Testing GR with GW polarizations

using LIGO and Virgo

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Testing GR with GWs

we have already learned a lot from transients:

dispersion

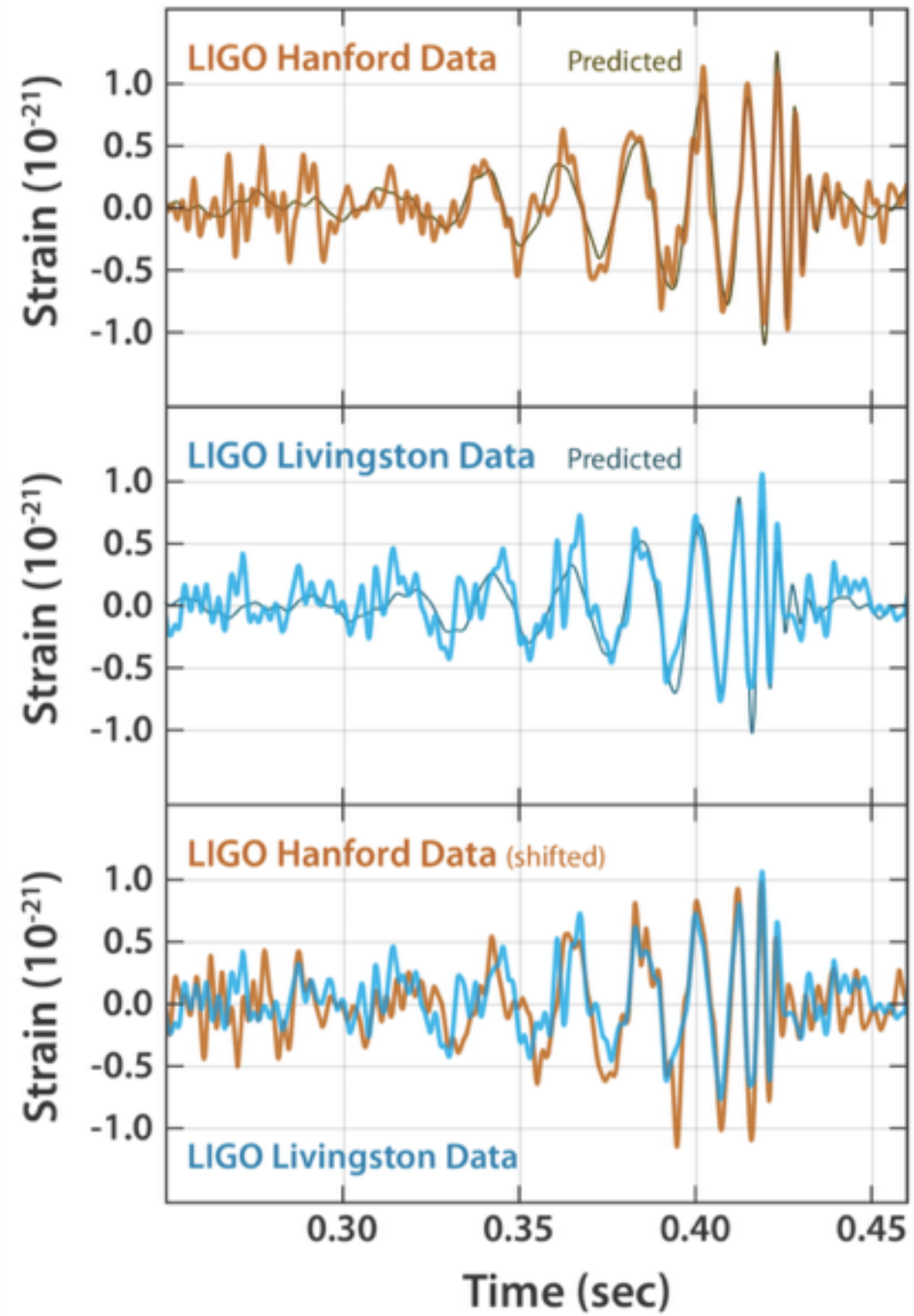
agreement with NR

self-consistency

...

not about polarizations!

there are currently no model-independent measurements of GW polarizations



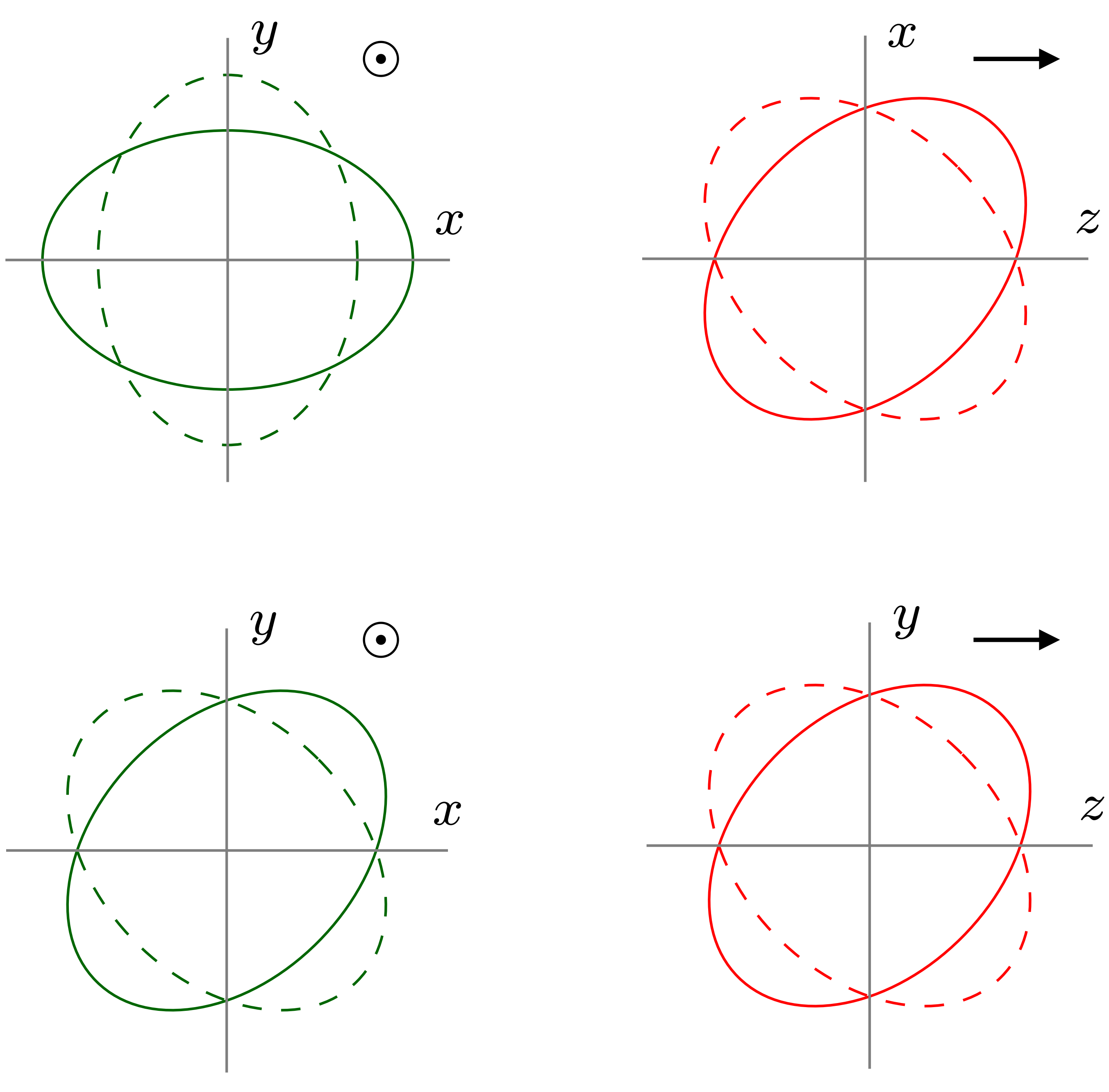
[tl;dr]

it is important to probe
GW polarizations

we can do so with current detectors
using long-lived signals

[too long ; didn't read]

plus | vector x | breathing



cross | vector y | longitudinal

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

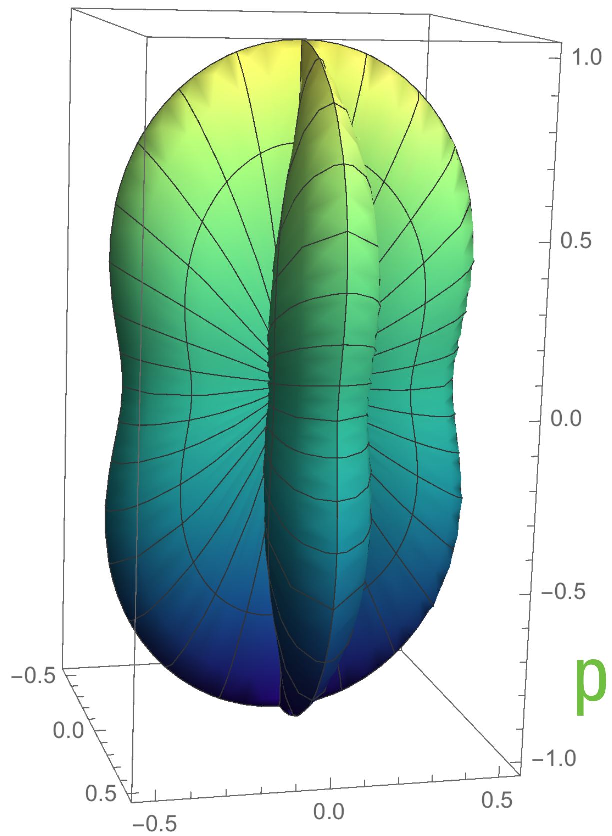
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].

allowed / depends / forbidden

motivation

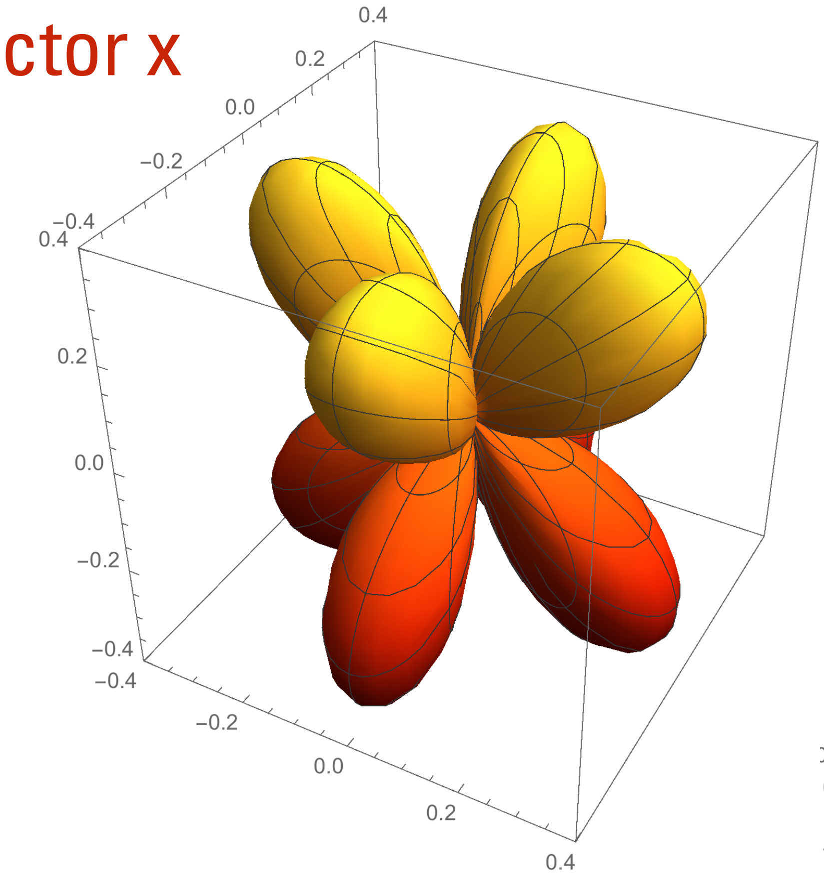
GR makes unequivocal prediction that
only + & x should propagate

polarizations are go/no-go test,
so let's check!

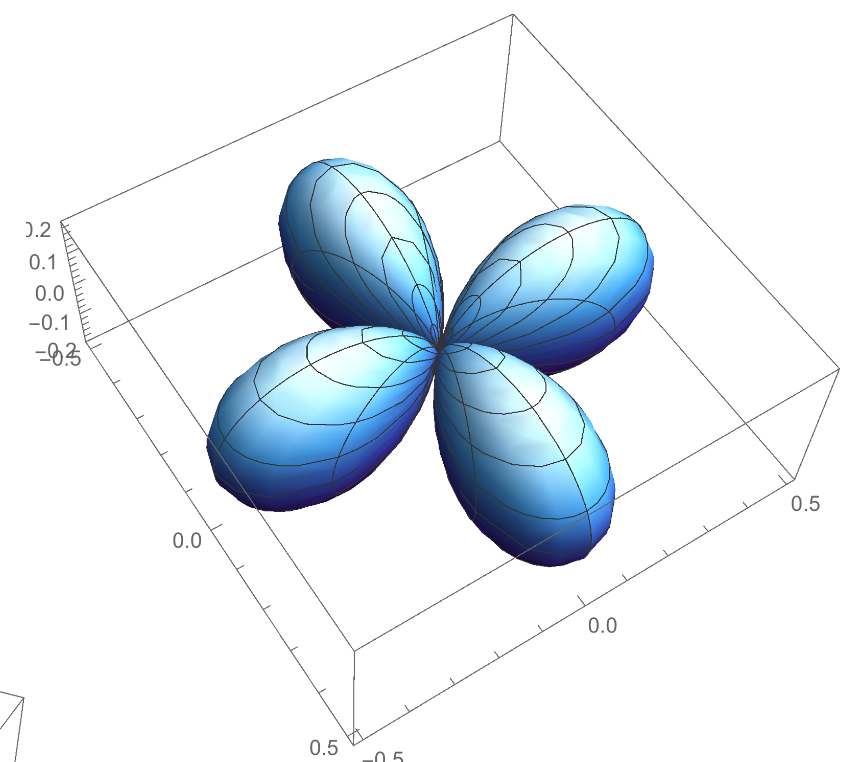


plus

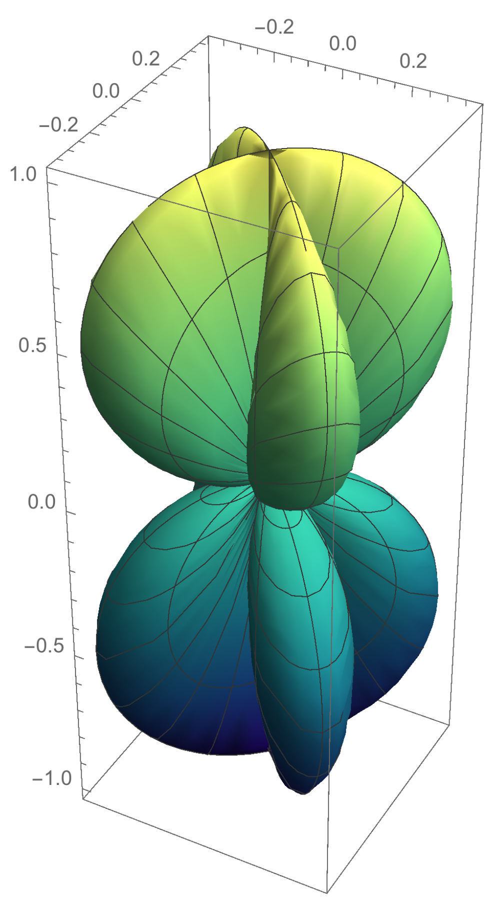
vector x



breathing

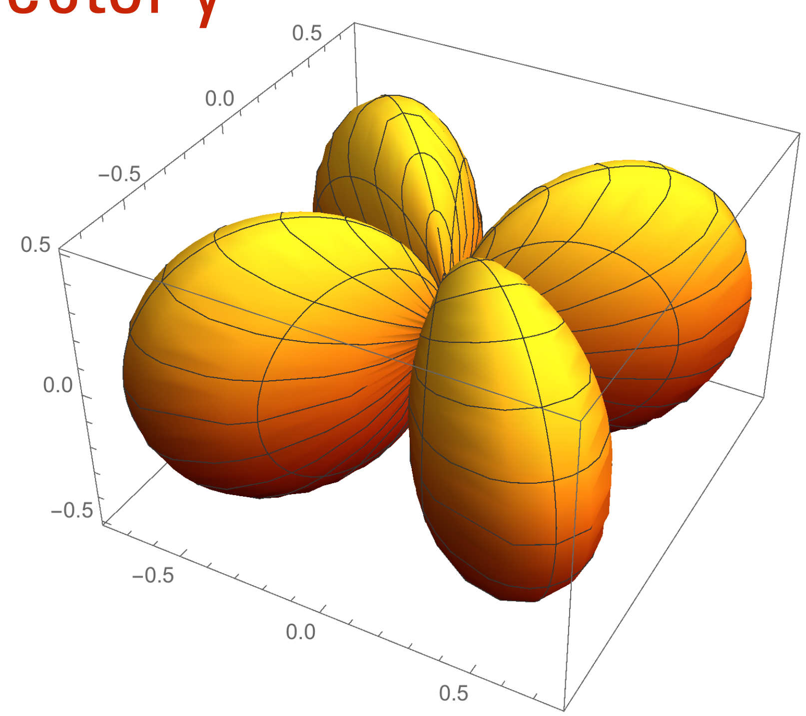


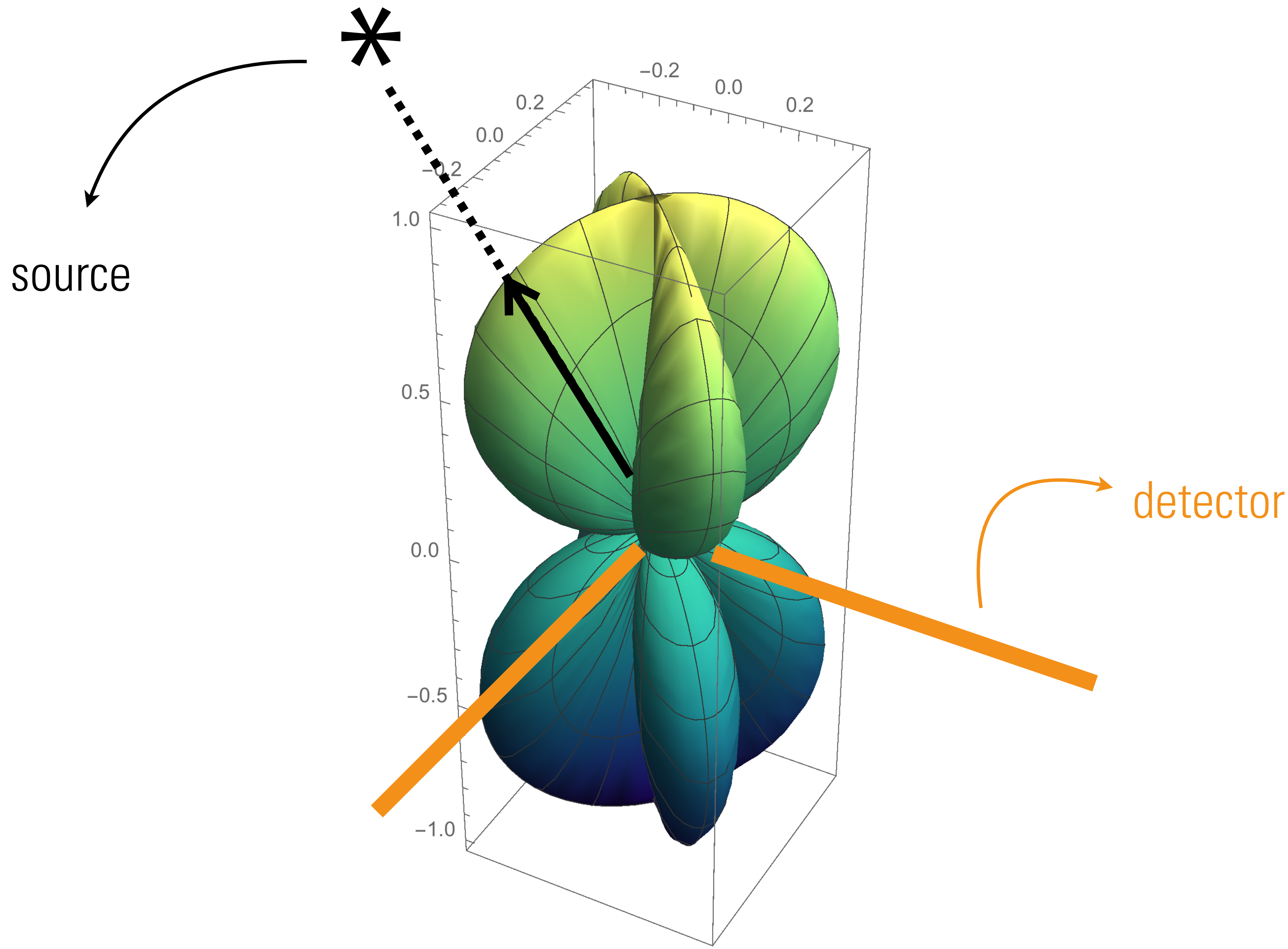
longitudinal



cross

vector y





antenna pattern for cross polarization

persistent signals

antenna patterns leave imprint in persistent signals characteristic of each polarization

continuous-waves
stochastic background

new bayesian analyses

detect long GWs of *any* polarization
(from known pulsars, or a stochastic background)

distinguish between GR and non-GR

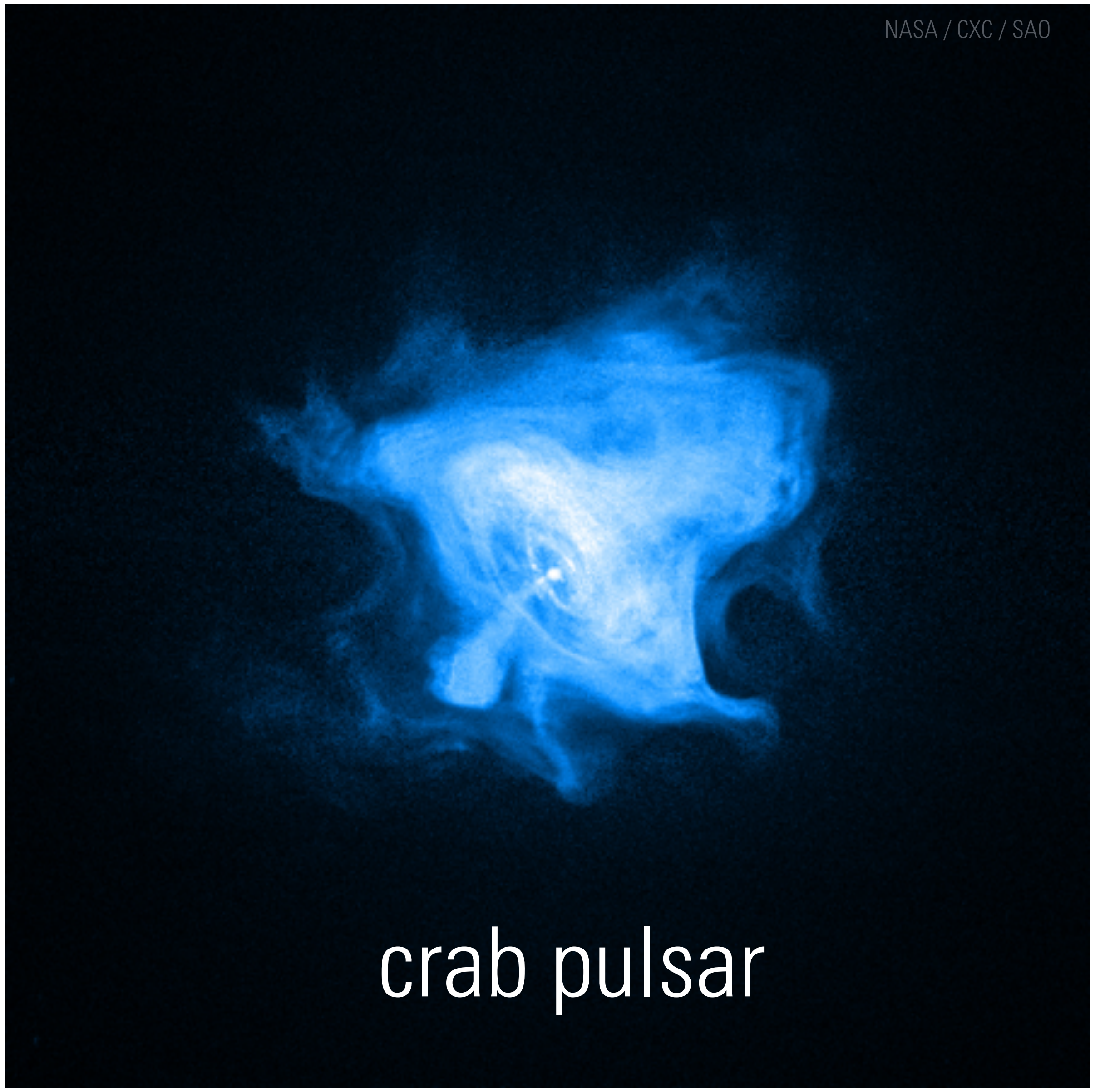
} model selection

limit amplitude of scalar/vector modes → parameter estimation

Isi et al. (2017) [arXiv:1703.07530]

Callister et al. (2017) [arXiv:1704.08373]

continuous waves



one of ~200 known pulsars potentially in LIGO's band

continuous waves

[arXiv:1703.07530]
CW

coherent, monochromatic, well-localized

simple form, in general relativity:

$$h(t) = h_0 \frac{1}{2} \left(1 + \cos^2 \iota\right) F_+(t) \cos\phi(t) + h_0 \cos\iota \, F_\times(t) \sin\phi(t)$$

$$\phi(t) \approx 2\pi \times (2 f_{\rm rot})$$

+ doppler and other timing corrections

in a generic metric theory of gravity:

$$h(t) = \sum_p F_p(t) a_p \cos(\phi(t) + \phi_p)$$

phase offset

polarization amplitude

$$p \in \{+,\ \times,\ \mathrm{x},\ \mathrm{y},\ \mathrm{s}\}$$

h_0, overall strength; ι, inclination; $F(t)$, antenna pattern; $f_{\rm rot}$, rotational frequency

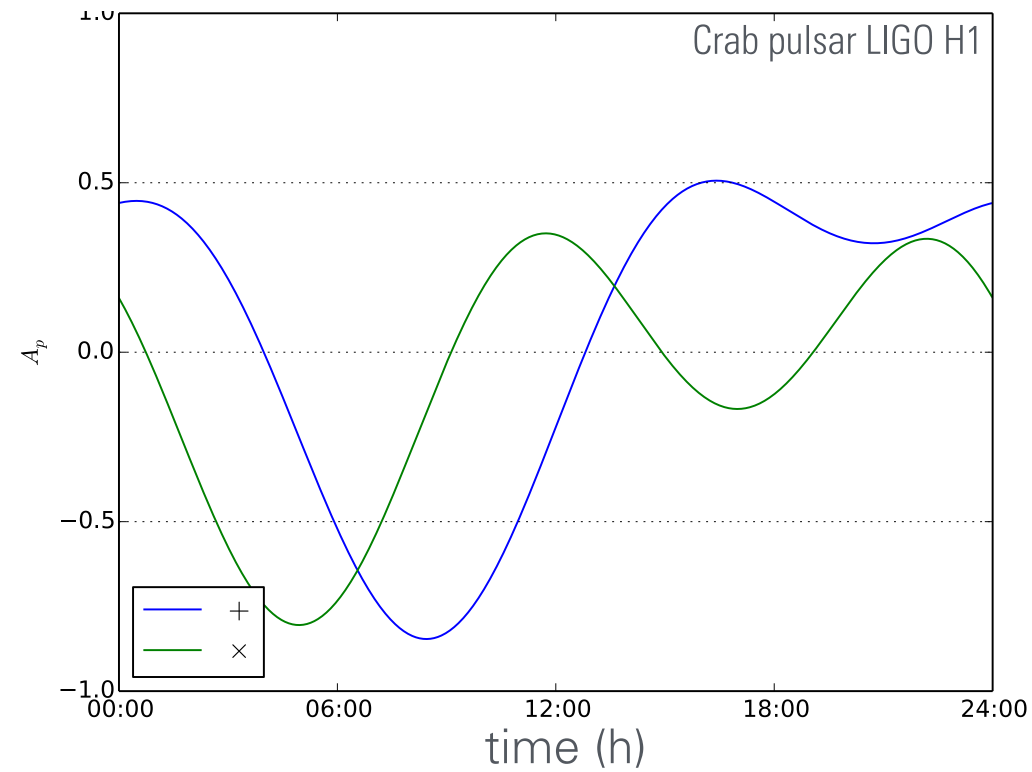
polarization antenna pattern

↓

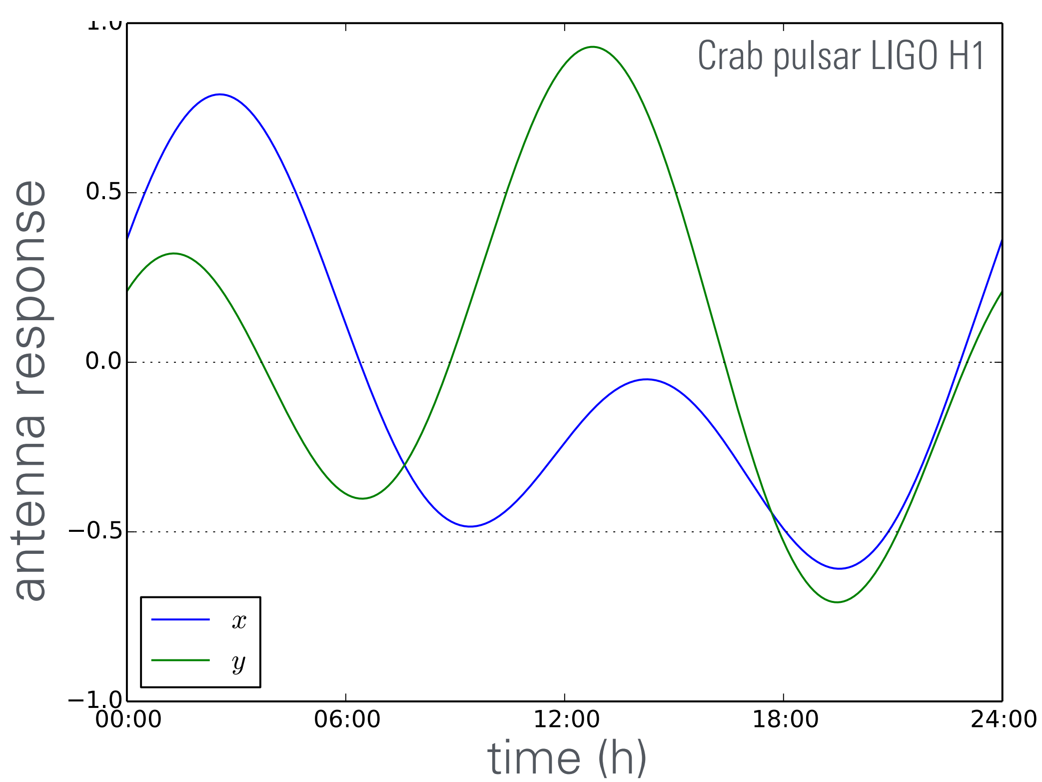
amplitude modulation

over a sidereal day

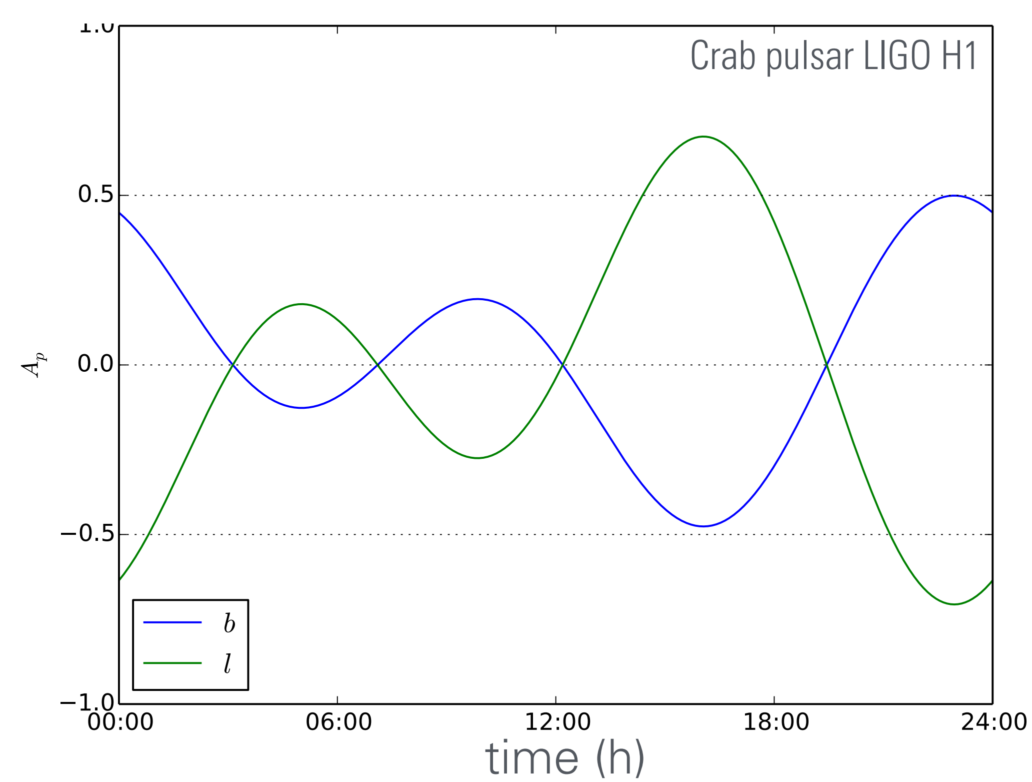
tensor



vector

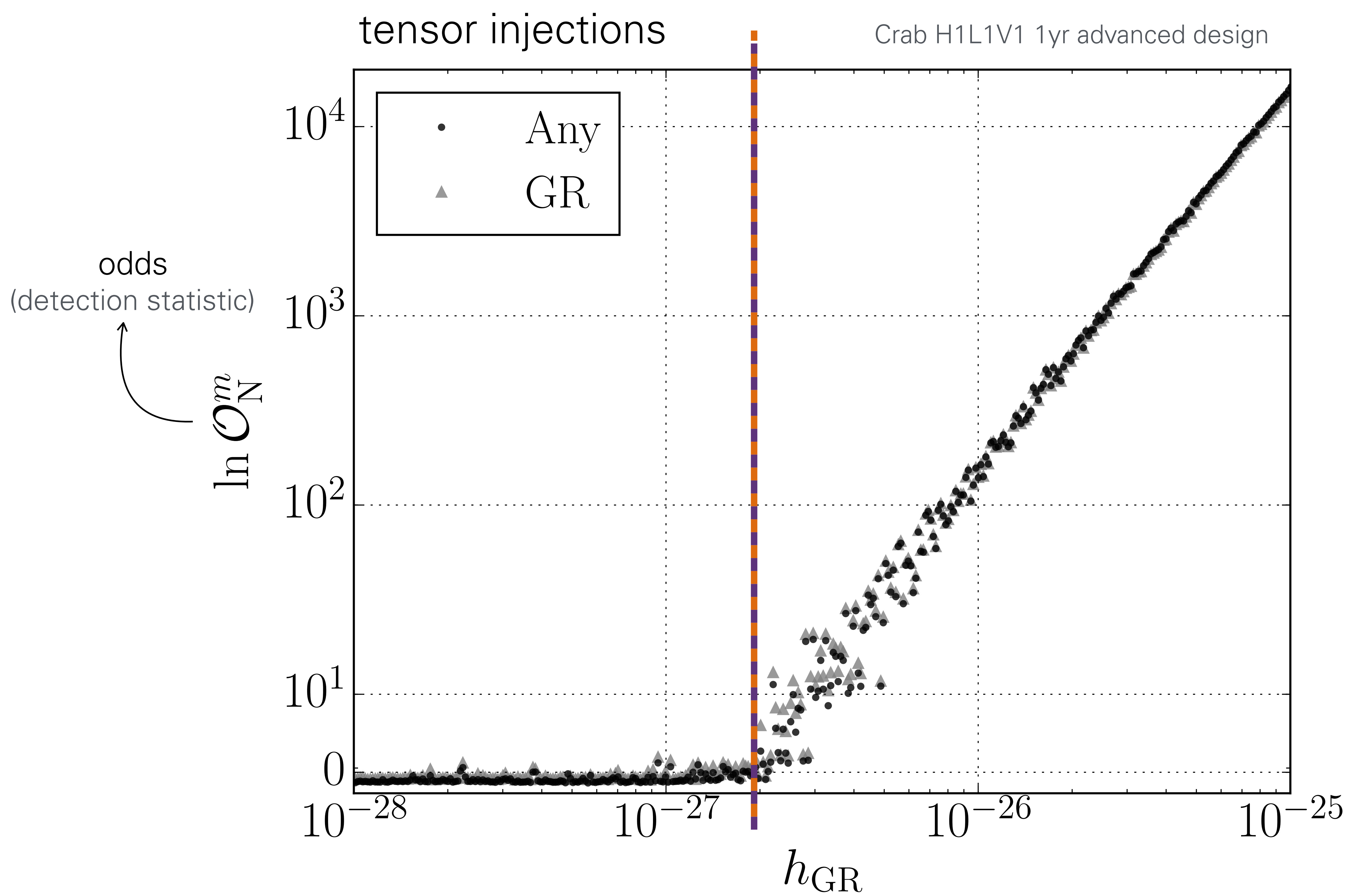


scalar



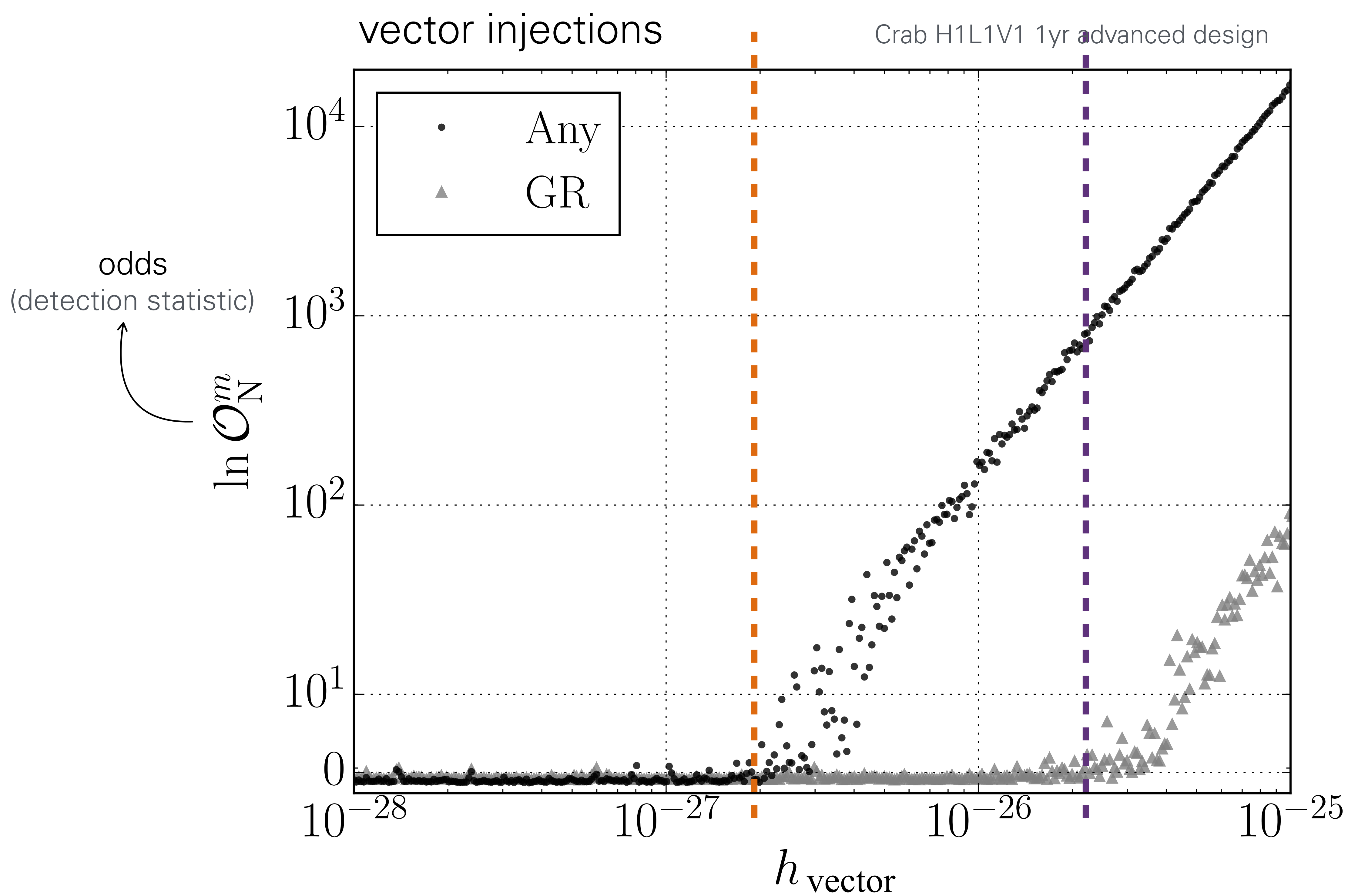
signal vs noise

CW [arXiv:1703.07530]

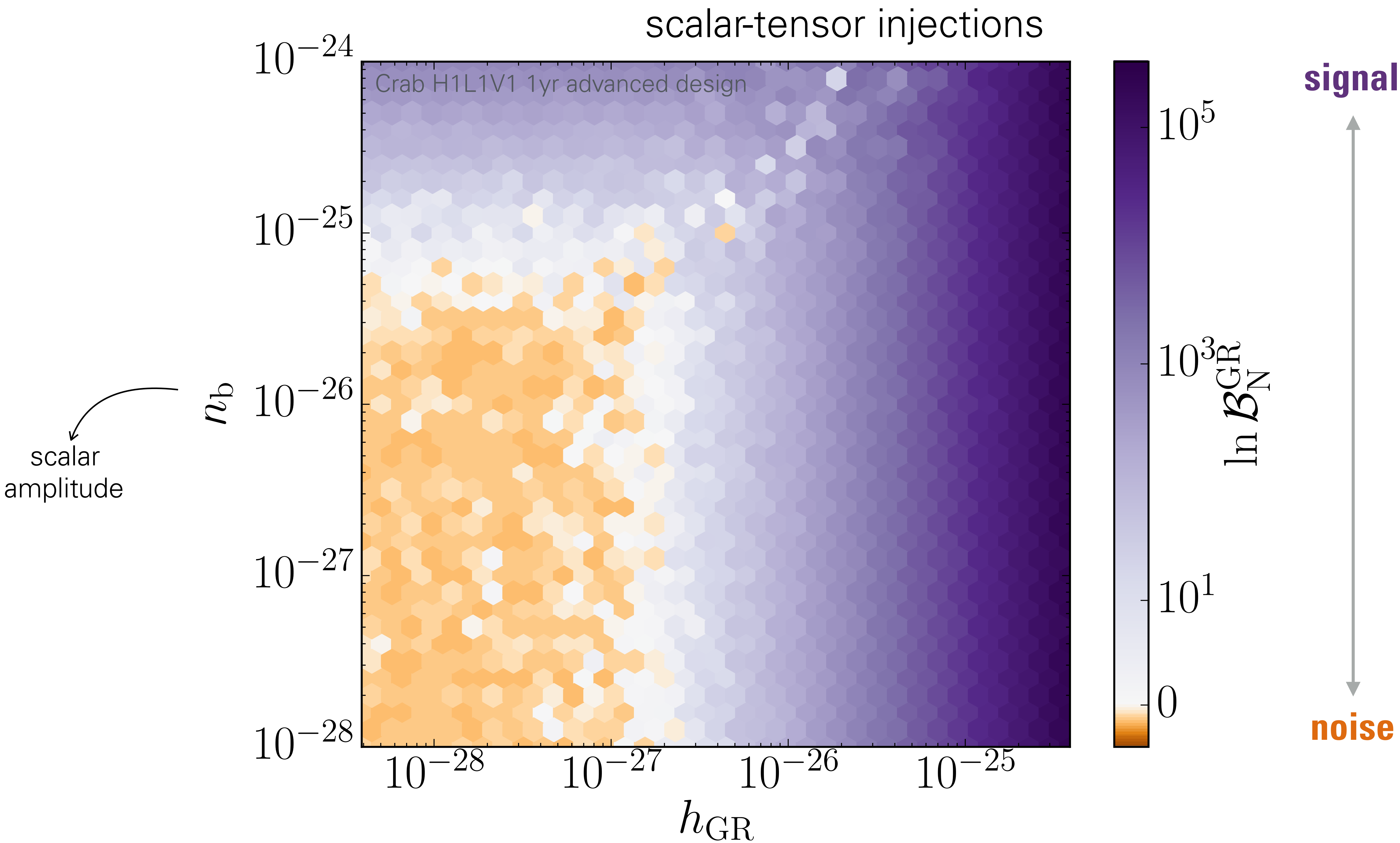


signal vs noise

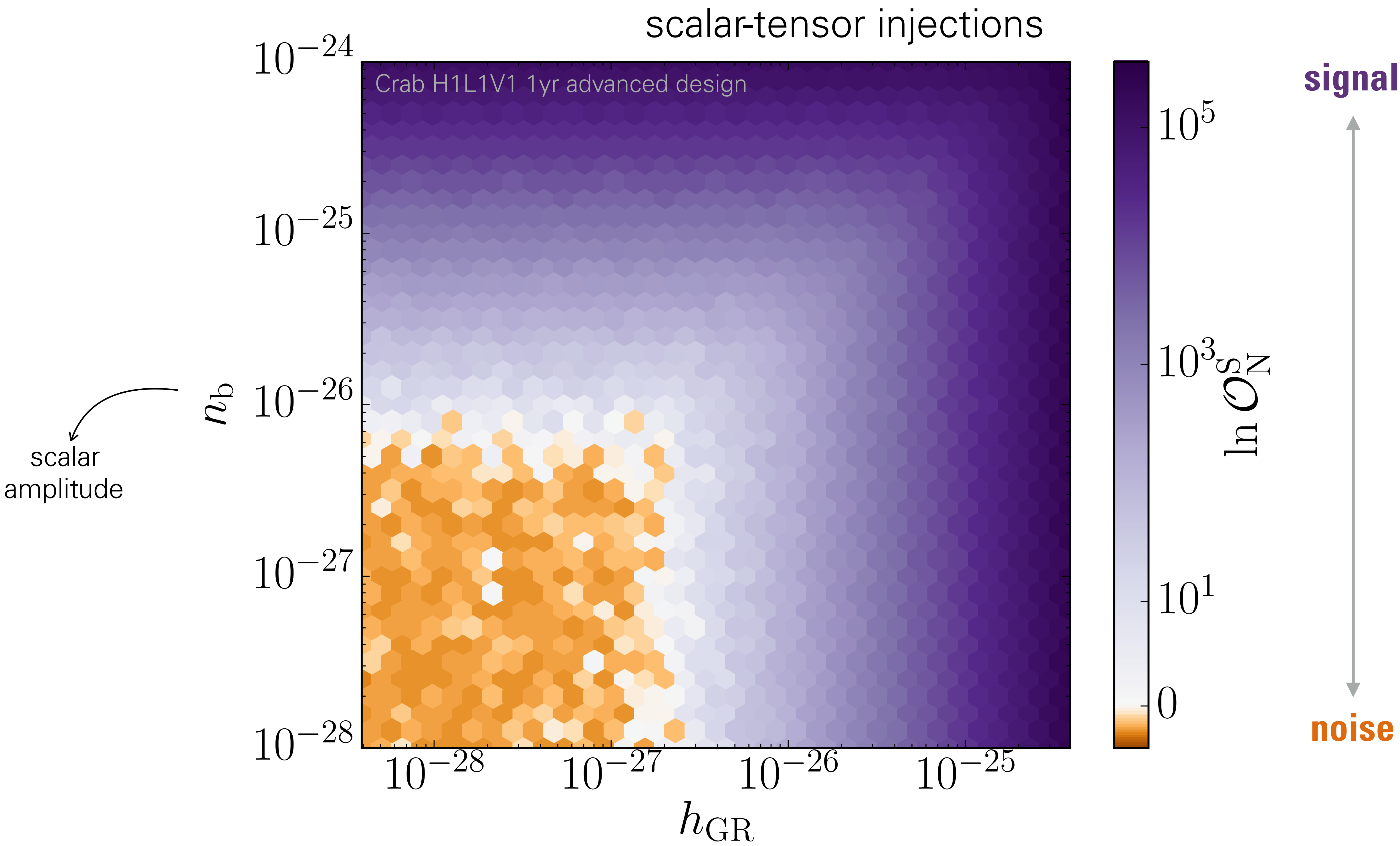
[arXiv:1703.07530]
CW



gr signal vs noise

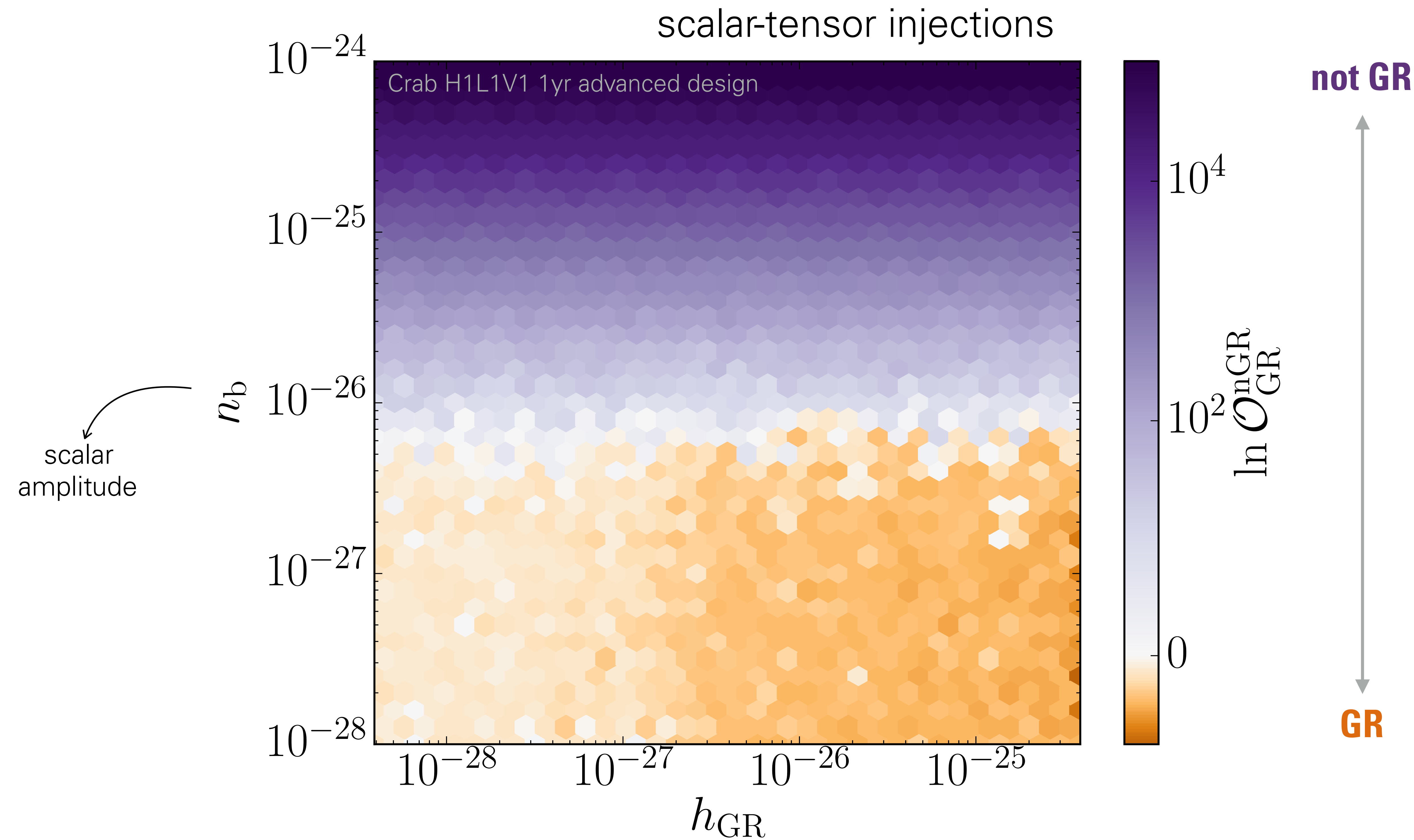


any signal vs noise



non-gr vs gr

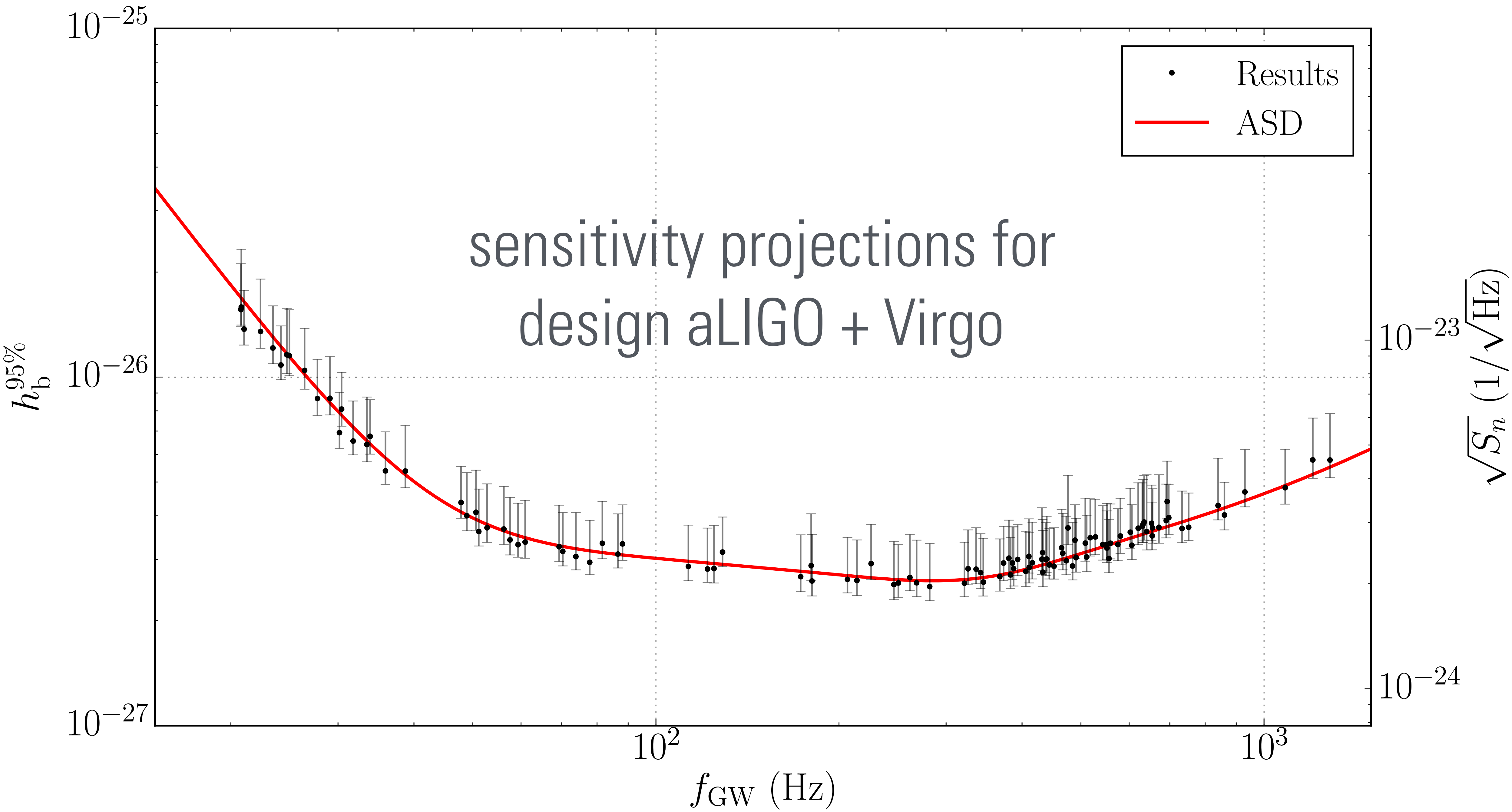
cw
[arXiv:1703.07530]


scalar-tensor injections
Crab H1L1V1 1yr advanced design
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
n_b
scalar
amplitude
10^{-28}
10^{-27}
10^{-26}
10^{-25}
h_{GR}
10^4
10^2
0
$\ln \mathcal{O}^{nGR}_{GR}$
not GR
GR

scalar upper limits

[arXiv:1703.07530]

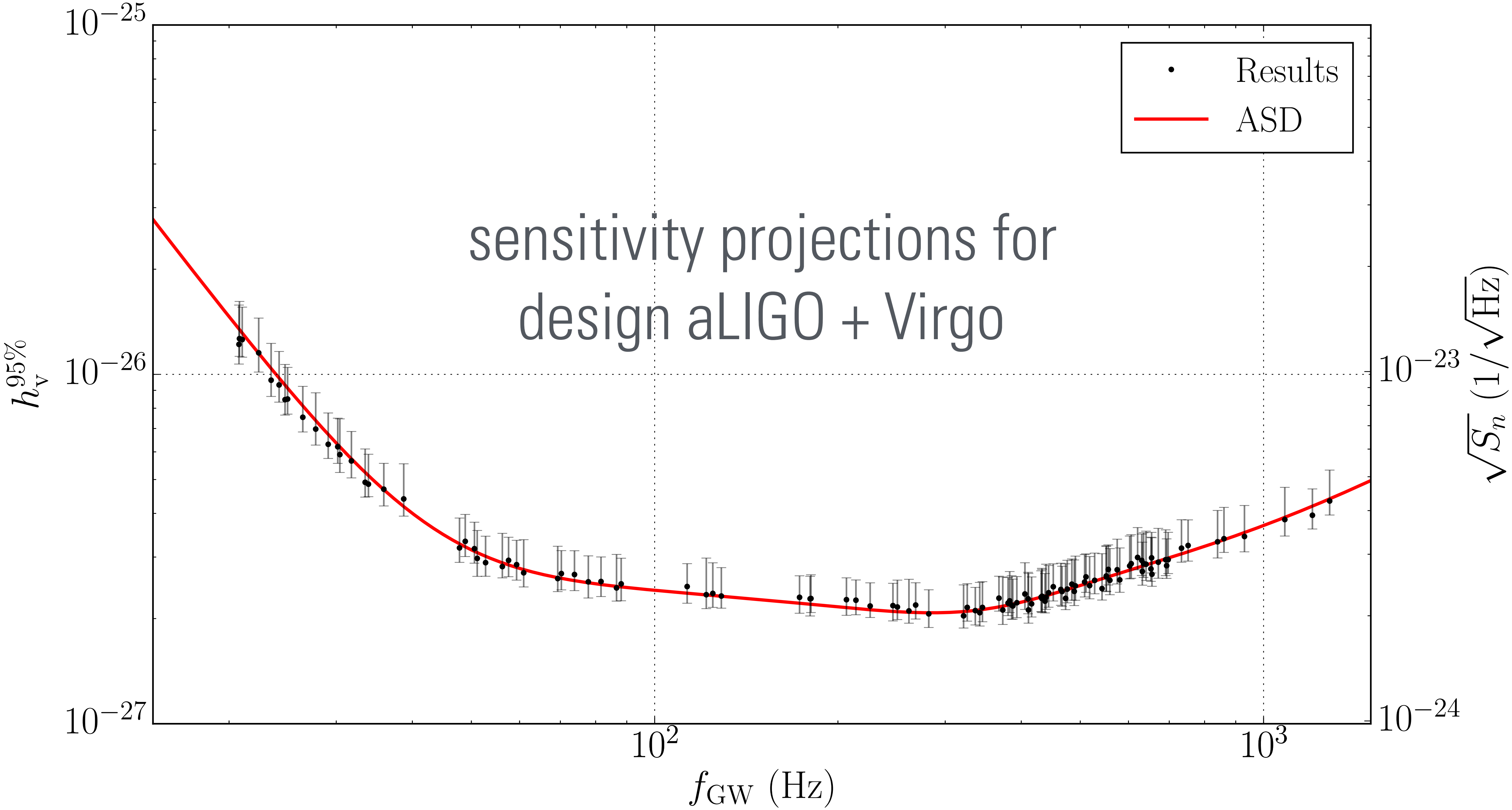
CW



(each point represents one pulsar)

[arXiv:1703.07530]

vector upper limits



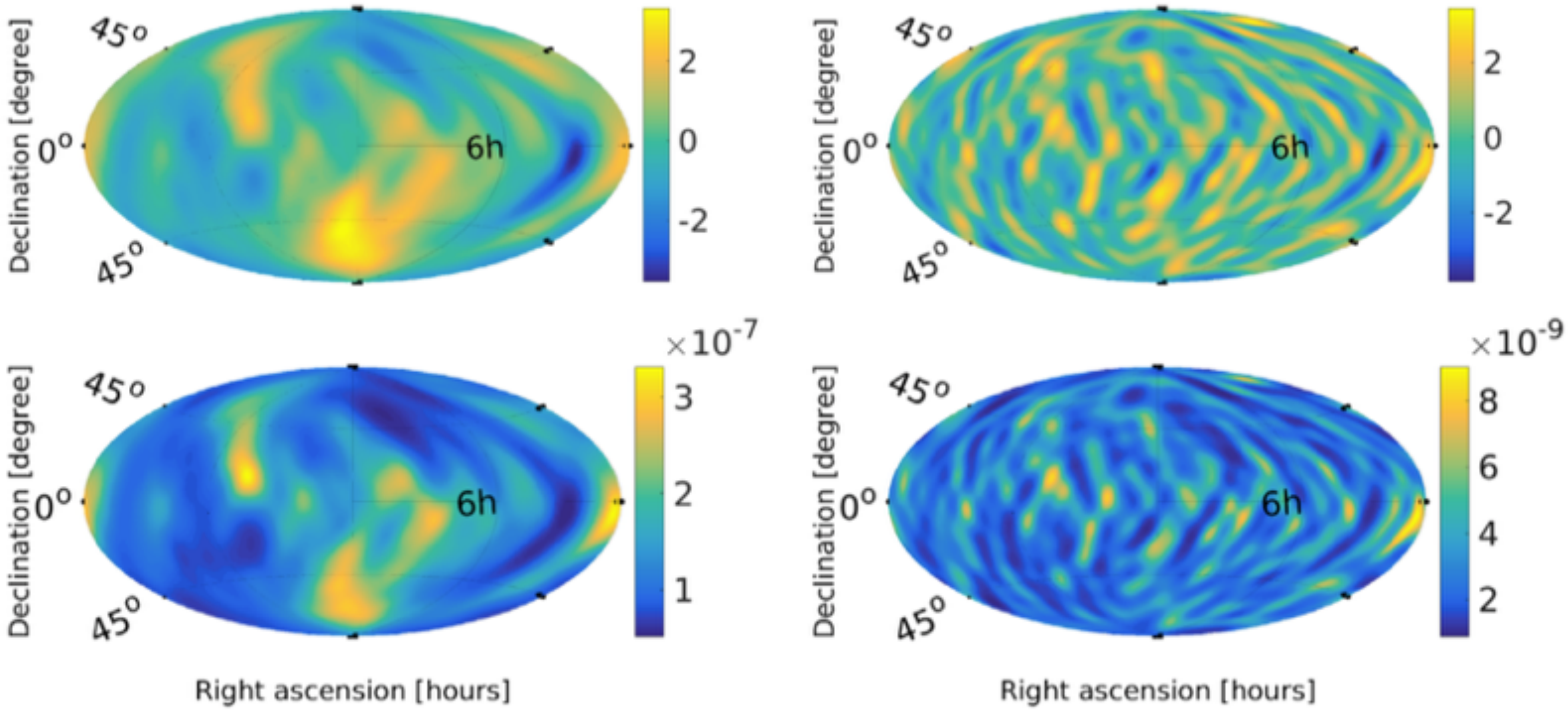
(each point represents one pulsar)

$$h_{\mathrm{v}} \equiv \left(h_{\mathrm{x}}^2 + h_{\mathrm{y}}^2\right)^{1/2}$$

stochastic background

incoherent superposition of myriad unresolvable sources

see Andrew Mata's overview talk on Friday!



SNR (top) and 90%-confidence upper-limits (bottom) from radiometer stochastic background search

[Abbott et al., PRL 118, 121102 (2017)]

stochastic background

SB

[arXiv:1704.08373]

incoherent, broadband, all-sky

measure correlated strain power in two detectors

$$\left\langle \tilde{h}_1^*(f)\tilde{h}_2^*(f')\right\rangle = \frac{3H_0^2}{20\pi^2}\delta(f-f')|f|^{-3}\Omega(f)\gamma(f)$$

overlap-reduction function

with the *canonical GW energy density* usually parametrized by

$$\Omega(f) = \Omega_0\left(f/f_0\right)^{\alpha}$$

in a generic metric theory of gravity:

$$\left\langle \tilde{h}_1^*(f)\tilde{h}_2^*(f')\right\rangle = \frac{3H_0^2}{20\pi^2}\delta(f-f')|f|^{-3}\sum_p \Omega_0^p\left(\frac{f}{f_0}\right)^{\alpha_p}\gamma_p(f)$$

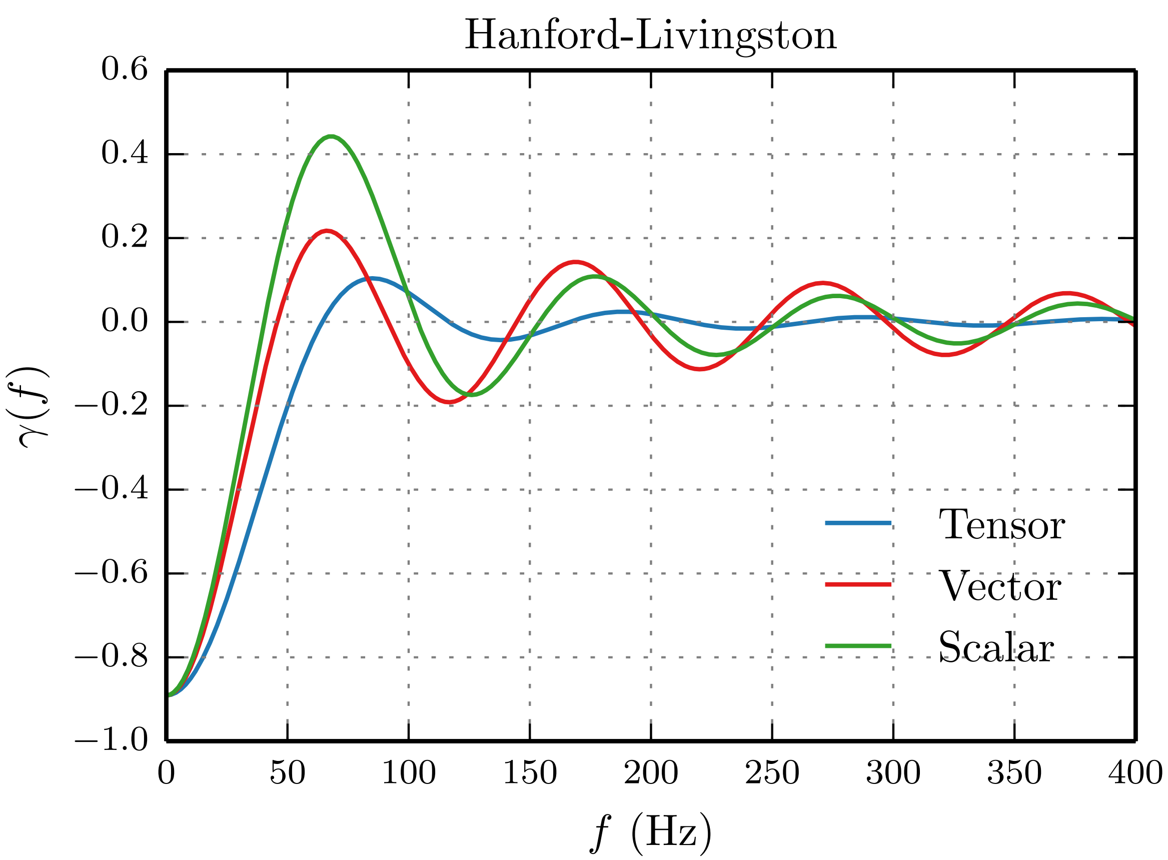
spectral index ("slope")

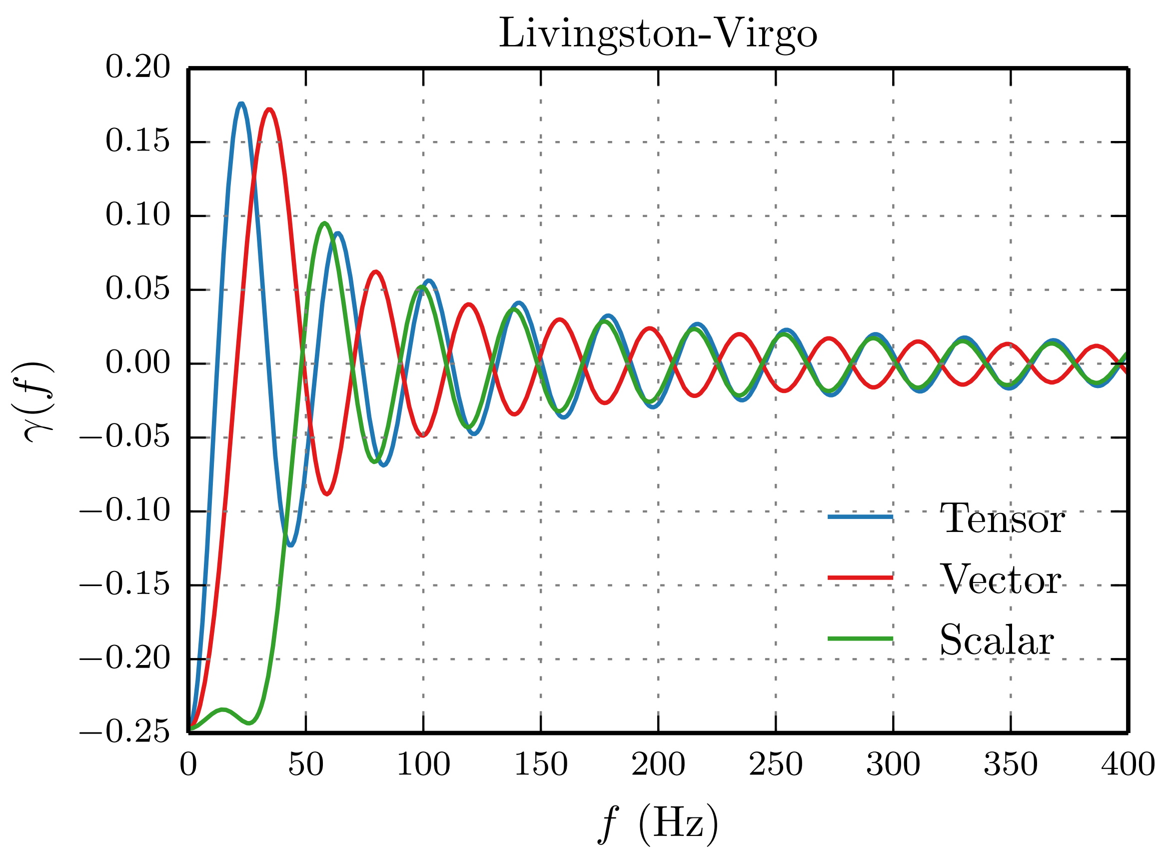
polarization amplitude

$$p \in \{+,\ \times,\ \mathrm{x},\ \mathrm{y},\ \mathrm{s}\}$$

stochastic background

overlap reduction functions encode effect of time-of-flight and differences between polarizations





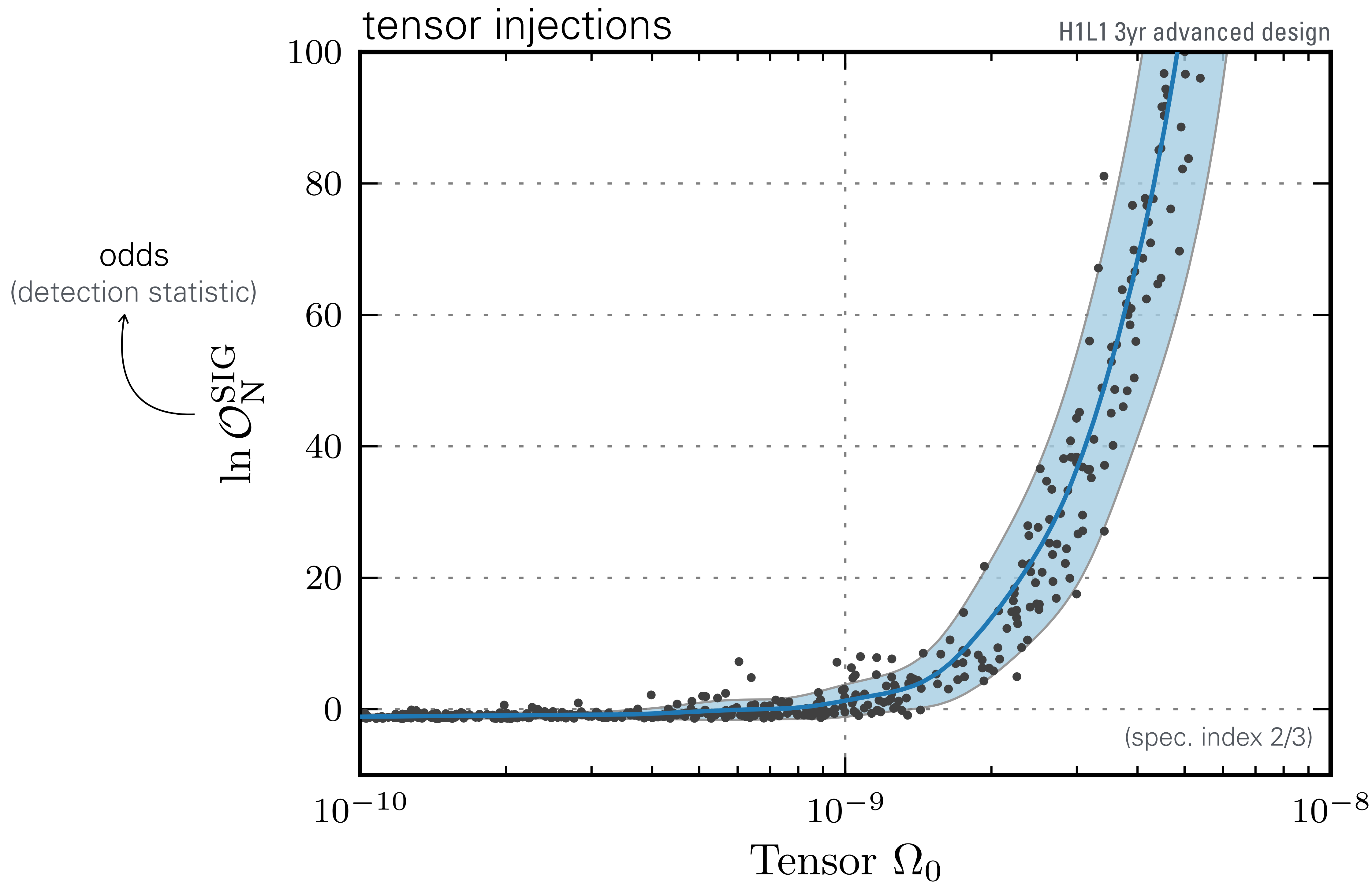
sky location

$$\gamma(f) = \frac{5}{8\pi} \sum_p \int_{\text{sky}} \mathrm{d}\hat{n}\; e^{i2\pi f \hat{n}\cdot\Delta\vec{x}/c} F_1^p(\hat{n}) F_2^p(\hat{n})$$

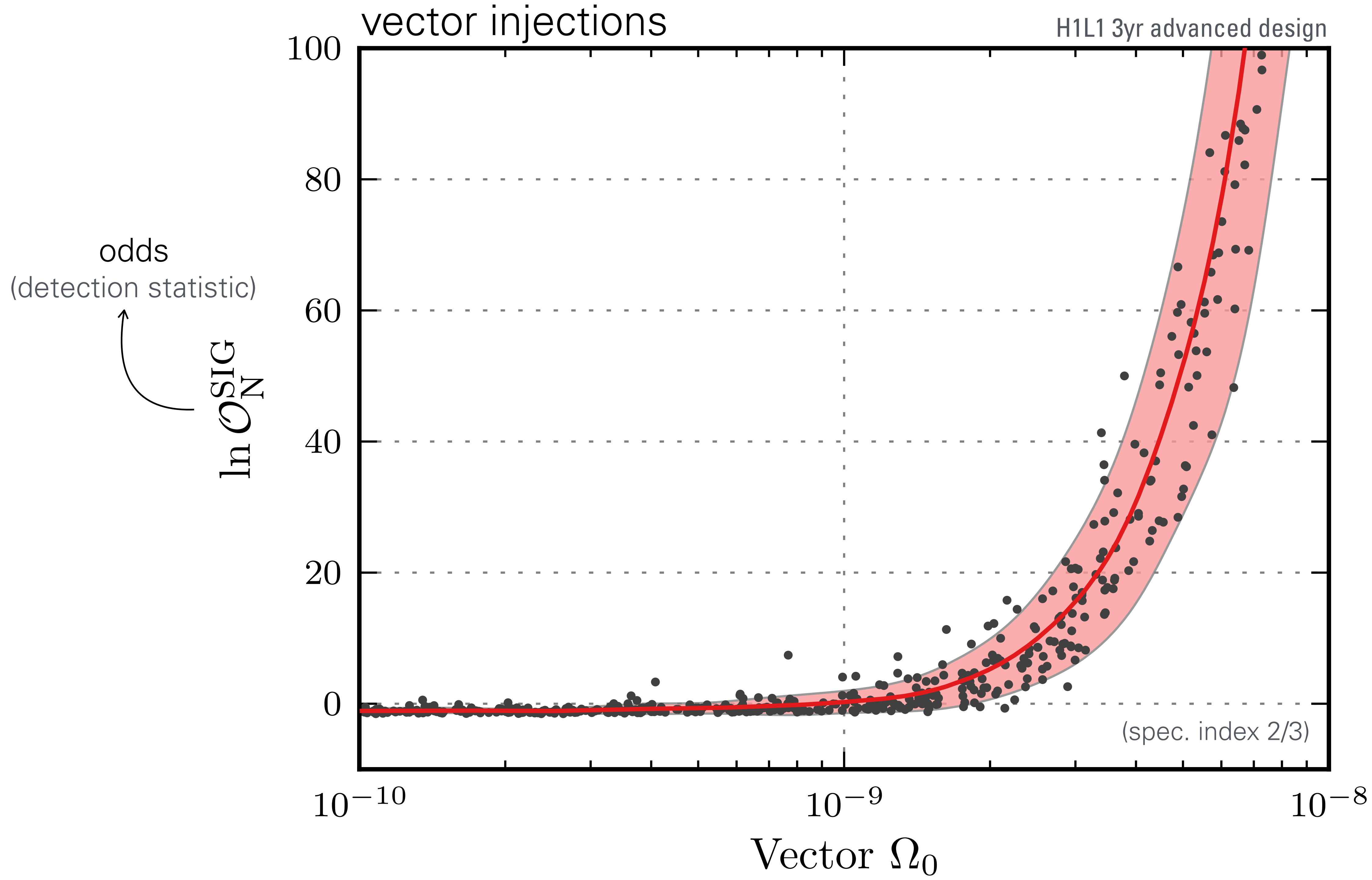
detector separation

signal vs noise

SB
[arXiv:1704.08373]

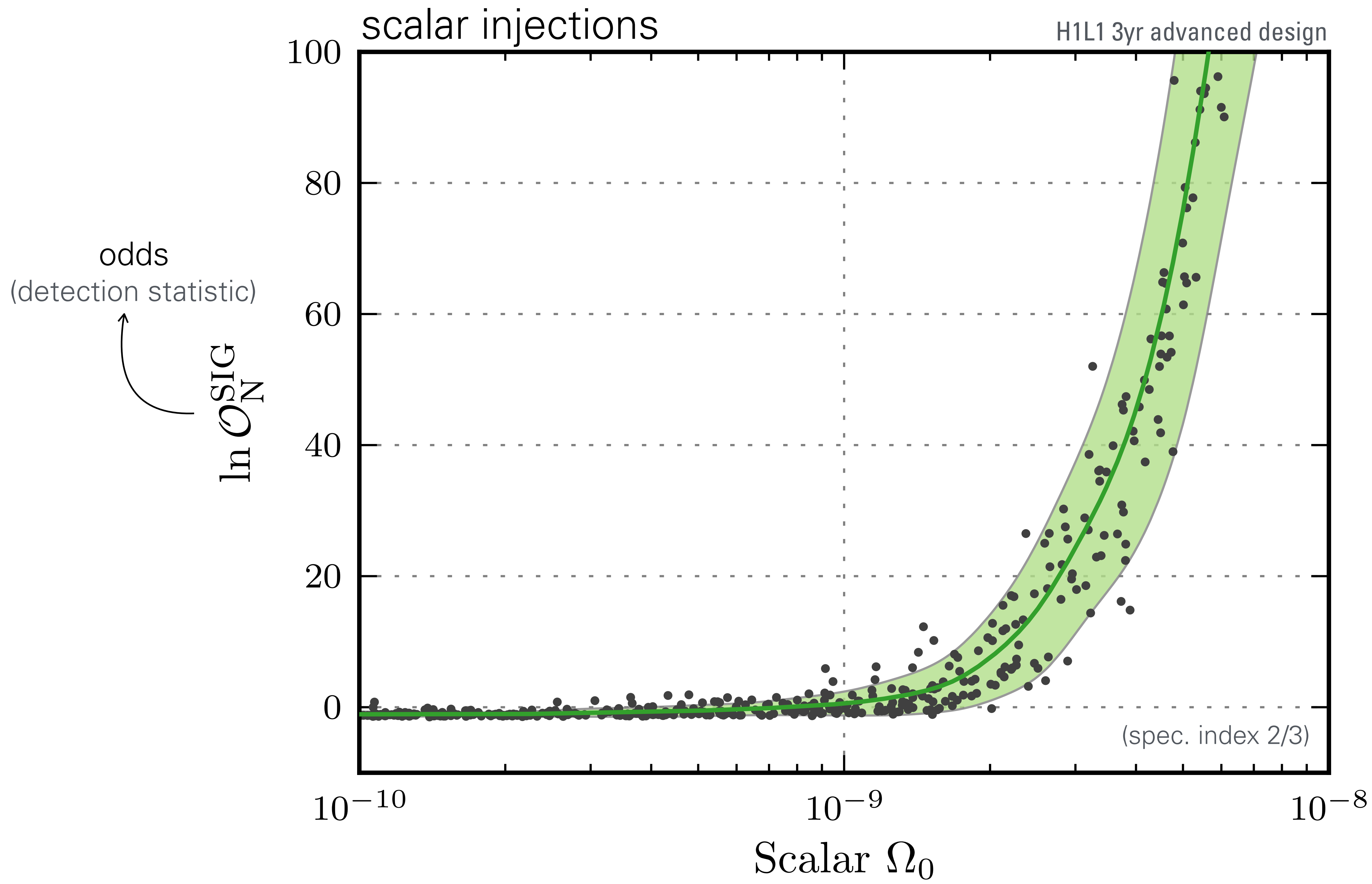


signal vs noise

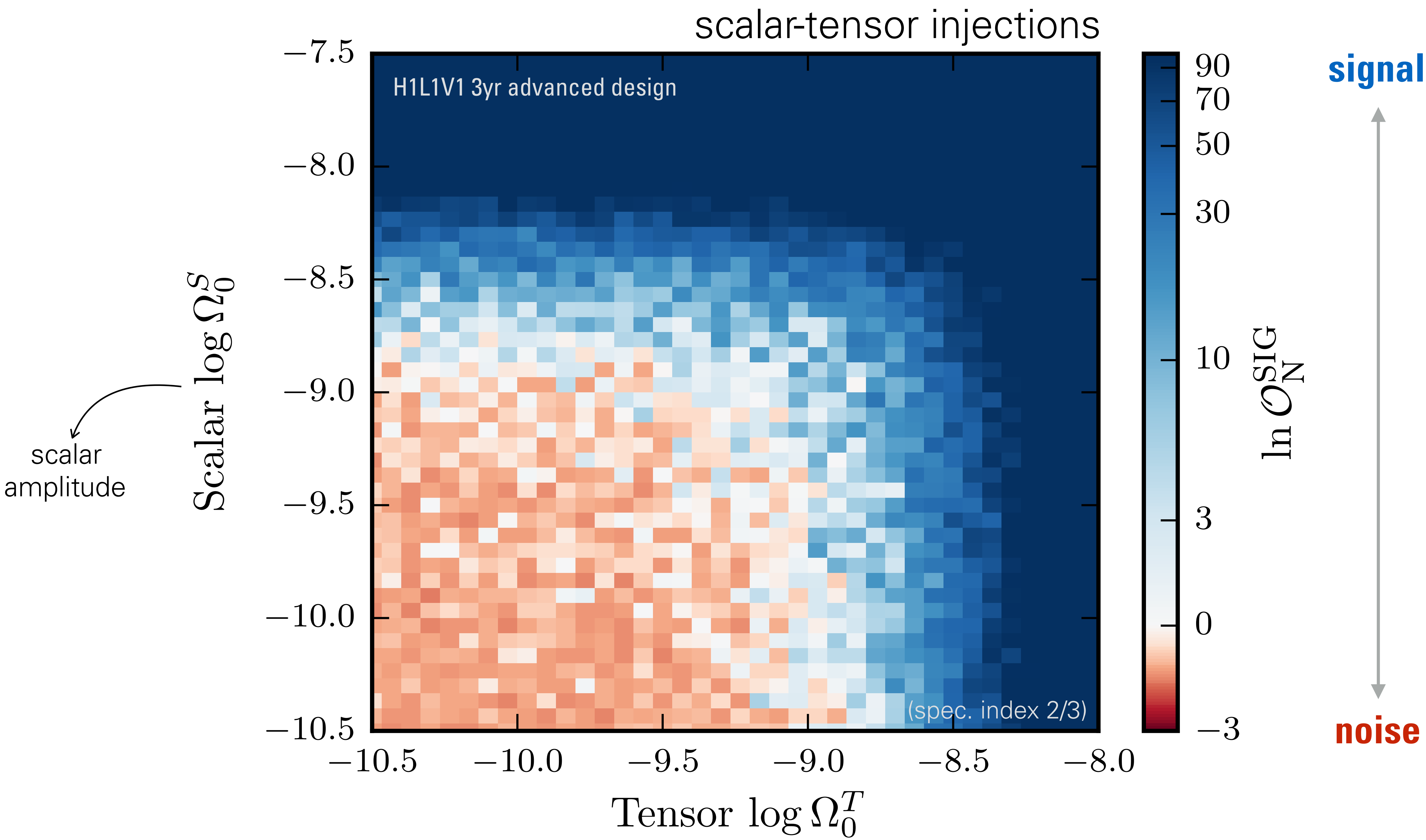


SB
[arXiv:1704.08373]

signal vs noise



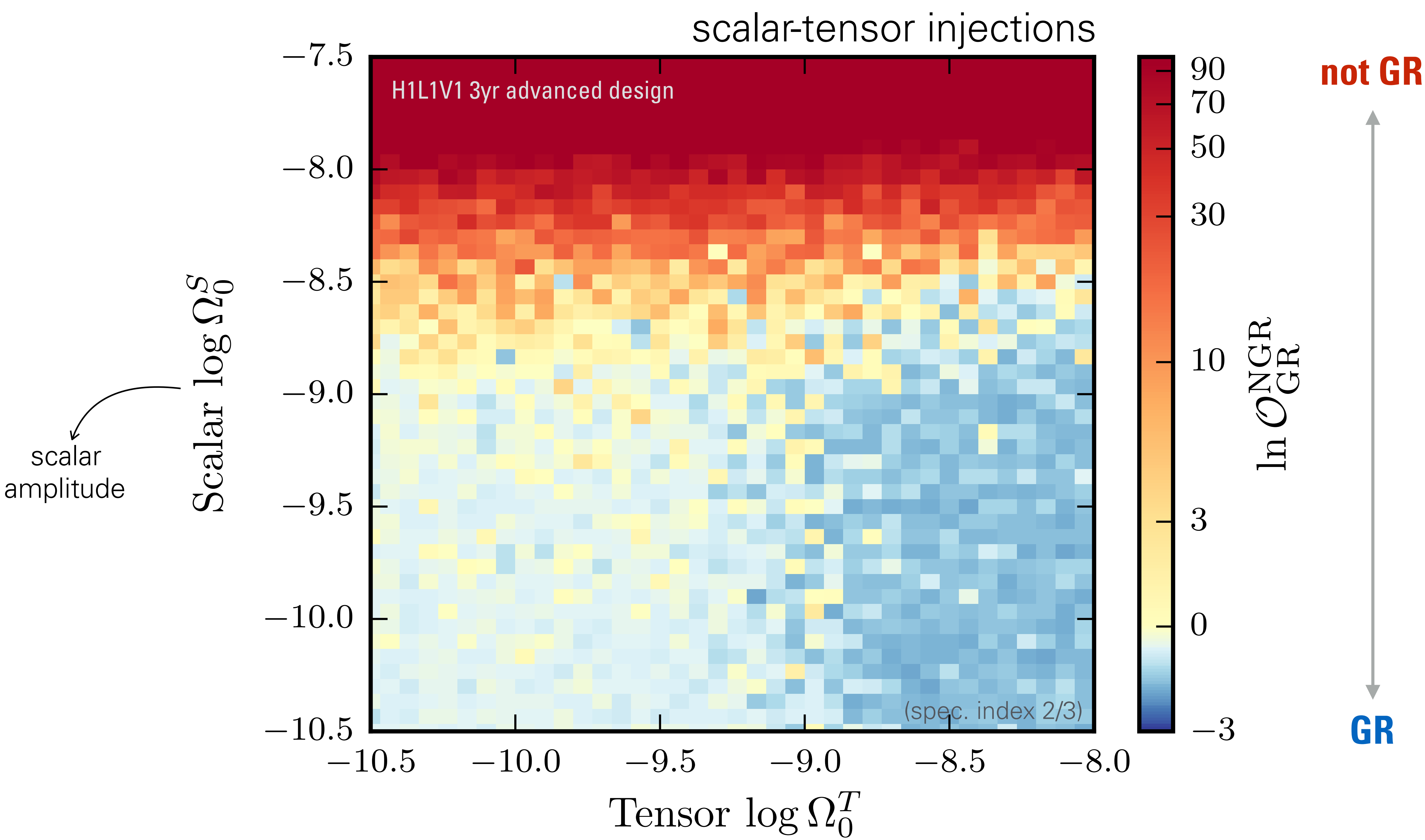
non-gr vs gr


scalar-tensor injections
H1L1V1 3yr advanced design
(spec. index 2/3)
−7.5
−8.0
−8.5
−9.0
−9.5
−10.0
−10.5
−10.5
−10.0
−9.5
−9.0
−8.5
−8.0
Scalar $\log \Omega_0^S$
Tensor $\log \Omega_0^T$
scalar
amplitude
90
70
50
30
10
3
0
−3
$\ln \mathcal{O}_N^{\mathrm{SIG}}$
signal
noise

non-gr vs gr

[arXiv:1704.08373]

SB

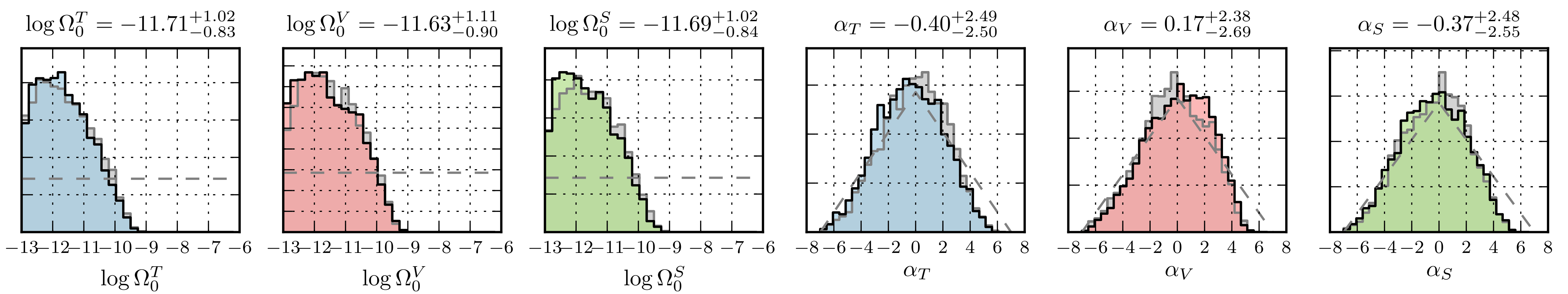


parameter estimation

[arXiv:1704.08373]

SB

3yr sensitivity projections for design aLIGO + Virgo



tensor vector scalar | tensor vector scalar

amplitudes | slopes

gray histograms are LIGO-only results, dashed lines mark priors

projected 95%-credible amplitude upper limits

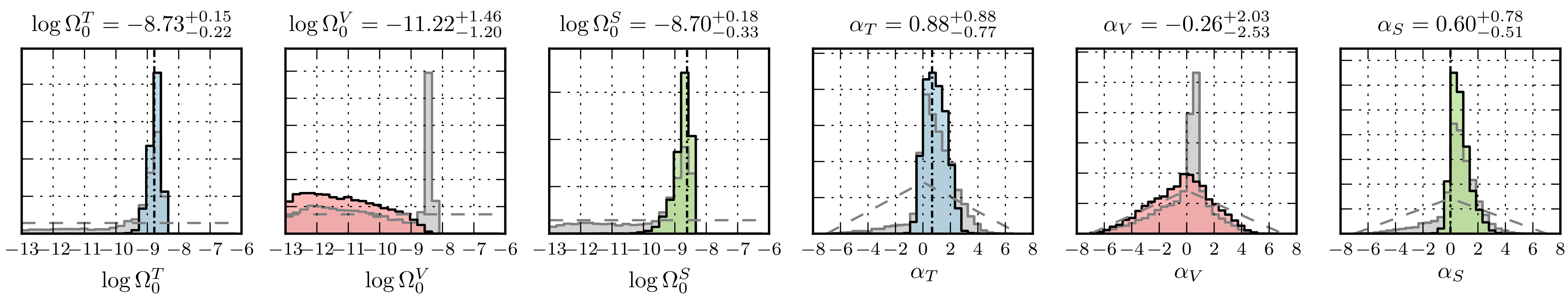
$$\log\Omega_0^{\rm T} < -10.1 \qquad \log\Omega_0^{\rm V} < -9.9 \qquad \log\Omega_0^{\rm S} < -10.0$$

parameter estimation

[arXiv:1704.08373]

SB

3yr scalar-tensor signal with design aLIGO + Virgo



tensor vector scalar | tensor vector scalar

amplitudes | slopes

gray histograms are LIGO-only results, dashed lines mark priors

Virgo does not increase sensitivity but helps break degeneracy between scalar and vector

conclusion

we are now able to **detect persistent signals of any polarization** content in a model-independent way

we can directly measure polarization content and **quantify agreement with GR**

this will allow us to explore a **new side of gravity**!

[arXiv:1703.07530] | [arXiv:1704.08373]

thank you!