Detection of Wave Messengers of the Universe

for Multi-messenger Astrophysics

IL H. PARK (SKKU, Korea)

KAIST-KAIX Workshop, KAIST, 2019.7.11

Wave & Particle Astronomy

- Constituent of the universe → energy & matter (visible & dark)
- How to probe & understand the universe (apart from theory) → wave & particle
- **"wave astronomy"** (EM and gravity only at large scale)
  - EM astronomy (optical, UV, IR, X, γ) → multi-wavelength now
  - GW astronomy → GW discovered in 2015 (GW150914)
- **"particle astronomy"** (why not)
- **GW170817 via GW & EM →** NS-NS merger & GRB & kilonova → **dawn of "multi-messenger astrophysics (MMA)"**
- **Future GW detectors → "multi-wavelength GW" astronomy**

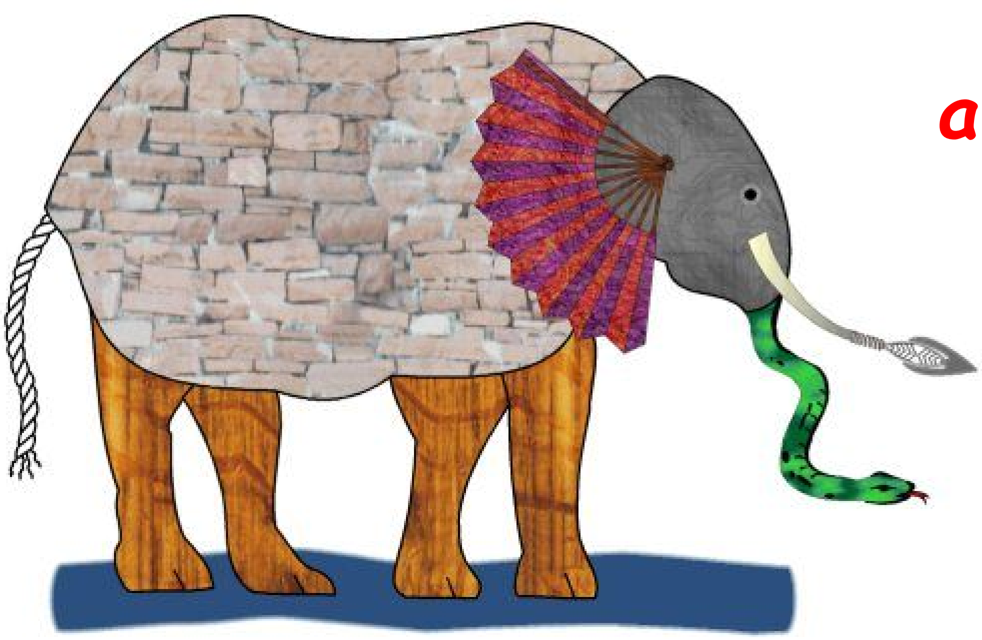
What are cosmic rays?

- Particles traveling the Universe at high speed (primary cosmic rays)
- Arrive to the Earth uniformly (0.1% level)
- Mostly proton (hydrogen nuclei)
- Others: light nuclei such as helium electrons

The Mystery of High Energy Cosmic Rays

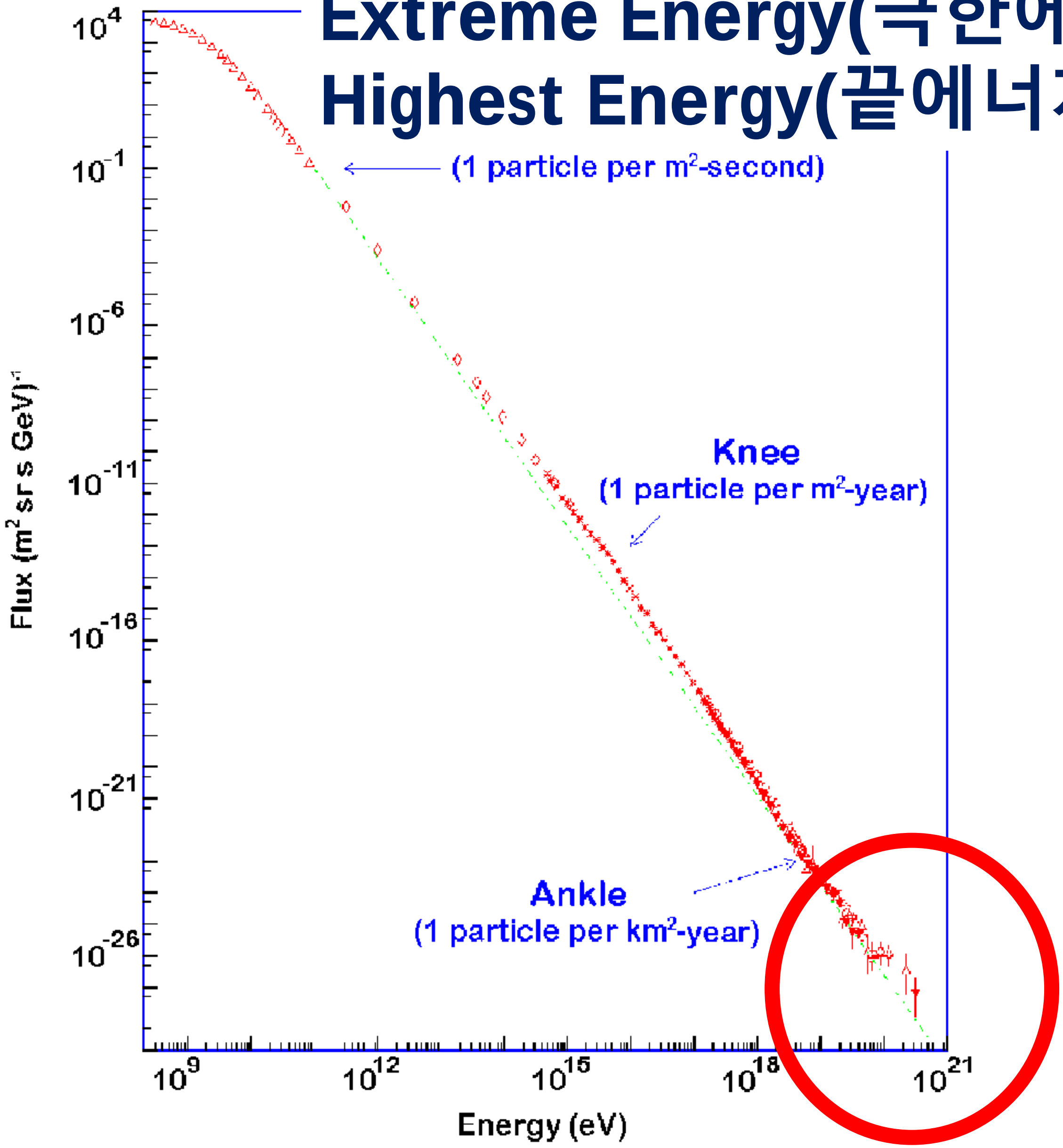
1. How accelerated to such very high energies?
2. Where do they come from?
3. What is the composition?

- No one knows …

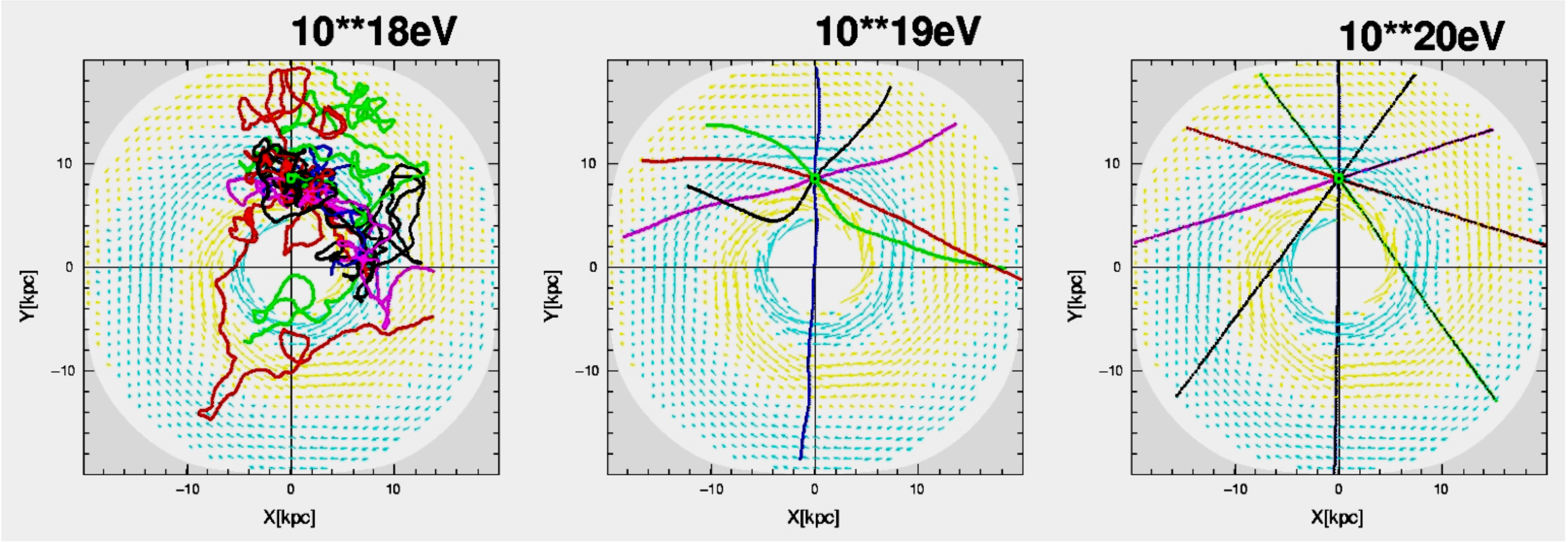


ORIGIN? Unknown!
a Century Old Puzzle!
at all energies…

Ultra High Energy(초고에너지)
Extreme Energy(극한에너지)
Highest Energy(끝에너지)



E>10^{20} eV particles are not reflected by GMF

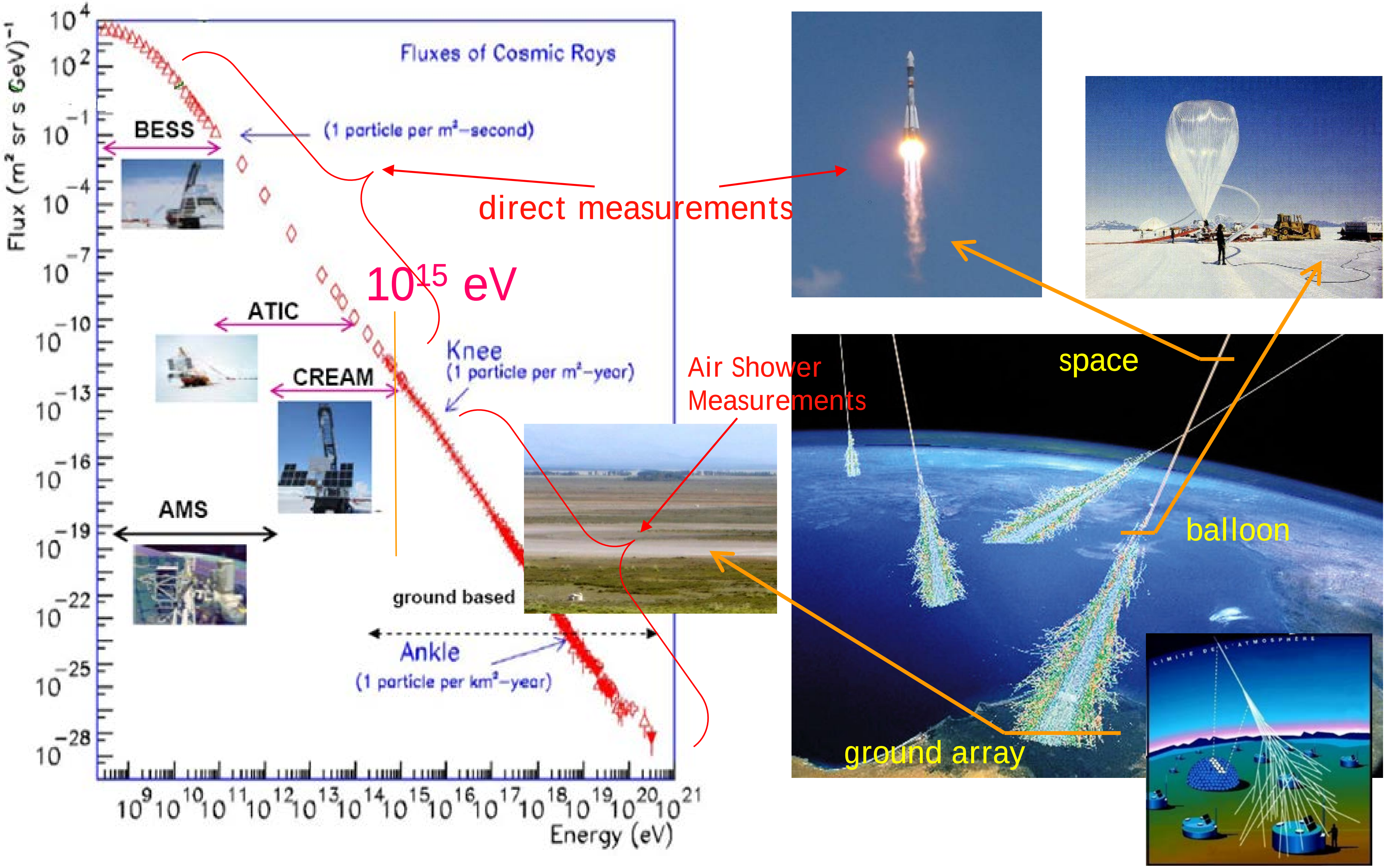


Specify origins by the arrival direction

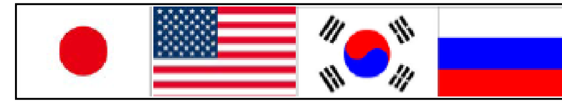
→ Particle Astronomy

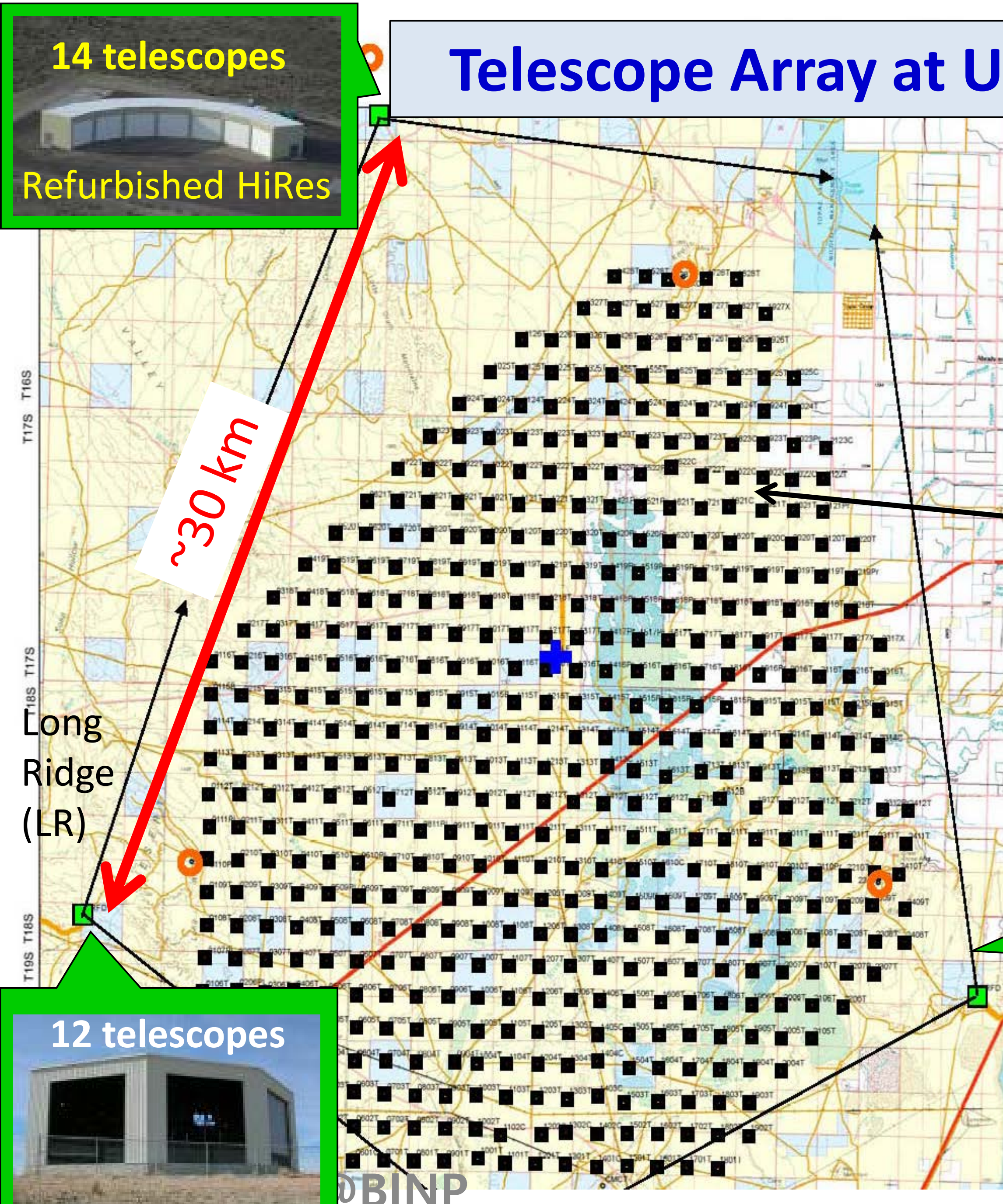
How to measure the cosmic rays?

Methods vary by detecting position in CR cascade



Telescope Array at Utah





Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

∼**700 km^2**

Fluorescence Detector(FD)

3 stations, 38 telescopes

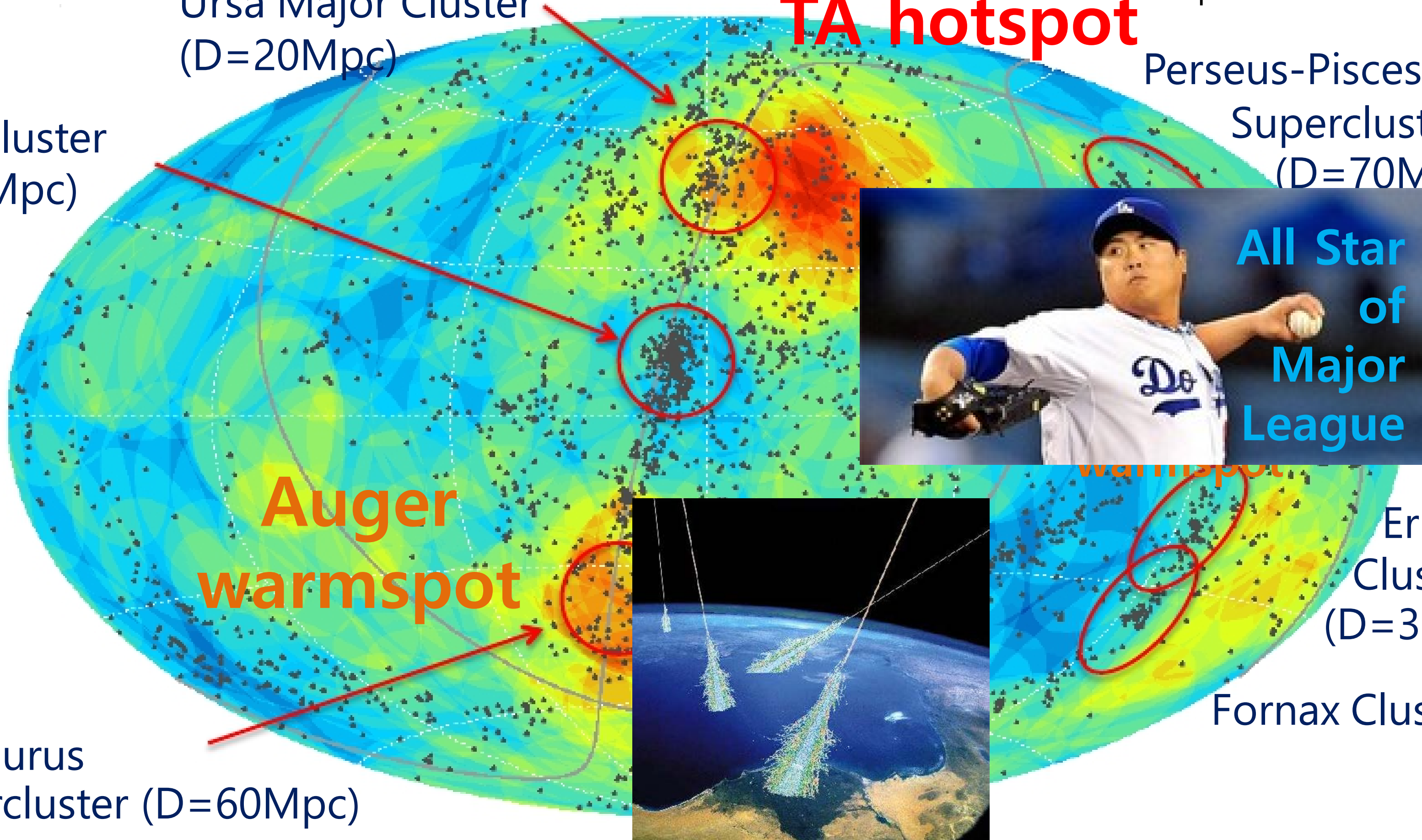
@BINP

FD and SD: fully operational since 2008/May

All sky survey with TA and Auger

TA 7 years (>57 EeV)
Auger 10 years (>57 EeV)

(no E scale adjust.)
Equatorial coordinates

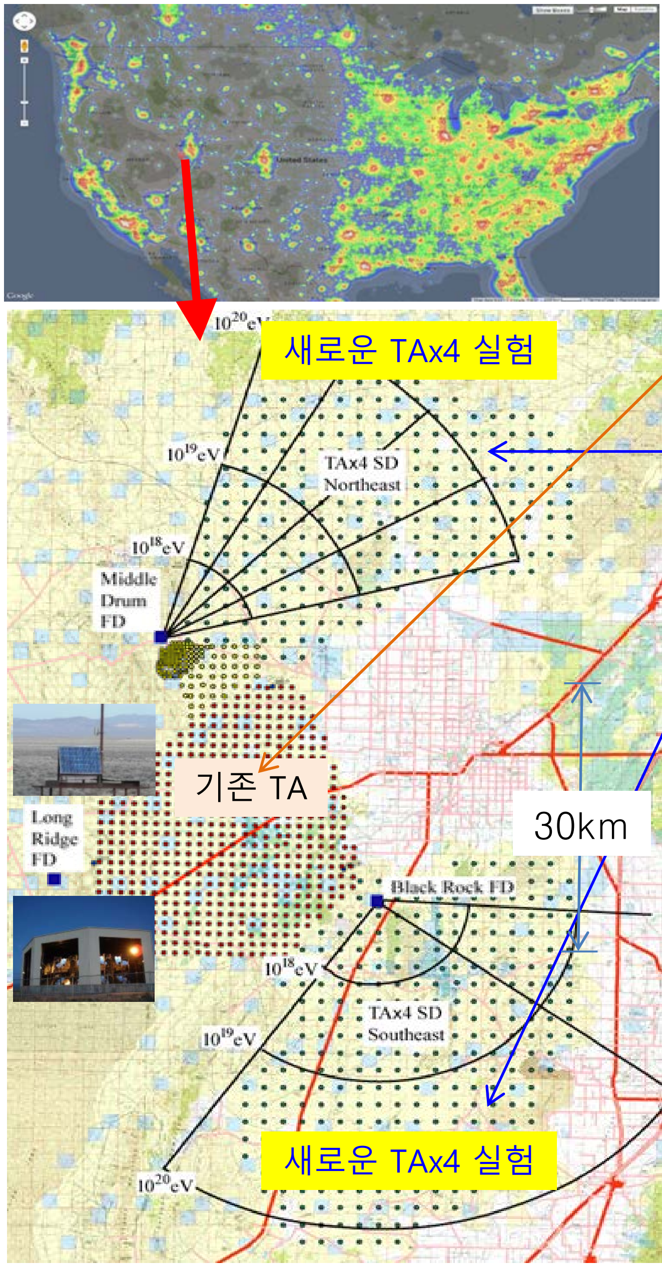


Huchra, et al, ApJ, (2012)

dots (·) : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster

A new TAx4 Experiment at Utah (2018-)



- **Telescope Array(TA): 700km^2 at a desert of Utah, 1.2km array of 507 scintillation detectors and 3 large fluorescence telescopes**
- **Extending 4 times larger (TAx4 experiment) starts in 2019, and a half completed. :**
- **SKKU and Hanyang Univ. contribute detectors for TAx4**

Fab & Deployment of TAx4 Detectors

Japan Korea

Utah, USA

① Scintillator counter assembly under way at Akeno observatory in Japan and CCRR of SKKU since March 2018

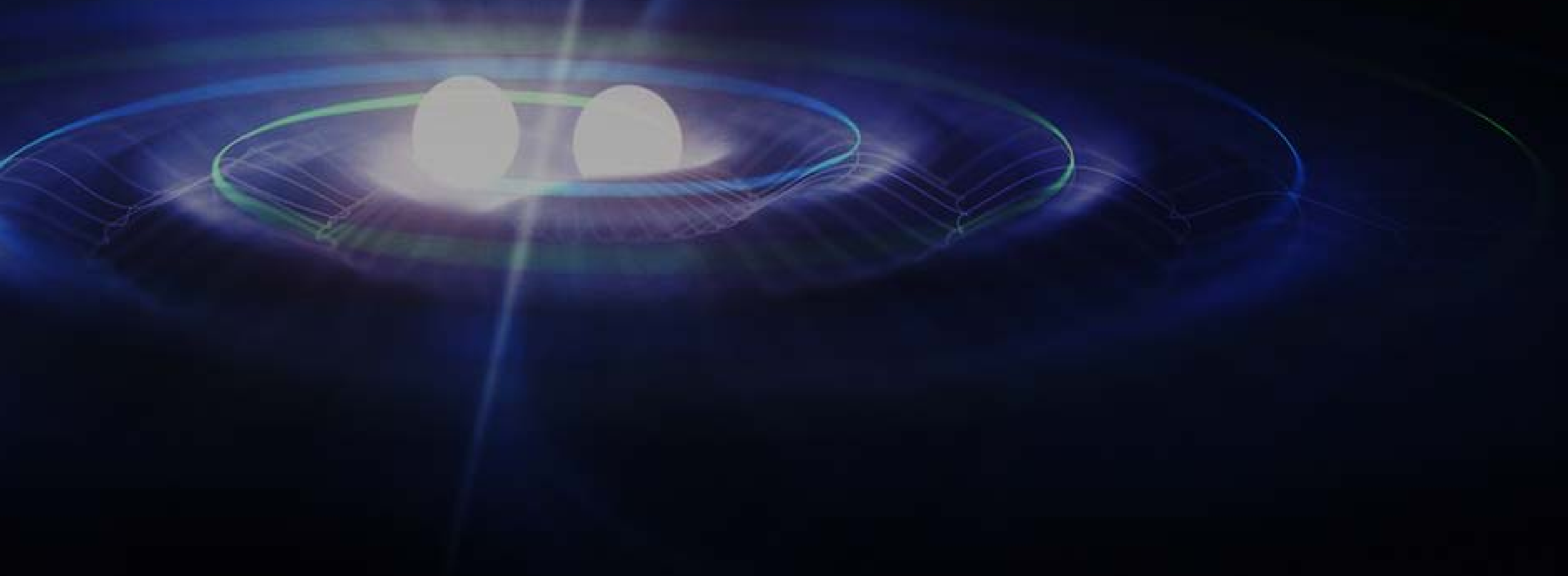
② Final assembly (workshop) at Utah

③ Assembled SDs (workshop) at Delta

④ Staking (for SD positioning and follow-up surveys) & Deployment by helicopters

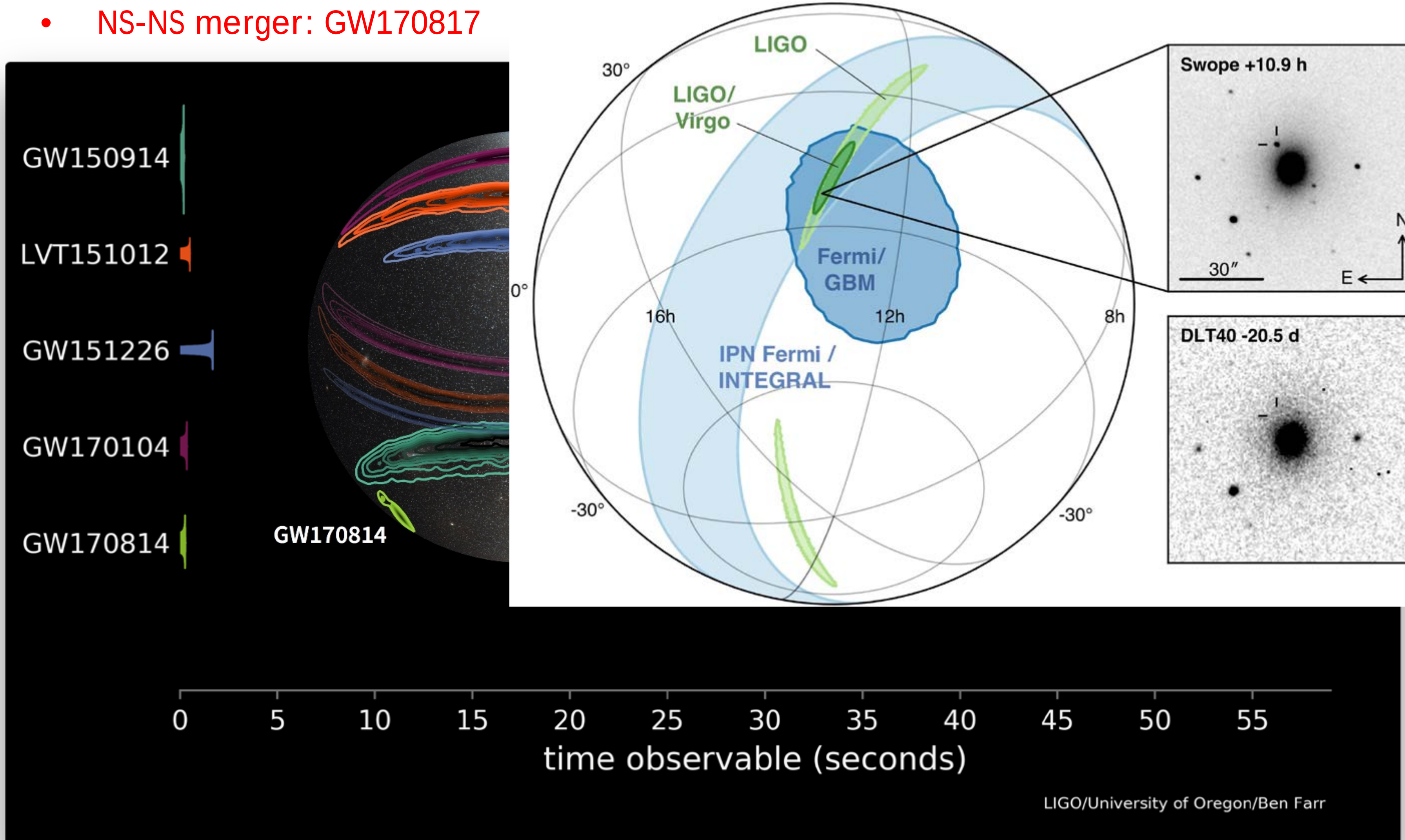
Detection of Multi-Wave Messengers (Gravitational Wave & EM Wave)

→ Dawn of Multi-Messenger Astrophysics

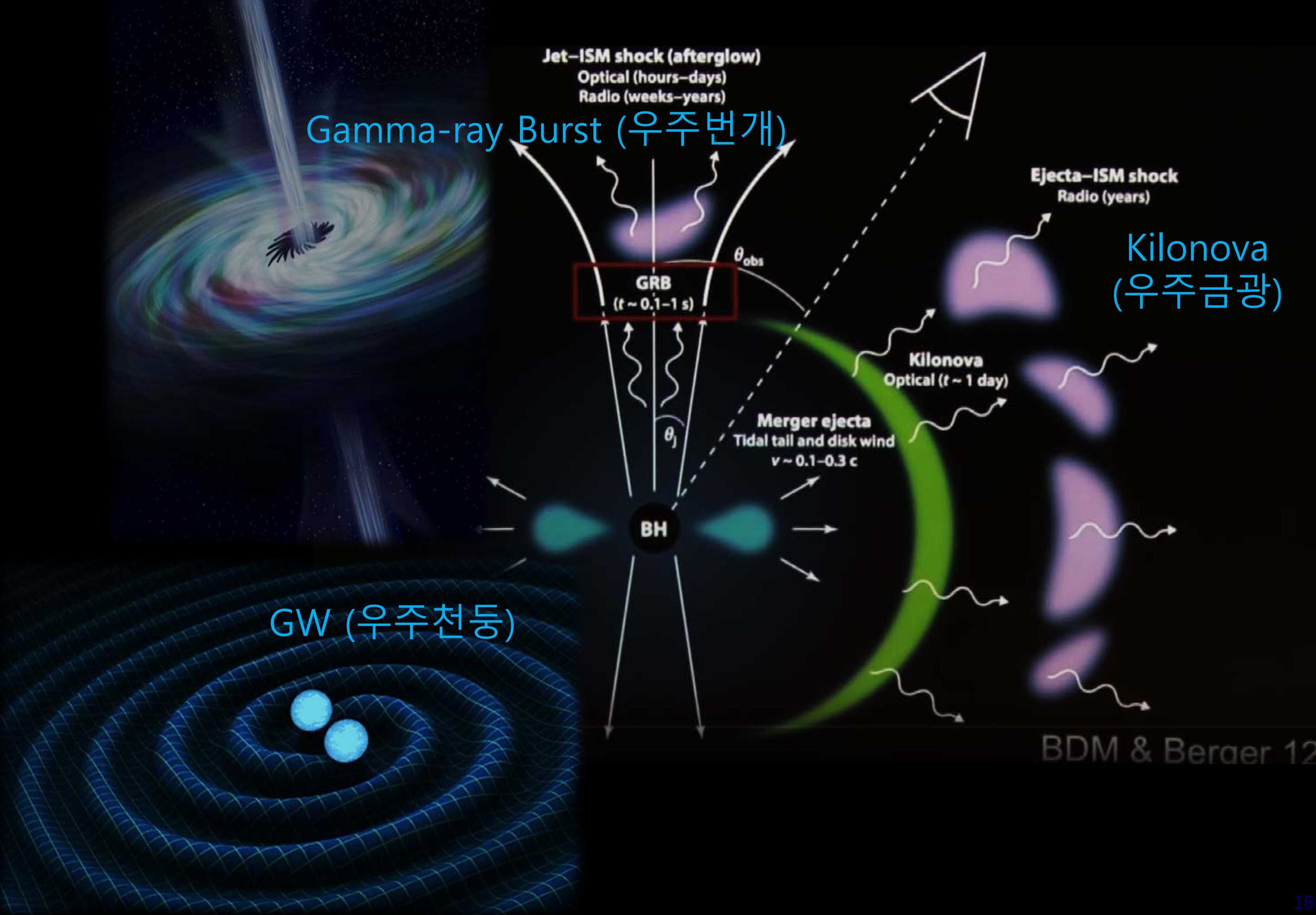


Discovered Gravitational Waves

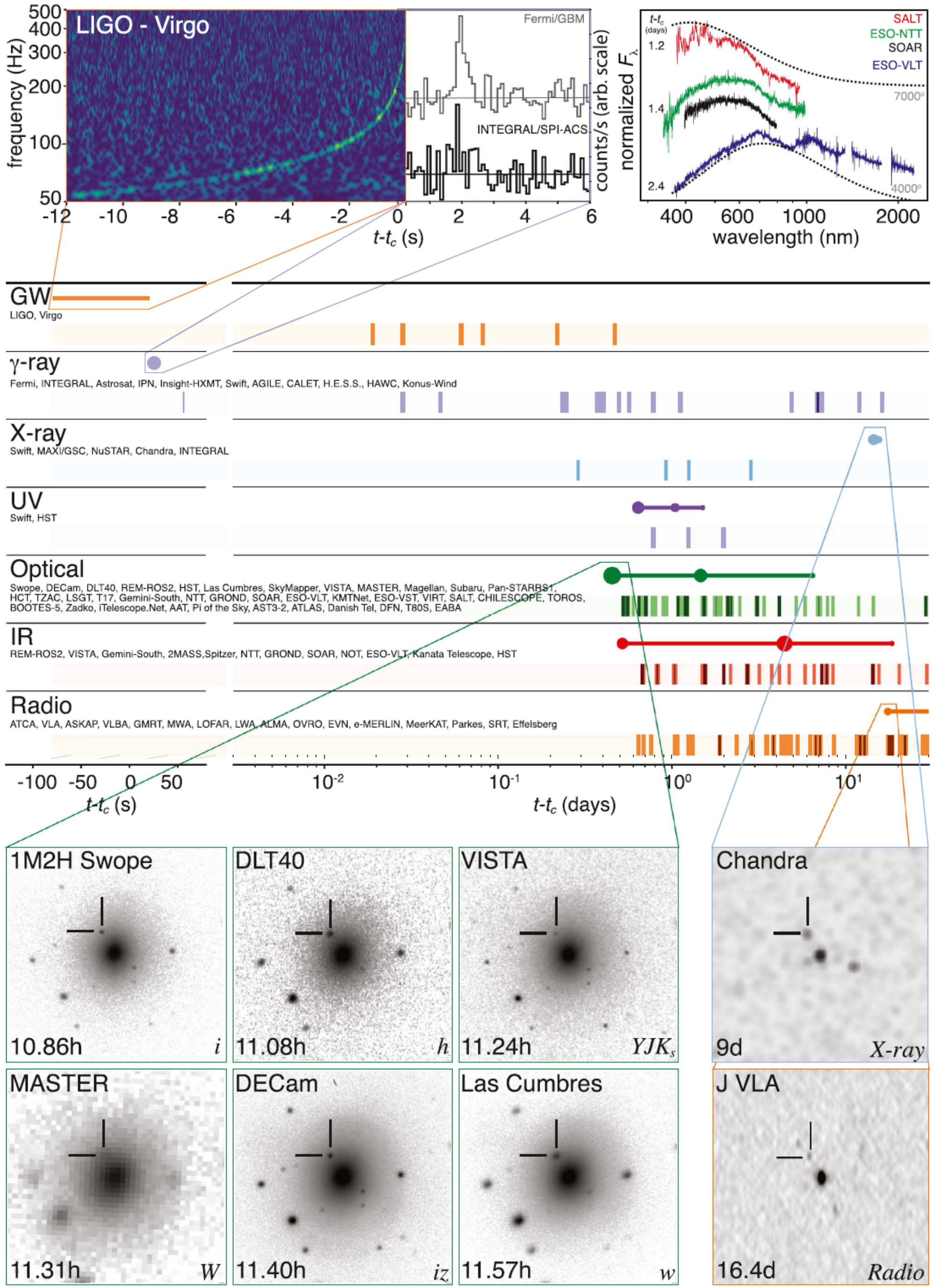
- BH-BH merger: GW150914, GW151226, GW170104, GW170814
- NS-NS merger: GW170817



NS-NS Merger



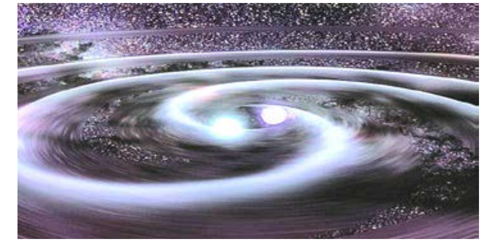
Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Gamma-ray Burst (우주번개)
Ejecta–ISM shock
Radio (years)
Kilonova
(우주금광)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θ_j
BH
GW (우주천둥)
BDM & Berger 12

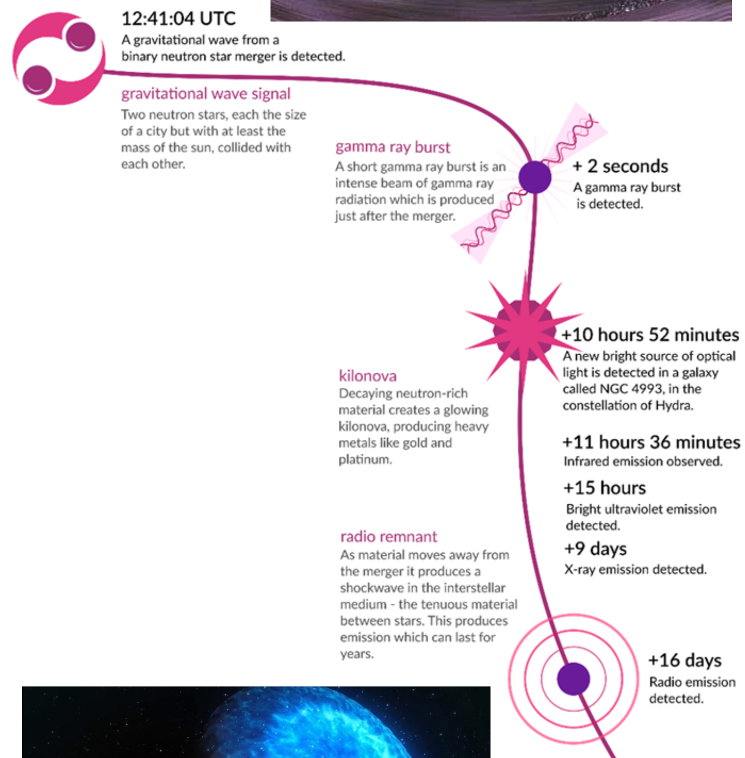


GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.





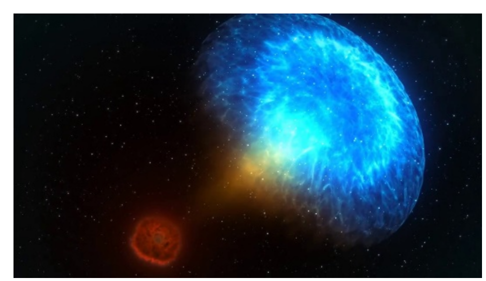


Figure 2. Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo, and the follow-up observations are shown by messenger and wavelength

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

1. Introduction

Over 80 years ago Baade & Zwicky (1934) proposed the idea of neutron stars, and soon after, Oppenheimer & Volkoff (1939) carried out the first calculations of neutron star models. Neutron stars entered the realm of observational astronomy in the 1960s by providing a physical interpretation of X-ray emission from Scorpius X-1 (Giacconi et al. 1962; Shklovsky 1967) and of radio pulsars (Gold 1968; Hewish et al. 1968; Gold 1969).

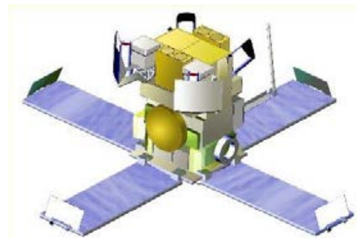
The discovery of a radio pulsar in a double neutron star system by Hulse & Taylor (1975) led to a renewed interest in binary stars and compact-object astrophysics, including the development of a scenario for the formation of double neutron stars and the first population studies (Flannery & van den Heuvel 1975; Massevitch et al. 1976; Clark 1979; Clark et al. 1979; Dewey & Cordes 1987; Lipunov et al. 1987; for reviews see Kalogera et al. 2007; Postnov & Yungelson 2014). The Hulse-Taylor pulsar provided the first firm evidence (Taylor & Weisberg 1982) of the existence of gravitational waves (Einstein 1916, 1918) and sparked a renaissance of observational tests of general relativity (Damour & Taylor 1991, 1992; Taylor et al. 1992; Wex 2014). Merging binary neutron stars (BNSs) were quickly recognized to be promising sources of detectable gravitational waves, making them a primary target for ground-based interferometric detectors (see Abadie et al. 2010 for an overview). This motivated the development of accurate models for the two-body, general-relativistic dynamics (Blanchet et al. 1995; Buonanno & Damour 1999; Pretorius 2005; Baker et al. 2006; Campanelli et al. 2006; Blanchet 2014) that are critical for detecting and interpreting gravitational waves (Abbott et al. 2016c, 2016d, 2016e, 2017a, 2017c, 2017d).

First MMA paper:
70 groups,
3500 scientists

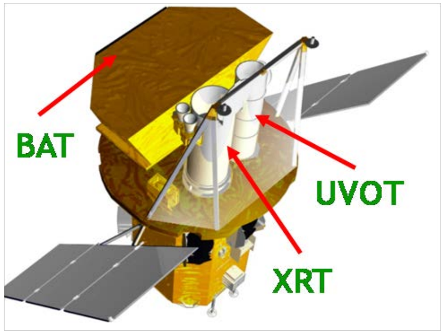
(including 35 Koreans including me)

Observatories of GRB

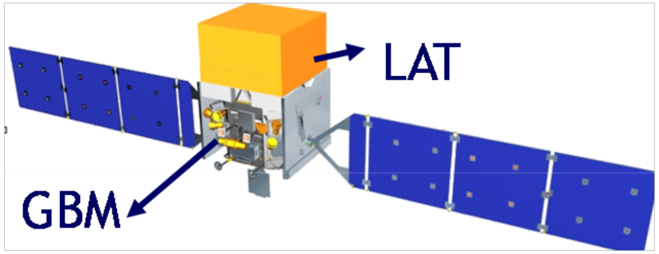
BATSE (1991)
(Burst and Transient Source Experiment)



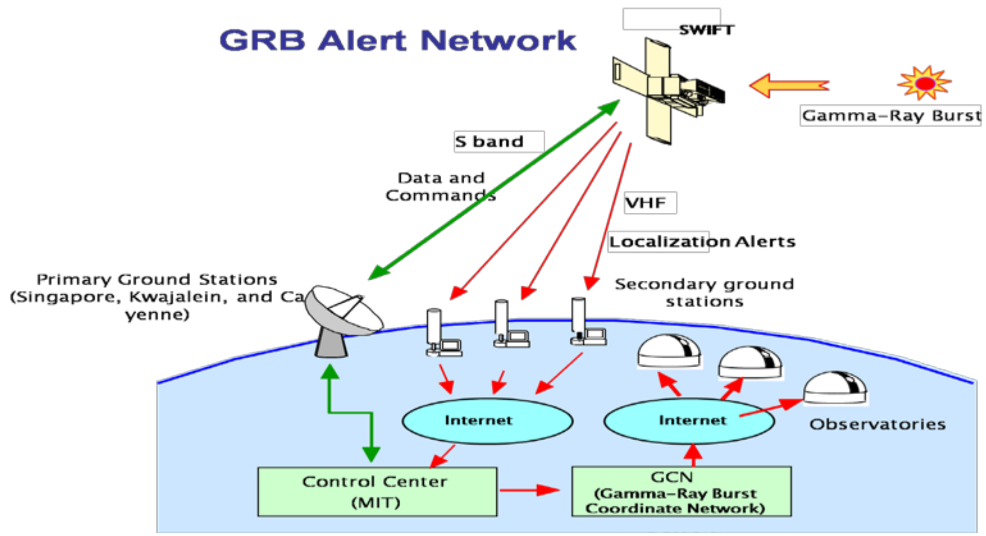
HETE-2 (2000)
(High Energy Transient Explorer-2)



SWIFT (2004)
NASA's MEDEX
GRB dedicated mission

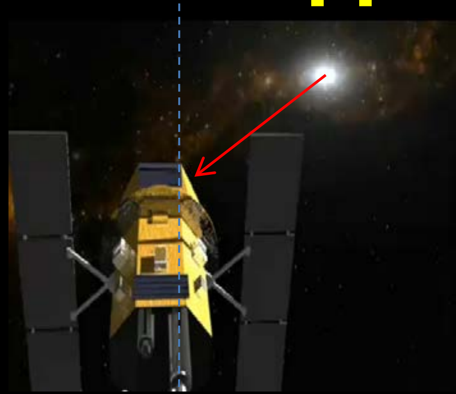


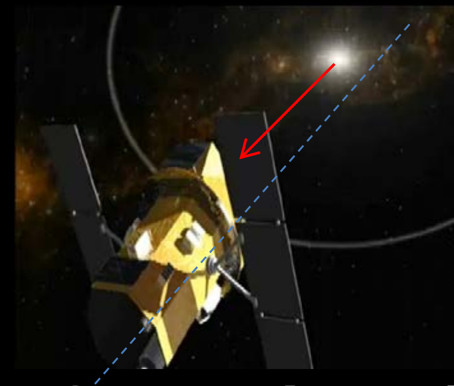
Fermi Gamma-ray Space Telescope (2008)



X-ray missions (BeppoSAX, Integral, MAXI, …), ground telescopes, as well, UFFO-pathfinder, SVOM, SRG, YANUS, POLAR, UFFO-100, … in near future

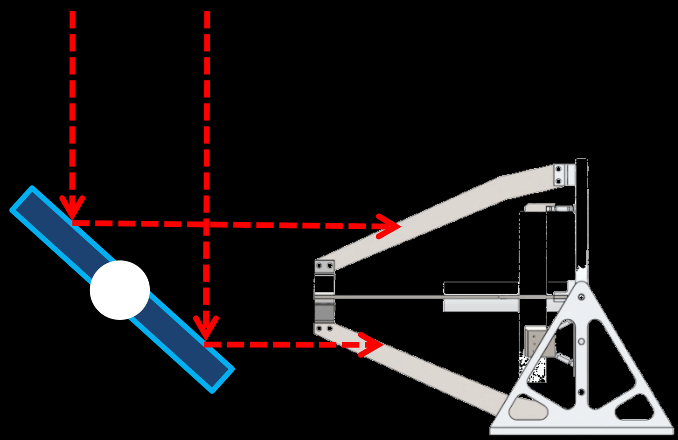
UFFO, the New Approach, "Swifter than *Swift*"

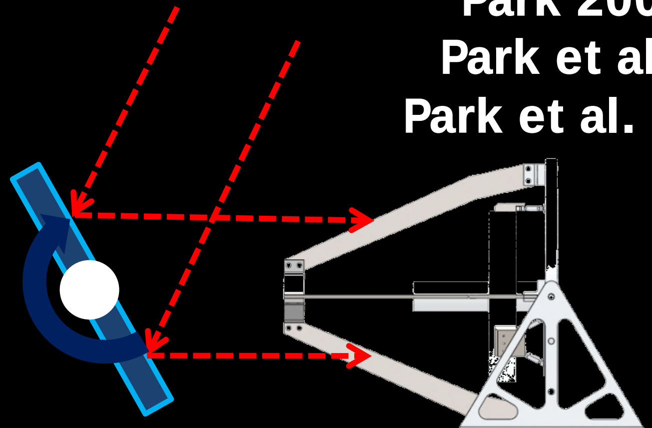




SWIFT rotates entire spacecraft to point telescopes

Park 2006;
Park et al. 2009;
Park et al. 2013

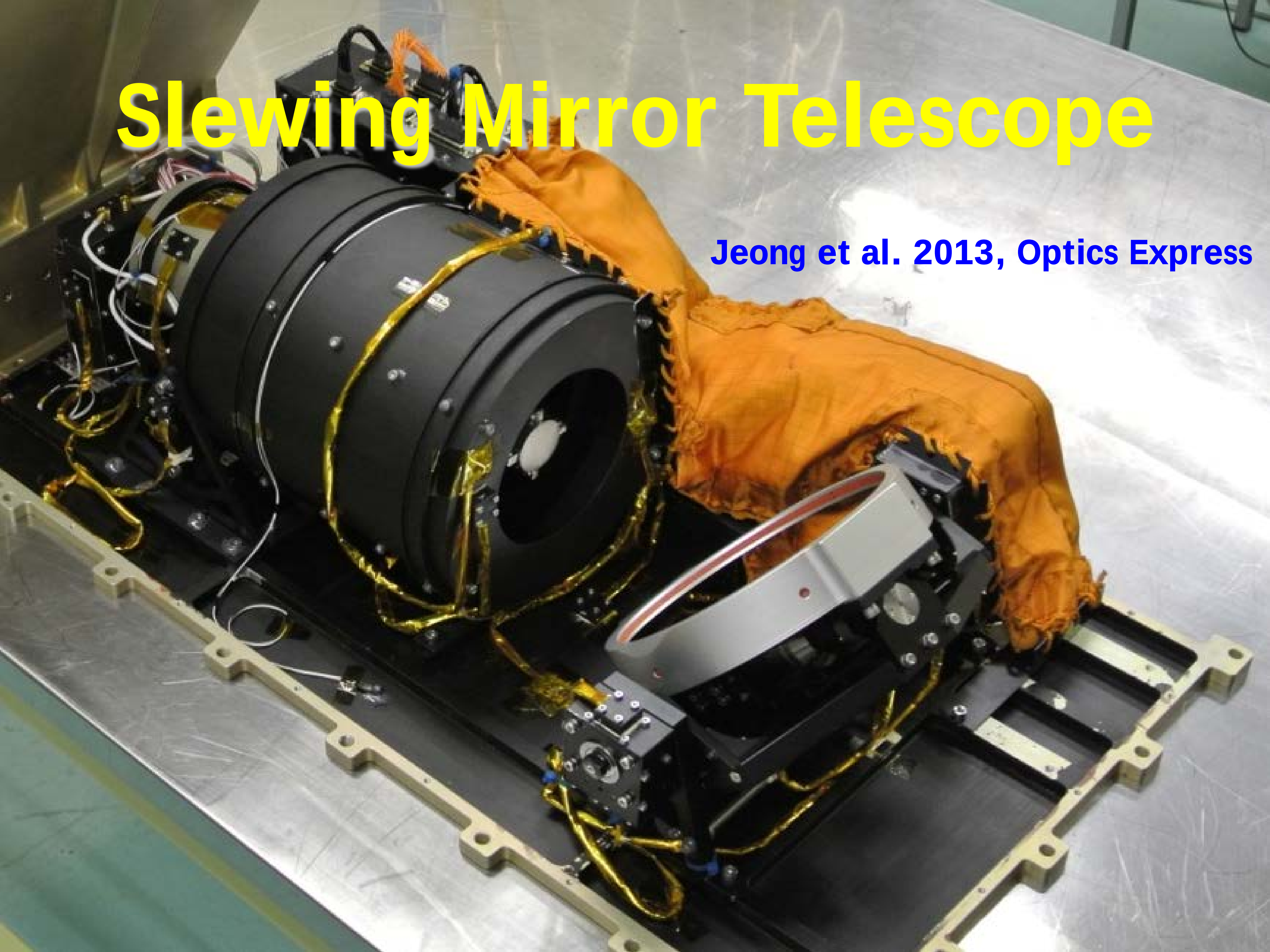




Move the optical path, not the spacecraft with fast slewing mirror system → much faster (~1sec)

Slewing Mirror Telescope

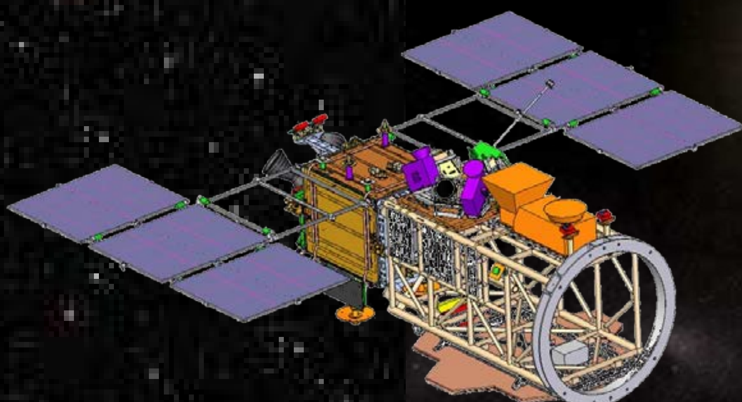
Jeong et al. 2013, Optics Express

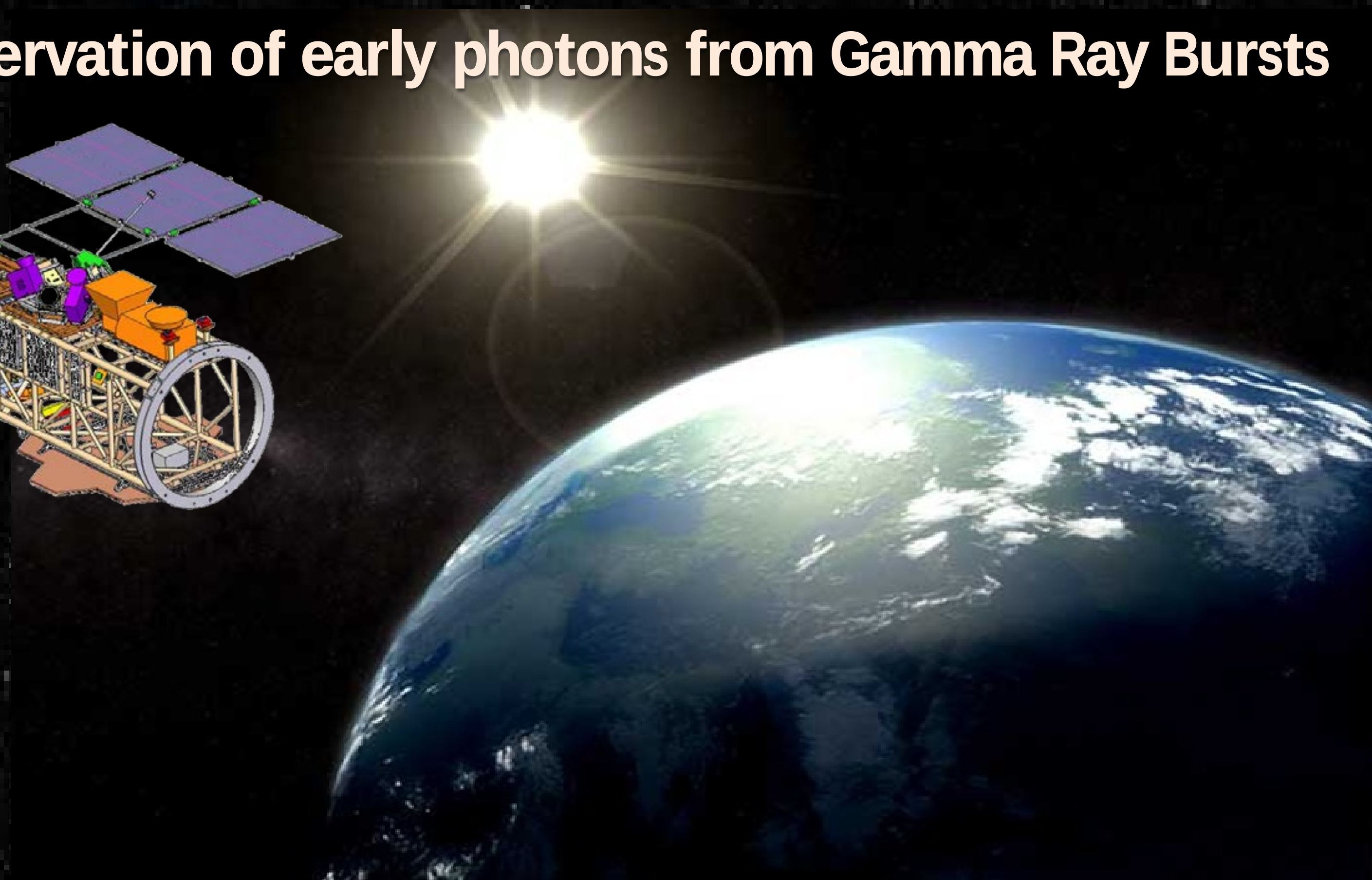


Ultra Fast Flash Observatory

UFFO

For observation of early photons from Gamma Ray Bursts



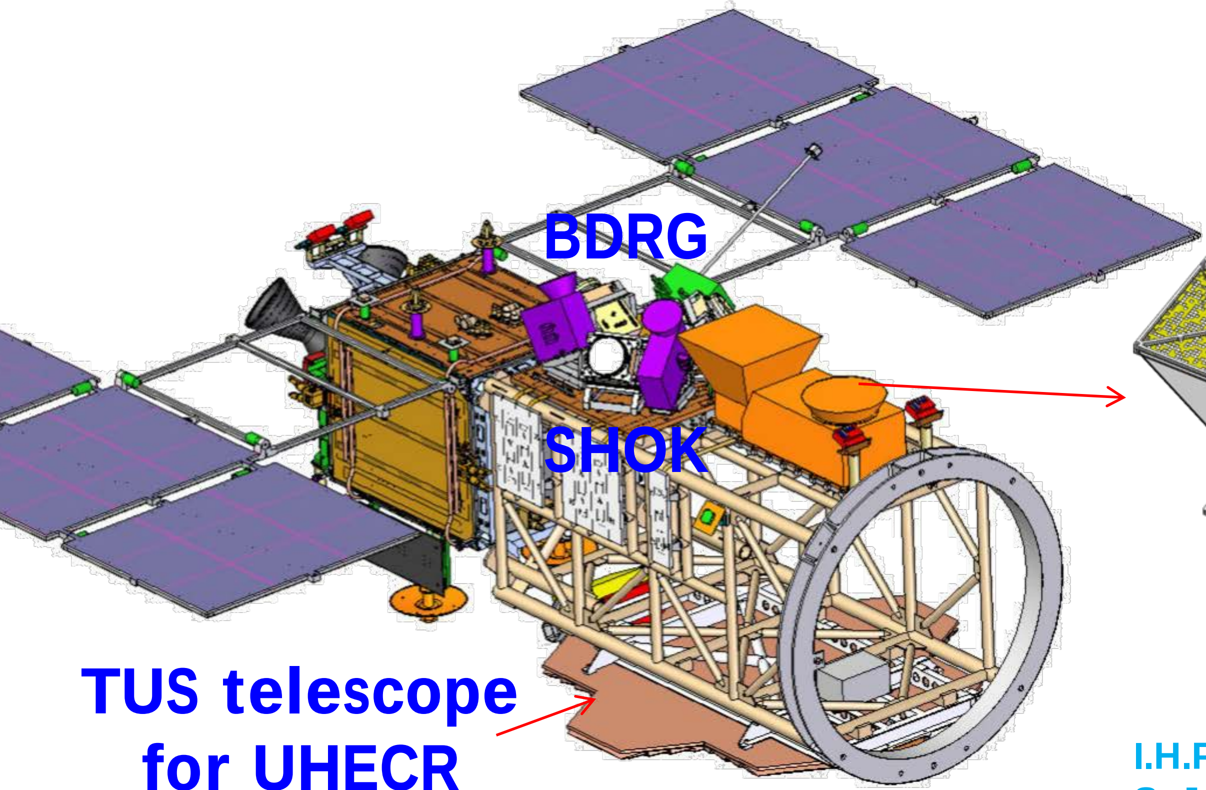


Comparison of Space Instruments

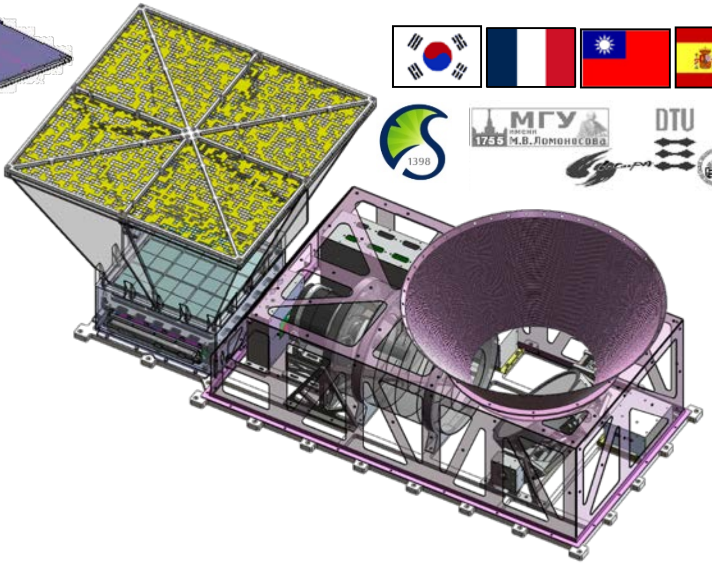
Space mission	*Swift*	GBM/*Fermi*	UFFO/*Lomonosov*	UFFO-100
Gamma/X-ray E range	15~150 keV	8 keV ~ 40 MeV	5 or 10~150 keV	5~300 keV
X-ray instrument: • detector type • detection area • FOV(half coded) • localization acc.	• coded mask + CZT • 5240 cm^2 • 100×60 deg^2 • 1~4 arcmin (4 in 8s)	• NaI+BGO • 14×126 cm^2 • 2.5 sr • 1~5 arcdeg	• coded mask + YSO • 191 cm^2 • 90.2×90.2 deg^2 • 10 arcmin in 7s	• coded mask + Si & YSO • 1024 cm^2 • 90×90 deg^2 • 7 arcmin in 7s
UV/optical/NIR	**30 cm diameter UV/optical**	None	**10 cm diameter UV/optical**	**40 cm diameter UV/optica/ NIR**
UV/optical/IR response time after trigger(typical)	**60 sec**	Not applicable	**1 sec**	**0.01~1 sec**
GRB events/year	~100	~260	20~30	> 70
Launch ~ termination year	2004~	2008~	2016~2017	2020s~

Park et al, New Journal of Physics 15 (2013) 023031

Lomonosov Spacecraft and Payloads



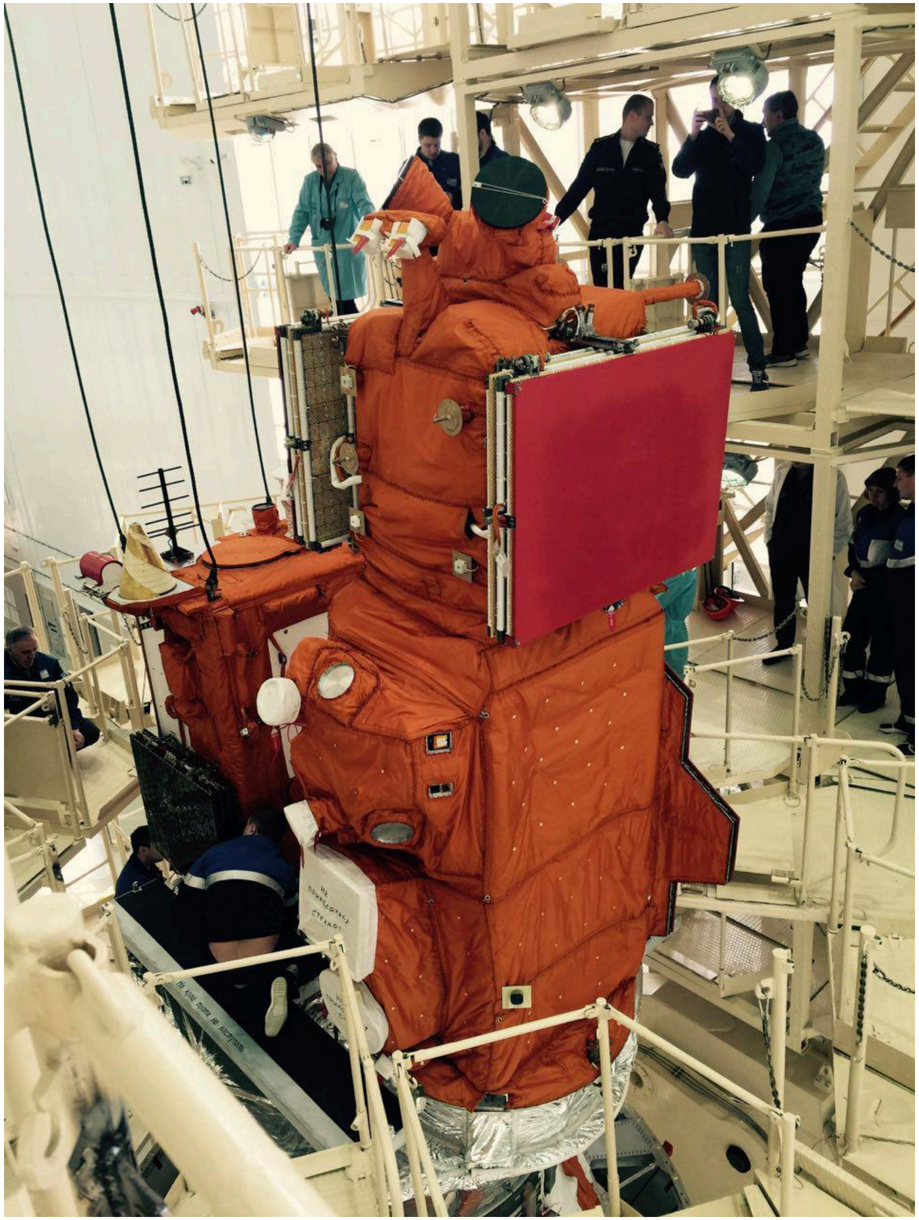
UFFO-pathfinder
for GRB



I.H.Park et al., NJP 15 023031 (2013)
S. Jeong et al., Opt. Exp. 21, 2, 2263 (2013)

- “UFFO/Lomonosov .. for GRBs”, I.H.Park et al. in Space Science Reviews 214:14 (2018)
- “UBAT of UFFO: The X-ray Space Telescope ..”, S.Jeong et al in Space Science Reviews 214:16 (2018)
- “Slewing Mirror Telescope of UFFO .. Photons from Gamma-Ray Bursts”, G.Geikov et al. in Opt. Exp. 21, 2, 2263 (2013)

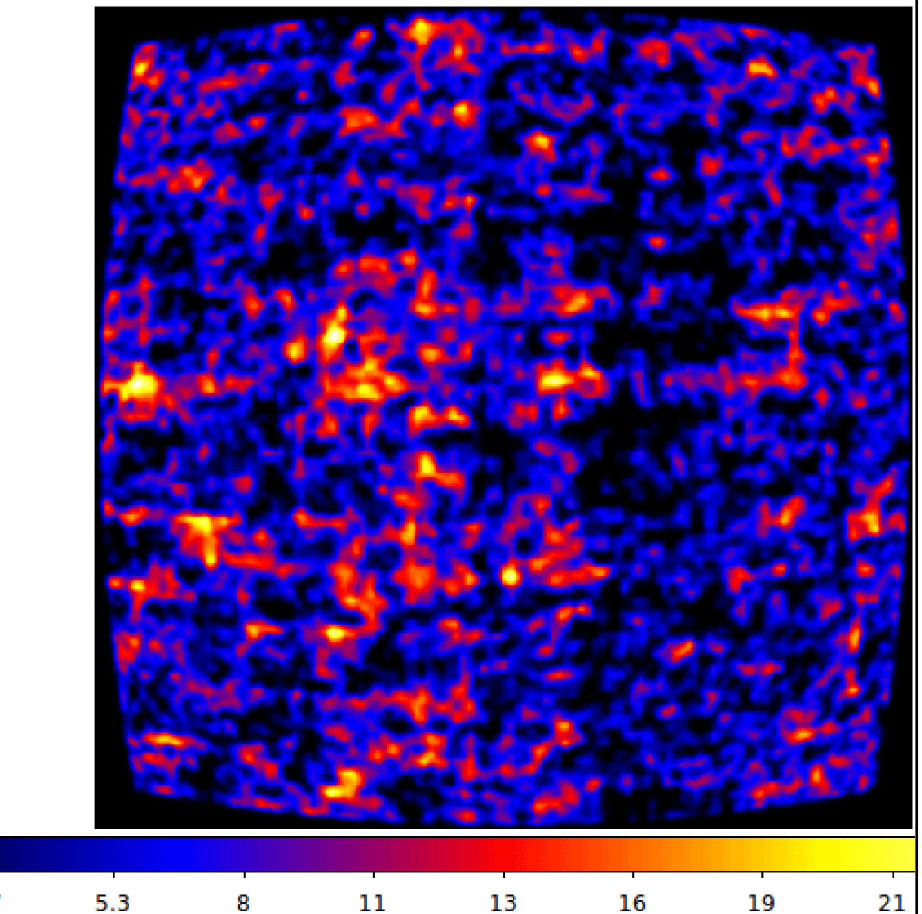
Launch of UFFO-pathfinder/*Lomonosov* (Apr. 28, 2016)



X-ray & UV/optical observation in space

(Instrument is under calibration)

X-ray sky image from UBAT



Remarks on SMT optical telescope results

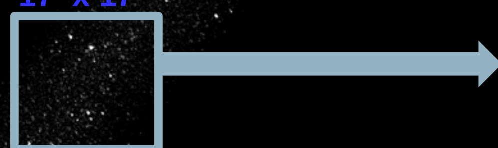
"The Slewing Mirror Telescope of UFFO-pathfinder: first report on performance in Space" in **Opt. Express 25**, 23, 29143-29154 (2017)

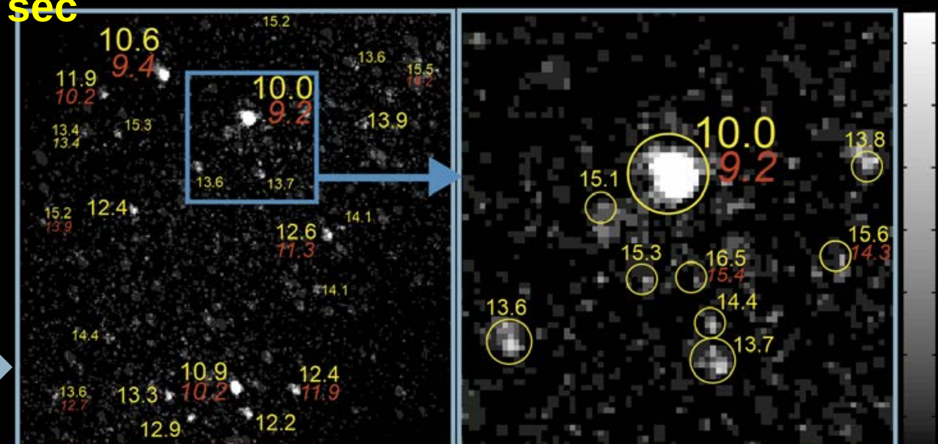
Date	Target position[1]		Response time, sec	Tracking time, sec^2
	X, degree	Y, degree		
Sep 26	8.58	−25.67	1.36	148
Sep 29	13.67	−19.67	1.72	88
Oct 4	13.75	−19.18	1.08	40
Oct 20	10.45	1.28	1.47	170
Nov 10	−4.55	5.92	1.04	191

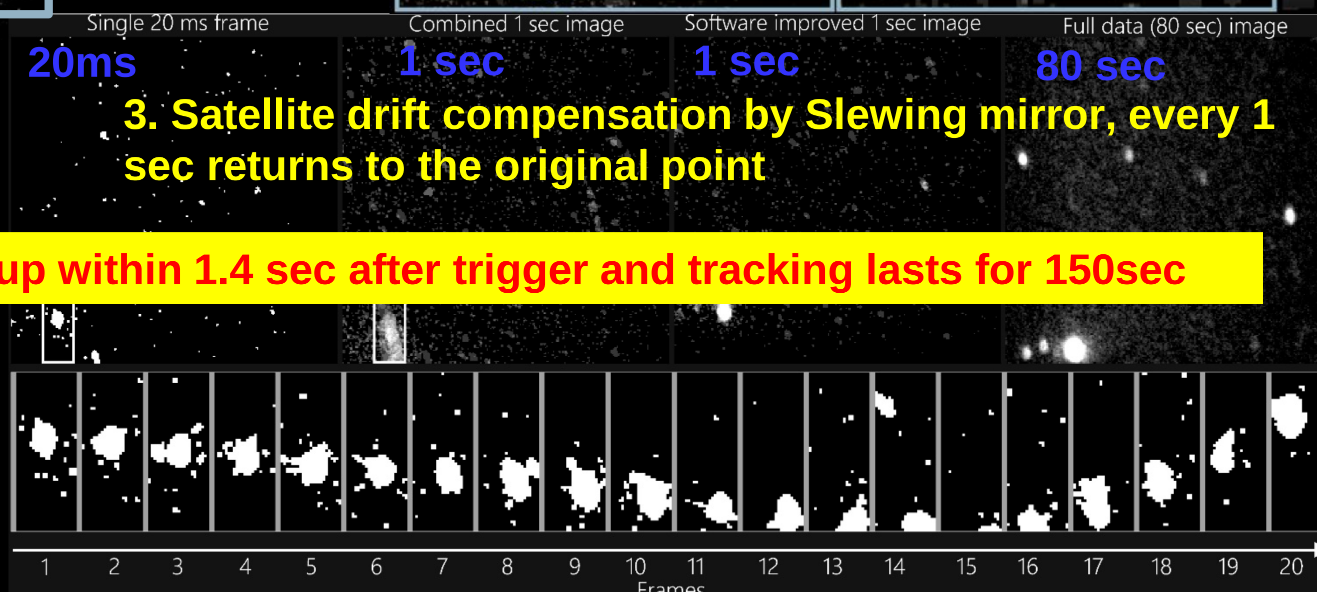
1. Slewing mirror can move the optical path from source within 1.4 sec after X-ray trigger

2. Sensitivity ~ 16 mag for 100 sec

17' x 17'



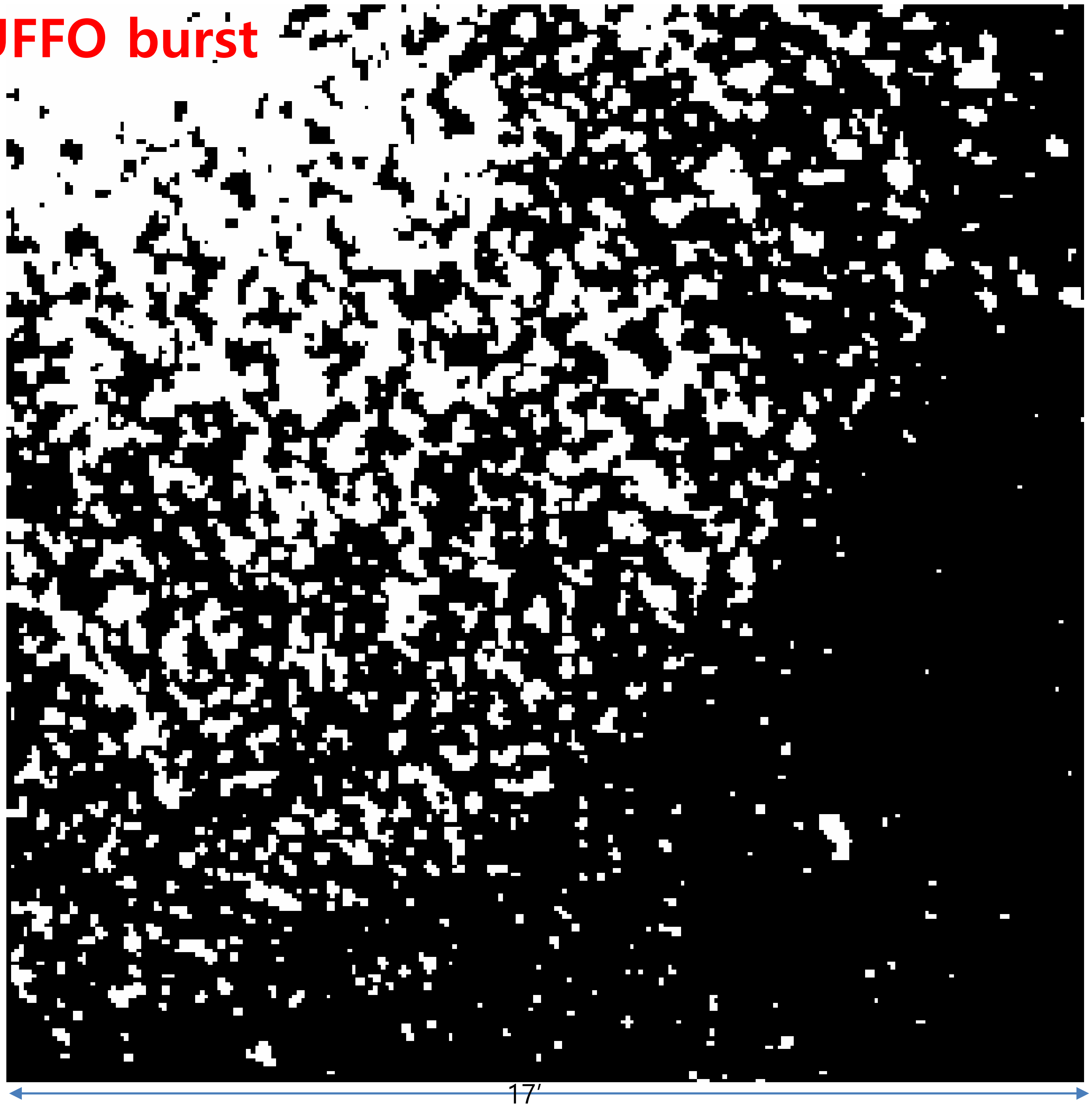




3. Satellite drift compensation by Slewing mirror, every 1 sec returns to the original point

Rapid optical follow up within 1.4 sec after trigger and tracking lasts for 150sec

UFFO burst

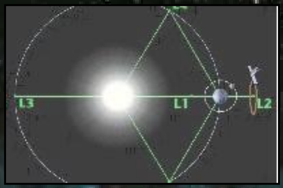


- **UV/optical image viewing to space**
- Image taken by UFFO SMT
  - SMT FOV: 17 arcmin
  - Intensified CCD size of 2.5 x $2.5mm^2$ with 256 x 256 pixels
- Time: 2016.07.05 22:26:20
- **Image of just one single frame of "35ms exposure time", while all the other frames show normal stars**
- **The size of ~0.5 degree (the size of full moon)**
- Burst-like structure

UFFO-300

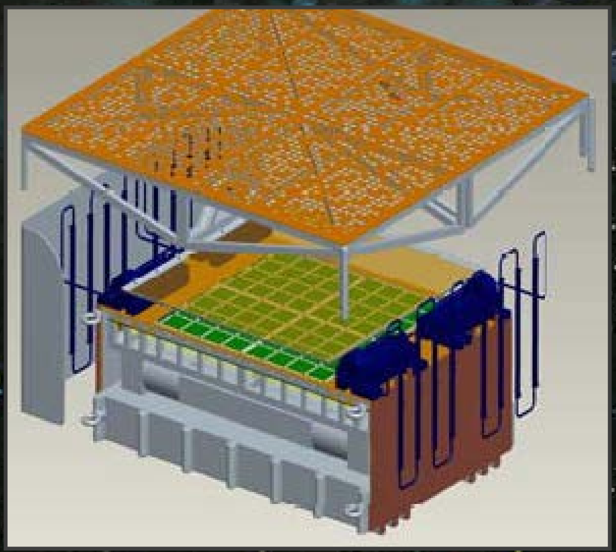
L2 궤도

- 달보다 5배거리, 150만km
- 지금까지 단 2 위성 (WMAP, Planck)

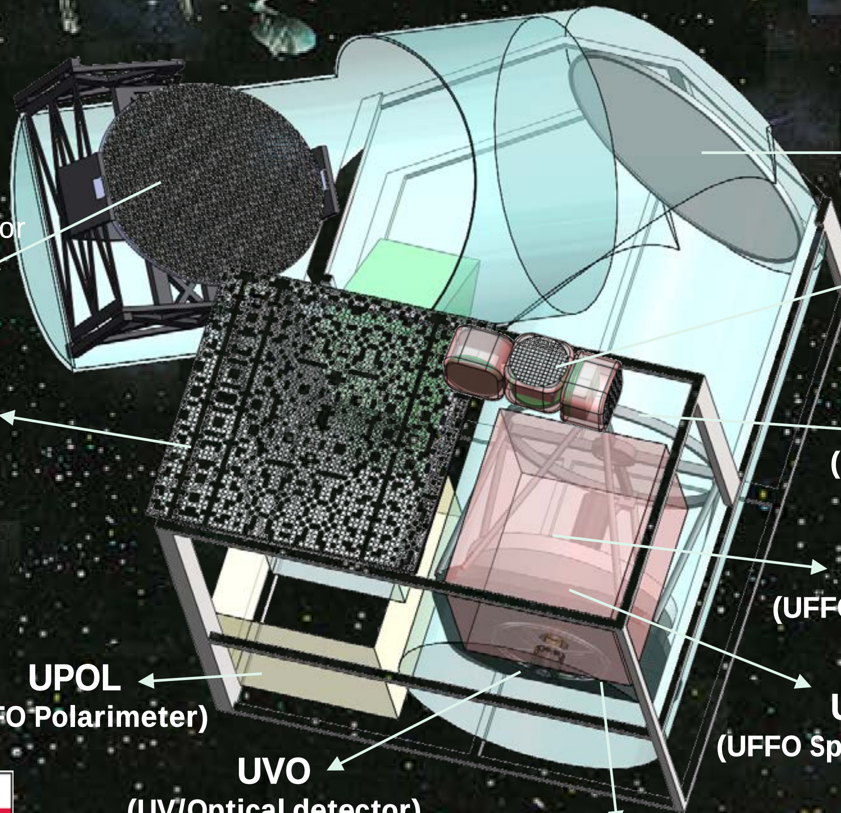


UFFO-300

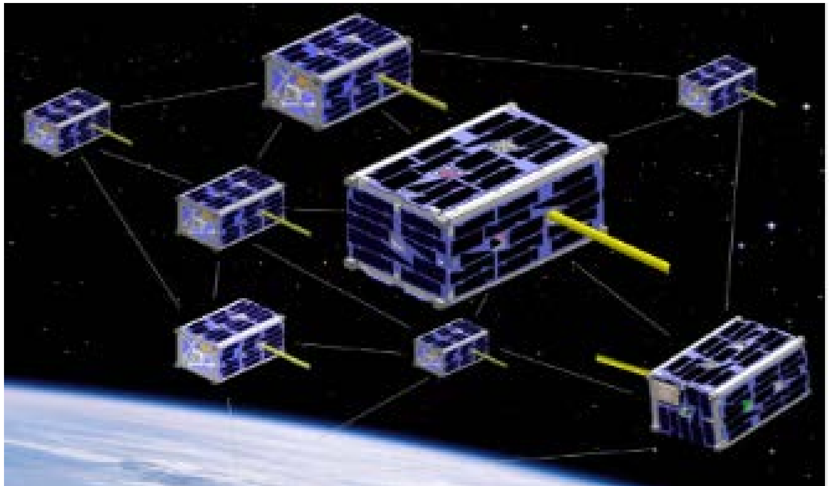
- Mass: 250~290 kg
- Volume: 1800 (L) x 1800 (W) x 1300 (H) mm^3
- Power: 230~280 Watts
- Data Size: 1 Gbytes/day



GRI view and main subsystems: Mask in yellow color, Si detectors in yellow, CdZnTe detectors in green, BGO´s in grey, PSU&DPU in black

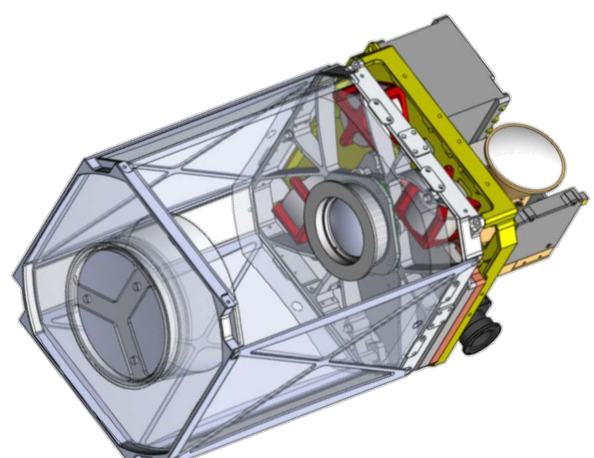


UFFO Constellation with CubeSats



- **Led by SKKU, with SatByul, MSU, …**
- A pathfinder of CubeSat constellation will be launched on Oct. 2017
  - Payload: **Micro UBAT of UFFO**
  - Coded mask + YSO+SiPM
  - Energy range: 5-200 keV
  - 60 degree FOV
- **Final constellation will be 6 of 16U satellites to cover all sky for optical follow-up of GW counterparts**
  - **EM of FOV 3^{o} telescope completed**

Manufactured Satellite platform



230mm aperture 3^{o} deg FOV telescope payload with 16U CubeSat

A New Detection Method of Gravitational Waves

SIGN (Stellar Interferometer for Gravitational wave)

IL H. PARK (SKKU, Korea)

NextGAPES-2019

Workshop on the Next Generation of AstroParticle Experiments in Space, Lomonosov Moscow State University, on June 21-22, 2019 arXiv:1906.06018v1 (14 June 2019)

Stellar Interferometry for Detection of Gravitational Waves

I.H. Park,[1,*] D.H. Kim,[1] K.-Y. Choi,[1] and E. Won[2,†]

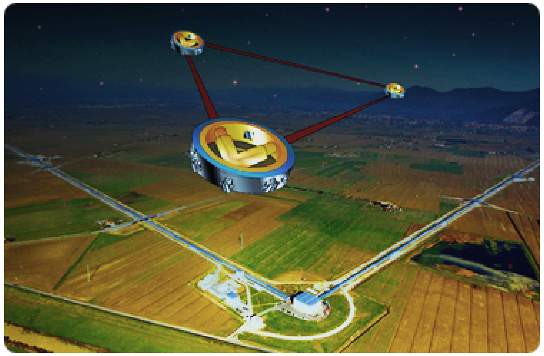
[1] *Department of Physics, Sungkyunkwan University (SKKU), Suwon, 16419, Republic of Korea*

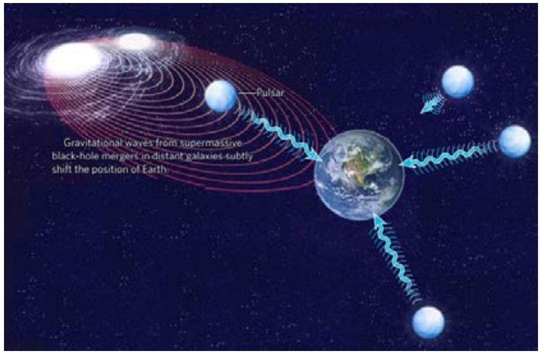
[2] *Department of Physics, Korea University, Seoul, 02841, Republic of Korea*

We propose a new method to detect gravitational waves, based on spatial coherence interferometry using star light as opposed to conventional laser light. Two beams of light from a distant star are used in our space-borne experiment. In contrast to existing or proposed future gravitational-wave detectors where the plane of two laser beams are located orthogonal to the propagation direction of gravitational waves at the maximum response to gravitational waves, our stellar interferometer configures the direction of gravitational waves along the plane of two light beams. This configuration is expected to reduce noises in the low-frequency range significantly. Our proposed experiment would be complementary to on-going and planned gravitational-wave detectors such as laser interferometers and pulsar timing arrays, by covering the frequency range of $10^{-7} - 10^{-4}$ Hz of gravitational waves.

Detection of Gravitational Wave

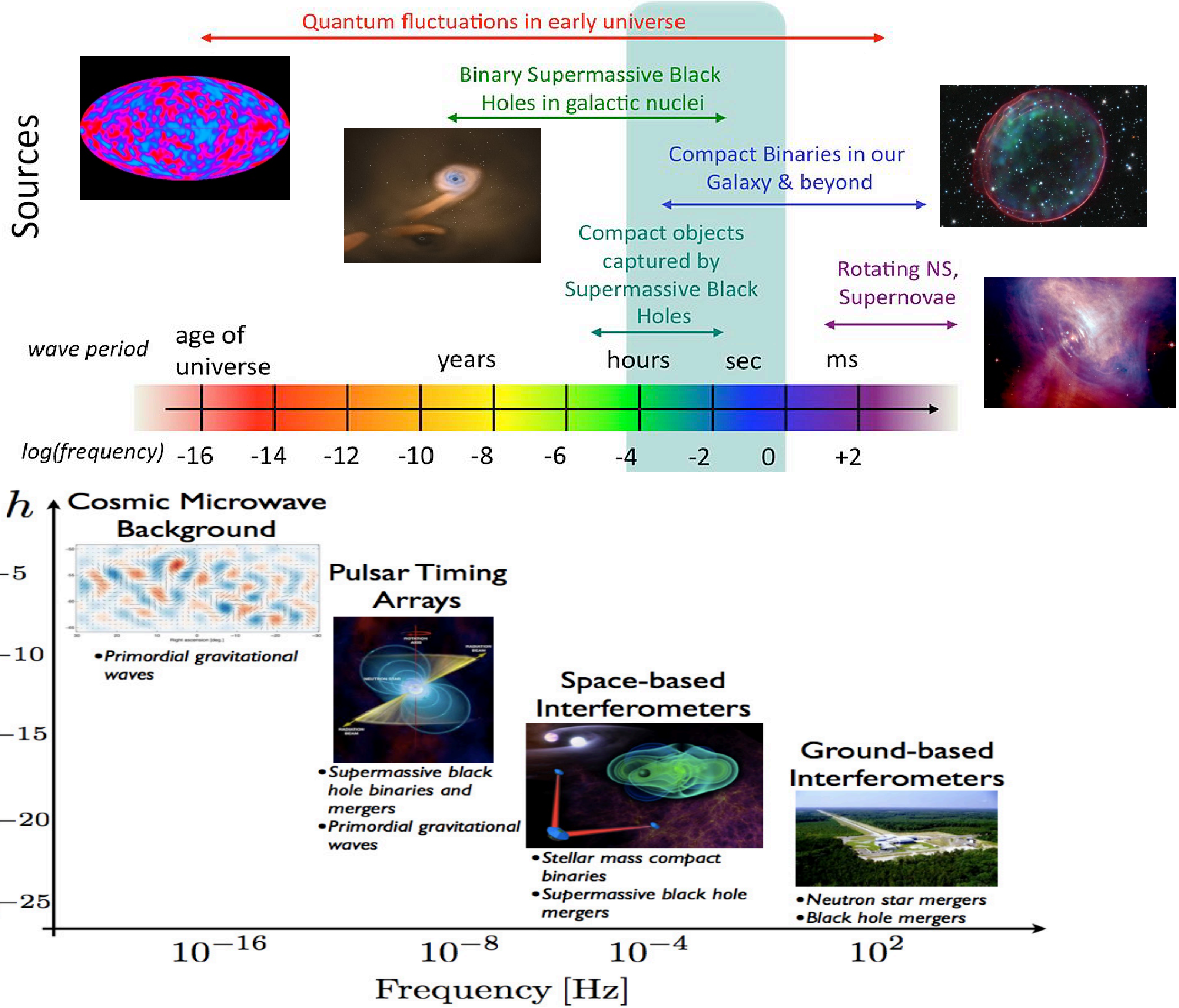
- Resonant Acoustic Detectors
  - Bar detectors: Auriga(Italy), ALLEGRO(USA) …
  - Spherical detectors: Mini-Grail (Netherlands) …
  - Sensitive to order of kHz of GW
- Laser Interferometers
  - Ground Laser Interferometers: LIGO, VIRGO, KAGRA
  - Space Laser Interferometers: LISA, DECIGO …
- Pulsar Timing Arrays
  - Maximize the sensitivity to relatively low-frequency hum of colliding supermassive black holes
  - Parkes PTA (Australia), NANOGrav (North America), European PTA (Europe), SKA … → dozens of pulsars
- CMB polarization
  - Preserved the space stretched/squeezed by Inflation
  - BICEP2 mistook dust in the Milky Way for its quarry
- Others
  - Doppler tracking, Atom interferometer …
  - **Stellar Interferometer** in this talk





Frequency range: $10^{-18} \sim 10^{8}$ Hz potential sources of GW

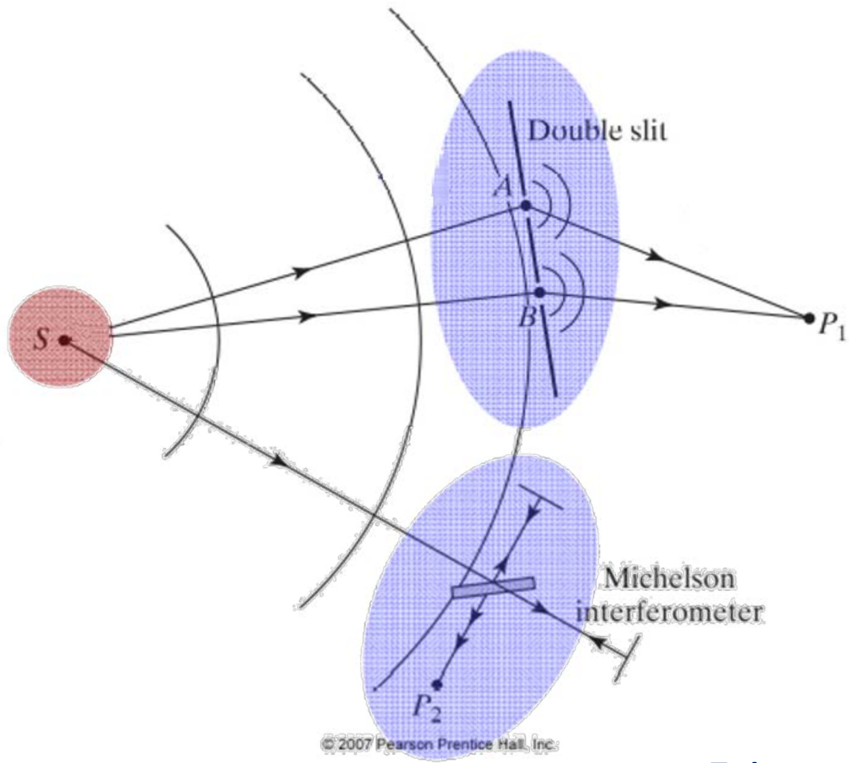
the range of freq to which different detectors are sensitive



Coherence Experiments (two types)

Coherence?

- Measure of the correlation between the phases measured at **temporally or spatially** different points on a wave



Spatial coherence(lateral coherence):
… difference at points transverse to the direction of propagation showing how uniform the phase of the wavefront is (size of the source)

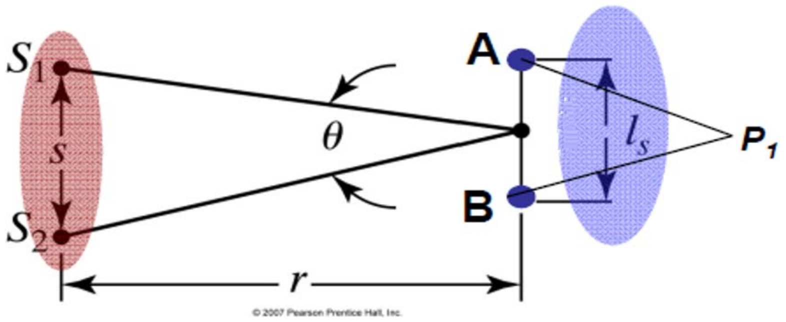
Temporal coherence(longitudinal):
… difference at points along the direction of propagation showing how monochromatic a source is (spectral purity of the source)

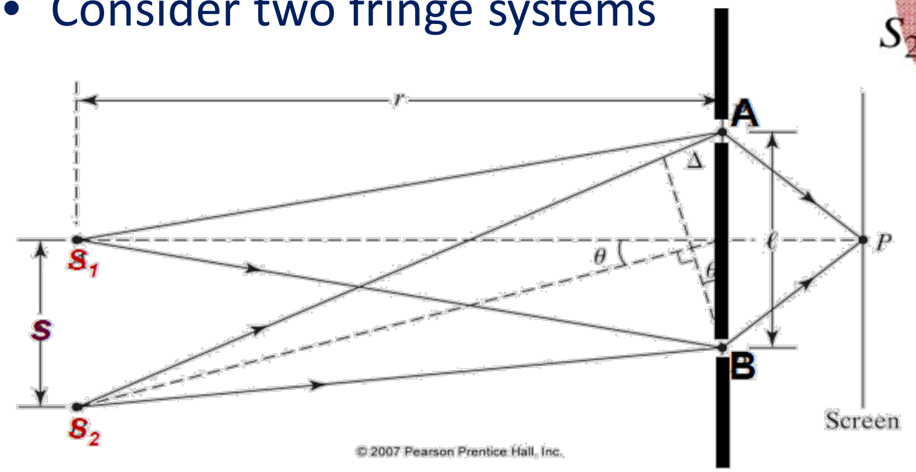
Fringe visibility: $l_t = c\tau_t = \frac{c}{\Delta\nu} \geq SAP_1 - SBP_1$

coherence length **coherence time** **Path length difference**

Spatial Coherence

- If extended source, fringe visibility depends on l_s
- Consider two fringe systems





$$S_2A - S_2B = \Delta = \frac{\lambda}{2} \approx l\theta = \frac{l \cdot s}{r}$$

- For a continuous source

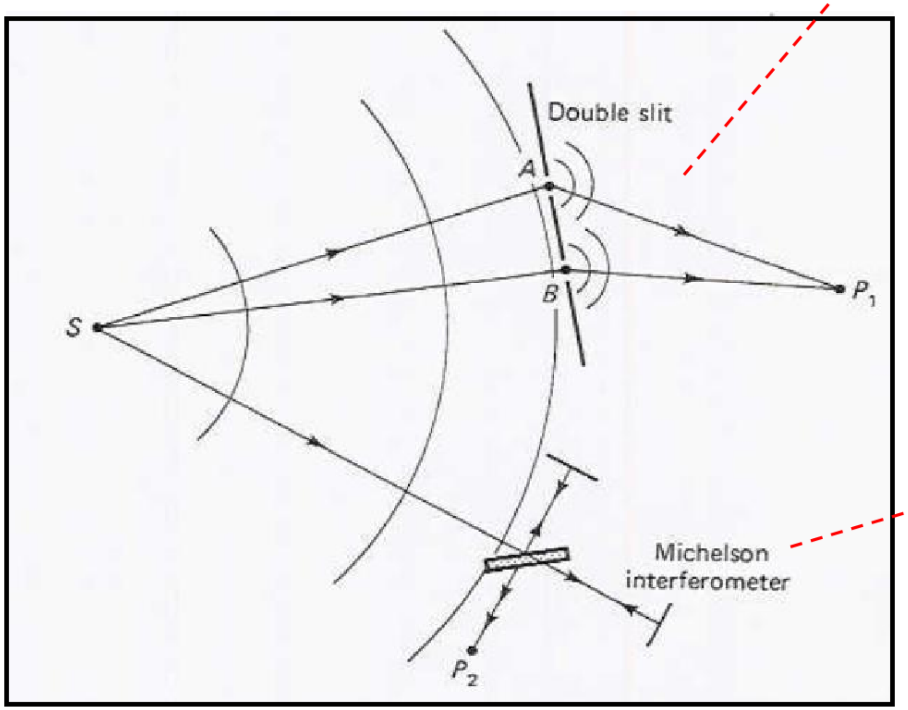
$$l = l_s \cong \frac{\lambda}{\theta} = \frac{r\lambda}{s}$$ → Spatial coherence width of an extended source

- If circular source,

$$l_s = \frac{1.22\,\lambda}{\theta}$$

Separation is bigger for smaller viewing angle of source.

Coherence Experiments (two types)



Spatial Coherence ➔ SIGN

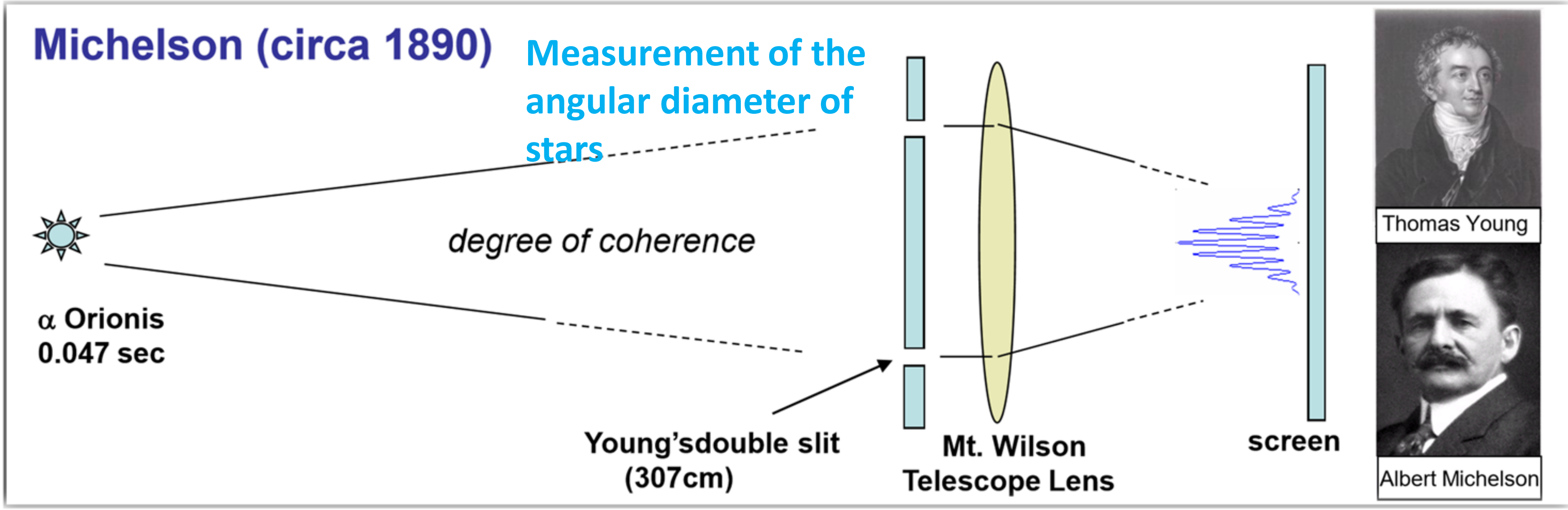
coherence length is inversely proportional to size

- Spatial extent of the source
- used for measuring angular diameters
- Basis for **stellar interferometry,** widely used these days for imaging of astrophysics objects

Temporal Coherence ➔ LIGO, LISA

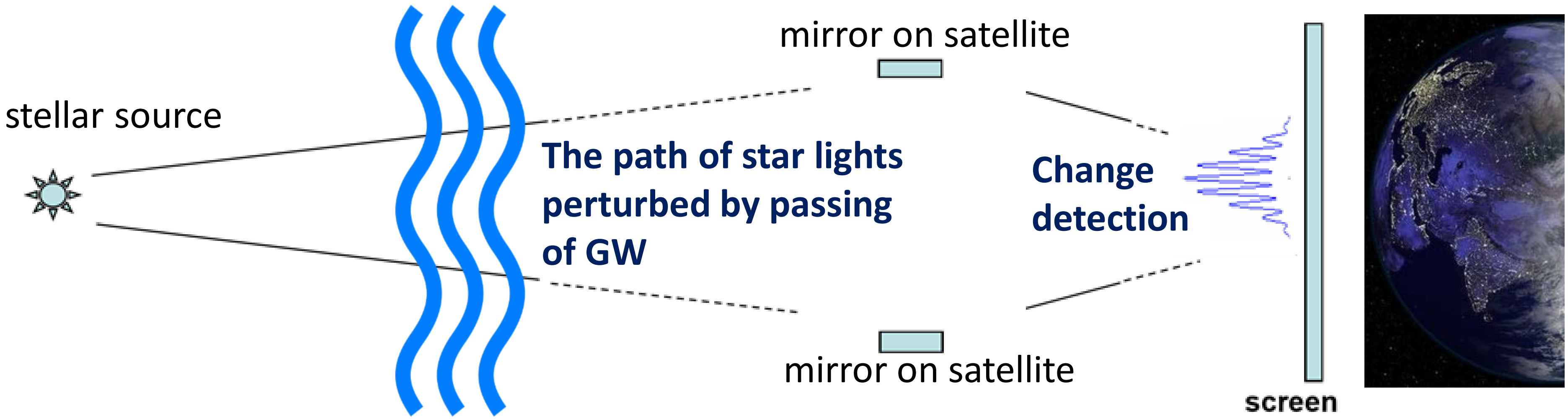
- Spectral purity, coherence time $\tau_c \approx 1/\Delta\nu$
- Laser has large τ_c up to some µs, while white light in the order of fs
- **Michelson interferometer**

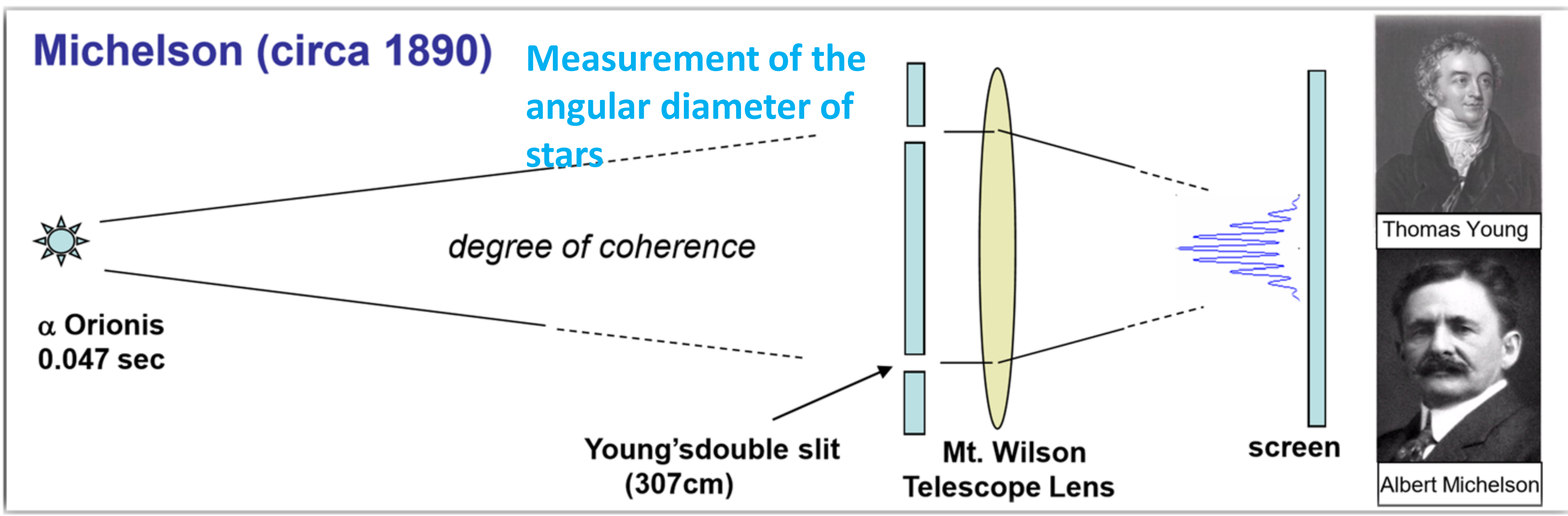
Stellar Interferometer (1920)



Concept of SIGN (2018)

measurement of GW intervention on spatial interferometer





SIGN (Stellar Interferometer for Gravitational wave)

MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

By A. A. MICHELSON and F. G. PEASE

ABSTRACT

Twenty-foot interferometer for measuring minute angles.—Since pencils of rays at least 10 feet apart must be used to measure the diameters of even the largest stars, and because the interferometer results obtained with the 100-inch reflector were so encouraging, the construction of a 20-foot interferometer was undertaken. A very rigid beam made of structural steel was mounted on the end of the Cassegrain cage, and four 6-inch mirrors were mounted on it so as to reduce the separation of the pencils to 45 inches and enable them to be brought to accurate coincidence by the telescope. The methods of making the fine adjustments necessary are described, including the use of two thin wedges of glass to vary continuously the equivalent air-path of one pencil. Sharp fringes were obtained with this instrument in August, 1920.

Diameter of α Orionis.—Although the interferometer was not yet provided with means for continuously altering the distance between the pencils used, some observations were made on this star, which was known to be very large. On December 13, 1920, with very good seeing, no fringes could be found when the separation of the pencils was 121 inches, although tests on other stars showed the instrument to be in perfect adjustment. This separation for minimum visibility gives the angular diameter as $0''.047$ within 10 per cent, assuming the disk of the star uniformly luminous. Hence, taking the parallax as $0''.018$, the linear diameter comes out 240×10^6 miles.

Interferometer method of determining the distribution of luminosity on a stellar disk.—The variation of intensity of the interference fringes with the separation of the two pencils depends not only on the angular diameter of the disk but also on the distribution of luminosity. The theory is developed for the case in which $I=I_0\,(R^2-r^2)^n$, and formulae are given for determining n from observations.

Table of values of $\int_0^1 (1-x^2)^{n+\frac{1}{2}} \cos kx\, dx$, for n equal to 0, $\frac{1}{2}$, 1, and 2, and for k up to 600°, is given.

It was shown in *Contributions* Nos. 184 and 185,[2] that the application of interference methods to astronomical measurements is not seriously affected by atmospheric disturbances, and indeed observations by these methods have proved feasible even when the seeing was very poor. The explanation of this apparent paradox lies in the fact that when the whole objective is effective, the atmospheric disturbances, being irregularly distributed over the surface, simply blur the diffraction pattern; but in the case of two isolated pencils too small to be affected by such an integrated disturbance, the resulting interference fringes, though in motion,

[1] *Contributions from the Mount Wilson Observatory*, No. 203.

[2] *Astrophysical Journal*, **51**, 257, 263, 1920.

are quite distinct, unless the period of the disturbances is too rapid for the eye to follow.

When it was found that the interference fringes remain at full visibility with the slits separated by the diameter of the 100-inch mirror, it was decided to build an interferometer with movable outer mirrors (Fig. 1) in order to make tests with separations as great as 20 feet.

The interferometer beam (Plate IV*a* and Fig. 2) was made of structural steel, as stiff and rigid as circumstances of weight and

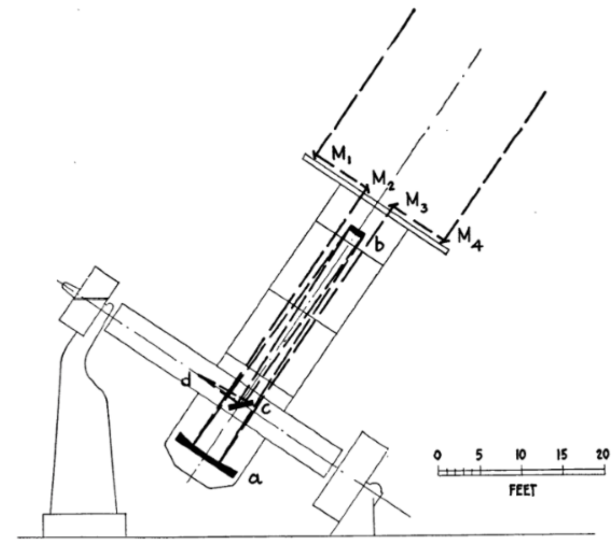


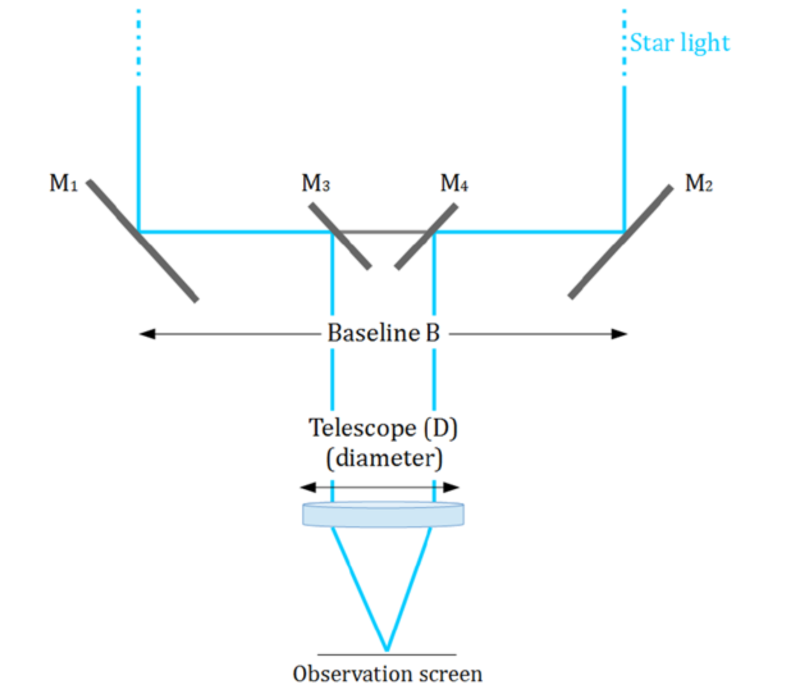
Fig. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

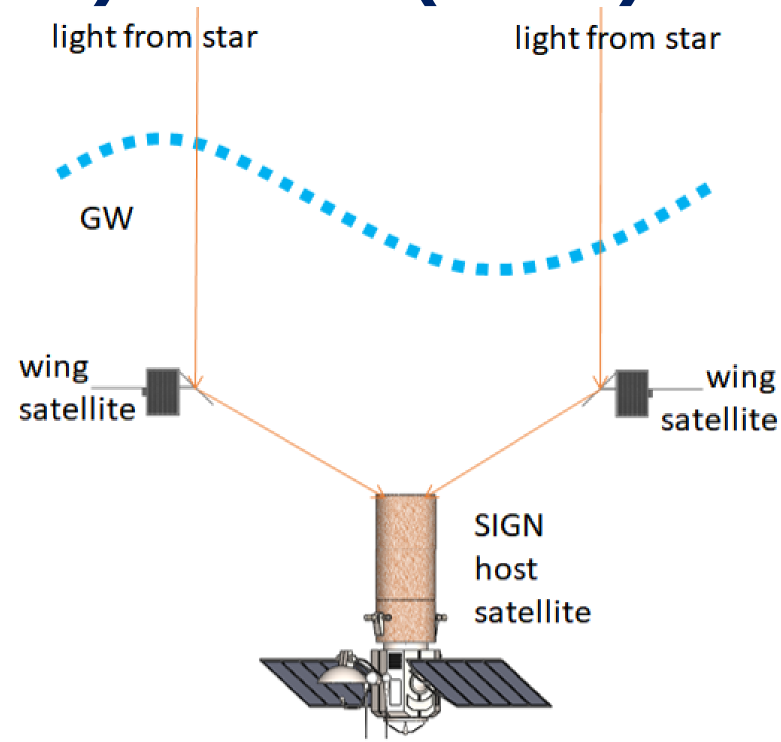
operation would permit, for flexure causes a separation of the two pencils, and any vibration as great as one-thousandth of a millimeter blurs the fringes.

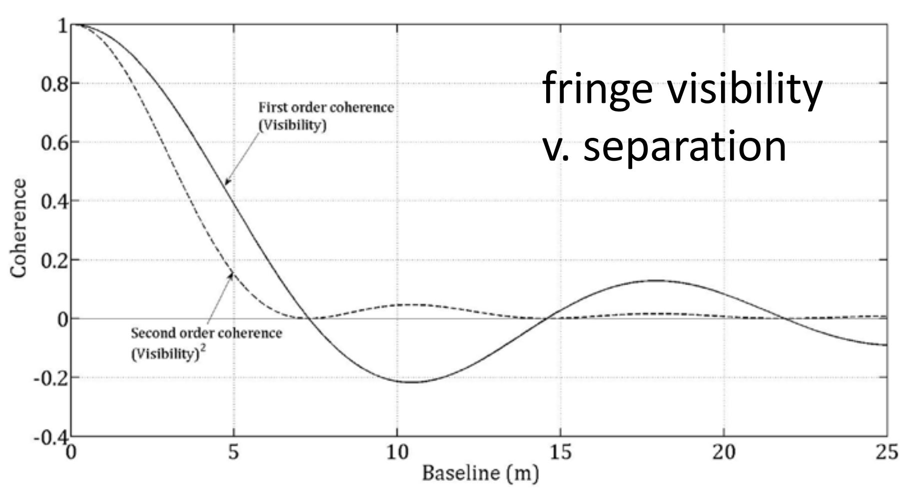
The beam is constructed of two 10-inch channels with flanges turned inward, separated by pieces of 12-inch channel and covered on the bottom with $\frac{3}{16}$-inch (4.75 mm) steel plate (*C*, Fig. 2), all riveted securely together.

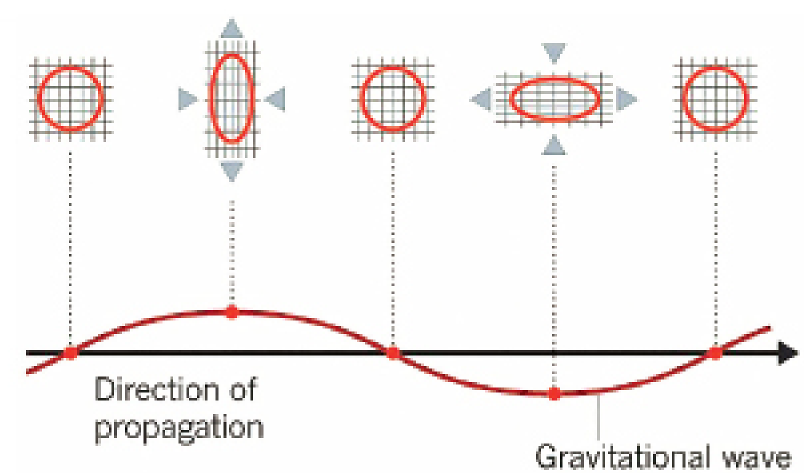
To reduce the weight holes were cut wherever the removal of metal would not cause a weakening of the structure. The inner edges of the top flanges were planed true to 0.001 of an inch

Michelson Stellar Int.(1920) → SIGN(2018)



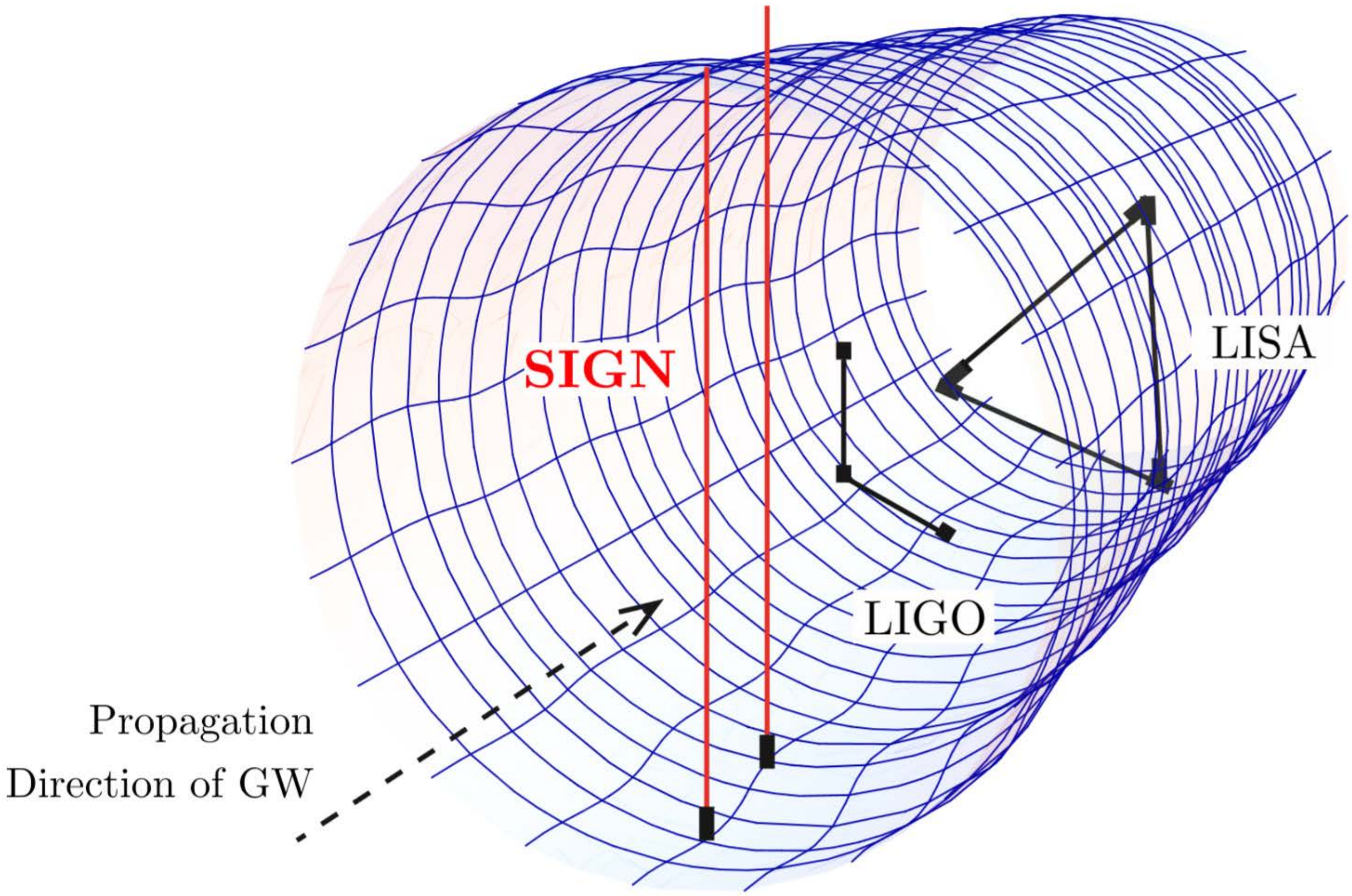






Comparison among LIGO, LISA, and SIGN

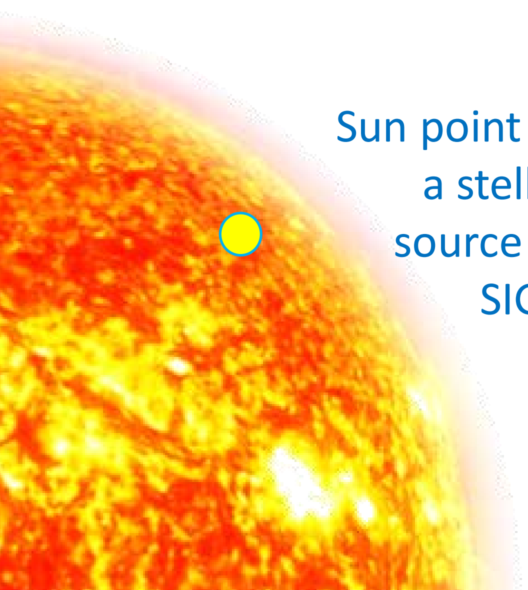
LIGO and LISA: A gravitational wave propagates normal to the interferometer plane
SIGN: it travels in the direction of the interferometer plane of two parallel EM lights



Candidates of Stellar Sources for SIGN

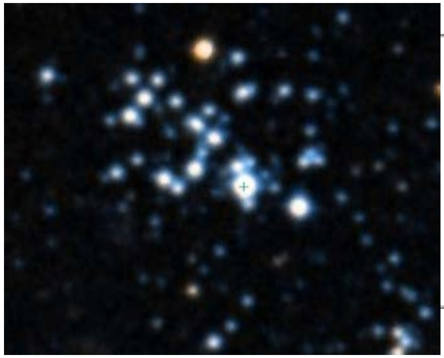
Major concerns are of coherent length, size, distance, apparant magnitude

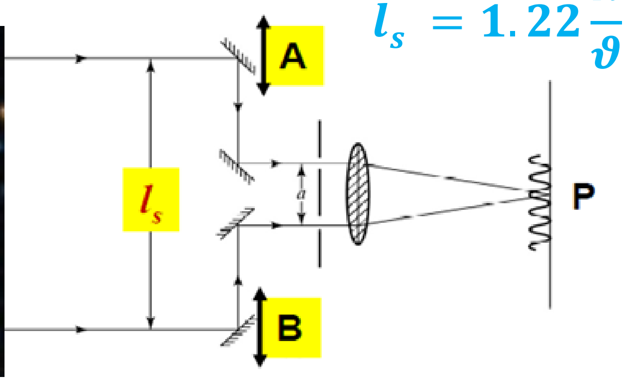
star	λ_{EM} (μm)	size of star (times Sun)	distance to star (Ly)	θ_s (μarcsec)	l_s (km)	sun seeing size (m)	apparent mag
SPICA	0.6	7.4	262	428.40	0.352		0.98
SPICA secondary	0.6	3.64	262	210.72	0.716		0.98
SMC AB8	0.6	2	197000	0.15	1000		12.83
WR1	0.6	1.33	11000	1.79	84		10.54
WR2	0.6	0.89	8200	1.60	94		11.33
R136a1	0.6	30	163000	2.72	55		12.23
Sun point (.1marcsec)	0.6	1	1.58E-05	100	5	15	~10



Sun point as a stellar source of SIGN

SMC AB8





$$l_s = 1.22\frac{\lambda}{\vartheta}$$

(to be published elsewhere)

Path length difference in SIGN

Interference of light rays

$$
\begin{aligned}
(E_{\rm I}+E_{\rm II})_{\rm (con/des)} \approx\; & (\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})\exp\left[{\rm i}\left(KL_{\rm I}-\omega_{\rm EM}t-\pi/2\right)\right] \\
& +\left[\mathcal{E}_{\rm I}\exp\left({\rm i}\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\pm\mathcal{E}_{\rm II}\exp\left(-{\rm i}\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\right] \\
& \times\frac{h_{+}\omega_{\rm EM}\left(\sin^2\phi\sin^2\theta-\cos^2\theta\right)+2{\rm i}h_{\times}\omega_{\rm EM}\sin\phi\cos\theta\sin\theta}{2\omega_{\rm GW}\left(1-\cos\phi\sin\theta\right)} \\
& \times\exp\left[{\rm i}\left(KL_{\rm I}-\left(\omega_{\rm EM}+\omega_{\rm GW}\right)t-\pi/2\right)\right].
\end{aligned}
$$

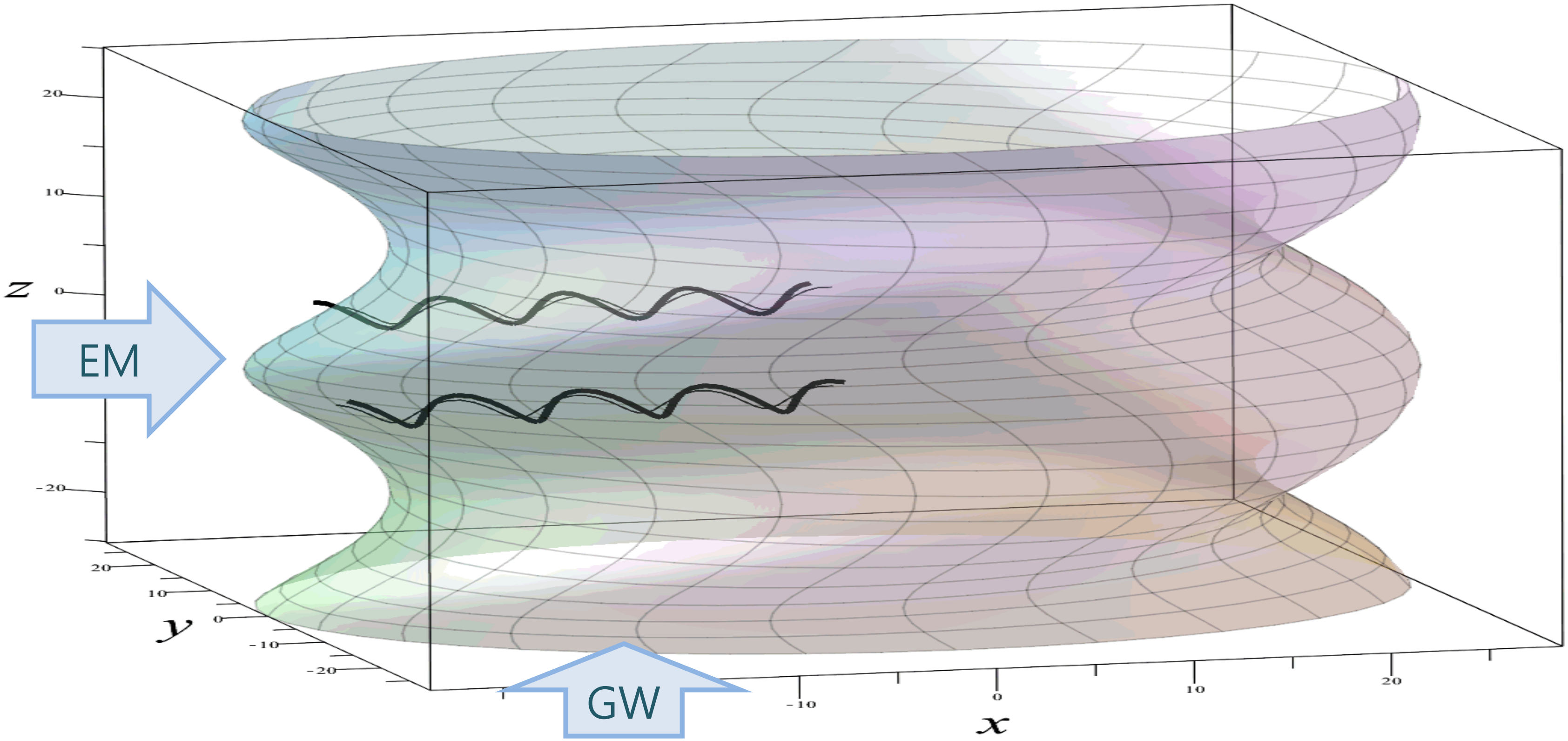
Intensity of superposed light waves

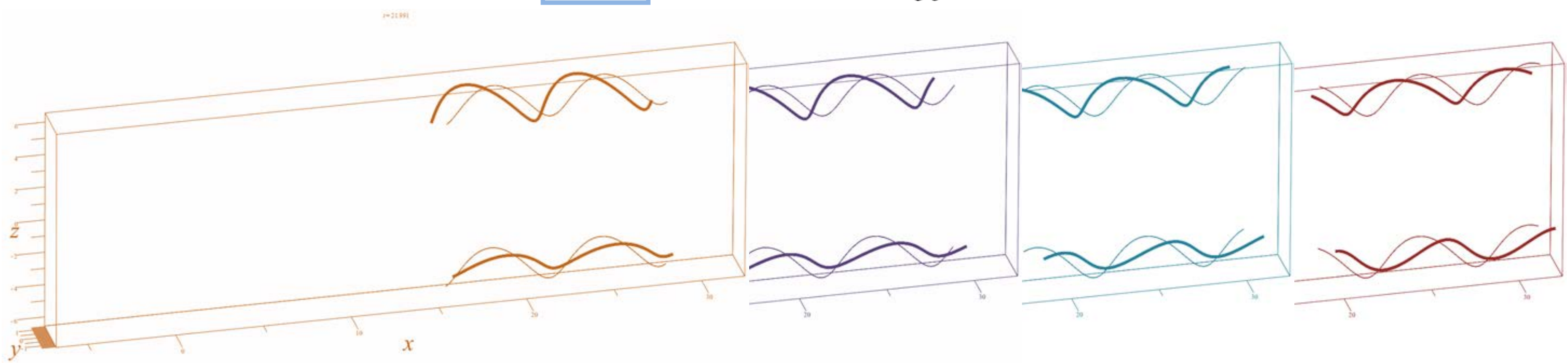
$$
\begin{aligned}
\mathcal{I}_{\rm (con/des)} =\; & (E_{\rm I}+E_{\rm II})(E_{\rm I}+E_{\rm II})^{*} \\
\approx\; & (\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})^2 \\
& +\left[\frac{h_{+}\omega_{\rm EM}}{\omega_{\rm GW}}\frac{\sin^2\phi\sin^2\theta-\cos^2\theta}{1-\cos\phi\sin\theta}(\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})^2\cos\left(\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\right. \\
& \left.-\frac{2h_{\times}\omega_{\rm EM}}{\omega_{\rm GW}}\frac{\sin\phi\cos\theta\sin\theta}{1-\cos\phi\sin\theta}\left(\mathcal{E}_{\rm I}^2-\mathcal{E}_{\rm II}^2\right)\sin\left(\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\right]\times\cos\left(\omega_{\rm GW}t\right) \\
& +\left[\frac{h_{+}\omega_{\rm EM}}{\omega_{\rm GW}}\frac{\sin^2\phi\sin^2\theta-\cos^2\theta}{1-\cos\phi\sin\theta}\left(\mathcal{E}_{\rm I}^2-\mathcal{E}_{\rm II}^2\right)\sin\left(\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\right. \\
& \left.+\frac{2h_{\times}\omega_{\rm EM}}{\omega_{\rm GW}}\frac{\sin\phi\cos\theta\sin\theta}{1-\cos\phi\sin\theta}(\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})^2\cos\left(\frac{1}{2}kl_{\rm s}\cos\phi\cos\theta\right)\right]\times\sin\left(\omega_{\rm GW}t\right)+\mathcal{O}\left(h^2\right)
\end{aligned}
$$

For $\theta=\varphi=0$, GW crosses EM light rays at a right angle by propagating in the *z*-direction while being polarized in the *xy*-plane

$$
\begin{aligned}
\mathcal{I}_{\rm (con/des)} \approx\; & (\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})^2 \\
& -\frac{h_{+}\omega_{\rm EM}}{\omega_{\rm GW}}\left[(\mathcal{E}_{\rm I}\pm\mathcal{E}_{\rm II})^2\cos\left(\frac{kl_{\rm s}}{2}\right)\cos\left(\omega_{\rm GW}t\right)+\left(\mathcal{E}_{\rm I}^2-\mathcal{E}_{\rm II}^2\right)\sin\left(\frac{kl_{\rm s}}{2}\right)\sin\left(\omega_{\rm GW}t\right)\right]+\mathcal{O}\left(h^2\right)
\end{aligned}
$$

Simulation of EM perturbed by GW





Shot (or quantum) noise

- A single photon creates an interference pattern but any attempt to see which slit the photon entered will destroy the interference pattern, otherwise the uncertainty principle would be violated.
  → $\Delta N_p \Delta\phi \sim 1$ (Uncertainty principle)
- $\Delta p\, \Delta x \sim \hbar/4\pi$ → $\Delta p = \Delta N \frac{\hbar}{\lambda}$ and $\Delta x = \delta L = hL_c$ (h: strain, Lc characteristic length of the SIGN and a wavelength of GW to be detected.) → $h = \frac{\lambda}{4\pi L_c}\frac{1}{\sqrt{N}}$
  - $N = P\frac{\lambda}{\hbar c}\tau$ (P is the optical power of a given star) → $\Delta N = \sqrt{N}$
  - Power $P_{m=8} \approx 10^{-10} W$ (note that available power for LISA $P_{LISA(available)} \approx 2 \times 10^{-10} W$)
  - $m = -\frac{5}{2}log_{10}(\frac{f}{f_0})$ where the reference flux $f_0 = 3.08 \times 10^{-20}\ \frac{erg}{s \cdot cm^2 \cdot Hz}$ for R-band with $\lambda = 0.64\mu m$
- Then, minimum detectable change from the short noise for a star of mag=8, $\tau = 1$ and $\lambda = 100nm$ is $\boldsymbol{\delta L_{SIGN} = 10^{-12}\ m}$

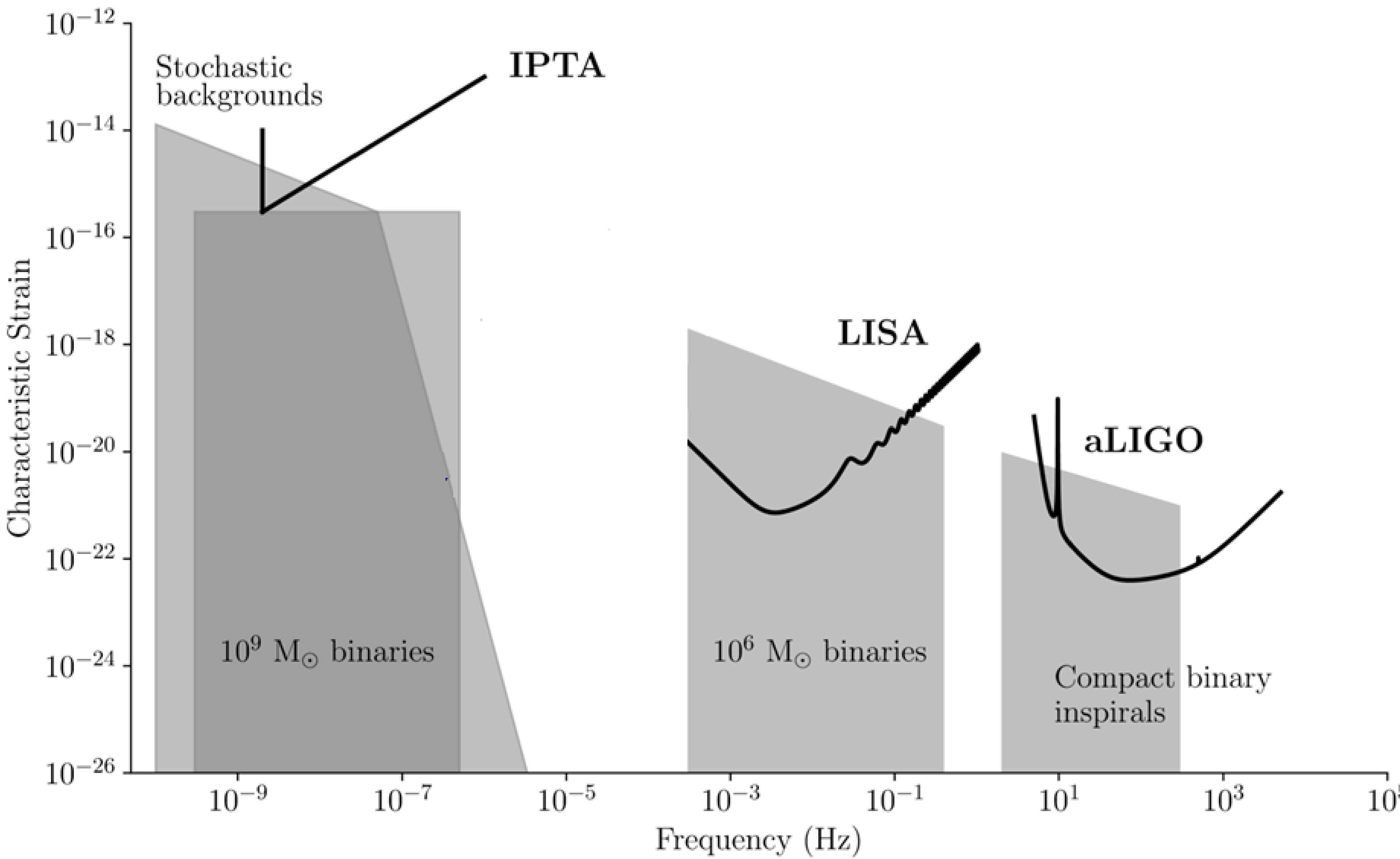
Sensitivity of SIGN with shot noise

Then the sensitivity of SIGN is derived to

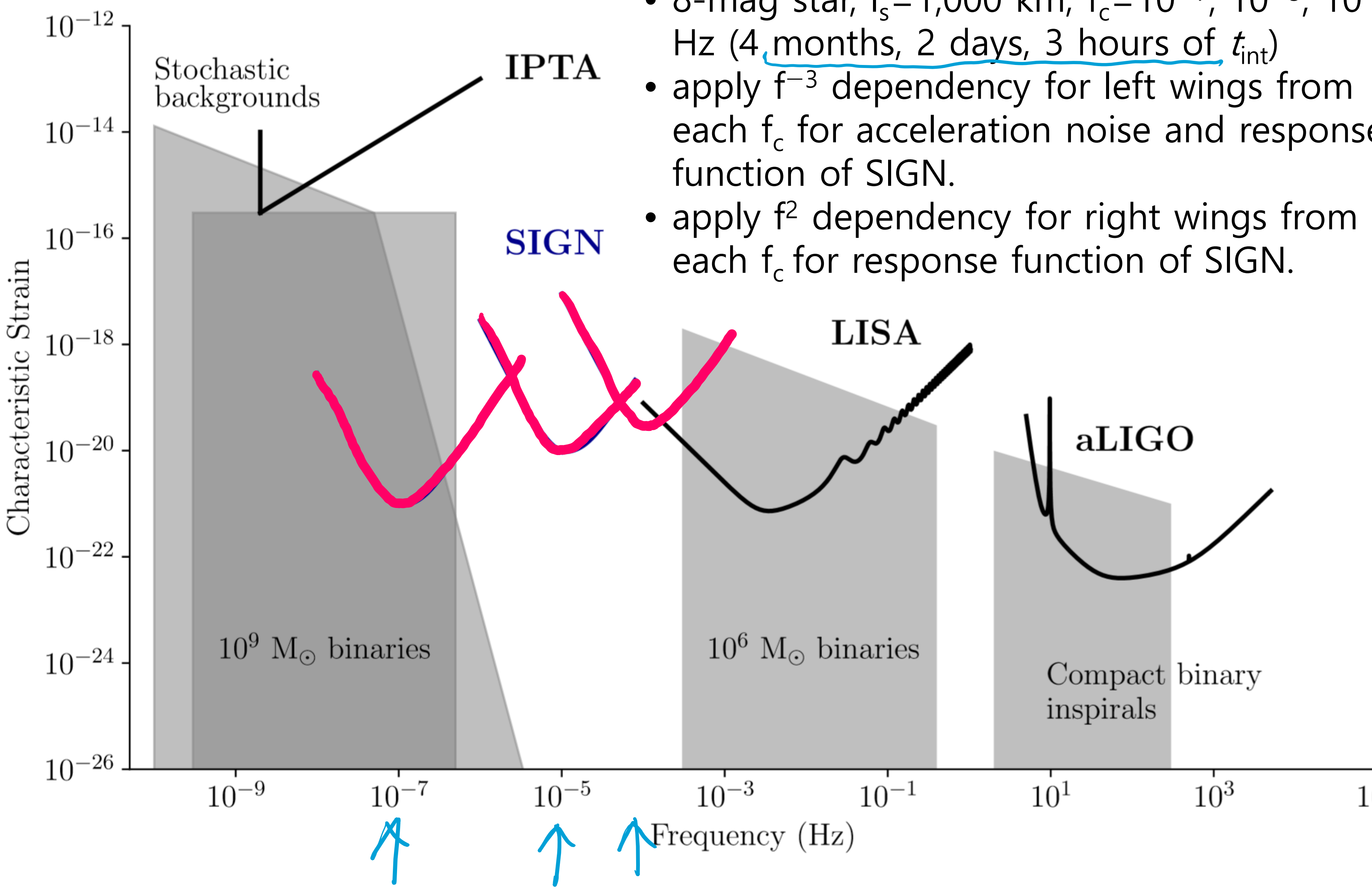
$$h_{\rm SIGN} = \left(\frac{\delta L_c}{L_c}\right) \cdot \left(\frac{L_c}{\ell_s}\right)$$
$$= \left(\frac{10^{-12}\ {\rm m}}{L_c}\right) \cdot \left(\frac{\lambda}{100\ {\rm nm}}\right)^{1/2} \cdot (2.5^{(8-{\rm mag})})^{1/2} \cdot \left(\frac{\tau}{1\ {\rm sec}}\right)^{-1/2} \cdot \left(\frac{L_c}{\ell_s}\right).$$

where the factor (Lc/ls) comes from the first-order detector response which reflects the fact that the separation between two satellites is not comparable to the wavelength of GW.

Sensitivity of running and planned GW exps

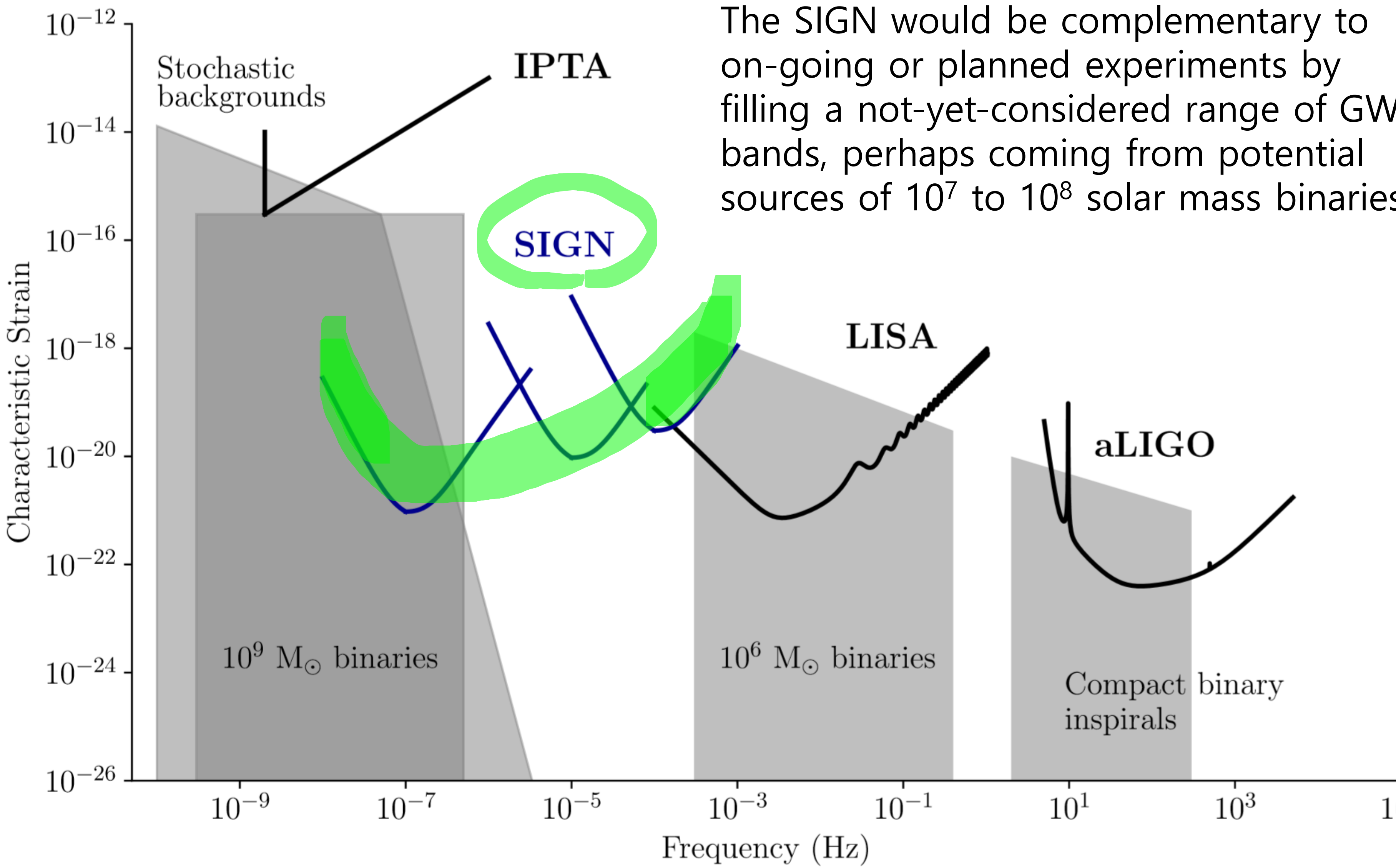


Sensitivity of running and planned GW exps



- 8-mag star, l_s=1,000 km, $f_c=10^{-7}$, 10^{-5}, 10^{-4} Hz (4 months, 2 days, 3 hours of t_{int})
- apply f^{-3} dependency for left wings from each f_c for acceleration noise and response function of SIGN.
- apply f^2 dependency for right wings from each f_c for response function of SIGN.

Sensitivity of running and planned GW exps

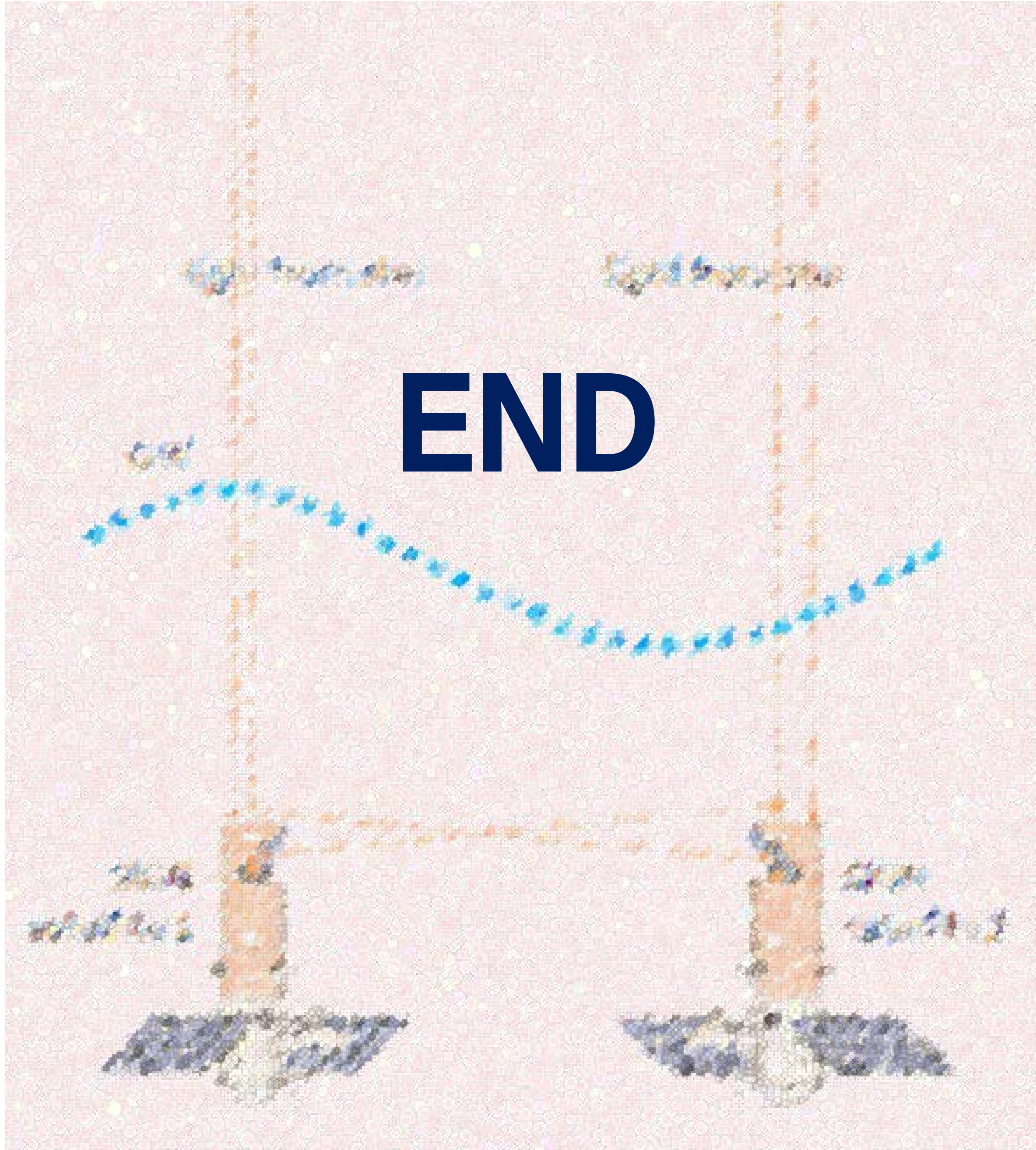


The SIGN would be complementary to on-going or planned experiments by filling a not-yet-considered range of GW bands, perhaps coming from potential sources of 10^7 to 10^8 solar mass binaries.

Conclusion

- We propose a full scale mission of **"UFFO"** providing not only observation of early photons from GRBs, but **concurrent measurement of EM with GW for multi-messenger astrophysics**.
- We propose a new method to detect GWs, **"SIGN"**, based on the **space-based spatial coherence interferometry using star light** as opposed to conventional laser light.

  → The SIGN would be complementary to existing GW detectors like laser interferometers and pulsar timing arrays, by **covering the frequency ranges of 10–7 –10–4 Hz of GWs**.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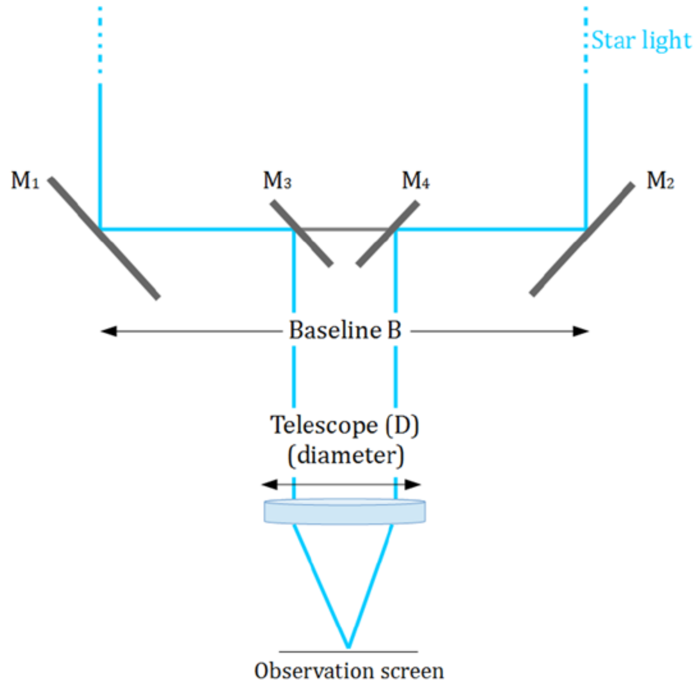
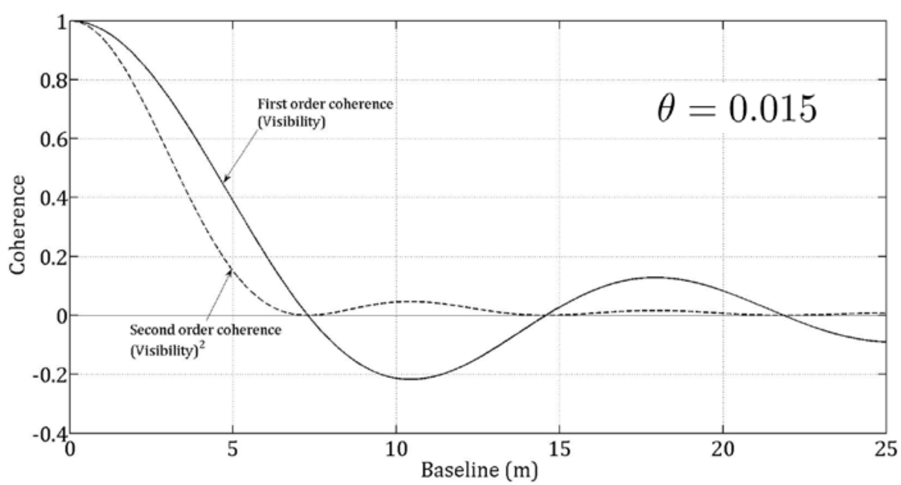
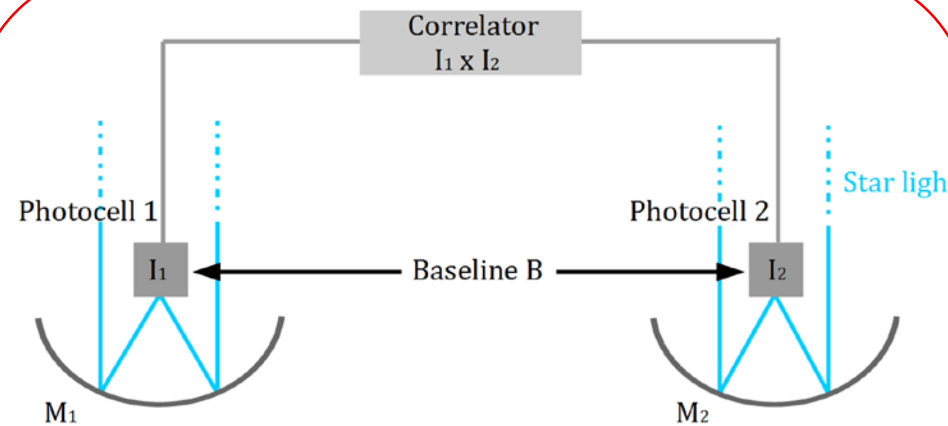
What about Intensity Interferometer





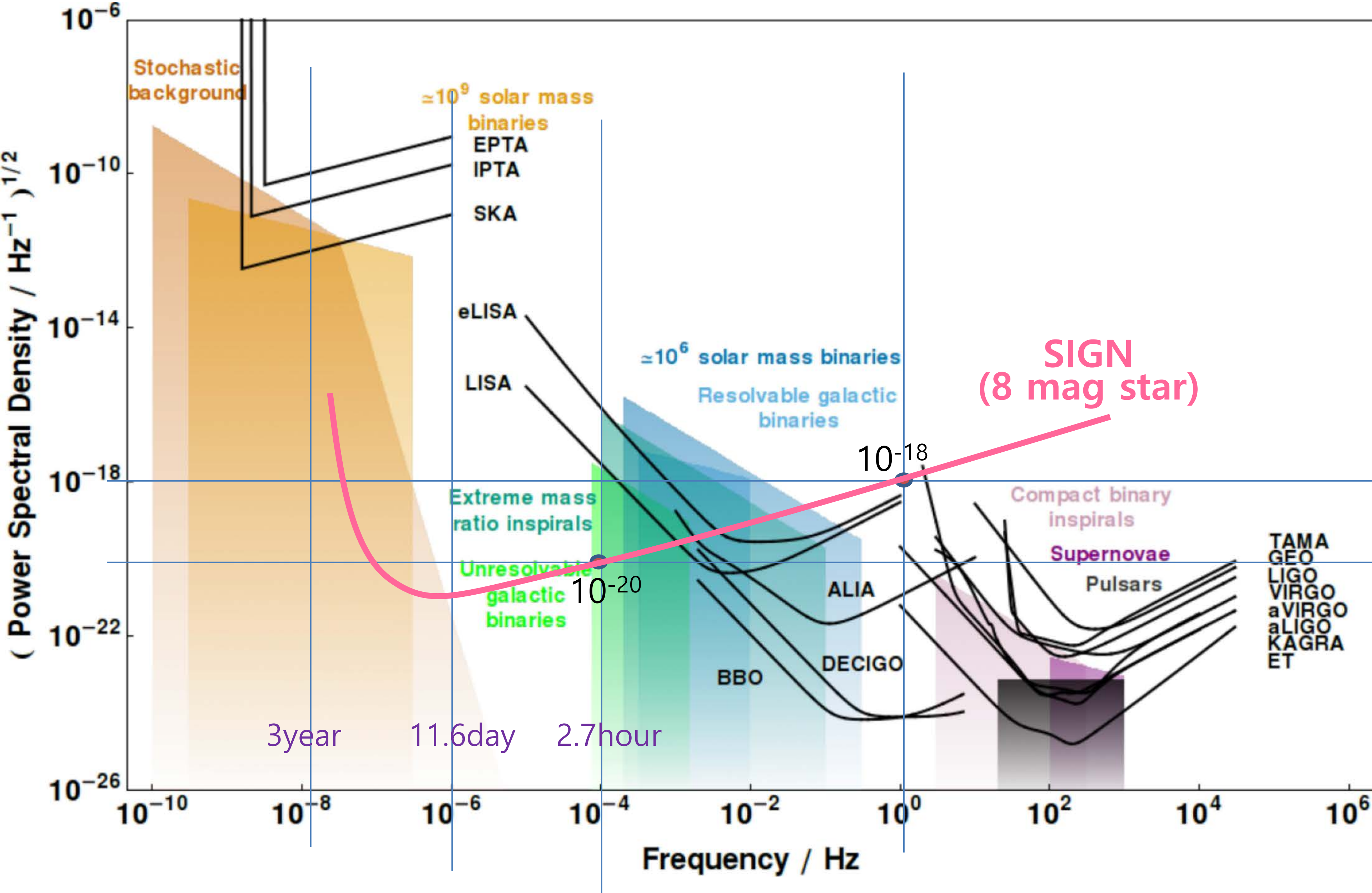


Stellar intensity interferometer. Two mirrors serve as light buckets and collect photons from a star. The intensity signal received at each photocell is converted into an electrical signal and sent to a correlator. The correlator multiplies the signal from the two detectors, providing the second-order coherence G(2). By changing the baseline B it is possible to retrieve a function similar to the visibility curve.

Amplitude vs. Intensity Interferometry

	Amplitude Interferometry	*Intensity Interferometry*
Signal	Optical → cannot be divided indefinitely → only few baselines possible → low interferometric-plane coverage High SNR	Electronic → can be copied → many baselines possible → Very good interferometric-plane coverage possible Poor SNR → need large flux collectors
Mechanical precision	High → baseline limited → expensive reflectors → better for longer wavelengths	Low → very long baseline possible ⟶ **very high resolution possible** → low cost reflectors → not problem for short wavelengths ⟶ even higher resolution
Correlation	Amplitude/phase → phase measured → image possible to retrieve	Intensity (amplitude squared) → phase lost → image hard to retrieve Immune to poor seeing
Source requirement	Cool and faint stars	Hot and bright stars → Long exposure times

Sensitivity of SIGN (old)



Technical challenge

- Pointing, stabilization & disturbance-free system
  - Interferometry: Track fringes to establish separation changes with 10pm accuracy
  - Inertial sensing: Sense deviations from inertial (geodesic) trajectories
  - Micro-newton thrusters: Mitigate against deviations from inertial trajectories owing to, e.g., acceleration noise from solar wind
- Maneuvering of satellites constellation
  - Tandem operation
  - Thrusters and fuel for long term operation in space
- Realization
  - Low cost: ~$60M depending on orbit chosen
  - Fast leadtime: 6 years after funding
  - A pathfinder experiment (or prototyping an idea) foreseen

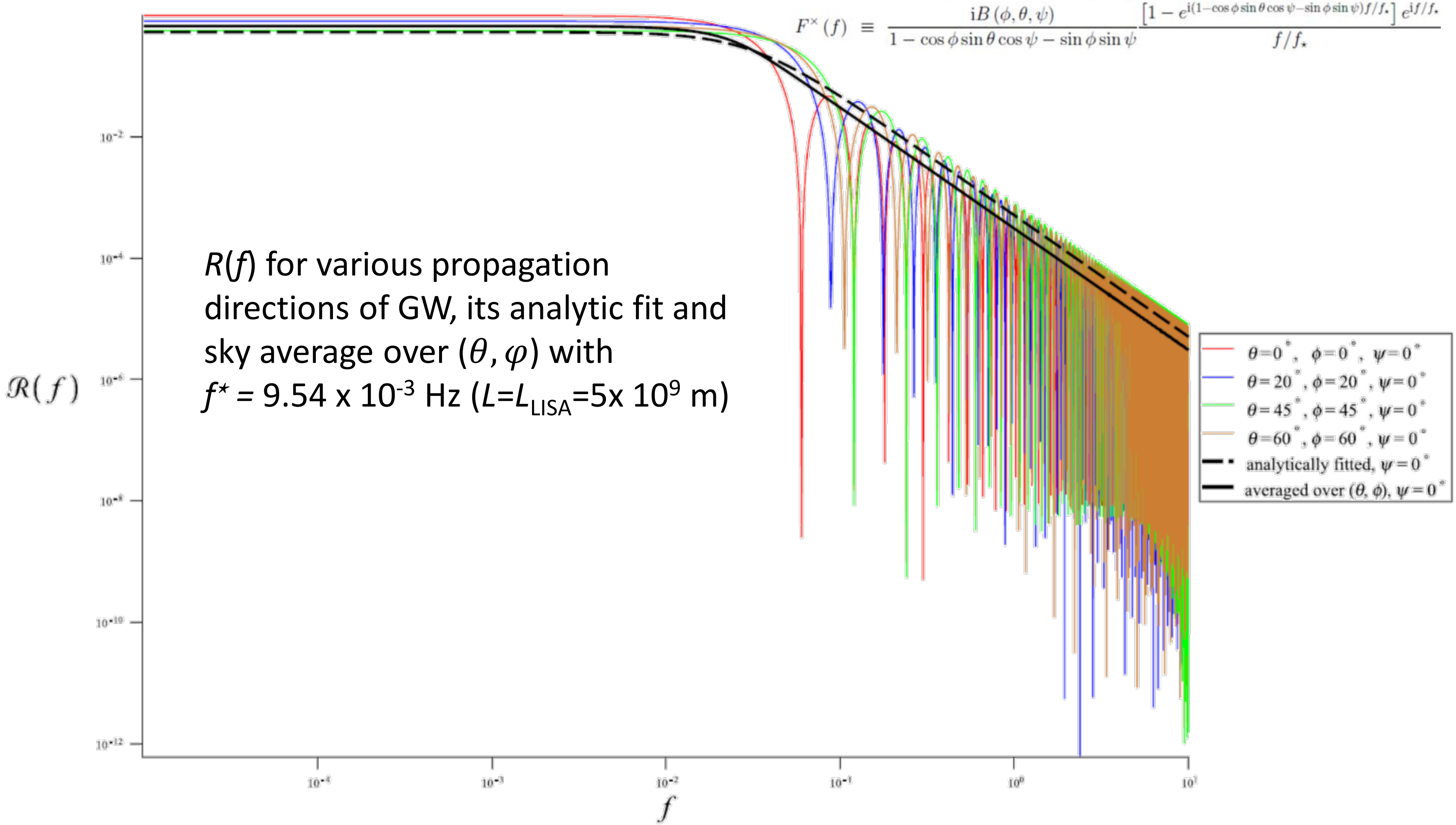
Response of the SIGN detector

Response function $R(f) \approx \dfrac{8}{15\left(1+\frac{2}{21}\left(\frac{f}{f_*}\right)^2\right)}$

$$\mathcal{R}(f) = \frac{1}{4\pi^2}\int_0^{\pi} d\psi \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \, \sin\theta \left[F^{+}(f)\,F^{+*}(f) + F^{\times}(f)\,F^{\times *}(f)\right]$$

$$F^{+}(f) \equiv \frac{\mathrm{i}A(\phi,\theta,\psi)}{1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi}\,\frac{\left[1-e^{\mathrm{i}(1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi)f/f_*}\right]e^{\mathrm{i}f/f_*}}{f/f_*}$$

$$F^{\times}(f) \equiv \frac{\mathrm{i}B(\phi,\theta,\psi)}{1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi}\,\frac{\left[1-e^{\mathrm{i}(1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi)f/f_*}\right]e^{\mathrm{i}f/f_*}}{f/f_*}$$



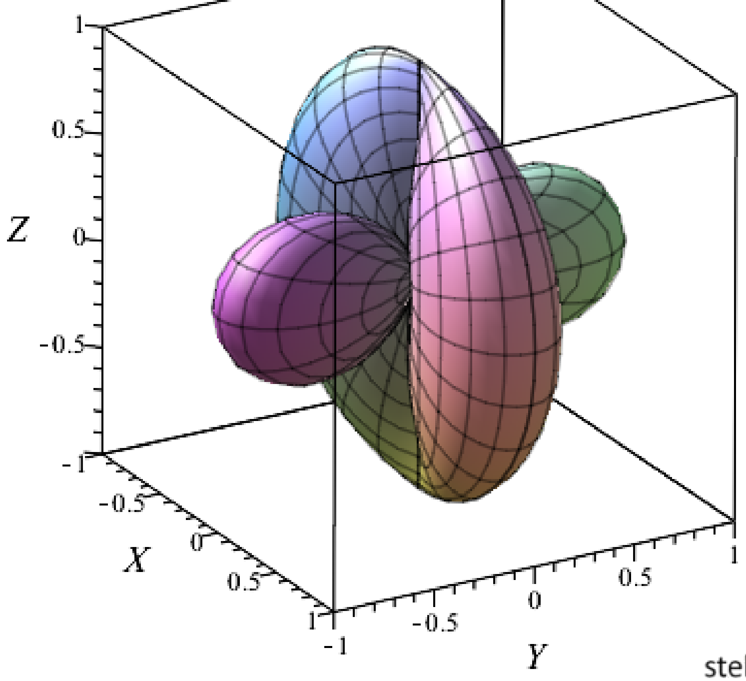
R(*f*) for various propagation directions of GW, its analytic fit and sky average over (θ, φ) with $f^{\star} = 9.54 \times 10^{-3}$ Hz ($L=L_{LISA}=5\times 10^{9}$ m)

Antenna patterns in long-wavelength approximation

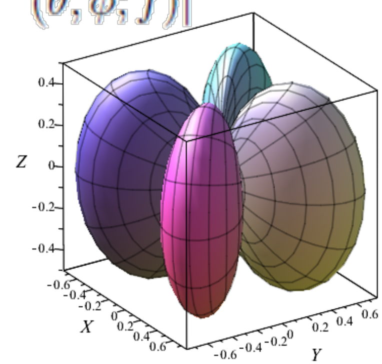
$$F^{+}(f) \equiv \frac{\mathrm{i}A(\phi,\theta,\psi)}{1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi}\frac{\left[1-e^{\mathrm{i}(1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi)f/f_{\star}}\right]e^{\mathrm{i}f/f_{\star}}}{f/f_{\star}}$$

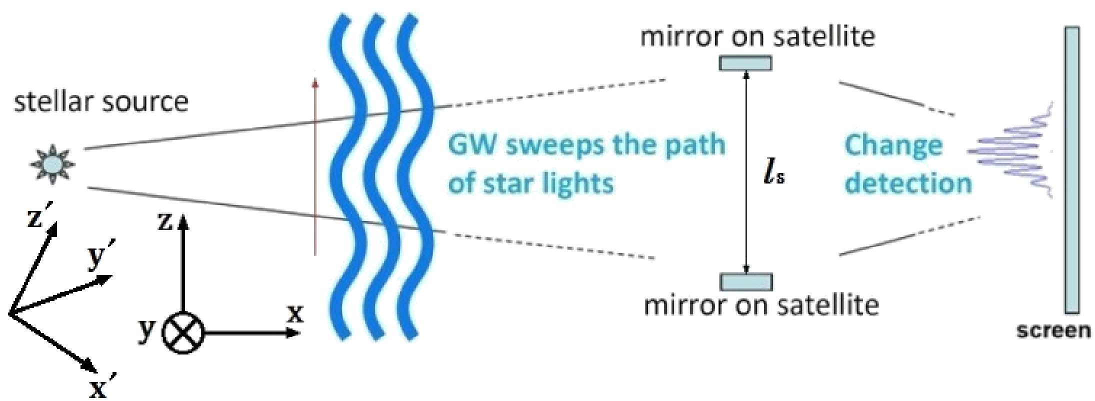
$$F^{\times}(f) \equiv \frac{\mathrm{i}B(\phi,\theta,\psi)}{1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi}\frac{\left[1-e^{\mathrm{i}(1-\cos\phi\sin\theta\cos\psi-\sin\phi\sin\psi)f/f_{\star}}\right]e^{\mathrm{i}f/f_{\star}}}{f/f_{\star}}$$

$\lim_{f\to 0}|F^{+}(\theta,\phi;f)|$



$\lim_{f\to 0}|F^{\times}(\theta,\phi;f)|$

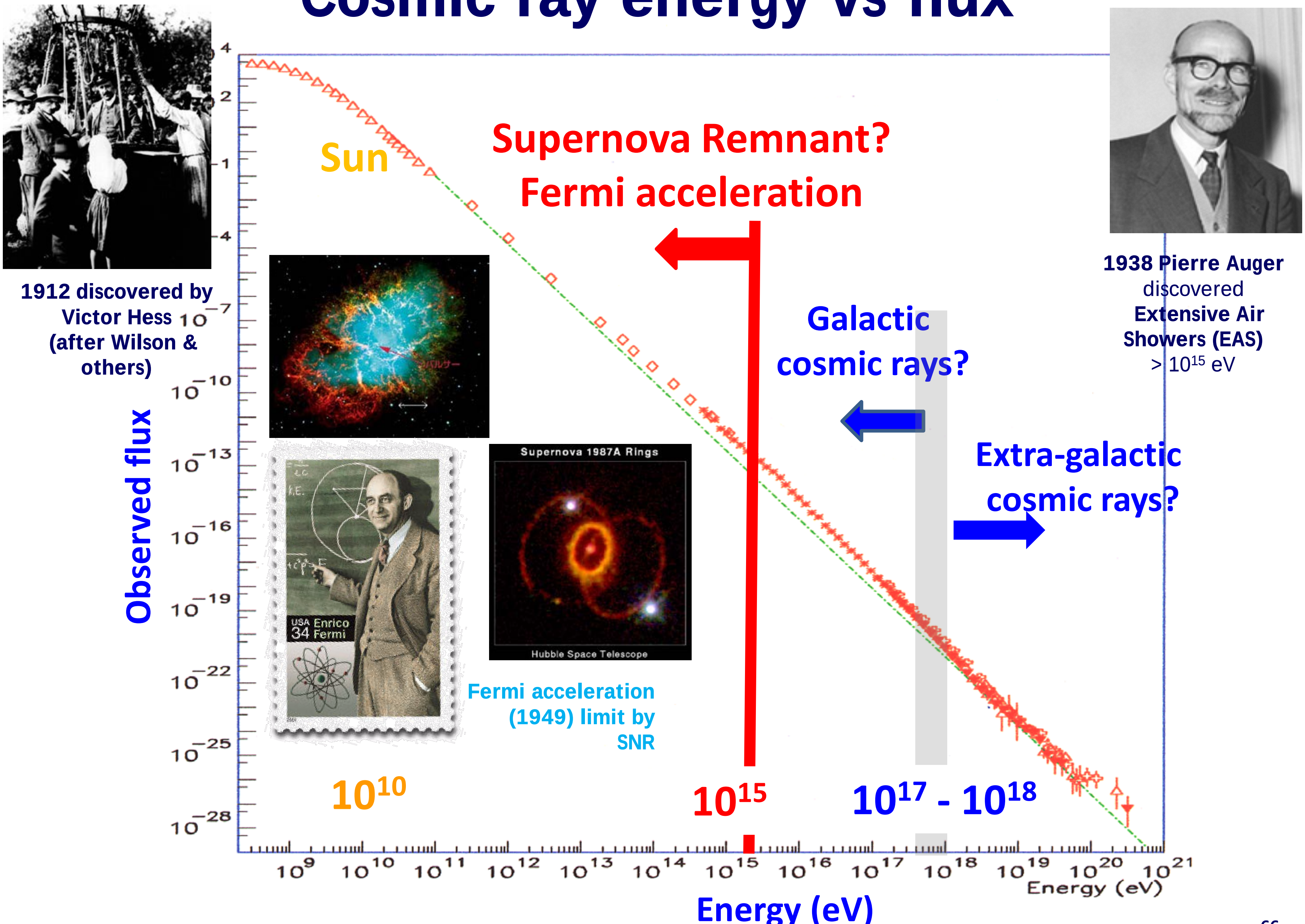




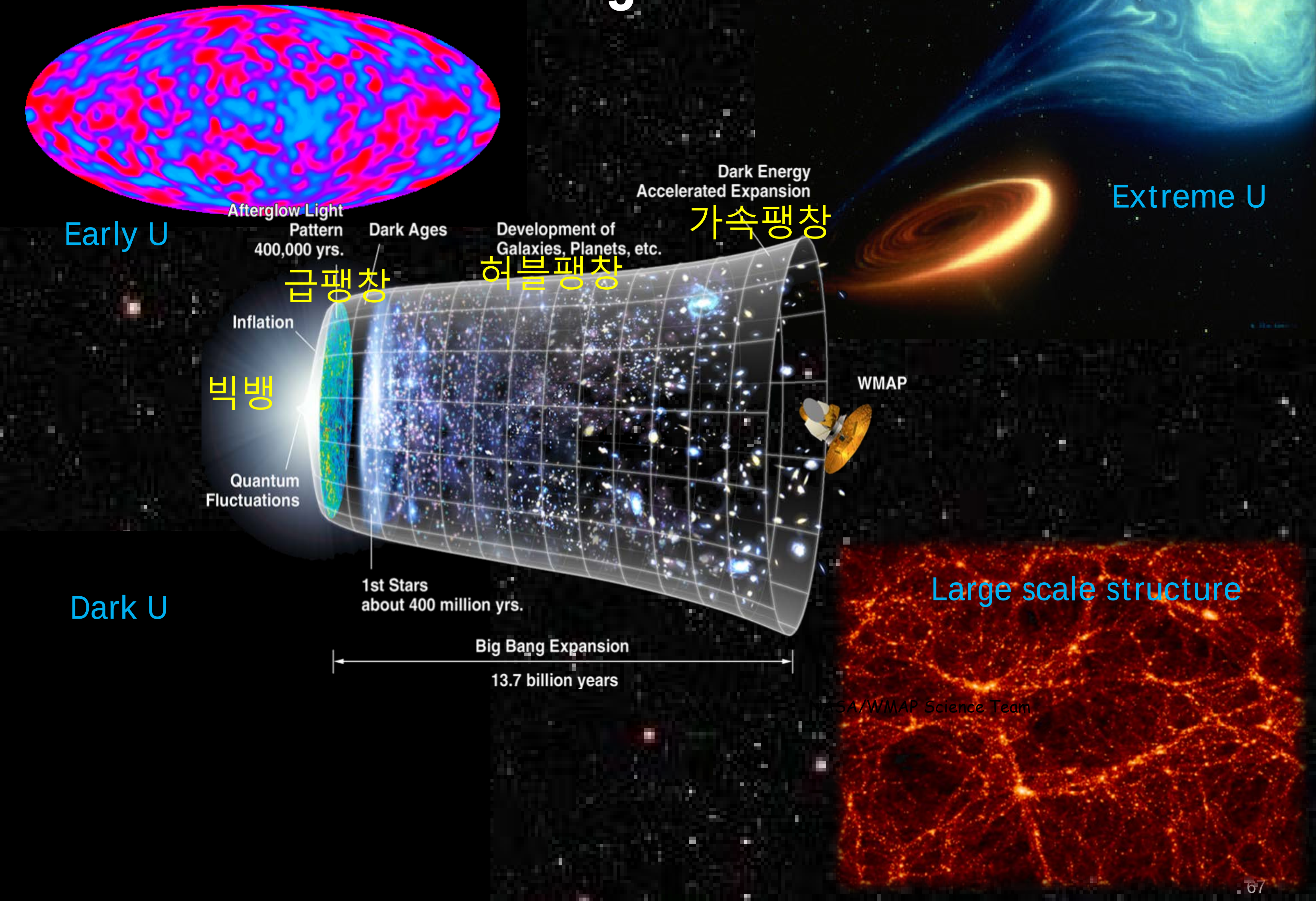
Content

- Gravitational wave detectors
- Coherence experiments in interferometry
- Proposed method of SIGN
- Sensitivity of SIGN
- Technical challenge
- Conclusion

Cosmic ray energy vs flux



Understanding of the Universe



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Research Themes

Table 1. A few selected research aims with observational tools to understand the structure and evolution of the Universe.

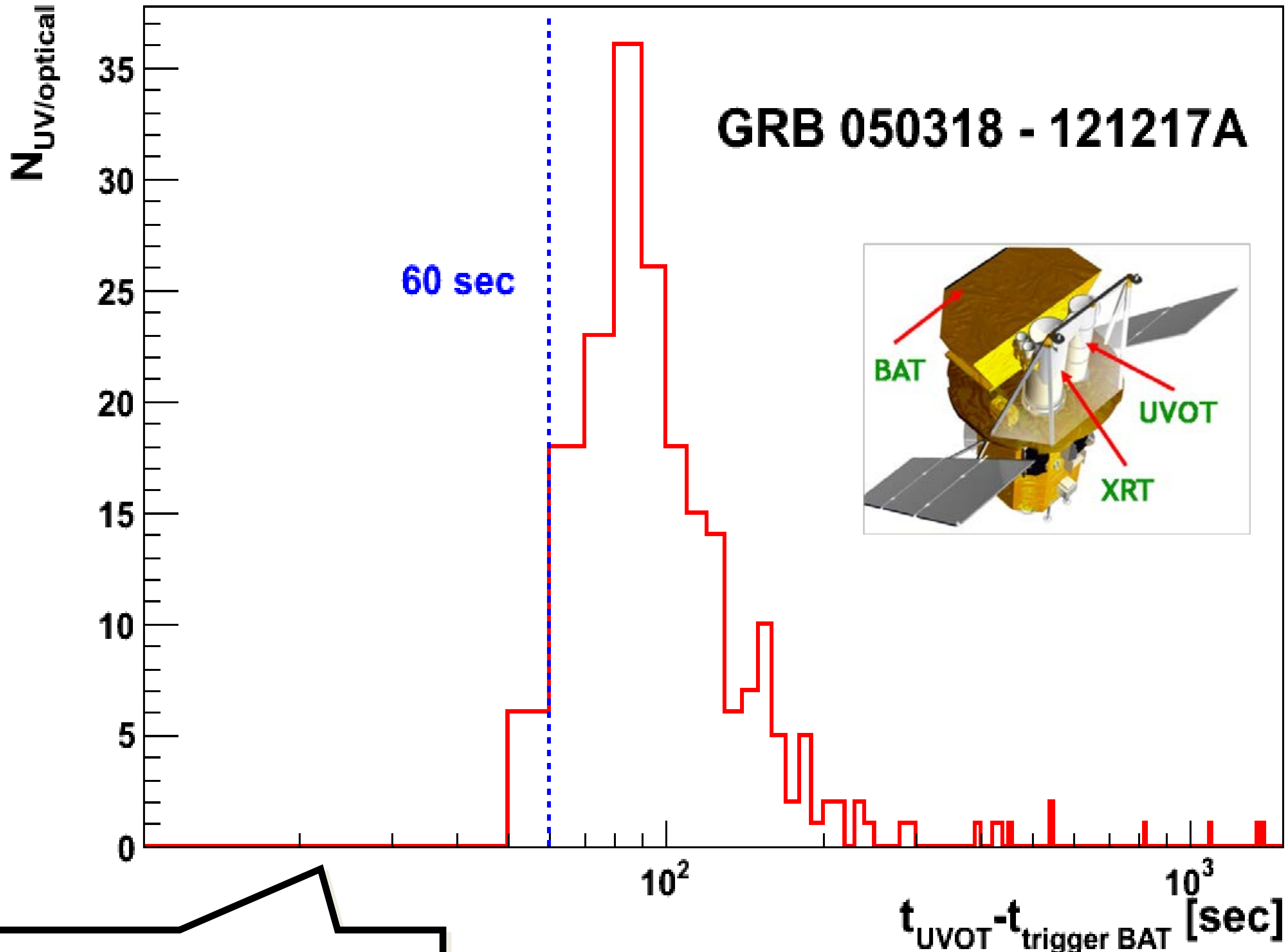
Grand theme	Structure and Evolution of the Universe		
Theme	Early Universe	Extreme Universe	Dark Universe
Scientific objectives	. Inflation, Big Bang afterglow, first star and galaxy, dark age, reionization epoch . Primordial GWs	. BH, NS, SN, AGN, . Primordial black holes . Lorenz invariance . Origins of GW, GRB, UHECR	. Expansion history . Content and evolution of dark energy . Next generation standard candle
Observations	CMB, large scale structure, gravitational lensing, GW, GRB	GW, GRB, SN, UHECR	CMB, GRB

In this talk

- **Cosmic Particle as a would-be messenger**
- **Gamma-Ray Burst as a source of MMA**
- **Recent discovery of Gravitational Wave**

→ **Dawn of Multi-messenger Astrophysics (MMA)**

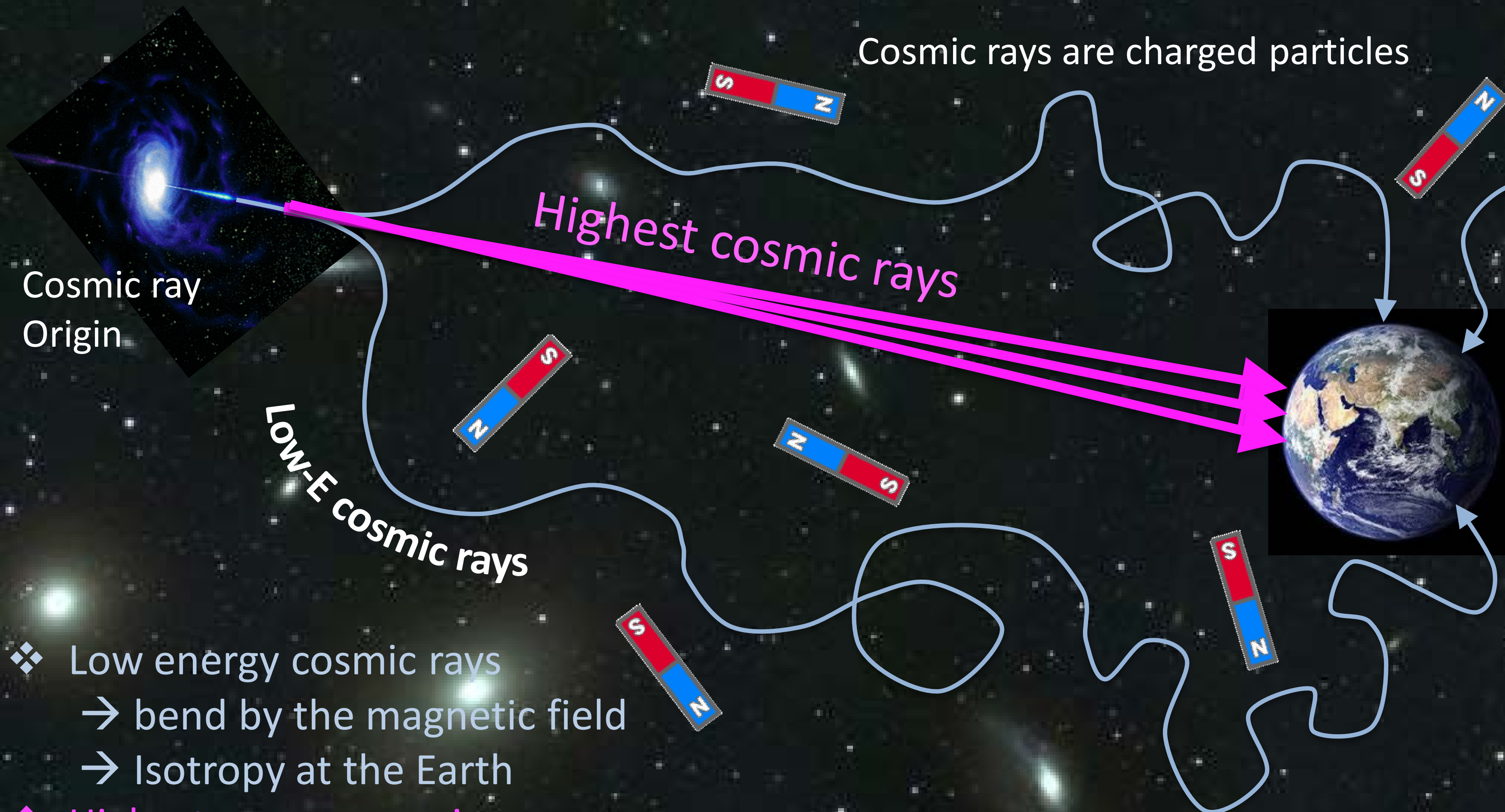
Limit in *Swift* Response Speed



What is happening (optically) at shorter time scales?

Park et al. 2013,
New Journal of Physics 15, 023031

Why highest energy cosmic rays?



- Low energy cosmic rays
  - → bend by the magnetic field
  - → Isotropy at the Earth
- Highest energy cosmic rays
  - → Almost go straight against magnetic field
  - → Possible to find cosmic-ray hotspot

Exciting discoveries of these days

To name a few below:

- Detail properties of **GRBs** accumulated mainly by 15 years mission of *Swift* together with millions of ground based EM observatories
- **Gamma-ray sky** dramatically improved by the *Fermi* telescope
- **Astrophysical neutrinos**, with the highest energy ever observed, detected by the *IceCube* neutrino observatory
- **Hot** and warm **spots of UHECRs** by the *Telescope Array (TA)* and the *Pierre Auger* observatories
- **Spectral break** around 200 GeV of all elements of cosmic rays implying a new paradigm of propagation by *CREAM, AMS, Pamela*
- **Gravitational waves** by *LIGO* and *VIRGO*
  - Multi-messenger observations of GW and all bands of EM from NS-NS merging for the first time by 70 world wide observatories
- etc.

→ open a new window of physics