

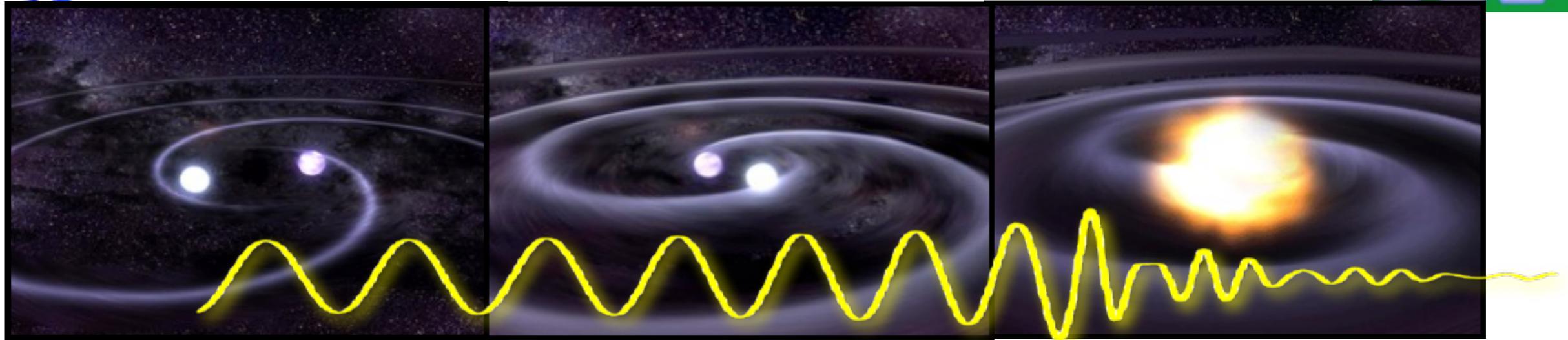
# 重力波の探査と マルチメッセンジャー観測



端山和大

*National Astronomical Observatory of Japan*

- 重力波と重力波望遠鏡
- **LIGO-Virgo**での重力波観測結果
  - 連星合体からの重力波、バースト性重力波の探査
  - マルチメッセンジャー観測
- **LCGT**世代の望遠鏡ネットワークの期待できる成果
- **Big Dog**といわれた信号
- (時間があれば) 重力理論のテスト(**Brans-Dicke**理論の場合)



NASA

- 星の重力場の変化で生じる**時空間のひずみが伝播する現象** (1916年にEinsteinが予言)
- だが**90年以上たった今でもまだ本物の重力波形を見た人はいない(直接観測)**  
**37万t/1mm<sup>3</sup>という超高密度の物性、天体の爆発のメカニズム、BH etc**
- **2017年には世界の重力波望遠鏡LCGT(日)、LIGO(米)、VIRGO(欧)により検出される**  
**年10回程度の中性子星連星合体、パルサーの1年観測、低質量X線連星の数ヶ月観測**

**重力波天文学の夜明けが間近に迫っている！**

準備すべきことも多い



## 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

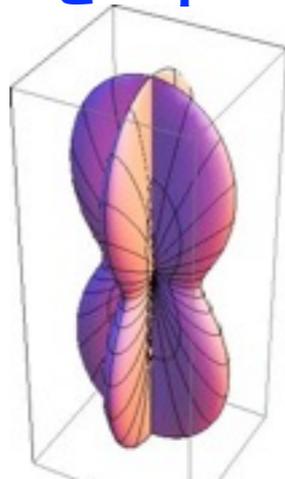


ミラーに反射させ再結合。干渉光を光検出器で観測

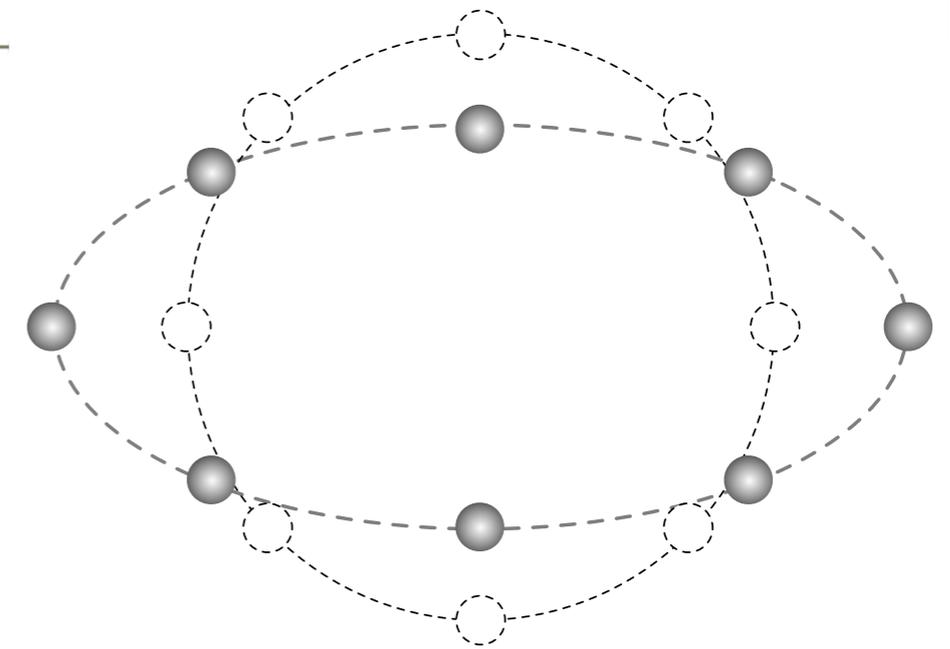
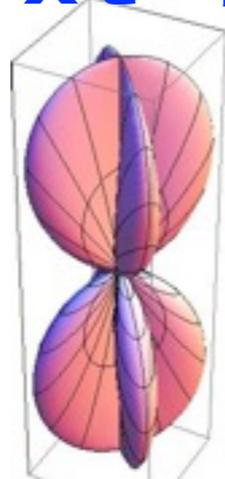
干渉光量に対応する時系列データから重力波信号を抽出する

## アンテナパターン

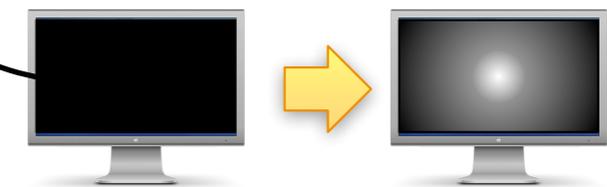
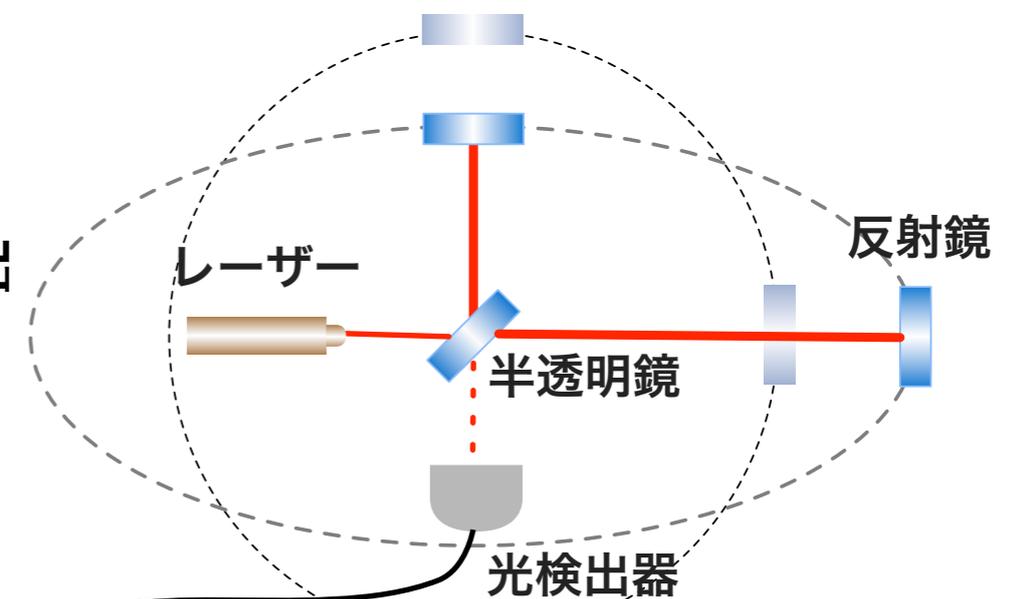
+モード



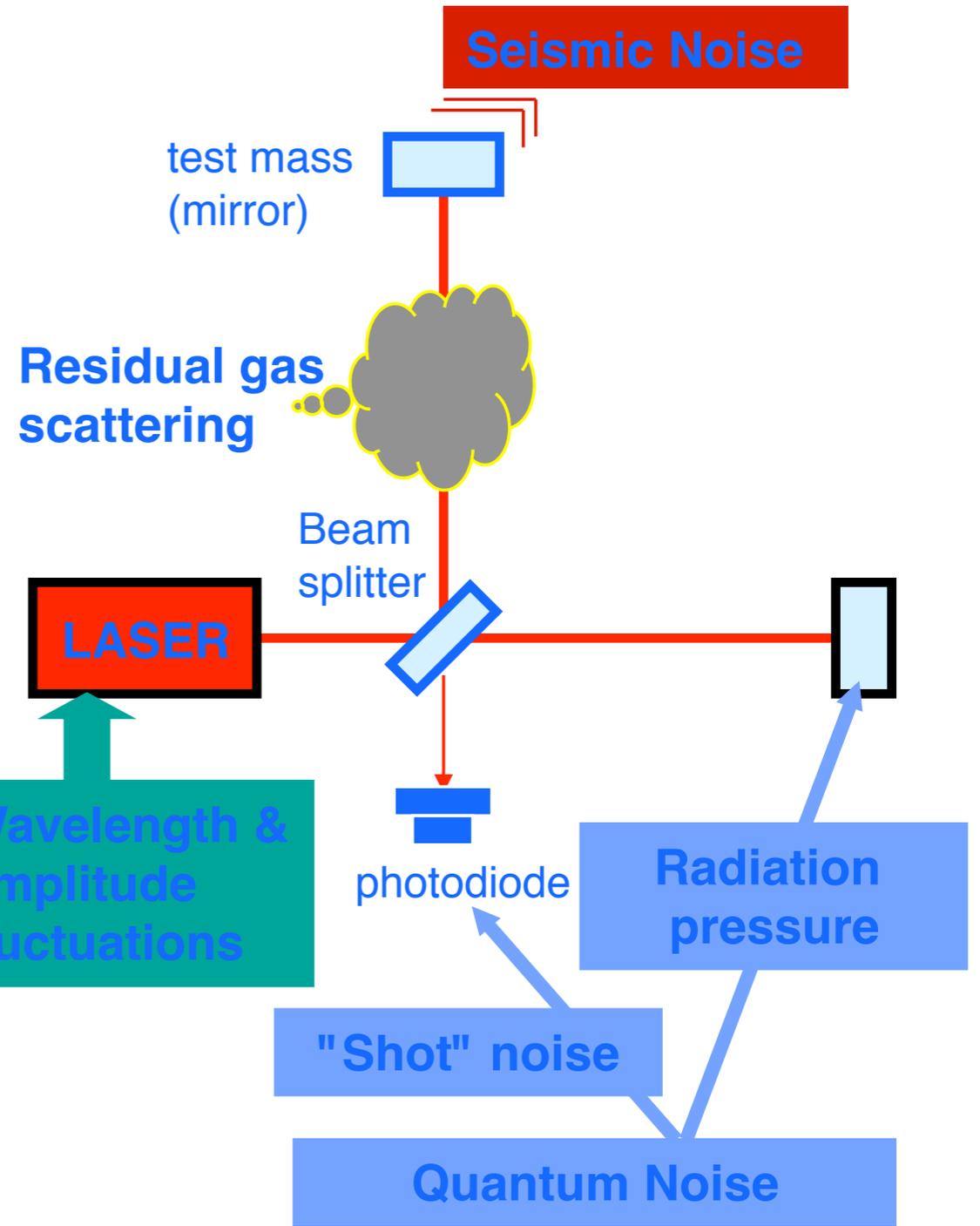
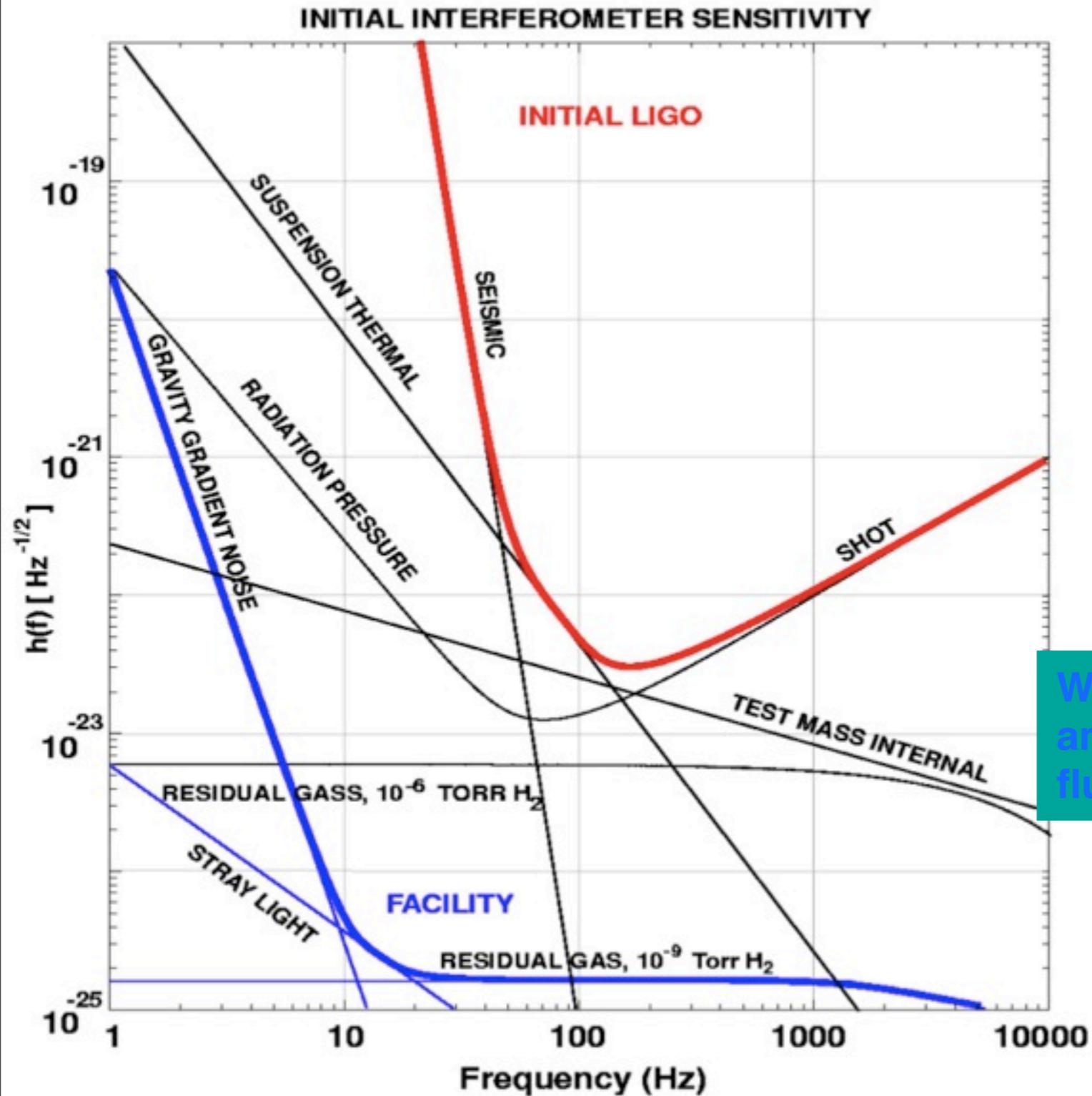
Xモード

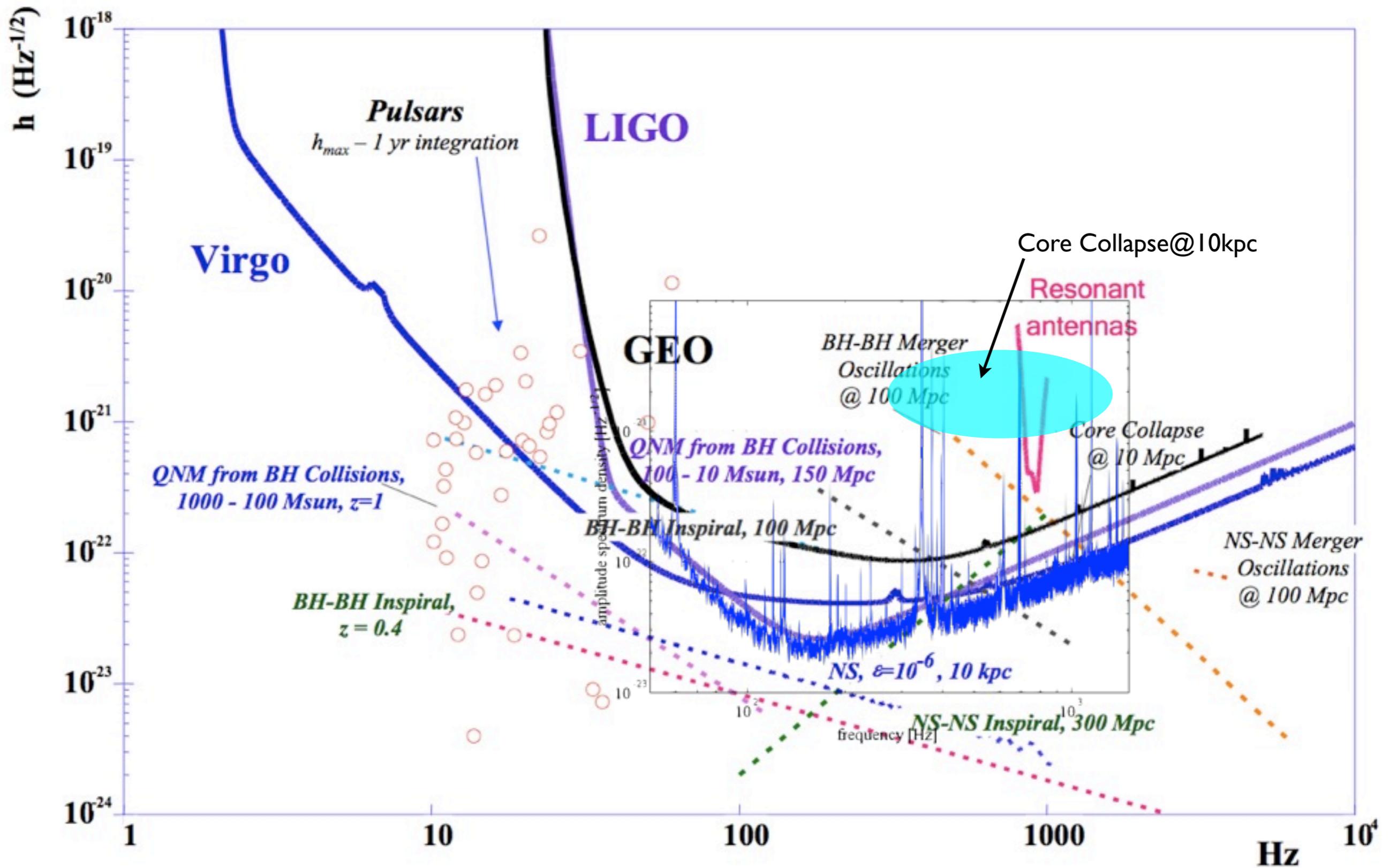


自由質点の応答



重力波望遠鏡の原理







~~● パルサーからの連続波~~

● コンパクト連星合体からの重力波

~~● 背景重力波~~

● 波形不明のバースト性重力波

● 超新星爆発

● GRB

● パルサーグリッチ

● 中性子星の星震(accreting mass等による)

● ....

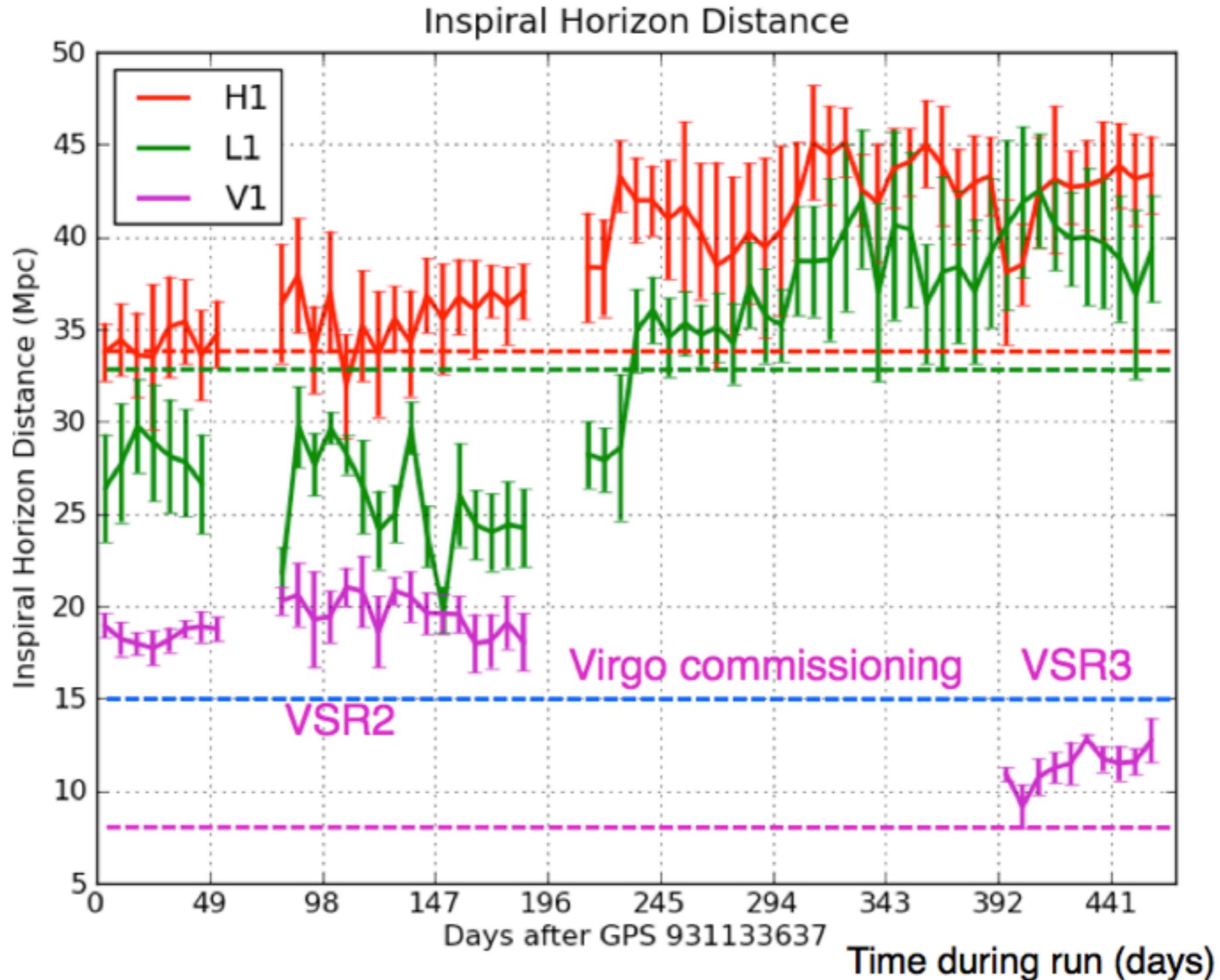
# コンパクト連星合体サーチ

- 重力波形が理論的に予想できるので、データと相関をとる**matched filter**解析が可能となる。

$$\rho = \frac{\langle s | h \rangle}{\sqrt{\langle h | h \rangle}} \quad \langle s | h \rangle = 4 \operatorname{Re} \int_{f_{low}}^{f_{high}} \frac{\tilde{s}(f) \tilde{h}(f)}{S_n(f)} df$$

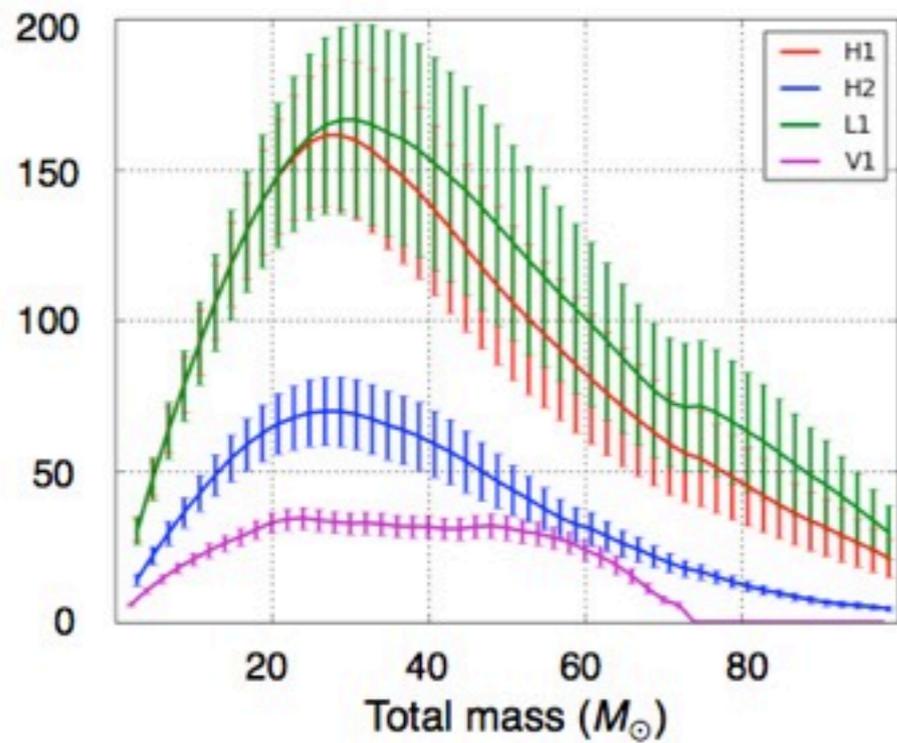
- 巨大なパラメタ空間(スピンを入れると12次元)
- モデルの選択という統計問題

- 信号-雑音比(SNR)が8で検出できる最大距離
- 2009-2010に行われた観測でのNS-NS連星合体についてのもの

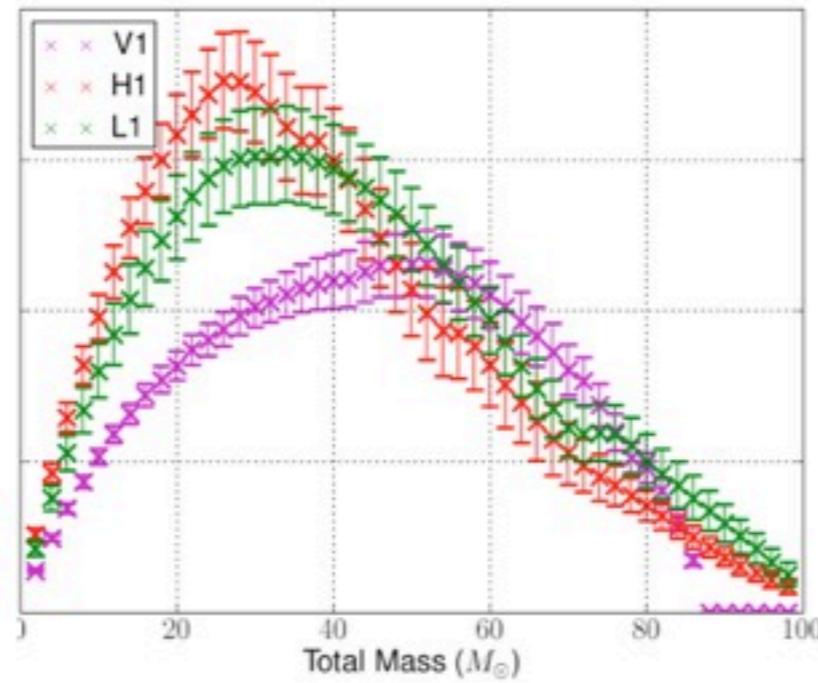




Inspiral horizon distance (Mpc)

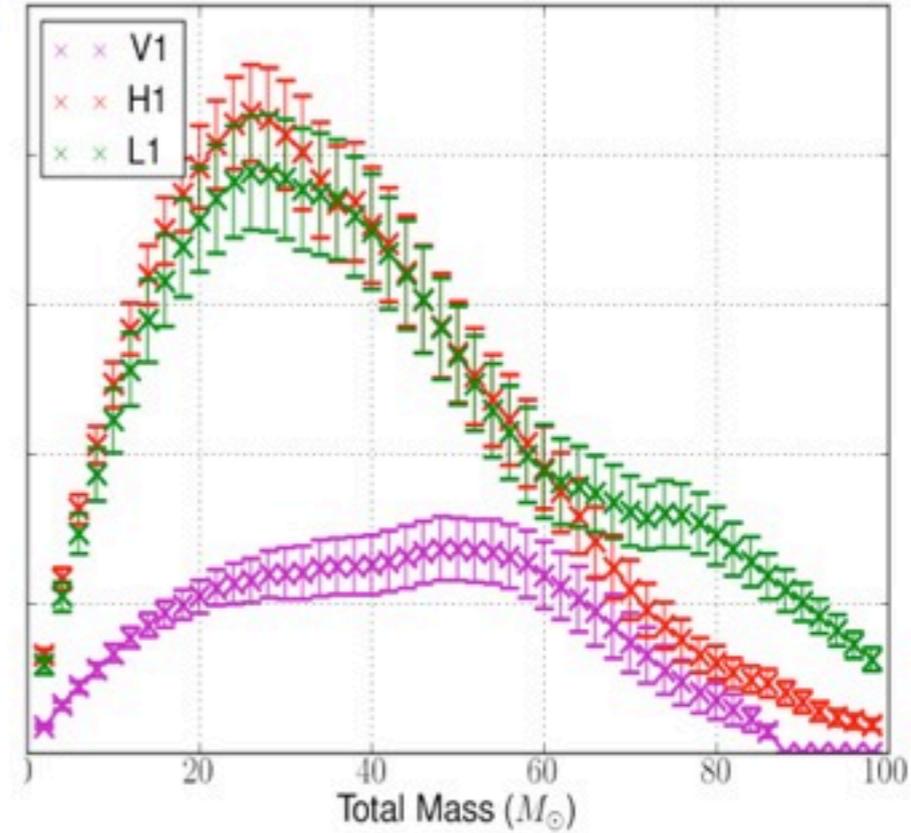


**S5**



**Beginning of S6/VSR2**

250



**End of S6/VSR2**



**Milky Way**  
(~50kpc)

**アンドロメダ銀河**  
(~700kpc)

**乙女座銀河団**  
(~15Mpc)

到達年

**2002年**

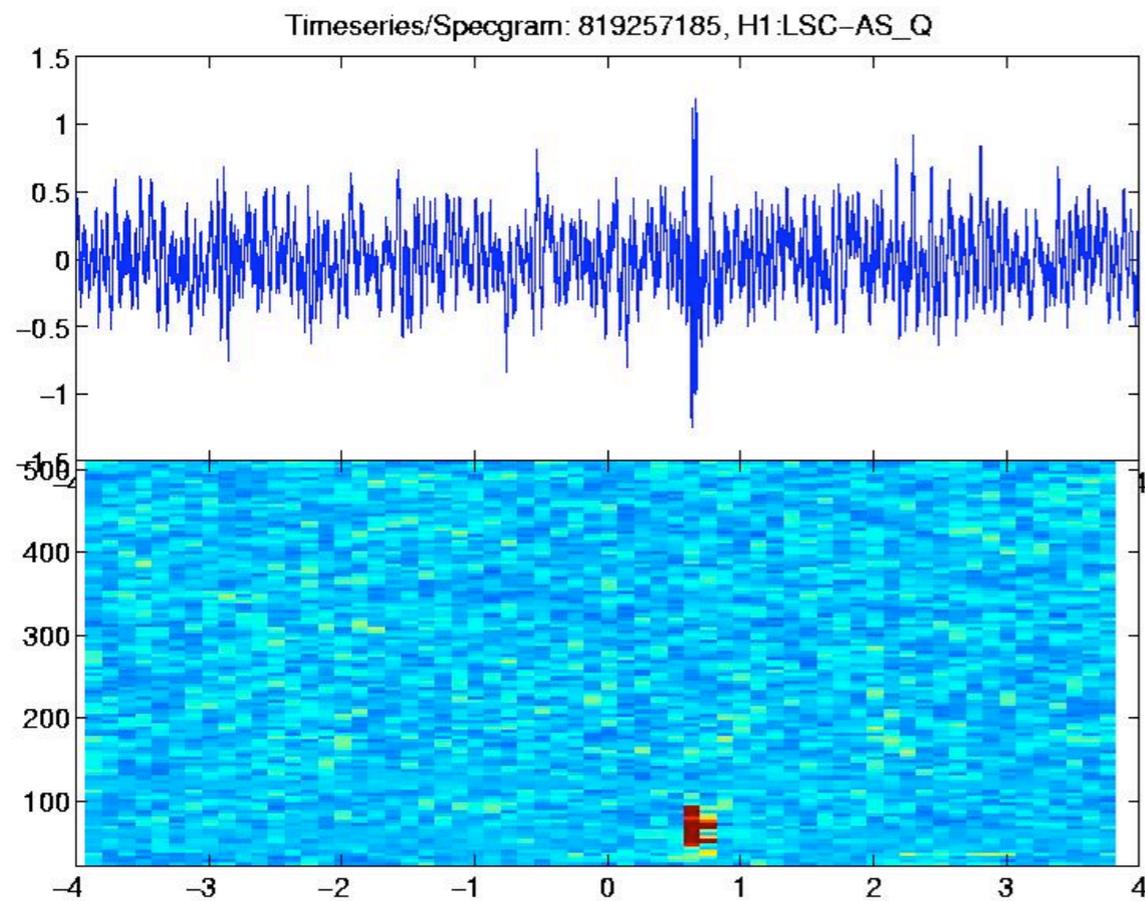
**2003年**

**2005年**

# バーストサーチ

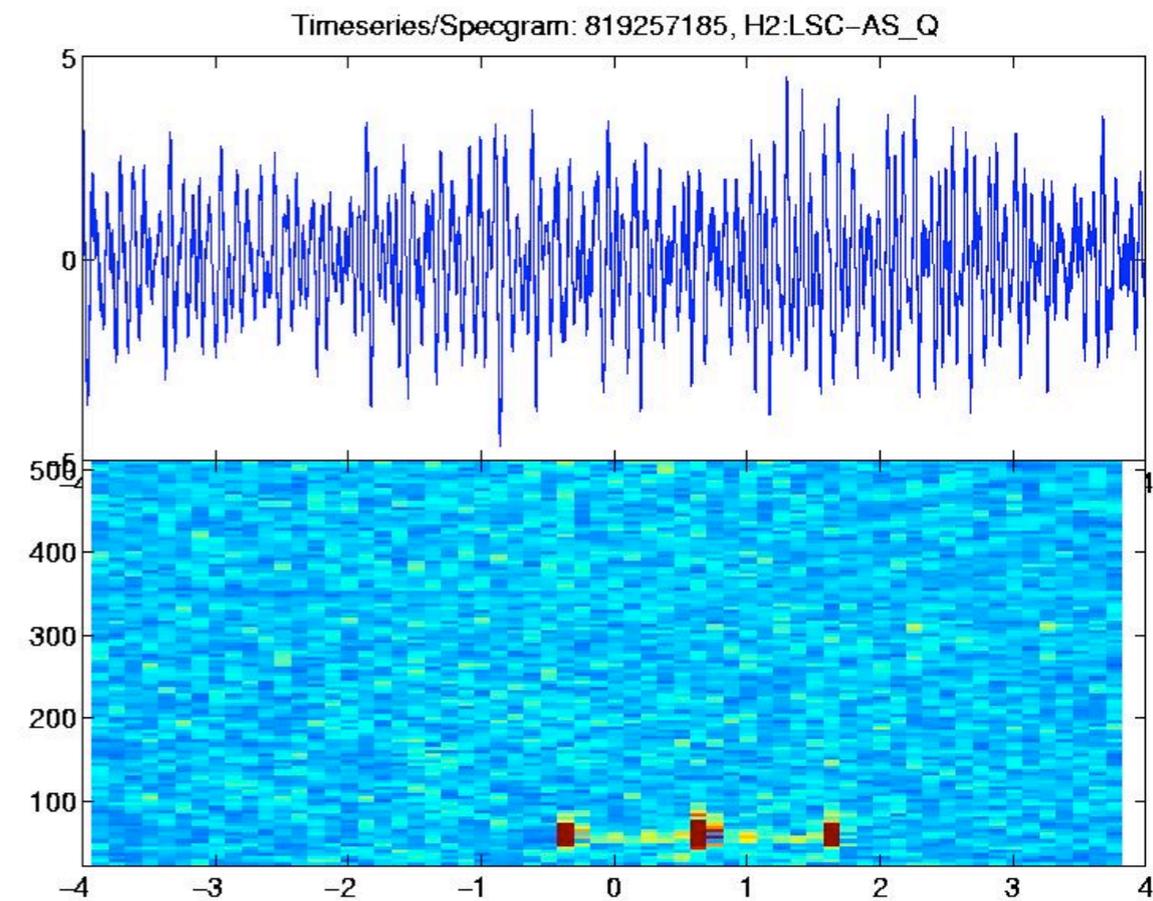
- 天体爆発によるバースト重力波の波形不定性が大きい。
- 望遠鏡が多く、バースト性雑音を含み、複数の望遠鏡を用いてさえコインシデンスイベントが多い。
- さまざまな情報を駆使して雑音と重力波を区別することが必要。

H1

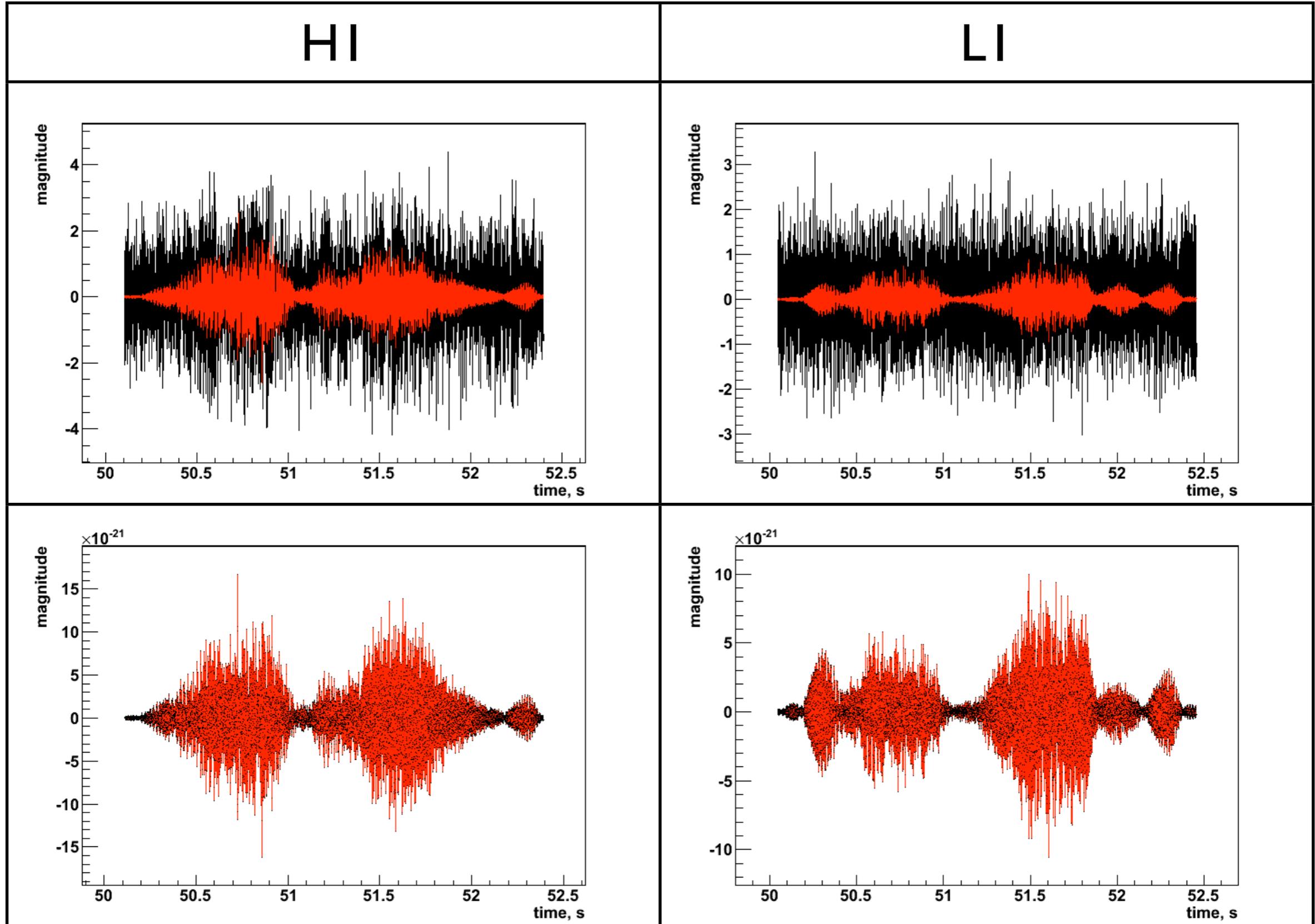


This plot made 16-May-2007 21:36:47

H2



This plot made 16-May-2007 21:38:53

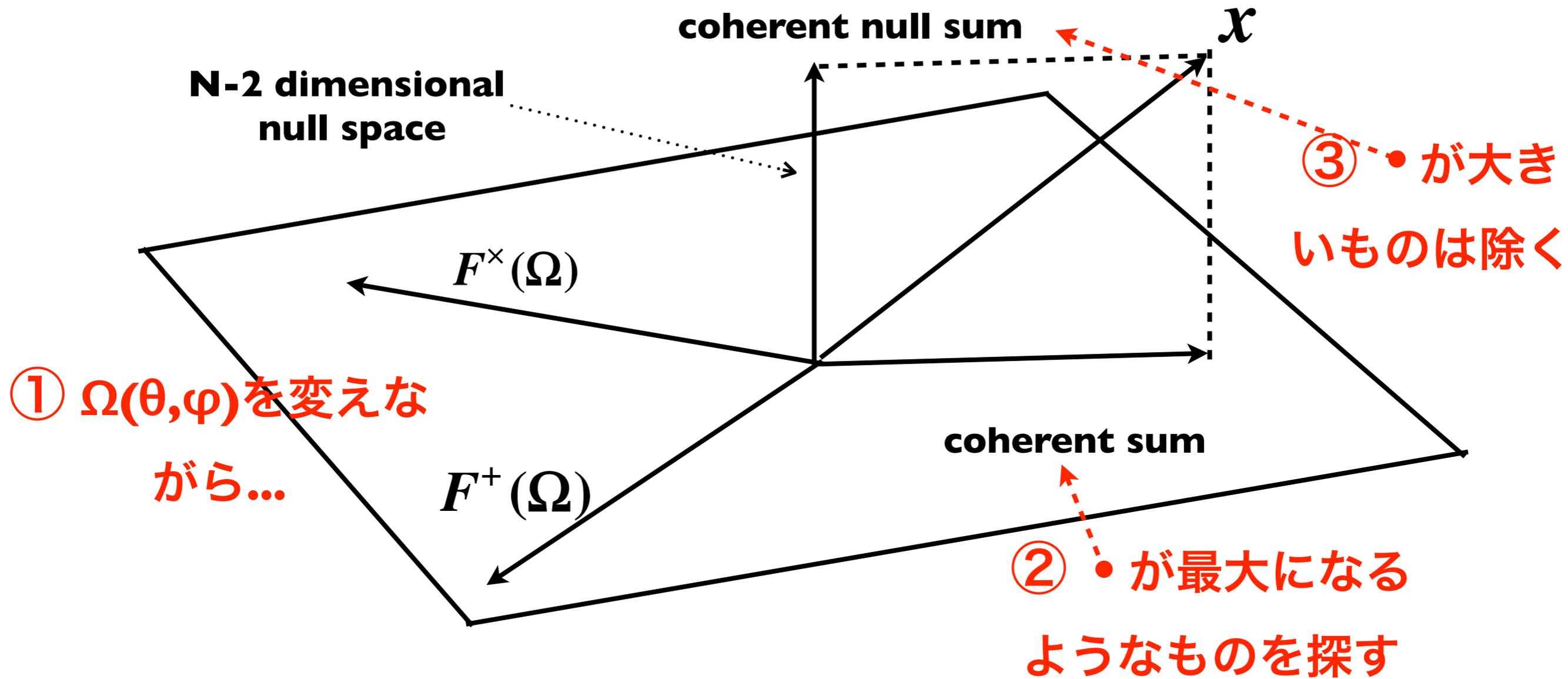


## 複数望遠鏡での観測の利点

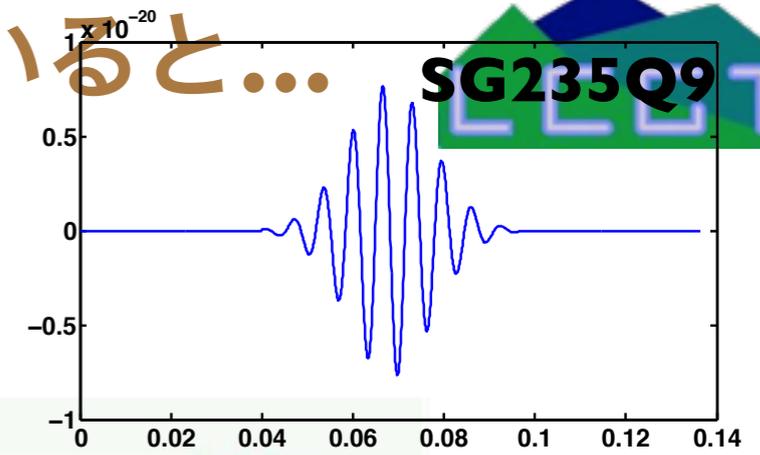
- LIGOは3台のkmクラスの望遠鏡で構成。
- 逆問題を解くことにより、+モードとxモードの偏波を分解できる。
- 重力波の到来方向がわかる。
- 重力波とノイズを区別するのに有効

望遠鏡データ	アンテナパターン	重力波	望遠鏡ノイズ
$\begin{bmatrix} x_1(t + \tau_1(\Omega)) \\ x_2(t + \tau_2(\Omega)) \\ \vdots \\ x_d(t + \tau_d(\Omega)) \end{bmatrix}$	$= \begin{bmatrix} F_1^+(\Omega) & F_1^\times(\Omega) \\ F_2^+(\Omega) & F_2^\times(\Omega) \\ \vdots & \vdots \\ F_d^+(\Omega) & F_d^\times(\Omega) \end{bmatrix}$	$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix}$	$+ \begin{bmatrix} n_1(t + \tau_1(\Omega)) \\ n_2(t + \tau_2(\Omega)) \\ \vdots \\ n_d(t + \tau_d(\Omega)) \end{bmatrix}$
	<p>↑</p> <p>+モード    xモード</p> <p>のアンテナパターン (天球位置<math>\Omega</math>に依存)</p>		

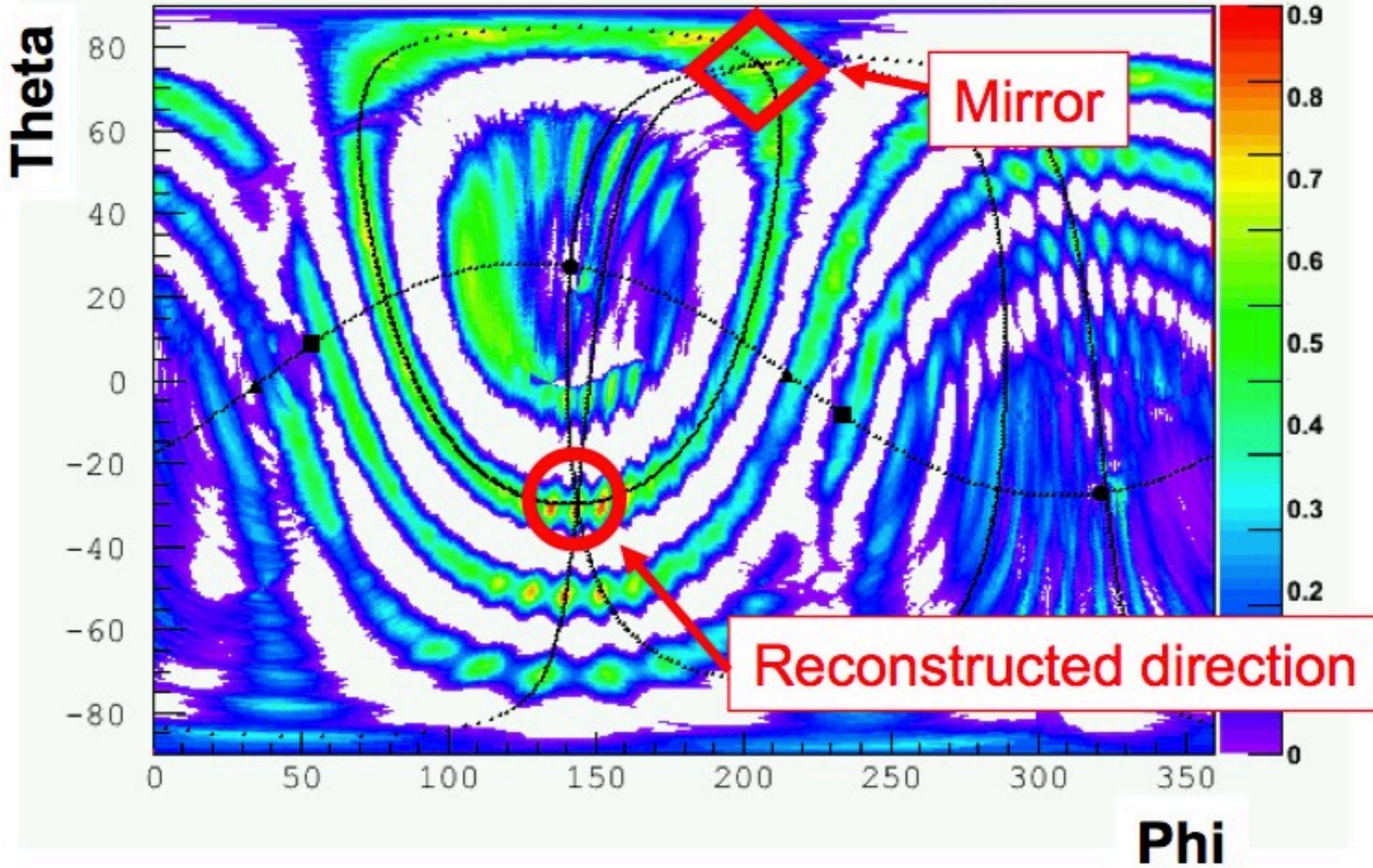
到達時間差の補正

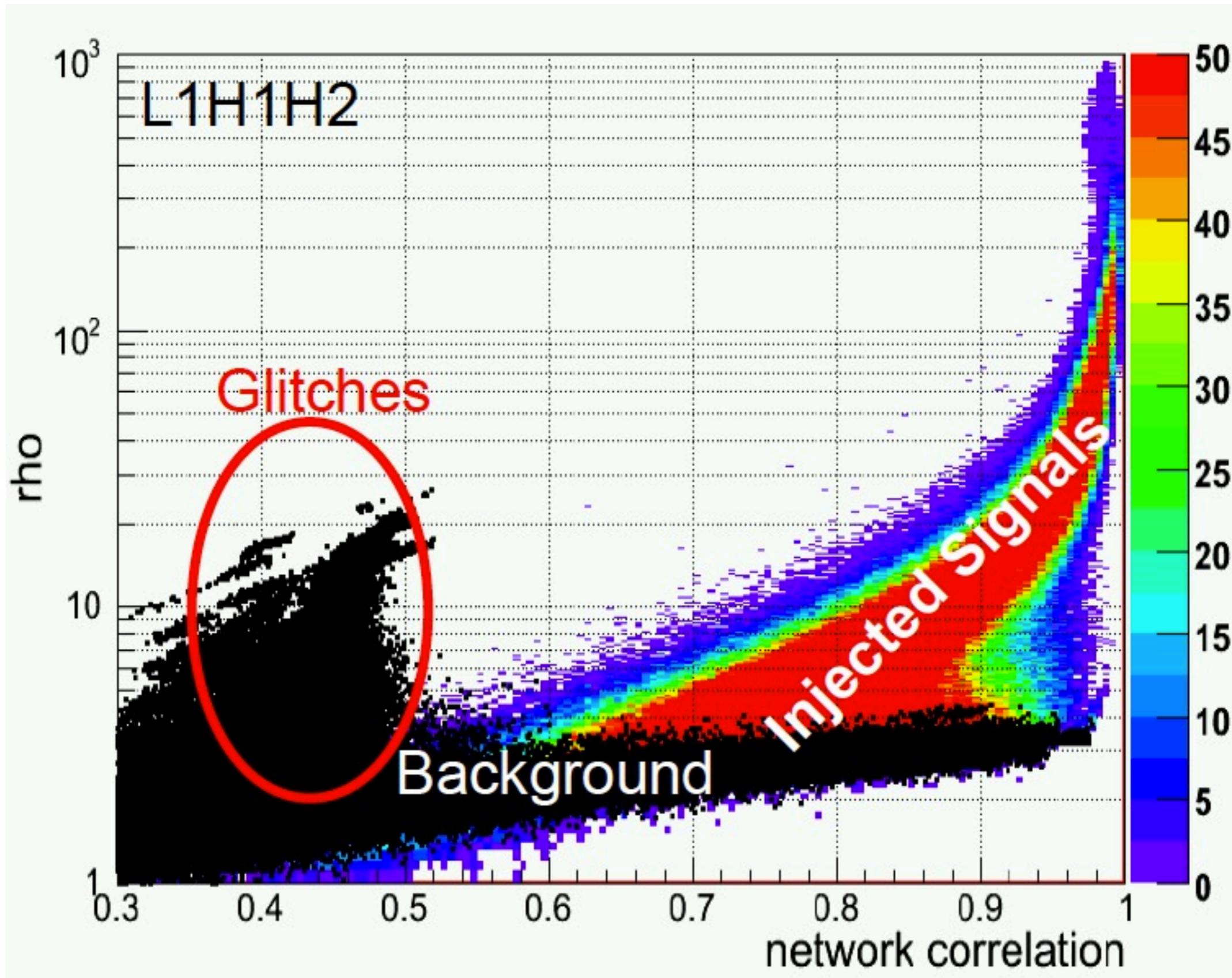


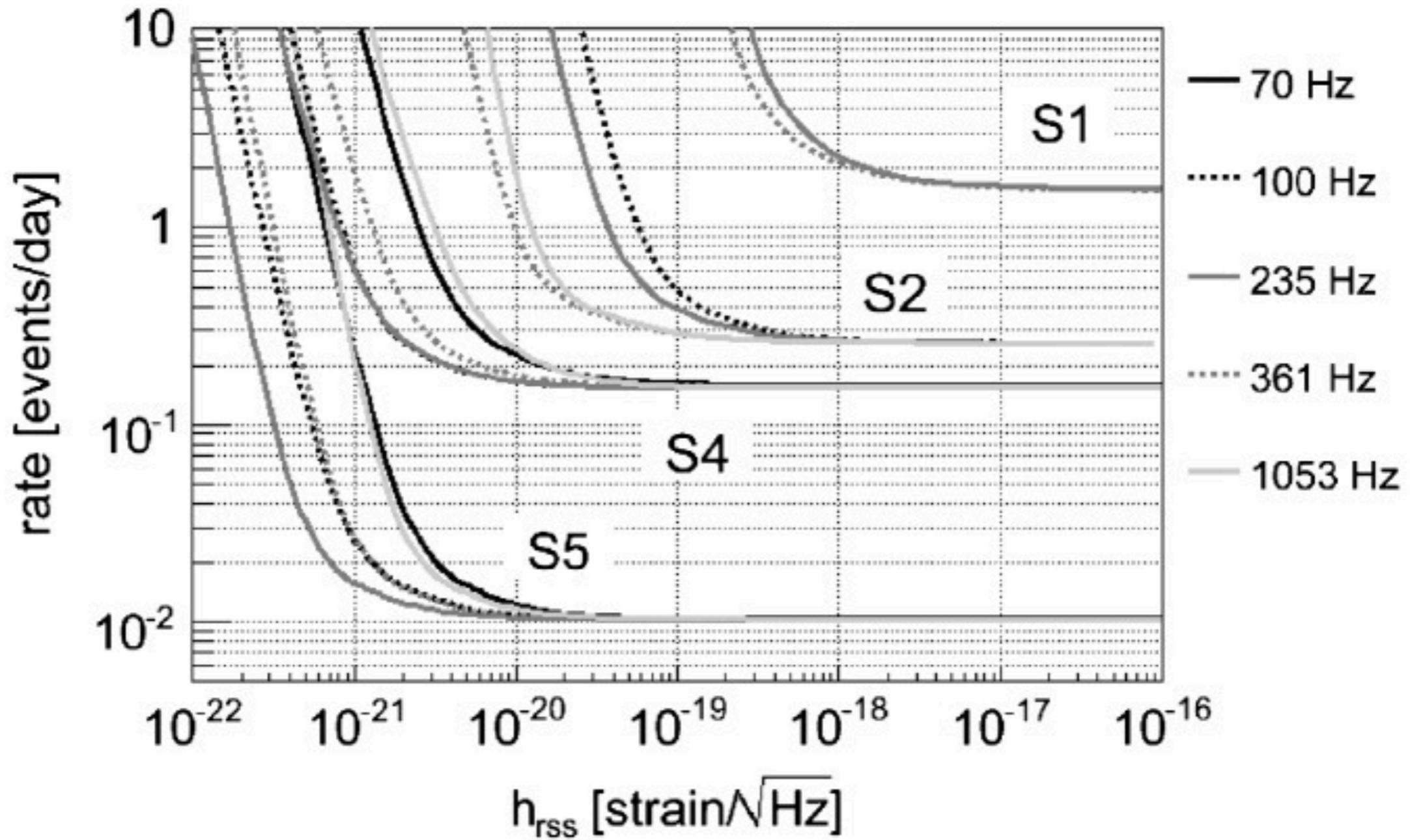
- **Coherent null sum:**  
すべての検出器データを上手く線形結合して重力波信号をキャンセルした、ノイズのみになるデータ⇒重力波と雑音を区別するための統計量となる。
- **Coherent sum:(~Likelihood statistics)**  
すべての検出器データを上手く線形結合して重力波信号の信号-雑音比を最大にする。



HILIVIネットワーク

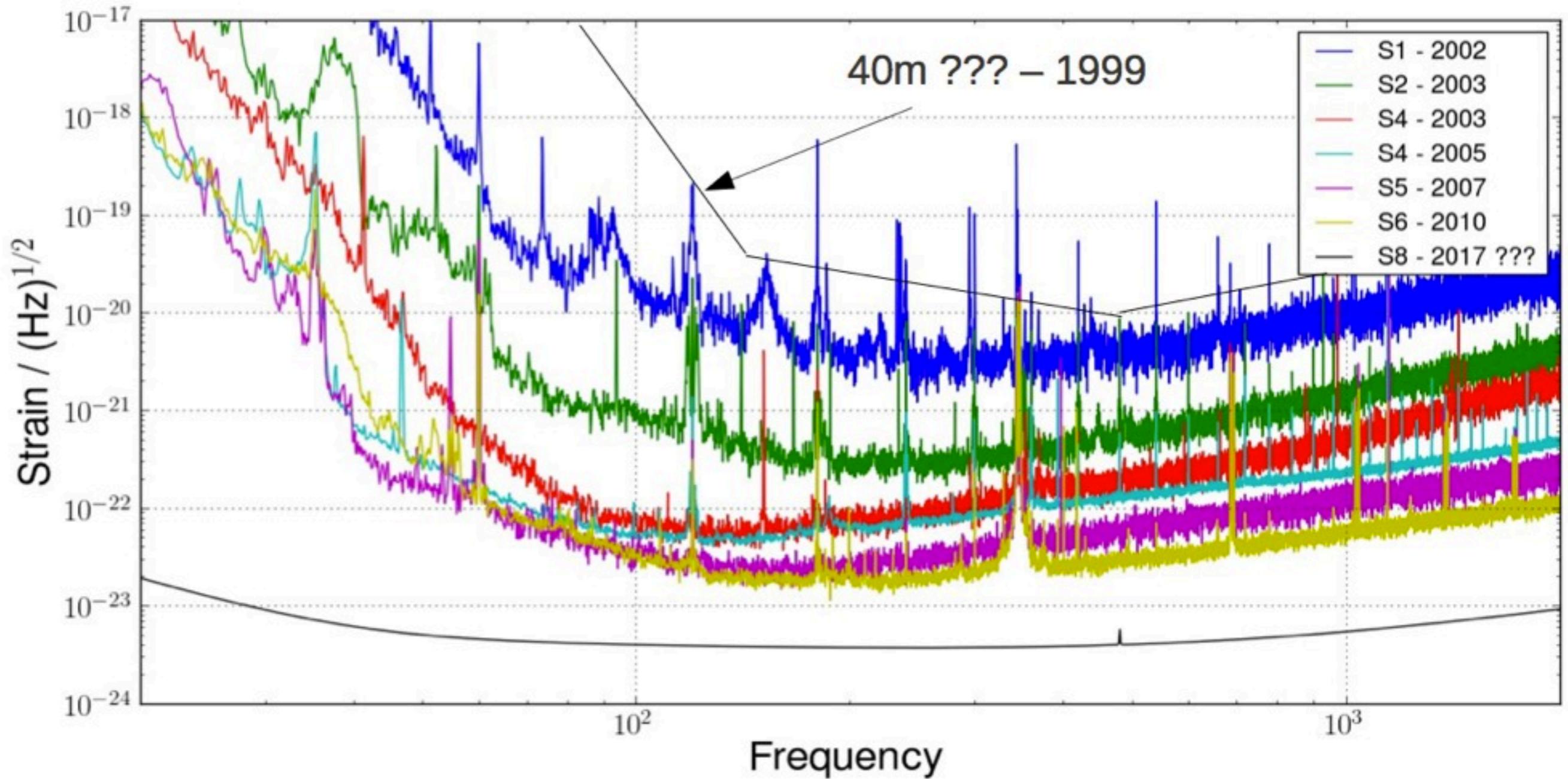






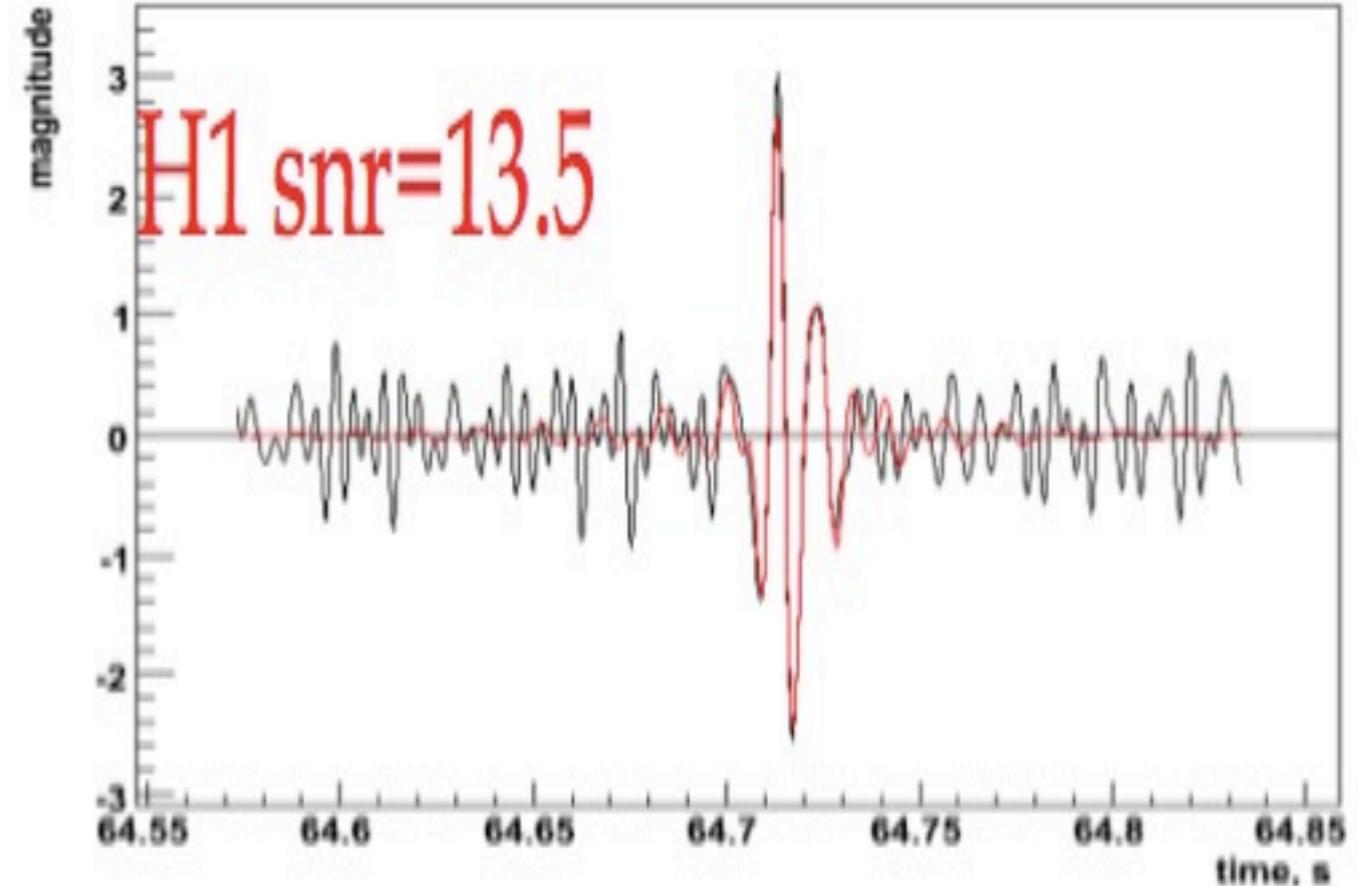
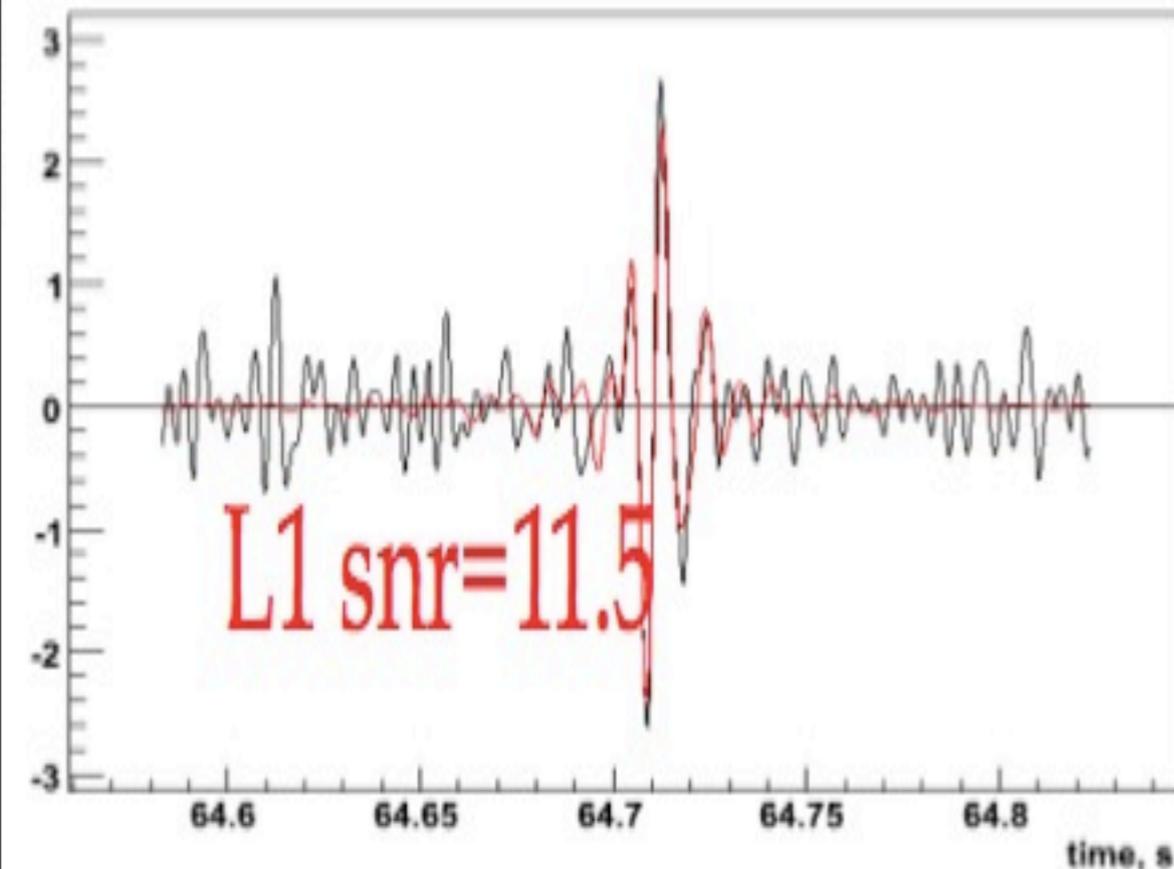
- **Upper limit on GW energy for a 153Hz burst**  
 $\sim 2 \times 10^{-8} M_{\odot} c^2$  at 10kpc,  $\sim 0.05 M_{\odot} c^2$  at 16Mpc

*Abadie et al., PRD 81, 102001 (2010)*



- kmクラス望遠鏡での観測S5, S6で非定常雑音(グリッチetc)はbackgroundを悪化させた。複数の望遠鏡間でも頻繁にaccidental coincidenceがみられた。
- 要求されるFalse Alarm Prob.(FAP)を満たすために検出しきい値は高く設定され、結局非定常雑音が重力波のアップーリミットを支配した。
- 検出するべきblind injectionも、最終的にrejectされた。

### blind injection signal



Discoveryには**FAP**が $10^{-6}$ 必要と言われている。

Blind injectionイベント : **P ~ 0.01** (veto後)

もしLIGOS5ネットワークと同じf.a.pであるとすれば、あと $10^4$ ほどPを下げる必要がある。

下げるための2つの方法：

- **Background**を下げる。
- **Astrophysical counterpart**によって、時間的、空間的コインシデンスをとる。

$$\text{Final FAP} \sim P \times (\Delta t \times N/T) \times (A/180)^2$$

1%

1%

1%

天球位置推定が20°で実現

event rate 1/day,  $\Delta t=180[s]$ で実現

0.1%

0.1%

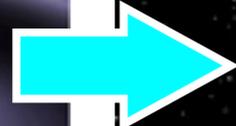
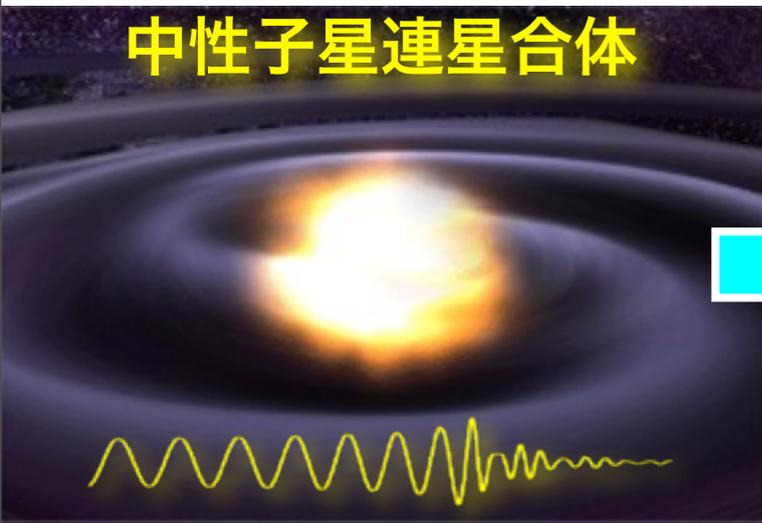
0.01%

1%

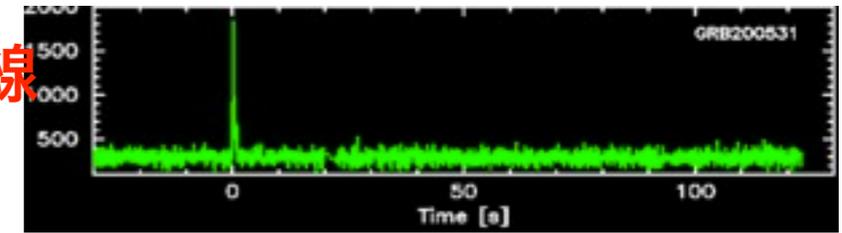
理論家、データ解析家の努力

実験家、データ解析家の努力

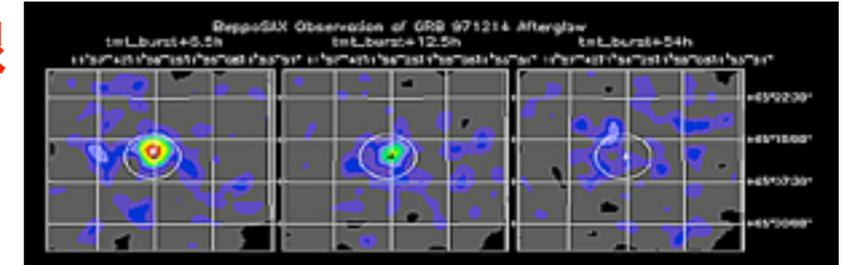
## $10^{-6}$ に到達が可能



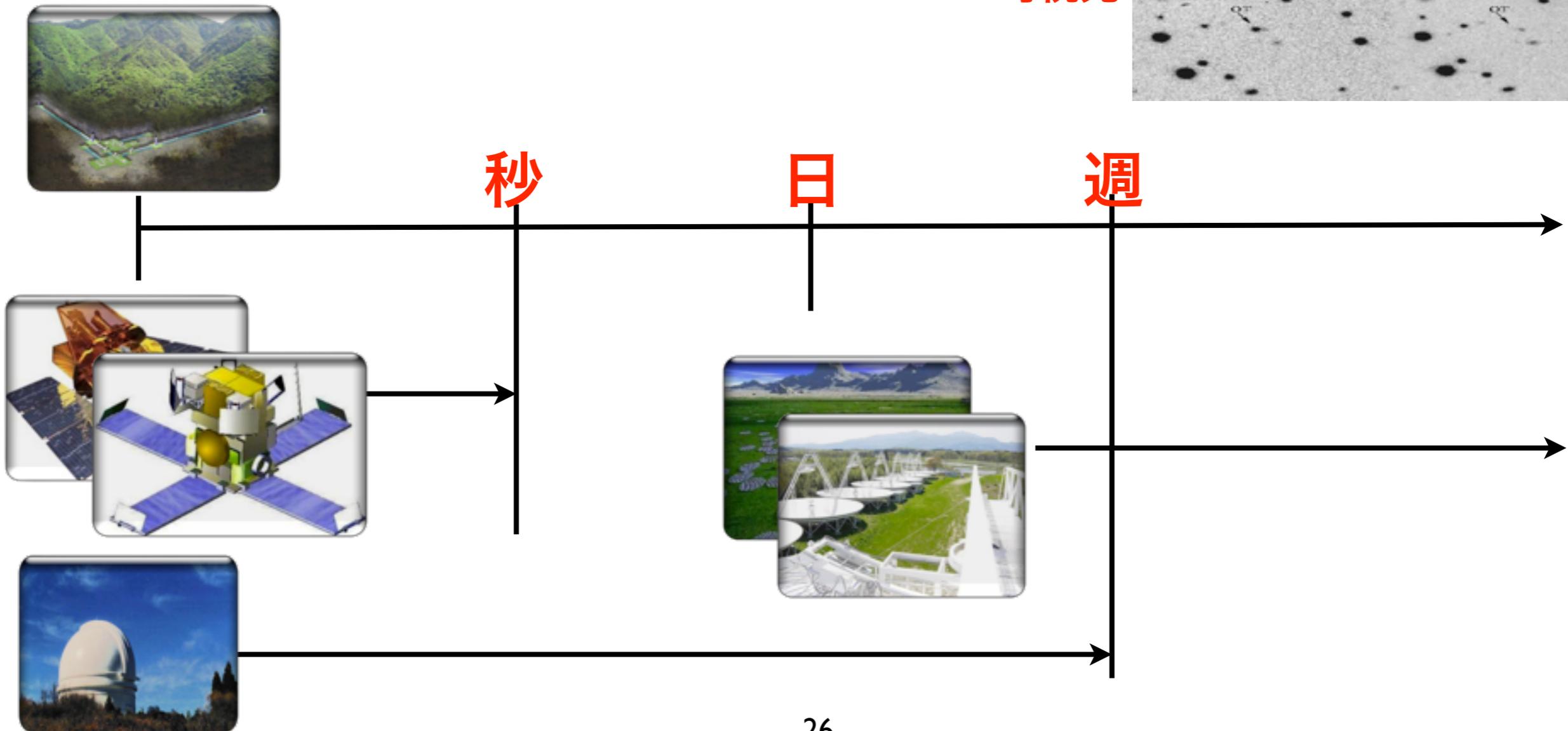
ガンマ線



X線

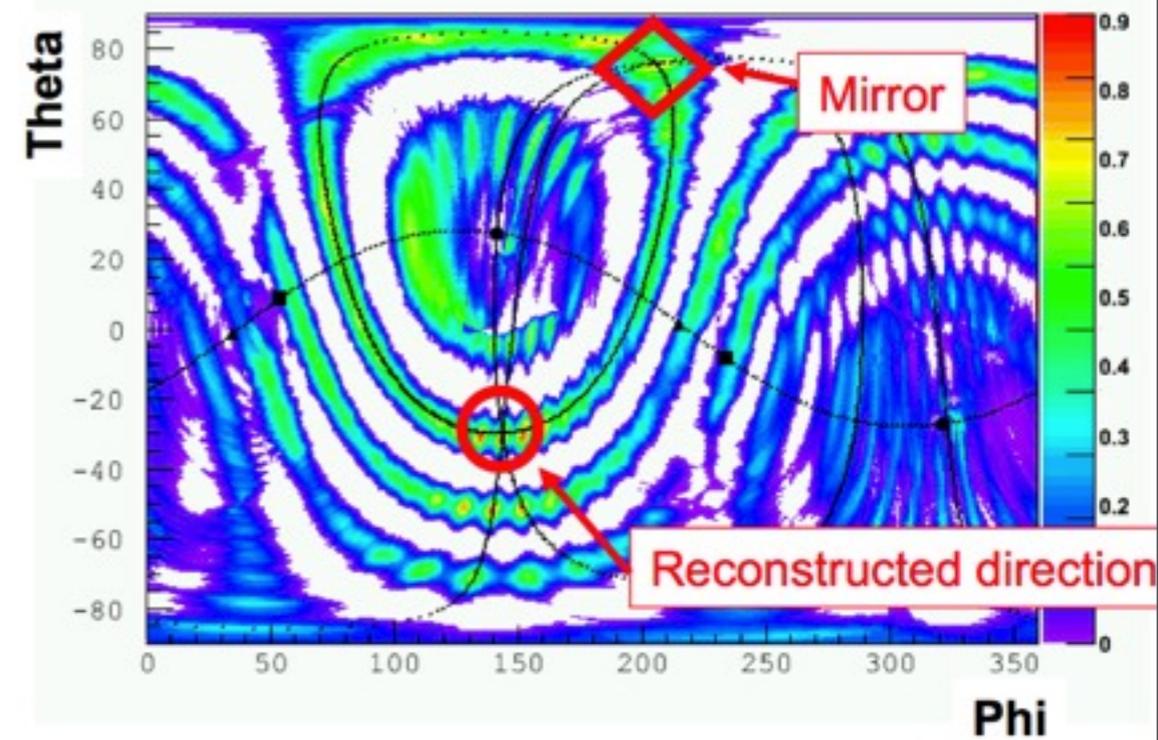


可視光

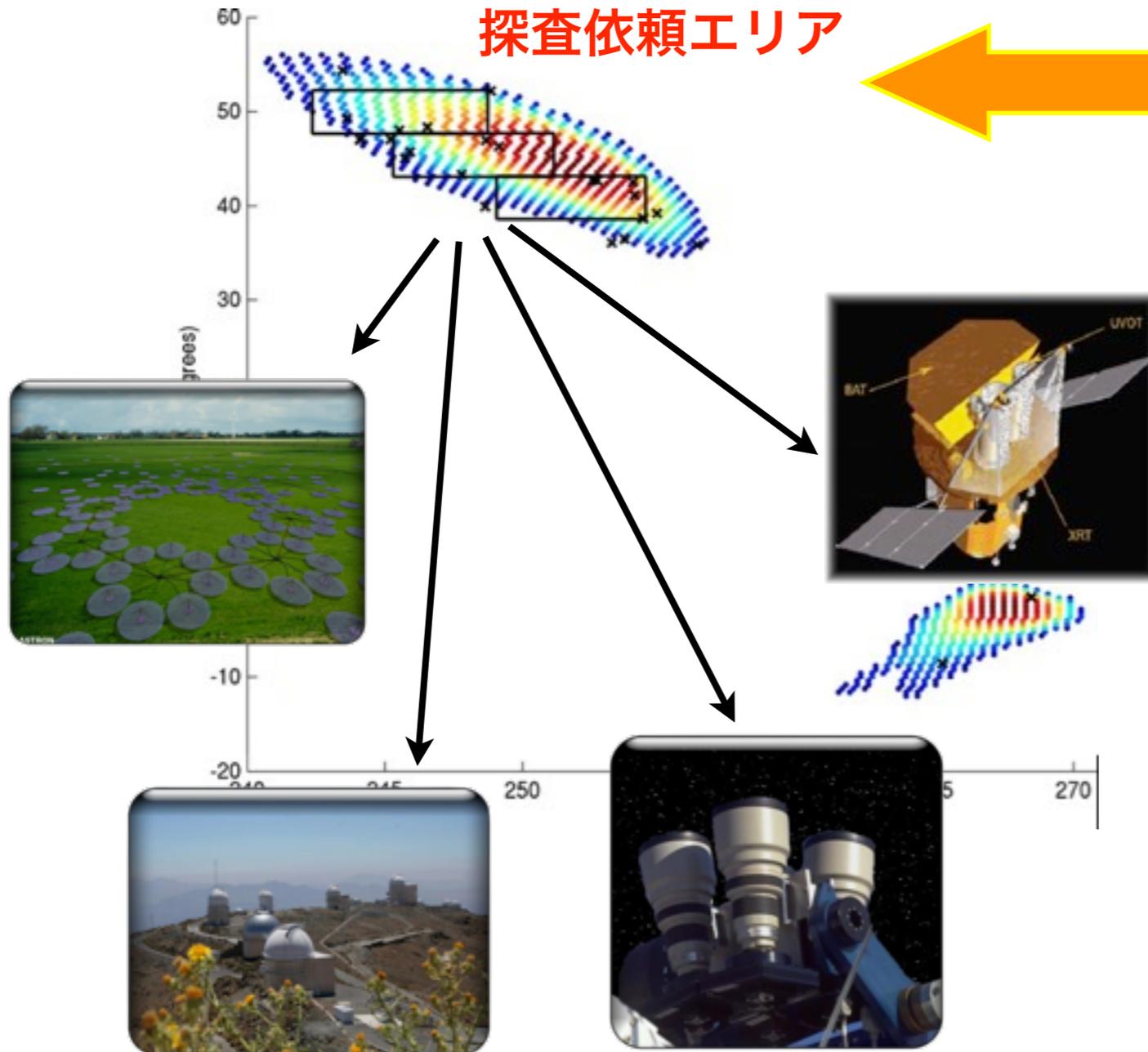
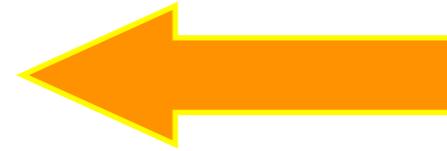


- リアルタイムバーストサーチにより、重力波イベント候補の推定天球位置を電磁波望遠鏡に送り、フォローアップ観測を依頼
- 逆に電磁波望遠鏡からのトランジェントアラートを受けて、重力波データを解析

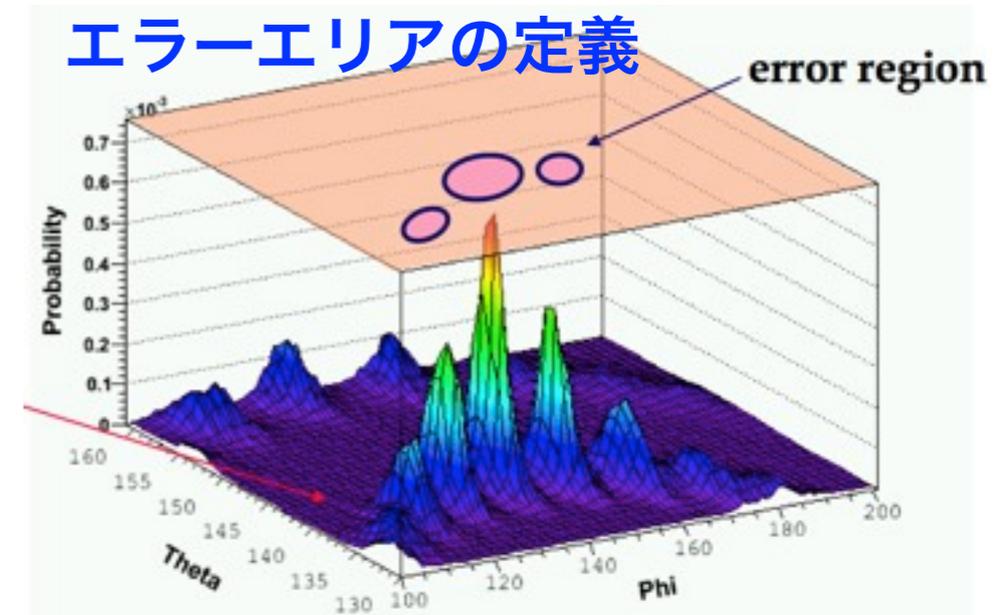
## イベント候補の天球位置の推定



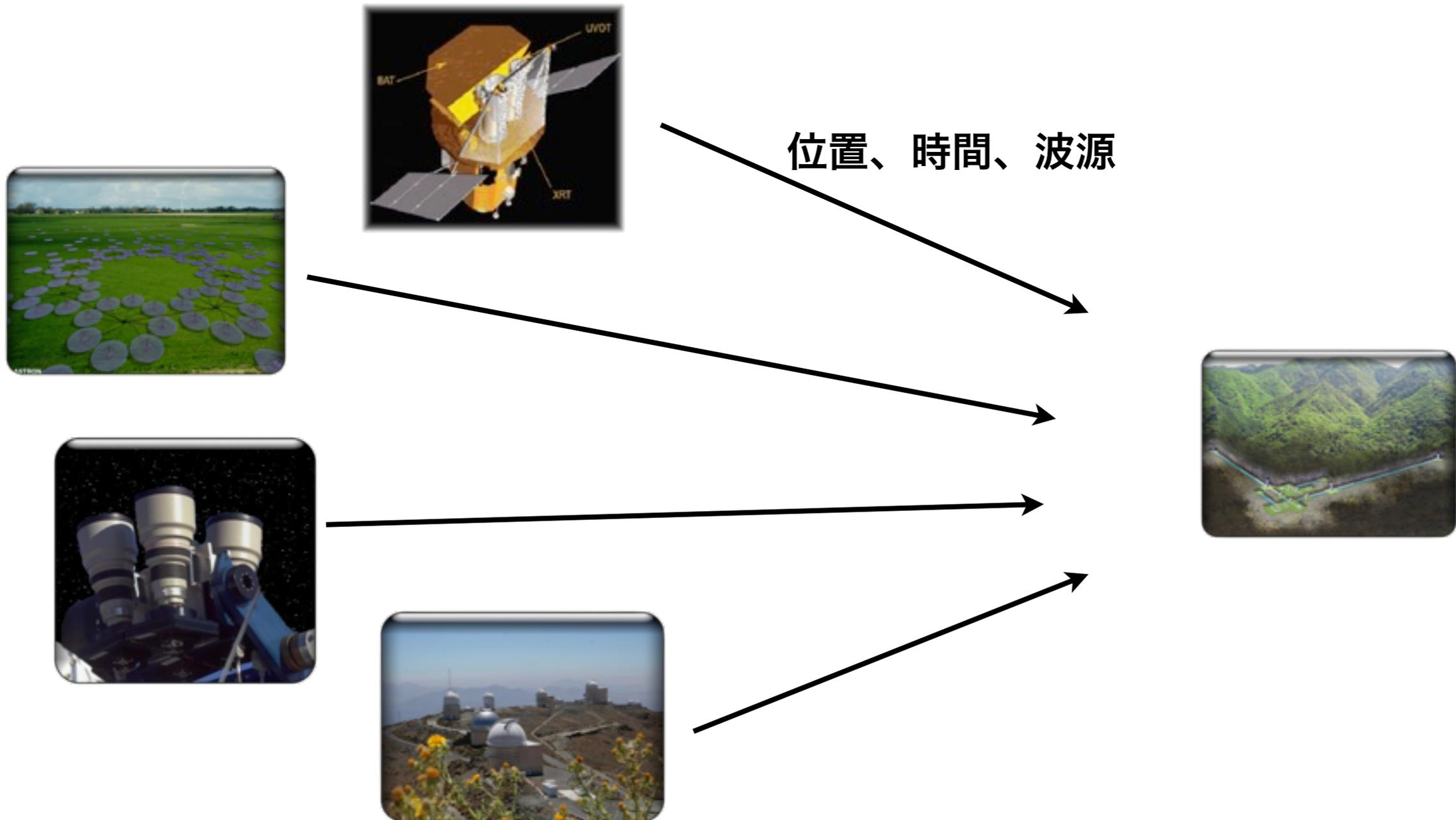
## 探査依頼エリア



## エラーエリアの定義

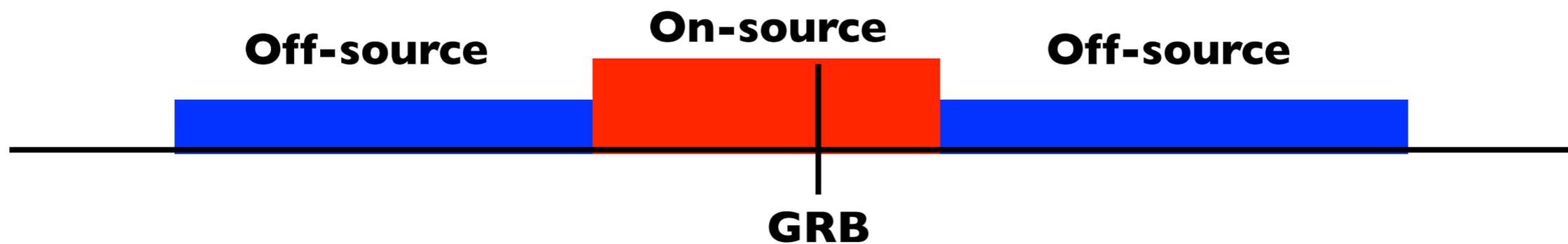


- リアルタイムバーストサーチにより、重力波イベント候補の推定天球位置を電磁波望遠鏡に送り、フォローアップ観測を依頼
- 逆に電磁波望遠鏡からのトランジェントアラートを受けて、重力波データを解析

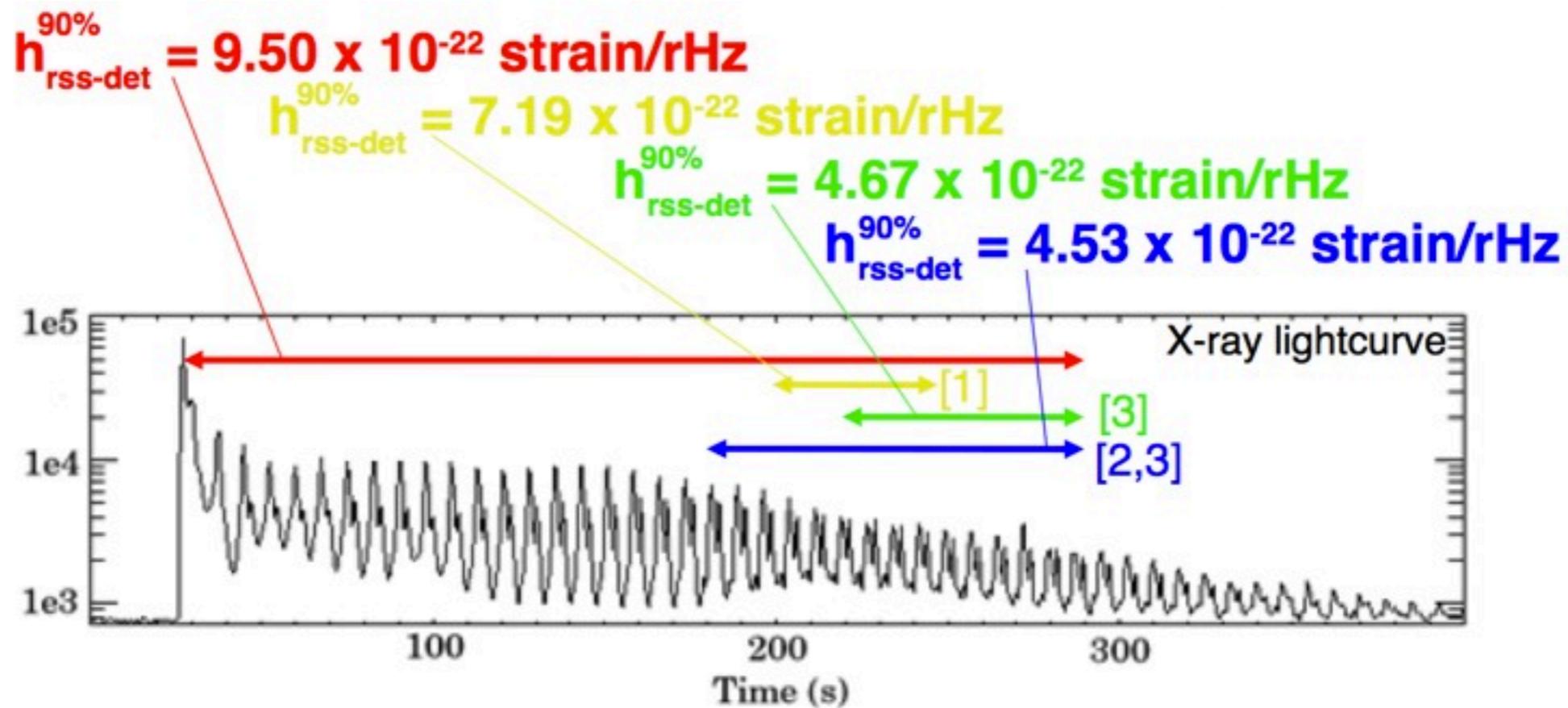


- $\gamma$ 線、 $X$ 線等の観測情報をトリガーとした重力波サーチ
  - 重力波源：GRB、SGR、パルサーグリッチ、、、
  - 重力波、電磁波望遠鏡の情報を統合して行うマルチメッセンジャー観測の一つ。
  - 電磁波イベントの時間、空間情報による探査効率の改善
  - 検出の信頼性の向上

### GRBトリガーサーチ



- Dec. 27th, 2004に起きたSGR hyperflare
- 距離：6-15kpc,  $E \sim 10^{46}$ erg, ~6分継続
- LIGO Hanford(4km)が運転していた。
- 92.5Hz QPOに関連する重力波のサーチ
- $E^{iso} = 4.3 \times 10^{-8} M_{\odot} c^2$



L. Matone G060631 - GWDAW-11 (Dec. 18<sup>th</sup> - Dec. 21<sup>st</sup>, 2006)

- [1] G. Israel et al, *ApJ* **628** L53 (2005)
- [2] A. Watts and T. Strohmayer, *ApJ* **637** L117 (2006)
- [3] T. Strohmayer and A. Watts, *ApJ* **653** L594 (2006)

15

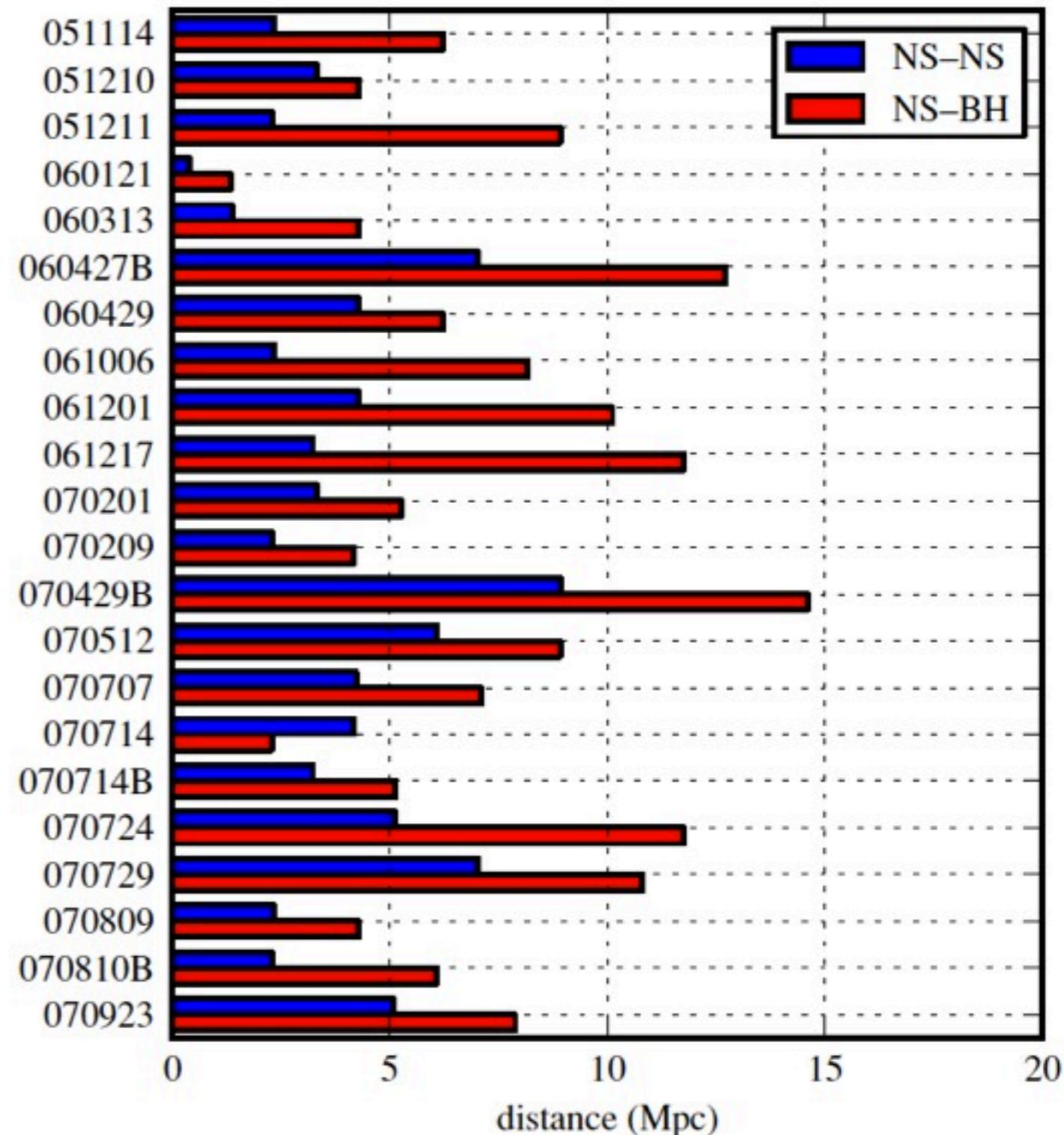
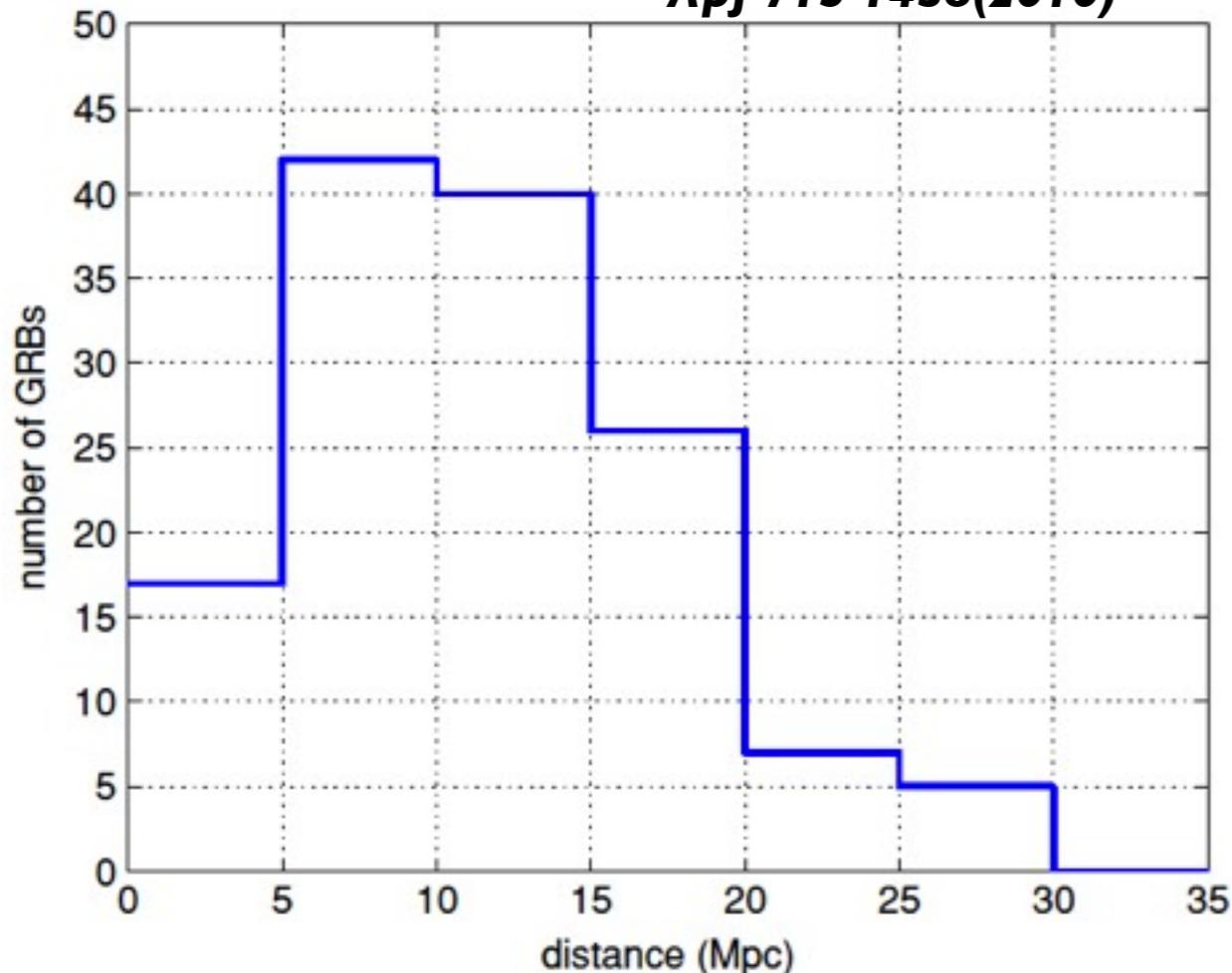
## 中性子星連星合体を仮定したGWサーチ

*ApJ 715 1435(2010)*

- S5(2005-2007)中に発見された137個のGRBを探索した
- Upper limitをつける為の信号モデル：**SineGaussian at 150Hz with  $0.01 M_{\odot} c^2 = 1.8 \times 10^{52} \text{erg}$**
- Upper limitを距離に換算

## バーストGWサーチ

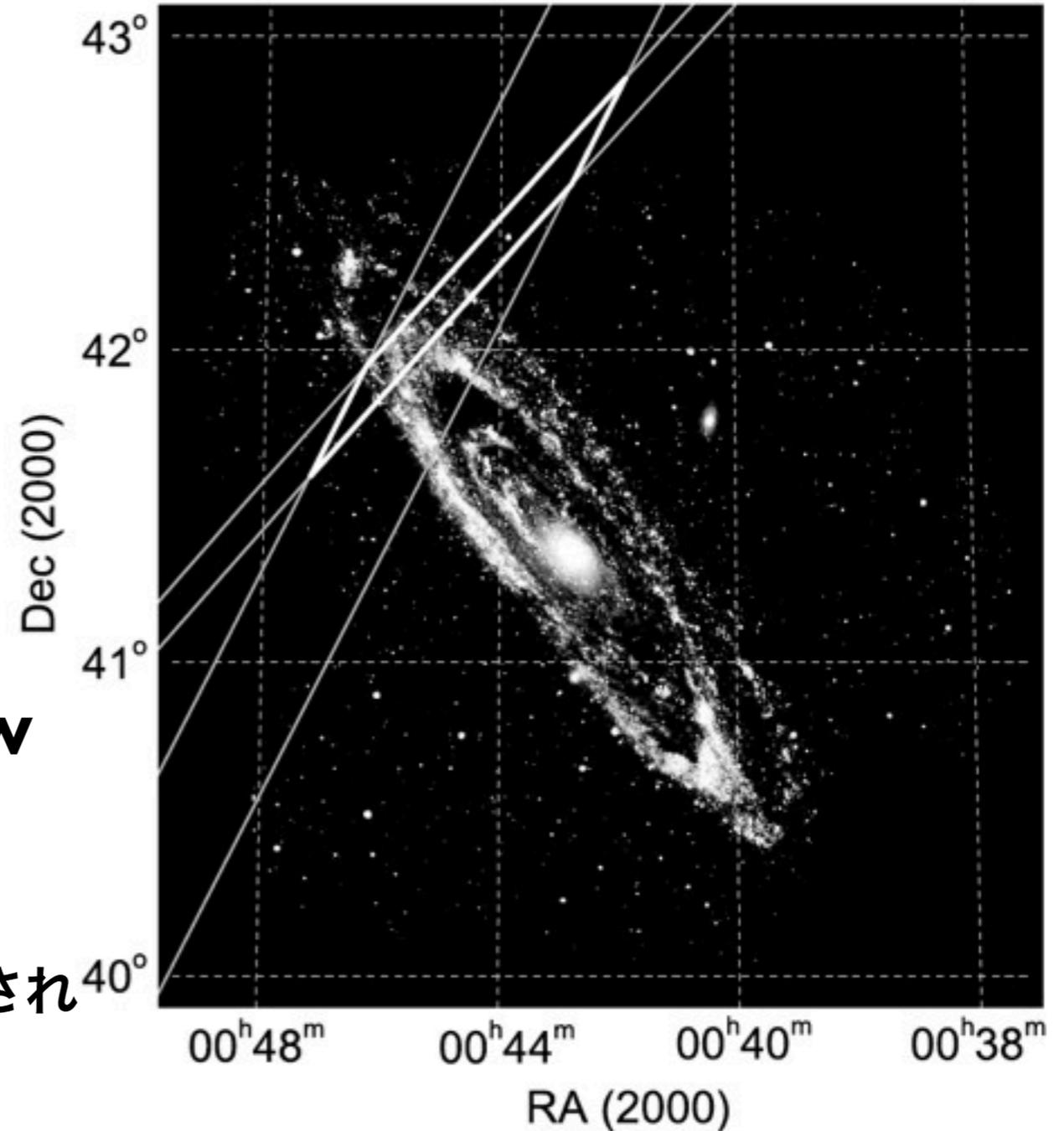
*ApJ 715 1438(2010)*



- **Konus-Wind, INTEGRAL, MESSENGER, Swift**によって検出
- **M31に所属?、~770kpc**
- **LIGO Hanford**が運転していた。
- **Inter-Planetary Network 3-sigma error region (Mazets et al. ApJ680,545)**

## 解釈

- バーストサーチで重力波は発見されず。  
波形を**Sine Gaussian**と仮定した時の**GW energy**のリミットは  
 $5 \times 10^{-4} M_{\odot} c^2$
- **Inspiral**サーチも行ったが重力波は発見されず。
- 最も可能性が高い解釈：  
**M31内で起きたSGR giant flare**



*Abbott et al., ApJ 681, 1419 (2008), Mazets et al., ApJ 680, 545 ; Ofek et al., ApJ 681, 1464*

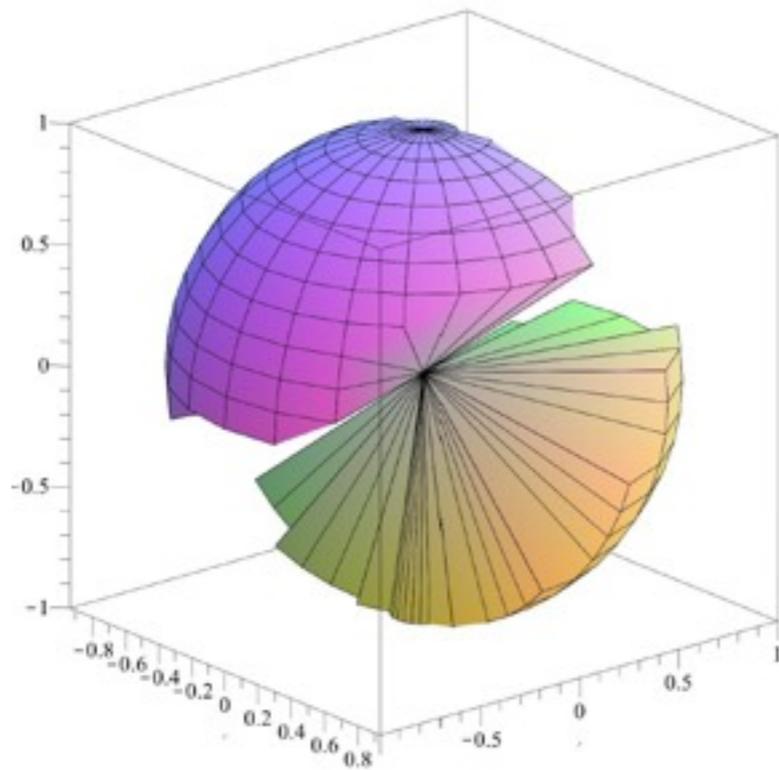
- パルサーグリッチに付随した重力波
- ニュートリノに付随した重力波
- X線バーストに付随した重力波
- .....

# LCGT世代の重力波望遠鏡ネットワーク

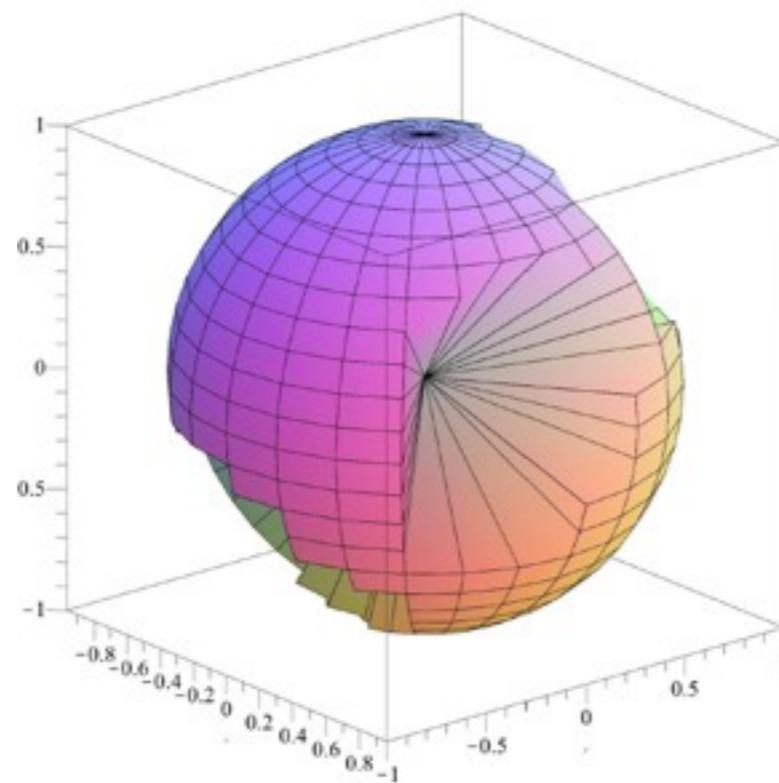


● 望遠鏡ネットワークのアンテナパターン。 ( $>1/\sqrt{2}$ のエリア)

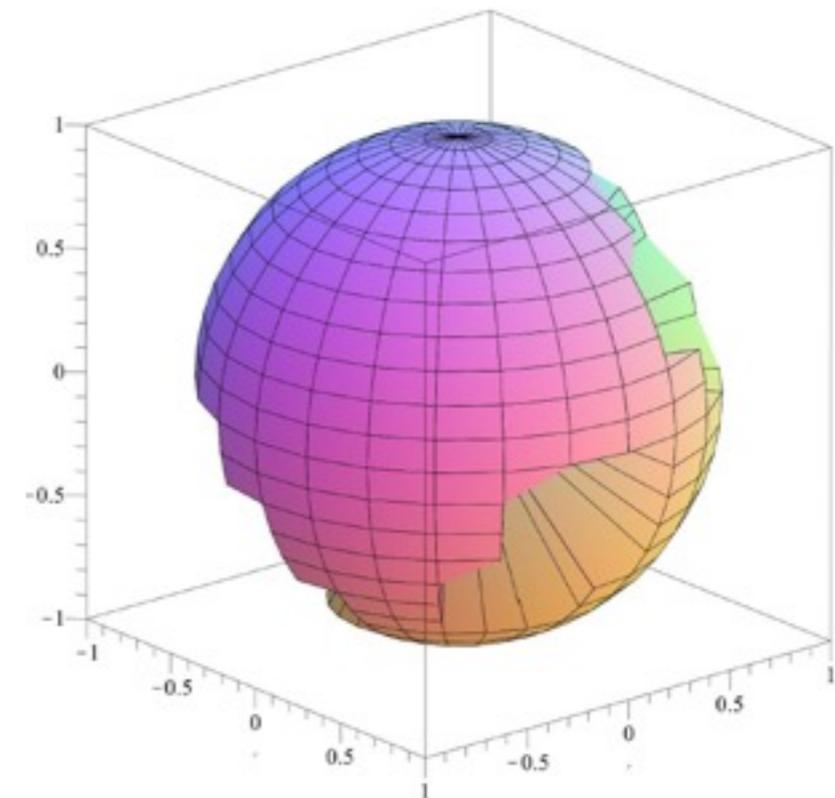
**HLV**



**HLVJ**



**HLVJA**



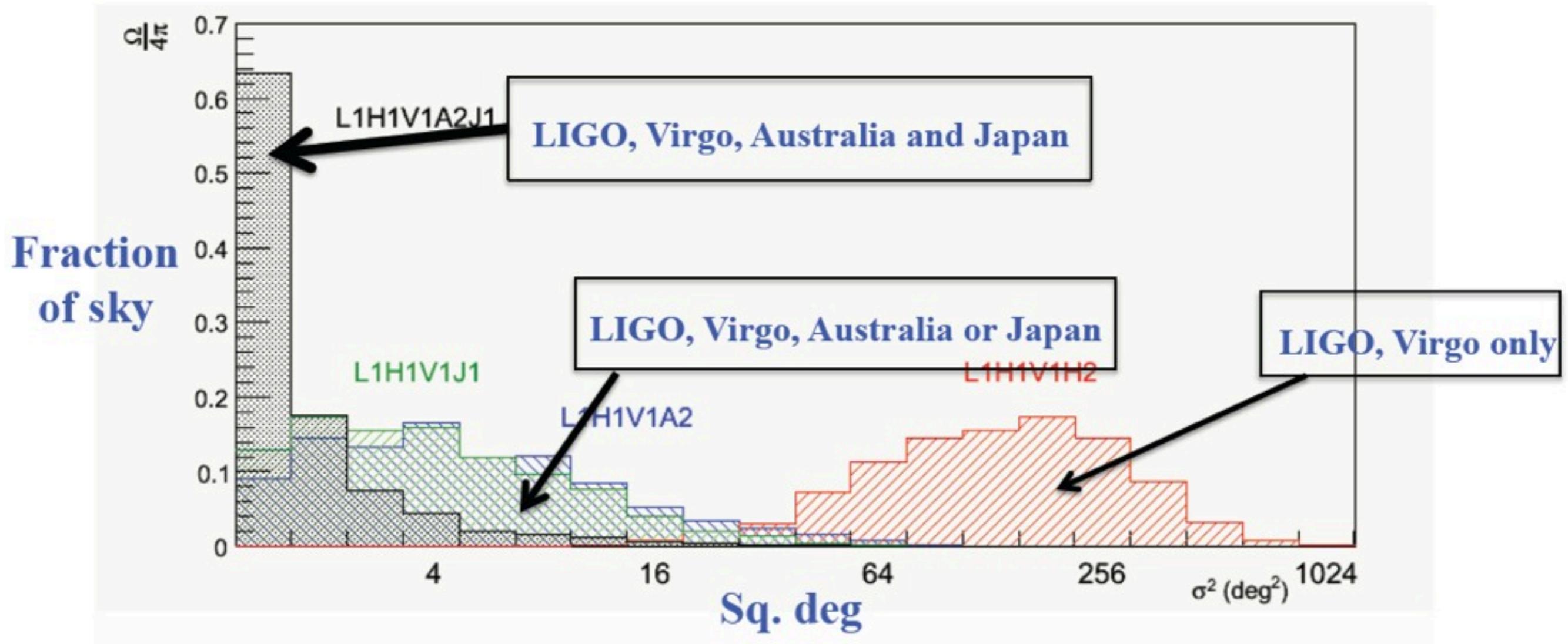
**B.Schutz(2011)**



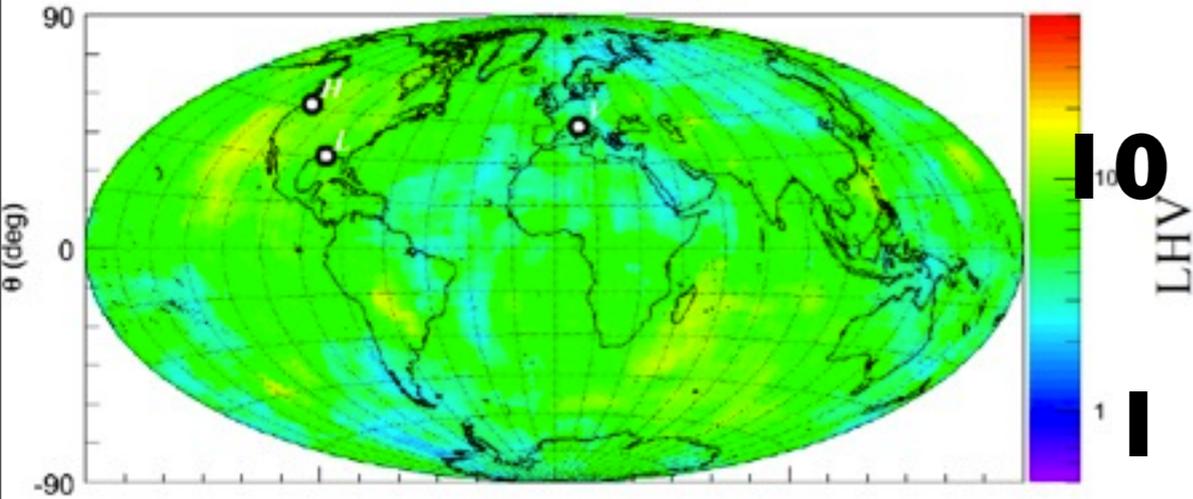
Network	Mean Horizon Dis- tance	Detection Volume	Volume Filling Factor	Triple Detec- tion Rate (at 80%)	Triple Detec- tion Rate (at 95%)	Sky Cover- age	Directional Preci- sion
L	1.00	1.23	29%	-	-	33.6%	-
HLV	1.43	5.76	47%	2.95	4.94	71.8%	0.68
HHLV	1.74	8.98	41%	4.86	7.81	47.3%	0.66
AHLV	1.69	8.93	44%	6.06	8.28	53.5%	3.01
HHJLV	1.82	12.1	48%	8.37	11.25	73.5%	2.57
HHILV	1.81	12.3	50%	8.49	11.42	71.8%	2.18
AHJLV	1.76	12.1	53%	8.71	11.25	85.0%	4.24
HHIJLV	1.85	15.8	60%	11.43	14.72	91.4%	3.24
AHIJLV	1.85	15.8	60%	11.50	14.69	94.5%	4.88

**B.Schutz(2011)**

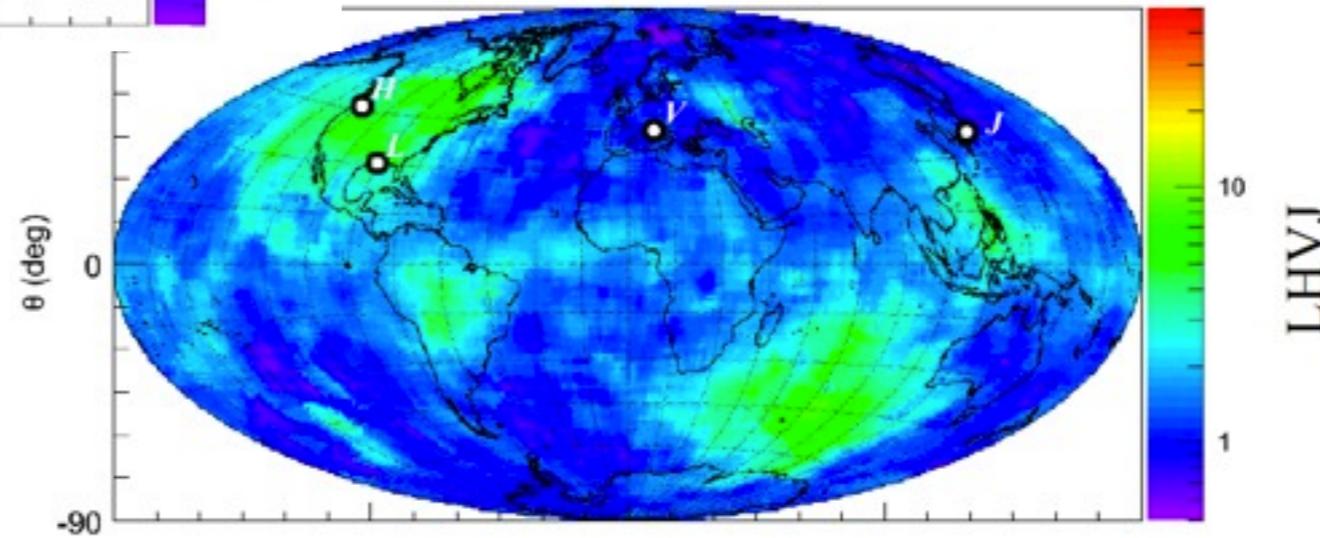
## 中性子星連星合体からの重力波の場合



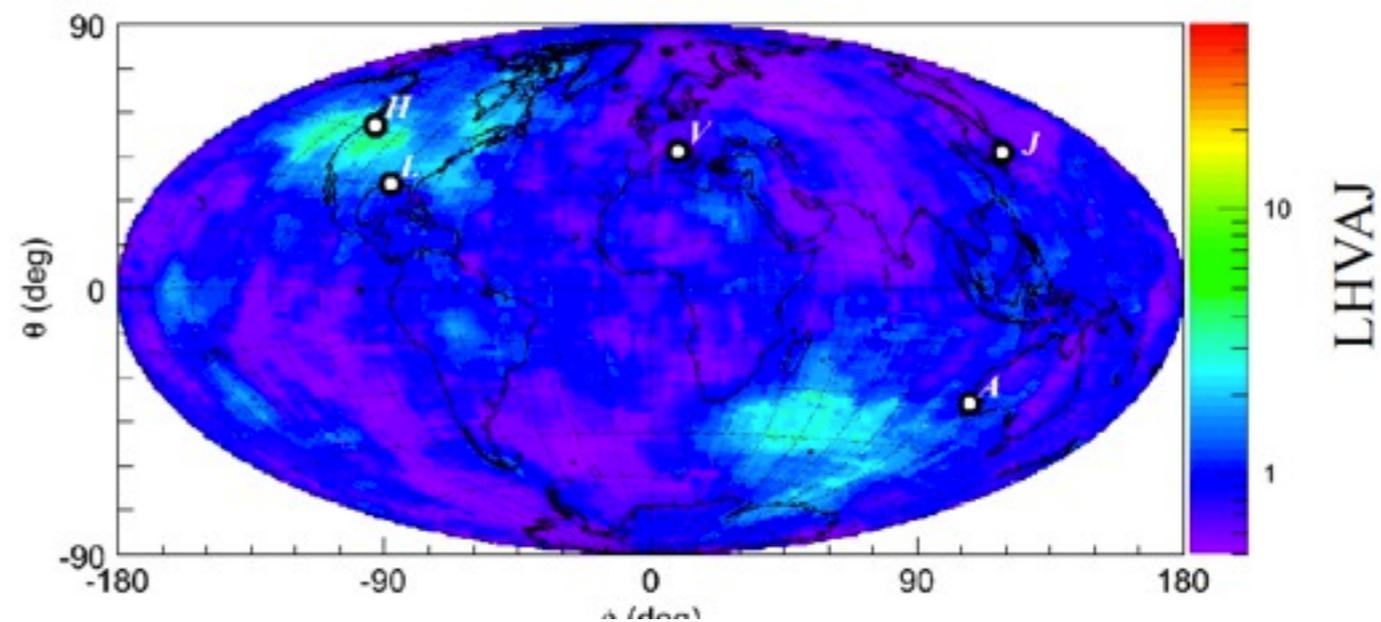
S. Witcomb (2011)



- LHVでは $>10^\circ$ だが、LHVJではほとんどの領域で $\sim 1^\circ$
- マルチメッセンジャー観測に重要！



Un-modeled	LHV	LHVA	LHVJ	LHVAJ
WNB LF	4.8° / 0.7°	1.1° / 0.4°	1.8° / 0.4°	0.8° / 0.4°
WNB HF	4.5° / 0.4°	0.6° / 0.4°	0.8° / 0.4°	0.4° / 0.4°
SGQ9 LF	6.4° / 0.7°	1.4° / 0.4°	1.6° / 0.4°	1.0° / 0.4°
SHQ9 HF	4.1° / 0.9°	1.0° / 0.4°	1.0° / 0.4°	0.5° / 0.4°
SGQ3 LF	9.4° / 0.5°	1.1° / 0.5°	1.5° / 0.4°	0.9° / 0.4°
SGQ3 HF	6.3° / 0.4°	0.9° / 0.4°	1.0° / 0.4°	0.5° / 0.4°
SGCQ9 LF	9.3° / 0.8°	1.7° / 0.4°	2.0° / 0.4°	0.9° / 0.4°
SGCQ9 HF	5.5° / 1.1°	1.4° / 0.4°	1.7° / 0.4°	0.9° / 0.4°



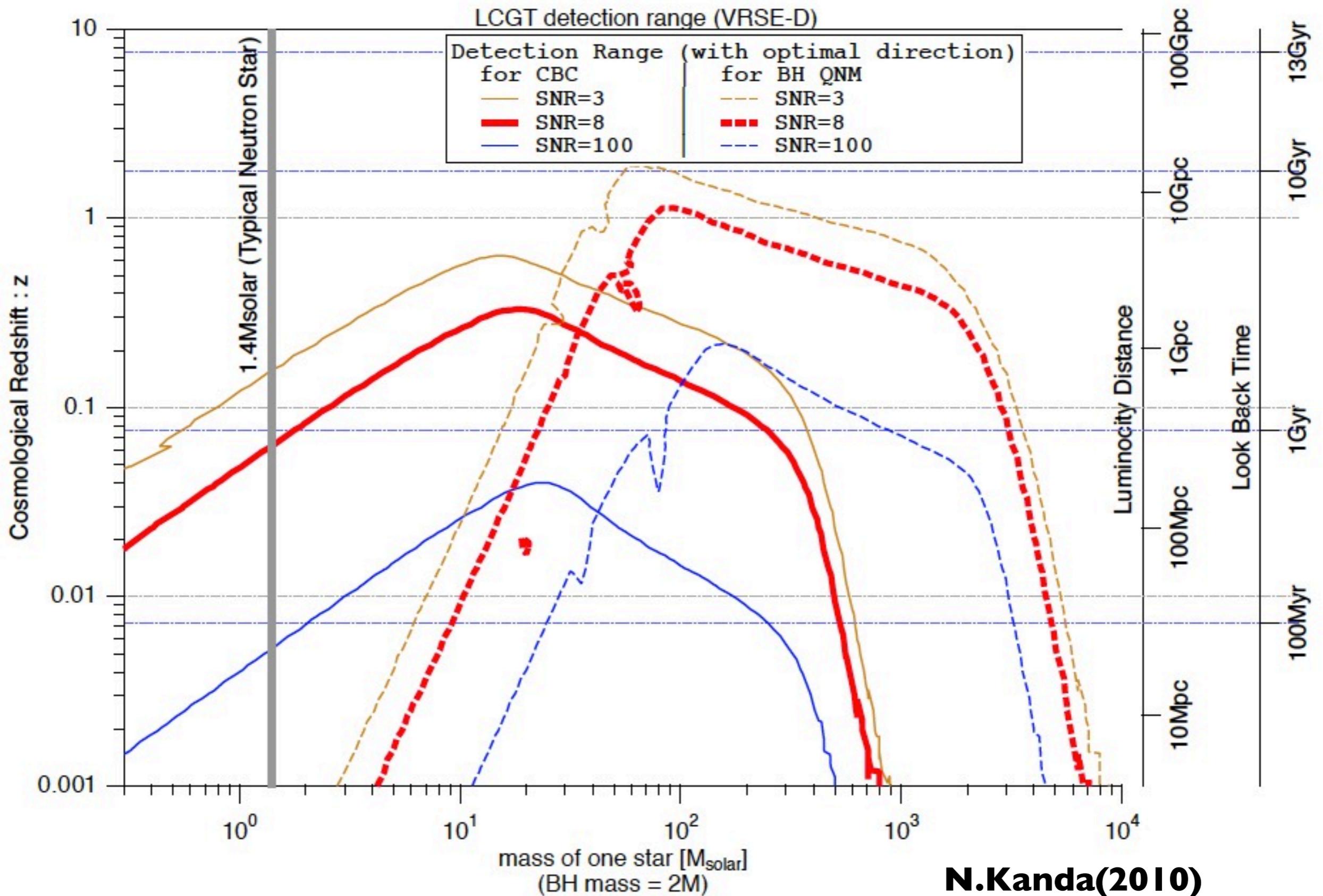
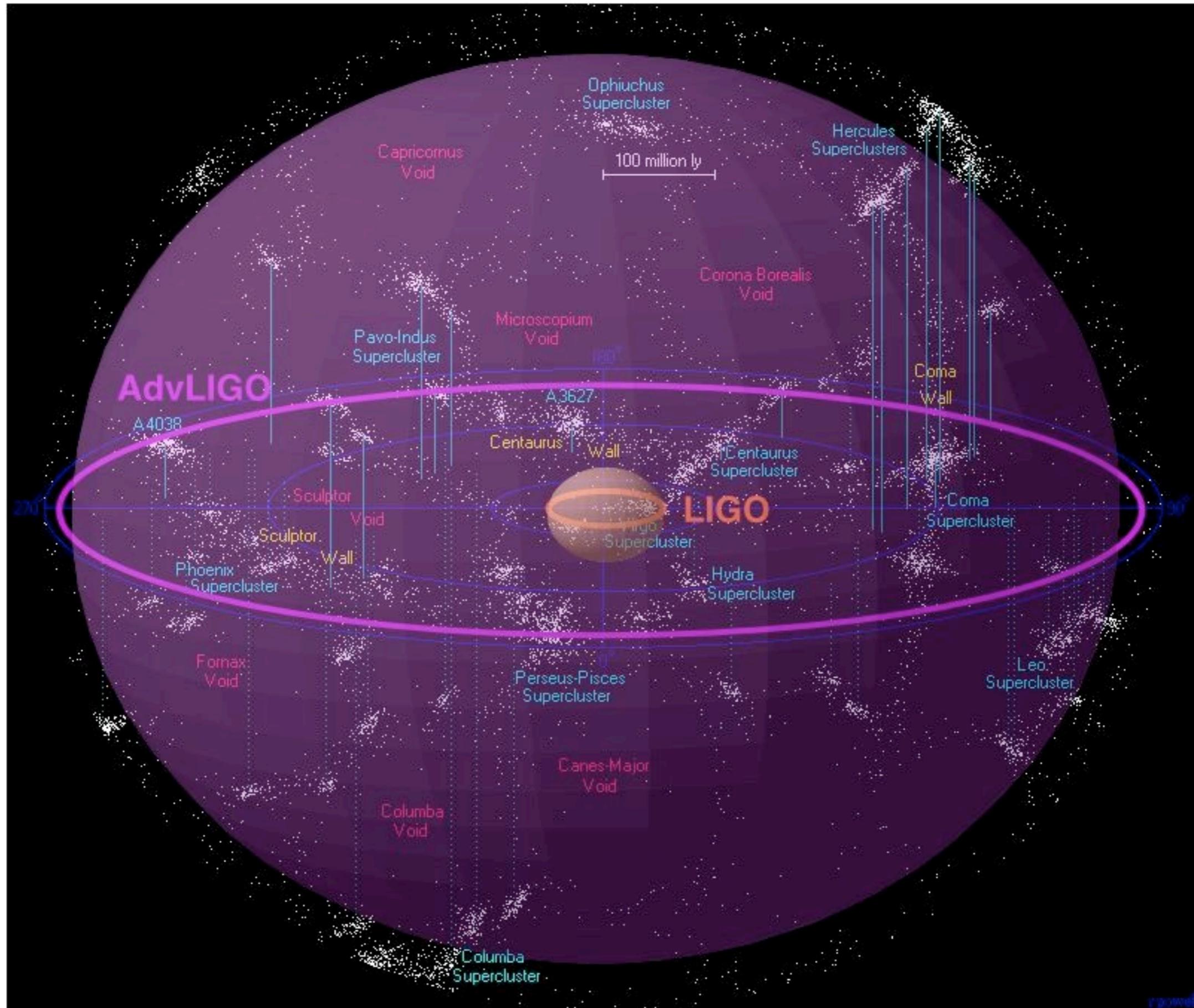
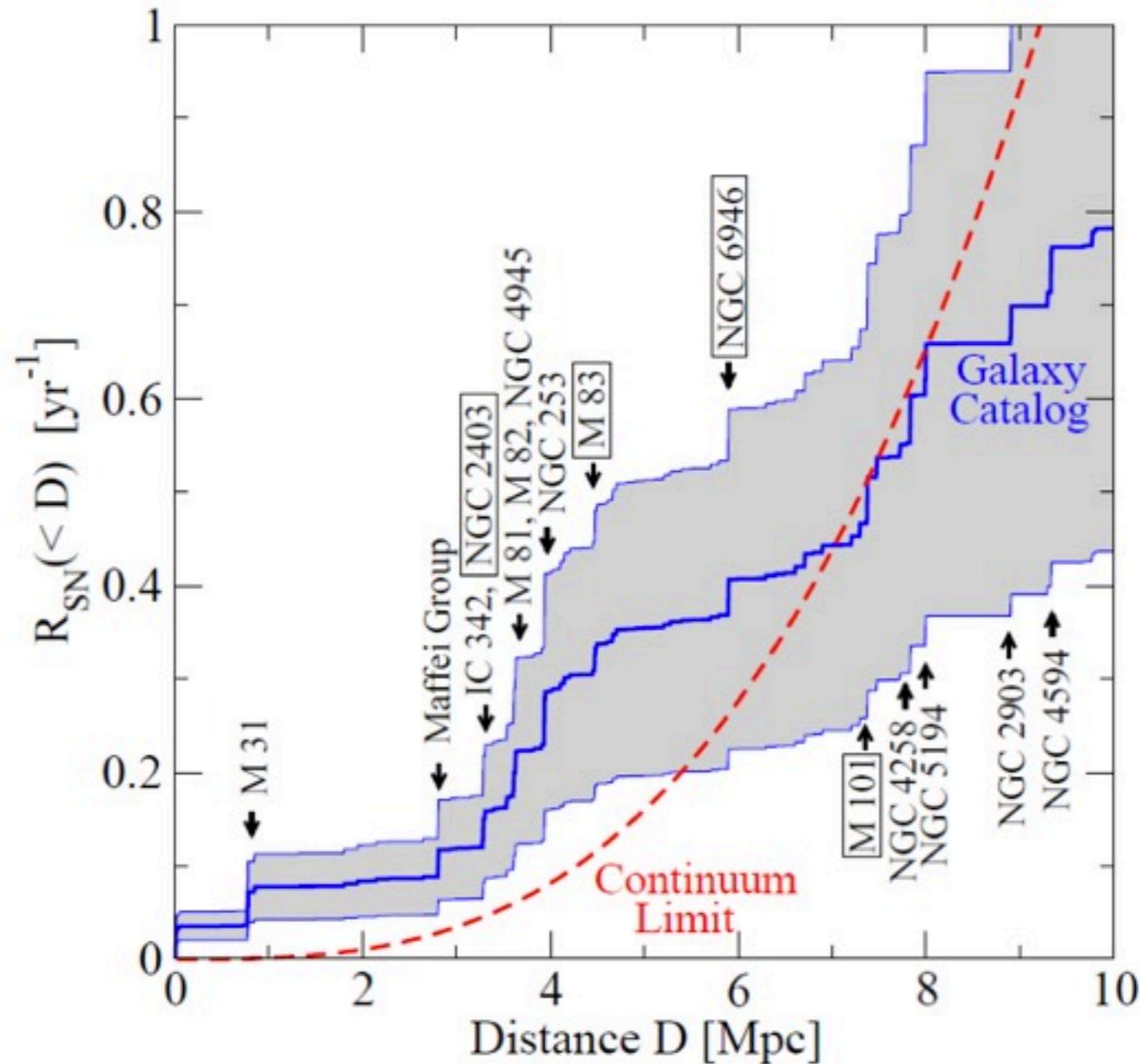


TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source <sup>a</sup>	$\dot{N}_{\text{low}}$ yr <sup>-1</sup>	$\dot{N}_{\text{re}}$ yr <sup>-1</sup>	$\dot{N}_{\text{high}}$ yr <sup>-1</sup>	$\dot{N}_{\text{max}}$ yr <sup>-1</sup>
Initial	NS-NS	$2 \times 10^{-4}$	0.02	0.2	0.6
	NS-BH	$7 \times 10^{-5}$	0.004	0.1	
	BH-BH	$2 \times 10^{-4}$	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	$0.01^c$
	IMBH-IMBH			$10^{-4d}$	$10^{-3e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			$10^b$	$300^c$
	IMBH-IMBH			$0.1^d$	$1^e$



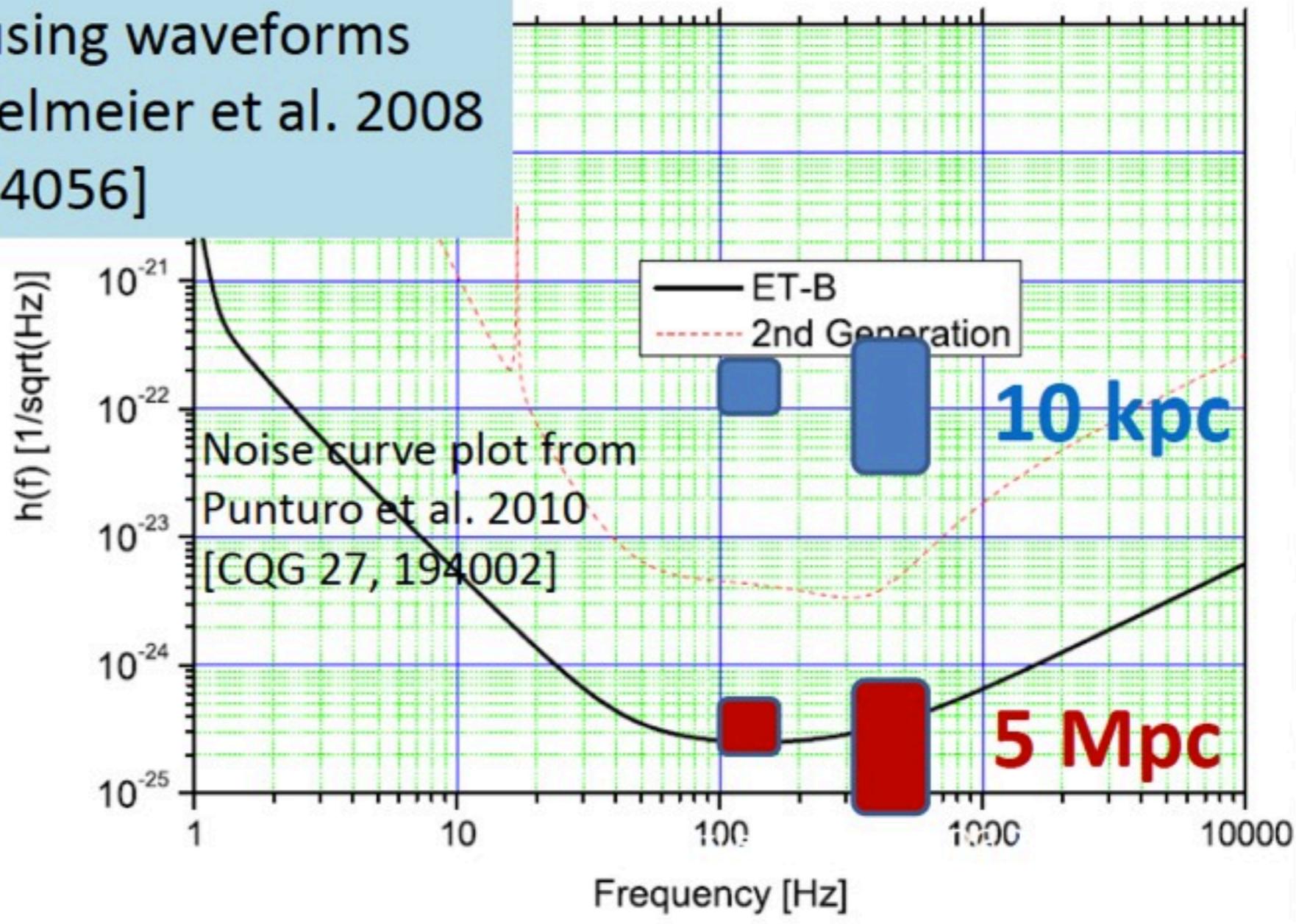
- Galactic rate  $\sim 1$  per 30–50 years
- Expect one core-collapse SN within 5 Mpc every 2–5 years



S. Ando et al. 2005 [PRL 95, 171101]

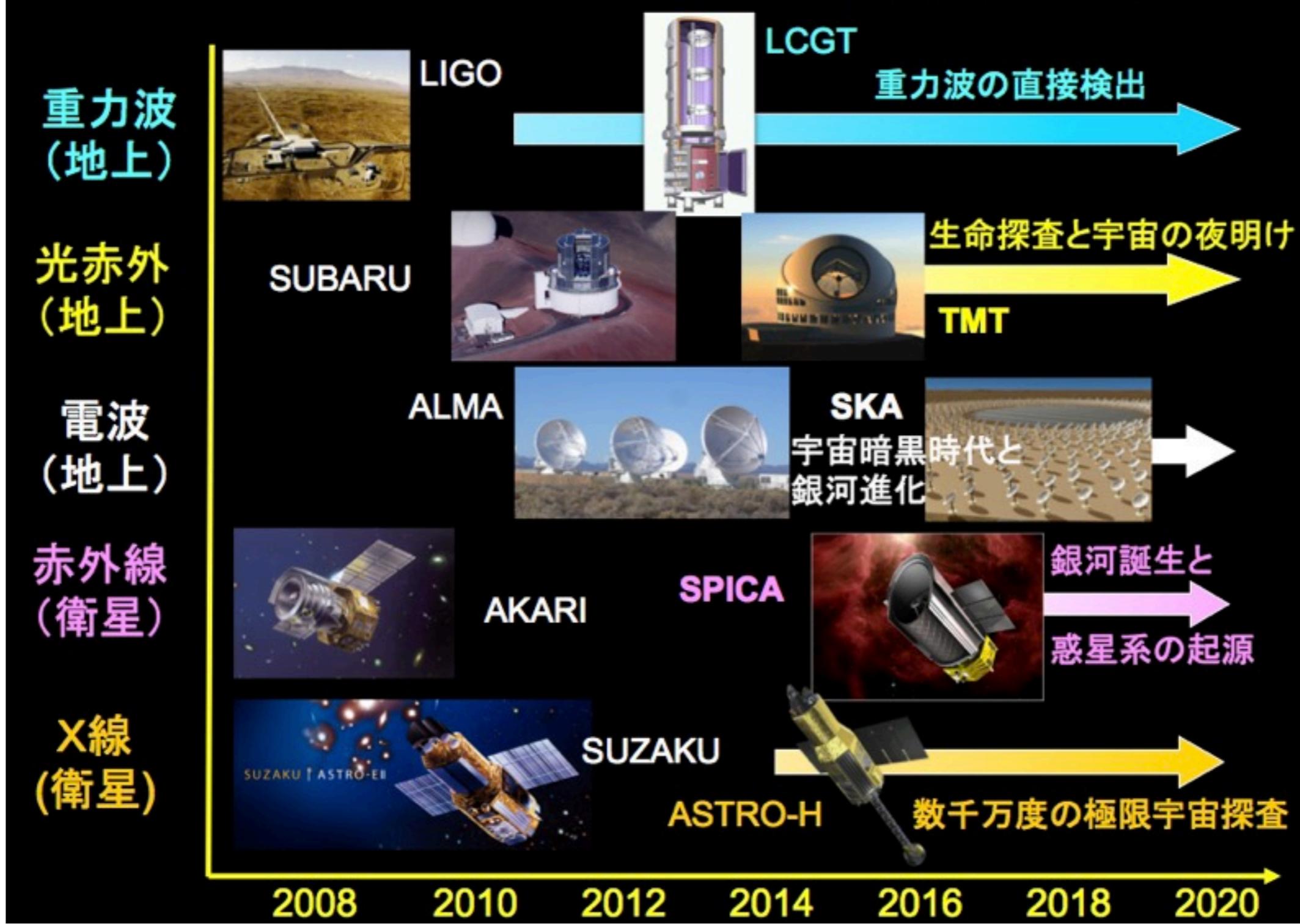


Estimated using waveforms  
from Dimmelmeier et al. 2008  
[PRD 78, 064056]

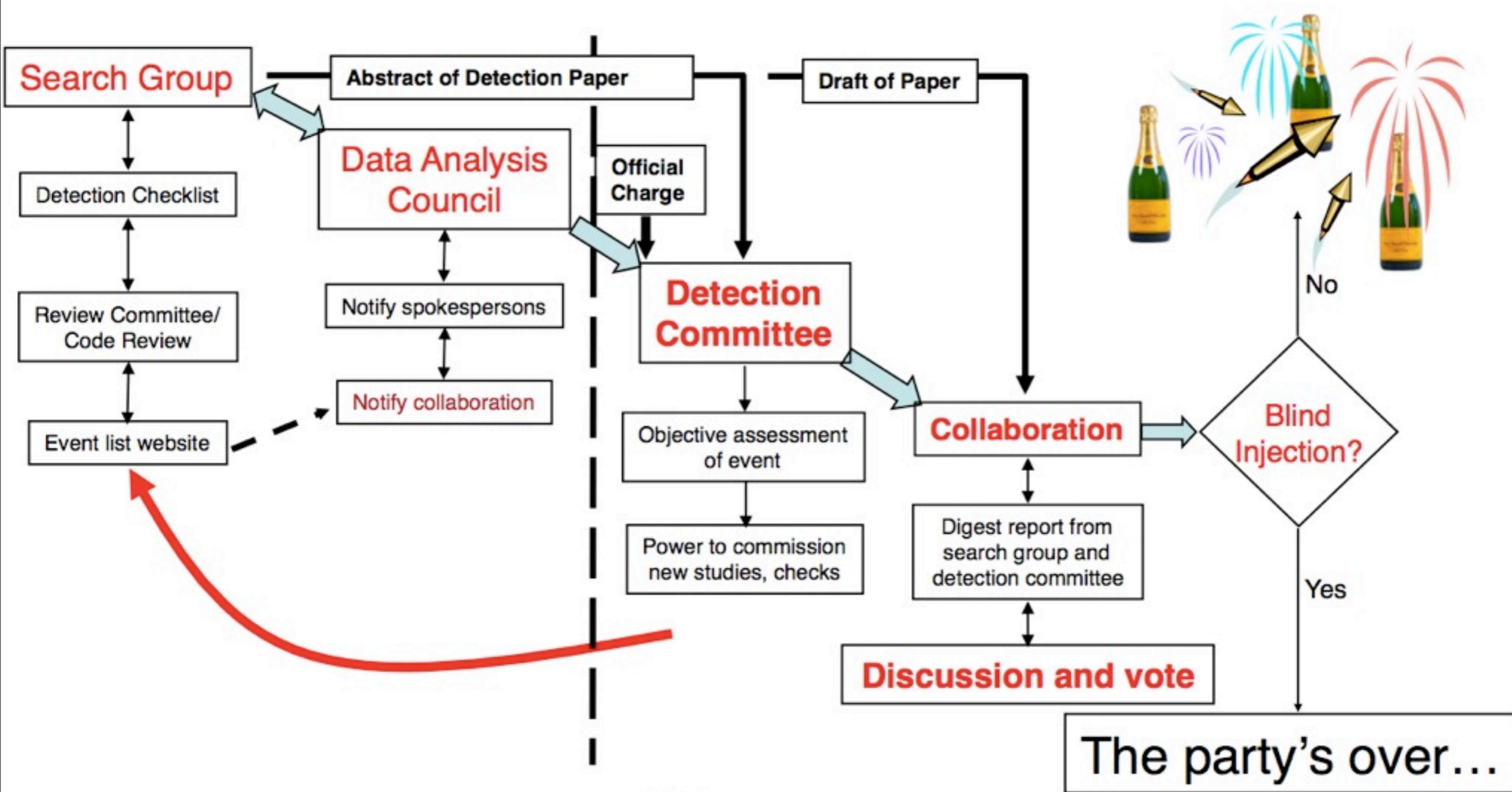


P.Shawhan(GWPAW,2011)

2010年代の日本の天体宇宙物理大型計画



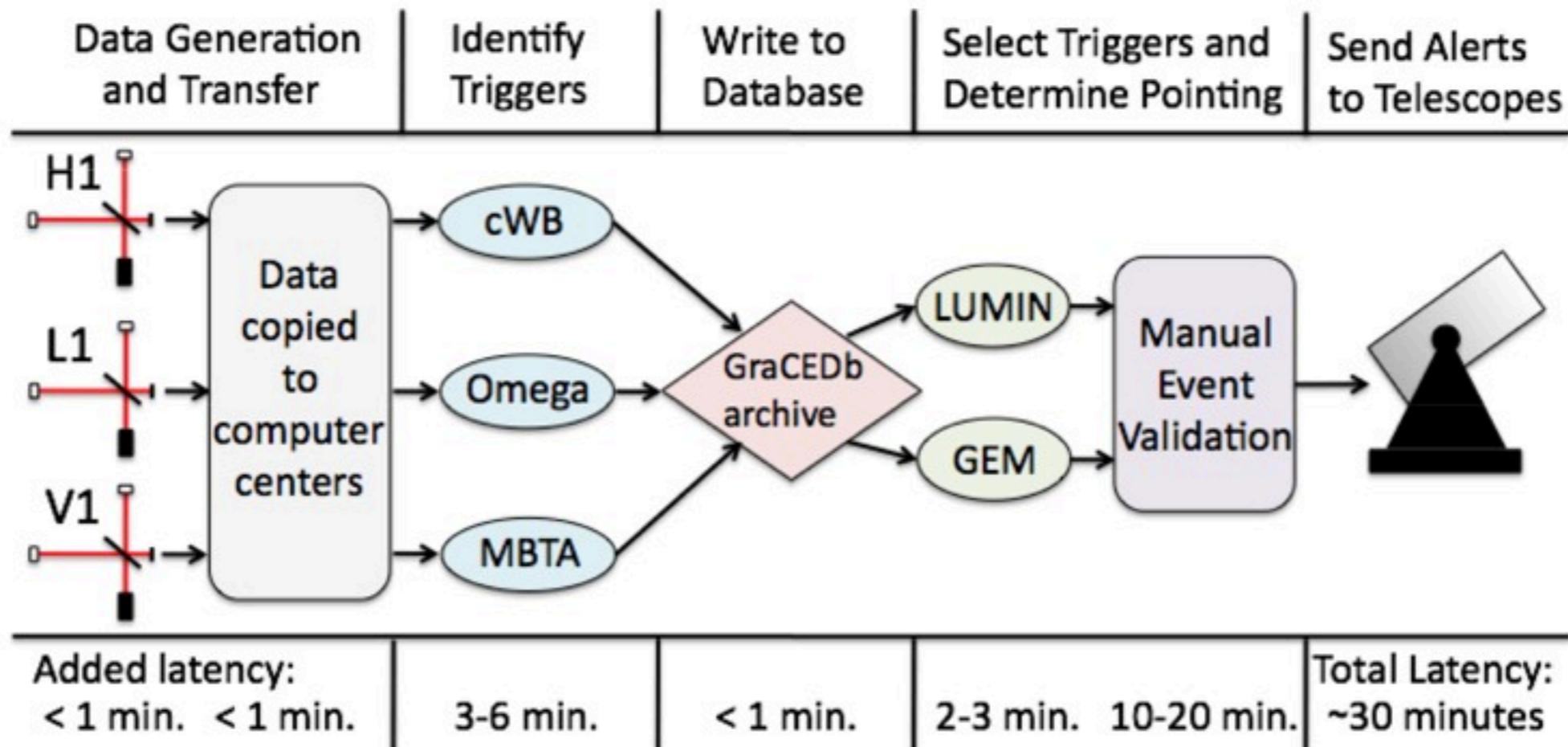
# Big Dogと言われた信号



R. Weiss (MIT)

- S6ではフォローアップ観測のテストが重要視されていたので
  - Low-latency on-line data analysis
  - Off-line data analysis
 が行われた。

## Flowchart of Low-latency on-line data analysis

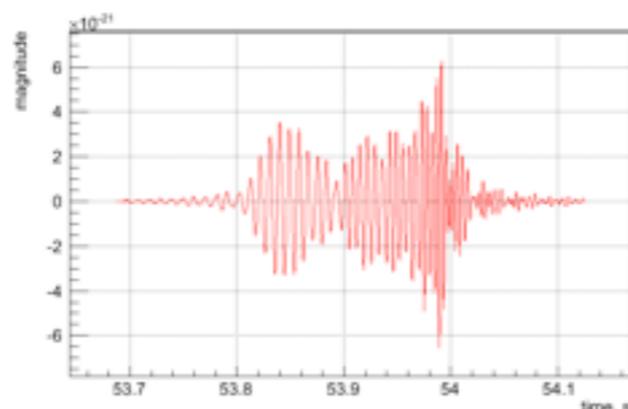
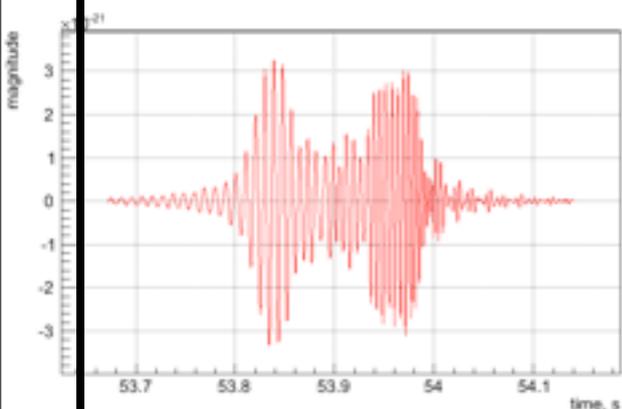
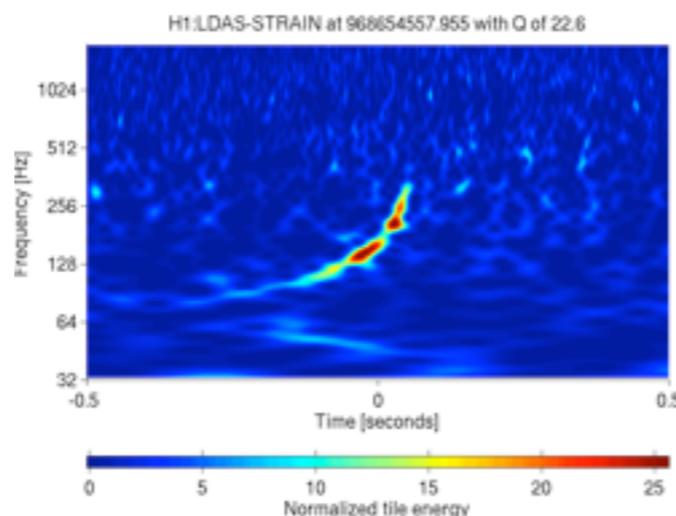
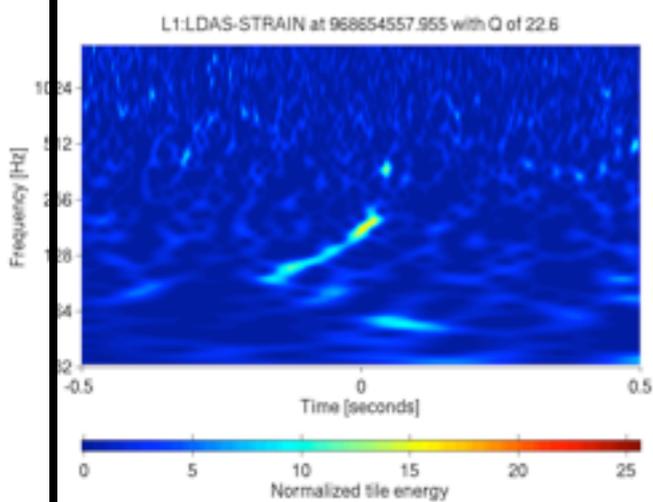


## Burst pipeline (cWB)

## Human Check

**L1**

**H1**



**'gold plated inspiral at first glance' (Igor)**

### Undefined flags

- Are there any undefined CAT 1 or CAT 2 flags? : No
- If Yes, please include the names of the flags here:
- GO/NOGO: **GO**
- Checked by: Christian Ott
- Comments:

### Sanity Checks Script

See sanity check script output - '+' means GO / '!' or '-' means NOGO

- Within detector locks: GO
- DQ Flags: GO
- KleineWelle trigger rate: GO
- GO/NOGO: **GO**
- Checked by: Christian Ott, Peter Shawhan, LLO [SciMon](#)
- Comments: Confusion about error messages concerning Virgo (script says 'ignore')

### Control Room Sign-off - Include any notes on Omega grams or FOM here

- H1:
  - Scimon Name: Kiwamu Izumi
  - GO
- L1:
  - Scimon Name: Rahul Kumar
  - GO
- V1:
  - Scimon Name: K.Borkowski
  - GO
- GO/NOGO: **GO**
- Comments:

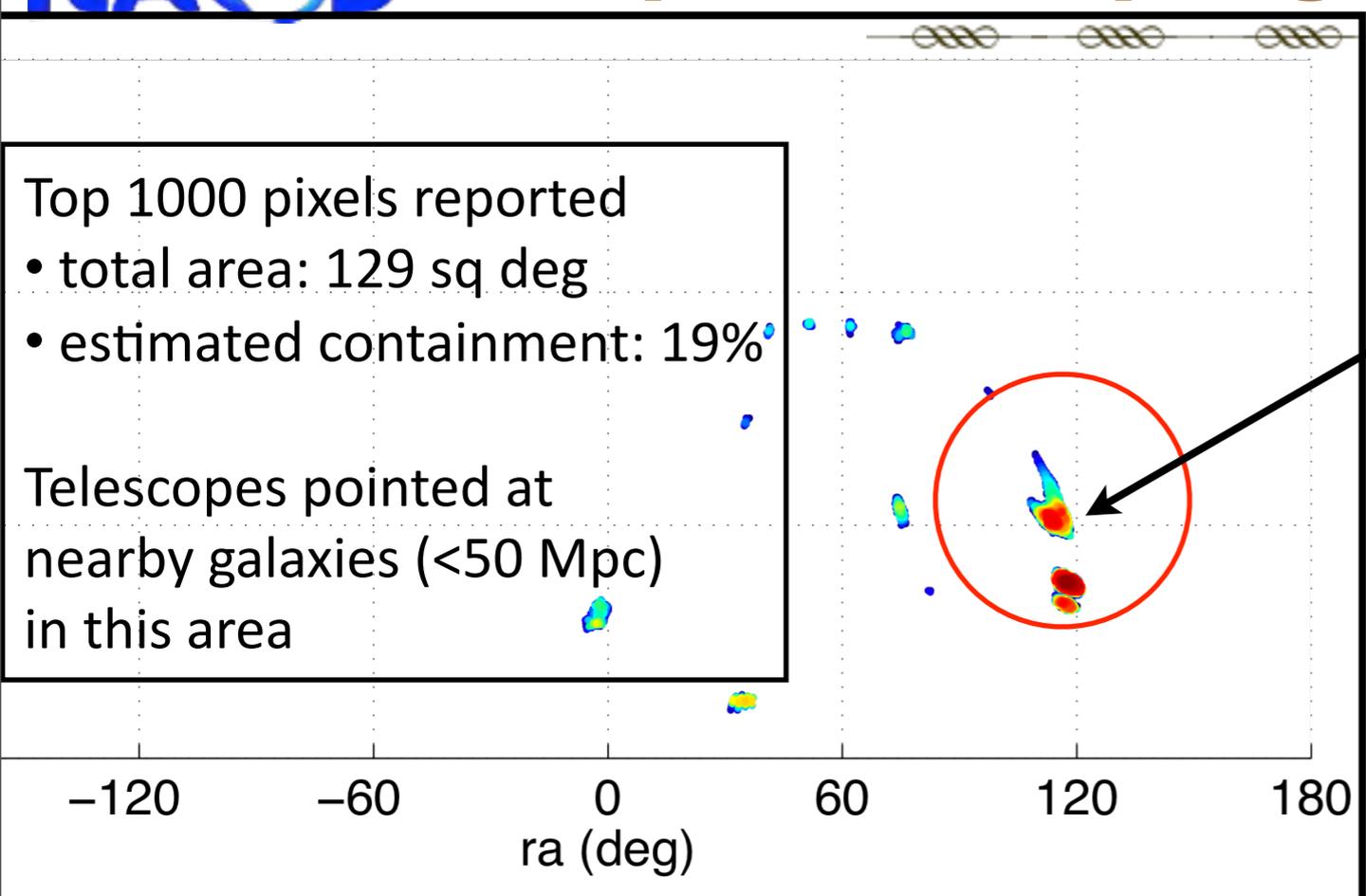
**$t_{\text{dog}}+8[\text{m}]$**

**$t_{\text{dog}}+42[\text{m}]$**

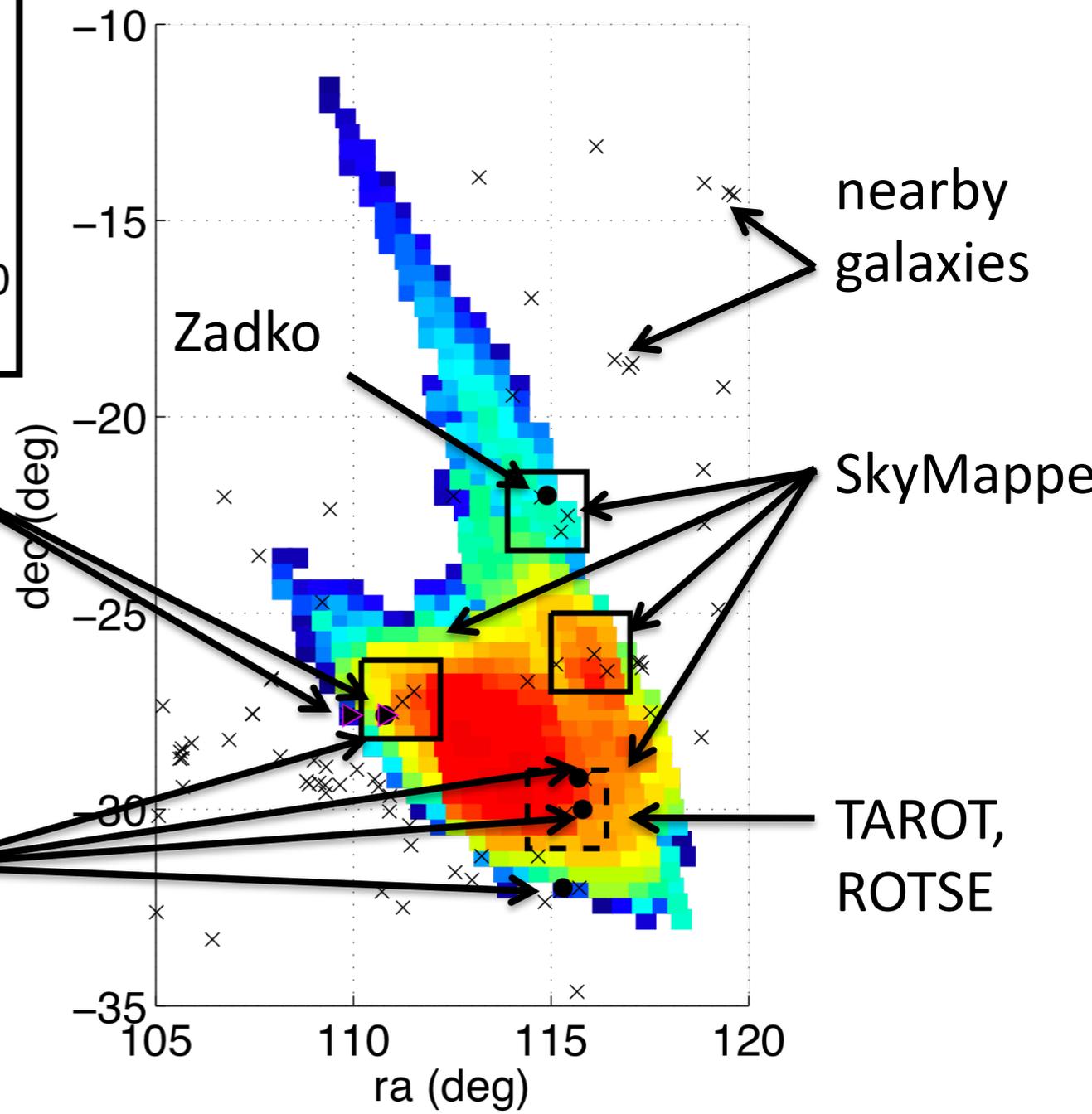
Top 1000 pixels reported

- total area: 129 sq deg
- estimated containment: 19%

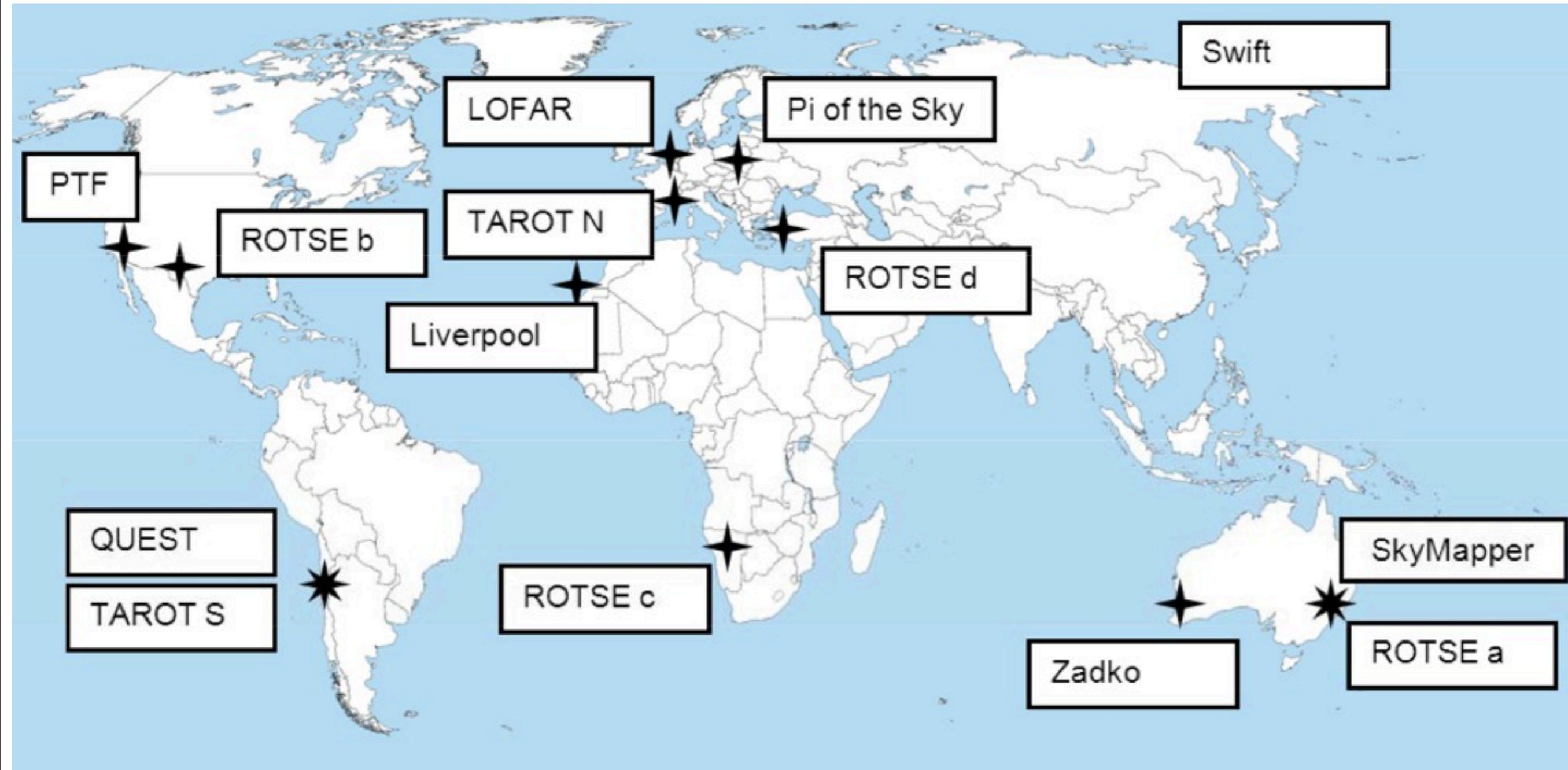
Telescopes pointed at nearby galaxies (<50 Mpc) in this area



**LUMIN pipeline**  
銀河カタログを参照して  
こちらの島が選ばれた

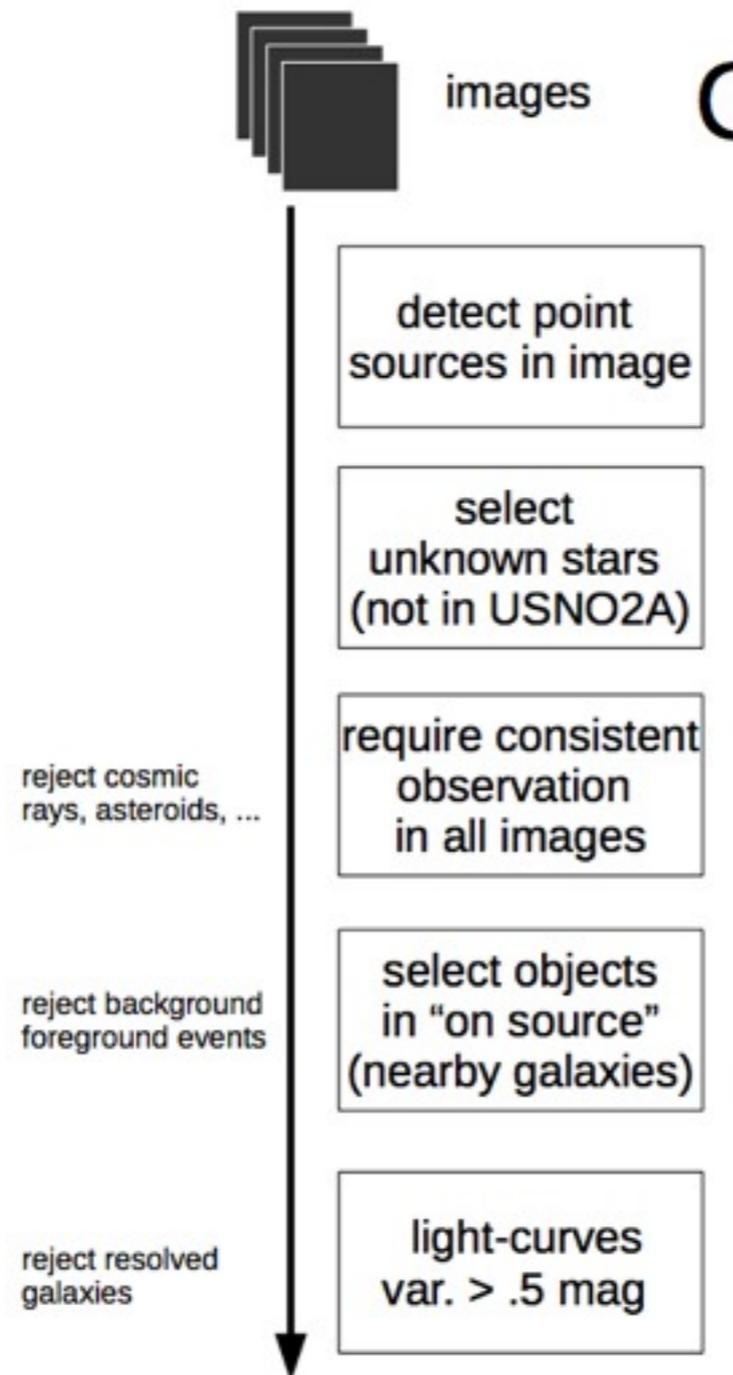


- Usable images:**
- TAROT: 20, + [44 min - 4 day]
  - ROTSE: 102, + [0.5 - 29] day
  - Zadko: 63, + [1, 160] day
  - SkyMapper: 21, + 8 day
  - *Swift*: 4, + [0.5, 105] day



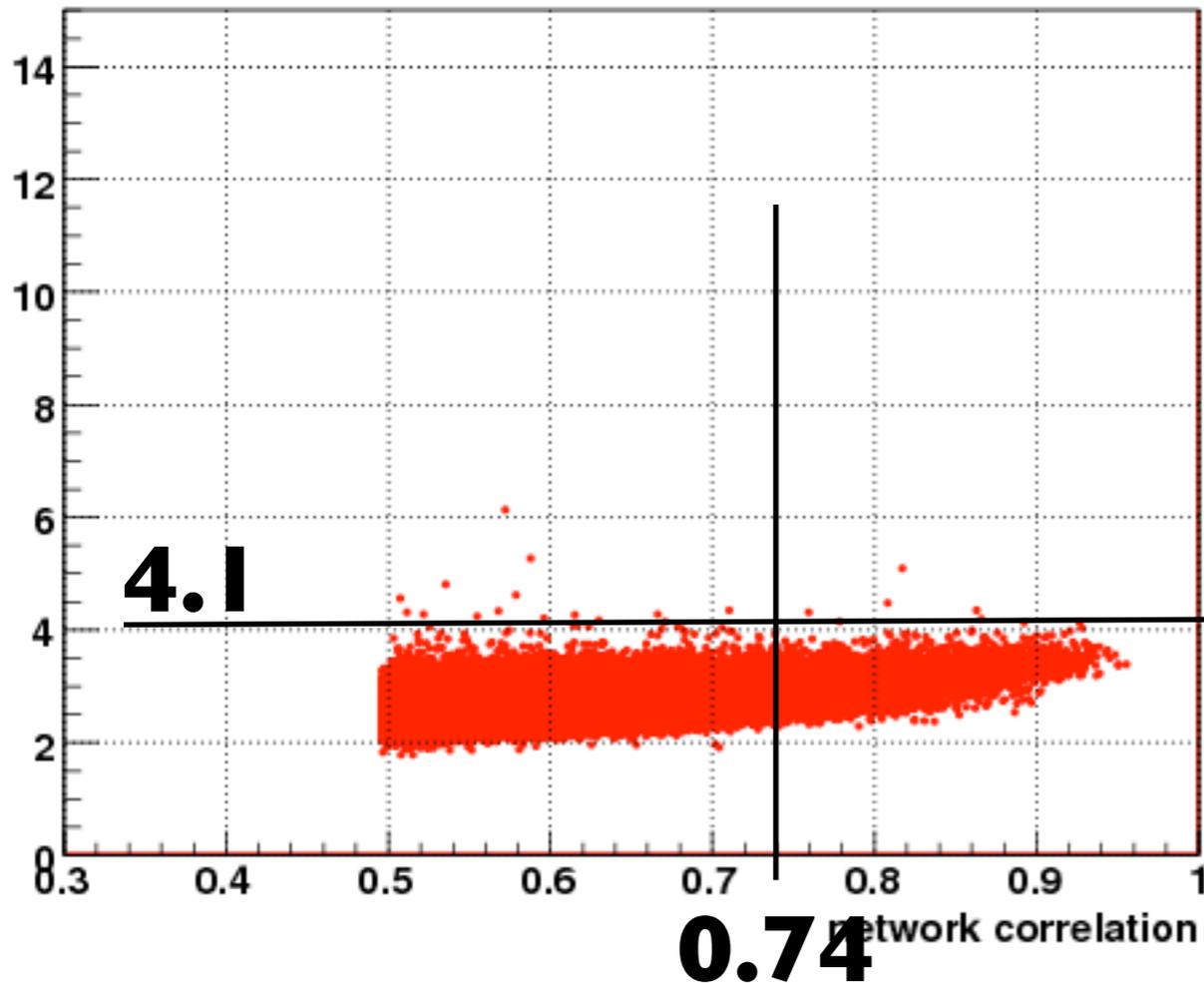


- **After image analysis, all EM telescopes did not find any transient events in their images.**

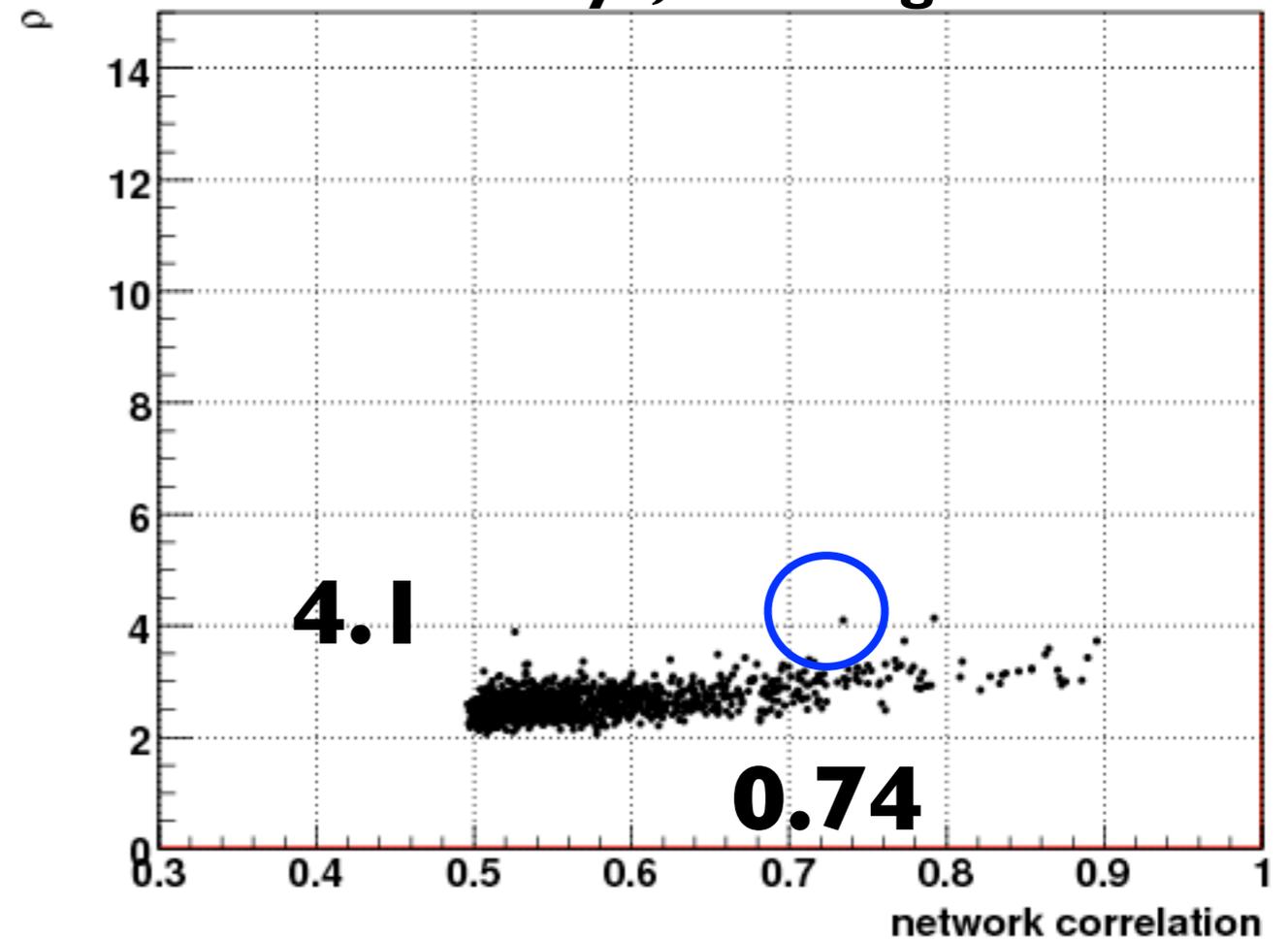


- **LI-HI-VI network**
- **SNR of LI:9.2, HI:13.8, VI:4.9**
- **network correlation: 7.4, rho: 4.1**
- **IFAR:3.27years ( < 8 years, our threshold)**
- **No detection from burst search**

**13.1 years, 200 non-zero lags**

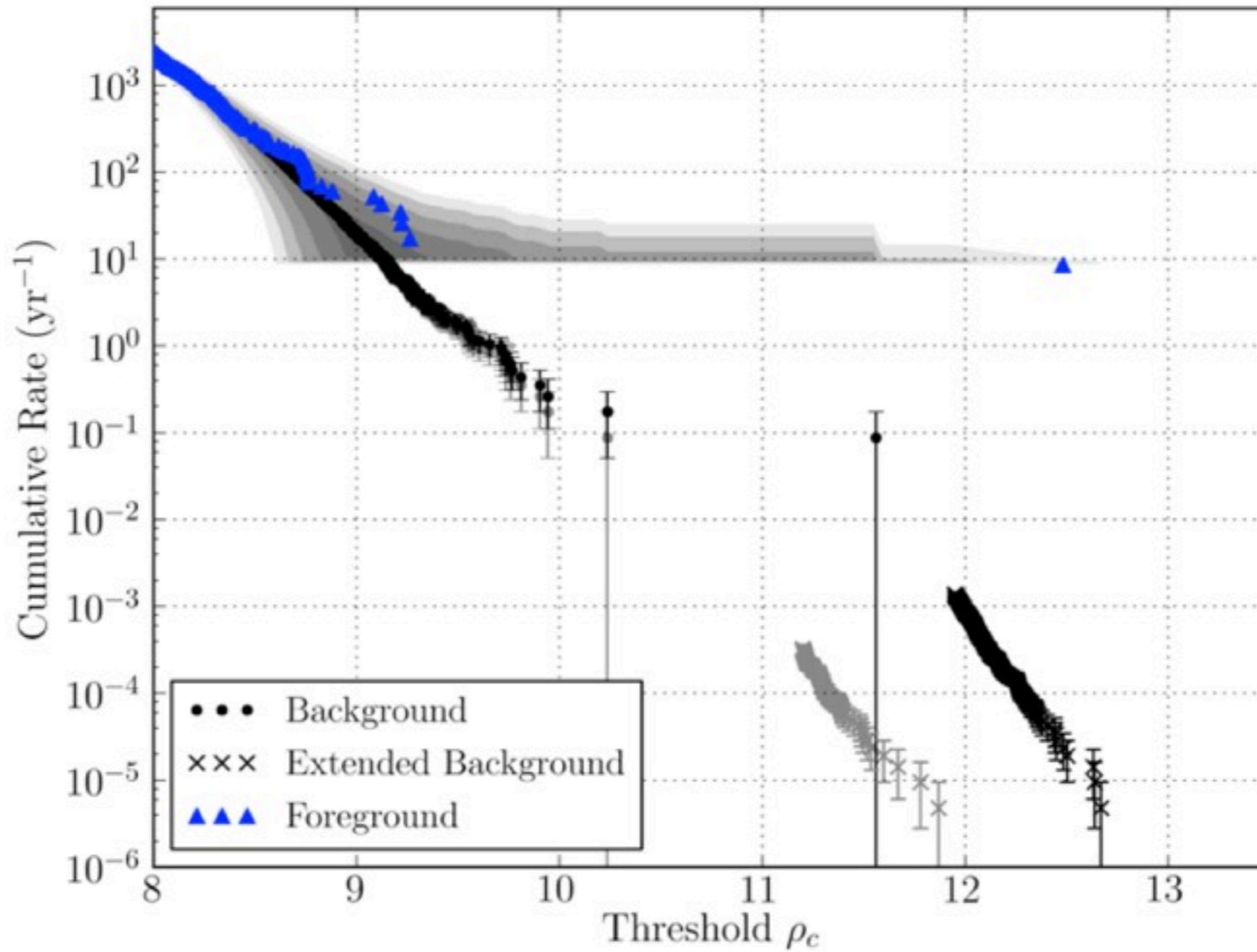


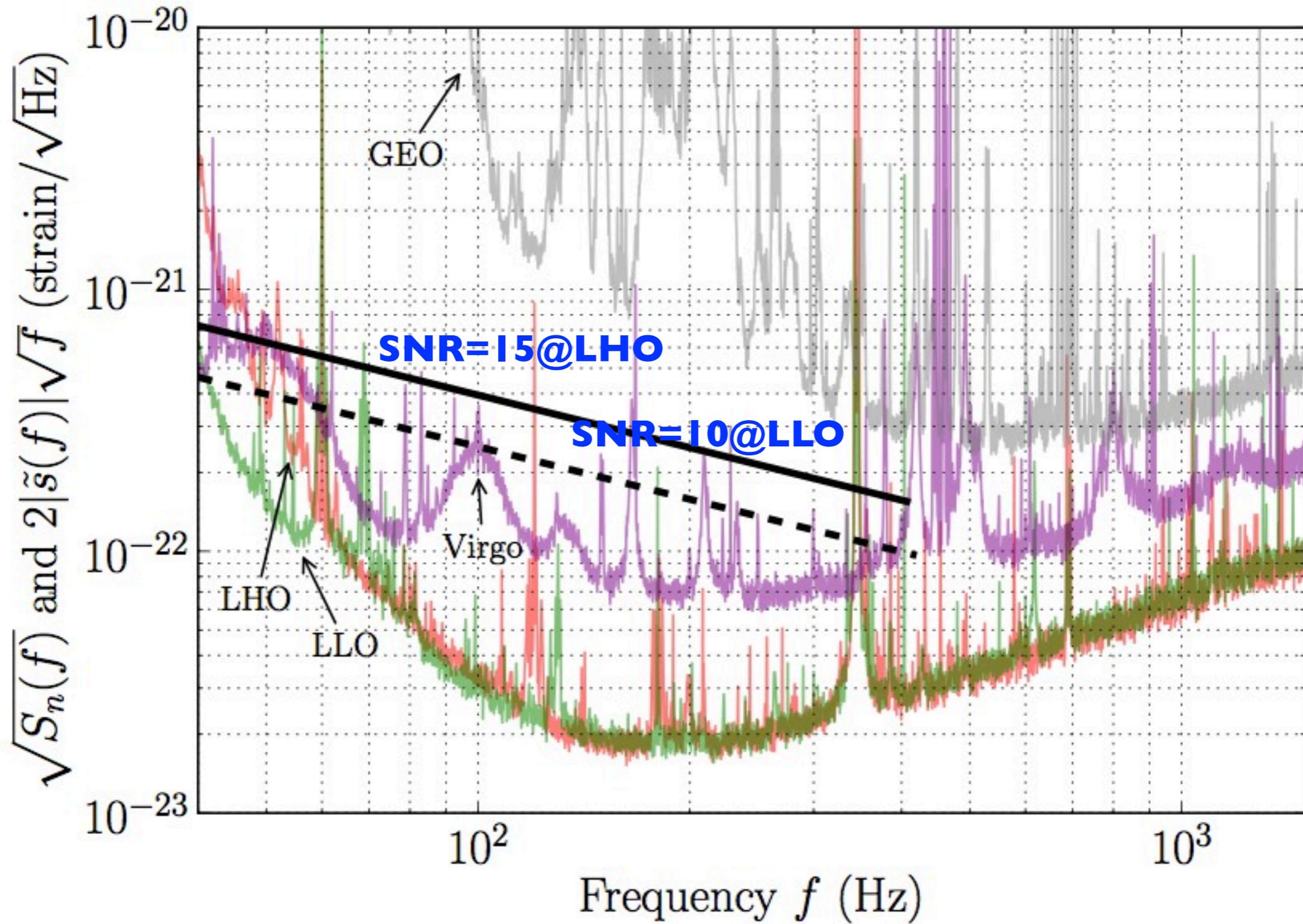
**24.9 days, zero lag**





**False alarm rate is 1/7000 years, significant enough!**





Parameter	Lower (5%)	Upper (95%)
Chirp Mass ( $M_{\odot}$ )	4.38	5.18
Symmetric mass ratio $\eta$	0.16	0.25
Distance (Mpc)	7	57
Larger mass $m_1$ ( $M_{\odot}$ )	5.4	10.5
Smaller mass $m_2$ ( $M_{\odot}$ )	2.7	5.5
Spin on $m_1$	0.67	1.0
Spin Tilt on $m_1$ ( $^{\circ}$ )	84	111

1

## The envelop

2

The Blind injection team provided TWO triple coincident signals during S6—

One NS-BH inspiral (the big dog) and one short-lived pulsar signal.

In addition to the two coincident injections listed below, there were a few ultra-low SNR tests and a few single-detector transient injections when the other detectors were not in science mode.

3

Injected a blind inspiral around GPS 968654558 in L1, H1 and V1.

- Mass 1 = 24.8140793 Msun
- Mass 2 = 1.73517299 Msun
- Distance = 9.74132919 Mpc
- Right Ascension = 0.241240293 rads
- Declination = -1.28577304 rads
- 1C at Geocentre = 968654558.0
- 1C at Hanford = 968654558.011451630
- 1C at Livingston = 968654558.005227478
- 1C at Virgo = 968654558.014196834
- Network SNR = 18

4

Inserted a pulsar signal during the last part of the run, starting at:

- H1 - 968637280
- L1 - 968637384
- V1 - 968638000

<ul style="list-style-type: none"> <li>• refTime = 752680033</li> <li>• alpha = 3.62930e-24</li> <li>• delta = 3.02726e-20</li> <li>• psi = 0.13821761</li> <li>• phi0 = 4.29</li> <li>• f0 = 683.3517313</li> <li>• latitude = 0.88349821</li> <li>• longitude = 2.453662475</li> <li>• fdot = 8.0</li> <li>• fddot = 8.0</li> </ul>	<ul style="list-style-type: none"> <li>• pulse reference time in SB frame</li> <li>• plus-polarization signal amplitude</li> <li>• cross-polarization signal amplitude</li> <li>• polarization angle psi</li> <li>• phase at tRef</li> <li>• GW frequency at tRef</li> <li>• latitude [in radians]</li> <li>• longitude [alpha, right ascension] in radians</li> <li>• spin-down parameters d/dt, d^2/dt^2</li> </ul>
---	---

5

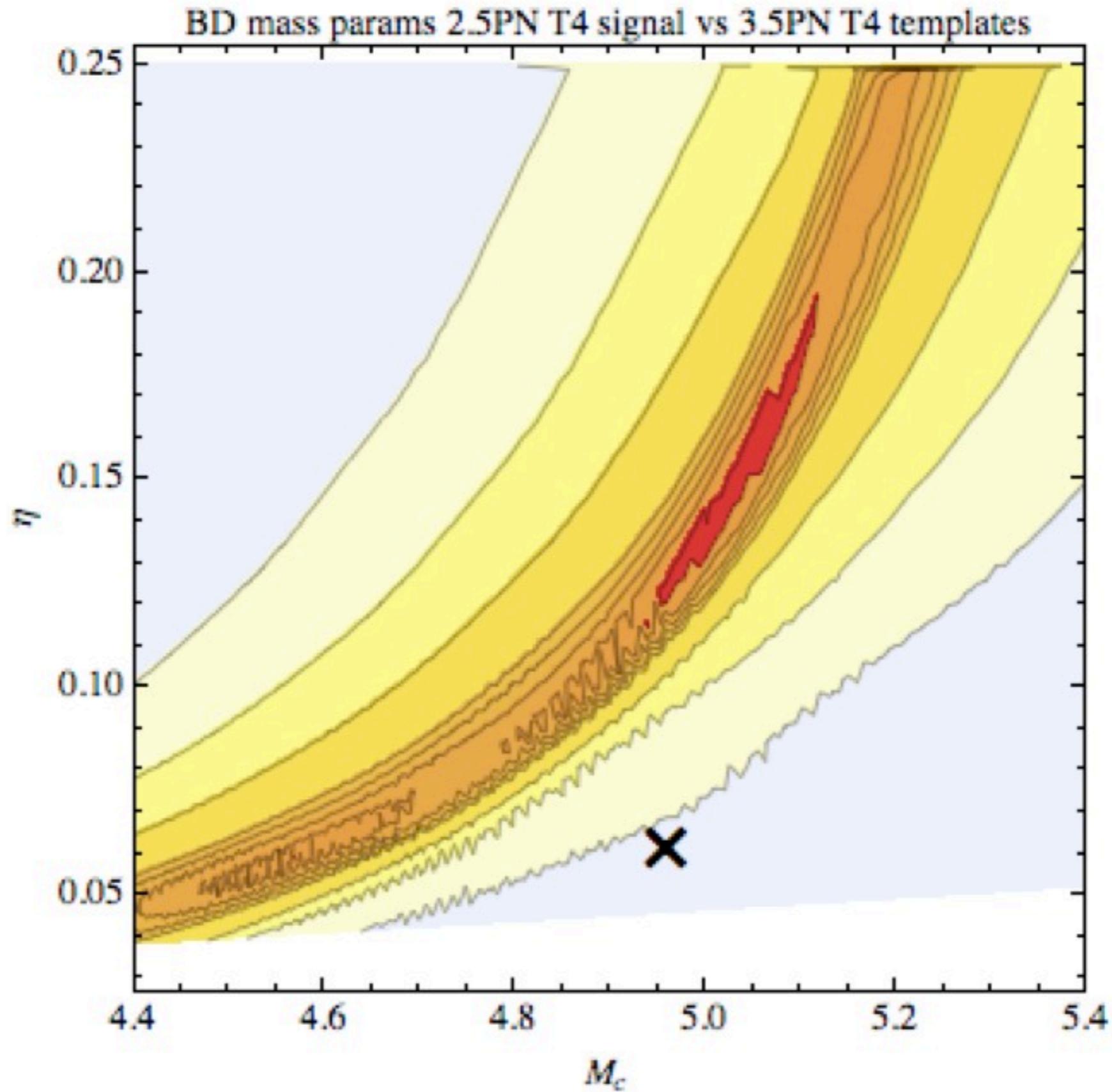
- All of the files that were created when `lalapps_makeblindinj` was invoked to create the big dog are available in a zip file at the following:
- temporary location (and will go to the DCC soon):  
[http://ligo.phys.lsu.edu/pickup/LSC\\_files/BigDog.zip](http://ligo.phys.lsu.edu/pickup/LSC_files/BigDog.zip)

- **Big Dog**はblind injectionだった。
- **signal generation**に古いコードを使っていたため、一つのデータストリームの符号が逆になっていた。
- **Post-Newton 2.5次**を使っていた。(解析では3.5次を用いている。)

Injected a blind inspiral around GPS 968654558 in L1, H1 and V1.

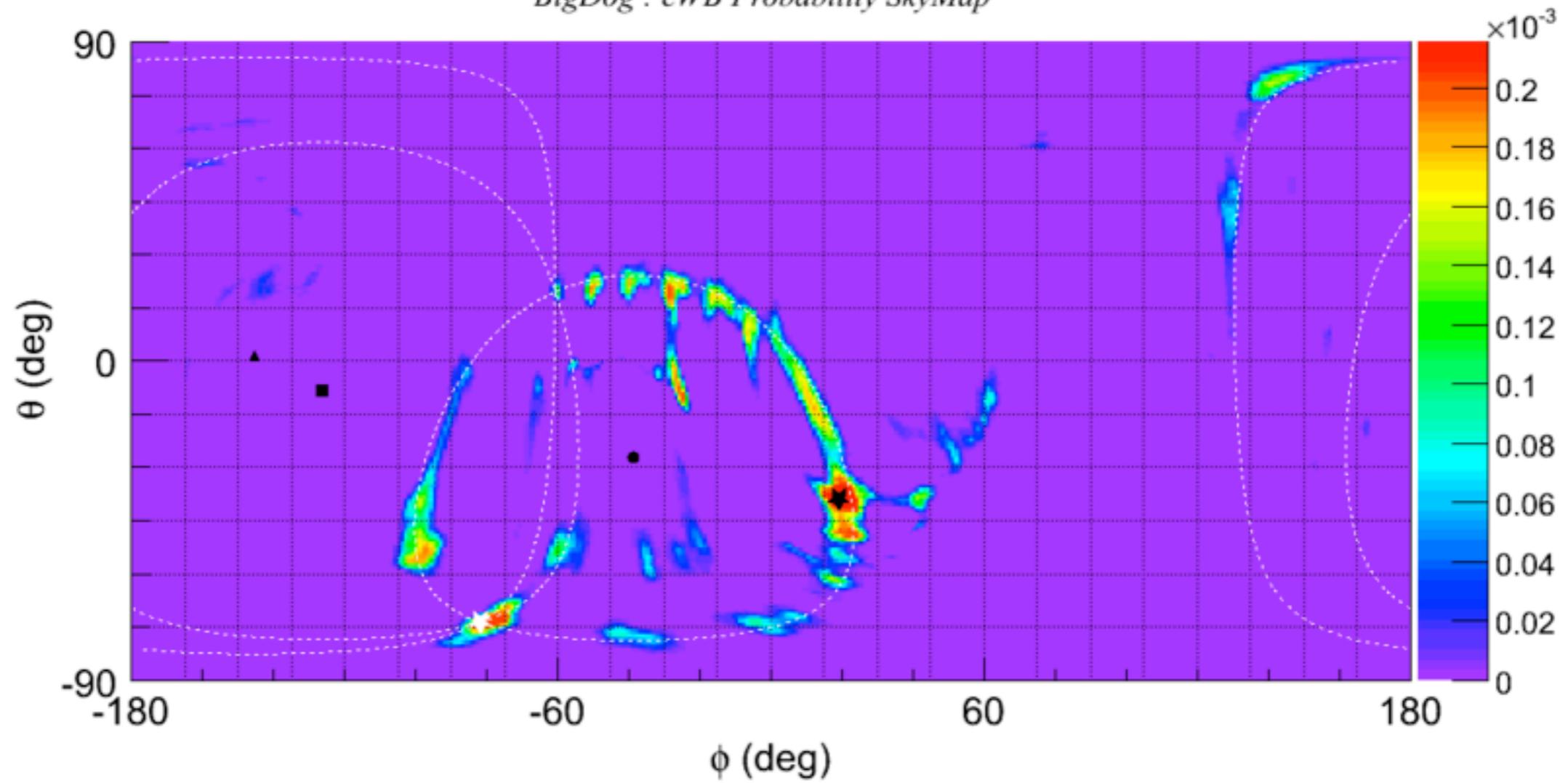
- Mass 1 = 24.8140793 Msun
- Mass 2 = 1.73517299 Msun
- Distance = 9.74132919 Mpc
- Right Ascension = 0.241240293 rads
- Declination = -1.28577304 rads
- tC at Geocentre = 968654558.0
- tC at Hanford = 968654558.011451630
- tC at Livingston = 968654558.005227478
- tC at Virgo = 968654558.014196834
- Network SNR = 18

# 2.5PN vs 3.5 PN





*BigDog : cWB Probability SkyMap*



● **まず初検出**

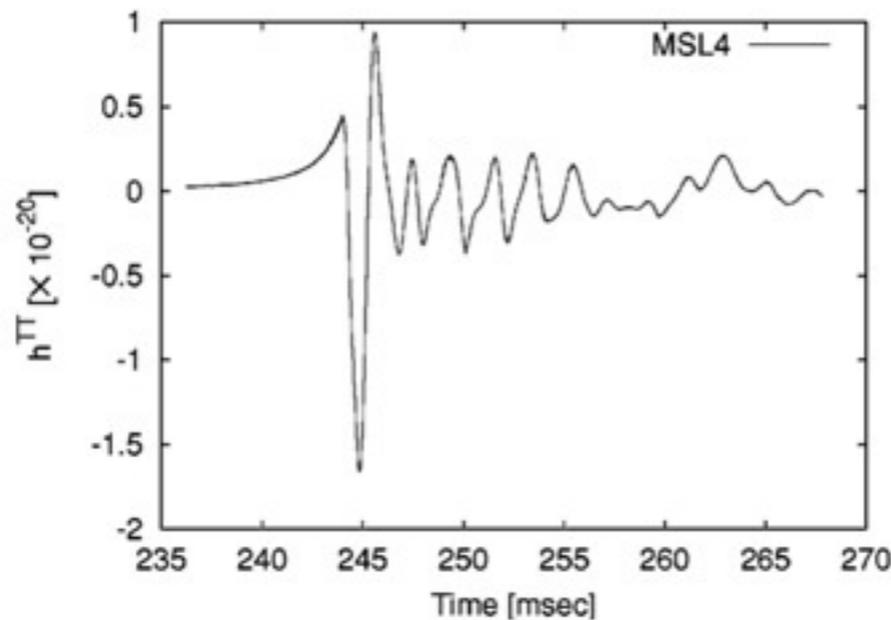
● 多くの天体現象では重力波とともにEM、ニュートリノ等が放出される。両方を考慮したモデルの作成。

● サーチパラメータ空間の制限(LMXB(Sco X-1等)の周期)

● **地上望遠鏡で検出できる重力波から何が分かるか**

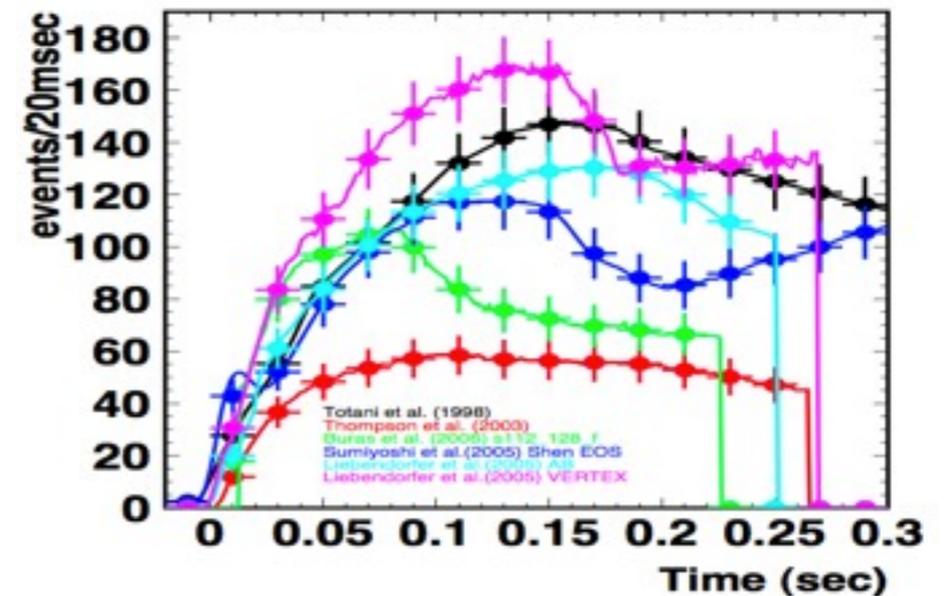
● 検出された重力波形からどのような物理が分かるか？そのためにはどれくらいの精度でパラメータ推定しなければならないのか？

**Gravitational wave**

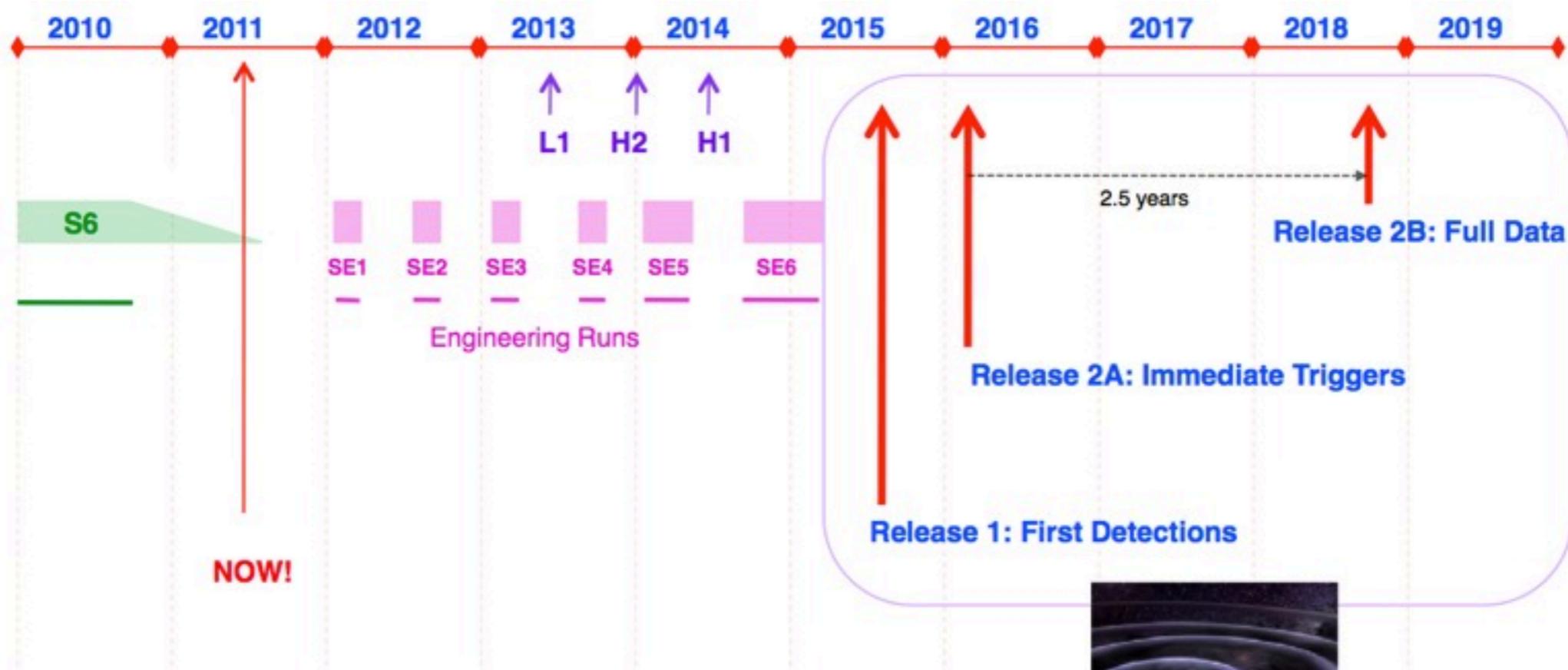
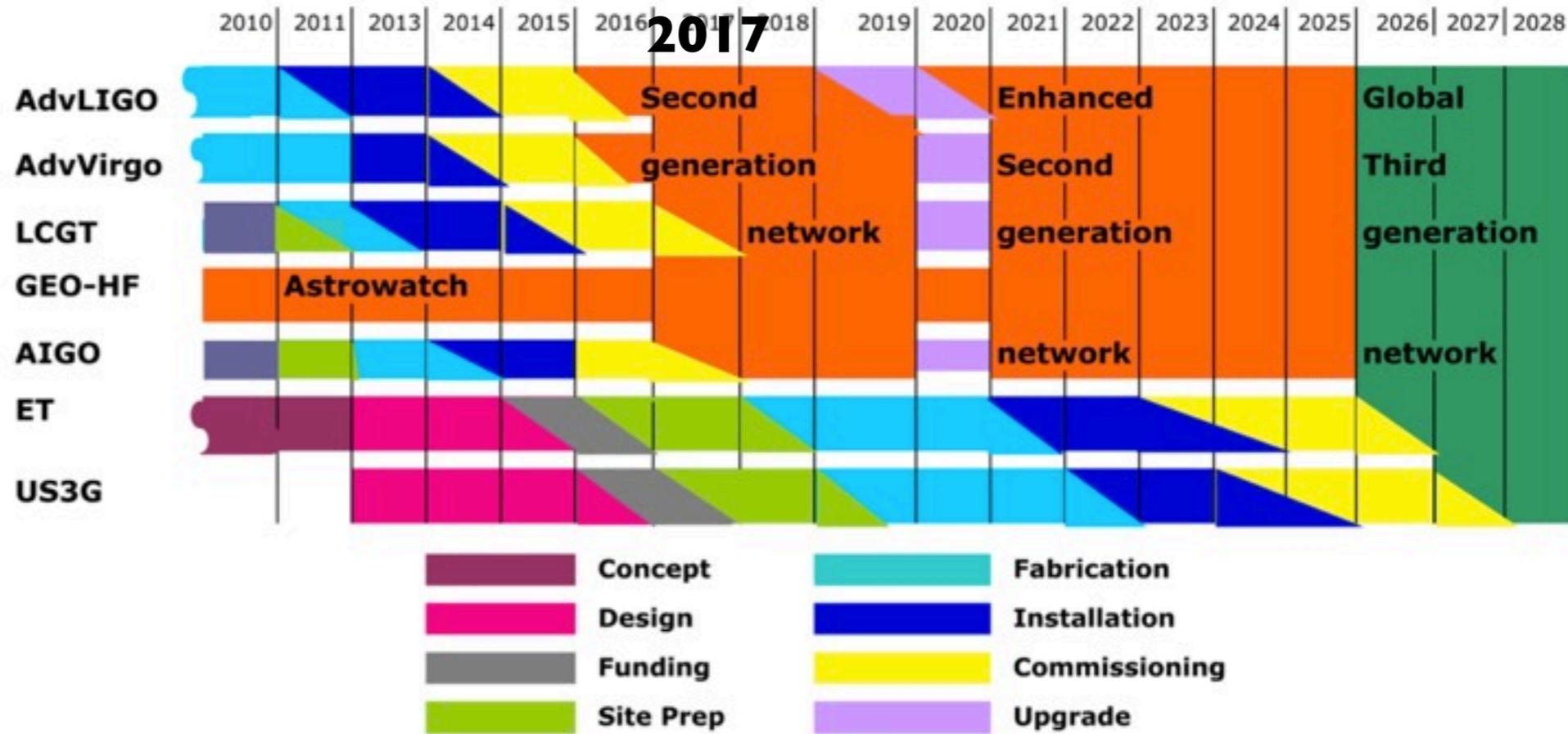


**Kotake et al. PRD (2004)**

**neutrino events (SK)**



**Nakahata JPCS (2008)**



- 初期世代重力波望遠鏡(**TAMA**、**initial LIGO**)を用いた重力波探査が行われ、次世代の観測に必要な問題点が洗い出された。
- **LCGT**の建設が開始され、～2016年にはアンテナパターンの**Blind area**、重力波の到来方向等が劇的に改善された望遠鏡ネットワークが完成される。
- (おそらく)重力波が初検出される。
- 重力波観測を含めたマルチメッセンジャー観測が本格的に実現する。



- **Testing relativistic gravity theory** is important for fundamental physics and cosmology e.g. dark matter, dark energy, accelerating the Universe.
- One of plausible gravity theories is **scalar-tensor theory**. Significant difference from the general relativity is the existence of a scalar field which is connected with the gravity field with coupling parameters, and a resulting **scalar gravitational wave**. **Brans-Dicke theory** is famous scalar-tensor theory which has a coupling parameter  $\omega_{BD}$ .
- **Tensor GW** search might miss some type of sources, e.g. highly spherical core collapse if scalar-tensor theory is correct. In this sense, search for **SGW** is complementary to current **GW** search.
- This talk will focus on search for **SGW** from **Galactic spherical core collapses in Brans-Dicke theory**.



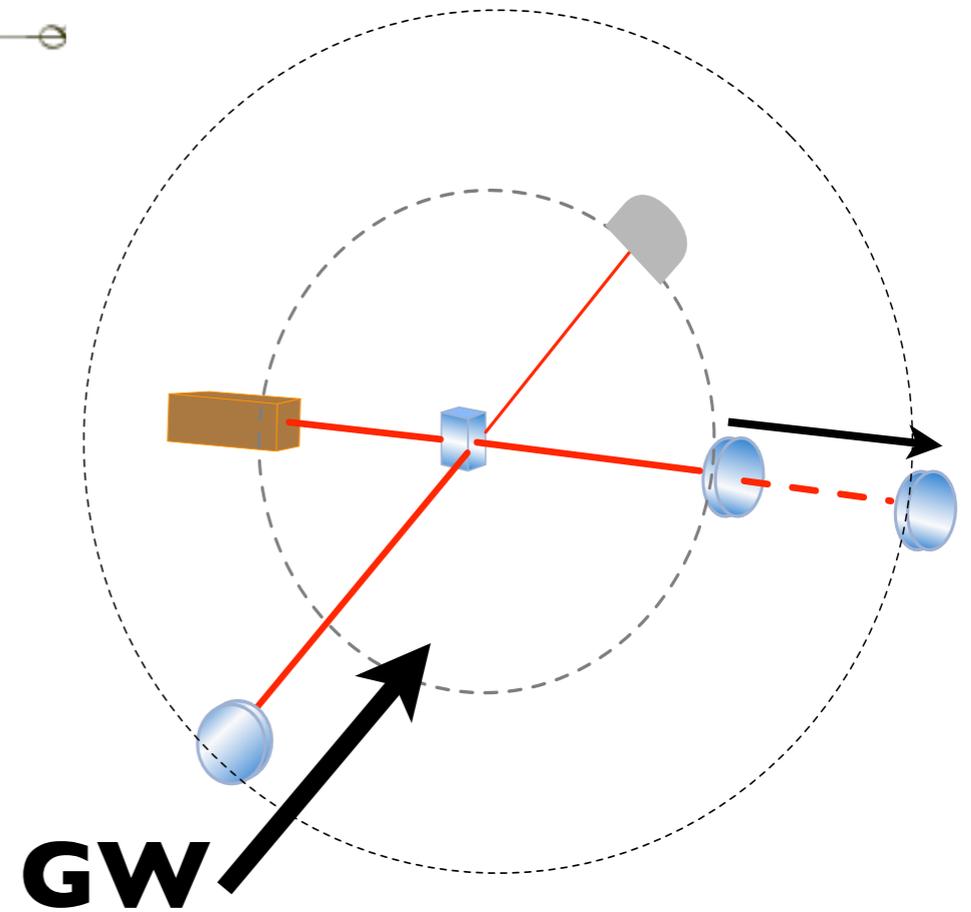
Antenna pattern function as a function of sky position  $(\theta, \phi)$  is written as

$$F_+(\hat{\Omega}) = \frac{1}{2}(1 + \cos^2 \theta) \cos 2\phi$$

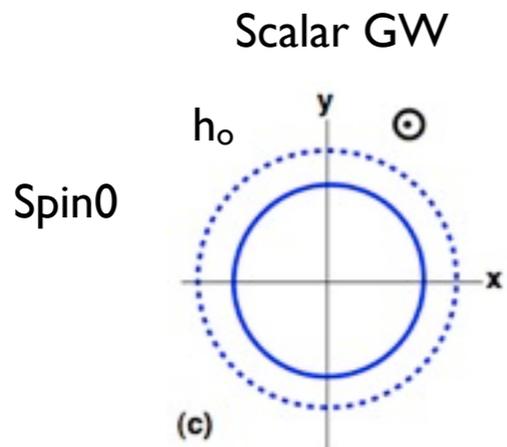
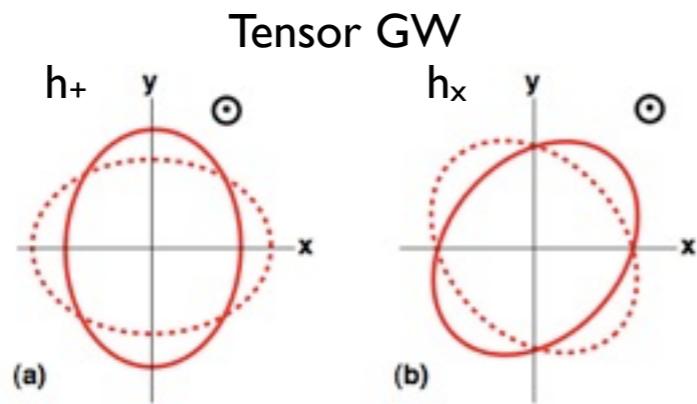
$$F_\times(\hat{\Omega}) = \cos \theta \sin 2\phi$$

$$F_o(\hat{\Omega}) = -\sin^2 \theta \cos 2\phi.$$

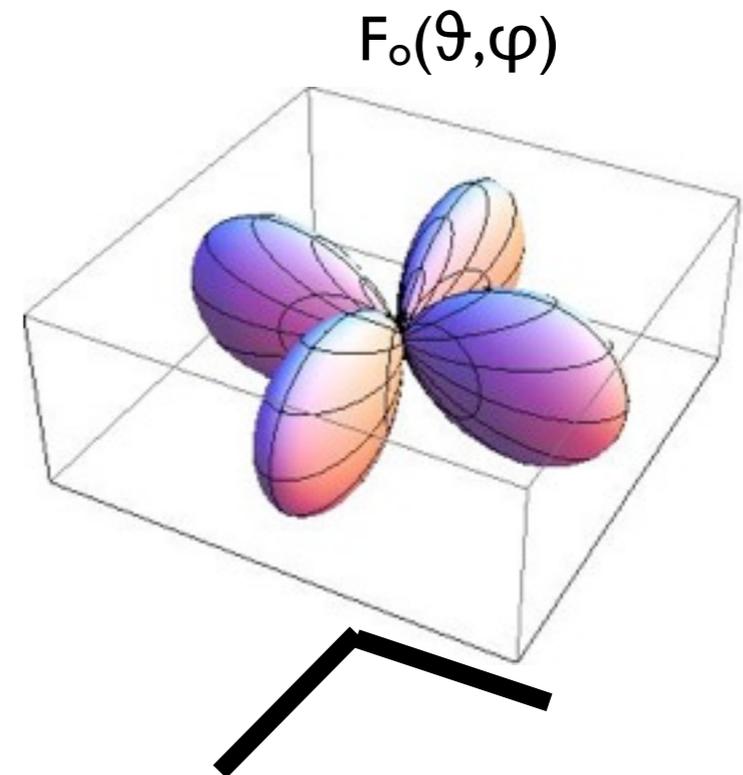
M.Tobar et al(1999), M. Maggiore et al(2000), K.Nakao et al(2001)

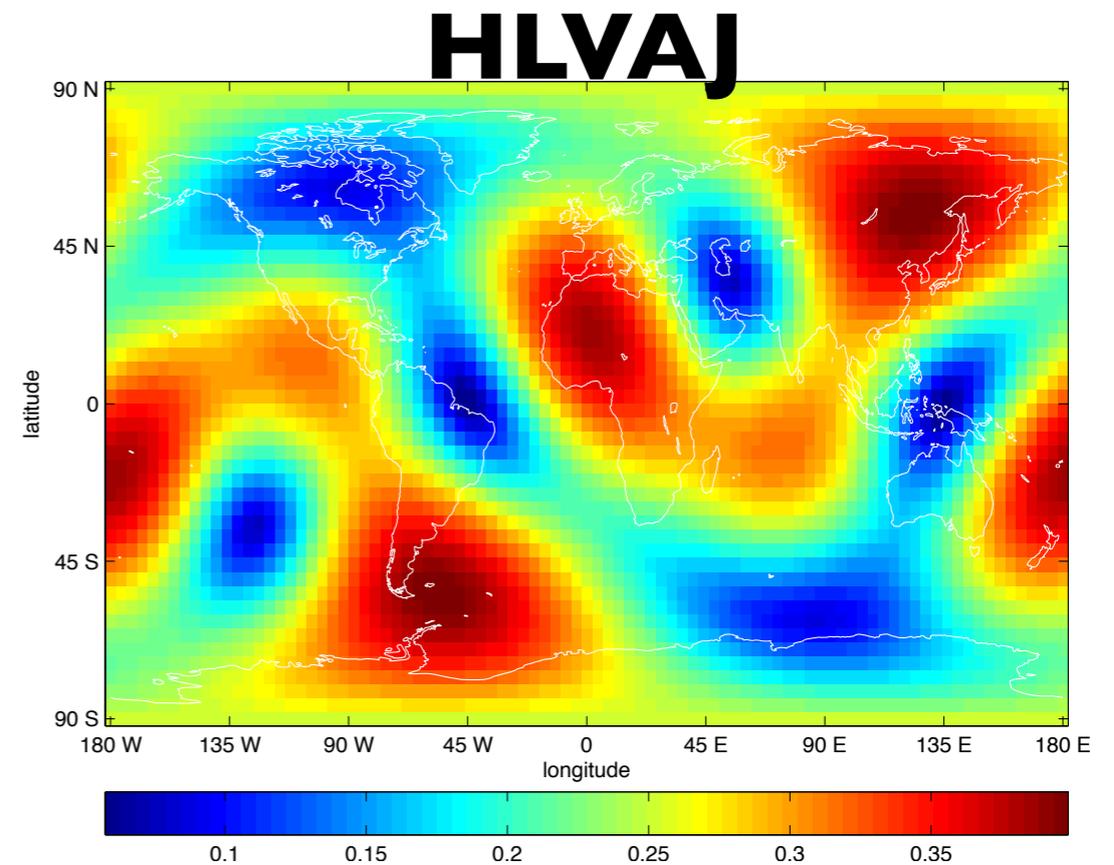
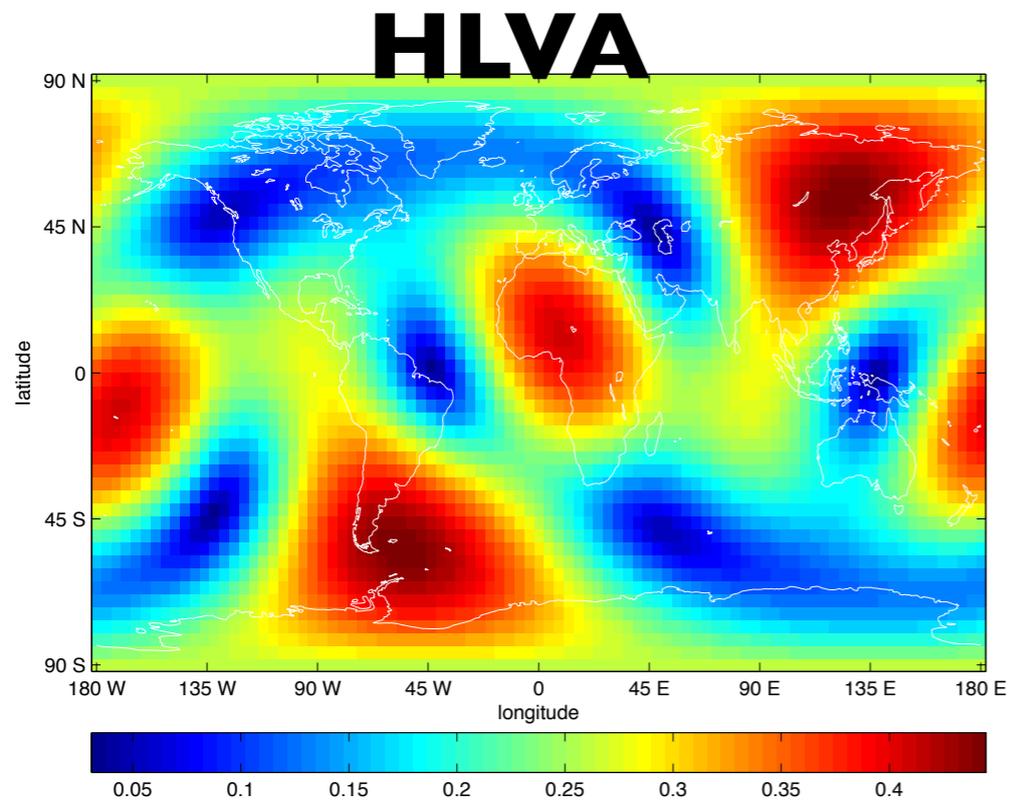
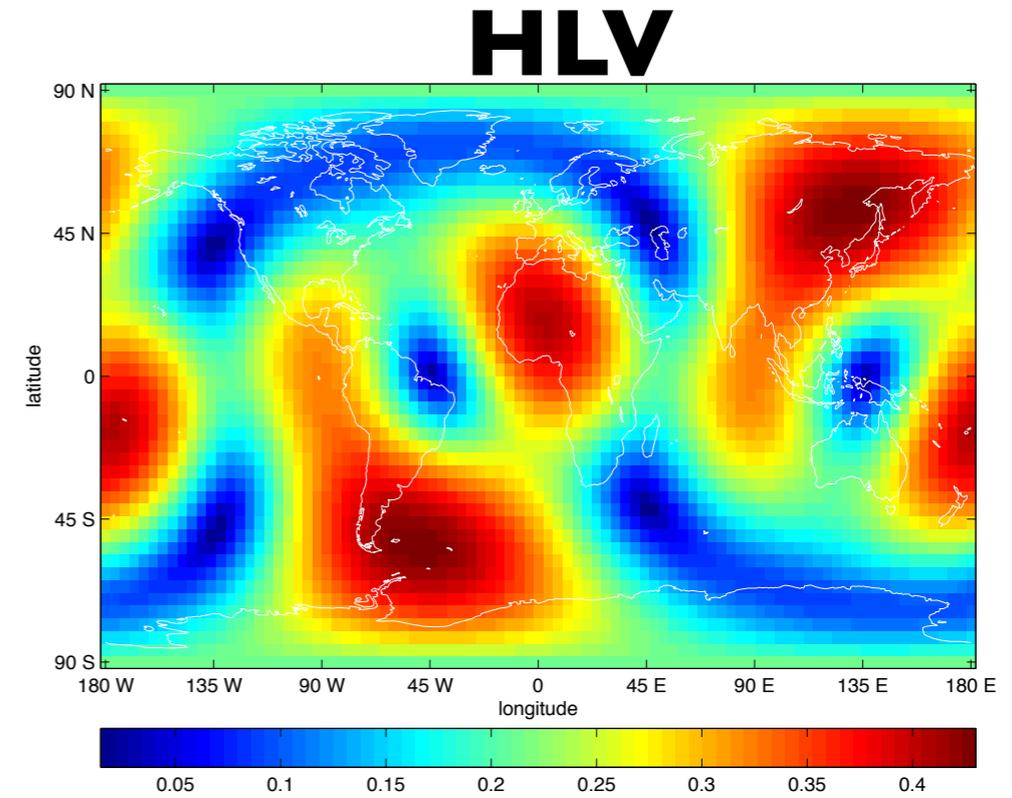
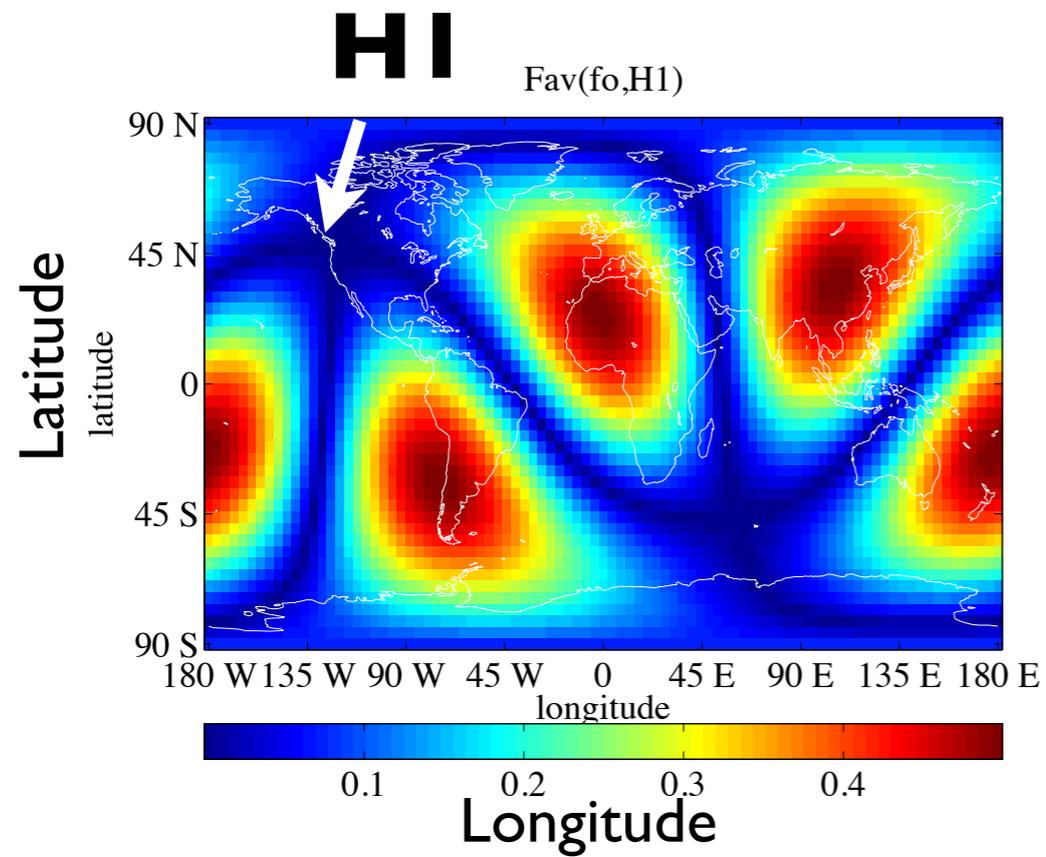


## Polarization of tensor, scalar gravitational wave



C.Will, Living Review (2006)







- Coherent network analysis can extract scalar gravitational wave with more than 3 world-wide detectors. This approach combines data taking account of the sky position  $(\vartheta, \varphi)$ , arrival time difference  $\tau(\vartheta, \varphi)$  coherently, and calculates all polarization components at a certain direction of the sky which is most likely.**

### Mathematical expression of the coherent network analysis

Expression of d-detectors can be taken as

$$\begin{bmatrix} x_1 \\ \vdots \\ x_d \end{bmatrix} = \begin{bmatrix} F_{1+} & F_{1\times} & F_{1\circ} \\ \vdots & \vdots & \vdots \\ F_{d+} & F_{d\times} & F_{d\circ} \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \\ h_\circ \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_d \end{bmatrix}$$

The reconstruction of a gravitational wave is an inverse problem.  
Maximum likelihood method to solve the inverse problem:

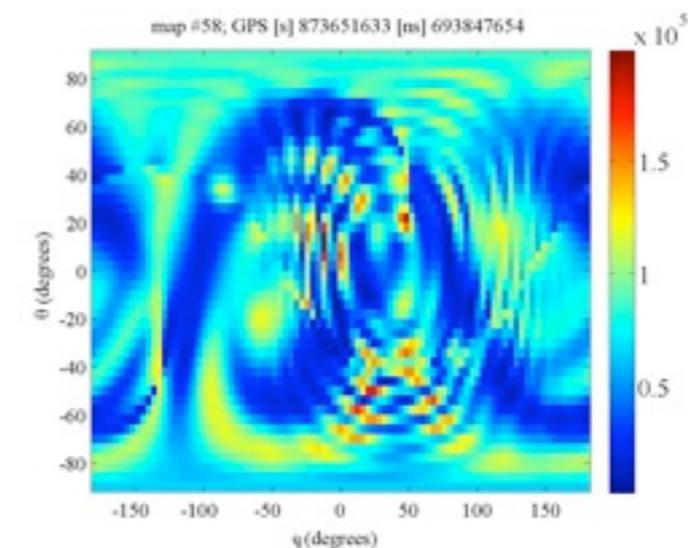
$$L[\mathbf{h}] := \|\mathbf{x} - \mathbf{F}\mathbf{h}\|^2$$

Changing sky position  $(\vartheta, \varphi)$ , time difference  $\tau(\vartheta, \varphi)$ .

The mathematical formula of the reconstructed scalar gravitational wave is

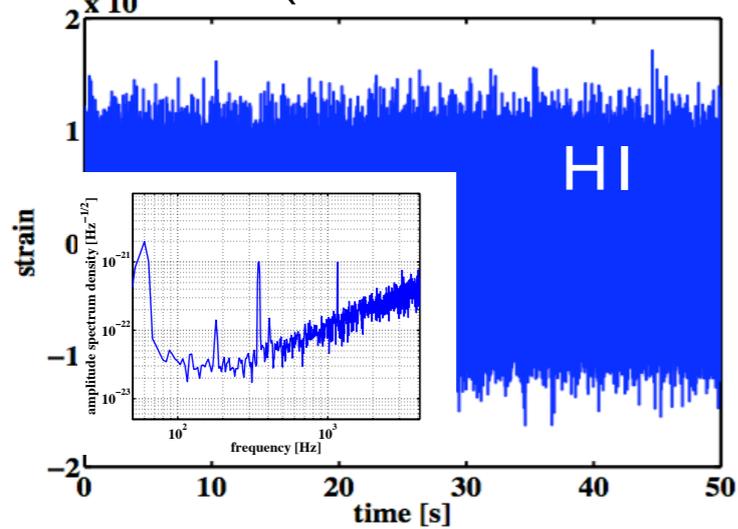
$$\begin{aligned} h_\circ &= \frac{1}{\det(\mathbf{M})} \left( ((F_+ \times F_\times) \cdot (F_\times \times F_\circ)) \cdot F_+ \right. \\ &\quad - ((F_+ \times F_\times) \cdot (F_+ \times F_\circ)) \cdot F_\times \\ &\quad \left. + ((F_+ \times F_\times) \cdot (F_+ \times F_\times)) \cdot F_\circ \right) \cdot \mathbf{x} \end{aligned}$$

Likelihood residual sky-map

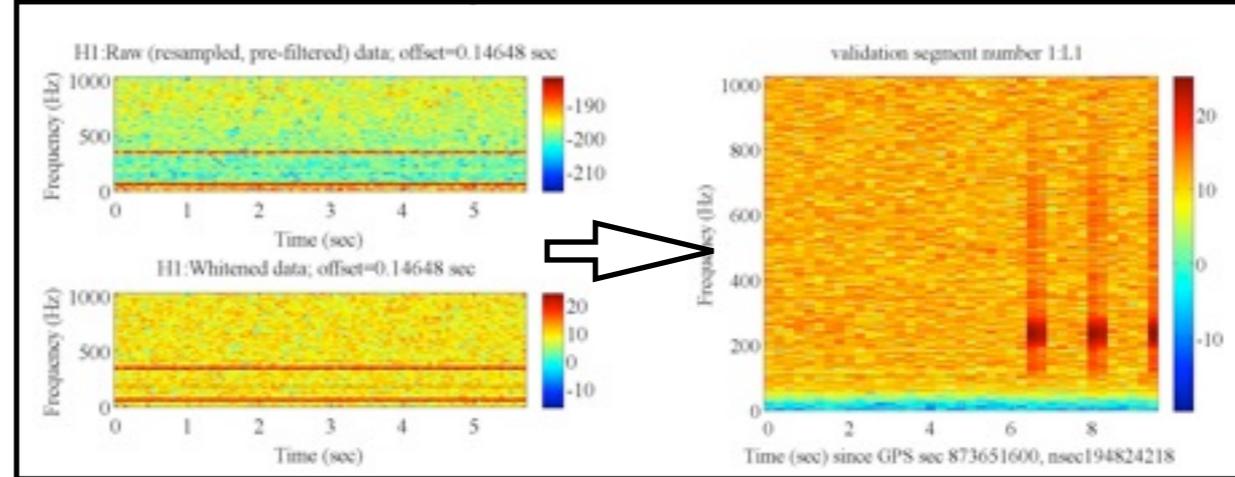


- **Full featured coherent network analysis pipeline(Data conditioning, detection stat., Veto analysis)**
- **One can apply the pipeline to HI,LI,VI,AI,LCGT**
- **Analysis result is output by a Web-based event display.**

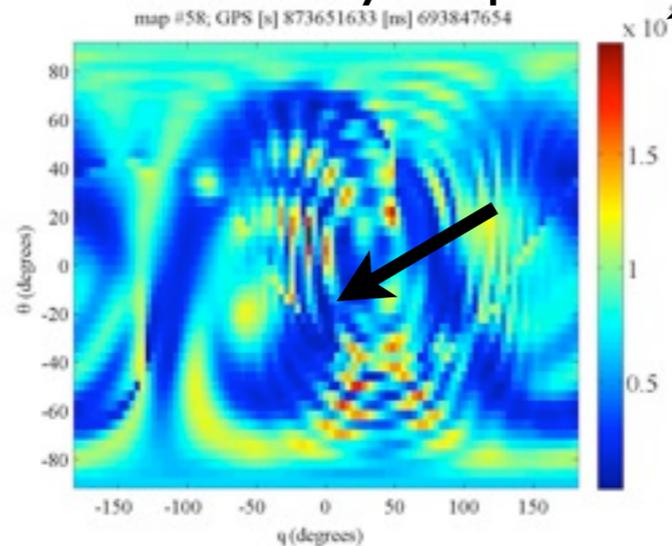
Data set (HI,LI,VI,AI,LCGT)



Data conditioning

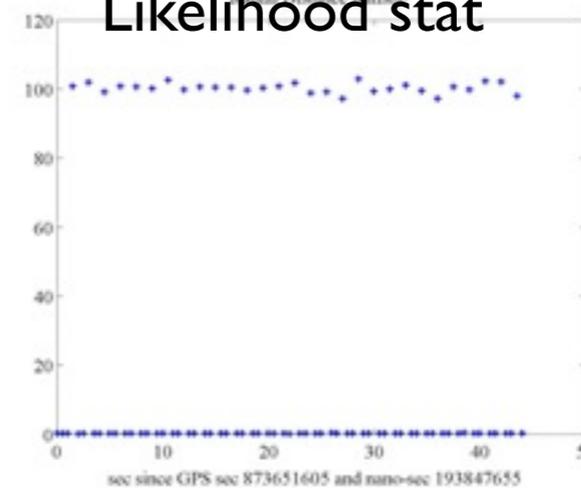


Residual sky-map



Coherent network analysis

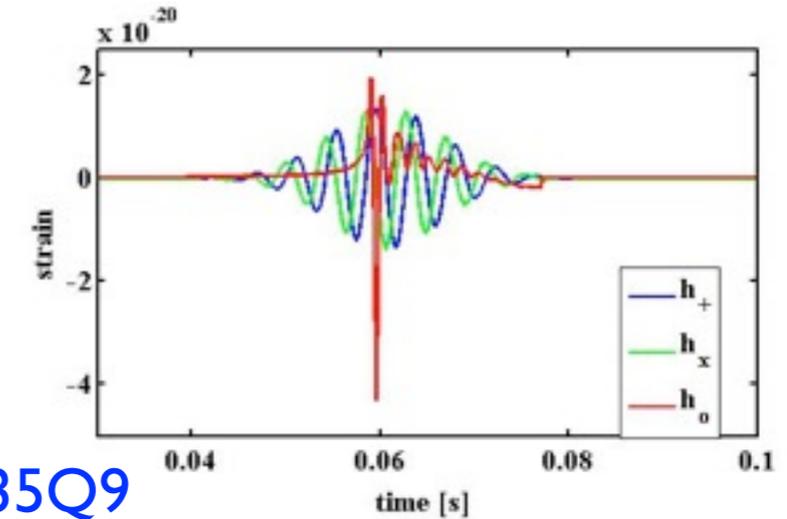
Likelihood stat





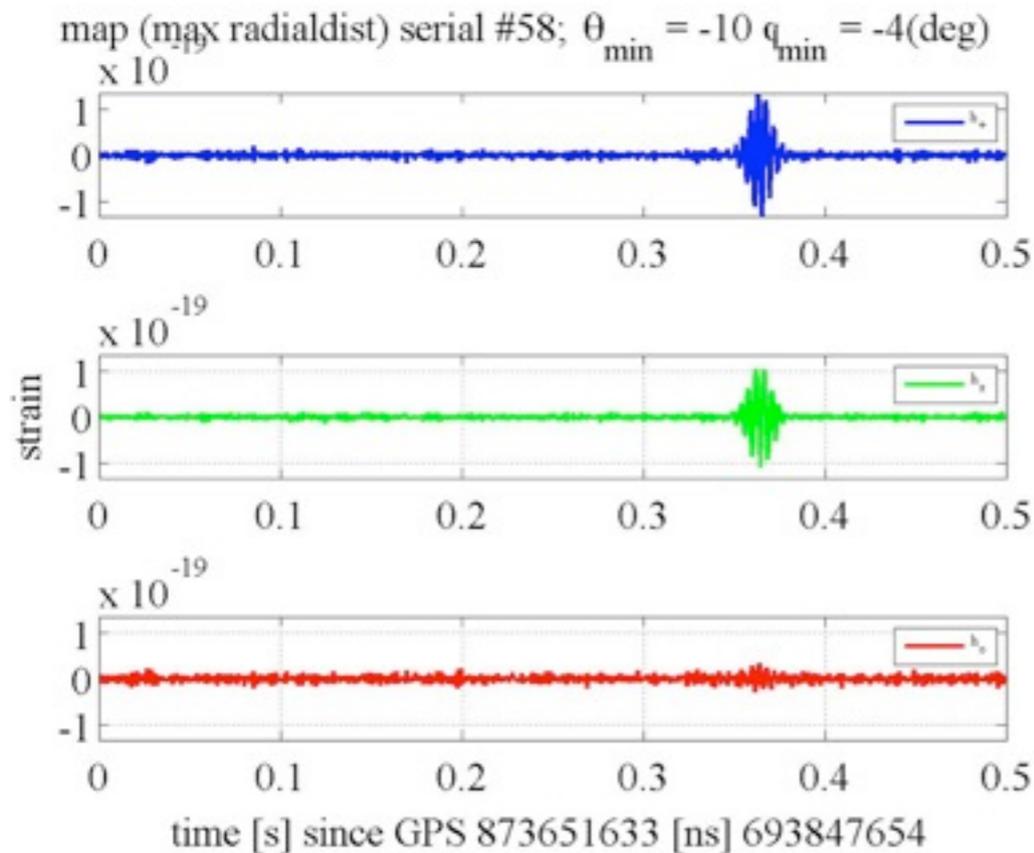
## Reconstruction of $h_+$ , $h_x$ , $h_o$

- As to injection signal, to see  $h_o$  clearly, I used spike-like burst as  $h_o$ .
- Although the grid of lat-lon map is coarse ( $4^\circ \times 4^\circ$ ) in the simulation,  $h_o$  is reconstructed clearly.



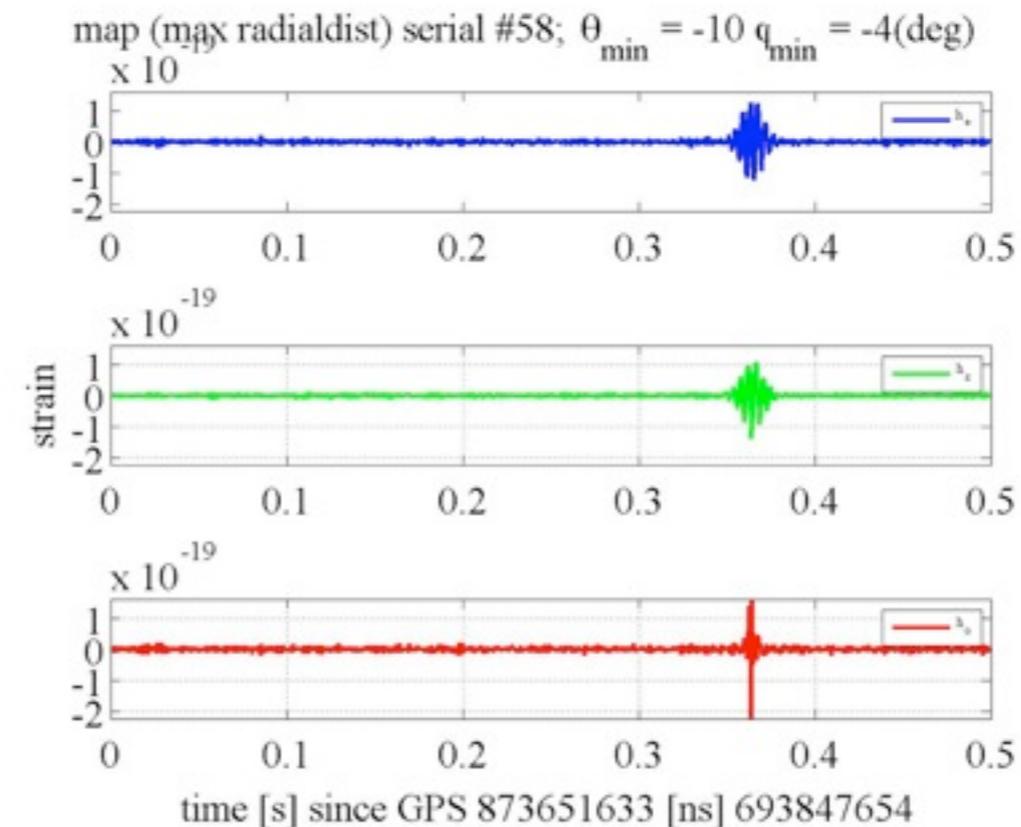
$h_+$ ,  $h_x$  : SG235Q9

$h_o$  : Not injected



$h_+$ ,  $h_x$  : SG235Q9

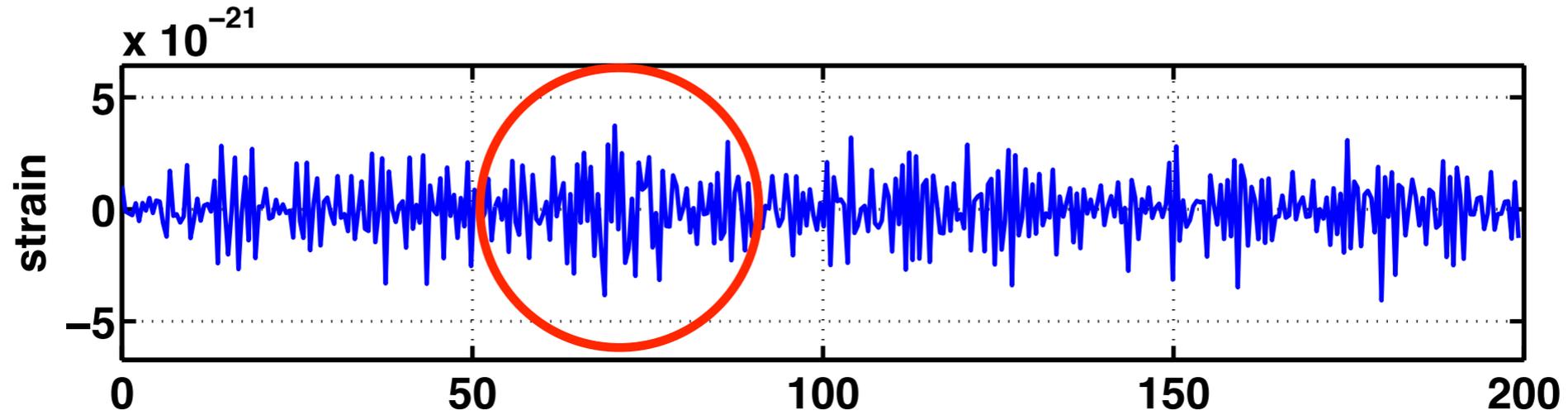
$h_o$  : Spike-like burst



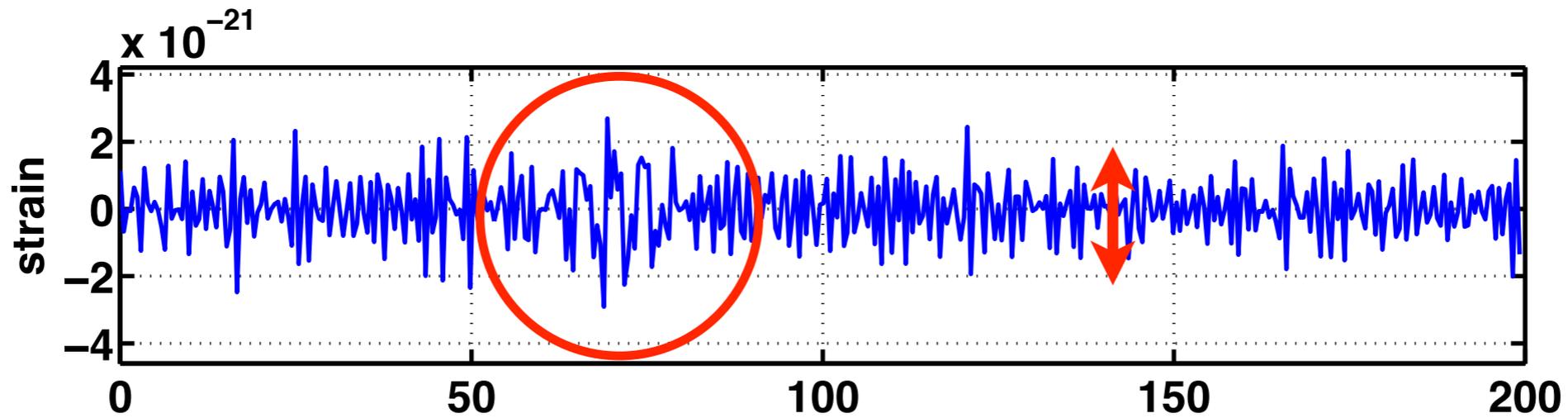


- Astrophysical model used is a spherically symmetric core collapse with 10Mo at the distance of 10kpc from the earth.(M.Sibata, 1994)

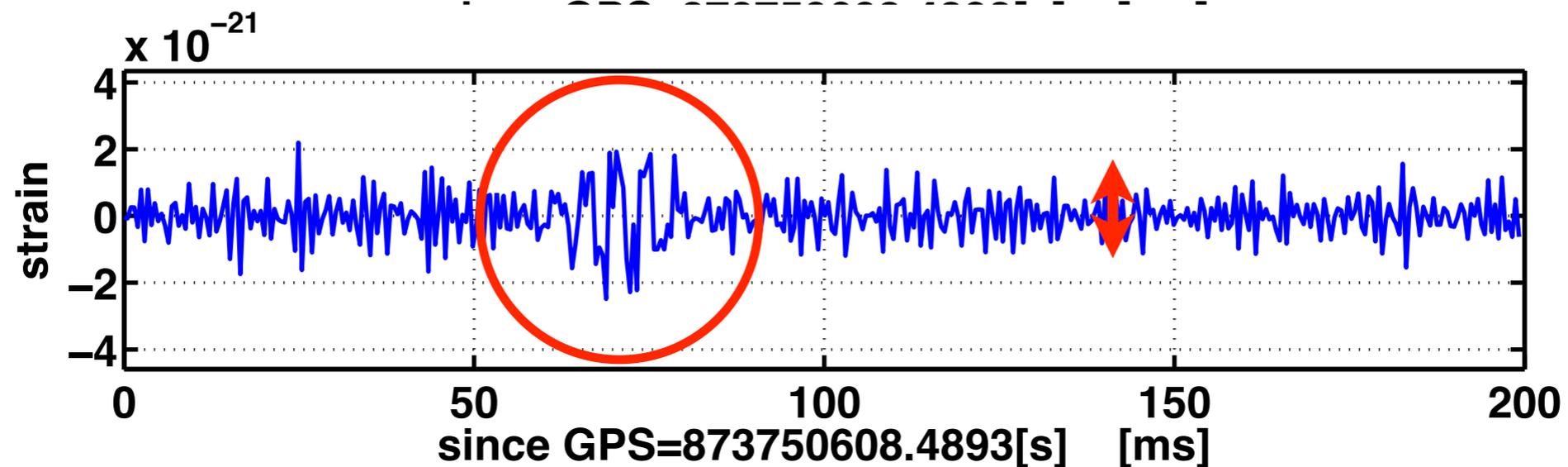
**HLV**



**HLVA**



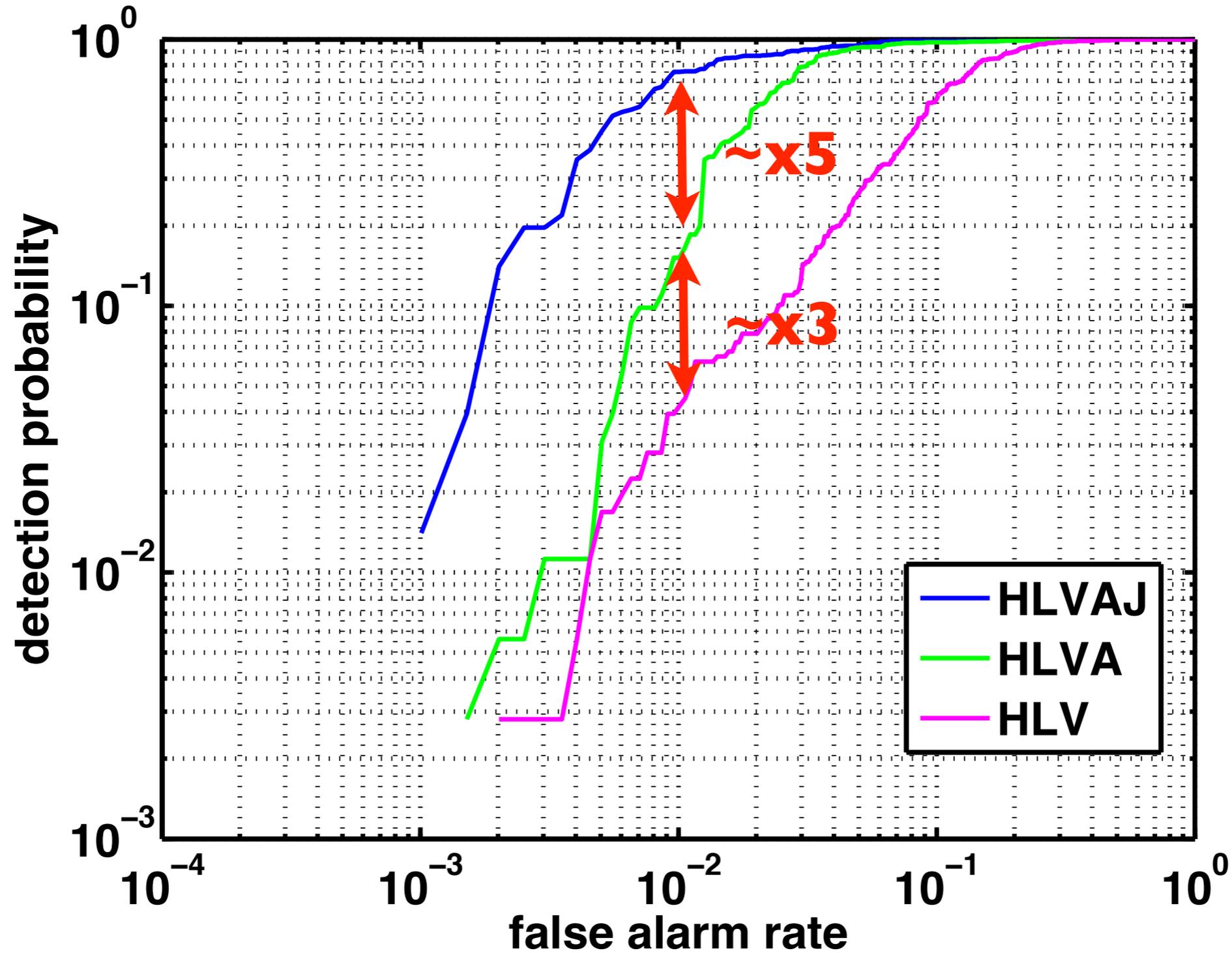
**HLVAJ**



since GPS=873750608.4893[s] [ms]



- Simulated GWs is from spherical core collapse at 10kpc. Sky directions are uniformly distributed.

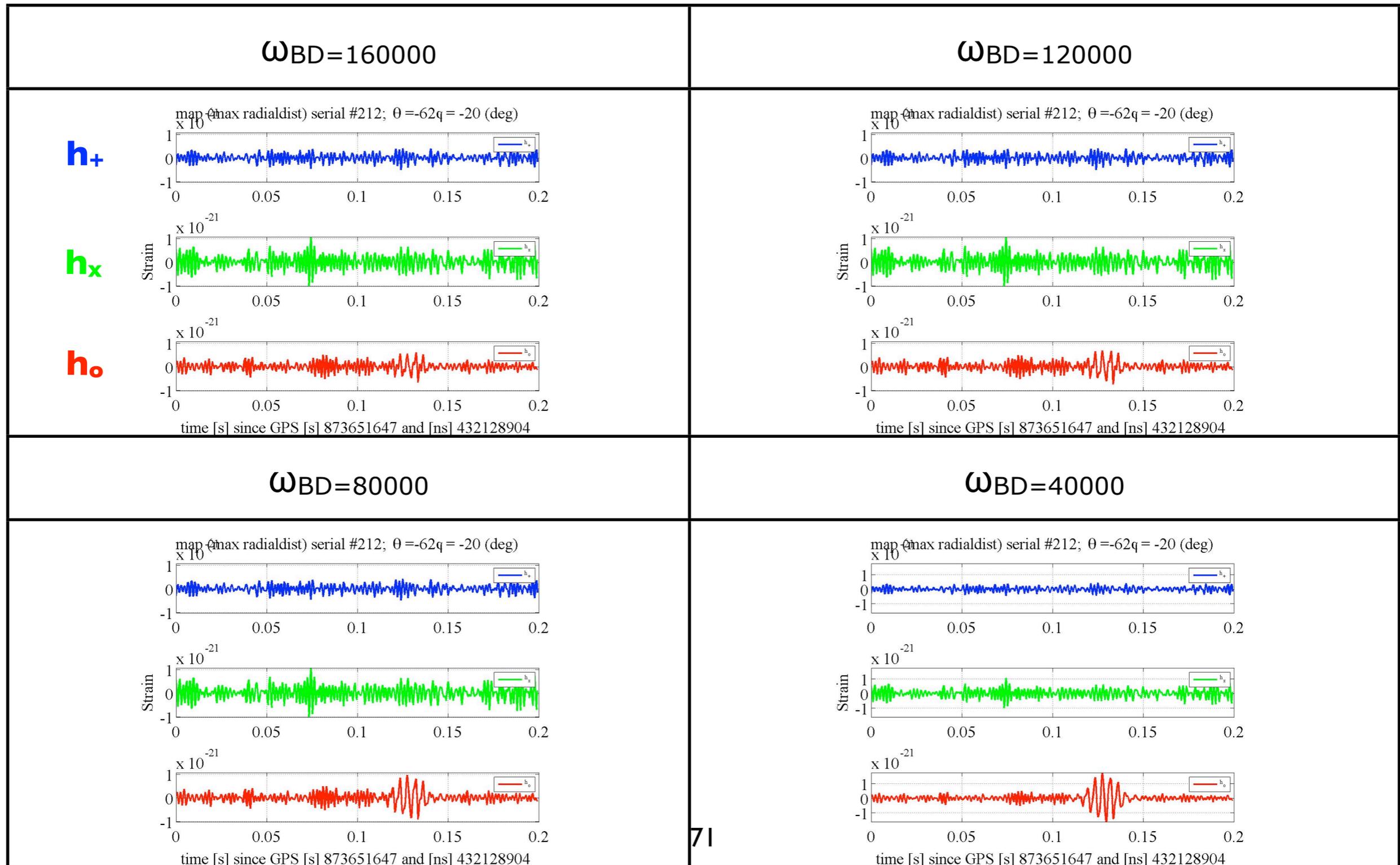


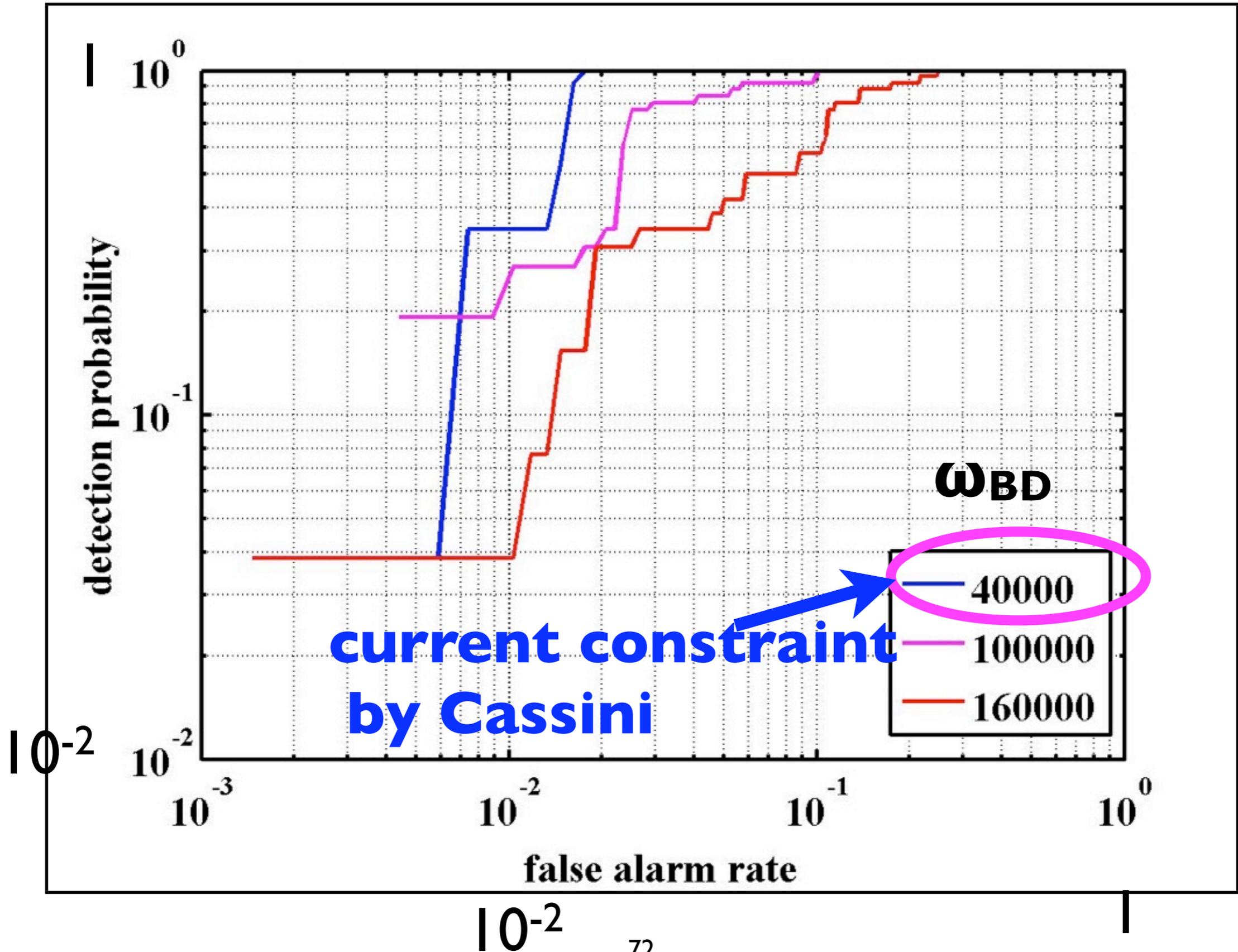


**We performed simulations to reconstruct scalar gravitational waves with  $\omega_{BD} = 40000, 80000, 120000, 160000$ .**

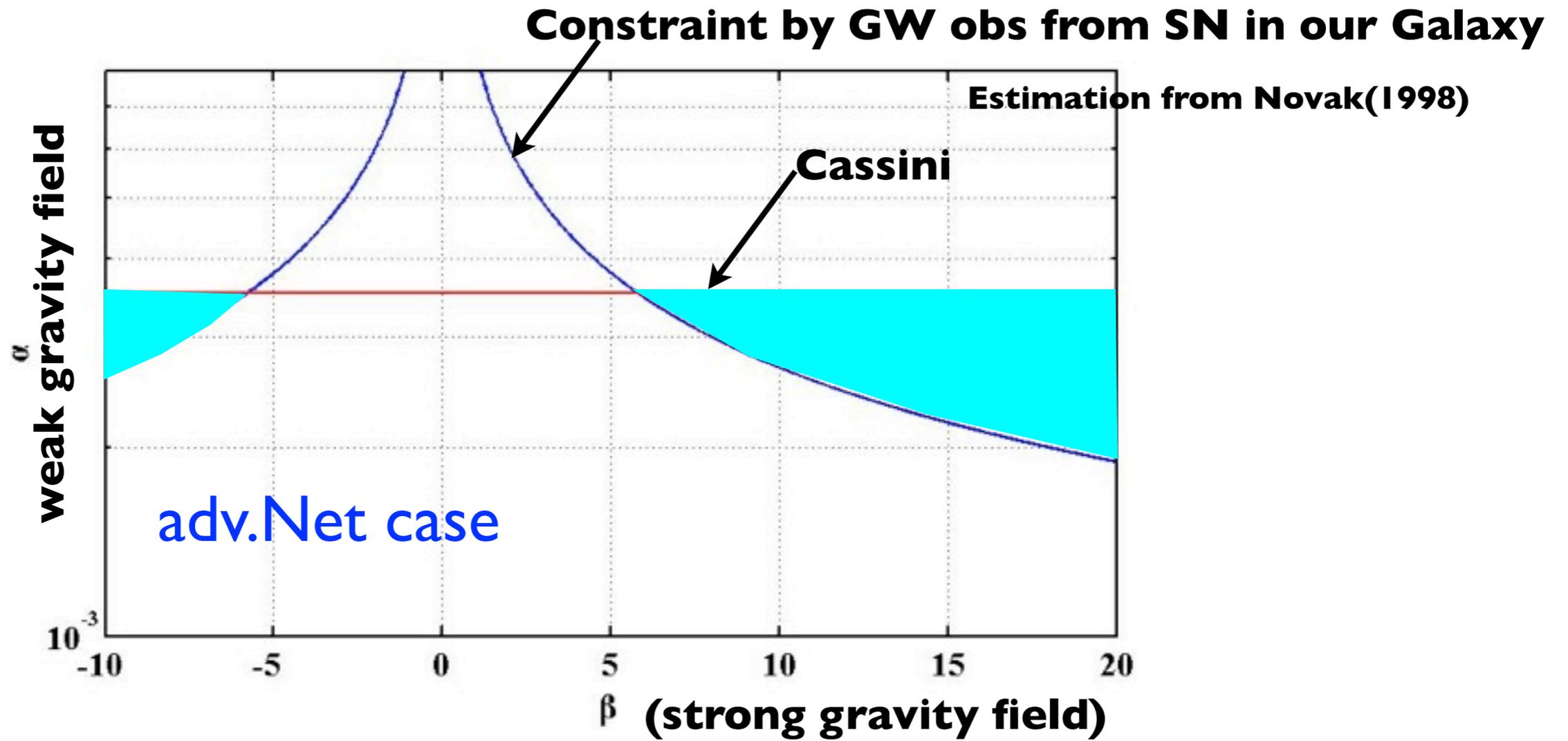
**This simulation uses the design sensitivity of advLIGO for LIGO, VIRGO, and LCGT.**

**Astrophysical model used is the same as the previous simulation.**





**General Scalar-tensor theory which is characterized by  $\alpha$  and  $\beta$ ...**



**$\beta$  is constrained by the use of the constraint of  $\alpha$  by Cassini.**

- We discuss search for scalar GW from Galactic spherical core collapse in Brans-Dicke theory with various adv det. network.
- Although depending sky location and models, **it is possible to put stronger constraint on  $\omega_{BD}$ .**
- **LCGT** and **LIGO-Australia** play an important role for search for scalar gravitational waves
- We need numerical simulations of scalar GW in S-T theory.



## Audio recordings of this candidate.

Caution: adjust volume before putting on headphones.

1. [H1\\_G19377.wav](#): audio file containing whitened and bandpassed  $h(t)$  from H1, courtesy of gstlal. With a decent pair of earbuds or headphones, the chirp can be clearly heard around 17 seconds into the recording.
  2. [L1\\_G19377.wav](#): audio file containing whitened and bandpassed  $h(t)$  from L1, courtesy of gstlal. With a decent pair of earbuds or headphones, the spike glitch can be heard around 8 seconds and the chirp can be heard around 17 seconds into the recording.
  3. [V1\\_G19377.wav](#): audio file containing whitened and bandpassed  $h(t)$  from V1, courtesy of gstlal.
  4. [L1.wav](#): Audio file of reconstructed L1 strain from cWB.
  5. [H1.wav](#): Audio file of reconstructed H1 strain from cWB.
- [stereo\\_H1L1\\_hoft.wav](#): Stereo recording of whitened  $h(t)$ ; channel 1 is H1 and channel 2 is L1.

**HI**

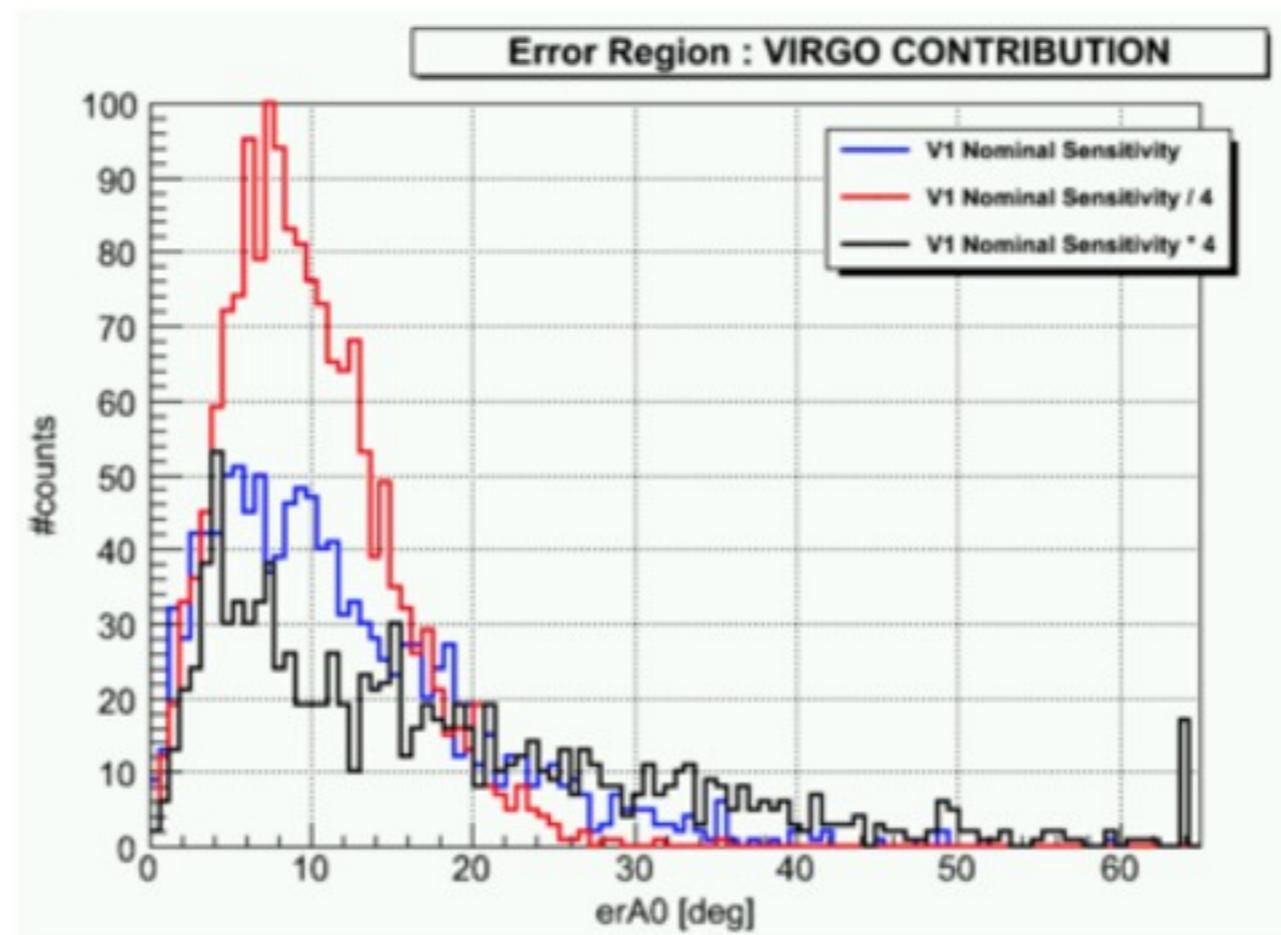
**LI**

生データ

再構成

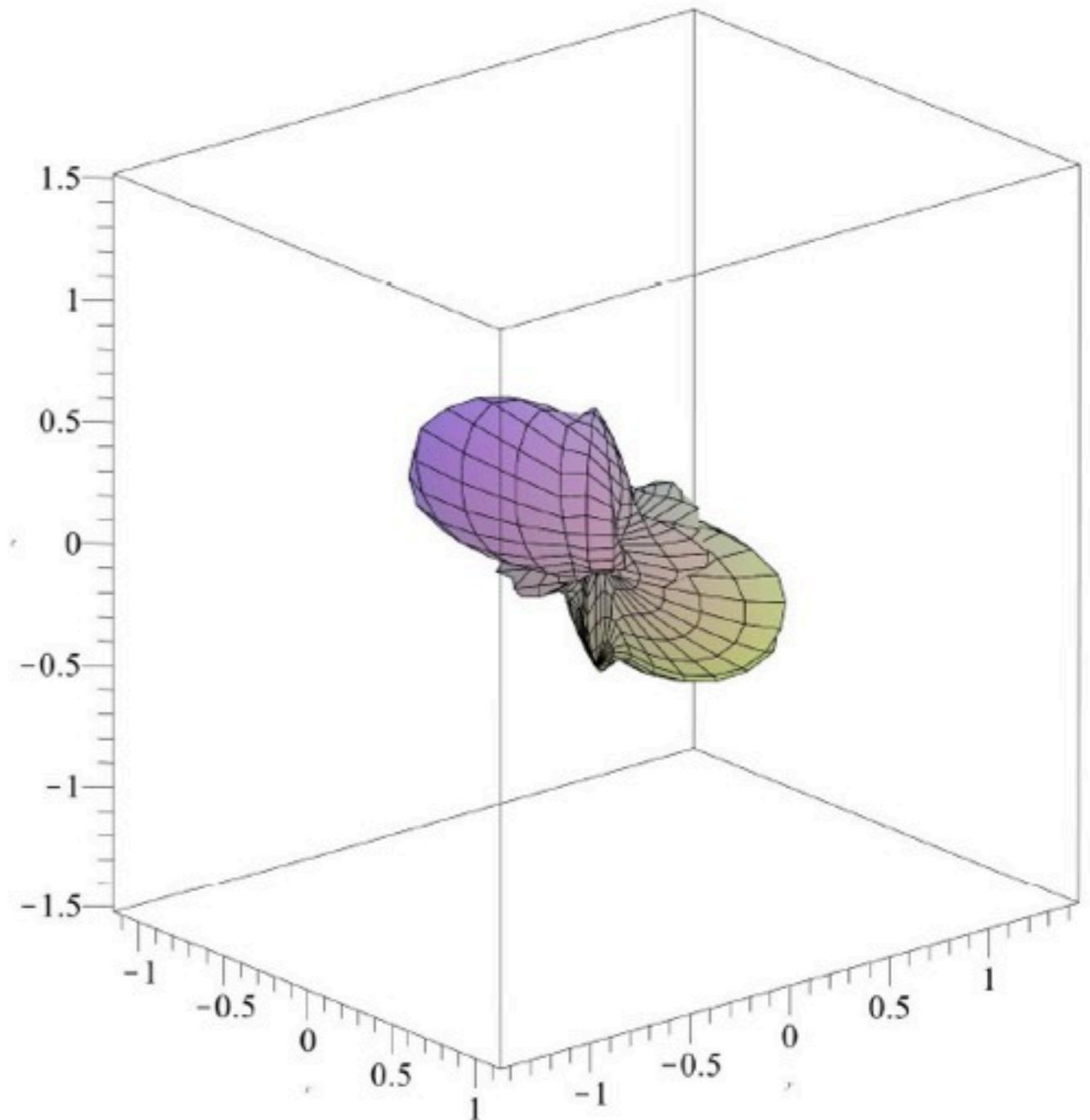
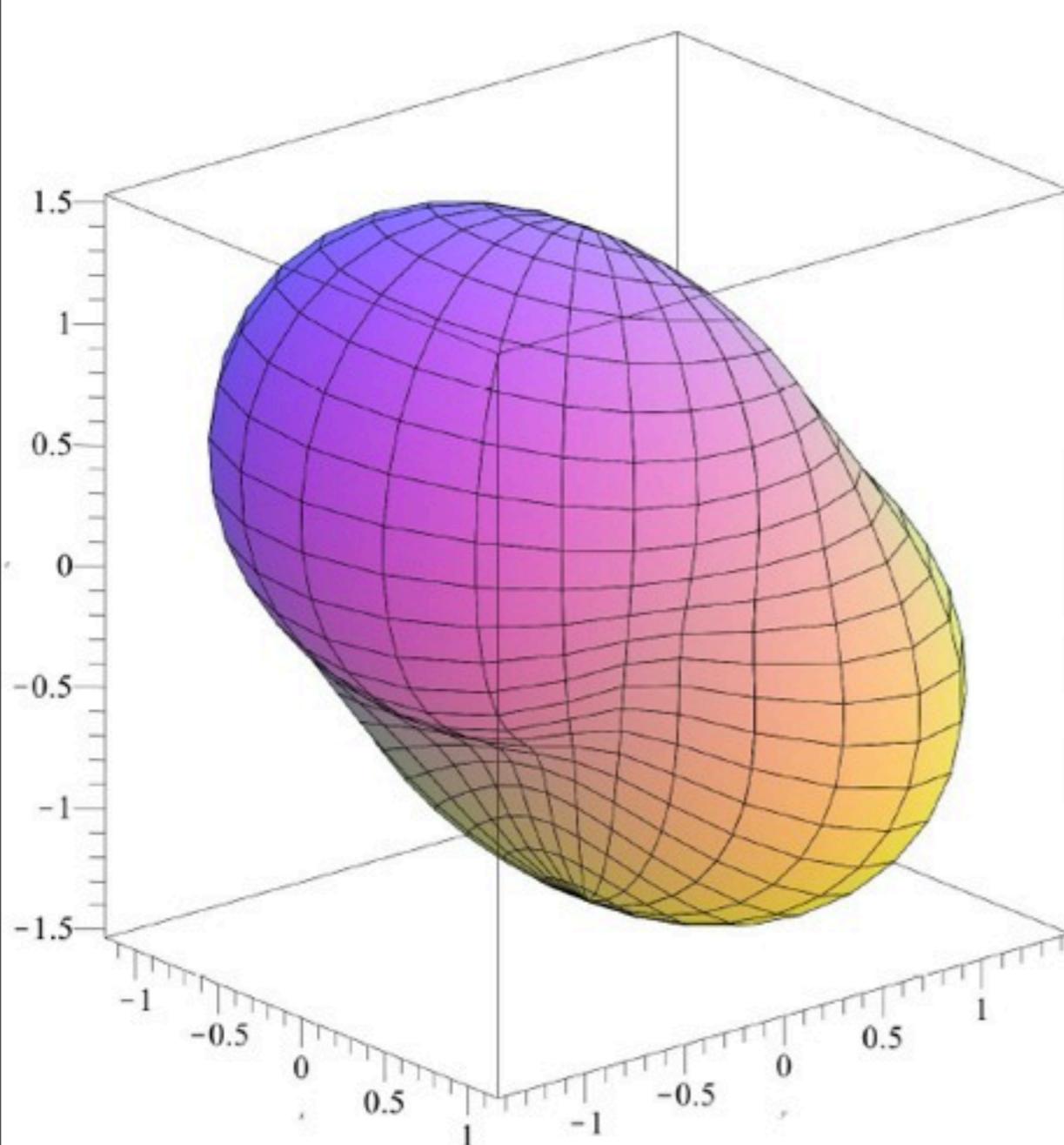


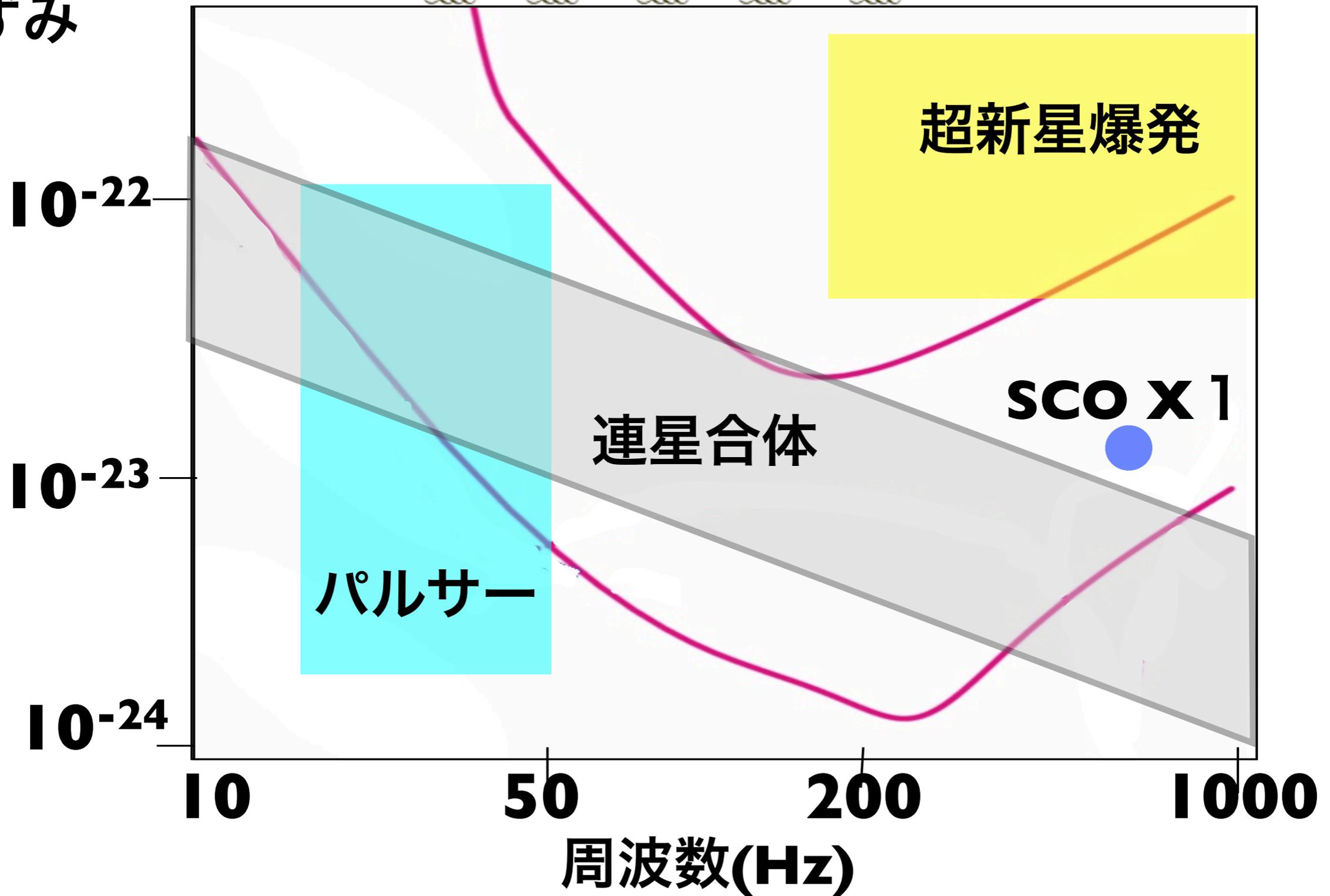
- **Virgoの感度を4倍にすると、重力波の到来方向推定は著しく改善される。**





● The antenna patterns of the LIGO-VIRGO detectors for (a) coherent and (b) coincidence analysis methods. The coherent pattern is the HHLV amplitude pattern. The coincidence pattern is the region in which, for random polarizations, an event crosses threshold in at least two of the detectors (but not allowing events that appear only in two Hanford detectors). The thresholds are assumed to be the same, e.g. if the individual detector thresholds for the coincidence analysis is 8, then the coherent data analysis threshold is also set at 8, as discussed in the text.





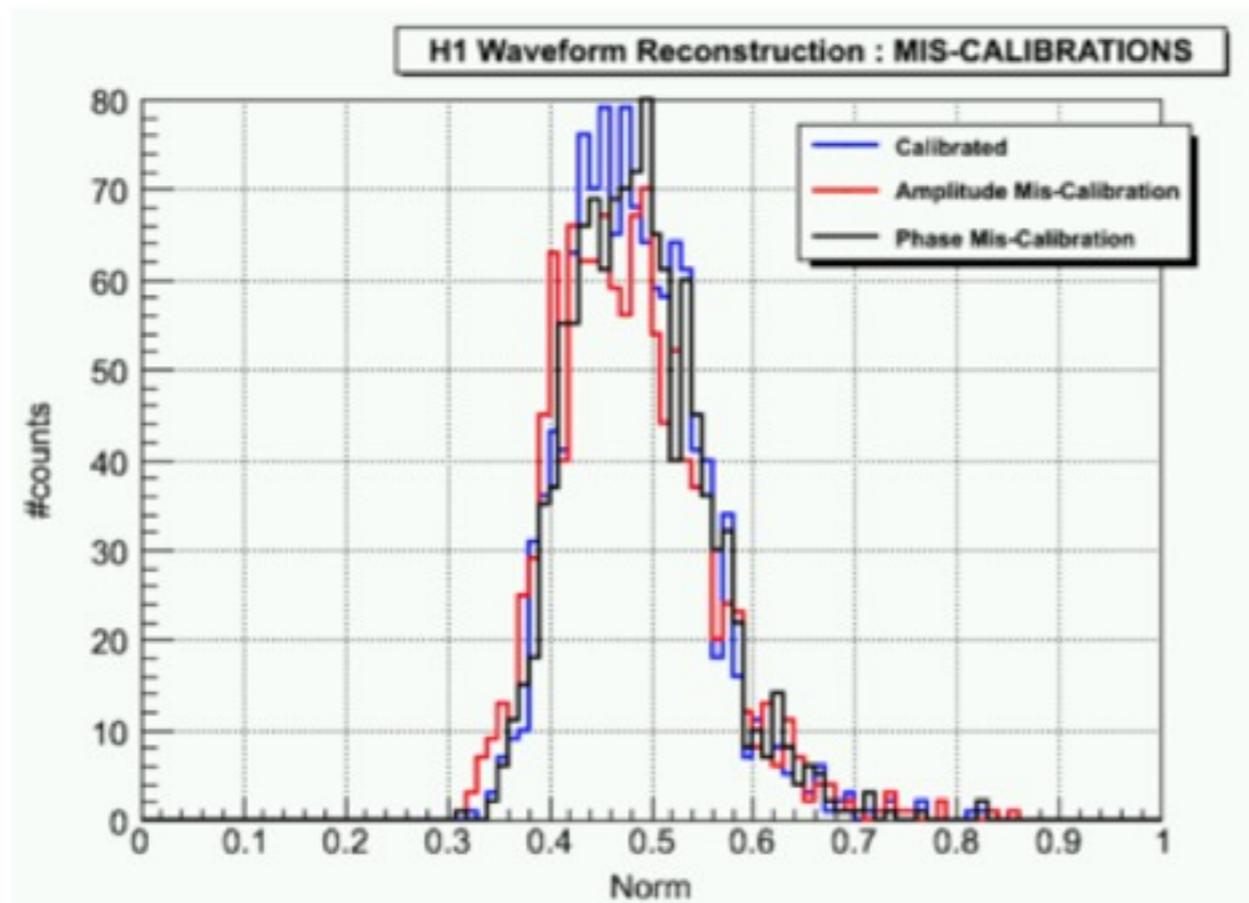
重力波の検出確率

初期望遠鏡 : 0.01%  
これからの望遠鏡 : 99.9%

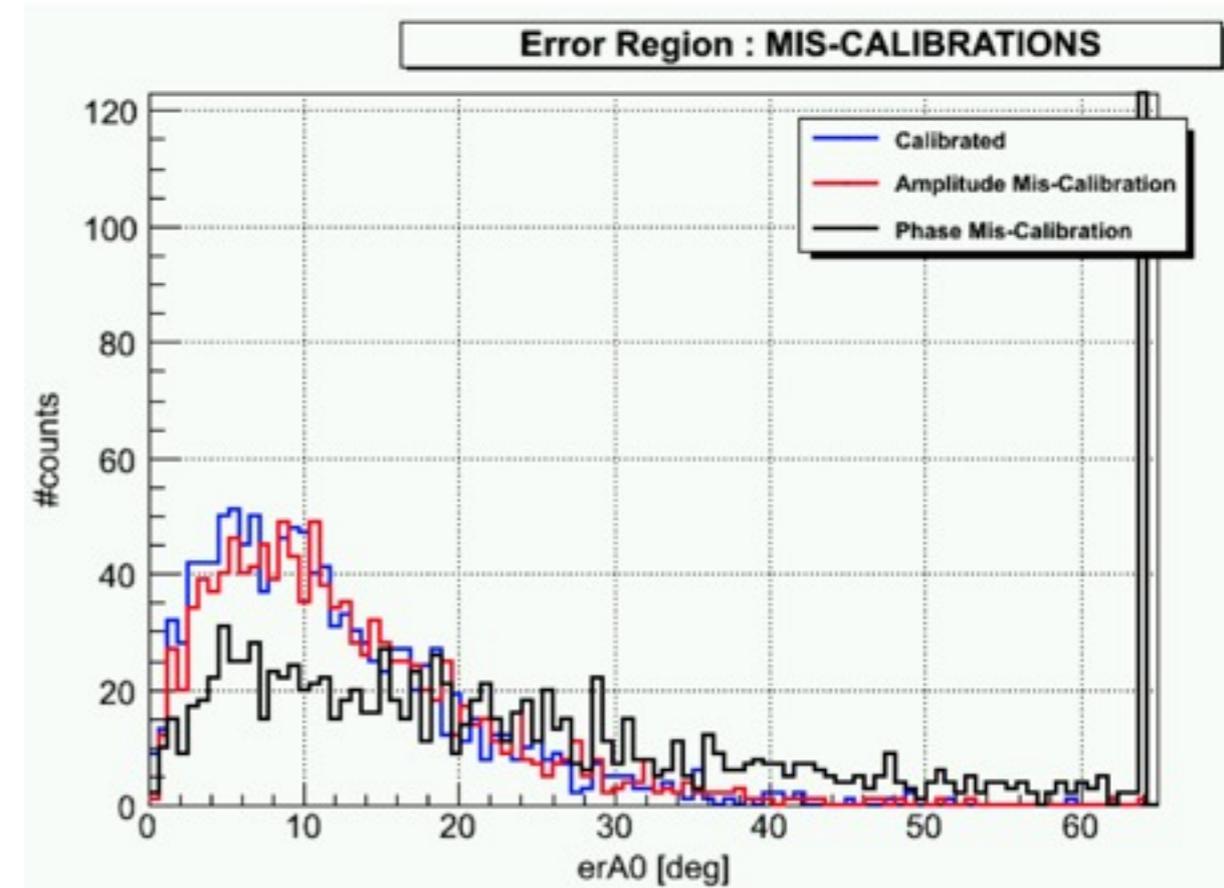


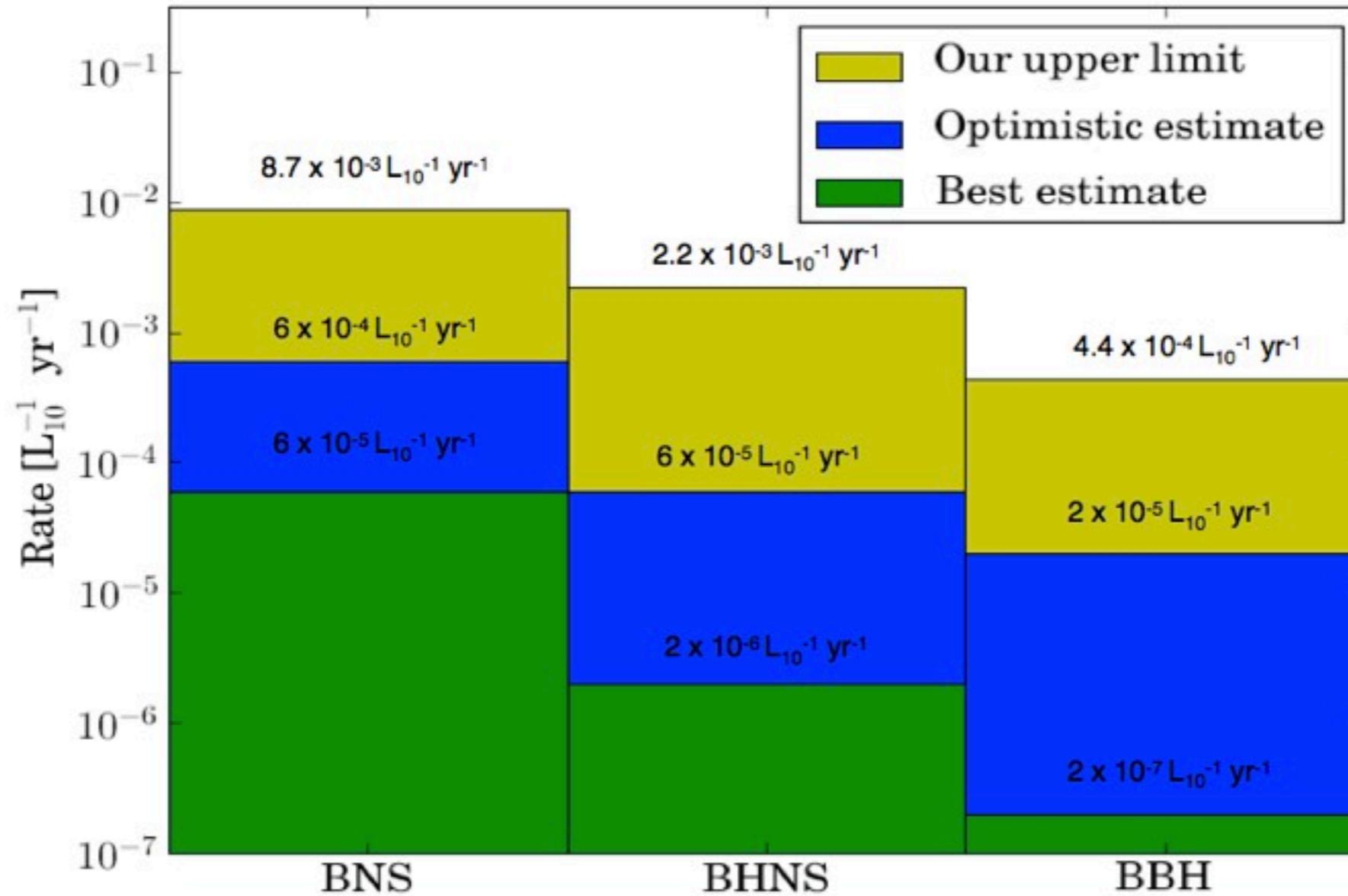
- キャリブレーションエラーの影響は結果を変えるほど大きなものではないことが分かった。

## Waveform reconstruction



## Sky location





**Figure 3:** Upper limits on the CBC rate calculated using data from LIGO's S5 and Virgo's VSR1 scientific runs are compared to the expected astrophysical rates.