measuring **GW polarizations beyond GR** recent results and future prospects

Maximiliano Isi
LIGO Laboratory
California Institute of Technology
Massachusetts Institute of Technology

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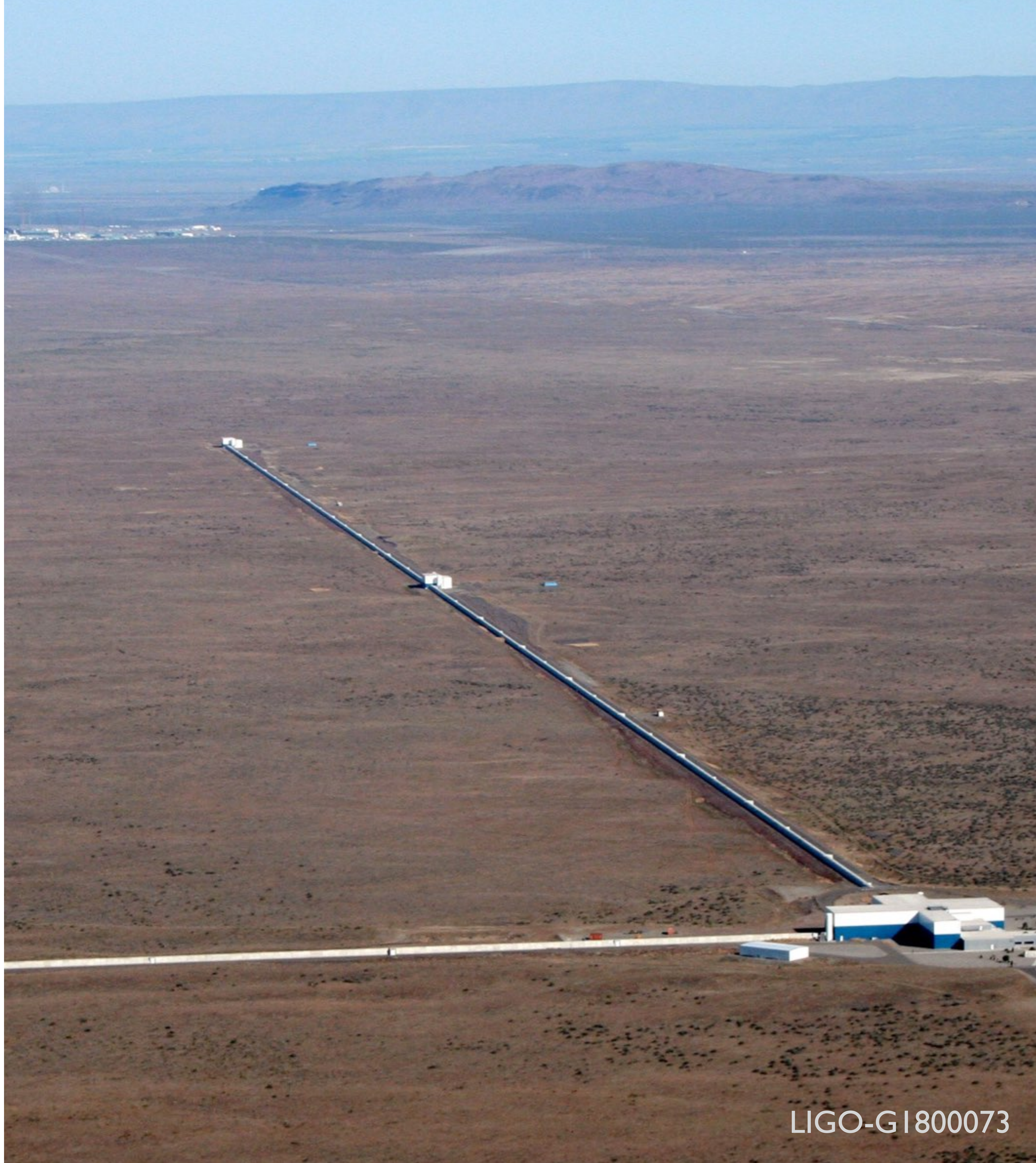
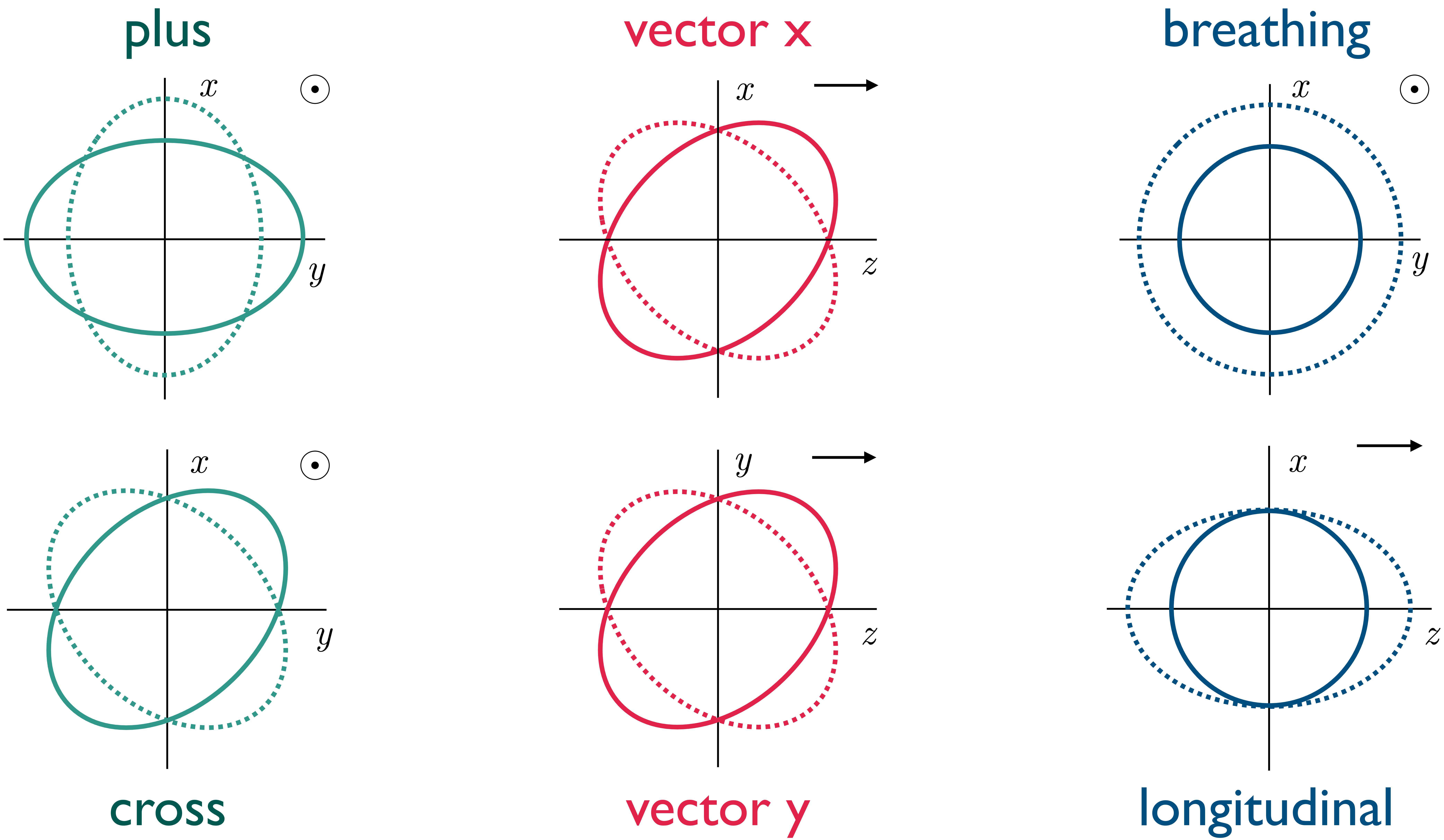
Caltech MIT LIGO



LIGO-G1800073



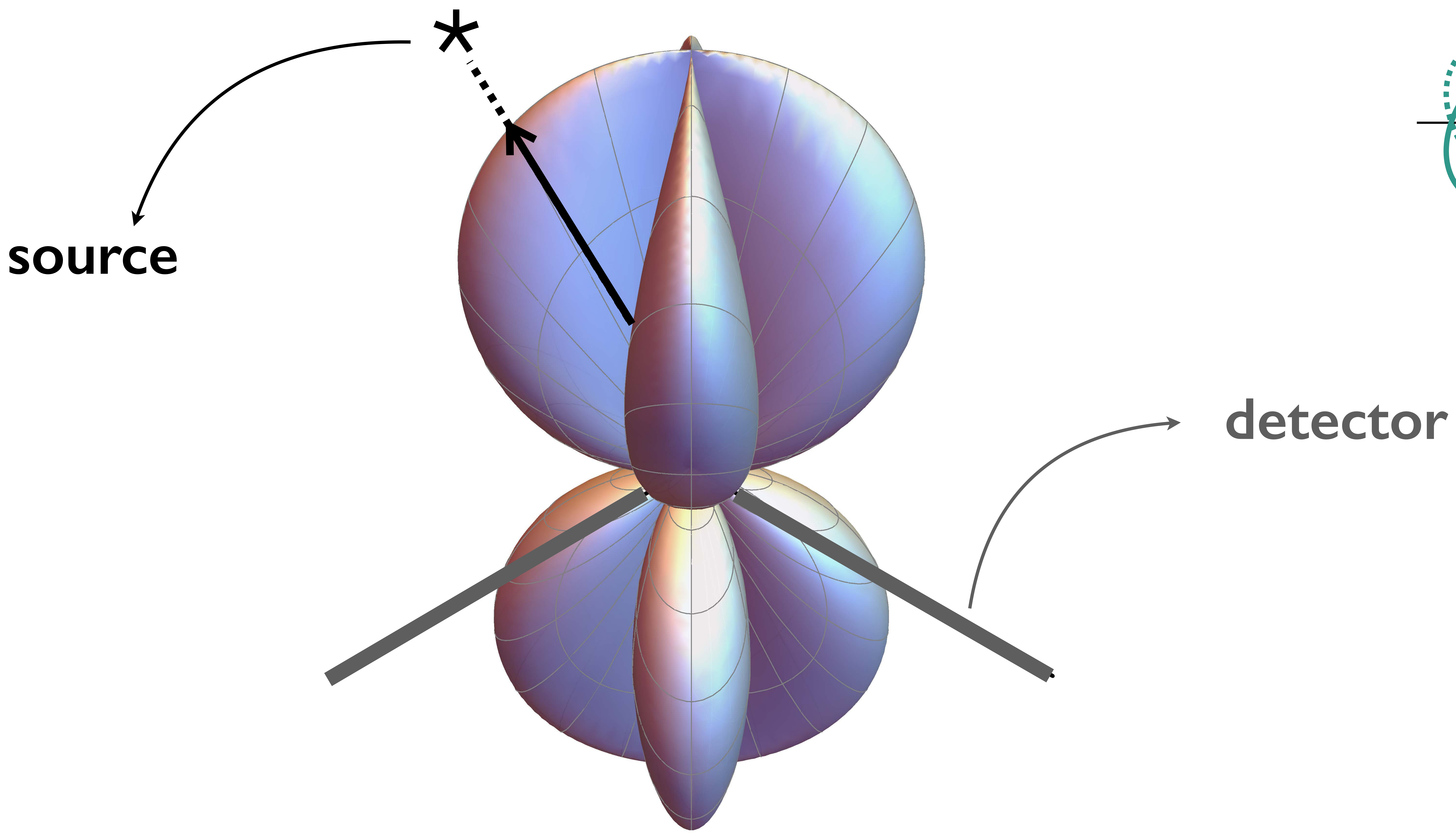
wave propagates always in z-direction

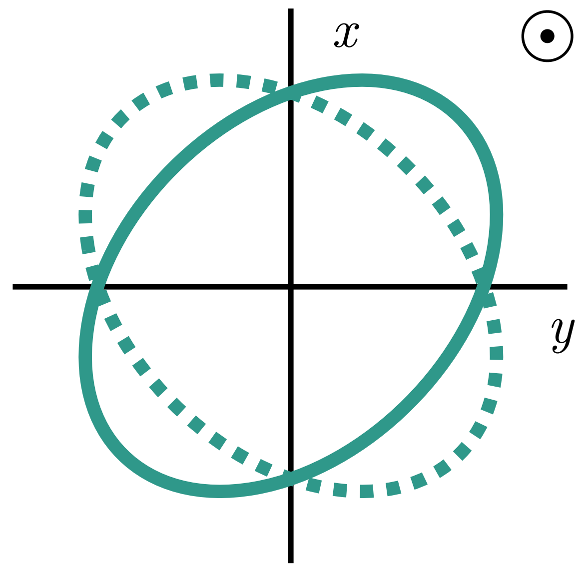
goal

**study polarizations* via
projection of GW onto detectors**

directly via a semi-local measurement
with the fewest possible assumptions
about source and phase evolution

*i.e. which directions are stretched/squeezed with respect to wave-vector

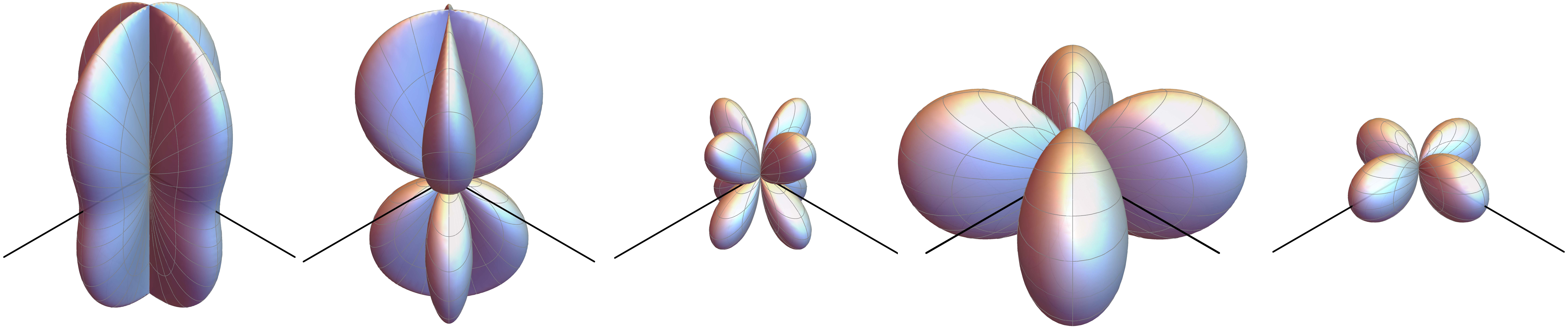




angular sensitivity to cross polarization

radial distance gives sensitivity to a wave from that direction; detector arms along *x* & *y* axis (straight lines)

angular sensitivity



plus cross vector x vector y scalar

detector arms have unit length in all plots

polarization measurement

polarization geometry gets encoded in
relative amplitude, phase and timing
at each detector via the antenna patterns

but…

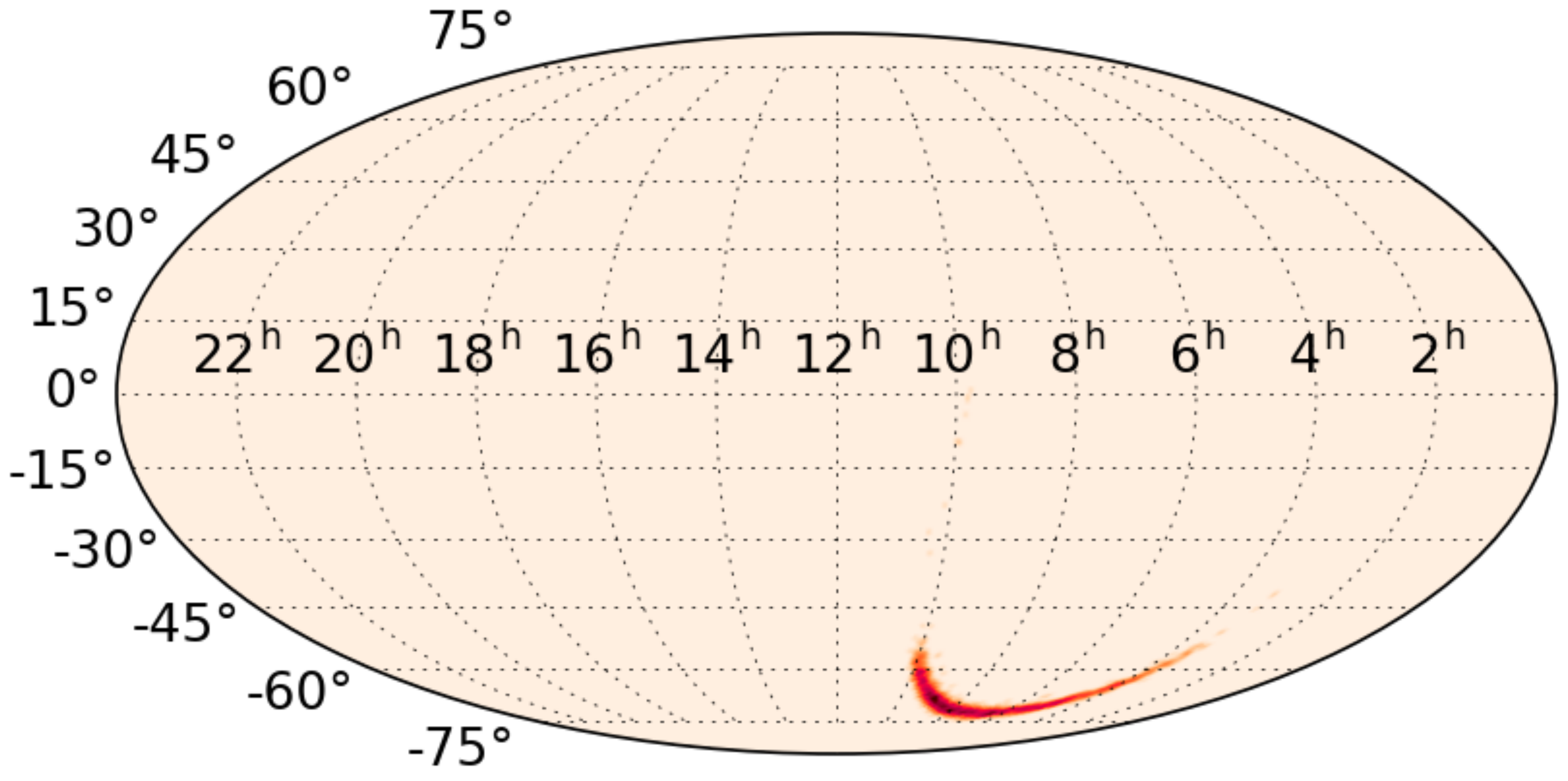
cannot break *all* degeneracies
with less than 5 detectors*

to make things worse, LIGO detectors are nearly coaligned

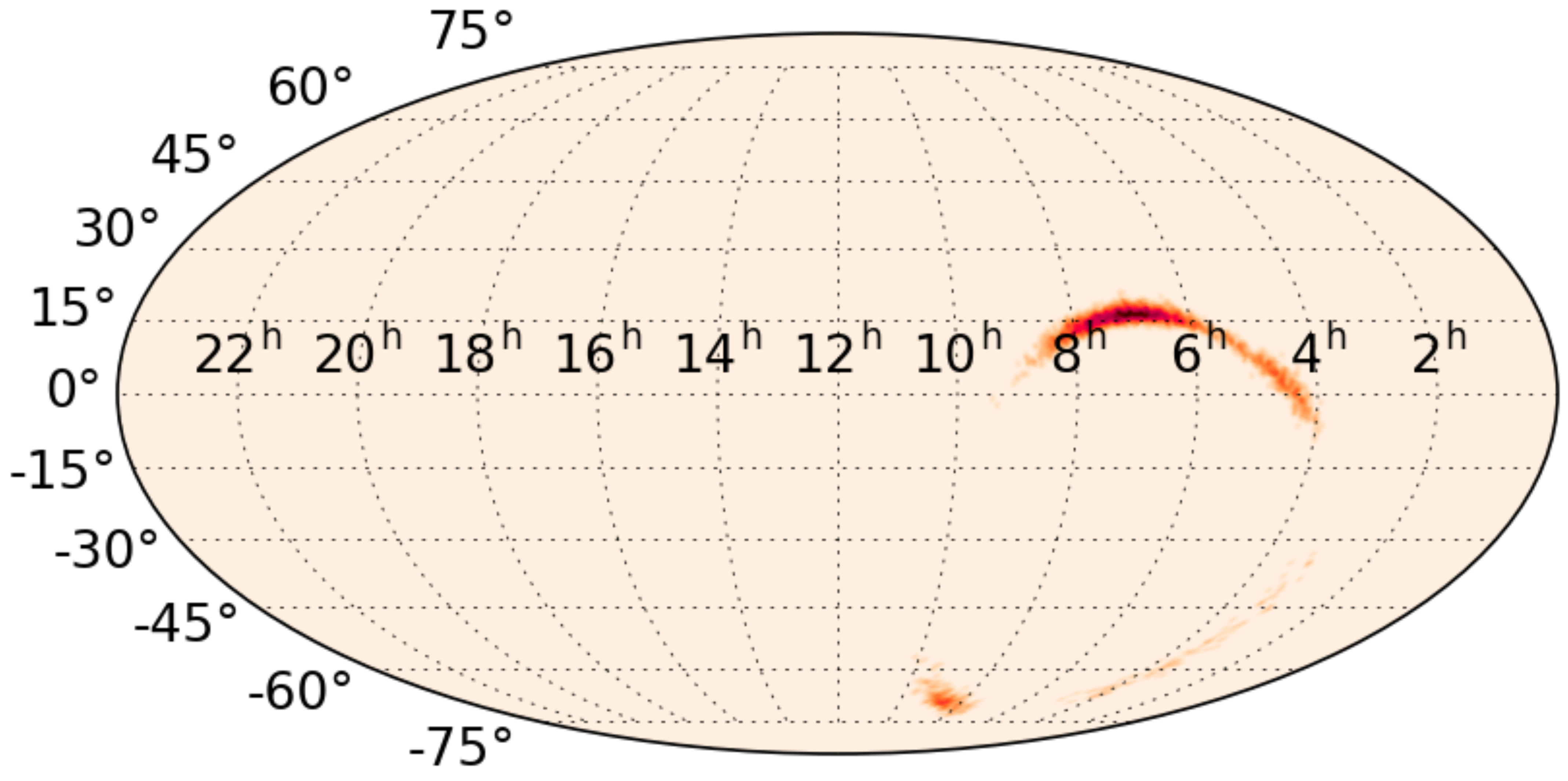
*non-coaligned differential-arm detectors, with *transient* signals, and even with an EM counterpart all LIGO-only detections are consistent with fully-non-GR polarizations for example

GW150914

tensor



vector



equally likely in a Bayesian sense

(i.e. both hypotheses yield same evidence)

Virgo helps break *some* degeneracies

start by looking at the extremes

tensor

VS

vector

VS

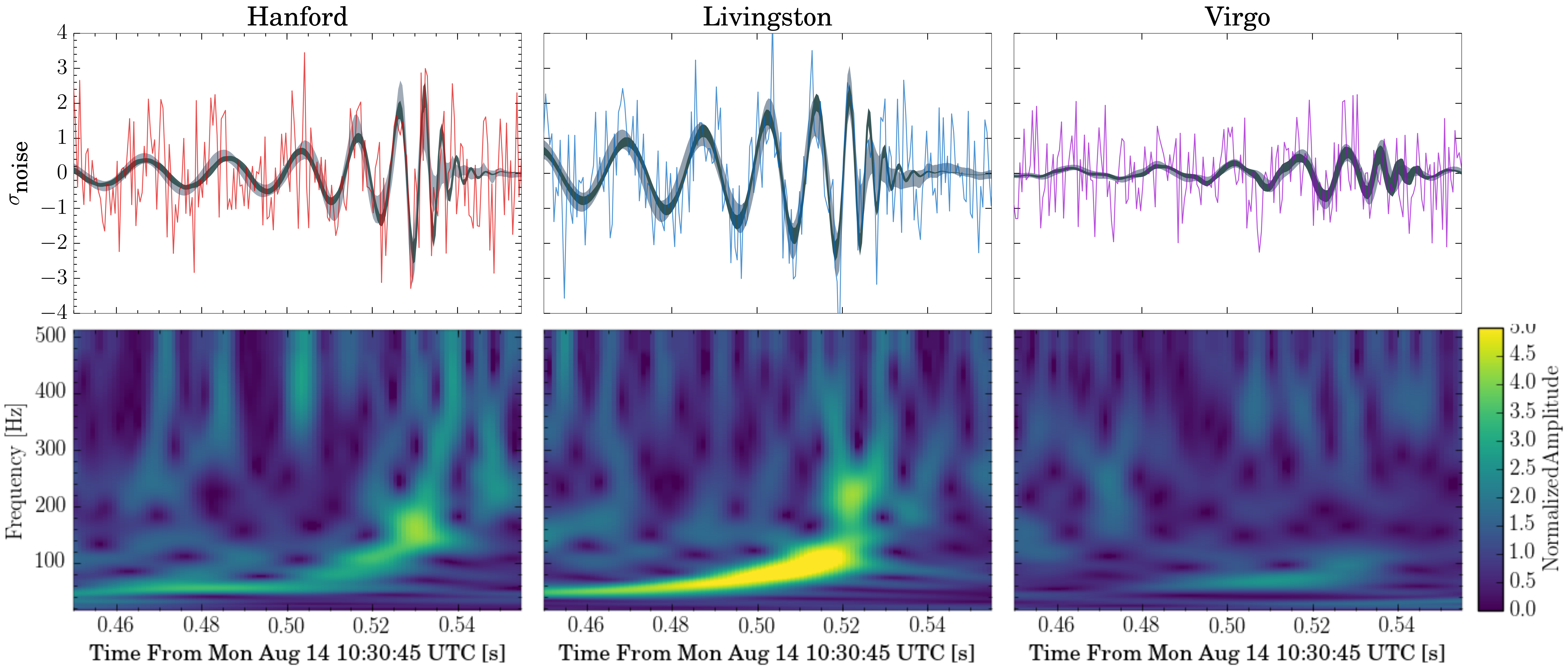
scalar

analyze the data under these 3 polarization hypotheses

no mixtures allowed!

GW170814

can the 3-detector data distinguish between a pure tensor, pure vector, or pure scalar signal?



[PhysRevLett.119.141101]

GW170814

$$\mathcal{B}^a_b \equiv \frac{P(\vec{d} \mid \mathcal{H}_a)}{P(\vec{d} \mid \mathcal{H}_b)}$$

bayes factors

tensor vs

	vector	**scalar**
HL	0.17 : 1	0.46 : 1
HLV	**>200 : 1**	**>1000 : 1**

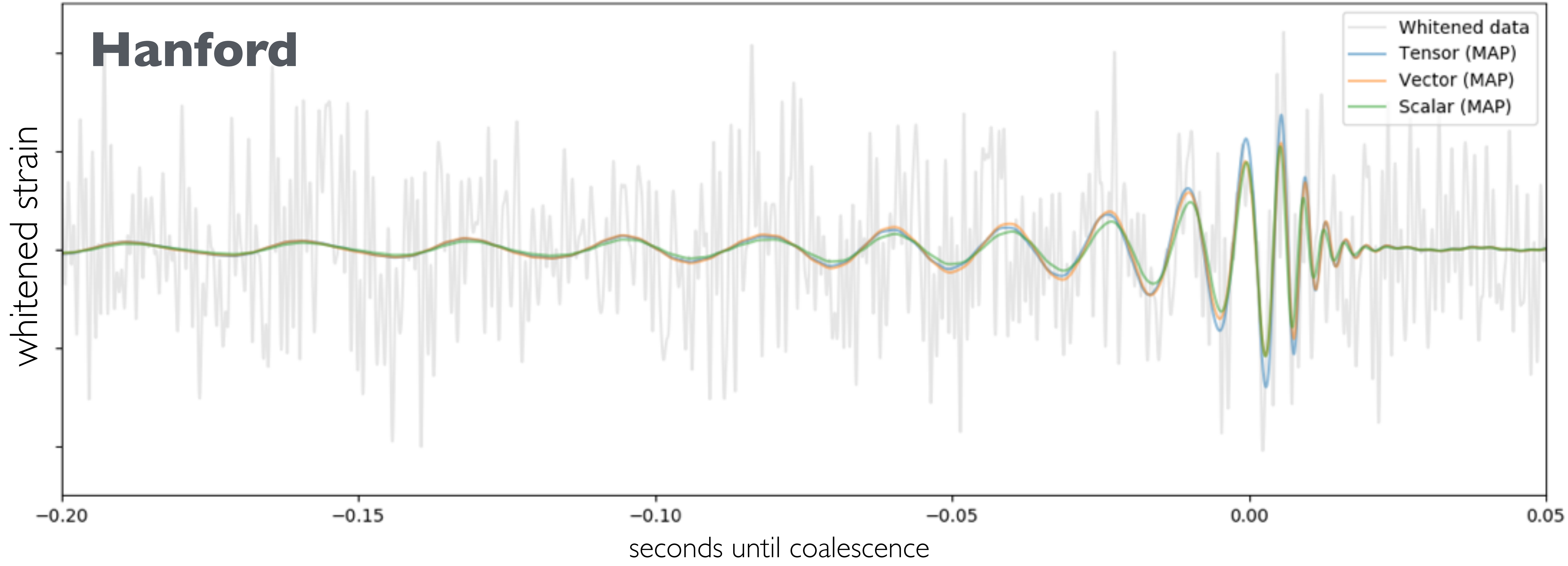
Virgo is key!

data favor GR

numbers from templated analysis—unmodeled sine-Gaussian studies reproduce these results

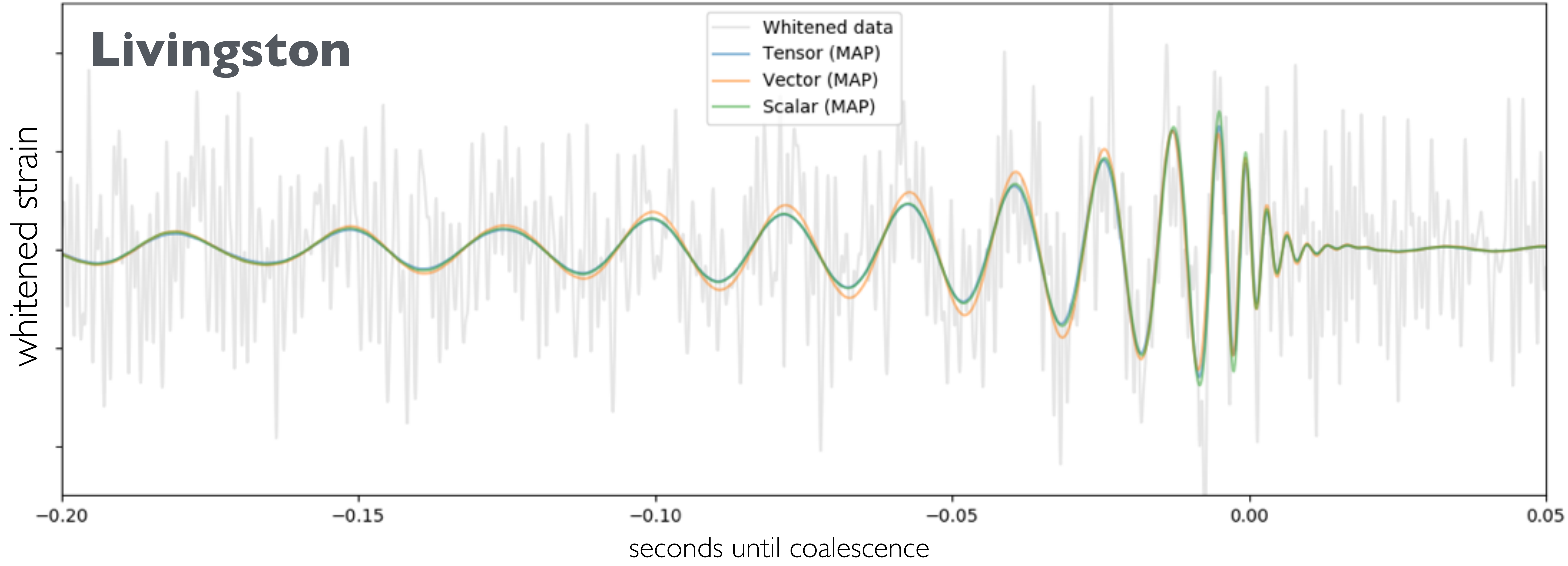
[PhysRevLett.119.141101]

GW170814

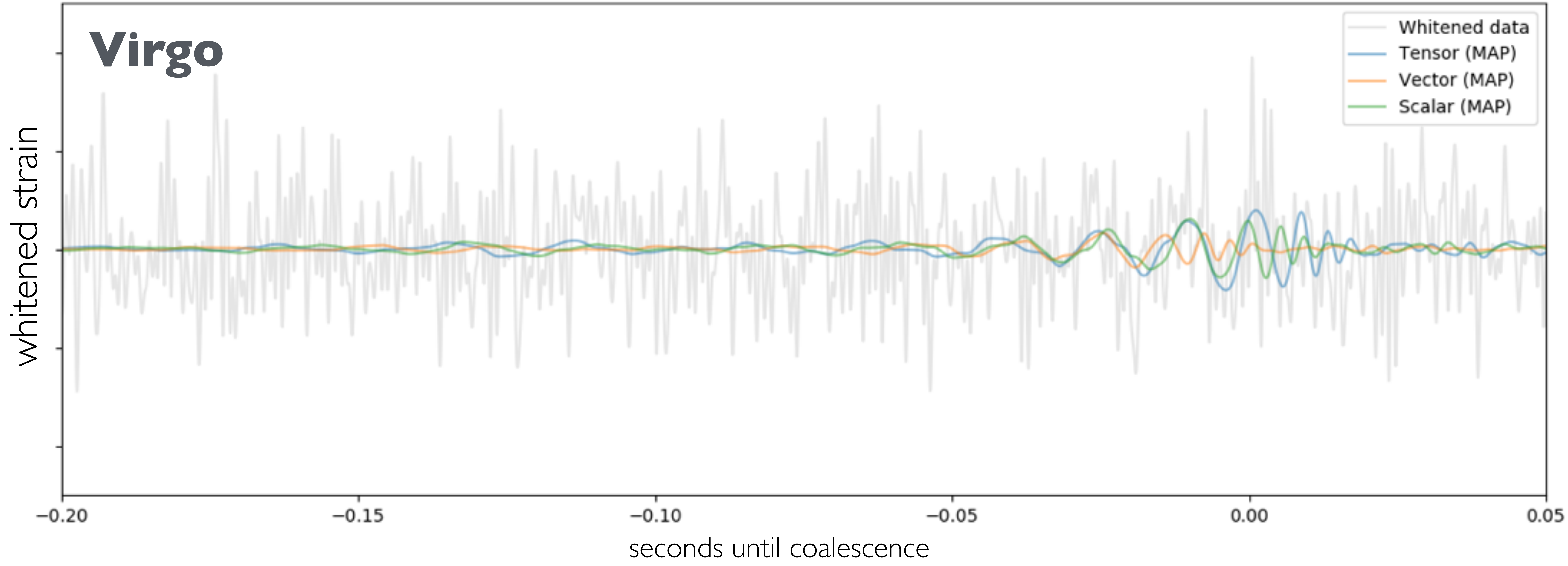


Hanford
Whitened data
Tensor (MAP)
Vector (MAP)
Scalar (MAP)
whitened strain
−0.20
−0.15
−0.10
−0.05
0.00
0.05
seconds until coalescence

GW170814


Livingston
Whitened data
Tensor (MAP)
Vector (MAP)
Scalar (MAP)
whitened strain
−0.20
−0.15
−0.10
−0.05
0.00
0.05
seconds until coalescence

GW170814

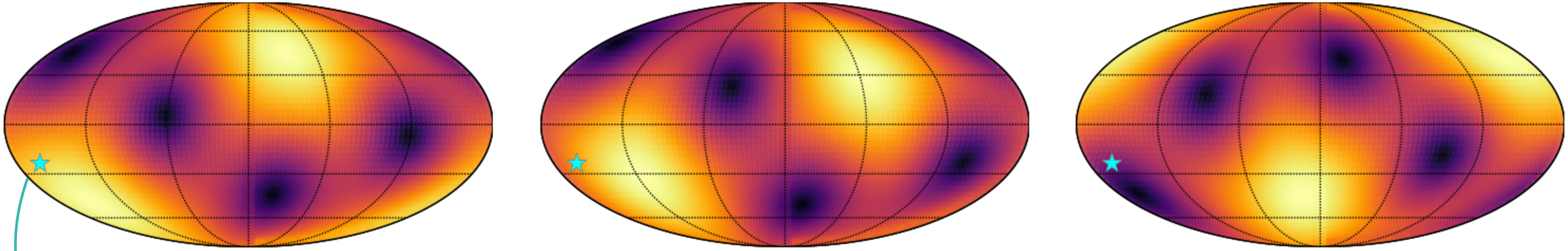


Virgo
Whitened data
Tensor (MAP)
Vector (MAP)
Scalar (MAP)
whitened strain
−0.20
−0.15
−0.10
−0.05
0.00
0.05
seconds until coalescence

no GW data here!

GW170817

tensor sensitivity



Hanford

Livingston

Virgo

EM counterpart

[Astrophys. J. 848 2 L13 (2017)]

low ↔ high

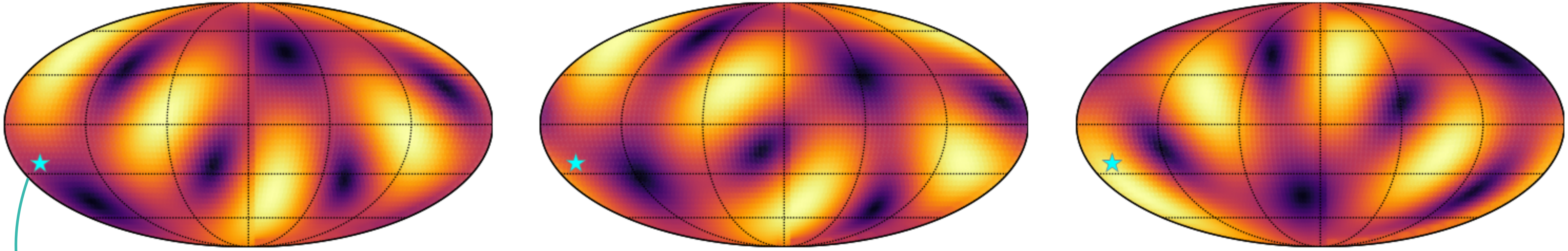
sensitivity

heat-maps show effective antenna pattens,
no GW data used

no GW data here!

GW170817

vector sensitivity



Hanford   Livingston   Virgo

EM counterpart

[Astrophys. J. 848 2 L13 (2017)]

0  1

low ⟷ high

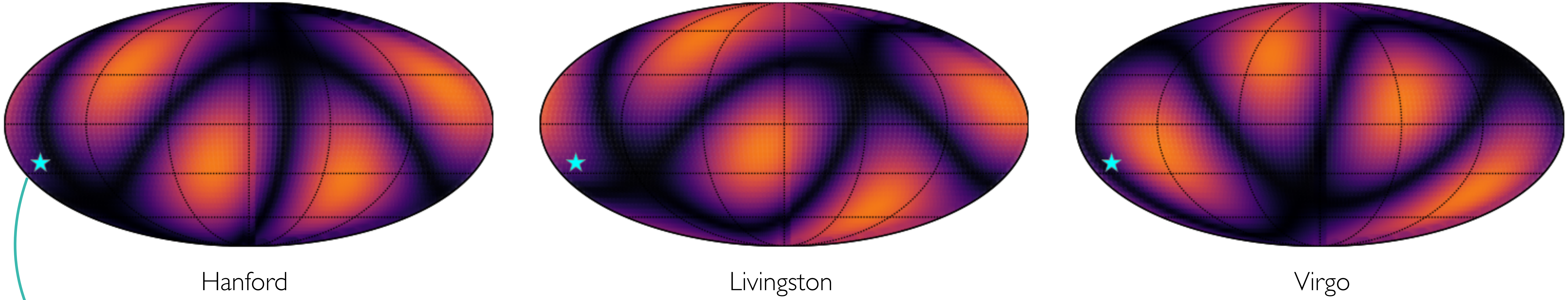
sensitivity

heat-maps show effective antenna pattens, no GW data used

GW170817

scalar sensitivity

no GW data here!



EM counterpart
[Astrophys. J. 848 2 L13 (2017)]

low ⟷ high
sensitivity

heat-maps show effective antenna pattens,
no GW data used

summary

need 5 detectors to fully disentangle polarizations of transient signals

but can already break *some* degeneracies with existing 3 detectors

GW170814 gave us first direct glimpse into GW polarization geometry

GR tensor hypothesis favored over extreme vector and scalar models

should expect odds from BNS detection to be much stronger

future prospects

method to handle mixed polarizations
under development for transients
(even though we will need more instruments for it to work fully)

but, there's more in life than compact binaries!

continuous waves
stochastic background

could measure all polarizations with current network

[PhysRevLett.120.031104] [PhysRevLett 120.201102]

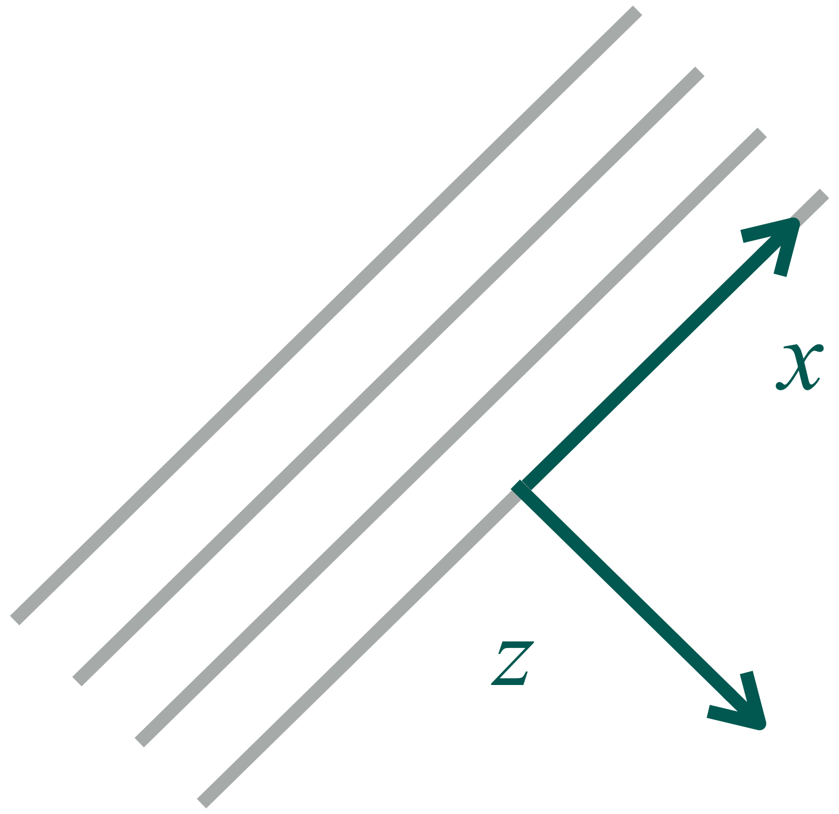
thank you!

Caltech MIT LIGO

LIGO-G1800073

extra

polarizations



linear basis decomposition

$$[h_{ij}] = \begin{pmatrix} h_{\mathrm{b}} + h_{+} & h_{\times} & h_{\mathrm{x}} \\ h_{\times} & h_{\mathrm{b}} - h_{+} & h_{\mathrm{y}} \\ h_{\mathrm{x}} & h_{\mathrm{y}} & h_{\mathrm{l}} \end{pmatrix}$$

in the Fourier domain and in a generic frame,
with ***k*** the 4-wave-vector

$$\tilde{h}_{ab}(\vec{k}) = \tilde{h}_A(\vec{k})\, e^A_{ab}(\hat{k})$$

predictions

Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

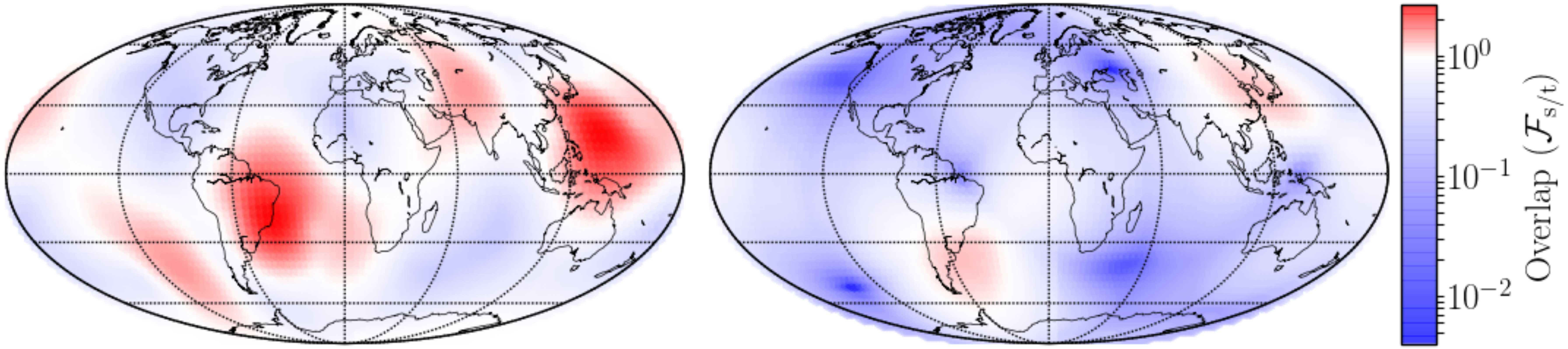
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].

allowed / depends / forbidden

HLV network response

not all sky-locations are equal

Isi & Weinstein (2017)



tensor vs vector

tensor vs scalar

nontensor response can be **more** or **less** than tensor at different points

"overlap" only quantifies overall magnitude, given by detector responses added in quadrature for different detectors—does not account for phasing/sign differences

[arXiv:1710.03794]

polarization measurement

$$h_I(t) = F^A{}_I h_A(t)$$

polarization geometry gets encoded in
relative amplitude, phase and timing
at each detector via the antenna patterns

but…

polarization measurement

cannot break *all* degeneracies with less than 5 detectors*

need to invert matrix to recover intrinsic polarization amplitudes

$$\begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_I \end{bmatrix} = \begin{bmatrix} F_{1+} & F_{1\times} & F_{1\mathrm{x}} & F_{1\mathrm{y}} & F_{1\mathrm{s}} \\ F_{2+} & F_{2\times} & F_{2\mathrm{x}} & F_{2\mathrm{y}} & F_{2\mathrm{s}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{I+} & F_{I\times} & F_{I\mathrm{x}} & F_{I\mathrm{y}} & F_{I\mathrm{s}} \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \\ h_\mathrm{x} \\ h_\mathrm{y} \\ h_\mathrm{s} \end{bmatrix}$$

signal at detector I = response of detector I to each polarization x intrinsic waveform

to make things worse, LIGO detectors are nearly coaligned

*non-coaligned differential-arm detectors, with *transient* signals, and even with an EM counterpart

assumptions

gravity is described by a metric theory
(i.e. all we need to know is Riem)

GWs propagate locally at *c*

no local polarization rotations

plane-wave & small-antenna approximations

…