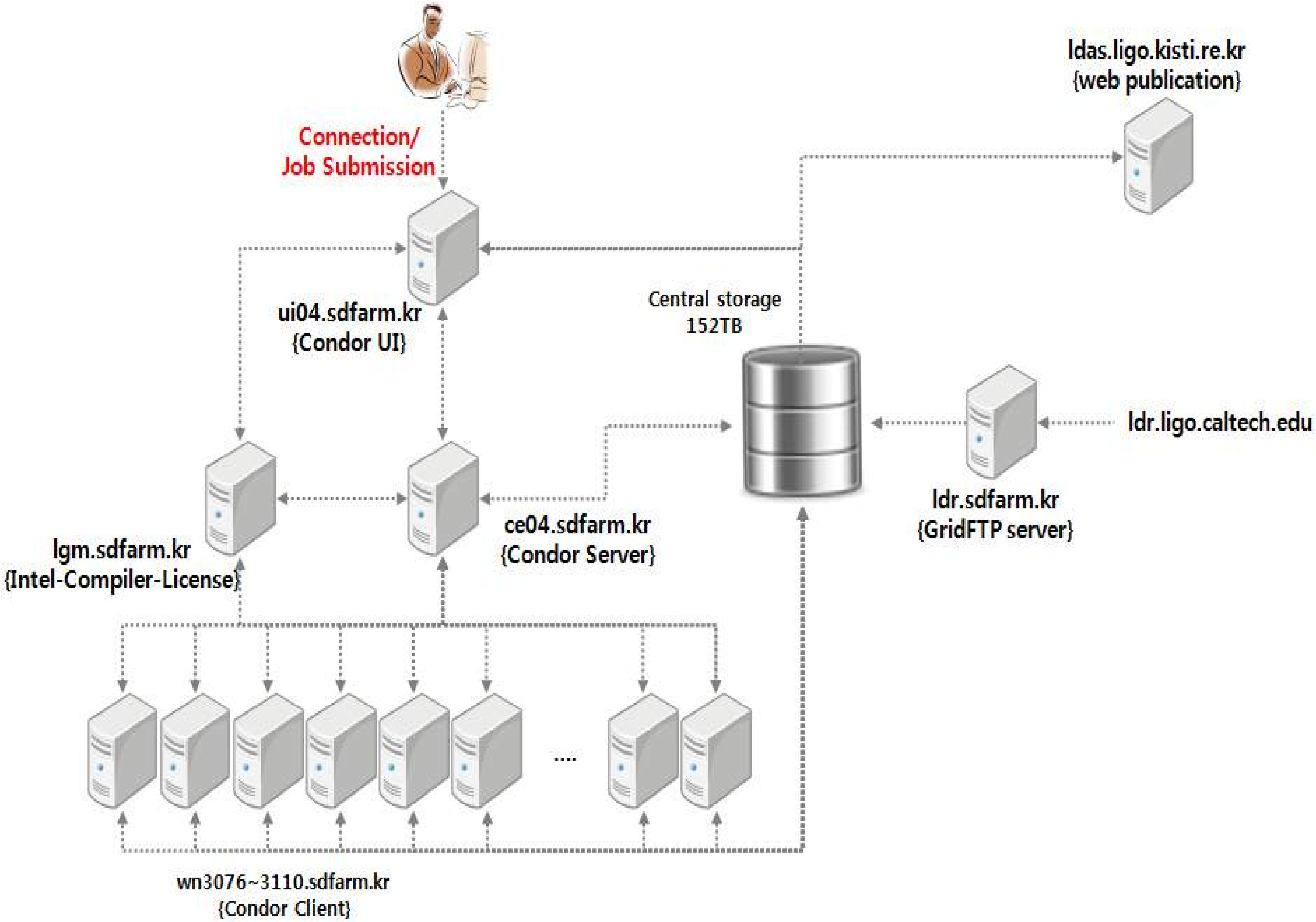
```
KISTI GSDC LIGO Cluster Network last hour
In    Now: 35.7k   Min: 11.6k   Avg: 15.5k   Max: 36.
Out   Now: 42.7k   Min: 40.0k   Avg: 46.3k   Max: 52.
```

LIGO Hanford Grid (tree view)

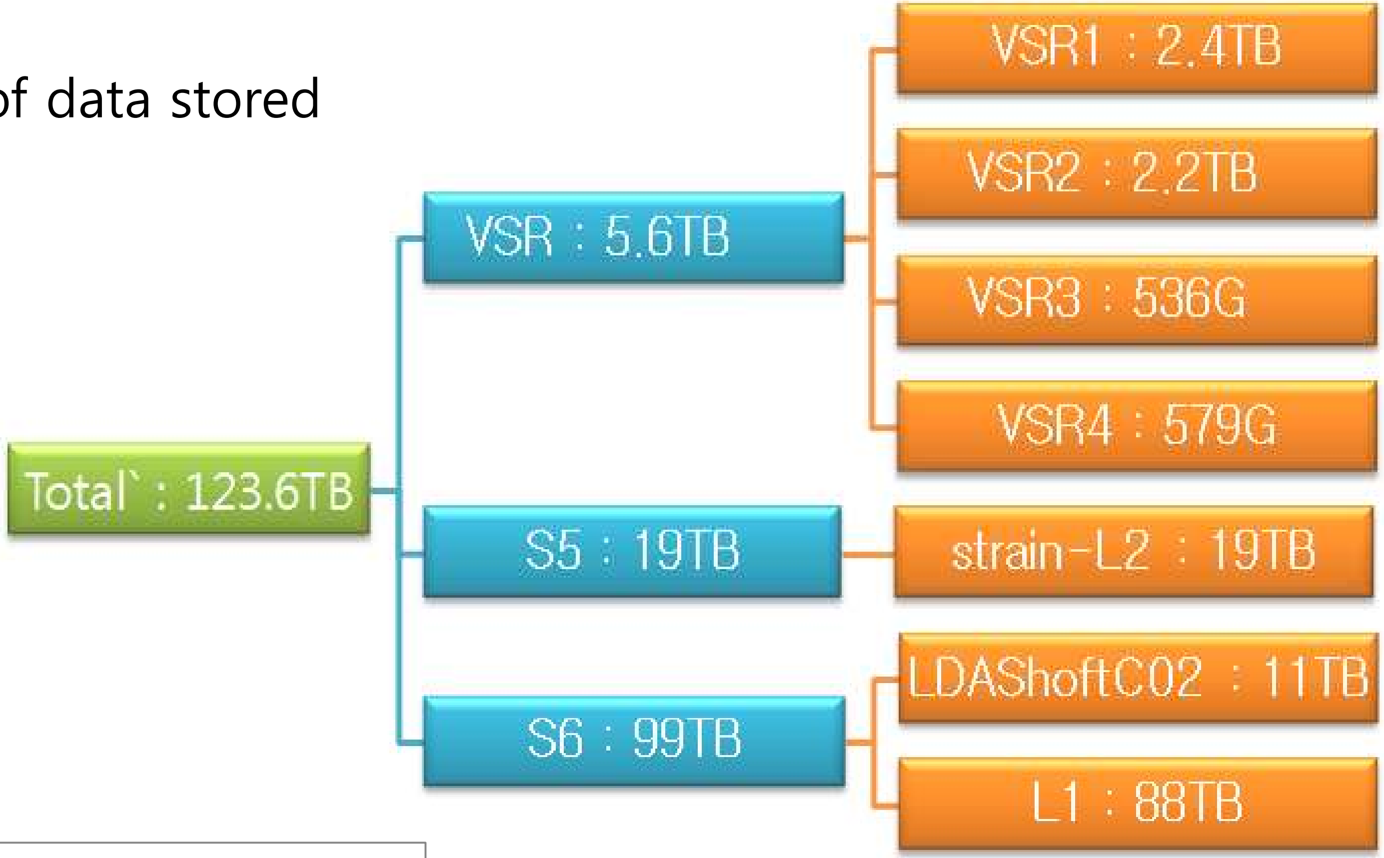
- System architecture of KISTI LDG T3



- Configuration of computing resources in the KISTI LDG T3



- Descriptions of data stored

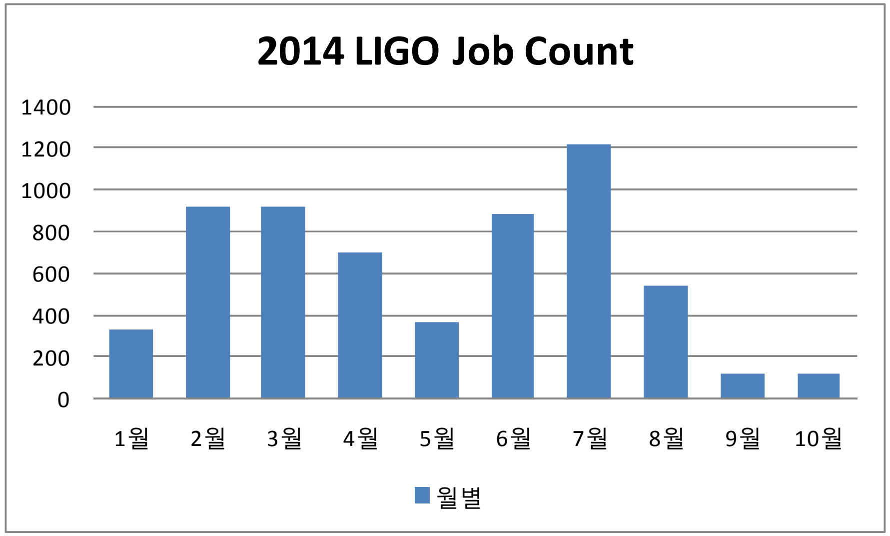


Total` : 123.6TB

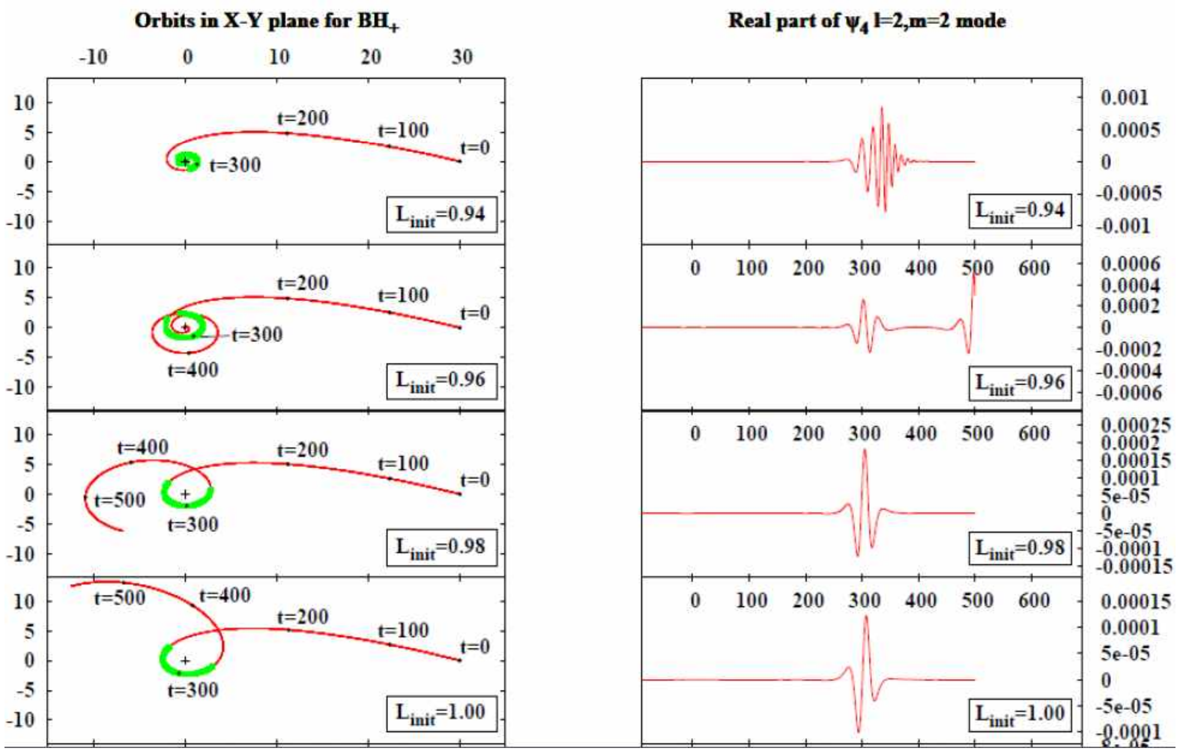
VSR : 5.6TB
- VSR1 : 2.4TB
- VSR2 : 2.2TB
- VSR3 : 536G
- VSR4 : 579G

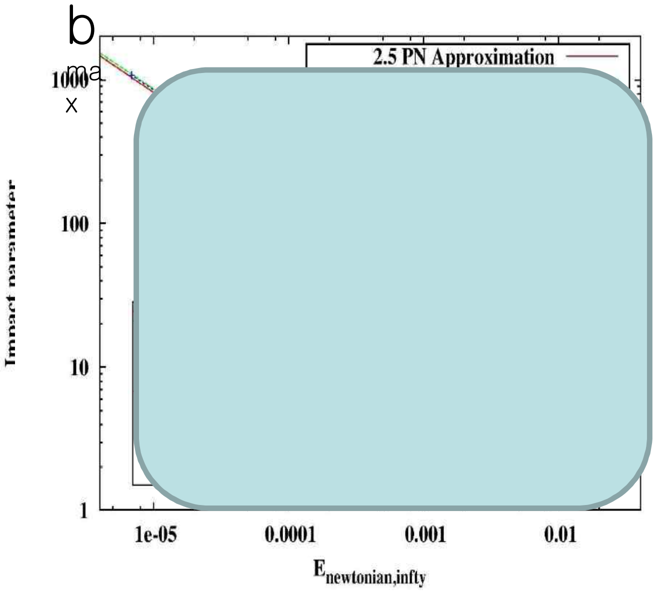
S5 : 19TB
- strain-L2 : 19TB

S6 : 99TB
- LDAShoftC02 : 11TB
- L1 : 88TB



- **Numerical relativity in Korea:**
  - Topics: black holes, Neutron stars, Equilibrium stars and perturbations, Scalar field dark matter model, Core collapse, etc.
  - Members: G. Kang, J. Hansen (KISTI), C. Park (KAIST & KISTI), Y. Bae (SNU & KISTI), H. Kim (SNU), M. Wan (APCTP), J. Kim (Notre Dame U.), S. Lim (KNU), D. Park (APCTP), C. Cho (KASI)
  - Collaborators: P. Diener, F. Loeffler (LSU), M. Shibata (YITP), ……





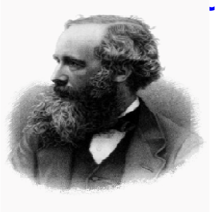
IV. Conclusion

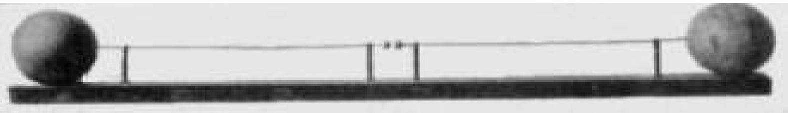
- Summary
  - I have reviewed a definition of GWs, GW spectrum, astronomical sources, physical significances, detection experiment, its principle, etc.
  - Current status of aLIGO and Korean activities are reported briefly.

  - First direct detection of GWs is anticipated in (very) soon!

EM waves

- Theory: Maxwell (1864)
- Detection: H. Hertz (1886)

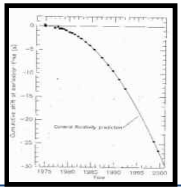




Gravitational waves

- Theory: Einstein (1915)
- Detection: Not yet

Weber (1960)



Hulse & Taylor (1975)

LIGO (?)

- Prospects
  - Rich sciences to investigate through GWs; A new window to our universe; “GW astronomy”

Crab Nebula: Remnant of an Exploded Star (Supernova)

Radio wave (VLA)

Infrared radiation (Spitzer)

Visible light (Hubble)

Ultraviolet radiation (Astro-1)

Low-energy X-ray (Chandra)

High-energy X-ray (HEFT)
*** 15 min exposure ***

Gravitational wave (LIGO)

- Prospects
  - Next generation detectors: Other freq. band, Lab-size detector, Use of quantum effect, etc.

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu},$$

  - Hint at quantum gravity
  - Urgent request: Human and monetary resources
  - Pay your attention to this new frontier!