OBSERVING BLACK HOLES VIBRATIONS

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IN SUPREMÆ DIGNITATIS 1343

DECEMBER 19-20, 2022

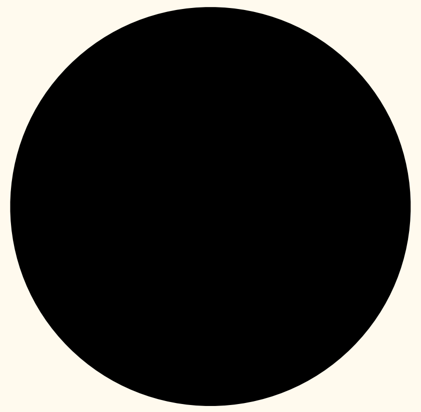
XV BLACK HOLES WORKSHOP - ISCTE

1. ringdown

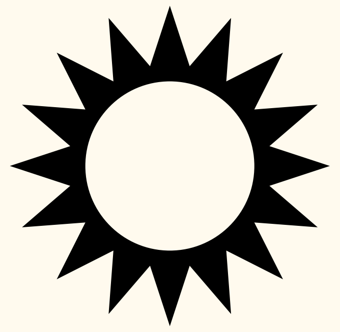
WHY STUDY RINGDOWN?

unique possibility of studying general relativity (GR)
in strong field and extreme curvature regimes

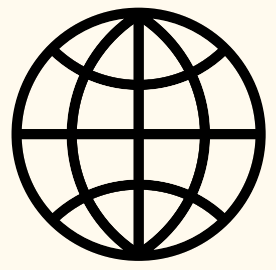
black hole



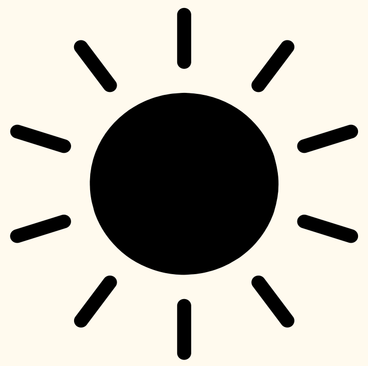
are we really observing black holes?



is GR the correct theory of gravity?



are there quantum effects at the horizon?



what is the ringdown?

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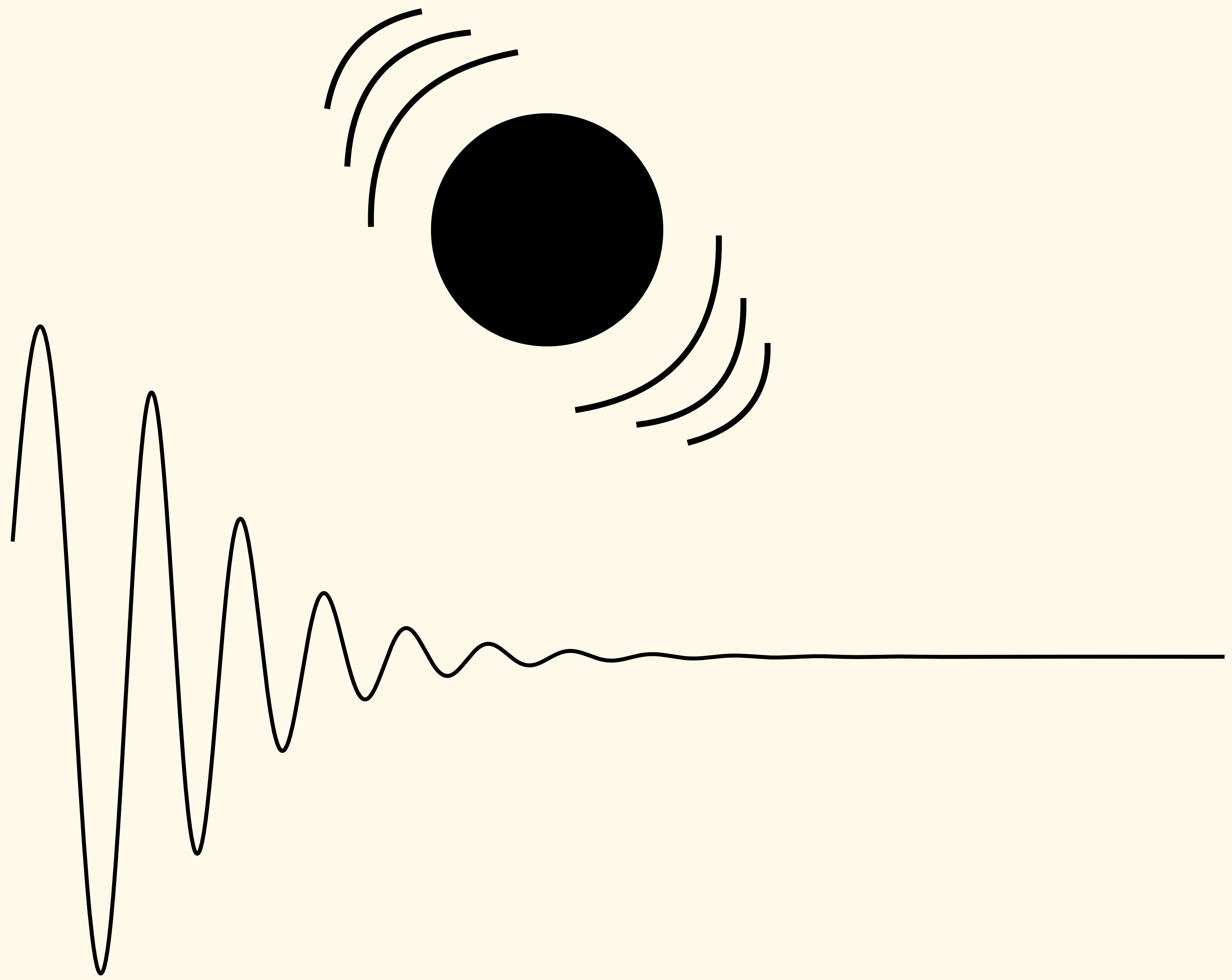
RINGDOWN WAVEFORM



black hole (BH) linear perturbation theory predicts:

$$h = \sum_{lm} A_{lm}\; e^{-i\omega_{lm}t - t/\tau_{lm}}\; {}_2Y_{lm}$$

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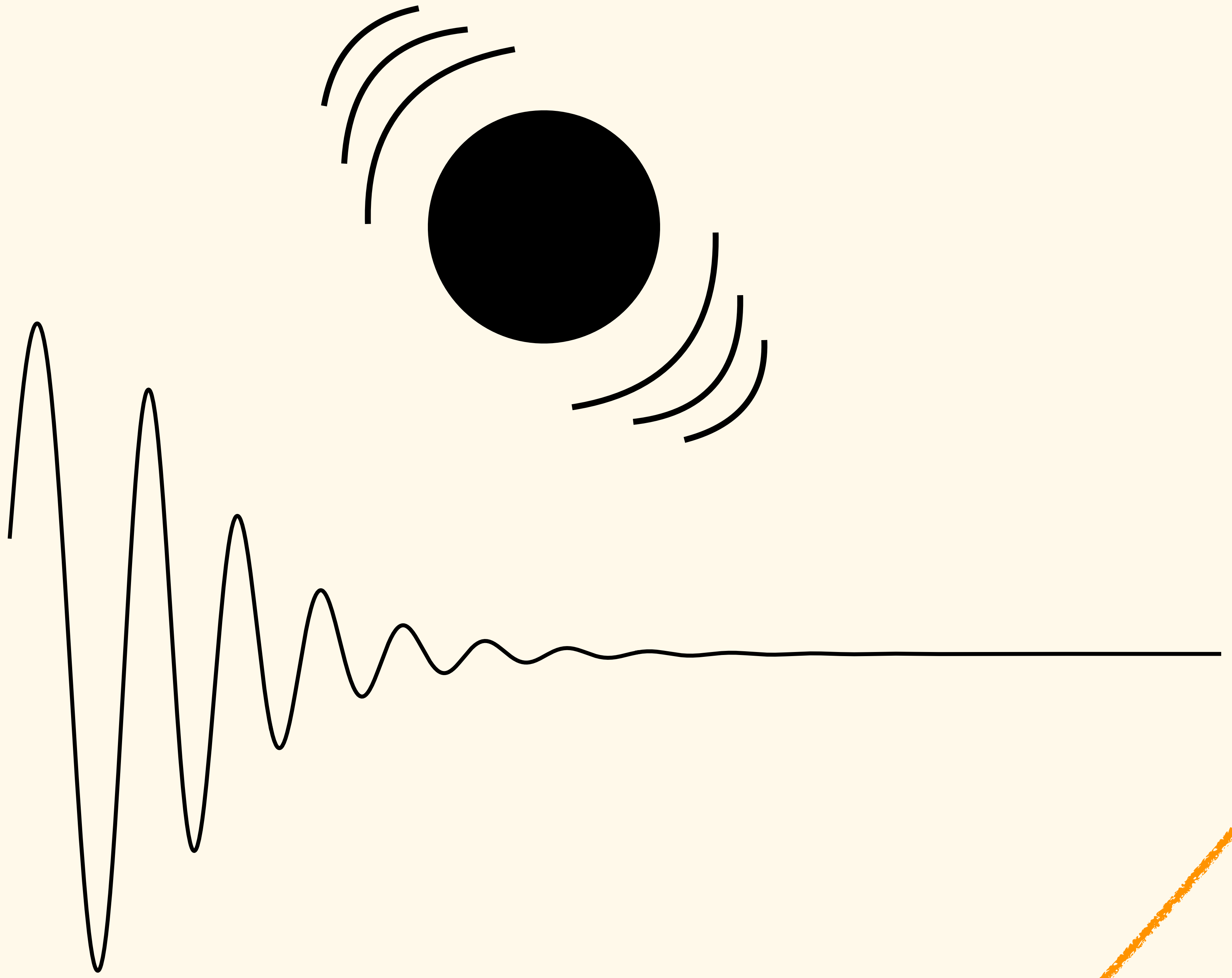

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different modes of vibration

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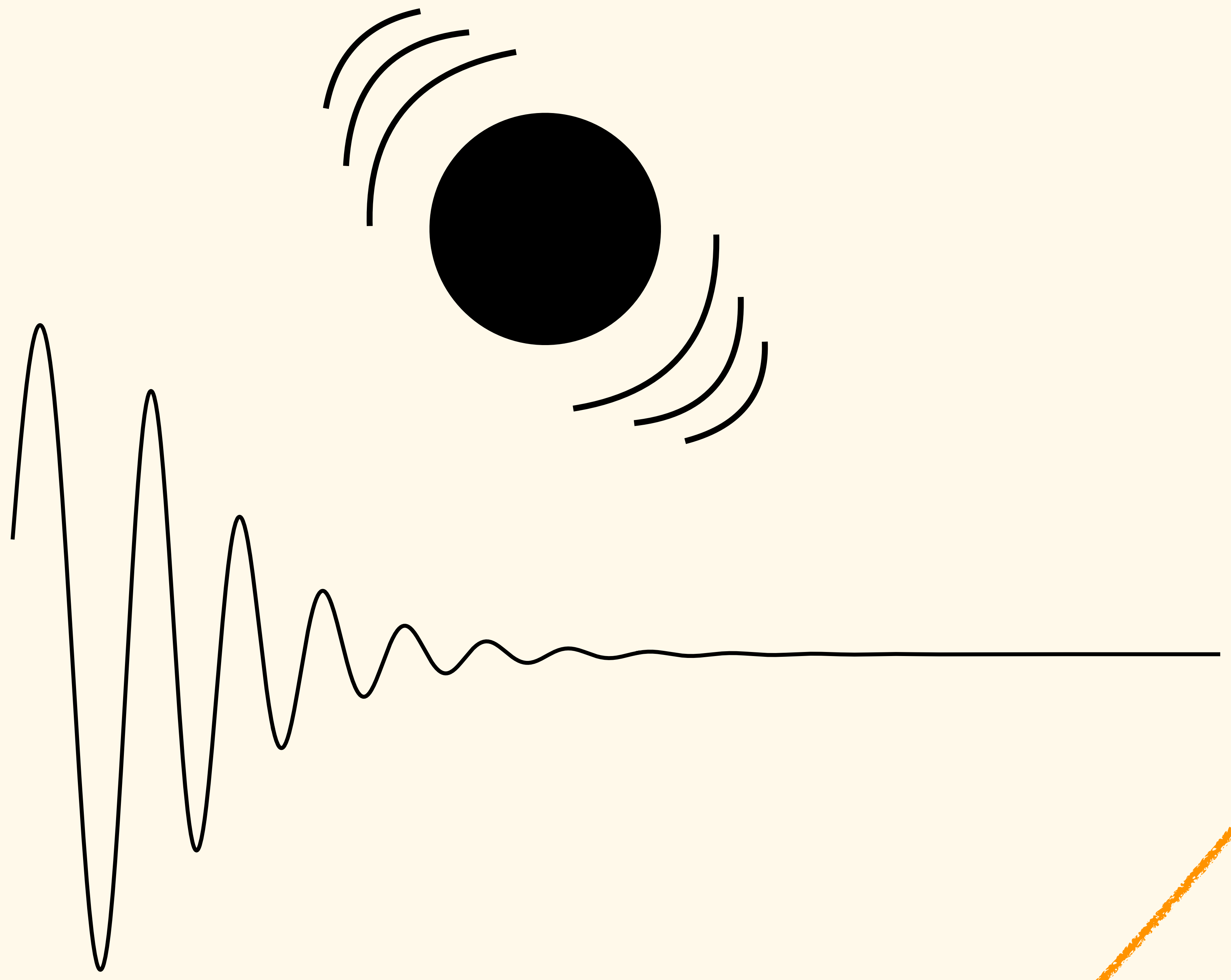

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different modes of vibration

amplitude

exponentially damped harmonic oscillations

(spin-weighted) spherical harmonics

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(spin-weighted)
spherical harmonics

${}_2Y_{lm}$ provide angular dependence for the modes

→ inclination ι

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$e^{-i\omega_{lm}t - t/\tau_{lm}}$ ω_{lm} and τ_{lm} are known once M and χ are fixed

→ quasinormal modes

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$e^{-i\omega_{lm} t - t/\tau_{lm}}$ ω_{lm} and τ_{lm} are known once M and χ are fixed

→ quasinormal modes

A_{lm} depend on the specific process that perturbs the BH

→ are not known analytically

2. higher modes

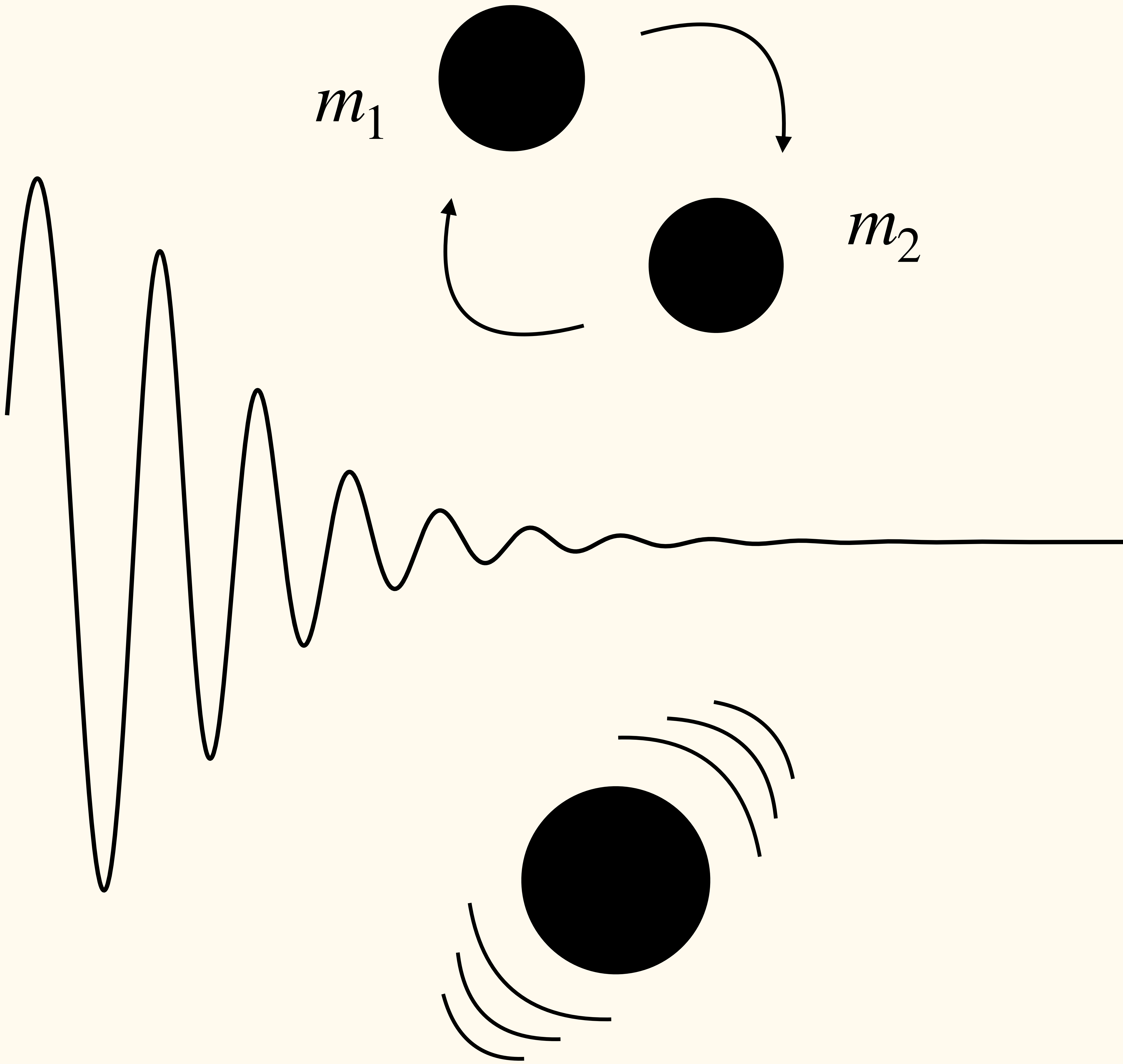
which modes are observable
in the ringdown?

HIGHER MODES (HMS)

which modes are observable in the ringdown?

for quasi-circular BHs with masses $m_1 \simeq m_2$:

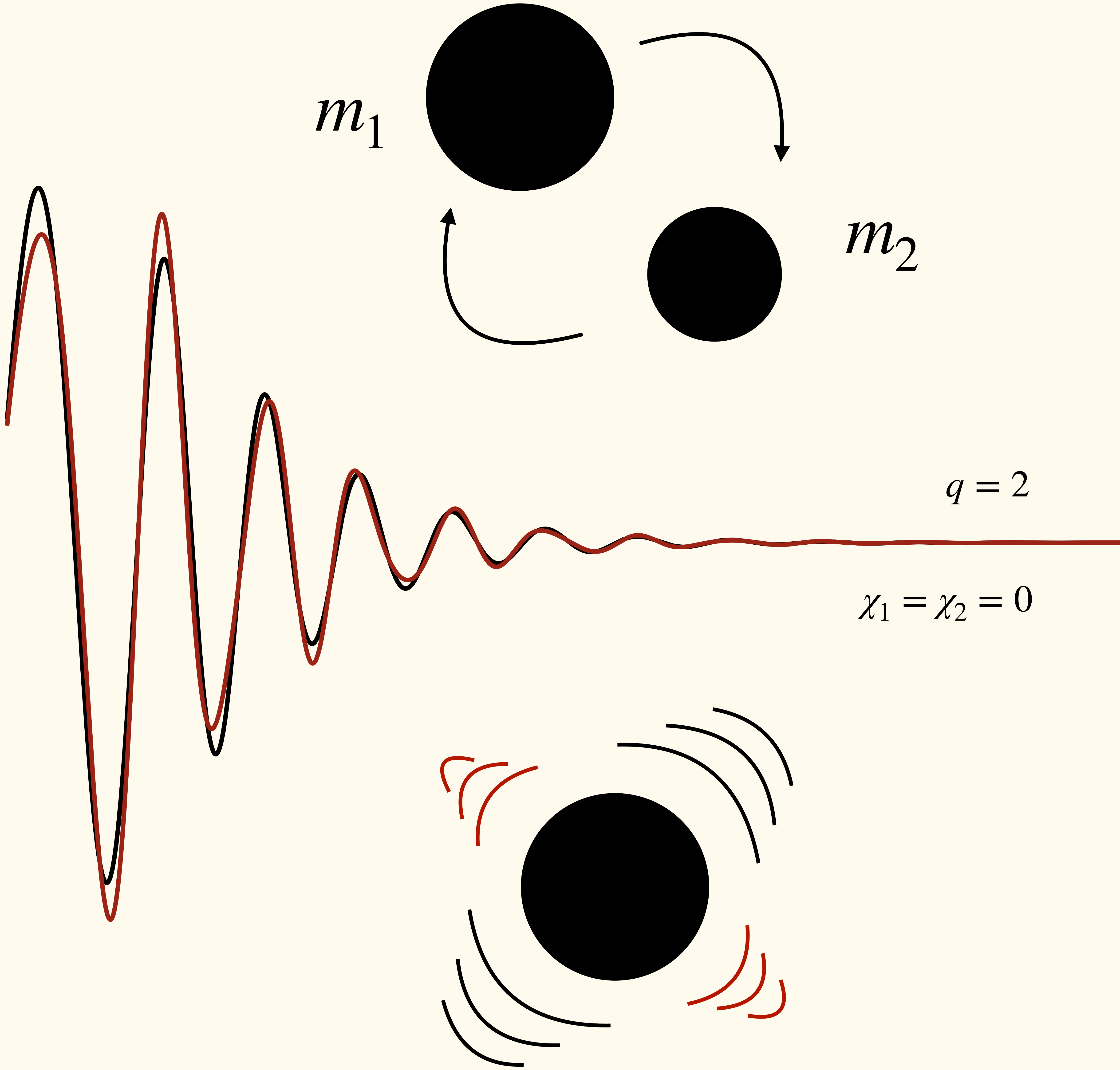
- dominant contribution (2,2) fundamental mode
- subdominant contribution (3,3), (2,1), (4,4) higher modes



HIGHER MODES EXCITATION

HMs can be excited by:

- increasing the mass ratio $q \equiv m_1/m_2$
- increasing the initial spins χ_1 and χ_2



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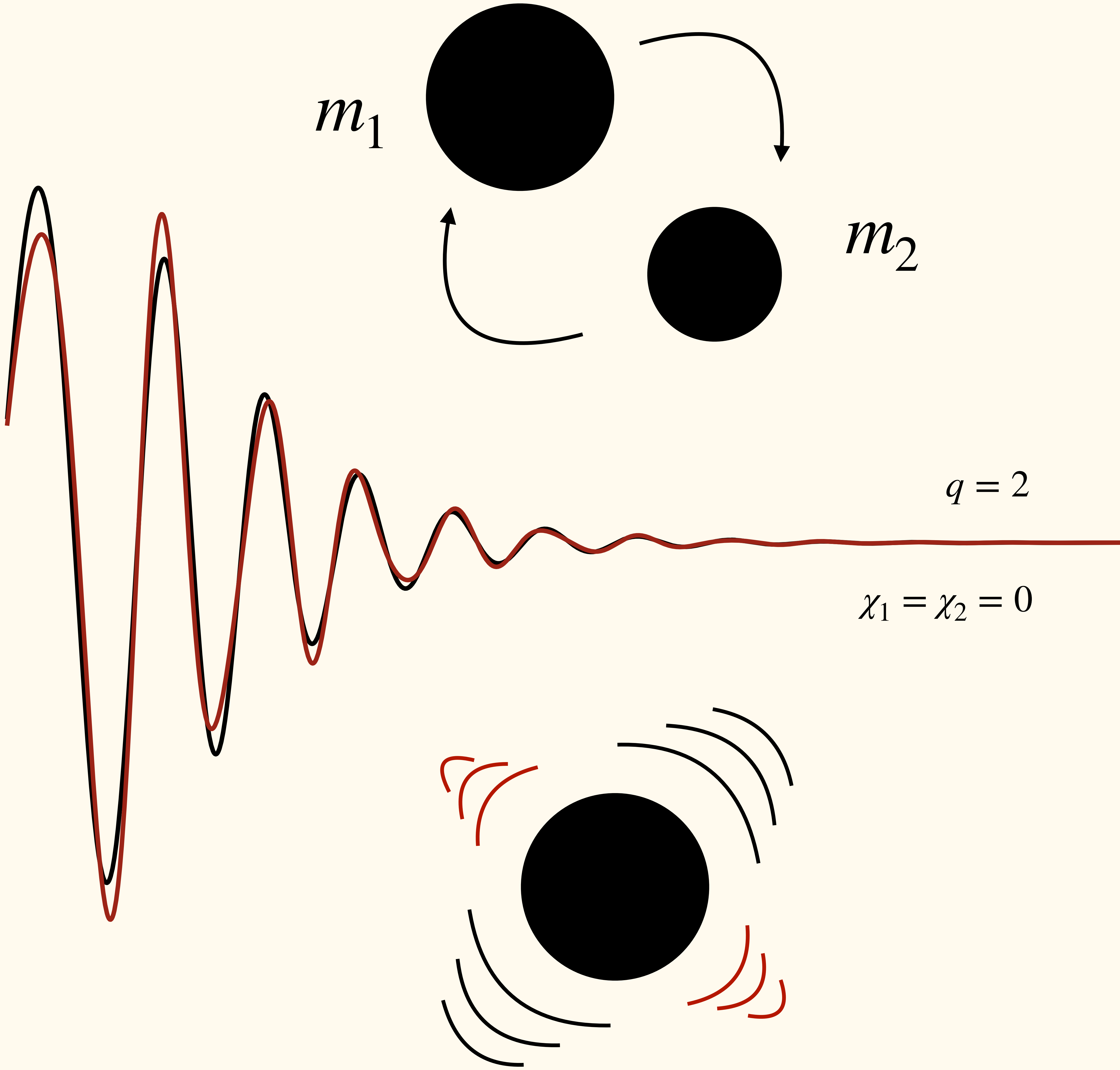
can we observe HMs with current detectors?



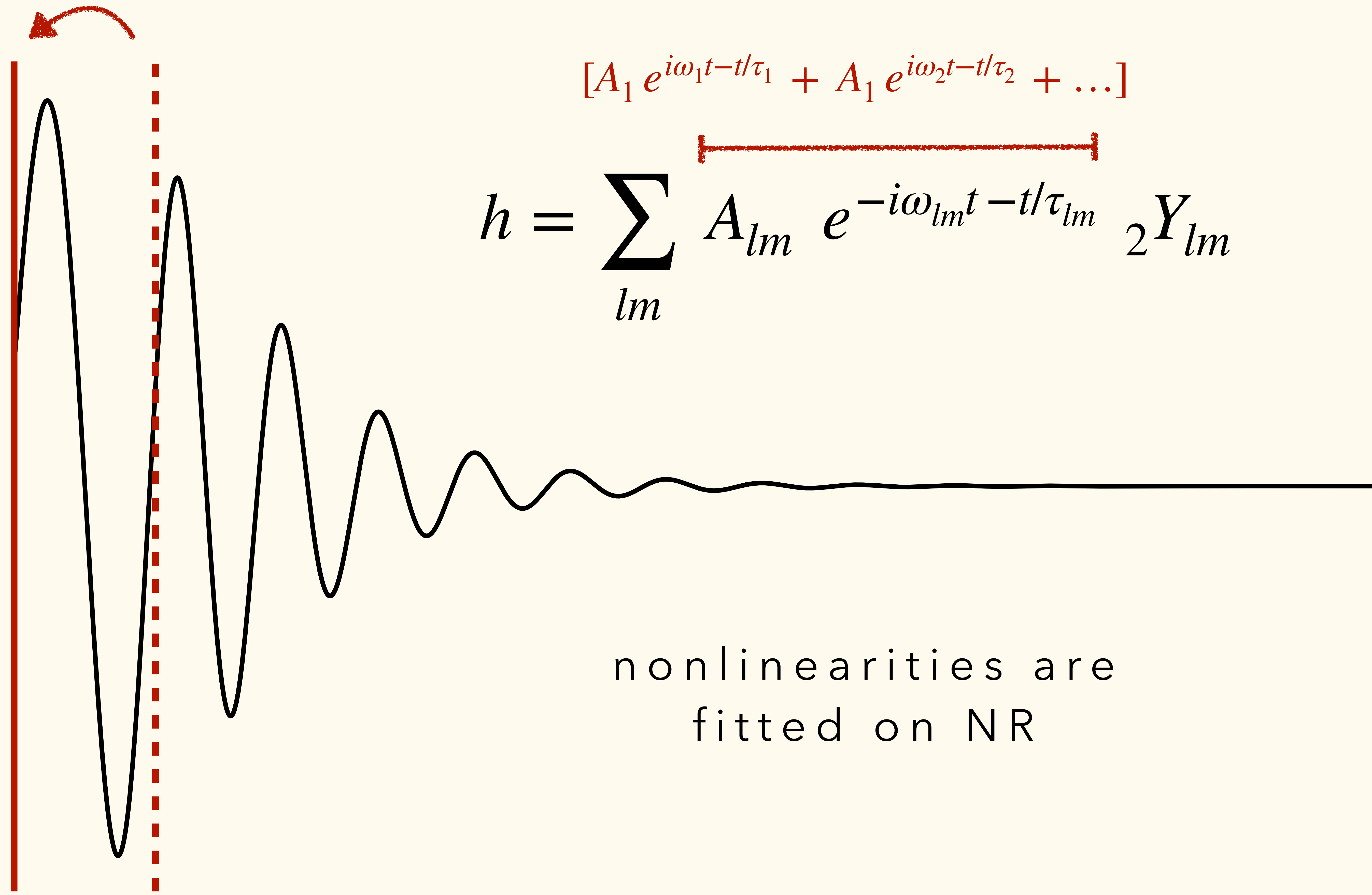
TEOBPM MODEL

Damour and Nagar (2014)
1406.0401

EOB model that includes post-merger nonlinearities

advantages:

- fixes the starting time
- more data with high SNR
- includes the A_{lm}



$$[A_1\, e^{i\omega_1 t - t/\tau_1} + A_1\, e^{i\omega_2 t - t/\tau_2} + \dots]$$

$$h = \sum_{lm} A_{lm}\ e^{-i\omega_{lm}t - t/\tau_{lm}}\ {}_2Y_{lm}$$

nonlinearities are fitted on NR

- unambiguous results
- more accurate results

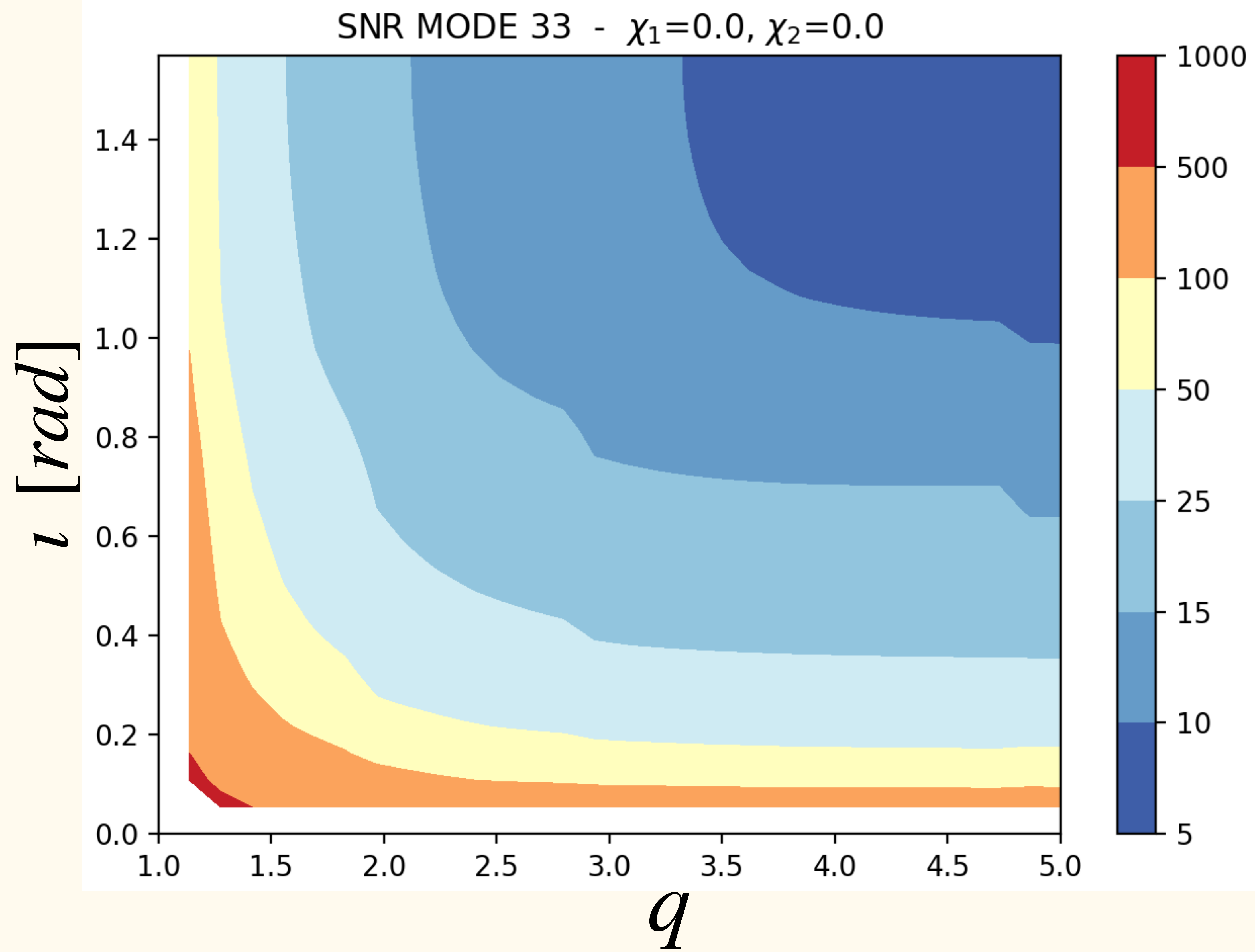
($\sim 20\%$ more SNR)

HMS DETECTABILITY

$$ln\, B \simeq \frac{1}{2}(1 - FF^2)\; SNR^2$$

SNR needed to detect the (3,3) mode

(with $ln\, B = 5$)



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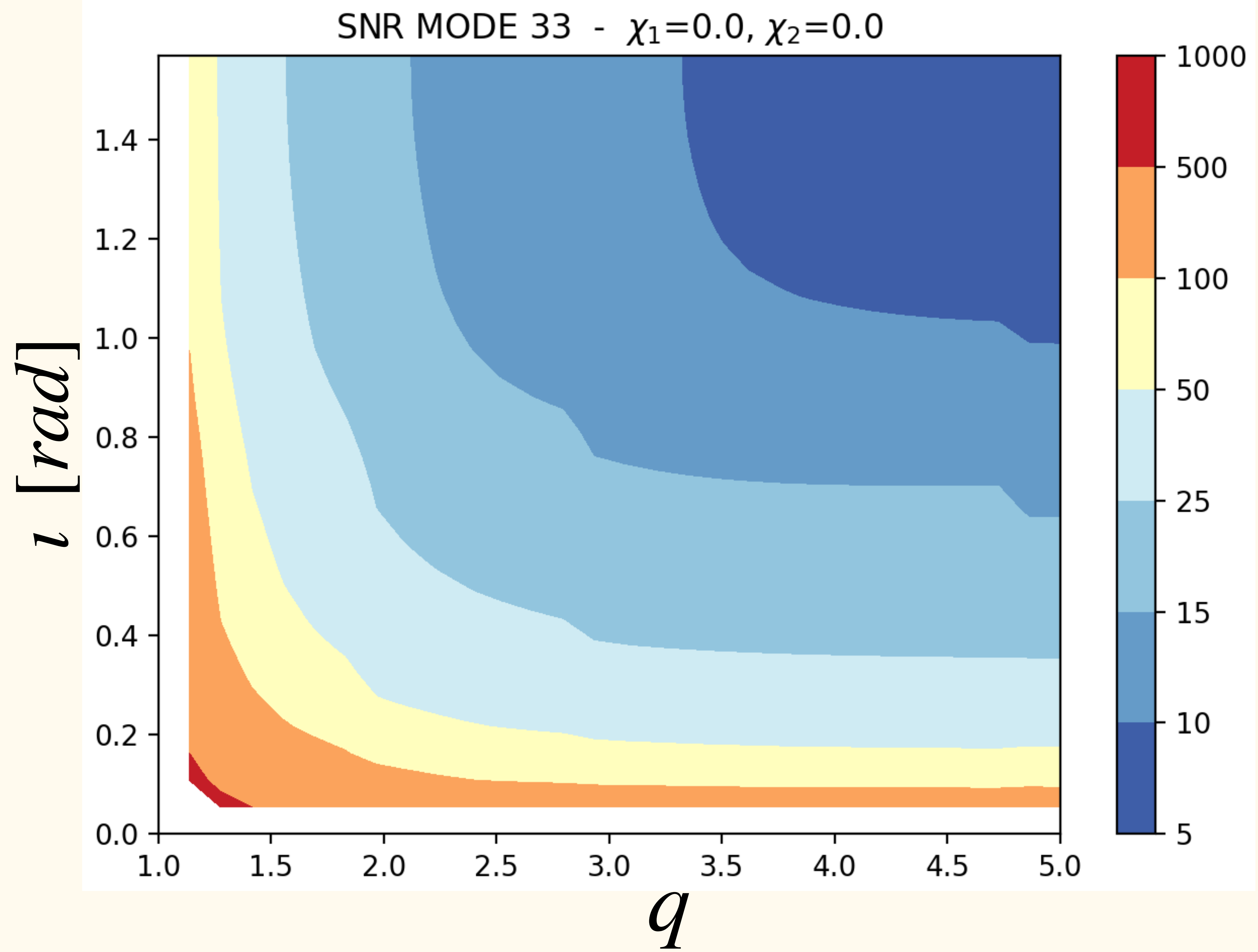
Bayes factor

fitting factor

signal-to-noise ratio



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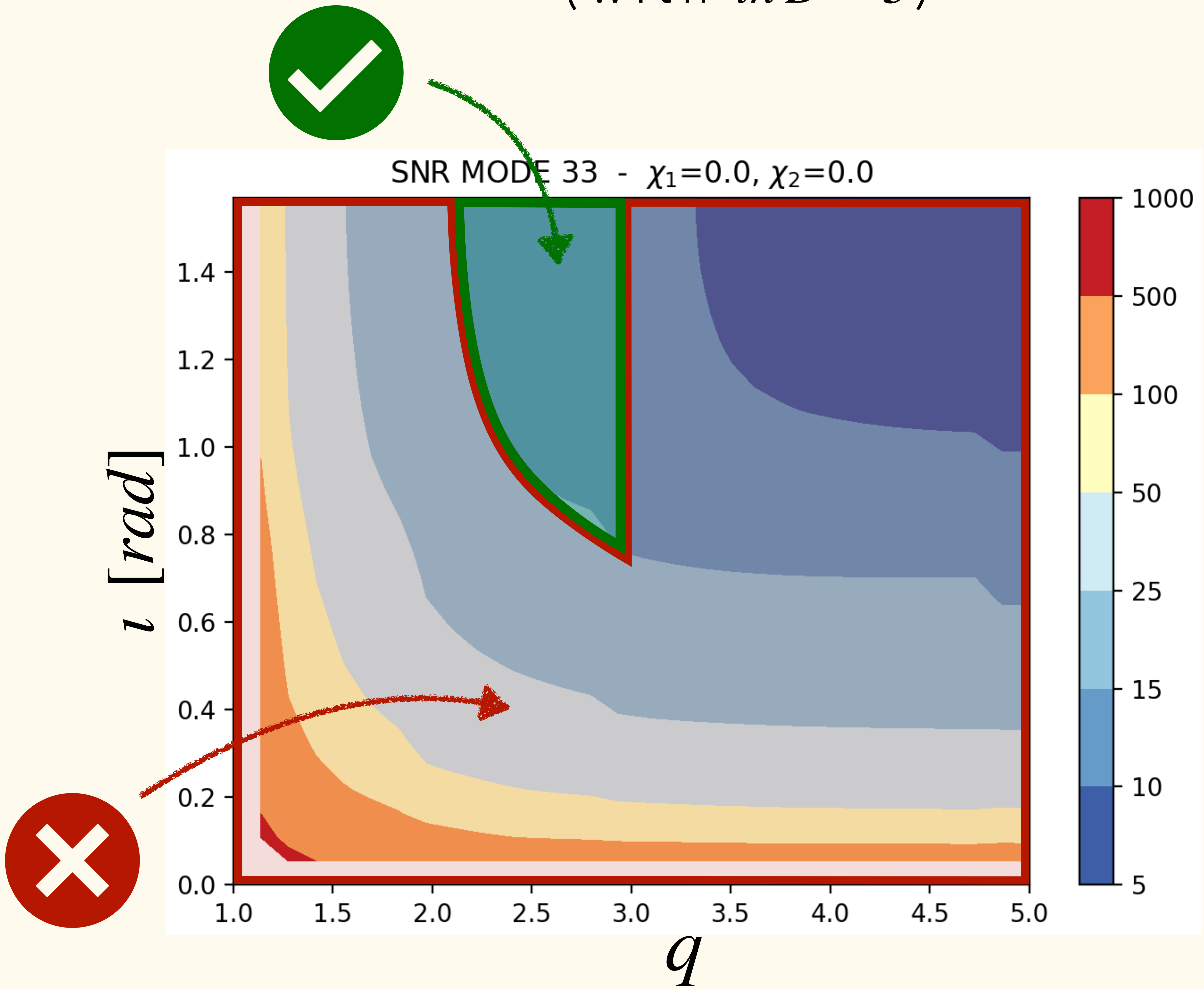

3. data analysis

INSTRUMENTAL NOISE

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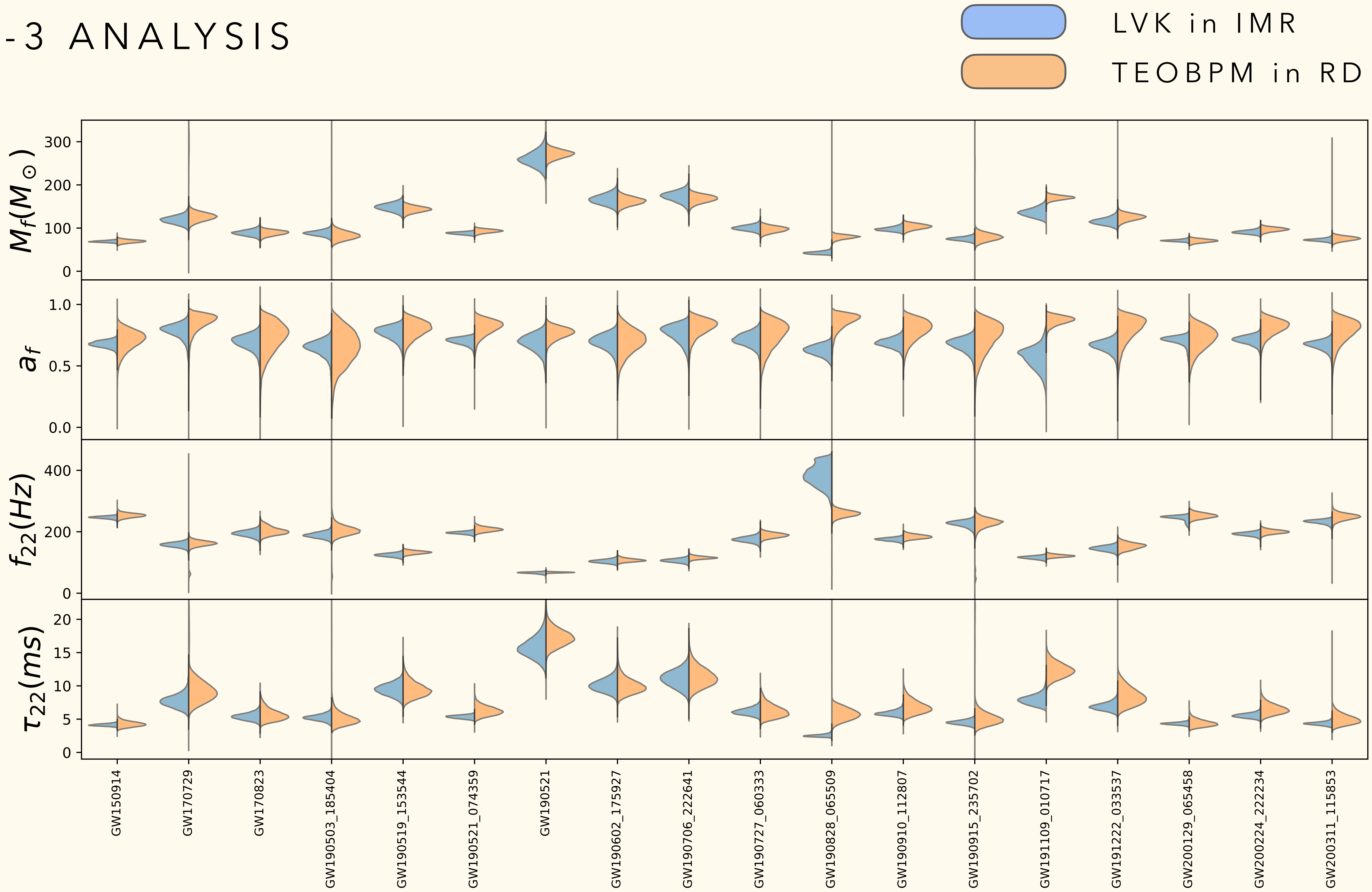
we used TEOBPM for a time domain analysis of LIGO-Virgo data with pyRing

GWTC-3 ANALYSIS



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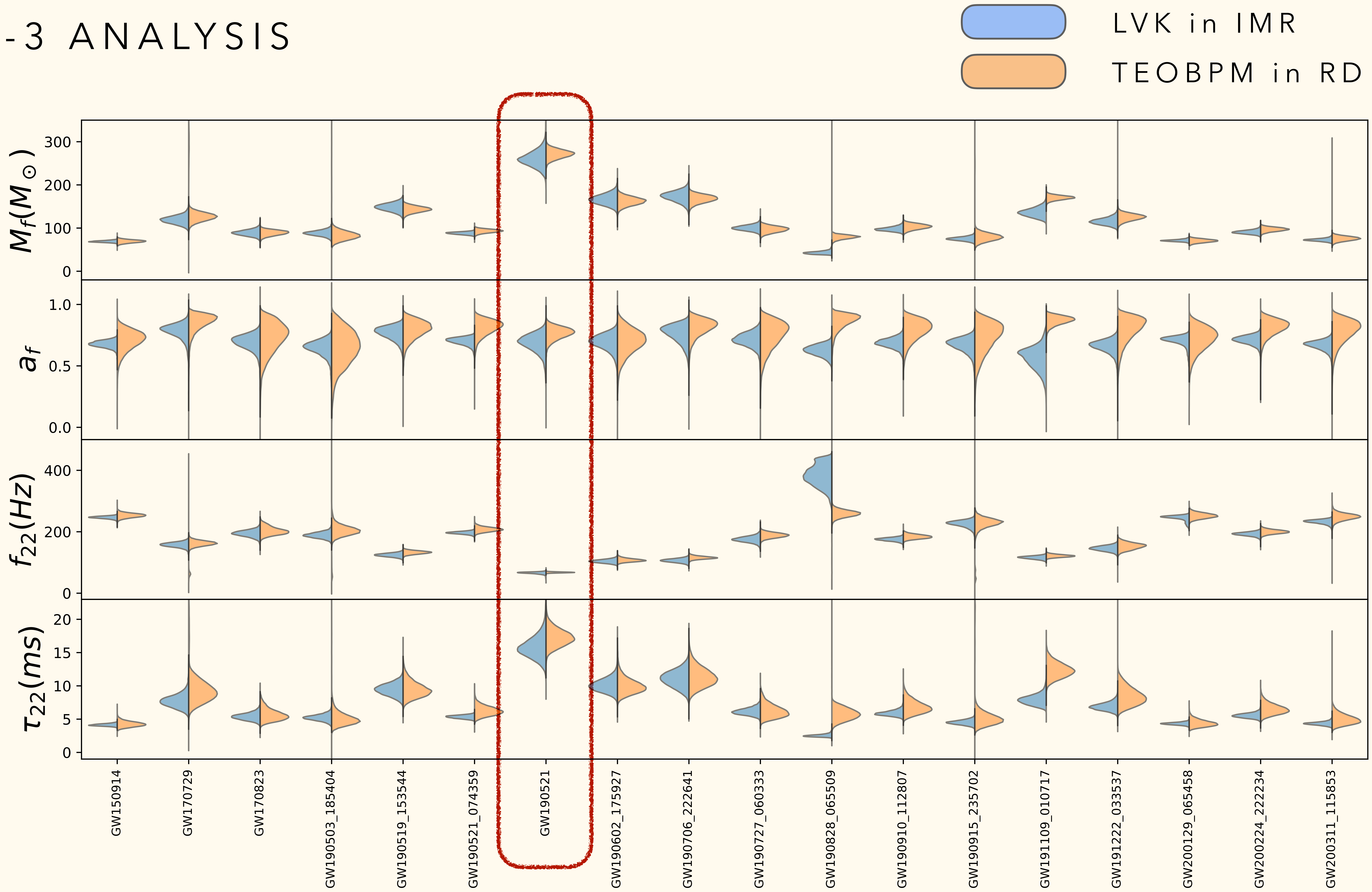

DID WE OBSERVED HMS?

observations of HMs in the literature:

RD-only analyses

event	reference	$\ln \mathcal{B}_{lm,22}$	coalescence	type
GW190521A	Capano et al. (2021)	3.8	IMBH	RD

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this work

no HMs in GW190521

$$ln\, B_{33,22} = 0.13$$

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precession? eccentricity? other?

2009.01075 2106.05575

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further analyses ongoing…

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further analyses ongoing...

IMR analyses

event	reference	$\ln \mathcal{B}_{lm,22}$	coalescence	type
GW170729	Chatziioannou et al. (2019)	1.6	BBH	IMR
GW190814A	Abbott et al. (2020c)	22.1	BH-(?)	IMR
GW190412A	Abbott et al. (2020a)	8.3	BBH	IMR

RD weakly measured and not informative

4. tests of no-hair

why are higher modes important?

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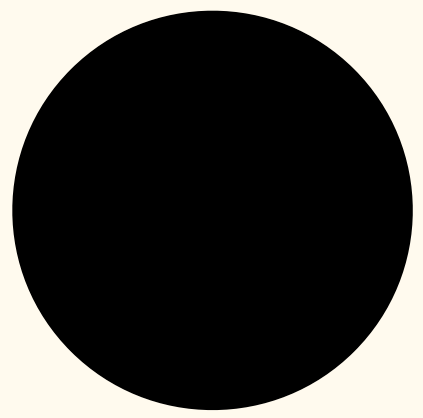
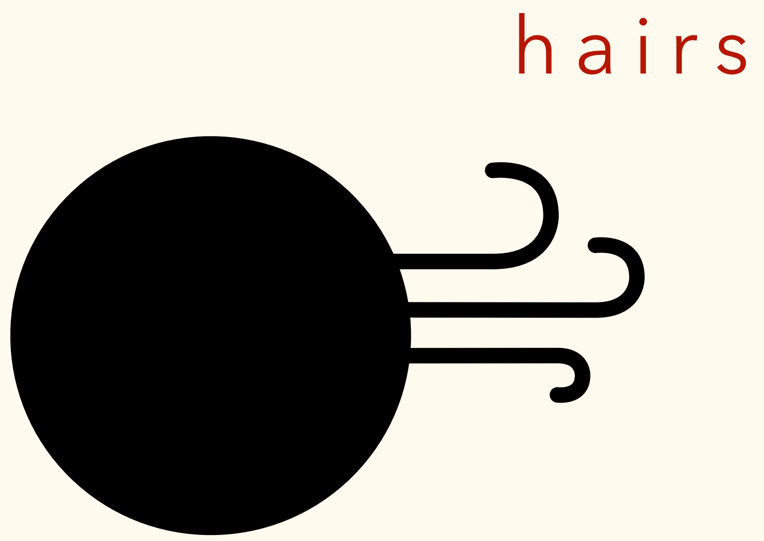
$\omega_{22}, \tau_{22} \longrightarrow \chi, M \longrightarrow$



why are higher modes important?

ω_{22}, τ_{22} → χ, M

ω_{33}, τ_{33} → $\delta\omega_{lm}$



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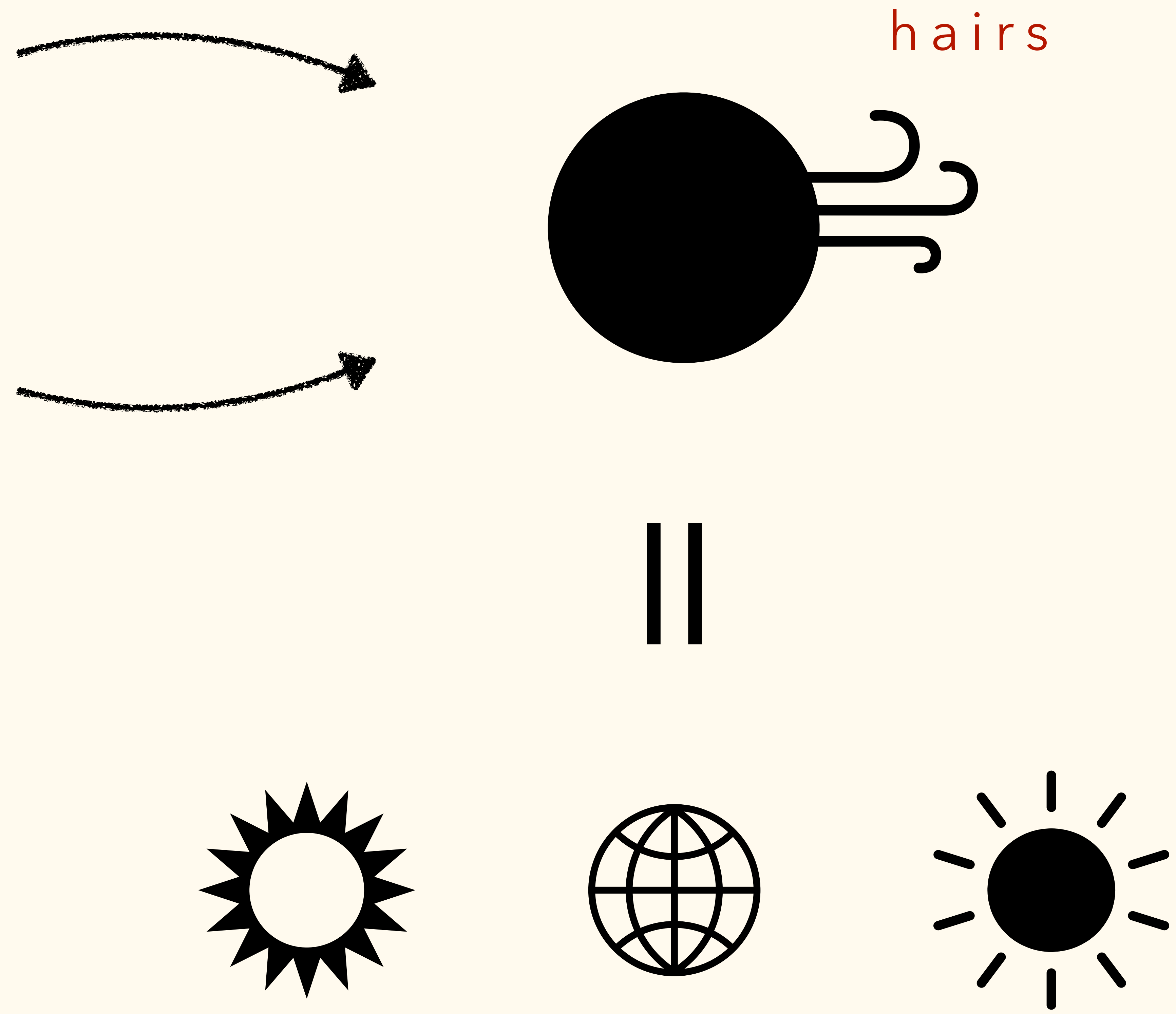


tests of the no-hair theorem

SUMMARY

- RD provides unique access to strong field and extreme curvature regimes
- the RD waveform is a superposition of quasinormal modes
- the excitation of HMs strongly depends on mass ratio and inclination
- we used a RD model that includes post-merger nonlinearities
- we developed an analytical procedure to predict the detectability of HMs
- we analysed the RD signals in GWTC-3 using TEOBPM
- we found results consistent with LVK and no HMs in GW190521
- importance of our results for future tests of the no-hair theorem

backup slides

GW SIGNAL

$$h_+ - ih_\times = \sum_{lm} A_{lm}\, e^{-i\omega_{lm}t - t/\tau_{lm}}\, {}_2Y_{lm}$$

ringdown waveform

$$h_{ij} = h_+ e^{+}_{ij} + h_\times e^{\times}_{ij}$$

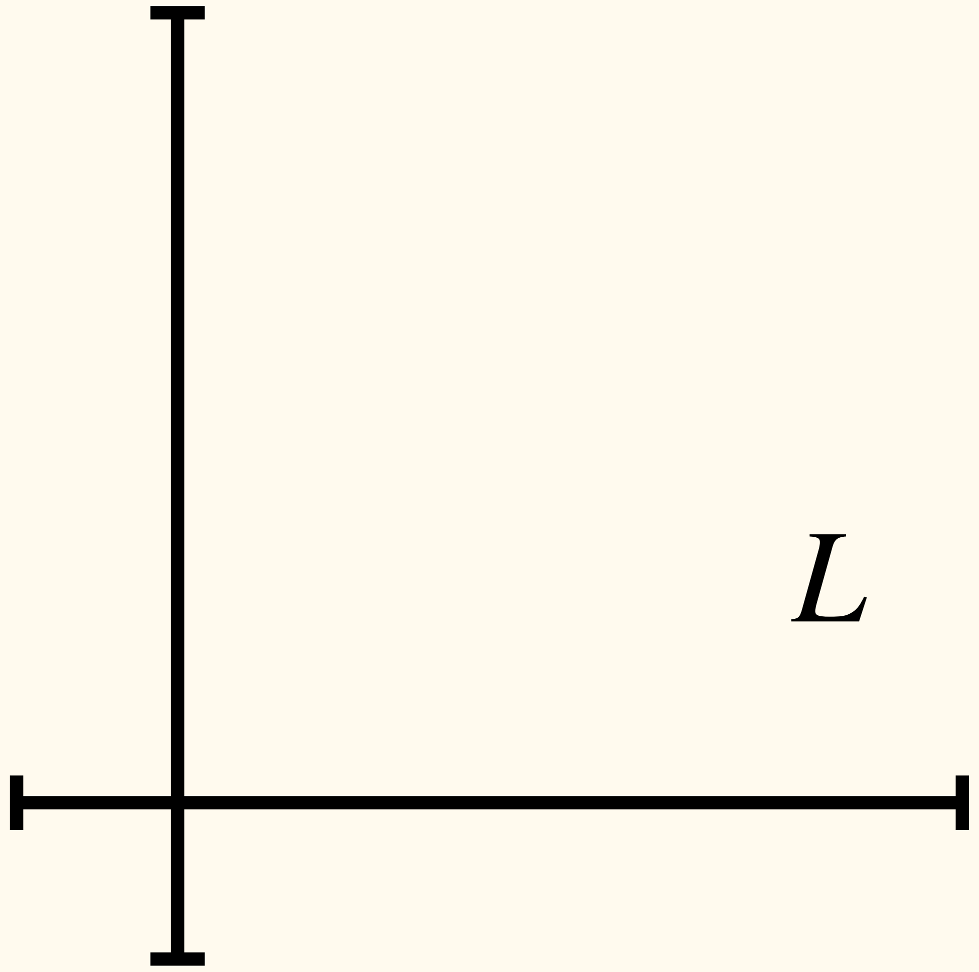
polarization tensors

$$h \equiv F_+ h_+ + F_\times h_\times$$

antenna functions

differential length of the interferometer

$$h = \frac{\Delta L}{L}$$



GW interaction is encoded in the amplitude and phase of the laser output

- parameter estimation

from Bayes theorem, we can find the probability density of the parameters

data → parameters

$$\frac{p(\boldsymbol{d}\,|\,\boldsymbol{\theta}, H)\, p(\boldsymbol{\theta}\,|\,H)}{p(\boldsymbol{d}\,|\,H)} = p(\boldsymbol{\theta}\,|\,\boldsymbol{d}, H)$$

posterior distribution

- model selection

the Bayes factor tells us which model better describes the data

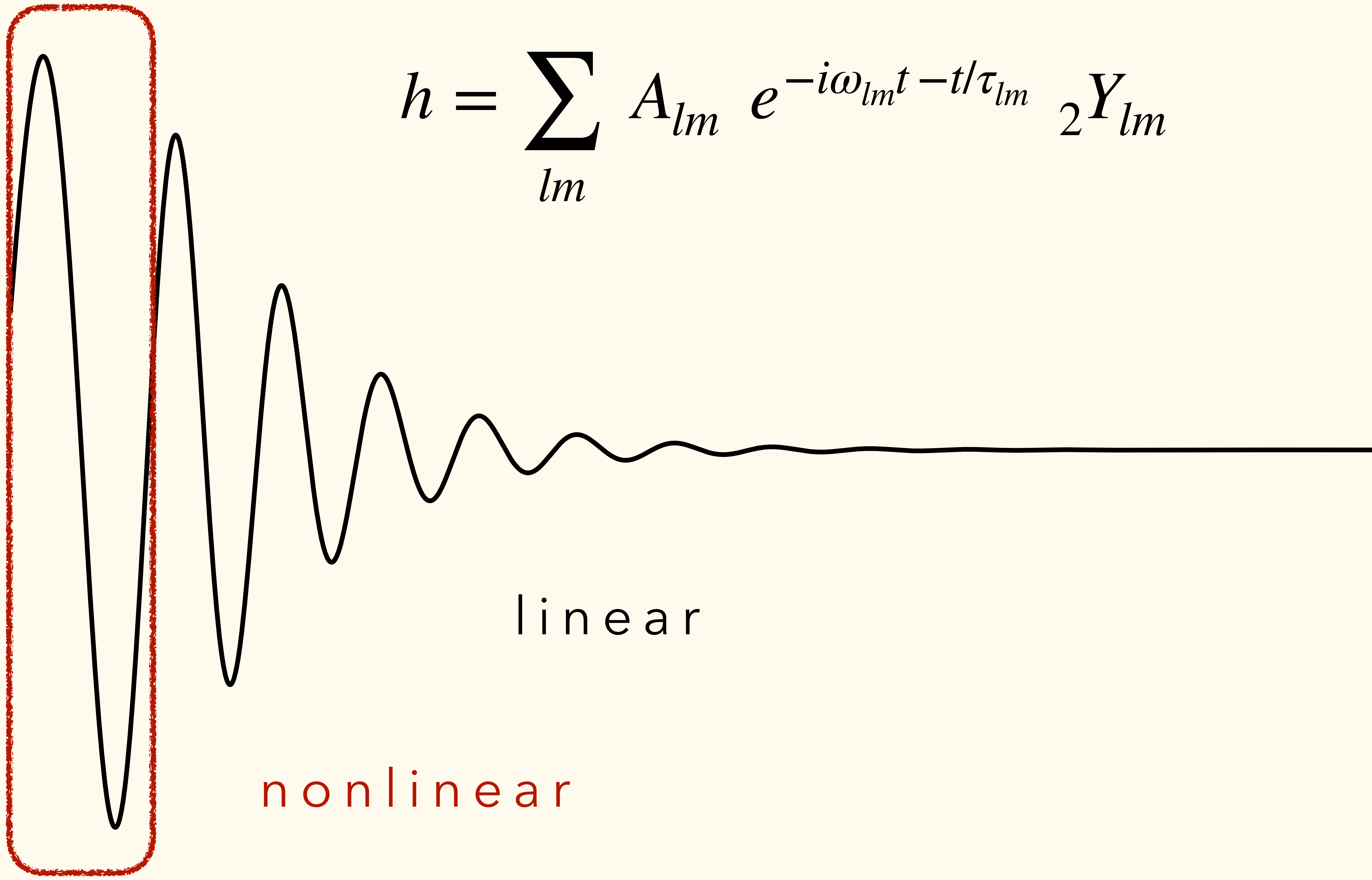
$$\frac{p(\boldsymbol{d}\,|\,H_1)}{p(\boldsymbol{d}\,|\,H_2)} \equiv B_{1,2}$$

linear perturbations

$$h = \sum_{lm} A_{lm}\; e^{-i\omega_{lm}t - t/\tau_{lm}}\;{}_2Y_{lm}$$

when the RD starts?

- too late, surely linear but lose all the signal
- too early, linear model to nonlinear data



difficult to choose the starting time → results depend on the starting time

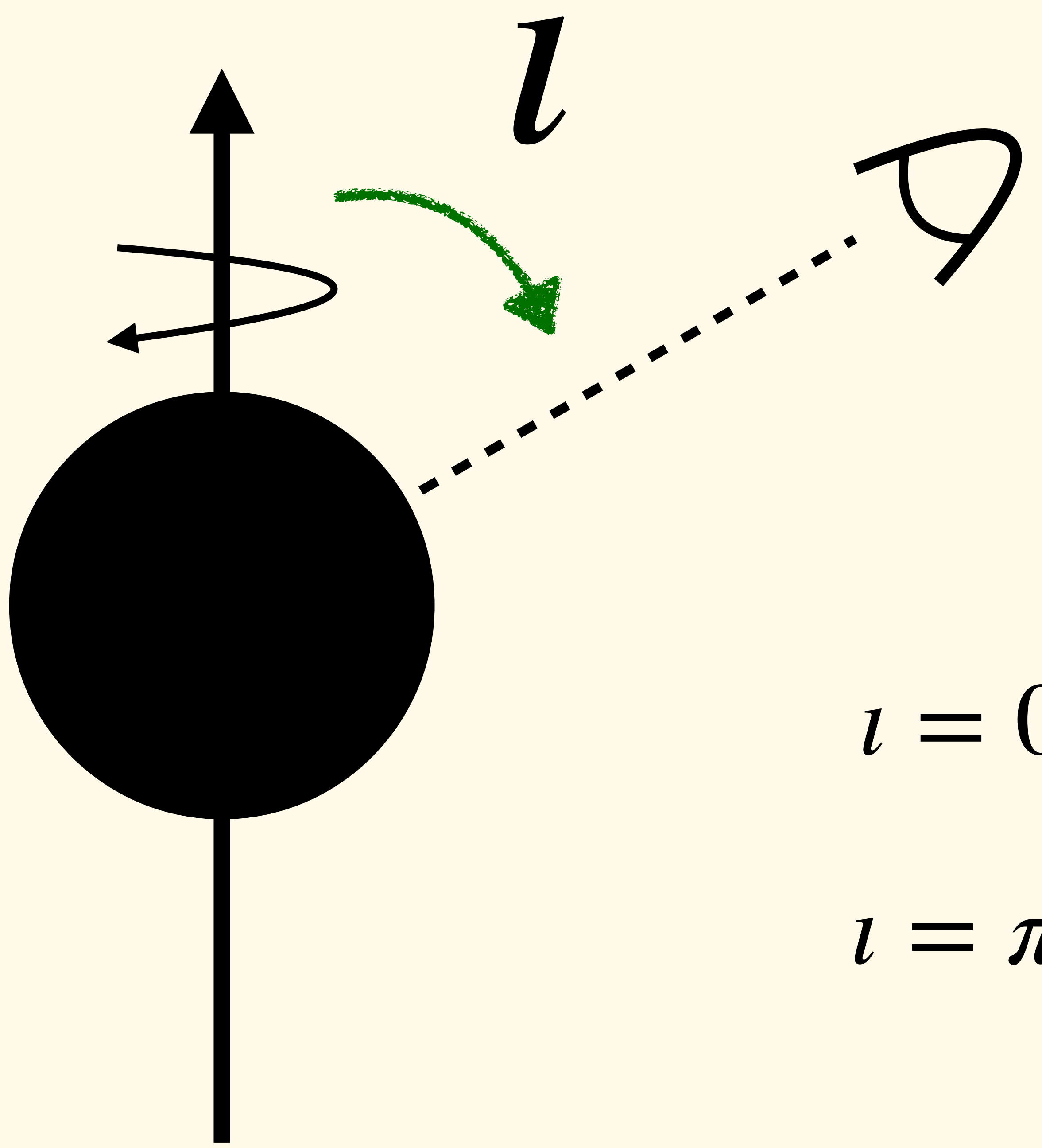
SPHERICAL HARMONICS

$$h = \sum_{lm} A_{lm} \, e^{-i\omega_{lm}t - t/\tau_{lm}} \, {}_2Y_{lm}$$

(spin-weighted) spherical harmonics

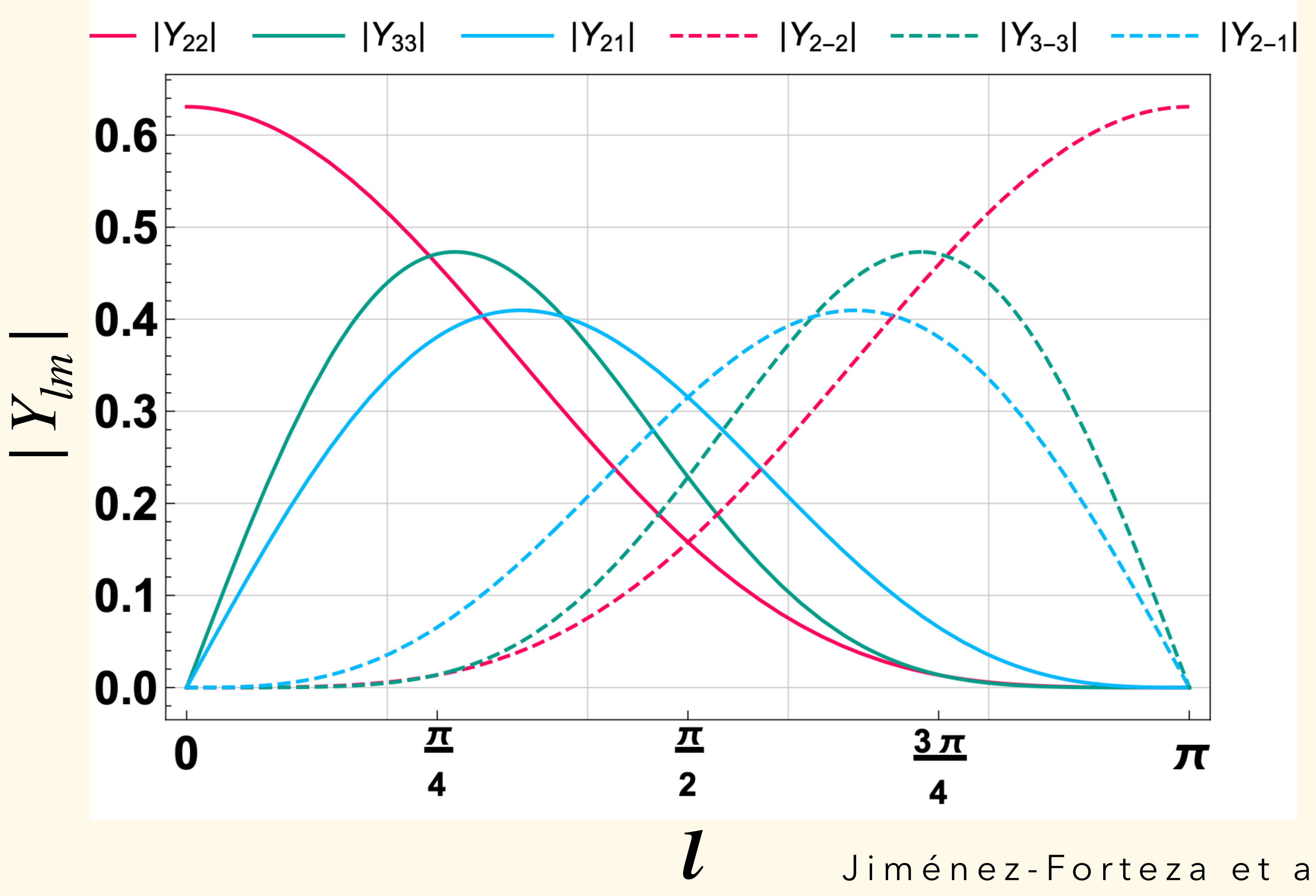
$${}_2Y_{lm}(\iota, \varphi)$$

ι is the inclination



$\iota = 0$ face-off

$\iota = \pi/2$ edge-on



Jiménez-Forteza et al. (2020) 2005.03260

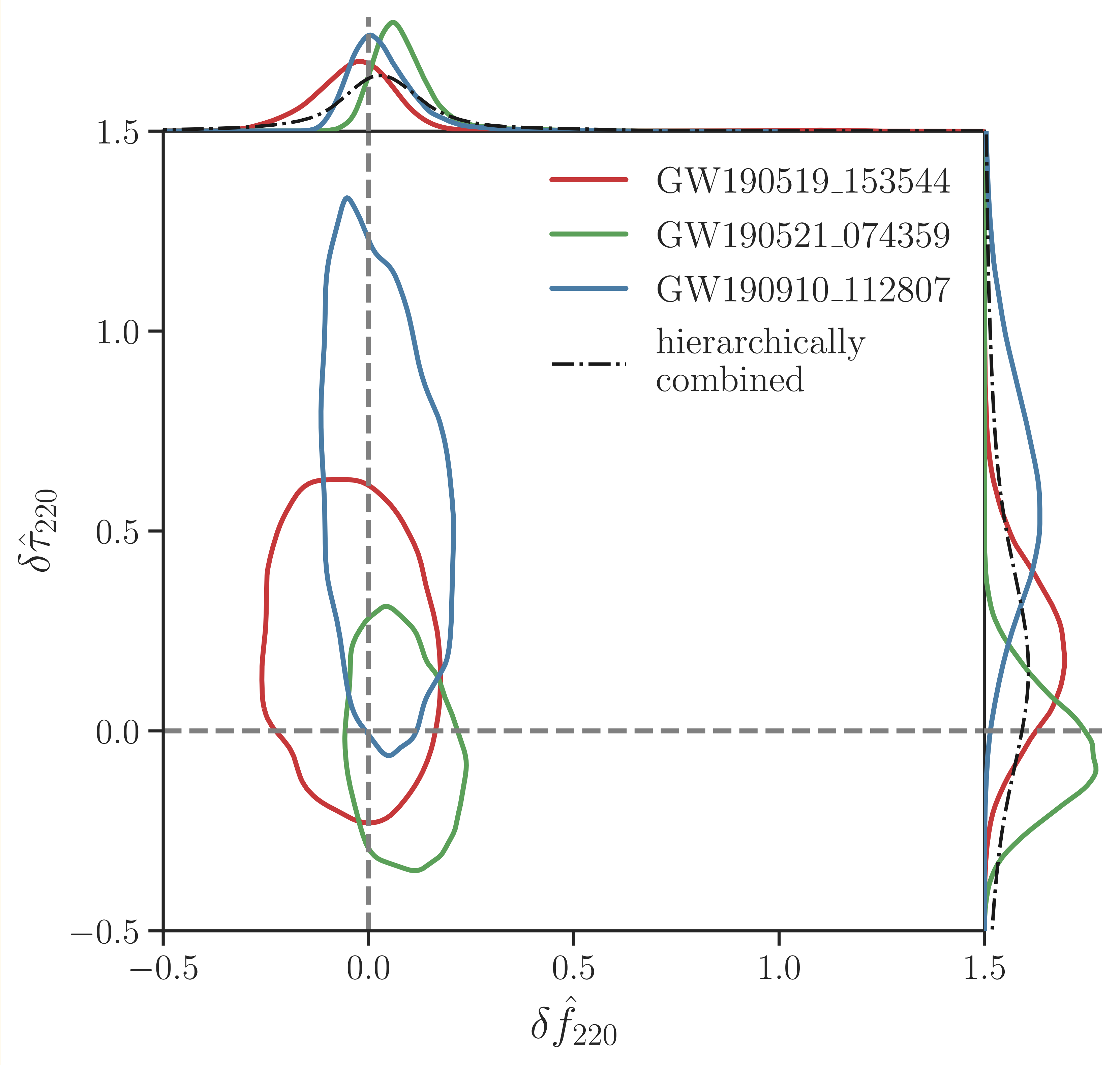
TESTS OF NO-HAIR

consider fractional deviations from GR

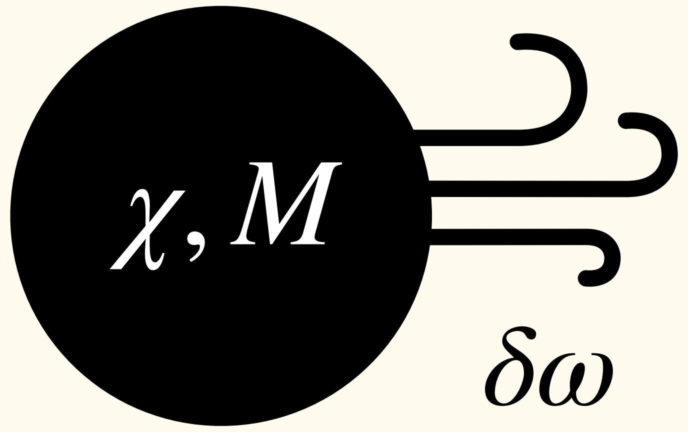
$$\omega_{lm} = \omega_{lm}^{GR}(1 + \delta\omega_{lm})$$

$$\tau_{lm} = \tau_{lm}^{GR}(1 + \delta\tau_{lm})$$

if the posteriors on $\delta\omega_{lm}$ and $\delta\tau_{lm}$ support zero, then GR is correct



Abbott et al. (2020)
2010.14529



- $\delta\omega_{lm}, \delta\tau_{lm}$ are generic additional degrees of freedom
- possibility to map $\delta\omega_{lm}, \delta\tau_{lm}$ to specific theories

ALTERNATIVE SCENARIOS

- are we really observing black holes?

  exotic compact objects (boson star, gravastar, fuzzball, ...)

- is GR the correct theory of gravity?

  modified theories of gravity (EdGb, dCS, EFT, ...)

- are there quantum effects at the horizon?

  area quantisation (Bekenstein-Mukhanov conjecture),
  BH entropy (Bekenstein-Hod bound)

→ systematics? unmodeled properties? environmental effects?