重力波源の電波対応天体

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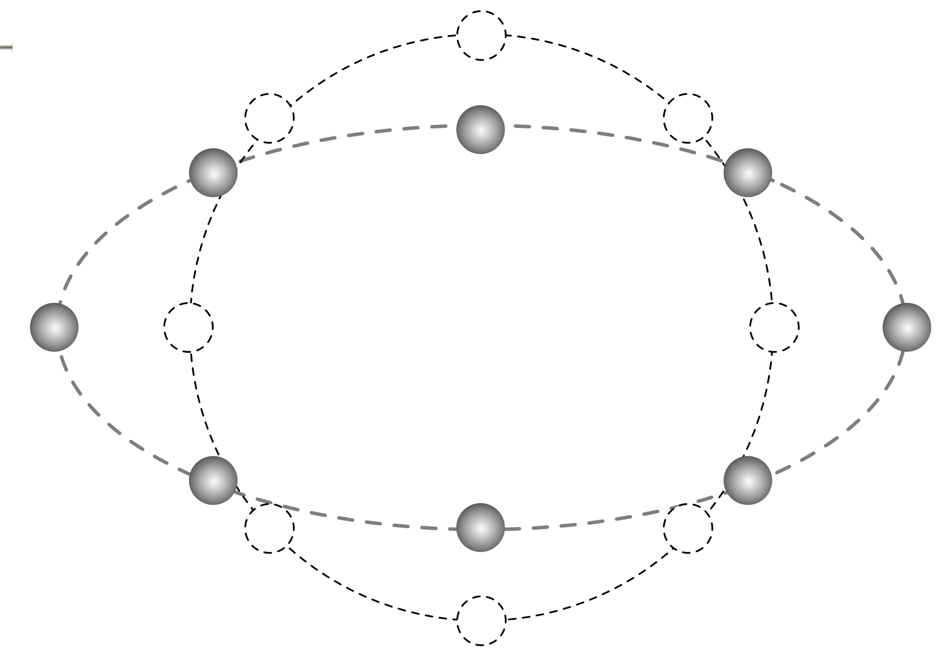
内容

- レーザ型重力波望遠鏡
- ターゲット（突発天体（連星合体、超新星爆発など））
- 望遠鏡建設状況
- 電波トランジェント
- マルチメッセンジャー観測に向けての準備
- 電波トランジェント-GW探査プラン例

重力波の検出



重力波の効果

○ 潮汐力の効果で自由質点間の距離が変化する

○ ＋モード、Xモードの２偏波がある

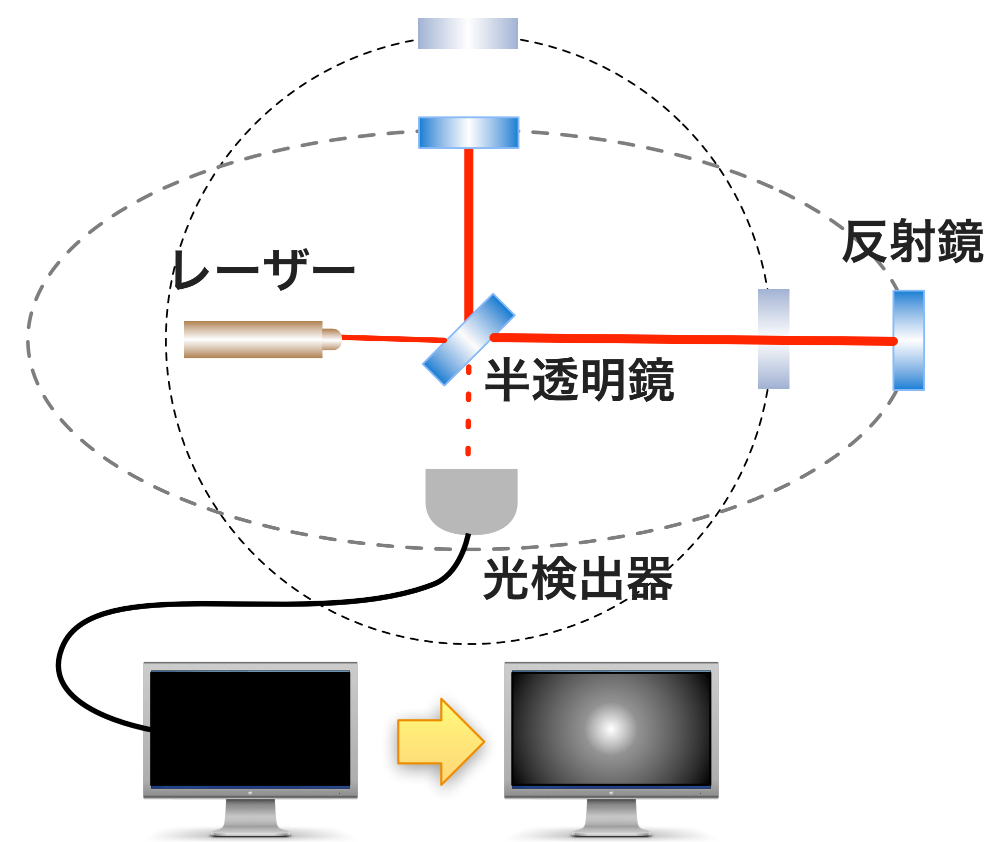
距離の変化をマイケルソン干渉計の原理で検出する

レーザー光を直交する２方向に分ける

⇩

ミラーに反射させ再結合。干渉光を光検出器で観測

干渉光量の時系列データから重力波信号を抽出する



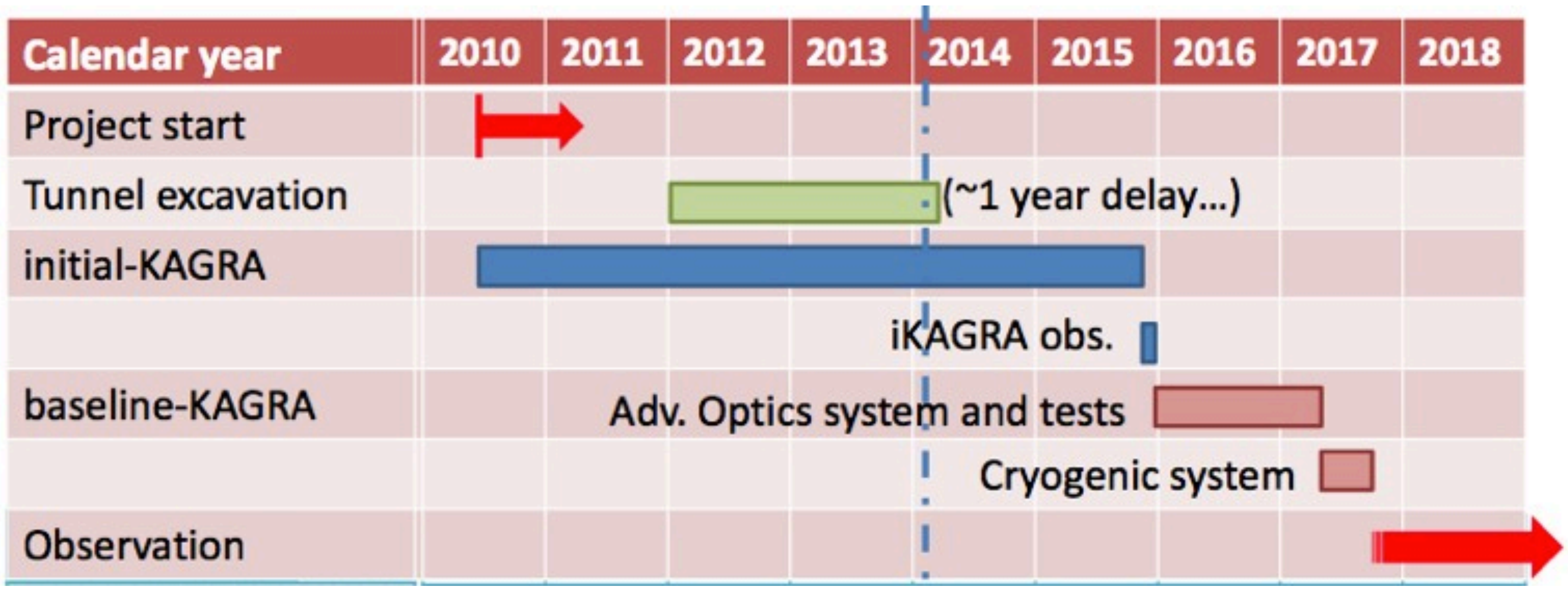
重力波望遠鏡の原理

ターゲット

- 突発性天体現象
  - 連星合体からの重力波
  - バースト性重力波（超新星爆発など）
- パルサーなどの連続的重力波
- 背景重力波

世界のレーザ干渉計型重力波望遠鏡の建設状況

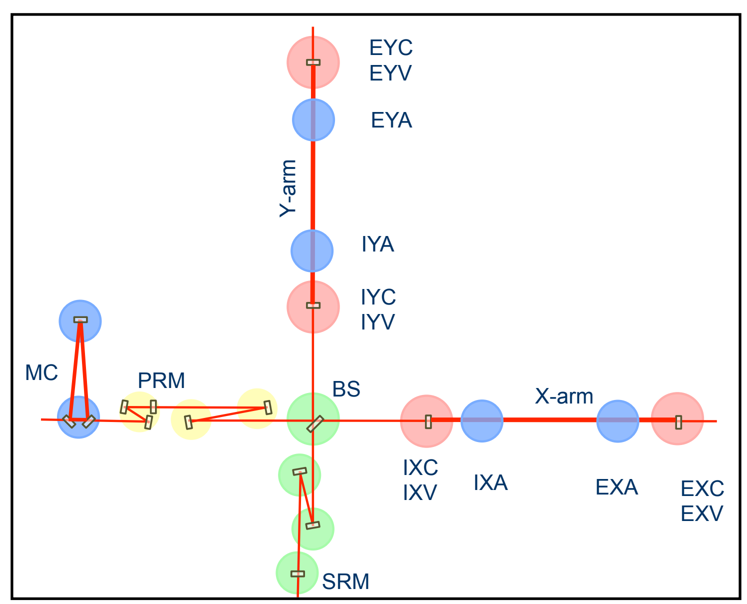
建設状況



Kajita,f2f,2014

2013年12月：片腕開通

2014年3月：もう片腕開通



2015末：常温で稼働

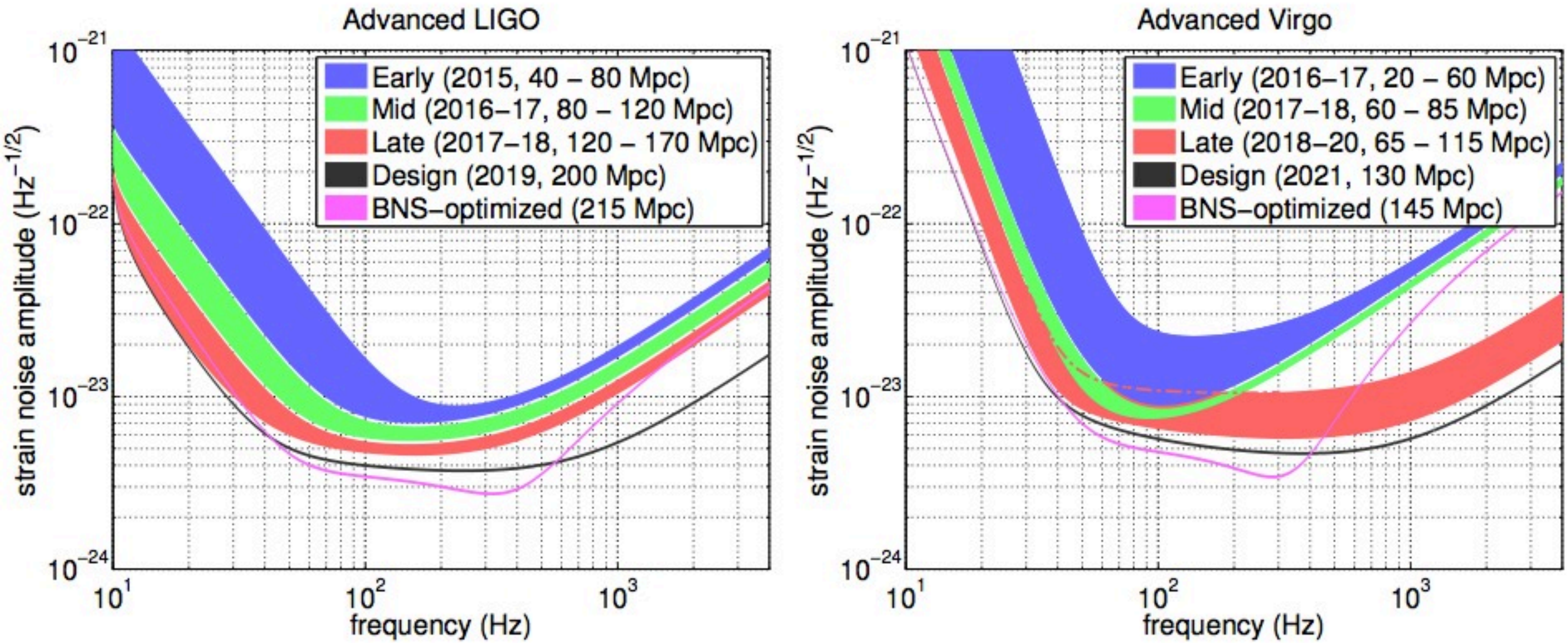
2017末。低温、RSE、..

フル装備で長期稼働

2014年3月：観測・解析用

施設完成

LIGO、Virgoはアップデート中



Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

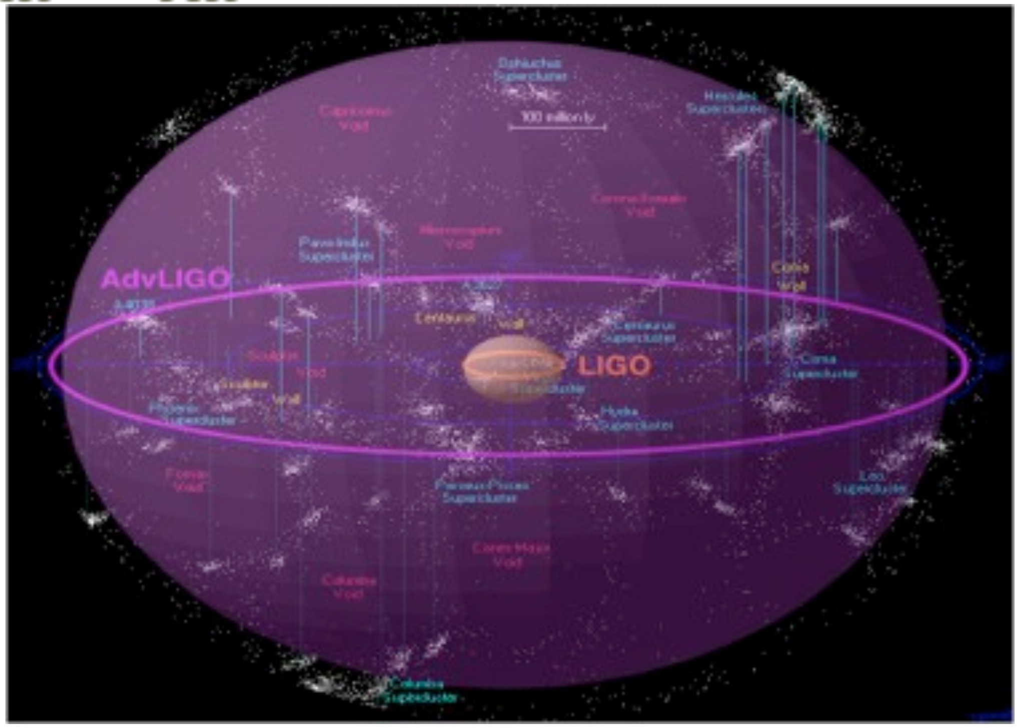
arXiv:1304.0670

到達距離

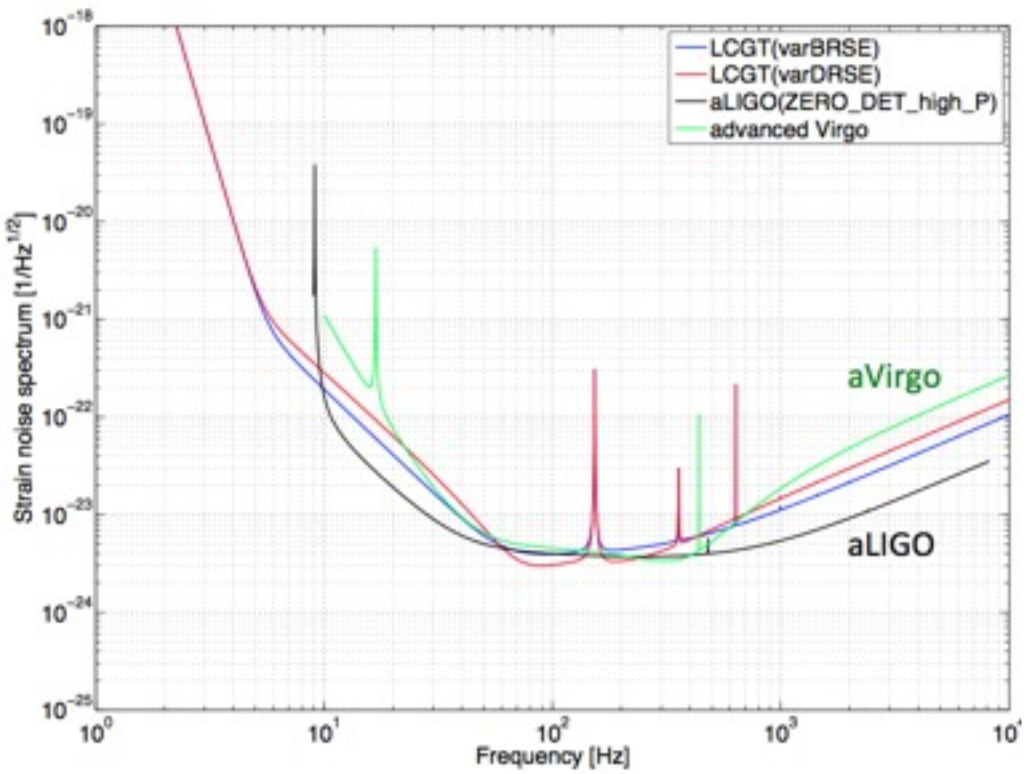
KAGRA,LIGO,Virgo、全天平均で

- 連星合体：100~200Mpc
- バースト：80-100Mpc

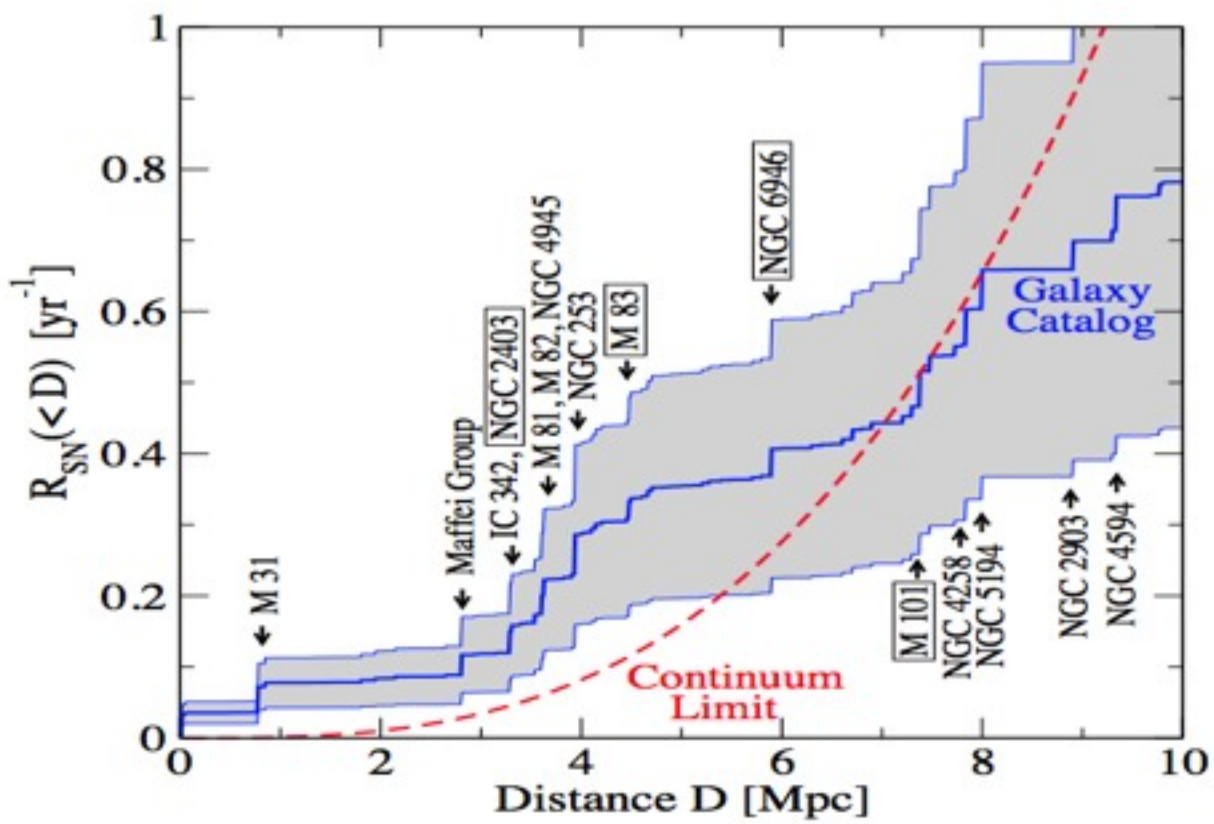
200Mpc



～ヘラクレス超銀河団



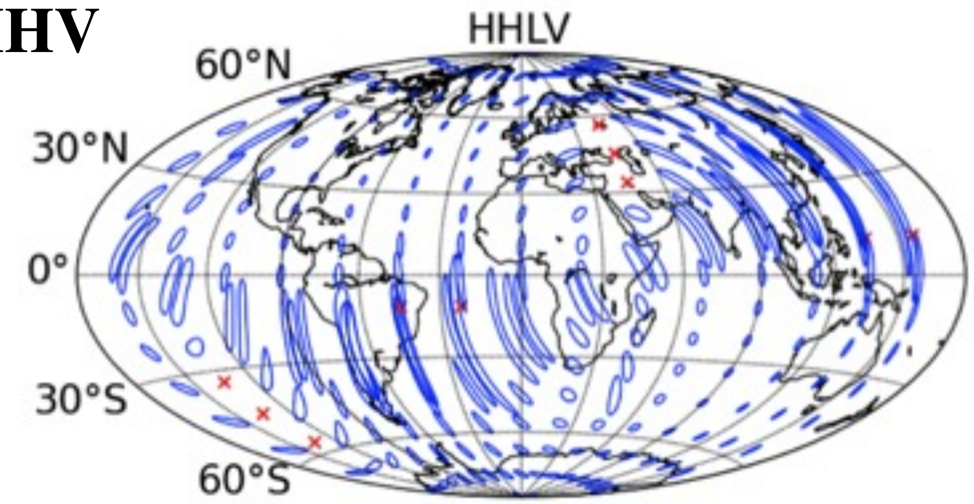
感度曲線



Ando, S. PRL(2005)

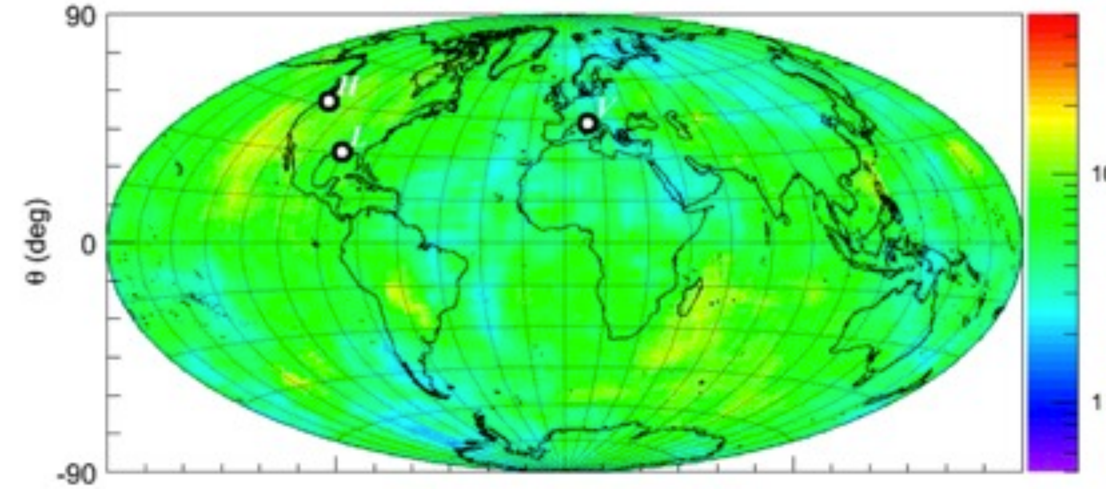
方向決定精度

LHHV



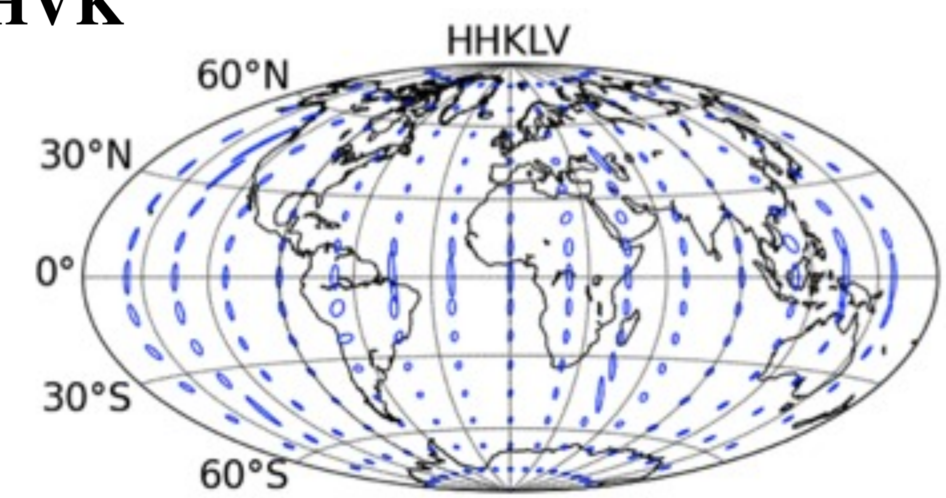
~20deg²

LHV



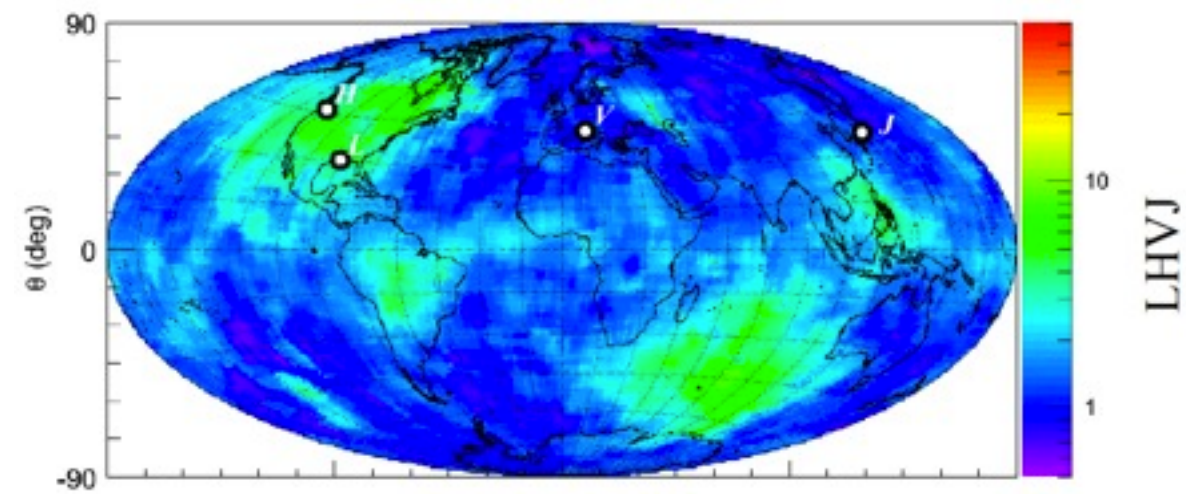
10~20deg

LHHVK



~10deg²

LHVK



1~10deg

SNR > 8

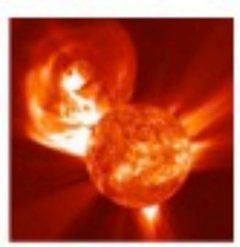
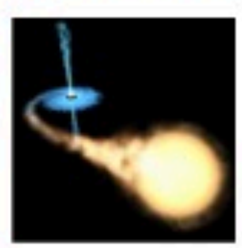
SNR 10-30

Fairhurst,proc.ICGC(2011)

Klimenko+,PRD(2011)

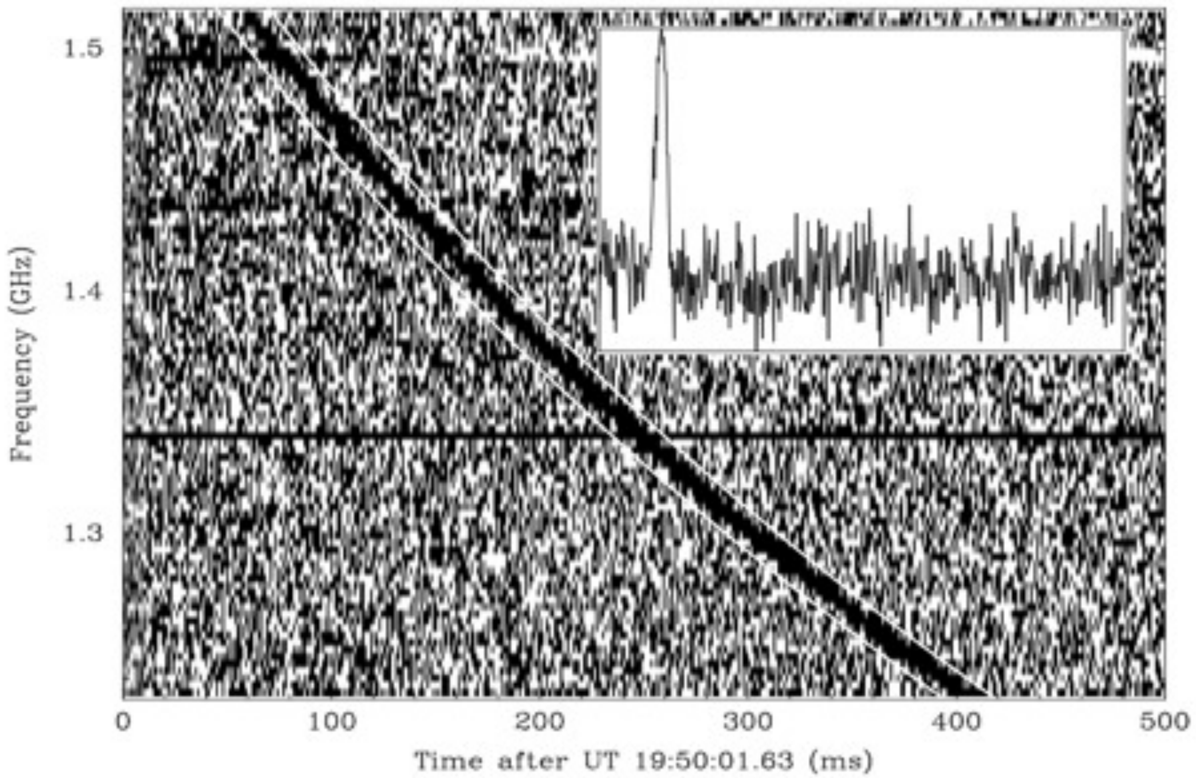
電波トランジェント

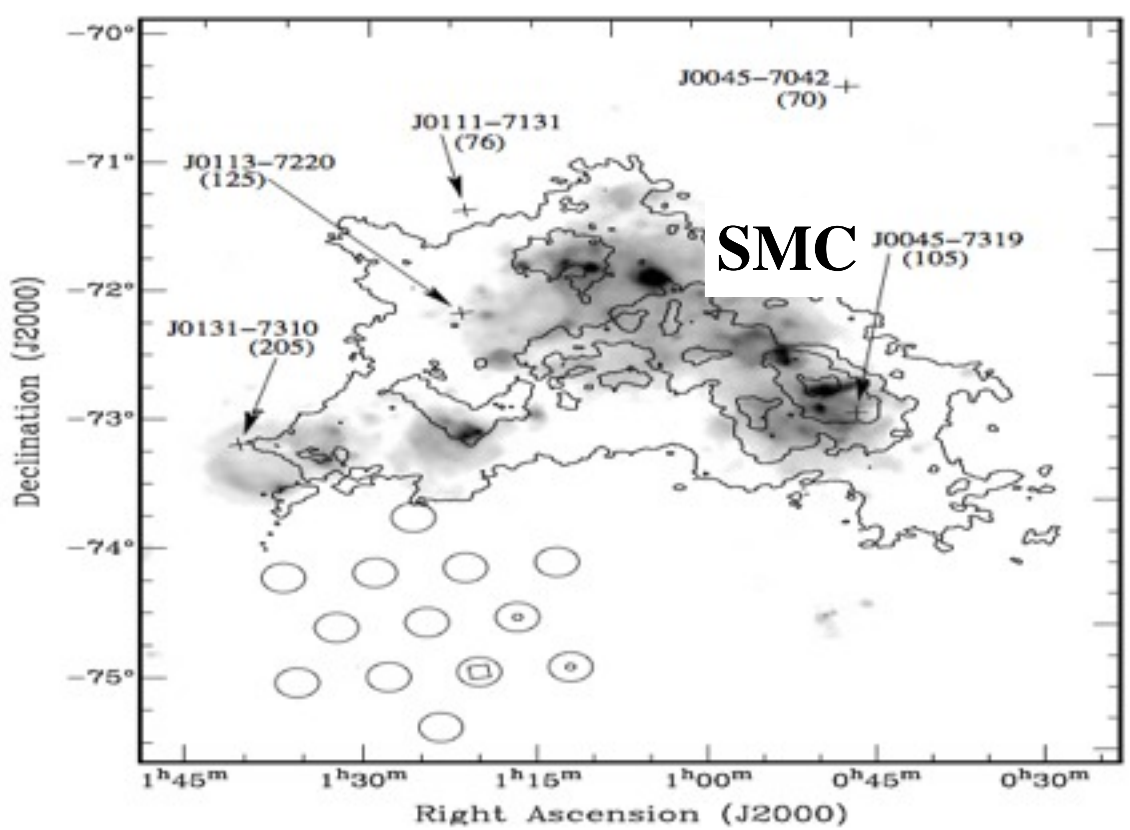
- 現在観測されている、電波トランジェントを継続時間で２つに分類
  - Short-Duration Radio Transient (FRB, pulsar,..)
  - Long-Duration Radio Transient(WJN, RT19870422,..)

	長寿命 (> 1 s)	短寿命 (< 1s)
銀河系外	超新星爆発，活動銀河核など   ?	Fast Radio Bursts (FRBs) ?
銀河系内	恒星フレア，X線連星など   ?	パルサー 

T. Aoki (Waseda)

Fast Radio Burst

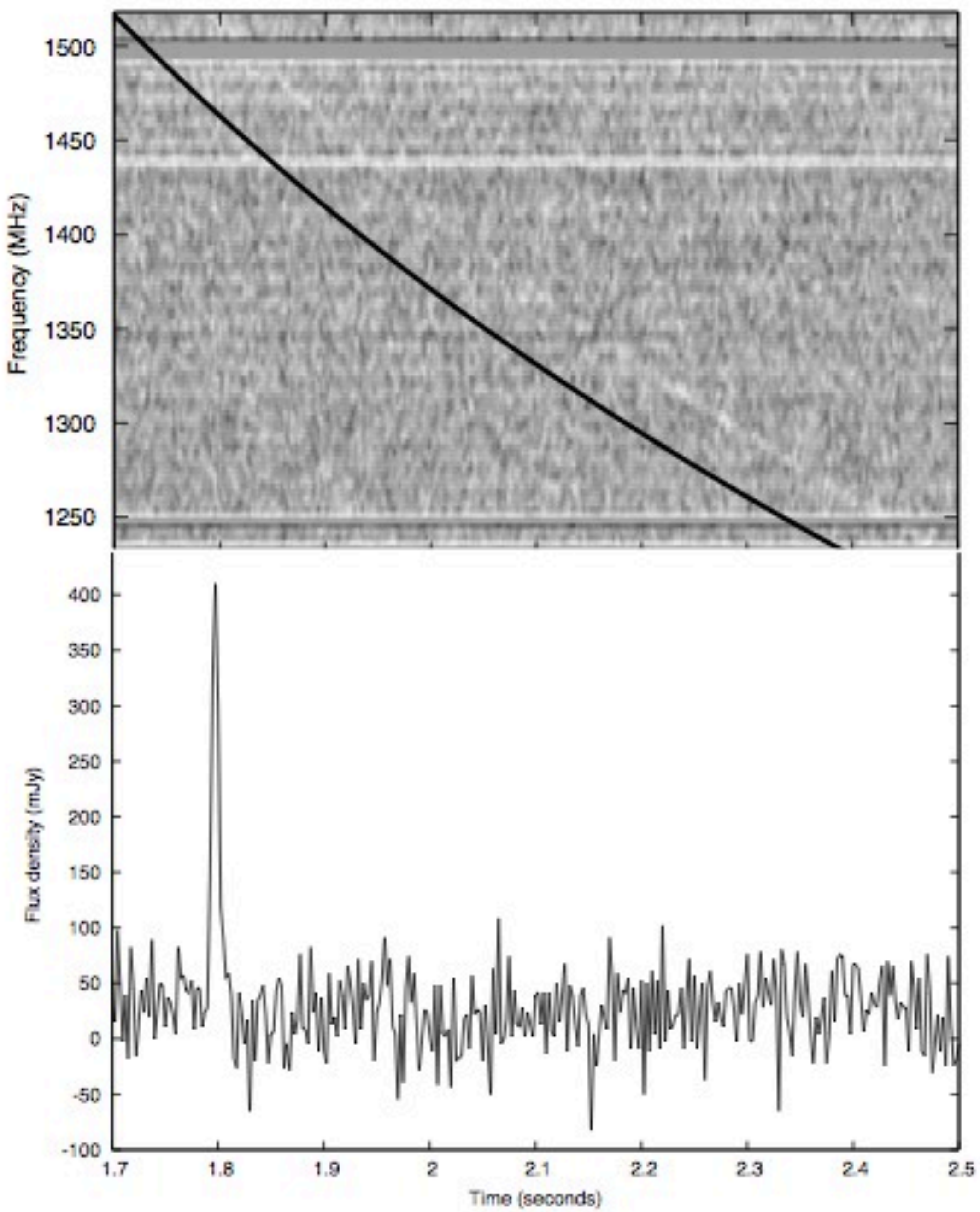




- 64m Parkes radio telescope
- 30Jy
- duration < 5ms
- DM 375 $cm^{-3}pc$
- <1Gpc
- duration ~ msec

Lorimer, science 318, 2007

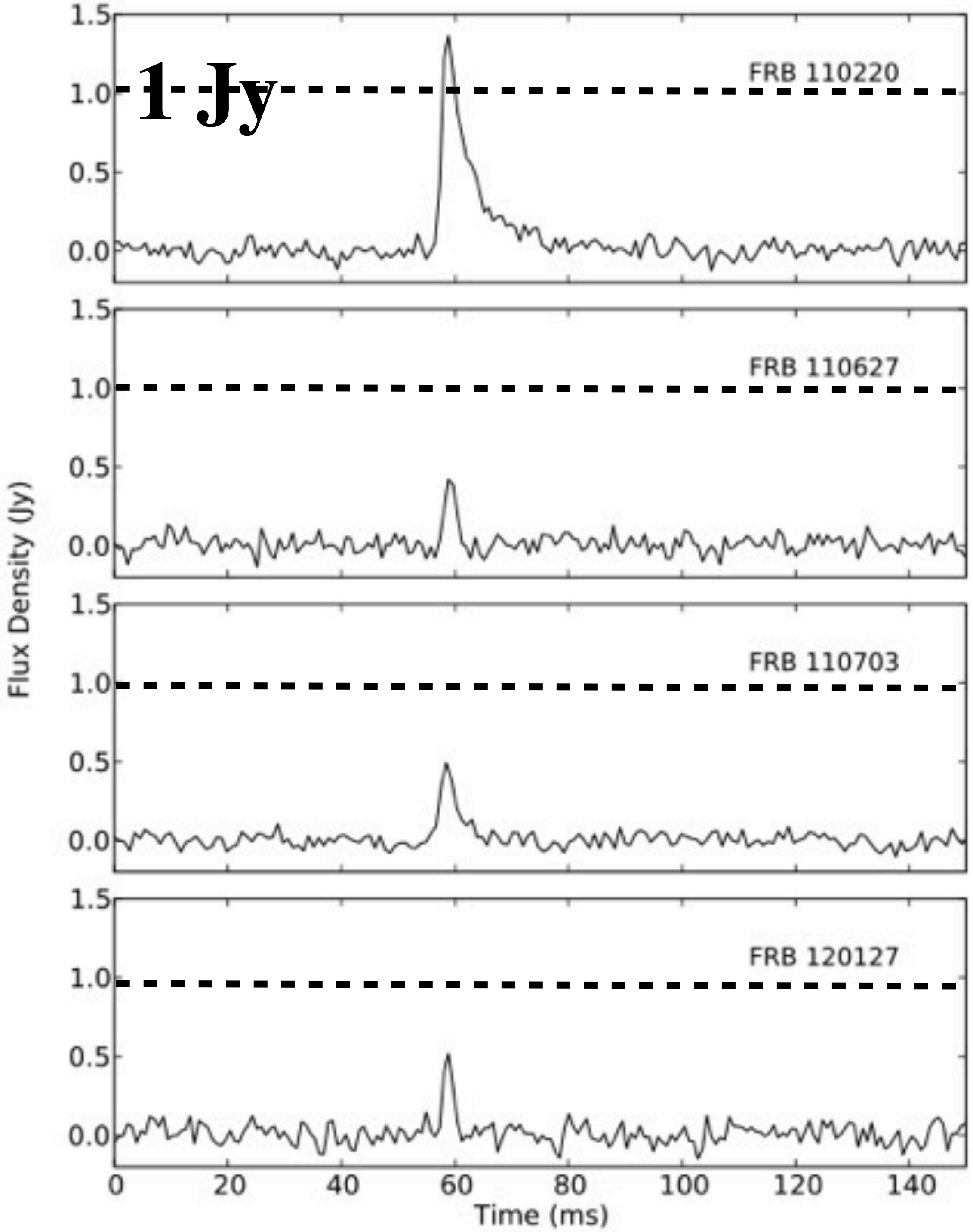
Fast Radio Burst(?)



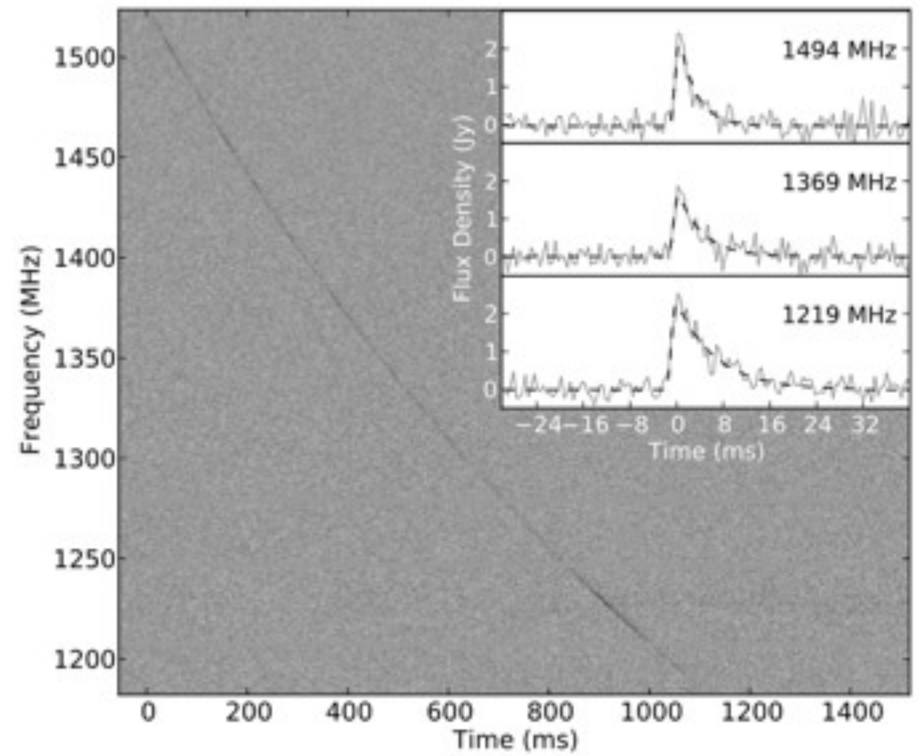
Keane+,MNRAS,2011

- **Parkes radio telescope**
- **J1852-08 burst in 2001**
- **DM 745cm^{-3}pc**
- **duration 7ms**
- **z~0.09-0.18**
- **~400mJy**

Fast Radio Burst



Thornton+, Science 341 53 2013



- 64m Parkes, 400M band, 1.38GHz
- z=0.5-1, < 3Gpc
- 0.4-1.3Jy
- DM 553-1100 $cm^{-3}pc$
- event rate ~$2x10^4$ $Gpc^{-3}yr^{-1}$

起源候補

- Rotating radio transients
- Nearby flaring stars(Loeb+2013)
- ccSN(Falcke+2013)
- WDWD merger(Kashiyama+2013)
- NSNS merger(Totani2013)
- Magnetar giant flare(Popov+2007,Thornton+2013)
- Collapse of HMNS
- Giant pulse from a young pulsar
- Evaporation of BH (Keane+2012)
- Superconducting cosmic strings (Cai+2012)

起源候補

- Rotating radio transients
- Nearby flaring stars(Loeb+2013)
- ccSN(Falcke+2013)
- WDWD merger(Kashiyama+2013)
- NSNS merger(Totani2013)

- NS-NS merger (Totani, PASJ(2013))
  インスパイラル時には２つの中性子星の回転は同期していないが、合体時に磁場が連星周期に同期、パルサーのように磁場と自転軸のズレでシンクロトロン放射が起きる。その後数msでBH形成時に消える。

NSNS merger とFast Radio Burst

- **NSNS mergerのイベントレート**($Gpc^{-3}yr^{-1}$, z=0)

low	reasonable	plausible high	max
1.00E+02	1.00E+03	1.00E+04	4.00E+04

- **FRBのイベントレート**

~$2x10^4$ $Gpc^{-3}yr^{-1}$
上限の方でコンシステント！

- **NSNS merger とFast Radio Burstの同時観測は？**

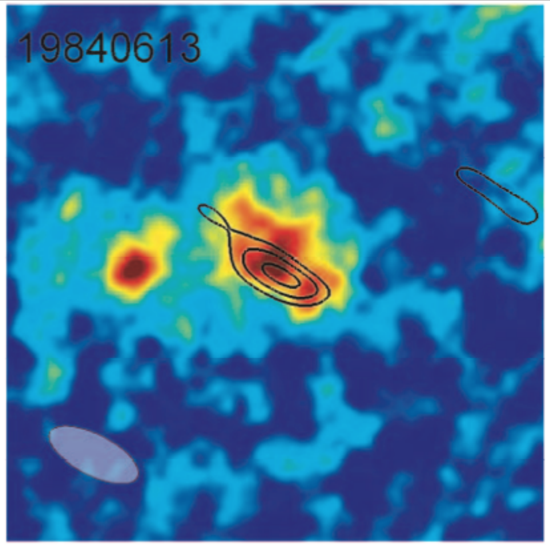
	2010	2015	2016	2017	2020
D(Mpc)	34	40-80	80-120	120-170	200
N_{re}	0.2	0.3-3	3-8	8-25	40
N_{high}	3	3-26	8-86	86-246	400
FRB	0.8	1-10	10-35	35-98	160

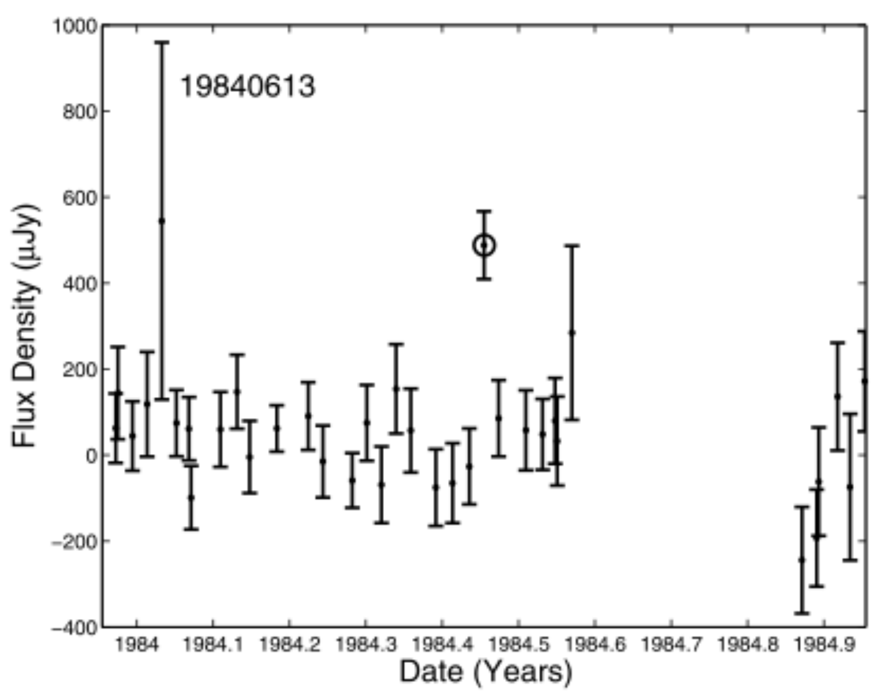
重力波付随のFRB探査の可能性

- 広域電波サーベイ専用望遠鏡で常にモニター
- イベントレートは~2x10^{4}Gpc/yrと大きく200Mpcまでで160個/年見えるかも
- 重力波との同時観測では100Jy(@200Mpc)の感度

Long-duration Radio Transients

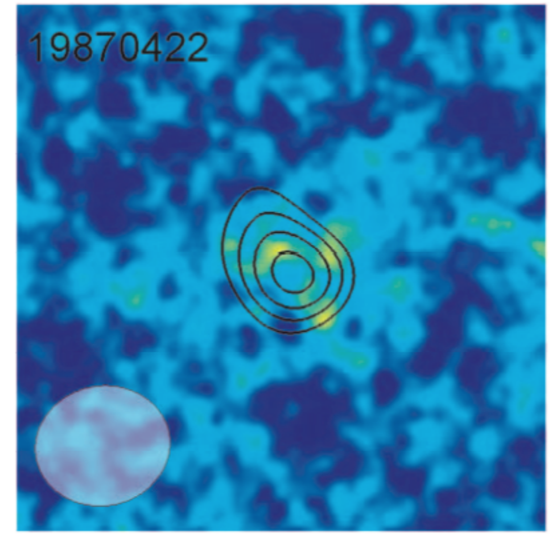
RT19840613

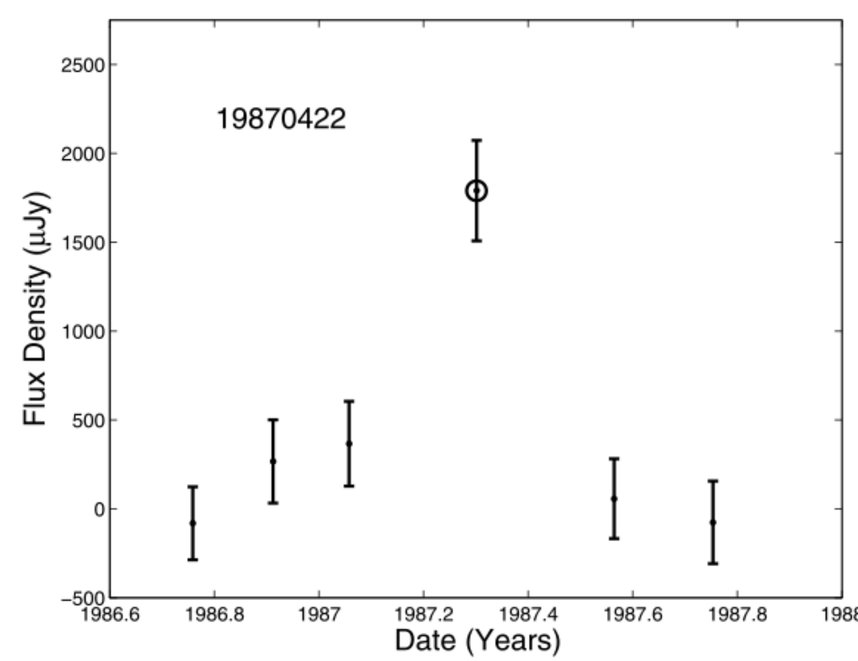




- o flux: 0.4-0.6mJy at 140Mpc
- o duration: < 7days
- o event rate: 6000-150000$Gpc^{-3}yr^{-1}$ (consistent with estimated CBC rate ref:J.Abadie et al. (2010))

RT19870422

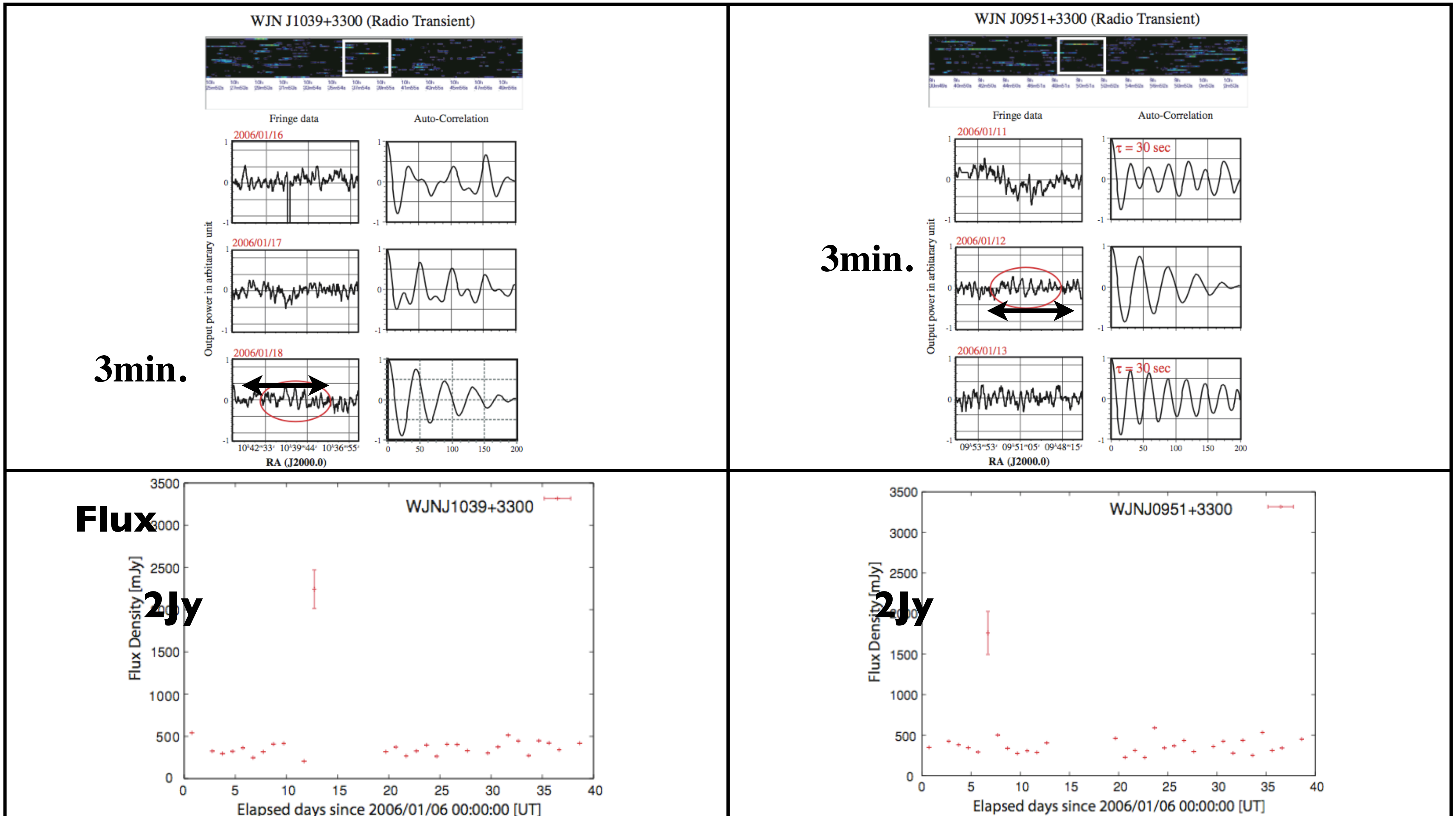




- o flux: 1.5-2.0mJy at 1.05Gpc
- o duration: ~2months
- o event rate: 80-20000$Gpc^{-3}yr^{-1}$ (consistent with estimated CBC rate)

Bower et al. ApJ 666 346-360 (2007)

WJN Radio transients



Time

Niinuma et al. 2009

過去に観測されたWJNイベント

Name	δ (J2000.0)	b (J2000.0)	Flux Density	Detection Date	Paper
WJN J0200+4142	41°42′	~-19°	~2.7±0.5Jy	2005Feb10	Matsumura et al.(2009)
WJN J0202+4142	41°42′	~-19°	~4.1±0.9Jy	2006Dec24	
WJN J0205+4142	41°42′	~-19°	~4.3±0.6Jy	2006Dec26	
WJN J0445+4130	41°30′	~-3°	~1.8±0.2Jy	2005Jan10	Matsumura et al.(2007)
WJN J0645+3200	32°00′	~+13°	~1.2Jy	2005Mar24	Kida et al.(2008)
WJN J0951+3300	33°00′	~+51°	~1.8±0.3Jy	2006Jan12	Niinuma et al.(2009)
WJN J1039+3200	32°00′	~+61°	~1.7Jy	2005Mar 4	Kida et al.(2008)
WJN J1039+3300	33°00′	~+61°	~2.2±0.2Jy	2006Jan18	Niinuma et al.(2009)
WJN J1043+4130	41°30′	~+60°	~1.7±0.2Jy	2005Jan 2	Matsumura et al.(2007)
WJN J1443+3439	34°39′	~+65°	~1.5±0.3Jy ~3.0±0.3Jy	2005Feb13 2005Feb14	Niinuma el al.(2007)
WJN J1737+3808	38°08′	~+30°	~1.6±0.2Jy	2004May20	Kuniyoshi et al.(2007)

Matsumura (2011)

起源候補

- 恒星フレア
- 活動銀河核
- 連星合体後の電波アフターグロー

重力波後weeks-years、継続時間days-years、1.4GHz

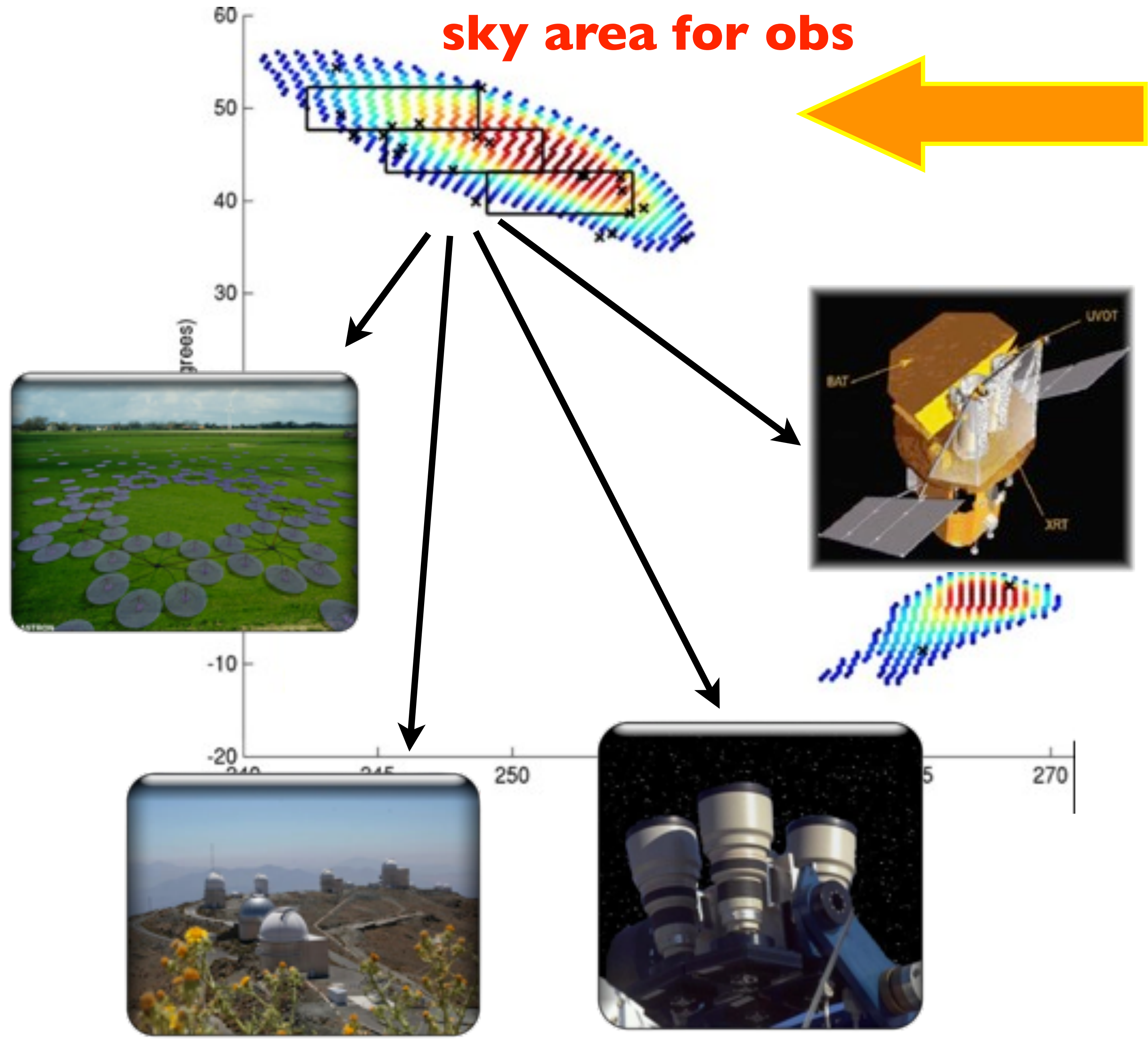
Table 4. Properties and detection horizons (neglecting cosmological corrections) of the sub-relativistic dynamically ejected outflow from 1.4-1.4 $m_\odot$ ns^2 and 1.4-10 $m_\odot$ nsbh mergers with different radio facilities.

Radio Facility	Obs Freq. (GHz)	Field of view (deg^2)	1 hr rms μJy	ns^2 1 hr horizon† $n = 1\text{cm}^{-3}$	ns^2 10 hr horizon†† $n = 0.1\text{cm}^{-3}$	nsbh 1 hr horizon† $n = 1\text{cm}^{-3}$	nsbh 10 hr horizon†† $n = 0.1\text{cm}^{-3}$
EVLA[a]	1.4	0.25	7	360 Mpc	200Mpc	1.8 Gpc	1.4 Gpc
ASKAP[b]	1.4	30	30	170 Mpc	100 Mpc	850Mpc	700 Mpc
MeerKAT[c]	1.4	1.5	35	160 Mpc	90 Mpc	800 Mpc	650 Mpc
Apertif[d]	1.4	8	50	135 Mpc	75 Mpc	670 Mpc	550 Mpc
LOFAR[e]	0.15	20	1000	70 Mpc	40 Mpc	300Mpc	250 Mpc

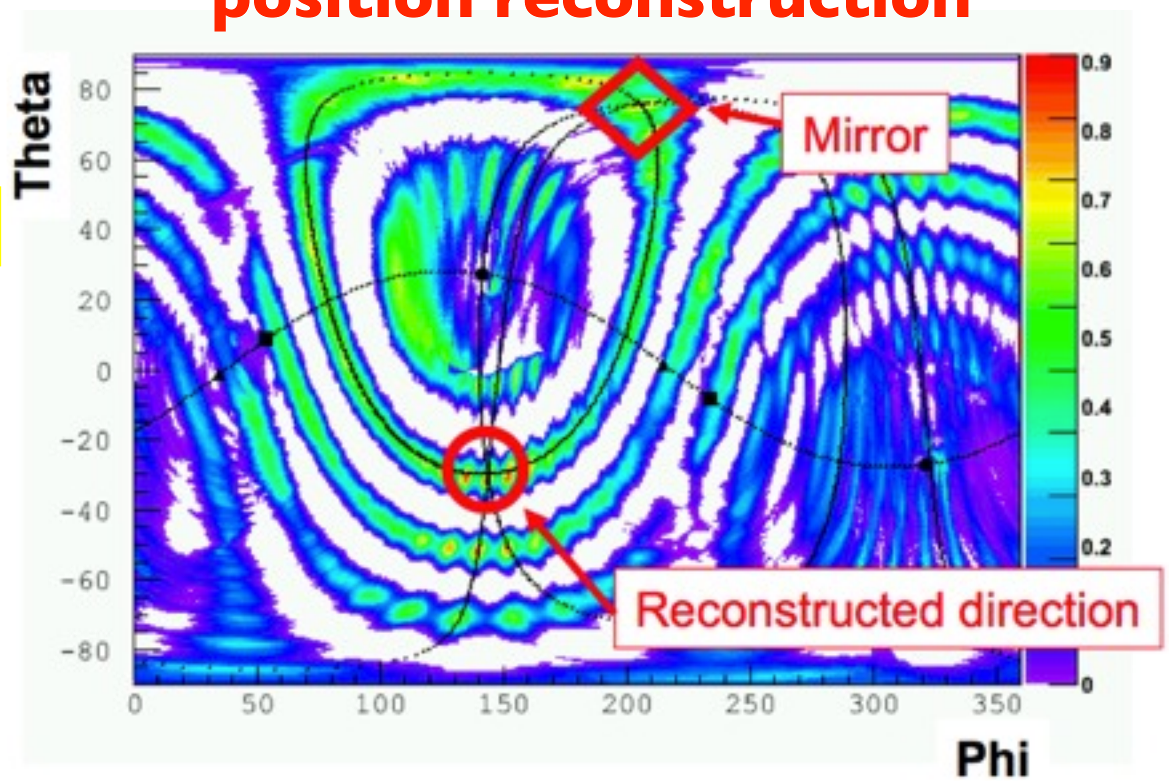
Piran+MNRAS(2013)

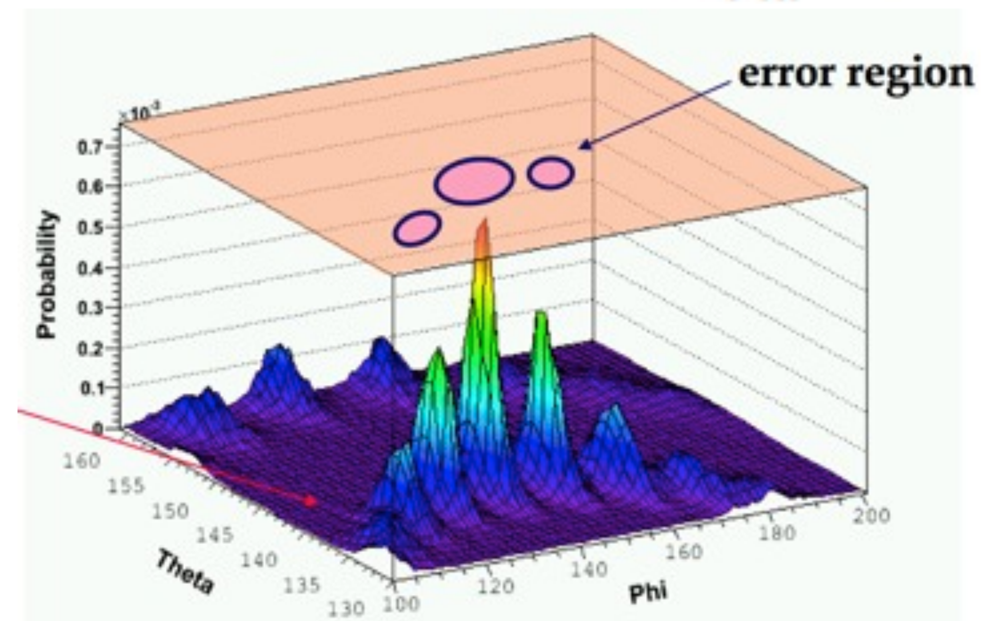
マルチメッセンジャー観測体制の準備

- **GW alert --> EM followup observation**
- **Transient alert from EM telescopes --> GW data analysis**



position reconstruction





マルチメッセンジャー観測体制の準備

- **GW alert --> EM followup observation**
- **Transient alert from EM telescopes --> GW data analysis**

Radio telescopes

Time, Location

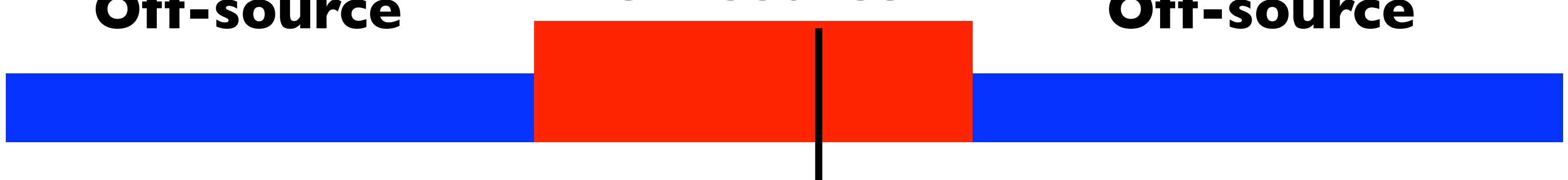
GW telescopes

$$\text{Final FAP} \sim P \times P_T \times P_{space}$$

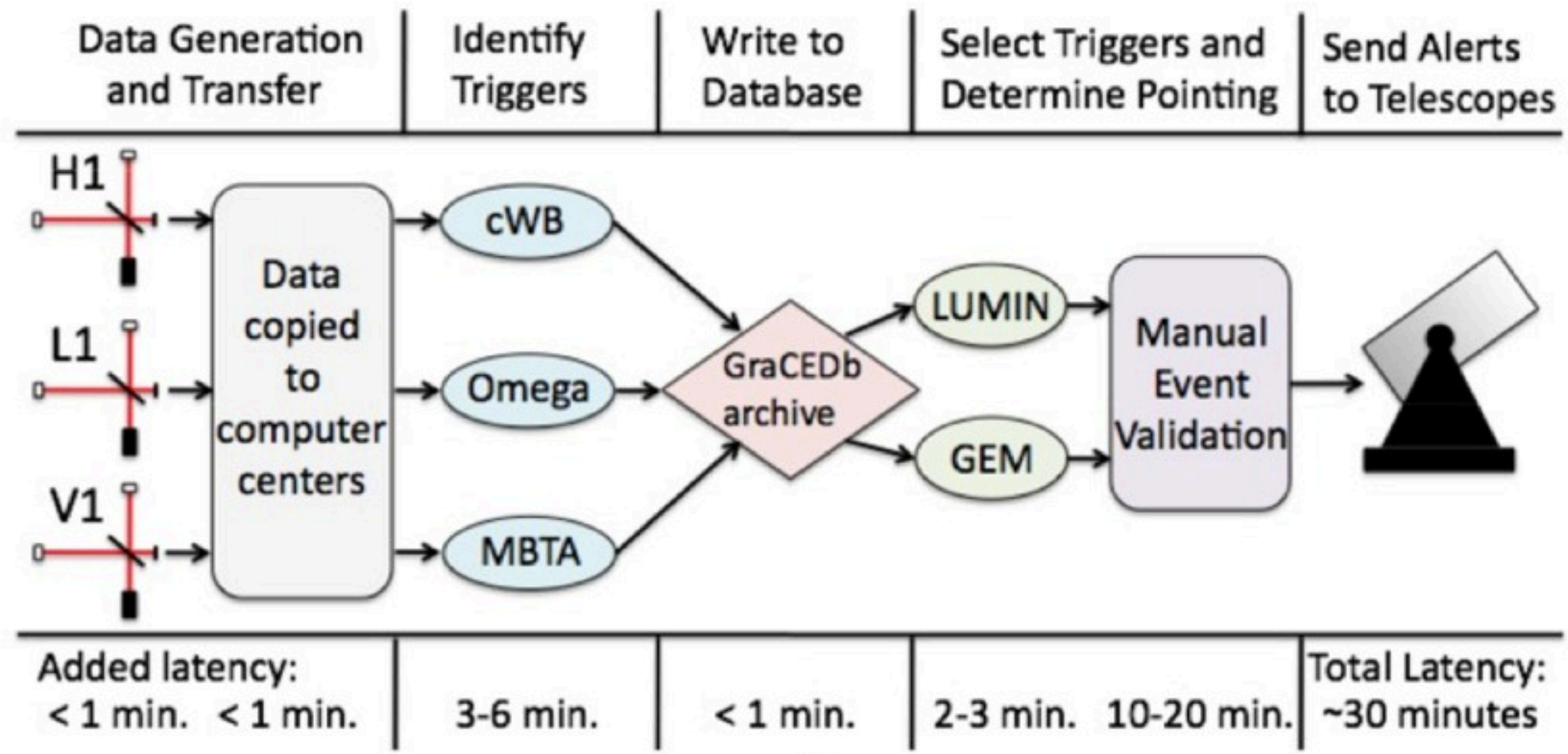
Triggered search

RT

Off-source **On-source** **Off-source**



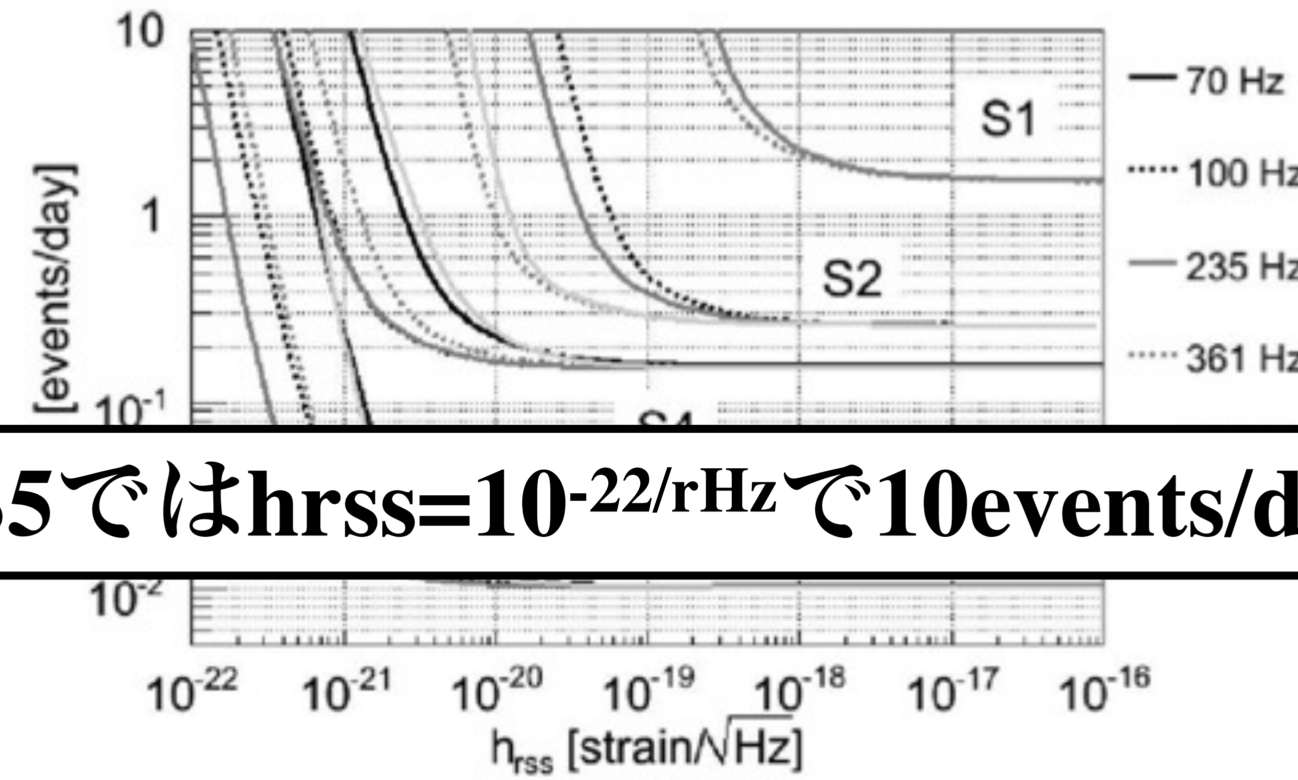
マルチメッセンジャー観測プロセス



- **Winter run : FAR < 1 per day**
- **Autumn run : FAR < 0.25 for most telescopes, < 0.1 for PTF and Swift**

マルチメッセンジャー観測の課題

- 重力波のFalse alarm rate（誤検出率）の改善。

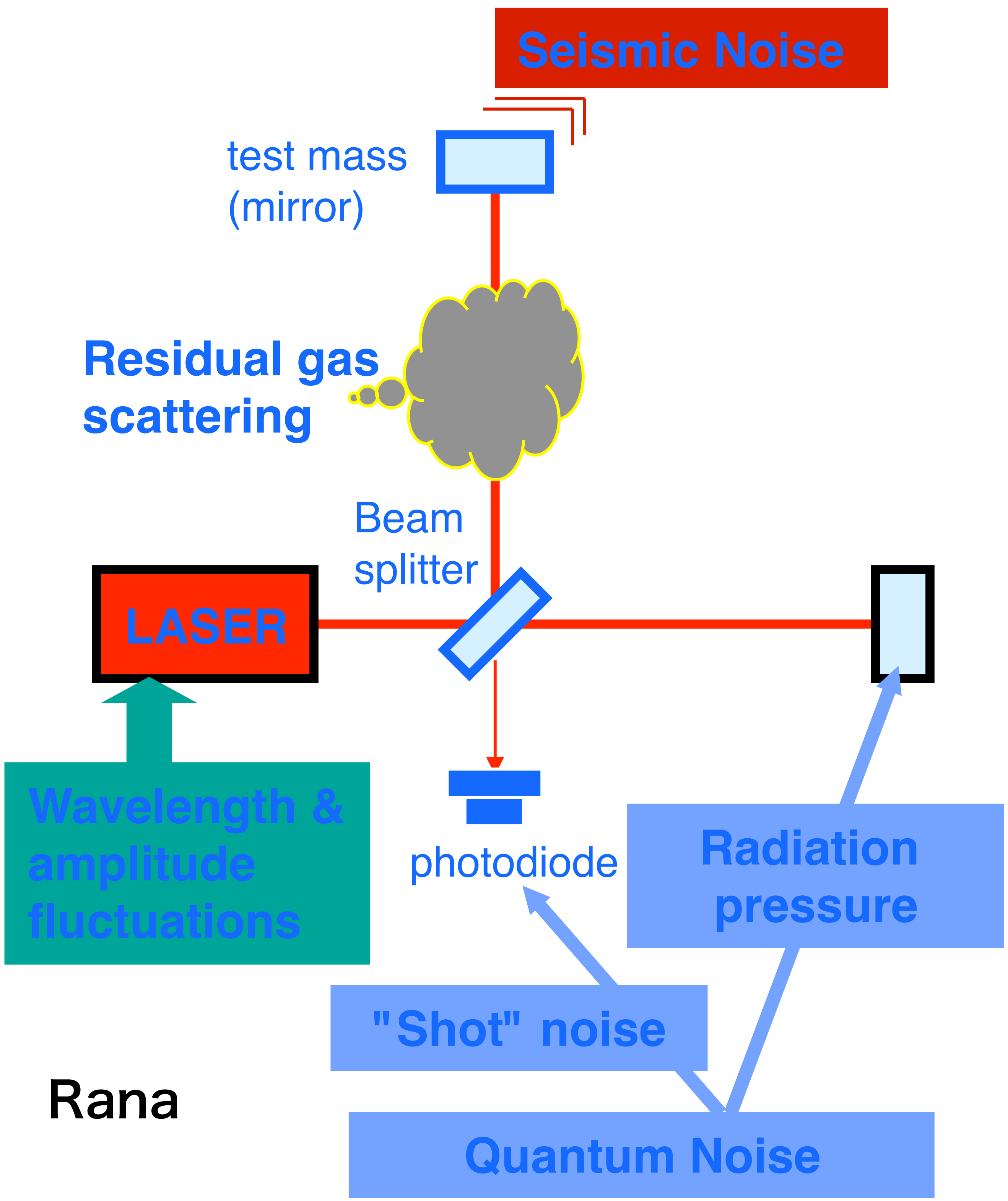


S5ではhrss=$10^{-22/\mathrm{rHz}}$で10events/day

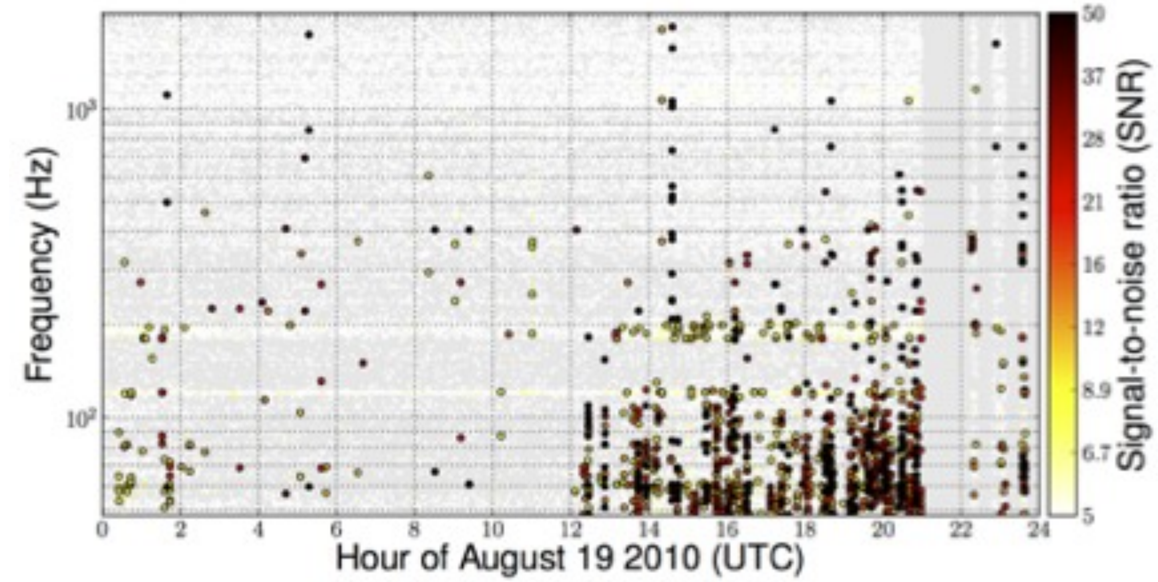
- 信号-雑音比（SNR）が小さい重力波信号の推定天球位置のエラー領域が広い。（ただし、SNRが大きければ（感度のよい望遠鏡を作れば）、それとともに精度が上がる。）

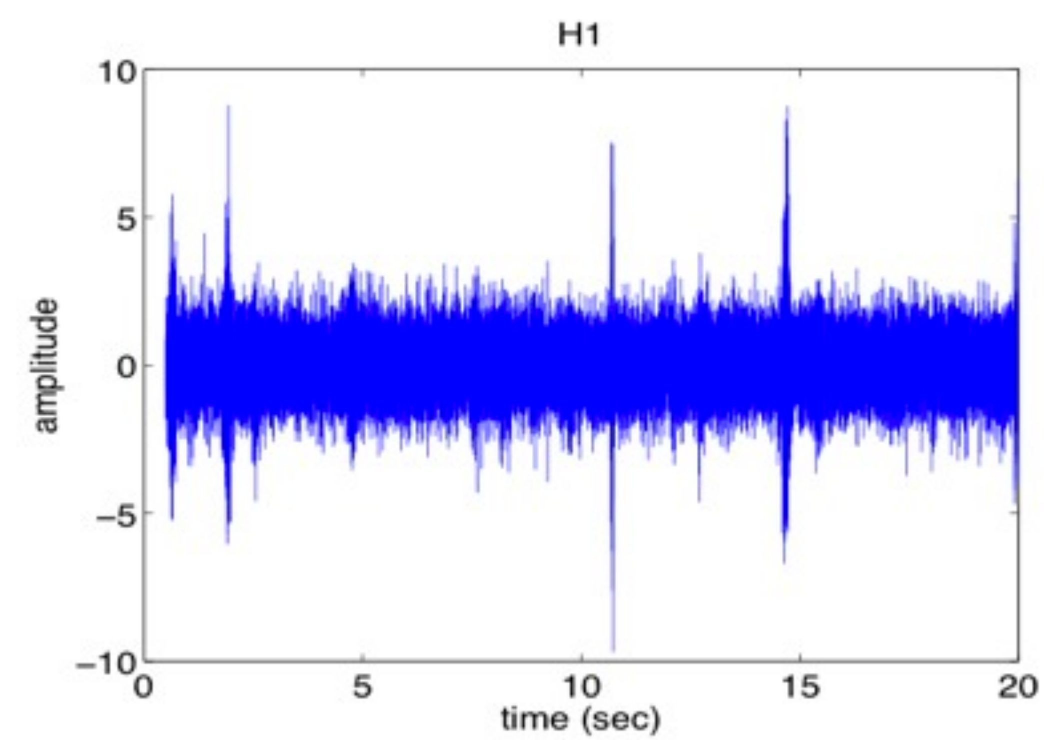
- リアルタイム解析

Fundamental detector noise



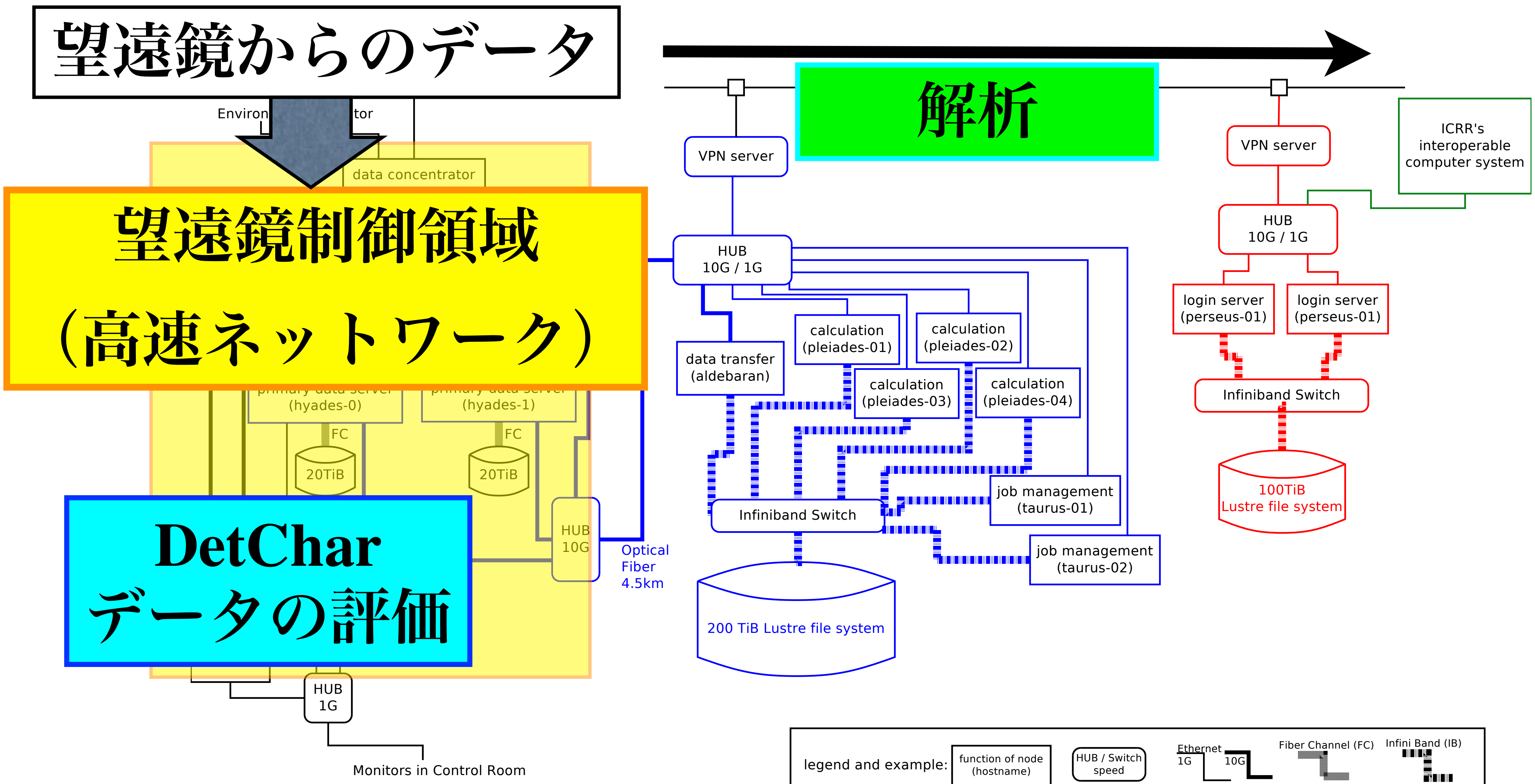
Rana





誤検出率の低減を目指す活動

Detector Characterizationの活動の一つ



Kanda

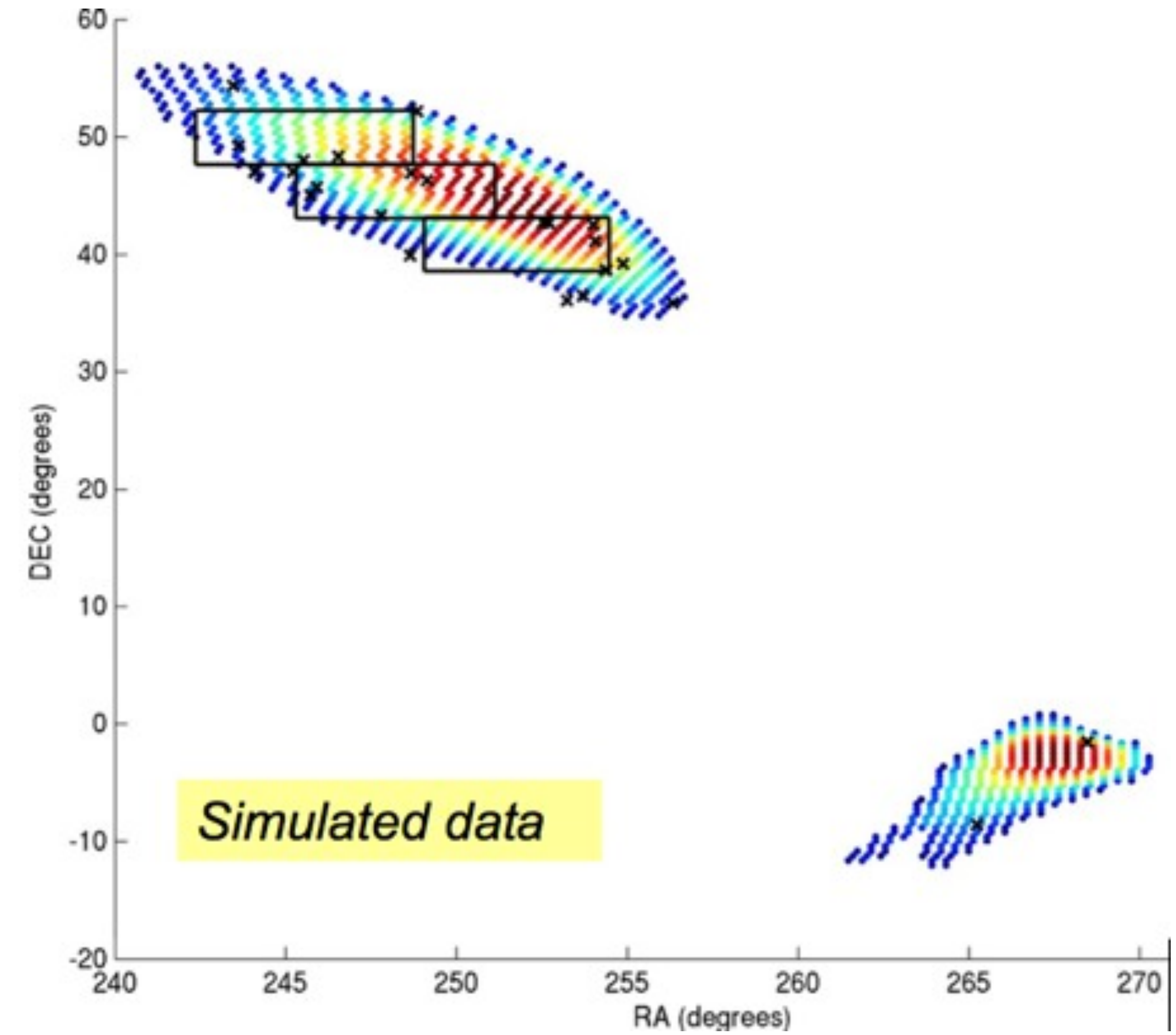
Select Observation region for follow-up

Blue Luminosity
(Bigger, More stars form)

GW data

$$P = \frac{L_B \times Likelihood}{Distance}$$

GWGC

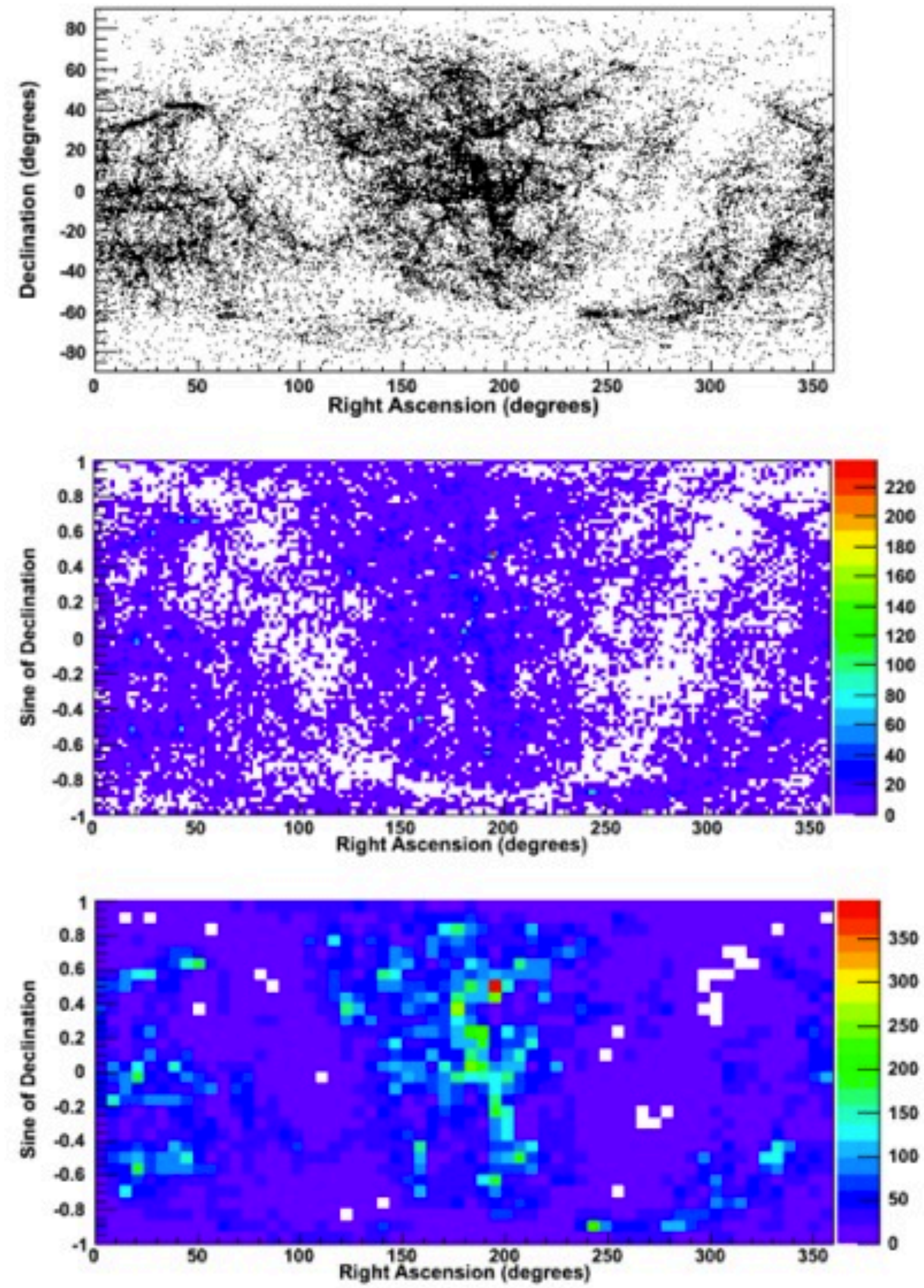


GWGC: Gravitational Wave Galaxy Catalog

- Contains ~50,000 galaxies within 100Mpc
- Four catalog compilation:
  Tully Nearby Galaxy Catalog,
  Neighboring Galaxies, V8k,
  HyperLEDA
- Uses Principal Galaxy Catalog(PCG) identifier to improve removal of degenerate galaxies from multiple catalog
- Main problem:
  Incompleteness

バースト探査では十分だが、

連星合体は？

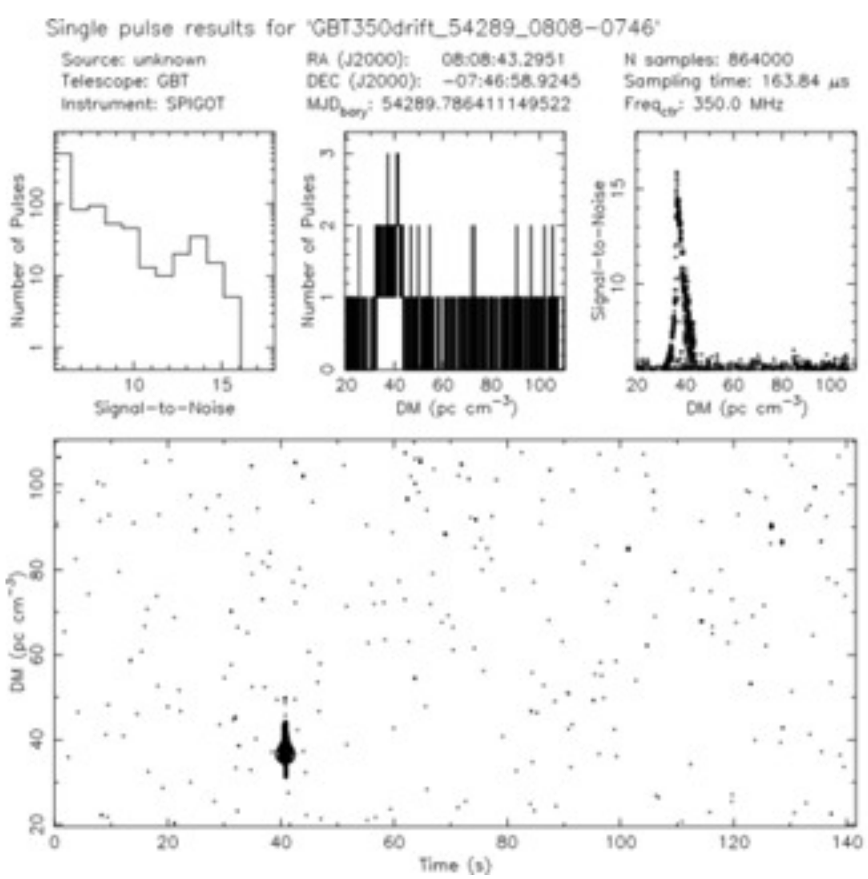


D. White et al, 2011

Green Bank Telescope

Brennan Hughey, David Stiles(ERA), Xavier Siemens(UWM)

- **Radio pulses from Green Bank Telescope Drift-scan**
- **Possible joint sources includes CBCs, Giant pulse, pulsar glitches, cosmic strings, ...**
  (although most pulses are probably just terrestrial background...)
- **32 single pulse candidates coincident with S5/VSR1**
- **Analysis is in progress.**



Parkes Telescope Fast Radio Bursts

Brennan Hughey, David Stiles(ERA), Xavier Siemens(UWM)

The Parkes telescope in New South Wales, Australia has observed a population of nominally extra-galactic (based on high dispersion measure) short duration radio bursts from observations in 2011

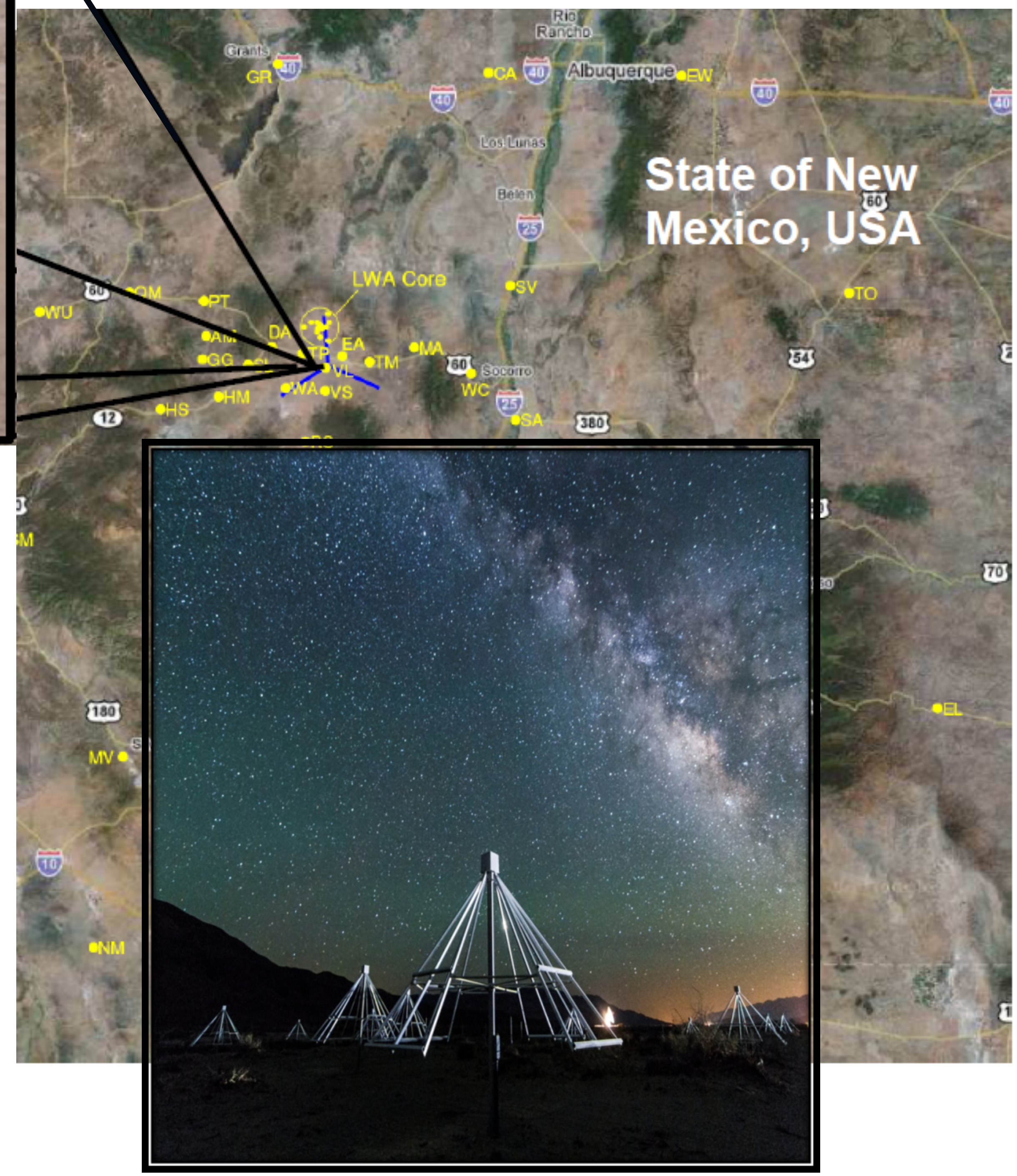
These are coincident with Virgo and GEO data

We have looked at GW interferometer data in coincidence with 4 published fast radio bursts using analysis similar to the Green Bank search

Thornton+, Science 341 53 2013

We have also negotiated an MoU to obtain additional fast radio burst triggers from Parkes

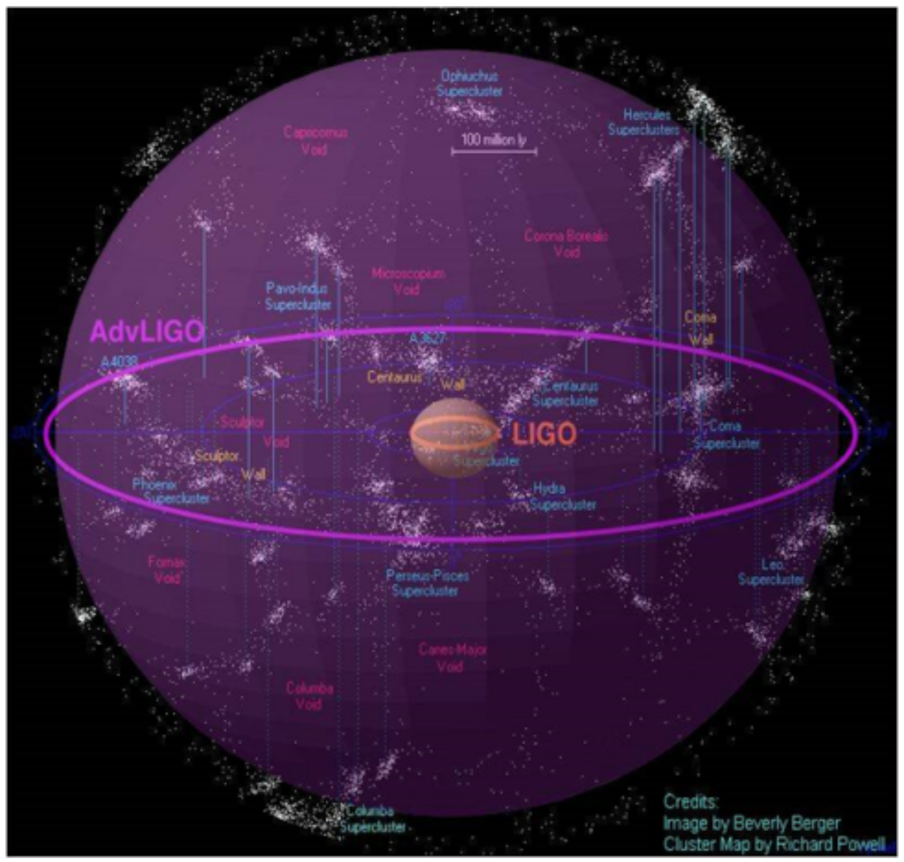
Long Wavelength Array (L

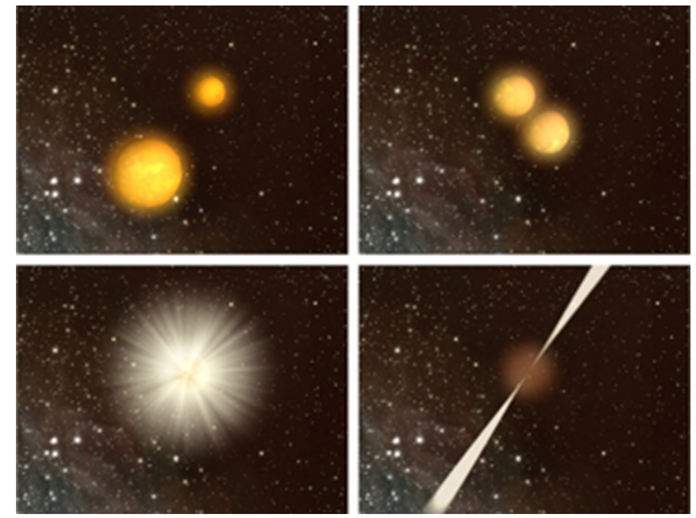


- The LWA is sensitive to a bandwidth of 10-88 MHz.
- The first station of the LWA (LWA-1) is composed of an array of 256 dual-polarization dipole antennas laid out in a 100m diameter aperture.
- LWA-1 can conduct all-sky imaging in addition to being able to form electronically steerable beams.

Coincident Emission from Compact Object Mergers

Neutron Star Binaries:
Initial LIGO: ~15 Mpc → rate ~1/50yrs
Advanced LIGO: ~ 200 Mpc
Realistic rate ~ 40/year !





$$D_{Gpc} \sim \left[0.8 \cdot 10^{15\gamma}\, \dot{E}_{50}^{\;1+\gamma} \left(\frac{SNR}{10}\right)^{-1} \nu_{120}^{\;3/4}\, B_4^{\;1/2}\, N_{ant}^{\;1/2} \right]^{10/19}$$

LWA-1 can detect these events out to ~1 Gpc.

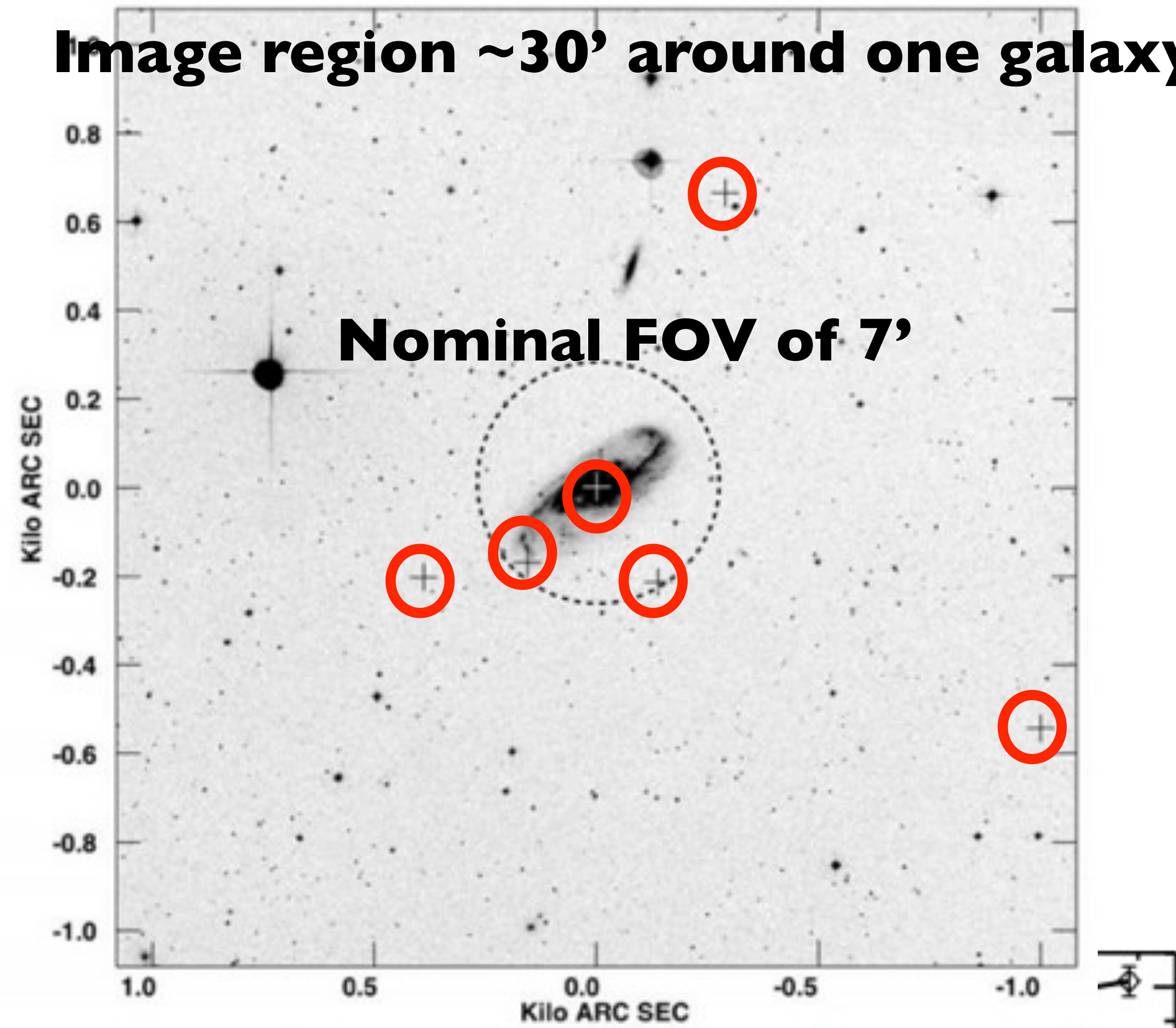
M.S. Pshirkov, K.A. Postnov
Astrophys.Space Sci. 330 (2010)

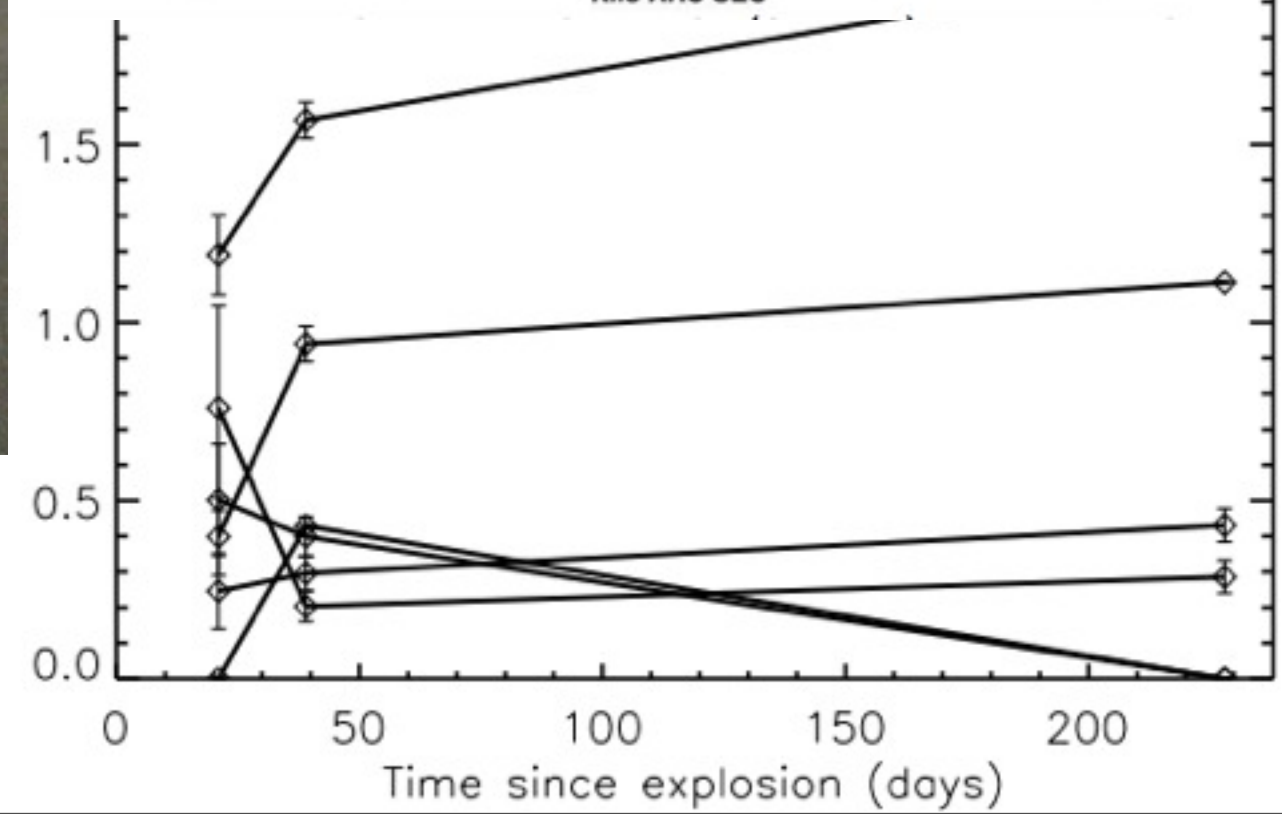
Michael Kavic
(Long Island University)

Collaborators: Bernadine Akukwe (LIU), Peter Shawhan, Cregg Yancey (UMD)
Jonah Kanner (Caltech) John Simonetti, Brandon Bear, Jr-Wei Tsai (VT),
Sean Cutchin (NRC-NRL)

Expanded VLA

- **Radio source detection**
- **Variability analysis**
- **Identification of contaminating transients (AGN?)**



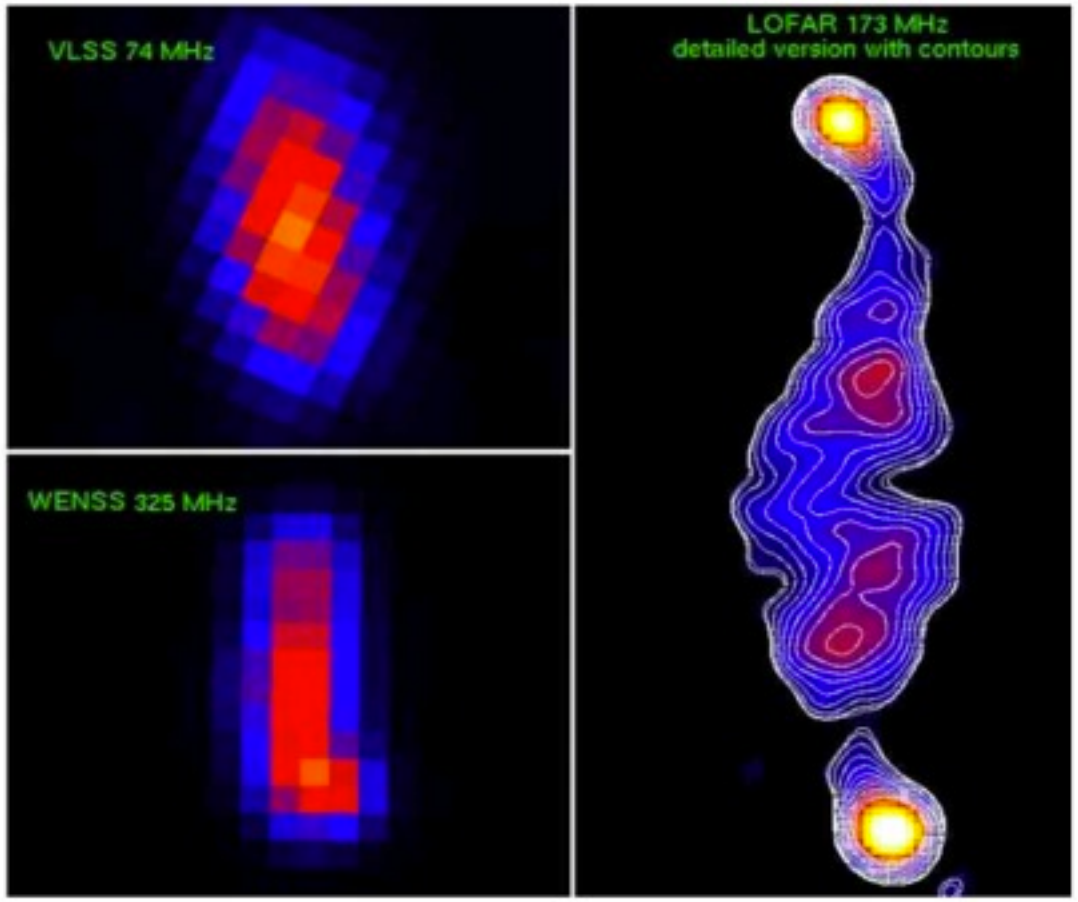


6 sources in the fields of each galaxy consistent with number of expected serendipitous sources (Windhorst, 2003)

LOFAR

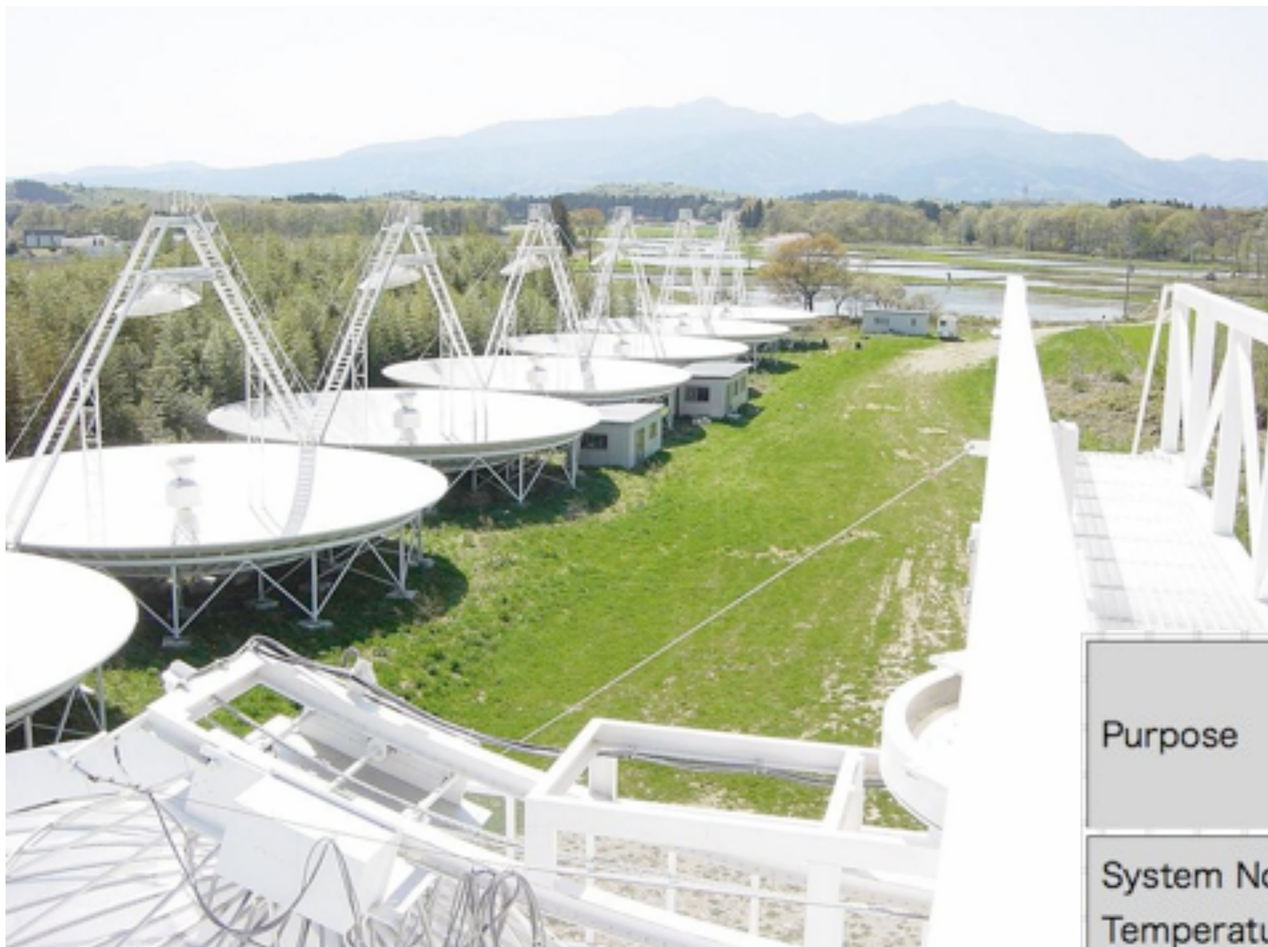
Ed Daw(Sheffield)+

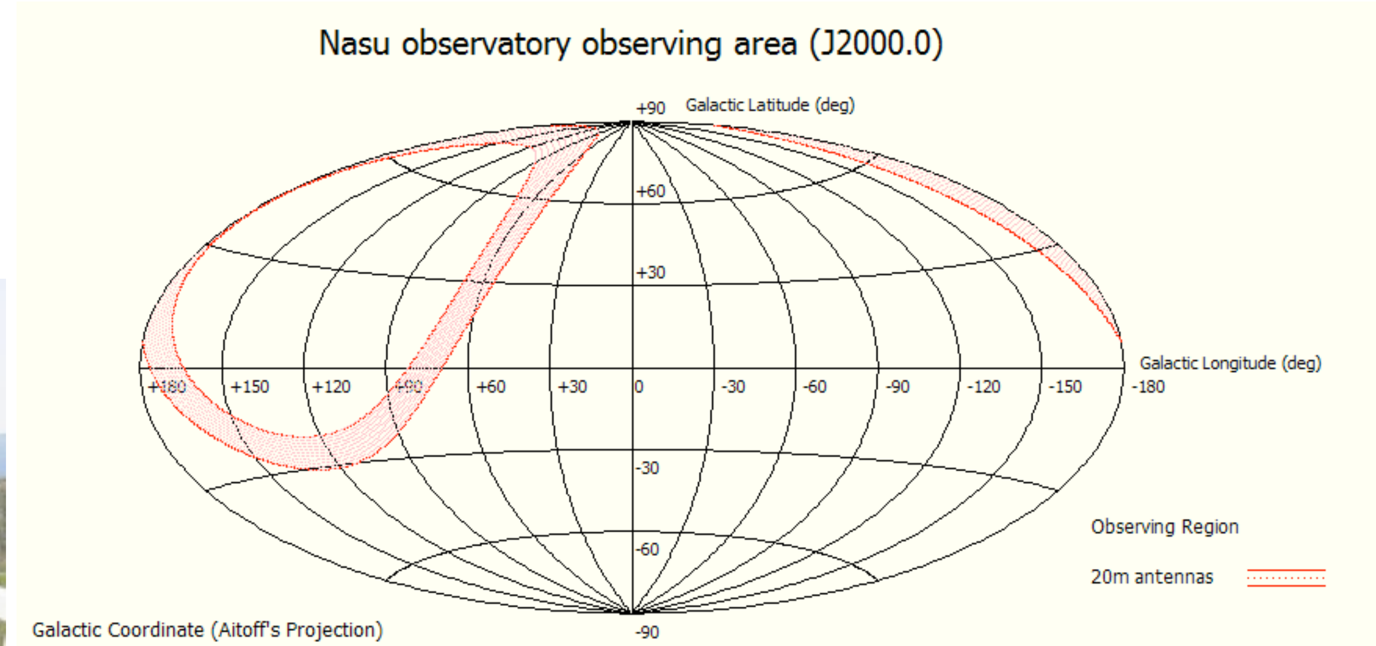
- Low frequency array
- LOFAR can image up to 24 5°x5° fields simultaneously.
- Low latency radio all-sky monitor
- LVC awarded ~4 hours-per-week observing-time during S6
- Followed up 6 GW alerts.
- Results not yet



Nasu radio telescope

Aoki, Kida, Daishido, (U. Waseda)





One can observe any direction within +/- 5deg from the zenith (Dec. +32deg ~ +42deg)

Purpose	Radio Interferometers for Wide Field Survey Eight 20 m diameter spherical dish antennas+ A 30 m diameter spherical dish antenna
System Noise Temperature	Appoximately 80K
Observing frequency	1.42 GHz
Bandwidth	20 MHz
Site	Nasu-Shiobara, Tochigi prefecture
Target	Radio Transients, Radio counterparts of EGRET un-id sources, Pulsars
Sensitivity	Several hundred mJy (1 sec integration)

For RT19870422-like events, Nasu reaches ~100Mpc

http://www.astro.phys.waseda.ac.jp/index-e.html

Comparison with LOFAR etc.

Instrument	Band	Type	Field of View	Slew Time
LOFAR	40-240 MHz	Array	30° beam(s)	Software
ETA	29-47 MHz	Array	Two 30° beams	Software
NRAO Green Bank	300MHz-50 GHz	Dish	0.027 sq. deg. (at 1 GHz)	18°/minute
Nancay	128-1400 MHz	Dish	4 by 22 arcmins	5-10 min
ARECIBO	312 MHz - 10.2 GHz (ALFA: 1.225 - 1.525 GHz)	Dish	15 arcmin @ 312 MHz 0.5 arcmin @ 10.2 GHz (ALFA: 10 arcmin @ 3.5 arcmin resolution (7 beams))	< 16 min

- **The observing frequency of Nasu 1.42GHz**
- **The observable region is from decl. 32 deg to decl. 42 deg**
- **The coverage is approximately 7.0% of the entire sky**

Nasu-TAMA, LIGO, Virgo

Detectors in science mode around WJN events

Nasu-TAMA

WJN J 1737+3808

- **TAMA was observation mode three months before.**

Nasu-LIGO, Virgo

WJN J 1039+3300

- **H1,H2 were in observation.**

WJN J 0951+3300

- **Part of H1,H2,L1 data were in observation.**

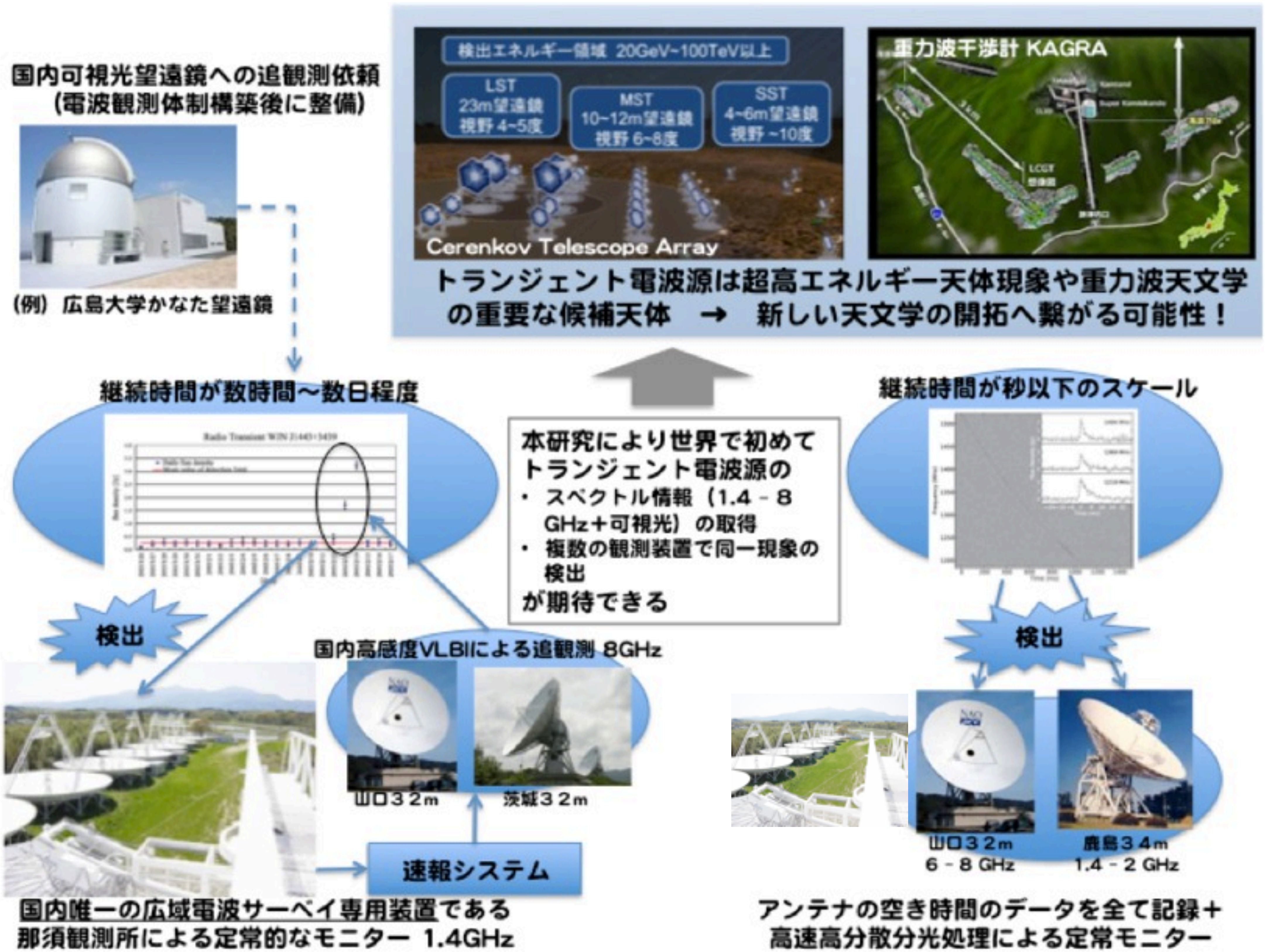
WJN J0205+4142

- **H1,H2,L1 were in observation.**

WJN J0202+4142

- **H1,H2,L1 were in observation.**

多様な電波トランジェント探査網の検討



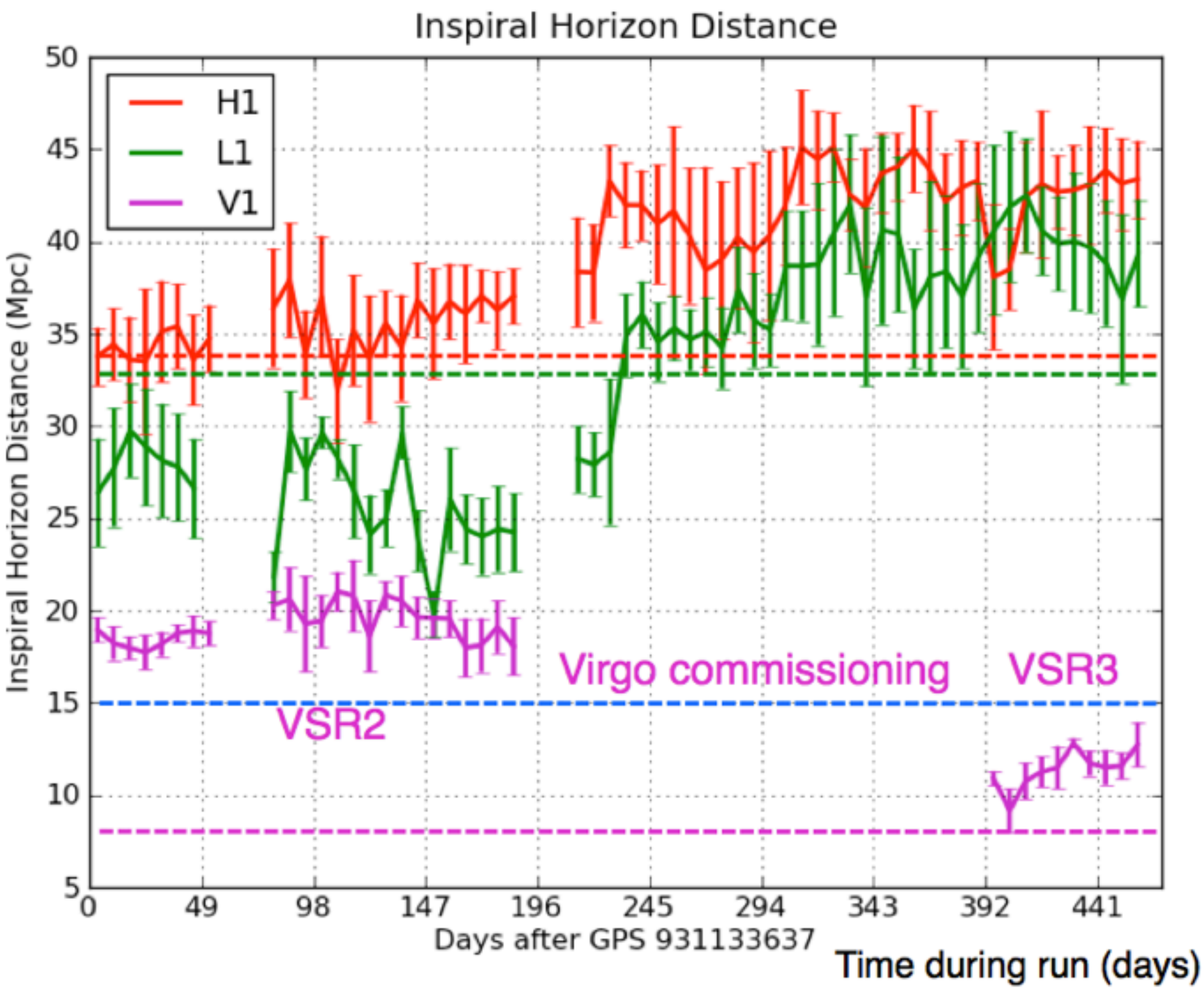
Niinuma

まとめ

- 近年、数ms〜数日〜数週間といった多様な時間スケールの電波トランジェントが検出されてきている。
- これらの起源の解明が待たれるが、中性子星連星合体など重力波天体の可能性も示唆されている。
- マルチメッセンジャー観測は重力波の初検出とともに、重力波源の特定に大切な役割を果たす。そのための準備を進めていきたい。

中性子星連星合体

S6 results



中性子星連星合体

Milky Way
(~50kpc)

アンドロメダ銀河
(~700kpc)

乙女座銀河団
(~15Mpc)

到達年

2002年

2003年

2005年

Coherent network analysis

$$\underbrace{\begin{bmatrix} x_1(t) \\ \vdots \\ x_d(t) \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{1d}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix}}_{\mathbf{h}} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

$$\xi_i(t) = F_{i+}(\theta,\phi)h_+(t) + F_{i\times}(\theta,\phi)h_\times(t)$$

$$h = (A^T A)^{-1} A^T x$$

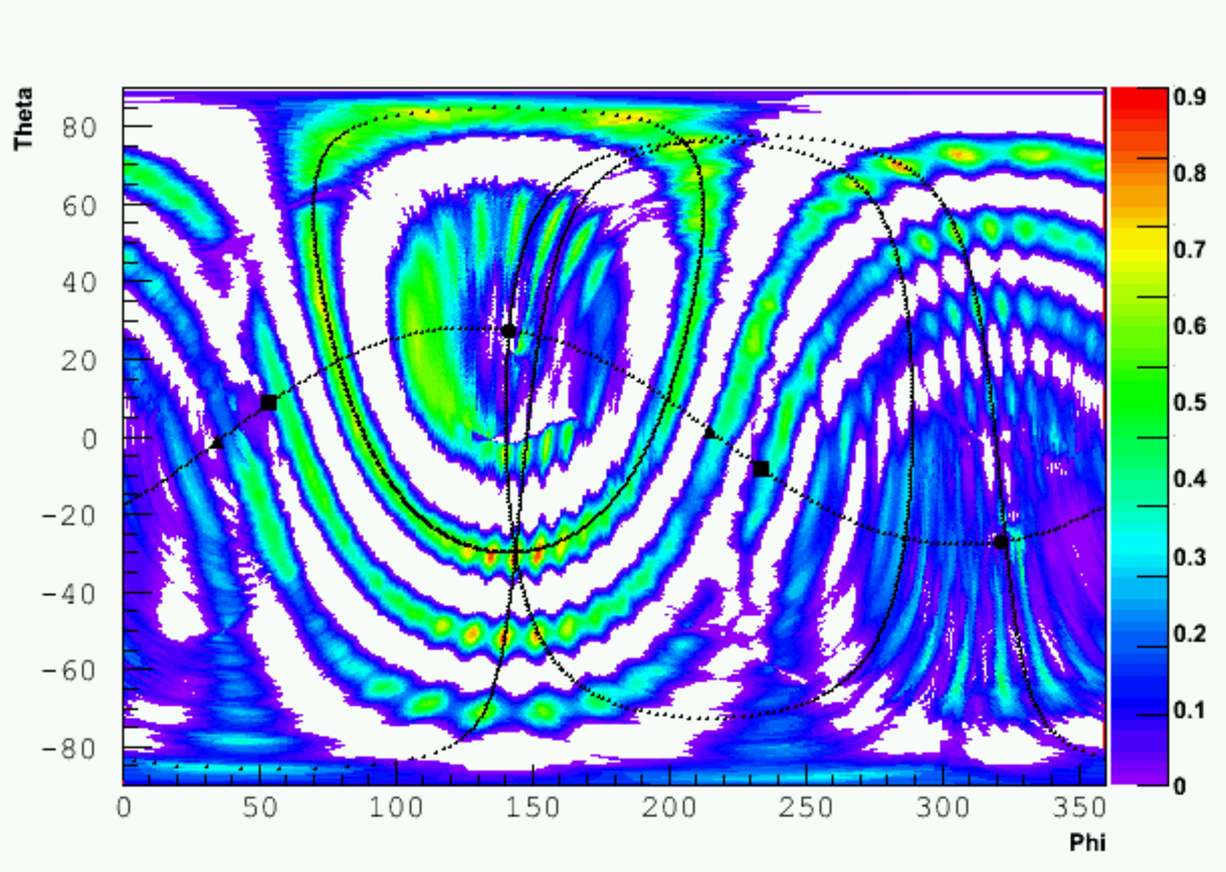
- **Solving the inverse problem using the maximum likelihood method.**
- **Calculating likelihood statistic at all over the sky position.**
- **The GW candidates are the signals of which *L* is beyond a given threshold set by the background noise study.**

$$L = \max(-\|x - Ah\|^2) \quad \text{where} \quad \|x\|^2 = \sum_{i=1}^{d} \int_0^T x_i(t)^T x_i(t)\,dt$$

$$\|data(x) - estimated\ signal(\xi)\|^2$$

$$h = (A^T A)^{-1} A^T x$$

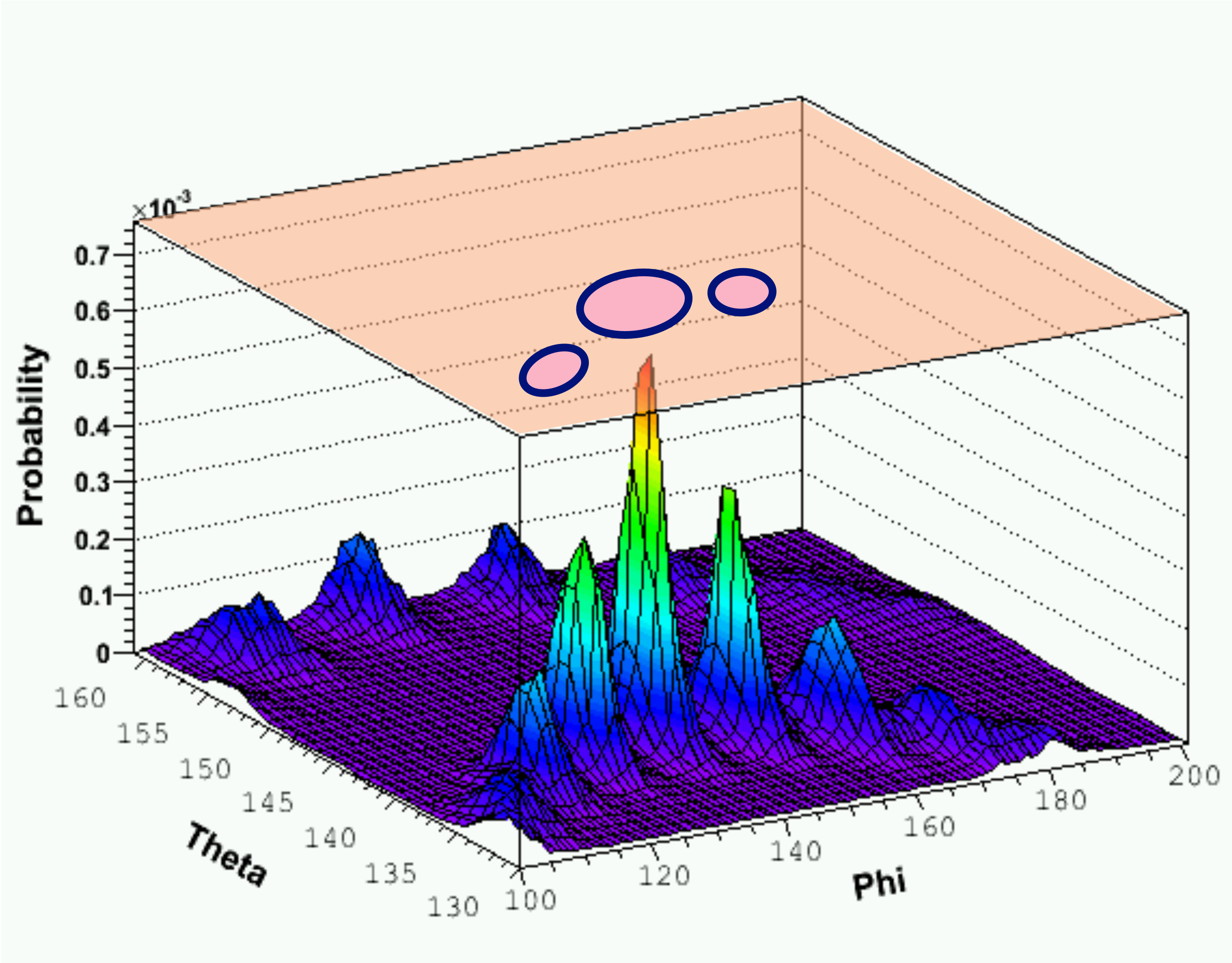
Error region



- H1L1V1 network Likelihood sky-map burst signal containing

Median Error Region

- The region where likelihood is larger than at true position and the true position is included with 50% probability
- The root of the total error area is called median error region



Name	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam Right Ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam Declination (J2000)	−12° 24'	−44° 44'	−02° 52'	−18° 25'
Galactic Latitude, b (°)	−54.7	−41.7	−59.0	−66.2
Galactic Longitude, l (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy hh:mm:ss.sss)	20/02/2011 01:55:48.957	27/06/2011 21:33:17.474	03/07/2011 18:59:40.591	27/01/2012 08:11:21.723
DM (cm^{-3} pc)	944.38 ± 0.05	723.0 ± 0.3	1103.6 ± 0.7	553.3 ± 0.3
DM_E (cm^{-3} pc)	910	677	1072	521
Redshift, z (DM_{Host} = 100 cm^{-3} pc)	0.81	0.61	0.96	0.45
Co-moving Distance, D (Gpc) at z	2.8	2.2	3.2	1.7
Dispersion Index, α	−2.003 ± 0.006	–	−2.000 ± 0.006	–
Scattering Index, β	−4.0 ± 0.4	–	–	–
Observed Width at 1.3 GHz, W (ms)	5.6 ± 0.1	< 1.4	< 4.3	< 1.1
SNR	49	11	16	11
Minimum Peak Flux Density S_ν (Jy)	1.3	0.4	0.5	0.5
Fluence at 1.3 GHz, F (Jy ms)	8.0	0.7	1.8	0.6
$S_\nu D^2$ (× 10^{12} Jy kpc^2)	10.2	1.9	5.1	1.4
Energy Released, E (J)	$\sim10^{33}$	$\sim10^{31}$	$\sim10^{32}$	$\sim10^{31}$

Science 341 53 2013

新学術「重力波天体の多様な観測による宇宙物理学の新展開」