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Six polarizations of GW and detector network with KAGRA

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1. Introduction

Six polarization modes

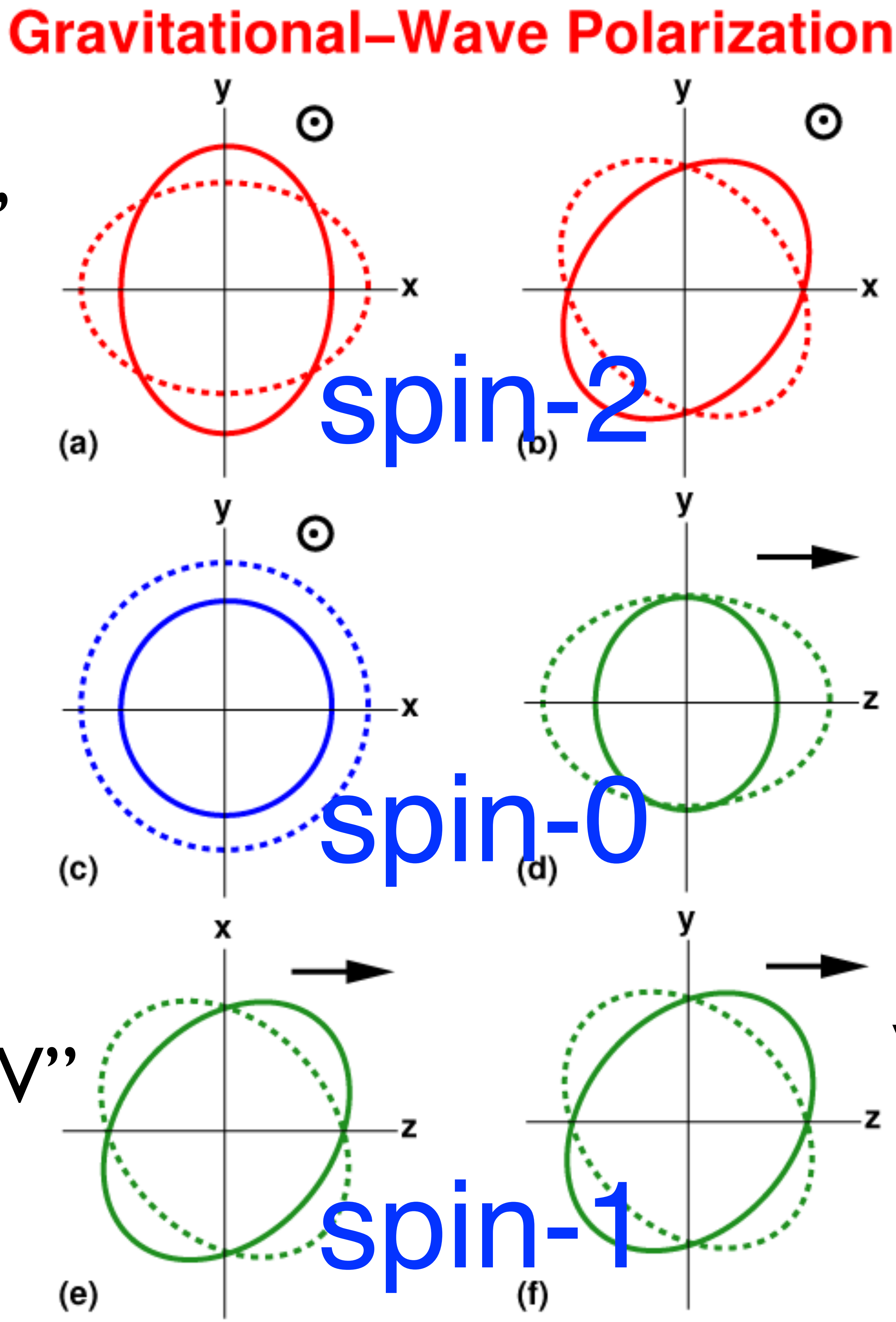
(two spin-0; two spin-1; two spin-2)

of gravitational waves (GWs)

are possible

in general metric theories of gravity

Will, Living Rev. Rel. (2014)



"Plus" h_{+}^{TT}

"Cross" h_{X}^{TT}

"Breathing" h^{S}

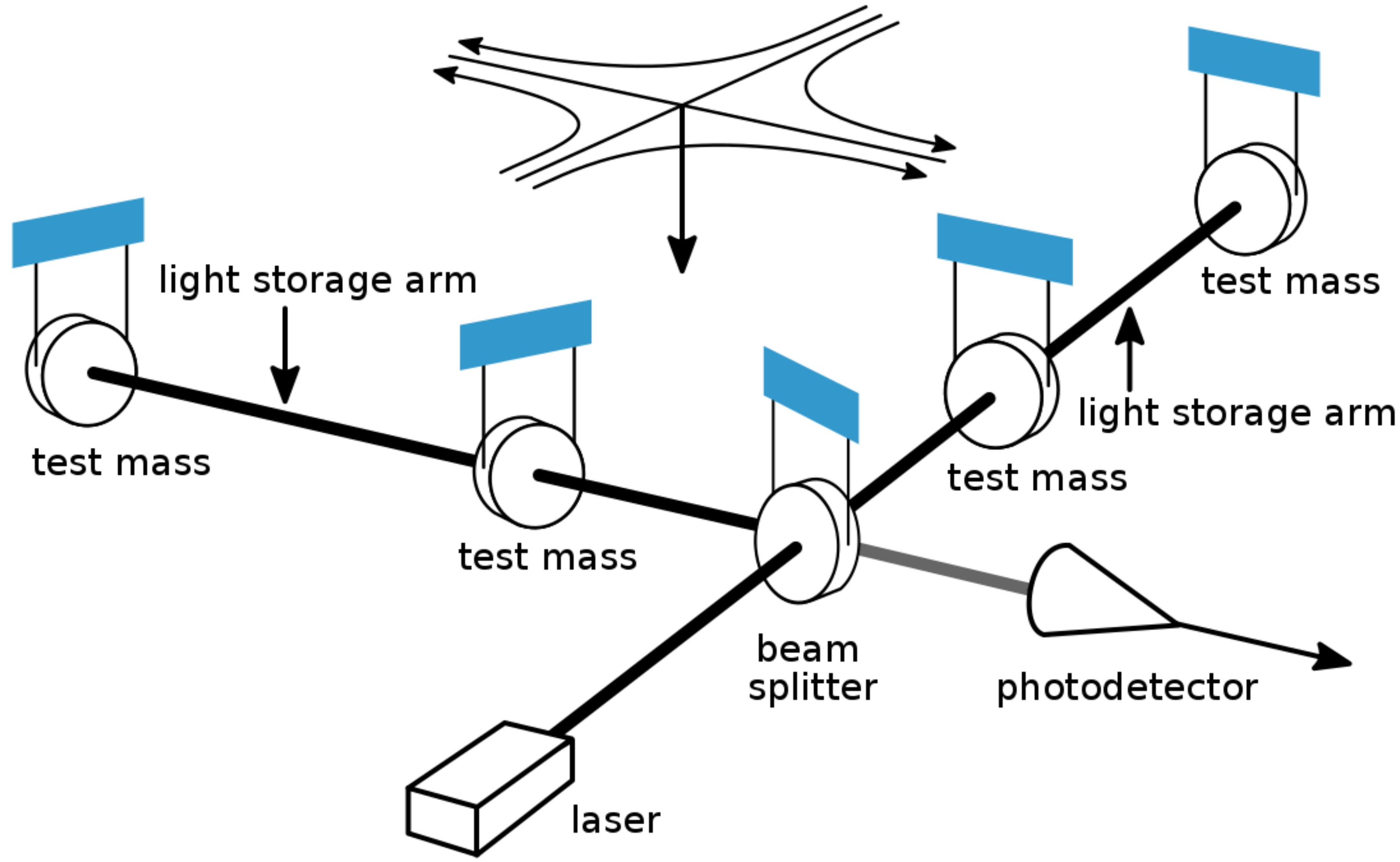
"Longitude" h^{L}

Vector "Vx=V" h^{V}

Vector "Vy=W" h^{W}

Detectors are labeled by “a”=1,2,…

Let “S_a” denote a signal output at the “a”-detector.



S1		h_+^{TT}
S2		h_X^{TT}
S3	⟷	h^S
S4		h^L
S5		h^V
S6		h^W

We need construct

six (non-co-aligned)

GW detectors

in order to test

six polarization modes

This is correct but …

Probing gravitational wave polarizations with Advanced LIGO, Advanced Virgo and KAGRA

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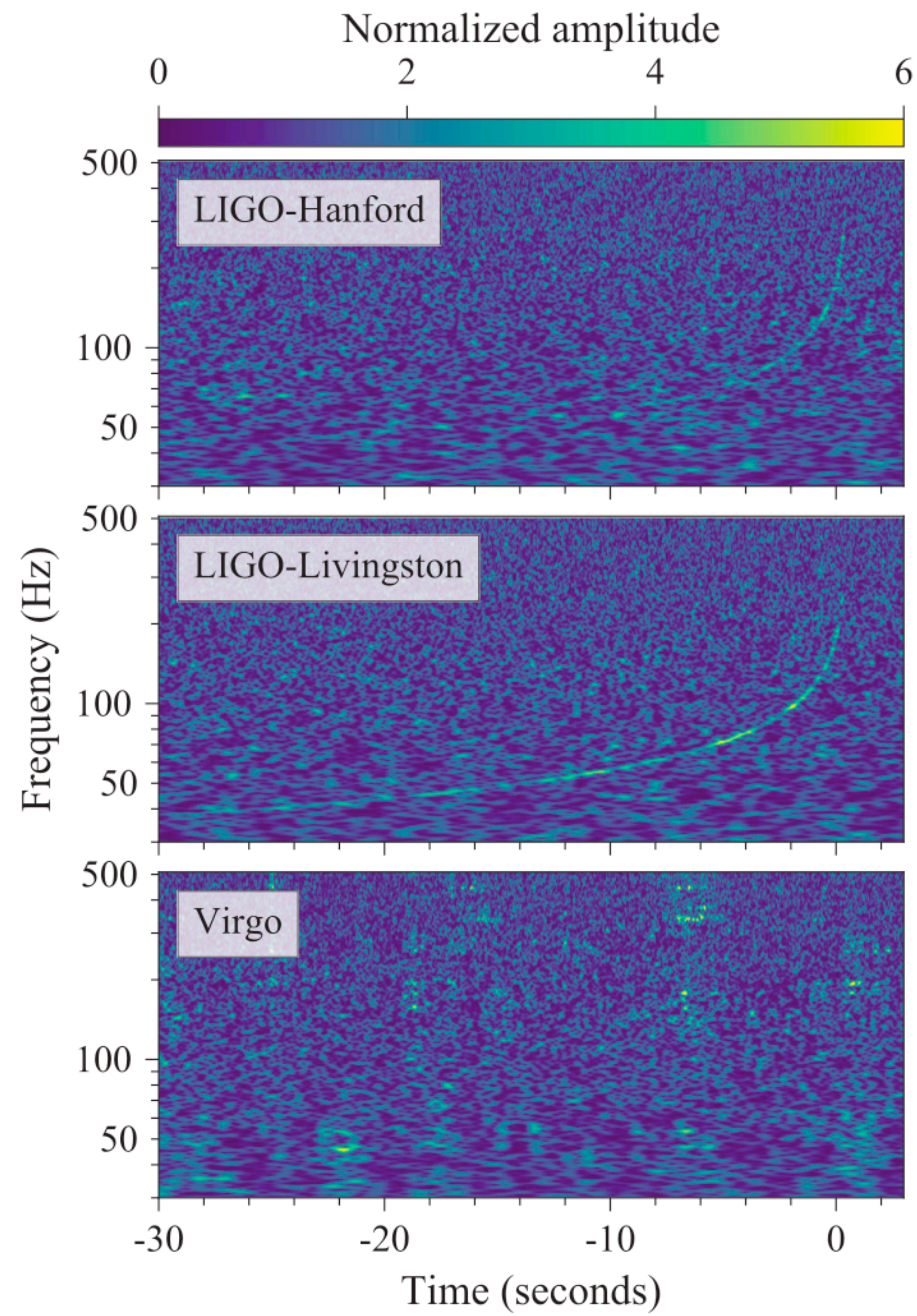
Graduate School of Science and Technology,

Hirosaki University, Aomori 036-8561, Japan

(Dated: July 20, 2018) ArXiv:1807.07234

This work was initiated in my three undergrad students' graduation thesis ("Sotsugyo-kenkyuu" or "Sotsu-ron" in Japanese, March 2018).

GW170817



Normalized amplitude
0
2
4
6
500
100
50
LIGO-Hanford
500
100
50
LIGO-Livingston
500
100
50
Virgo
Frequency (Hz)
-30
-20
-10
0
Time (seconds)

In today's my talk,

GW Inverse Problem

First, GW detector signals are given.
Then, we want to know the GW polarizations.

Please do not be confused with
a forward problem on GWs;

First, we assume GW sources.

Next, we calculate GW generation (and propagation).

Thirdly, we compute what signals are detected.

Assume

(1)

We know the sky location of
a GW event with an EM counterpart
such as GW170817.

(2)

Four (less than 6) unaligned GW detectors ---

aLIGO-Hanford (H)

aLIGO-Livingston (L)

Advanced Virgo (V)

KAGRA (K)

GW170817 tells us

GW speed = Light speed at $O(10^{-15})$

In my talk, GW speed = Light speed .

By the assumption (1) that we know the GW/EM source position, we can shift the arrival time from detector to detector.

GW sources are generally very far from the Earth.

The plane wave approximation of GWs can be thus used and hence the GW propagation direction (θ, Φ) is the same for all four detectors (with respect to Earth frame but not the detector frame).

2. What is a null stream?

Idea behind the null stream(NS)

Gursel and Tinto(1989)

In GR with ignoring detectors' noise,
we assume three detectors

$$S_1 = C_1 h^+ + D_1 h^\times$$
$$S_2 = C_2 h^+ + D_2 h^\times$$
$$S_3 = C_3 h^+ + D_3 h^\times$$

Overdetermined System: 3 equations for 2 variables

$$
\begin{aligned}
&(C_2D_3 - C_3D_2)S_1 \\
&+(C_3D_1 - C_1D_3)S_2 \\
&+(C_1D_2 - C_2D_1)S_3 = 0
\end{aligned}
$$

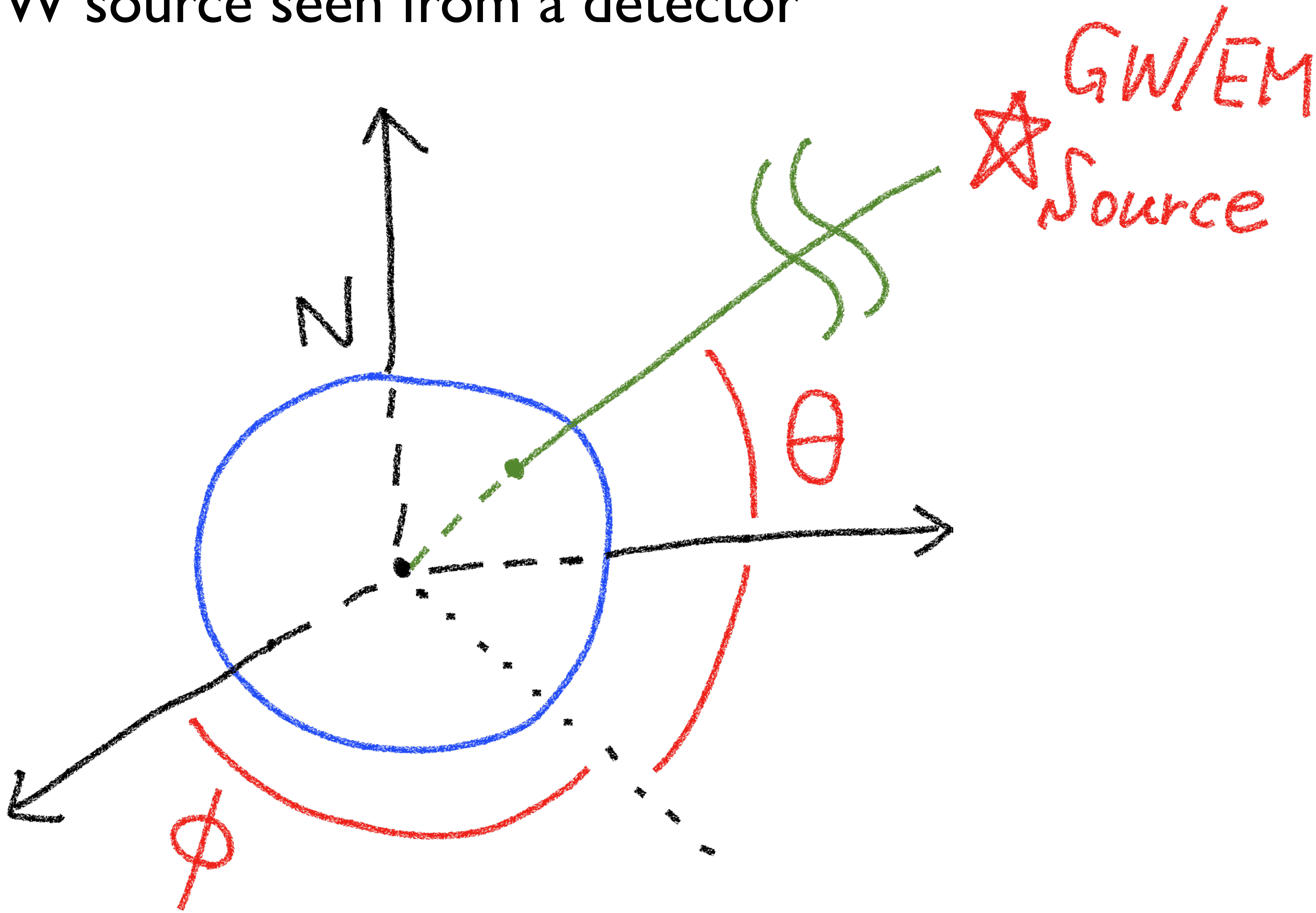
This is often called **Null Stream**

See also Eq. (9) in Wen and Schutz (2005)

Here, our idea is that spin-0 and/or spin-1 GW modes will make the R.H.S. of the NS non-zero and hence they may be probed in the null steam approach.

3. Four unaligned GW detectors

GW source seen from a detector



Signal at the a-th detector

$$S_a = F_a^+ h^+ + F_a^\times h^\times + F_a^S h^S + F_a^L h^L + F_a^V h^V + F_a^W h^W + n_a$$

F_a^* = Antenna Pattern Function

= f(θ, Φ; ψ)

Sky position   Polarization angle (w.r.t detector x-arm)

Nishizawa et al (2009) proved

$$F_a^S = -F_a^L$$

We thus rewrite

$$\begin{aligned} S_a = & C_a h^+ + D_a h^\times \\ & + E_a(h^S - h^L) \\ & + V_a h^V + W_a h^W + n_a \end{aligned}$$

Four null streams in GR with ignoring noise

$$\delta_{23}S_1 + \delta_{31}S_2 + \delta_{12}S_3 = 0,$$

$$\delta_{34}S_2 + \delta_{42}S_3 + \delta_{23}S_4 = 0,$$

$$\delta_{41}S_3 + \delta_{13}S_4 + \delta_{34}S_1 = 0,$$

$$\delta_{12}S_4 + \delta_{24}S_1 + \delta_{41}S_2 = 0.$$

$$\delta_{ab} \equiv C_a D_b - C_b D_a.$$

Hagihara+(2018) shows that two of the four null streams can construct the remaining two almost everywhere.

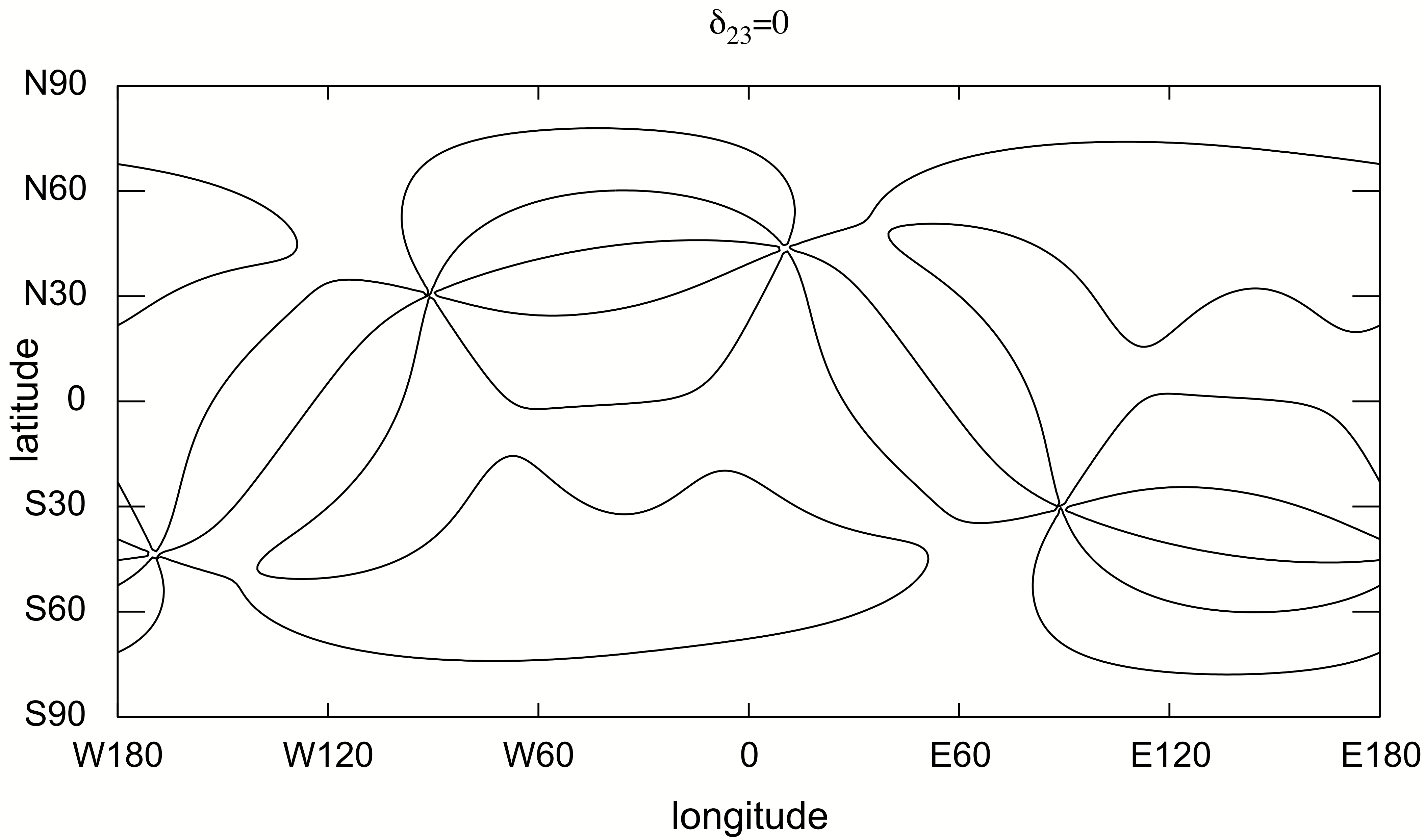


FIG. 1: Curves for $\delta_{23} = 0$ in the sky, where L=2 and V=3 are assumed.

Without loss of generality, we choose two NSs

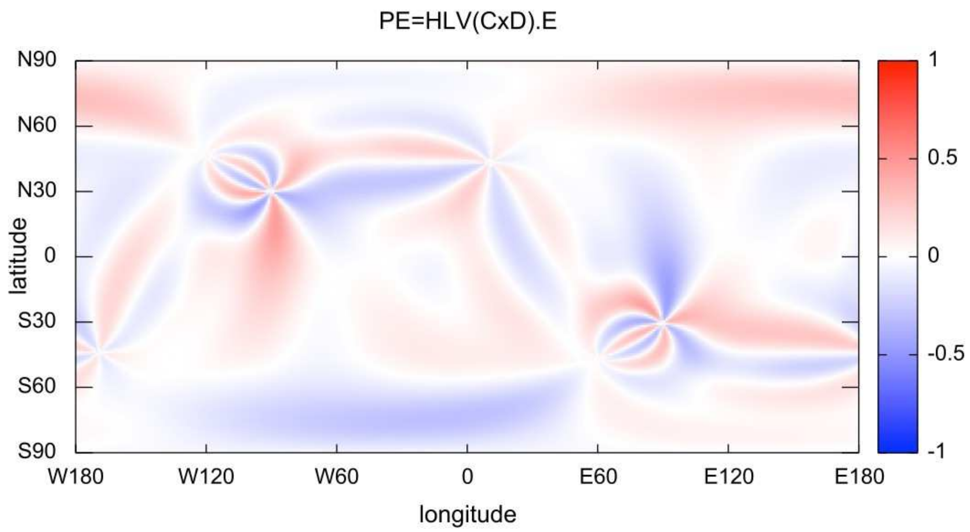
$$(P_a) = (\delta_{23}, \delta_{31}, \delta_{12}, 0)$$

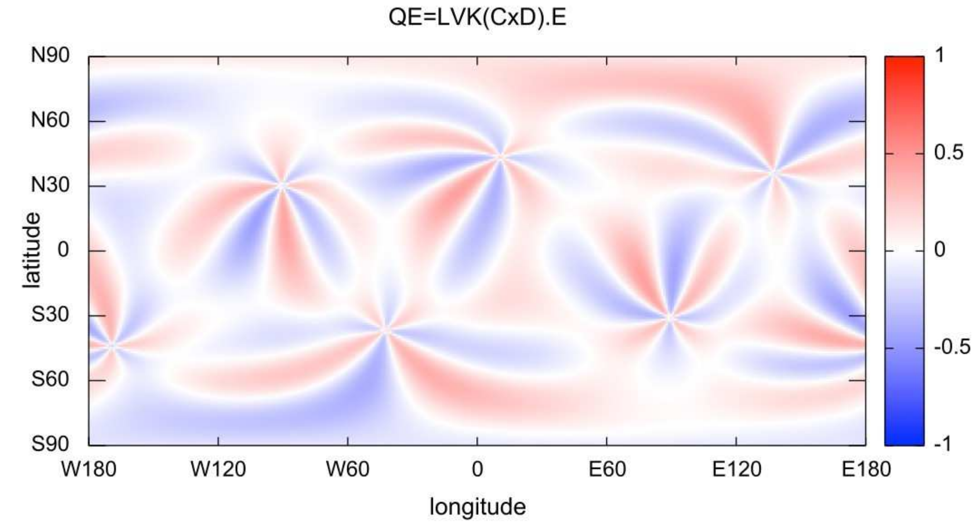
$$(Q_a) = (0, \delta_{34}, \delta_{42}, \delta_{23})$$

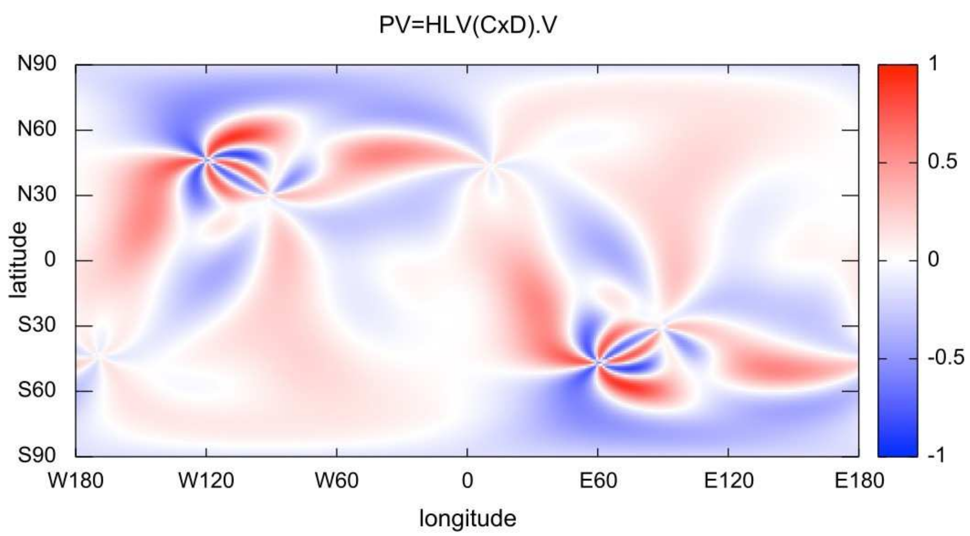
$$P_a S_a = (P_b E_b)(h^S - h^L) + (P_c V_c) h_V + (P_d W_d) h_W + P_e n_e,$$

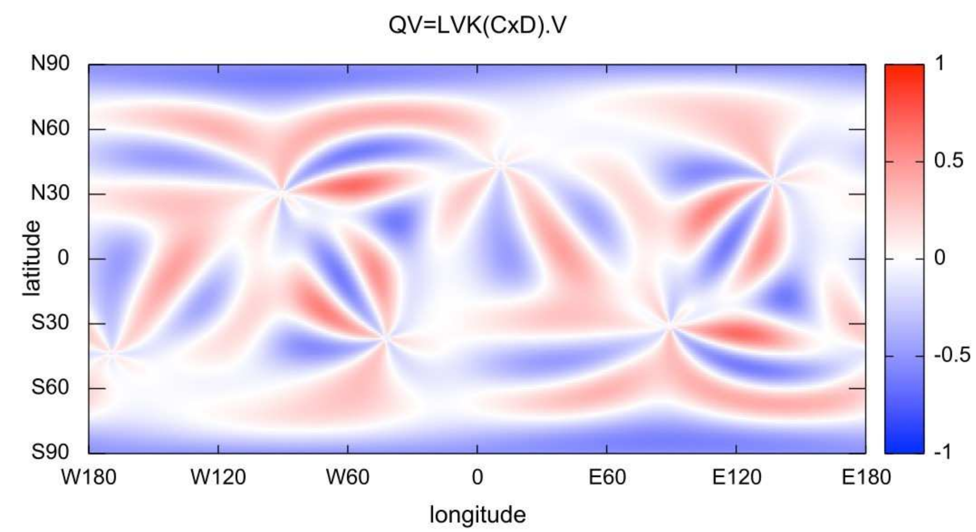
$$Q_f S_f = (Q_g E_g)(h^S - h^L) + (Q_h V_h) h_V + (Q_i W_i) h_W + Q_j n_j,$$

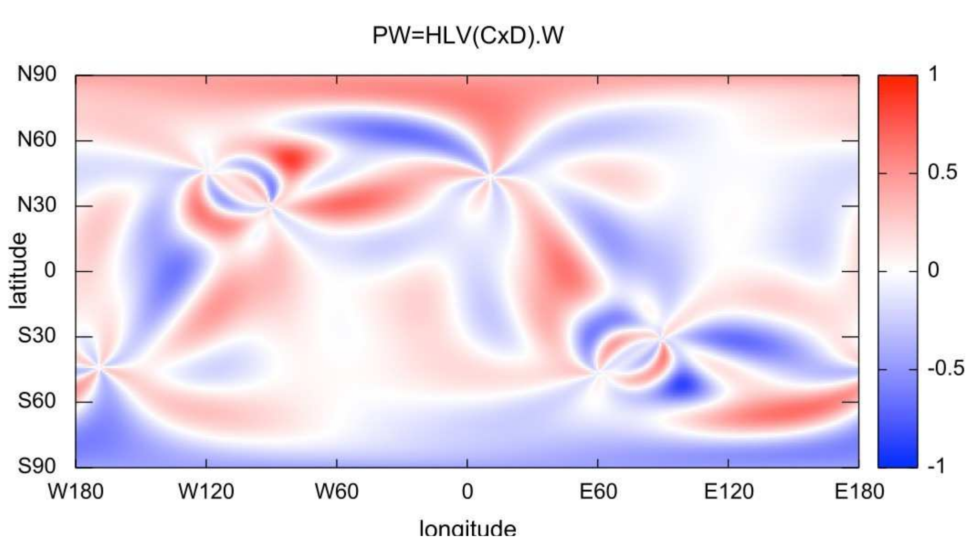
In our numerical study, H=1, L=2, V=3 and K=4.

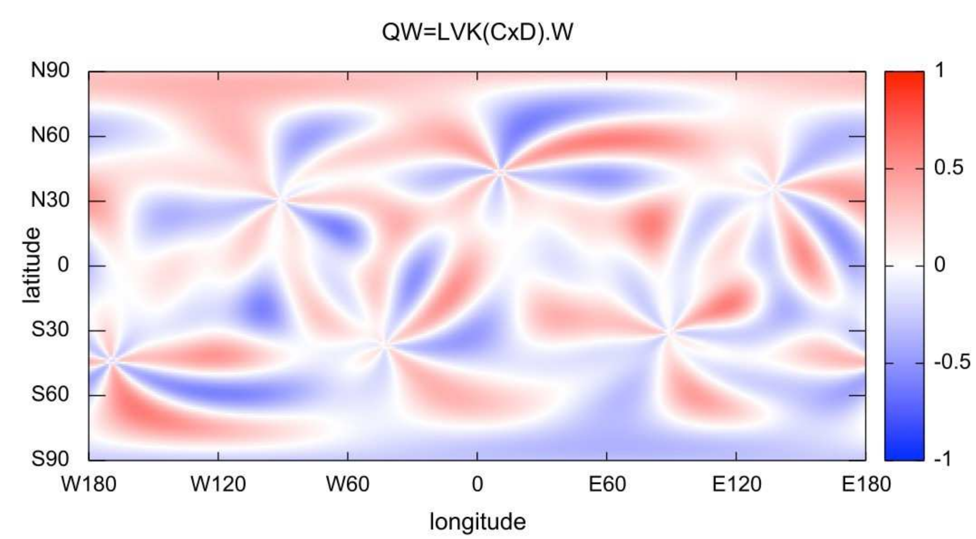

PE=HLV(CxD).E
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1


QE=LVK(CxD).E
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1


PV=HLV(CxD).V
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1


QV=LVK(CxD).V
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1


PW=HLV(CxD).W
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1


QW=LVK(CxD).W
N90
N60
N30
0
S30
S60
S90
latitude
W180
W120
W60
0
E60
E120
E180
longitude
1
0.5
0
-0.5
-1

We examine a sky position that simultaneously

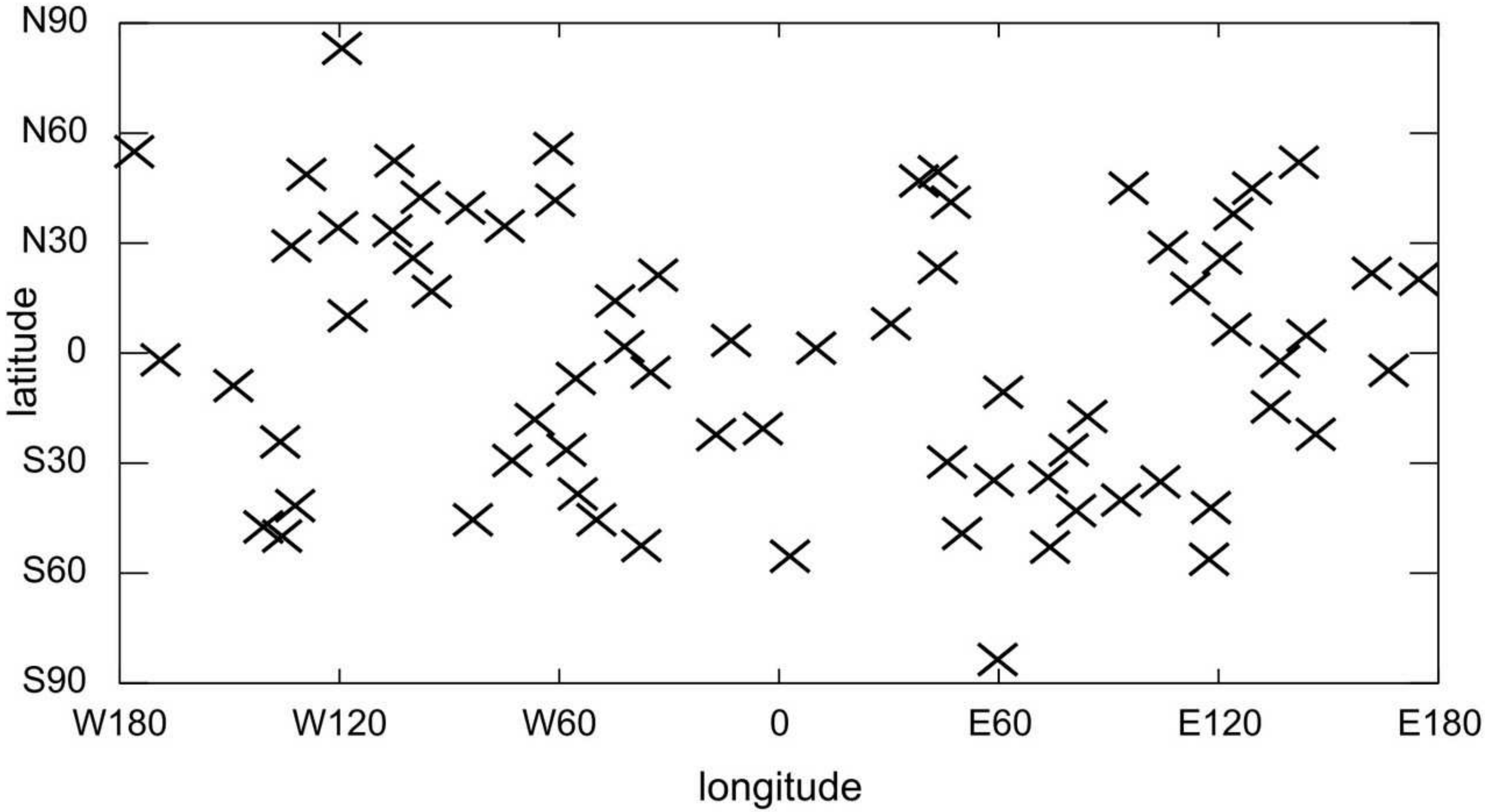
$$P_a E_a = 0 \qquad Q_a E_a = 0$$

for which the spin-0 modes are killed in NSs.

Therefore, spin-1 modes will be testable.

$$\begin{pmatrix} h^V \\ h^W \end{pmatrix} = \begin{pmatrix} P_a V_a & P_b W_b \\ Q_c V_c & Q_d W_d \end{pmatrix}^{-1} \begin{pmatrix} P_e(S_e - n_e) \\ Q_f(S_f - n_f) \end{pmatrix}$$

How small (or large) is the probability ?



"Treasure Map"

4. Conclusion

Even with the only four detectors HLVK, we will be able to probe separately GW spin-0 and/or spin-1 polarizations, if someone of HLVK members is super-lucky (like Professor Koshiba-sensei) to observe a GW/EM source in one of the nearly one hundred sky positions.

Thank you!

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