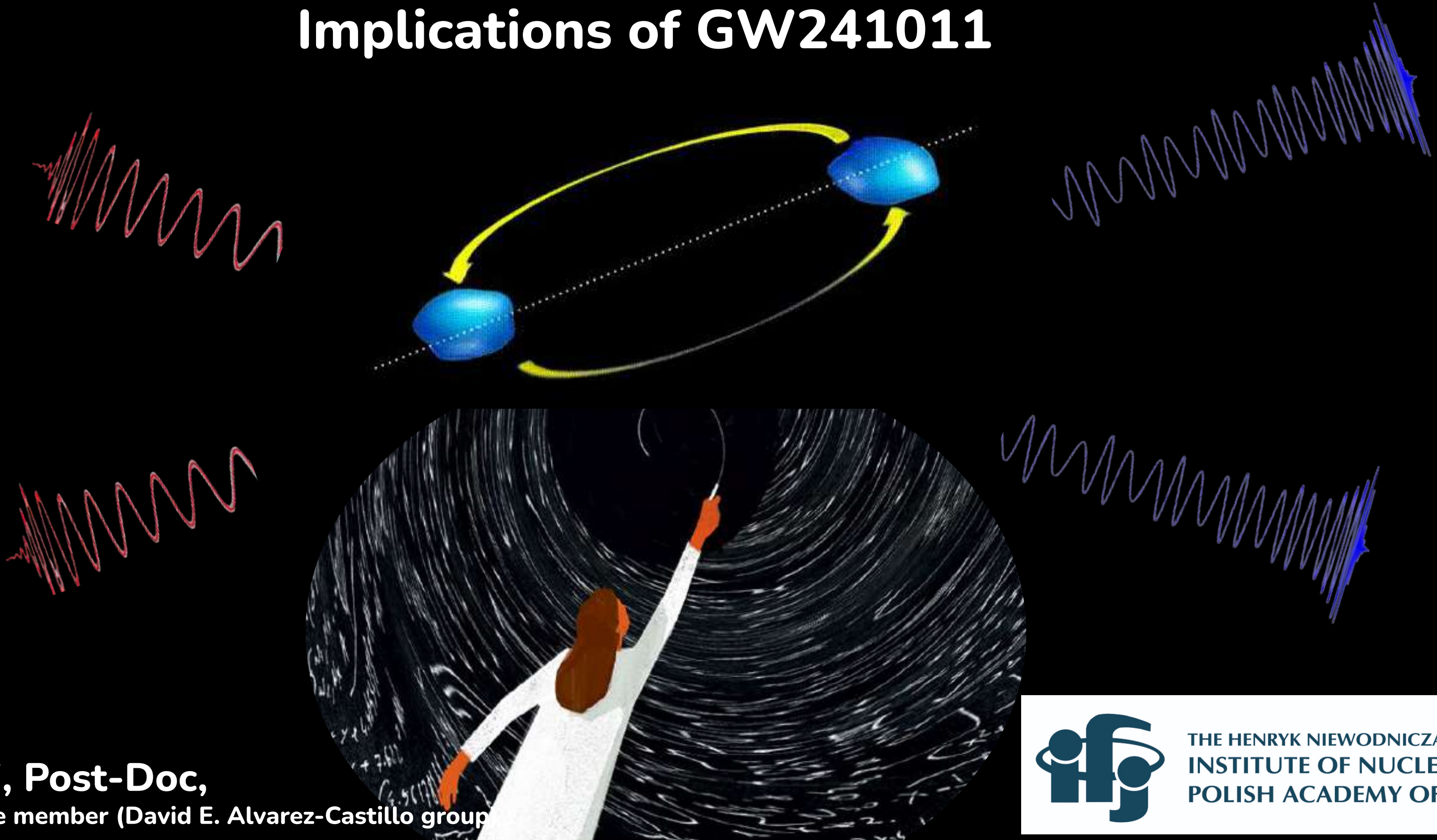
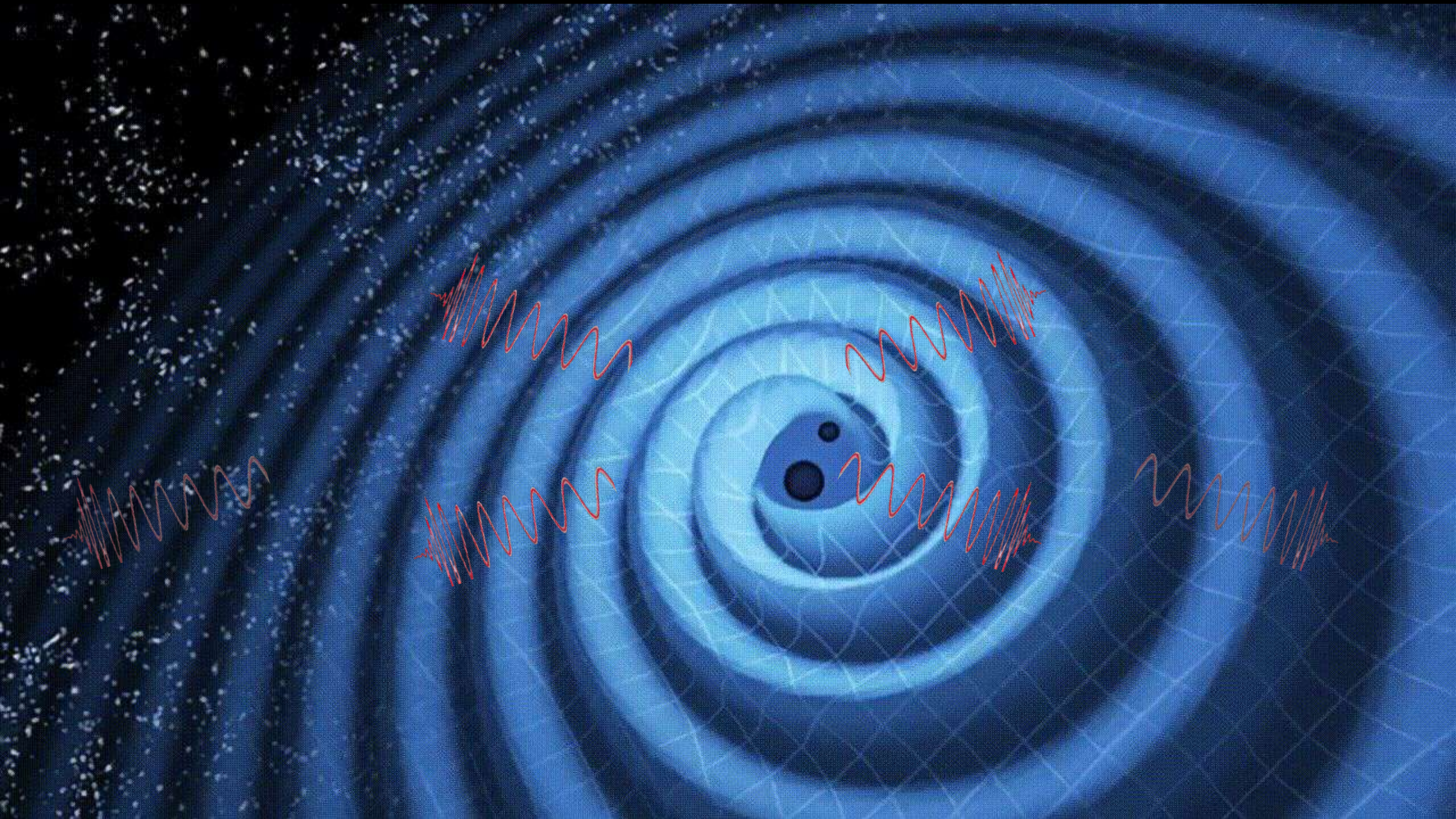
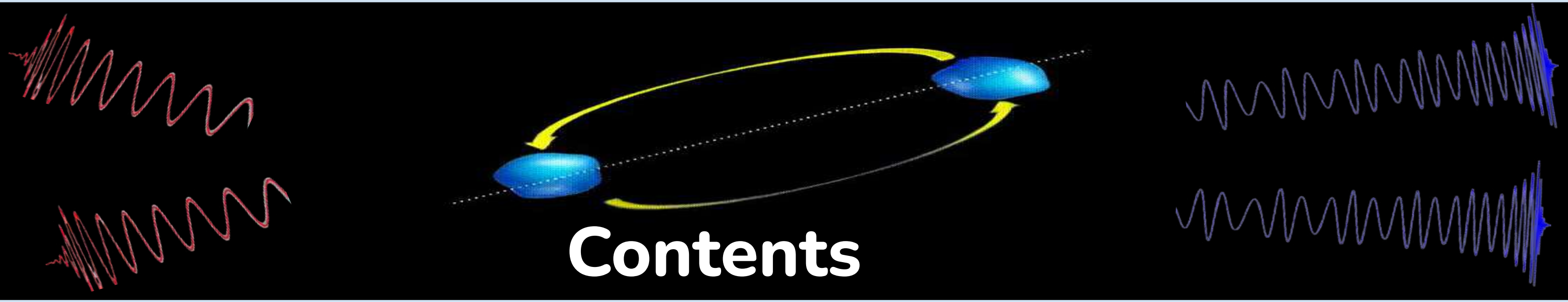
Testing the Nature of Compact Objects with GWs:
Spin-Induced Quadrupole Moments & Implications of GW241011



Syed Naqvi, Post-Doc,
Einstein Telescope member (David E. Alvarez-Castillo group)

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES





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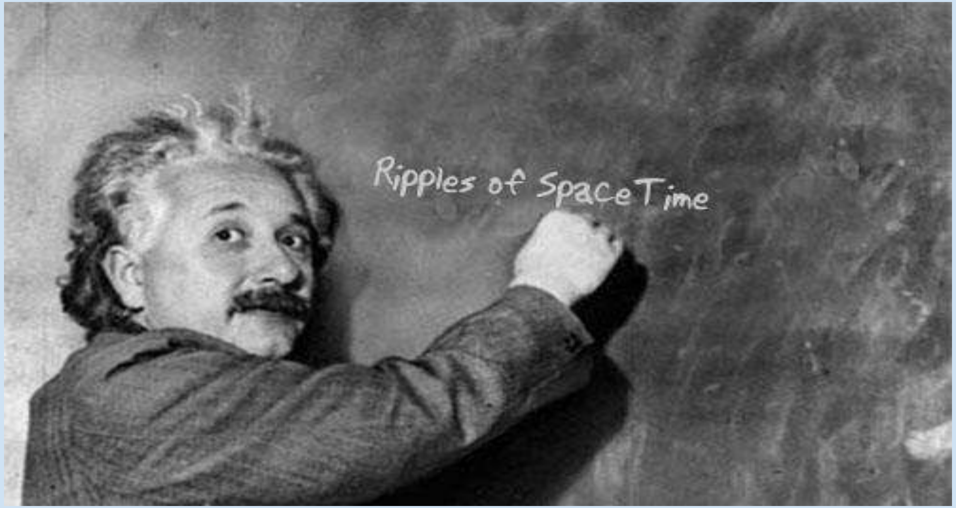
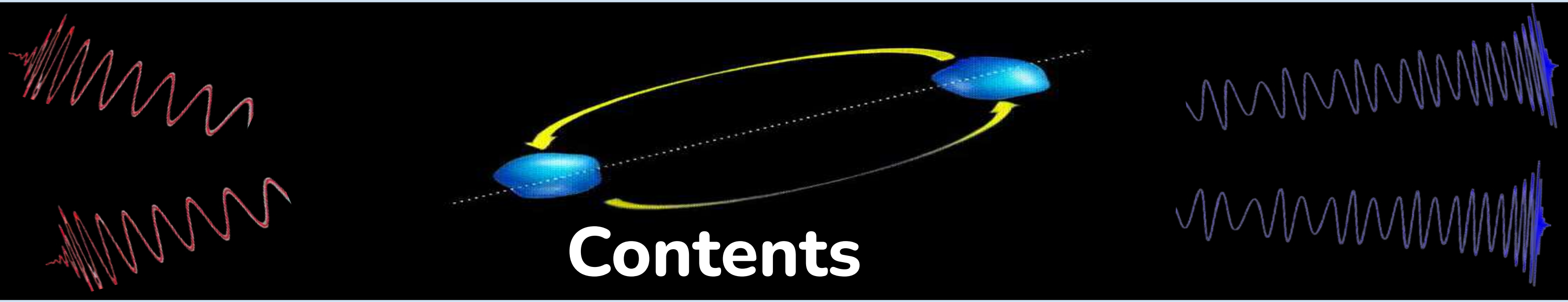


$$h \sim \ddot{Q}$$



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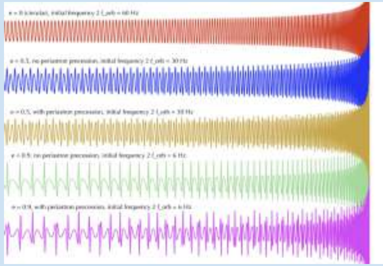

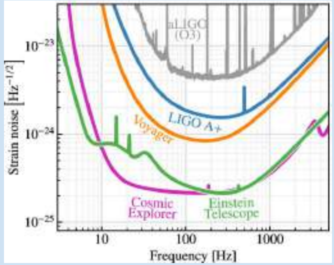

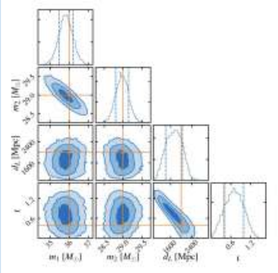

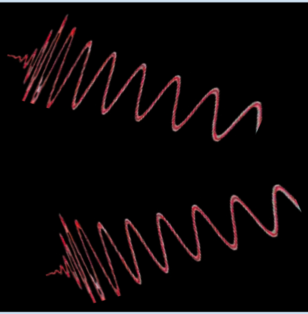

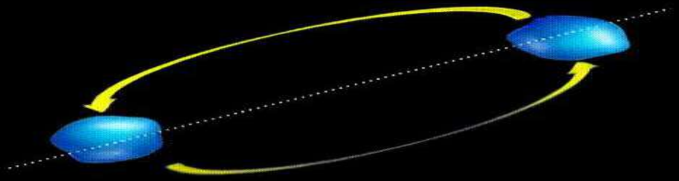

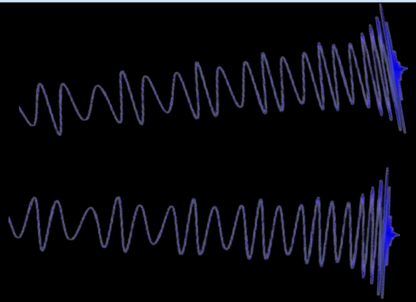

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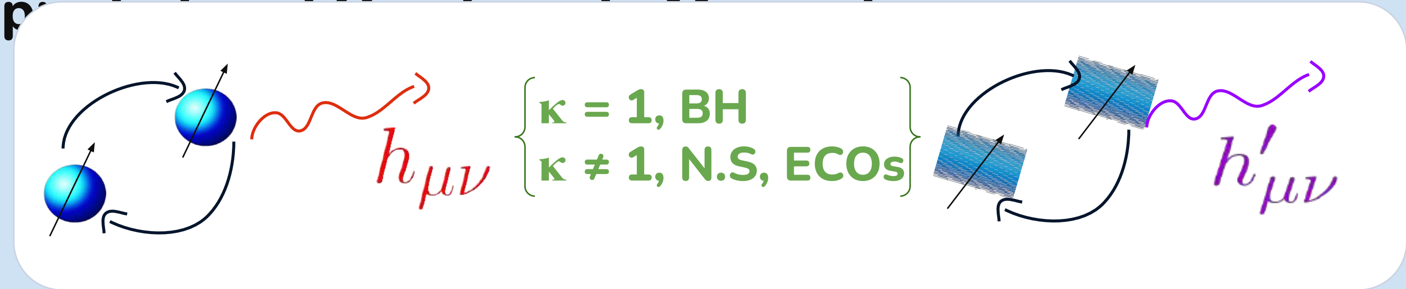

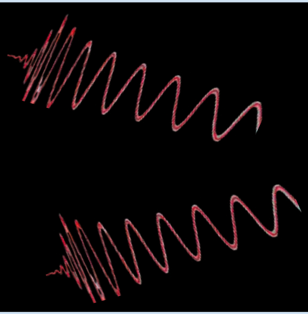

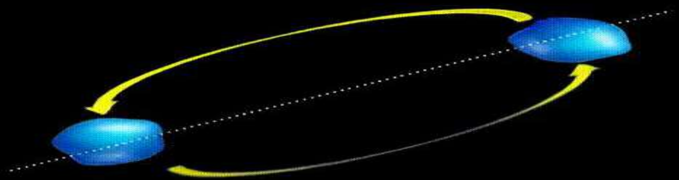

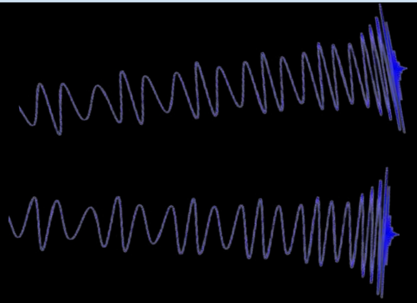

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- **Spin-Induced Quadrupole Moment**
- **GW241011** **(spins i unequal mass ratios)**

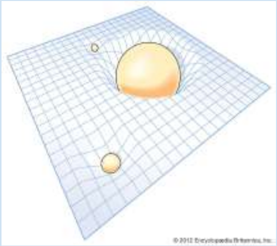
Einstein Field Equations : Meme Version

- Non-linear nature, many types of spacetimes(compact objects, universe expanding etc . . .)

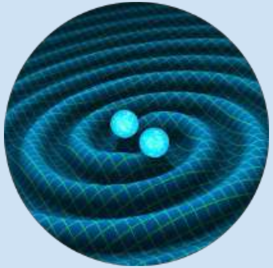
Different spacetimes represent different settings...

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$$

Pierogi Ruskie: Spacetimes of heavy objects Black Holes, NS etc....

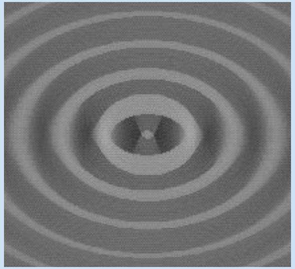


Pierogi ze szpinakiem i serem feta: Spacetimes having radiation/Grav Waves from astrophysical sources

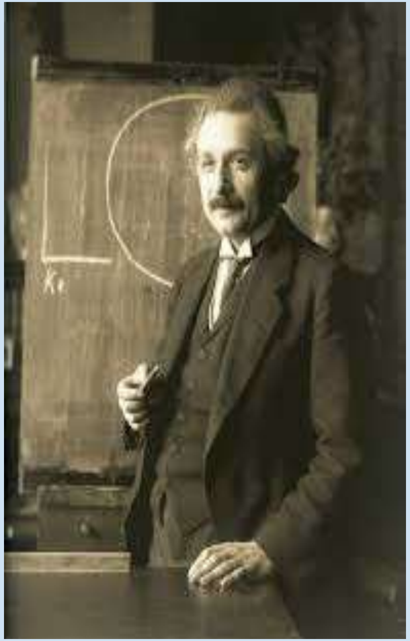


⋮

Indyjskie pierogi: Spacetimes having Standing Grav. Waves



From doubt...



Einstein

Rosen

- 1905 : Henri Poincare
- 1915-16: Einstein linearized gravity
- Issues :
  > Plane GWs in full theory?

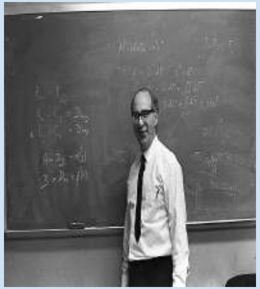
  > Do full Einstein Equation have solution which can be interpreted a GW?

  > Do GWs carry energy?
  >......
- 1937 : Einstein- Rosen metric, exact solution but with singularities

To belief…

Bondi

Pirani



Robinson

Trautman

- **1959, Bondi-Pirani-Robinson :**
  > the plane wave in the full theory is defined ✓
  > found as a class of solutions of Einstein fields equations ✓
  > they carry energy in a form of a sandwich wave which affects test particles ✓

- **1958, Andrzej Trautman:**
  > Radiation is nonlocal
  > defining GW in full Einstein theory = boundary conditions at infinity

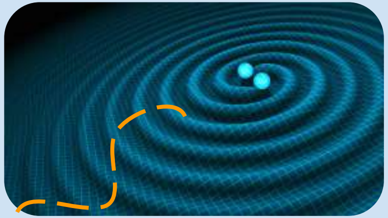
Credit: Green light for GW search, Hill & Nurowksi

GWs = Ripples of spacetime = Perturbations

Einstein Field Equations in LINEARIZED form : *weak field*

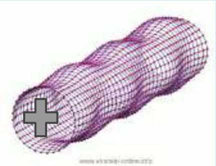
$$||h_{ab}|| << 1$$

$$R_{\mu\nu}-\frac{1}{2}Rg_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$$



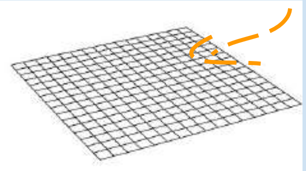
Metric Perturbations

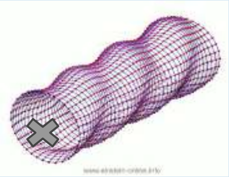
$$g_{ab} = \eta_{ab} + h_{ab}$$



Wave Equation
(TT gauge)

$$\Box \bar{h}_{ab} = 0$$





Hartle Book: Rough GW and EM analogy

	Linearized Gravitation	Electromagnetism
Basic "potentials"	Linearized metric perturbation $h_{\alpha\beta}(x)$	Vector and scalar potentials $(\Phi(t,\vec{x}),\ \vec{A}(t,\vec{x}))$
Field quantities	Linearized Riemann curvature $\delta R_{\alpha\beta\gamma\delta}(x)$	Electric and magnetic fields $\vec{E}(t,\vec{x}),\ \vec{B}(t,\vec{x})$
Gauge transformation leading to new potentials but the same fields	$h_{\alpha\beta} \to h_{\alpha\beta} - \partial_\alpha \xi_\beta - \partial_\beta \xi_\alpha$	$\vec{A} \to \vec{A} + \nabla \Lambda$ $\Phi \to \Phi - \partial \Lambda / \partial t$
Example of a gauge condition	Lorentz gauge $\partial_\beta h_\alpha^\beta - \frac{1}{2} \partial_\alpha h_\beta^\beta = 0$	Lorentz condition $\vec{\nabla} \cdot \vec{A} + \partial \Phi / \partial t = 0$
Field equations simplified by the gauge condition	$\Box h_{\alpha\beta} = 0$	Maxwell's equations $\Box \vec{A} = 0$ $\Box \Phi = 0$

Generation of G.Ws = Quadrupole radiation

Including matter source term

$$\Box \bar{h}_{ab} = -16\pi T_{ab} \quad \Longrightarrow \quad \bar{h}_{ab}(t, \mathbf{x}) = 4 \int d^3x' \frac{T_{ab}\left(t - |\mathbf{x} - \mathbf{x}'|, \mathbf{x}'\right)}{|\mathbf{x} - \mathbf{x}'|}$$

Quadrupole Formula
(in units c,G)

$$Q^{jk} = I^{jk} - \frac{1}{3}\delta^{jk}\delta_{lm}I^{lm}$$

$$\bar{h}^{ij}(t,r) = \frac{2}{r}\frac{G}{c^4}\frac{d^2}{dt^2}Q^{ij}\left(t - \frac{r}{c}\right)$$

Reduced Quadrupole Moment

$$I^{jk} = \int d^3x\, \rho(t, \vec{x}) x^j x^k .$$

Moment of Inertia tensor

$$I_p = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & I_{-yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix}$$

Generation of G.Ws = Quadrupole radiation

Including matter source term

$$\Box \bar{h}_{ab} = -16\pi T_{ab} \Longrightarrow \bar{h}_{ab}(t,\mathbf{x}) = 4\int d^3x' \frac{T_{ab}\left(t - |\mathbf{x}-\mathbf{x}'|, \mathbf{x}'\right)}{|\mathbf{x}-\mathbf{x}'|}$$

Quadrupole Formula (in units c,G)

$$\bar{h}^{ij}(t,r) = \frac{2}{r}\frac{G}{c^4}\frac{d^2}{dt^2}Q^{ij}\left(t - \frac{r}{c}\right)$$

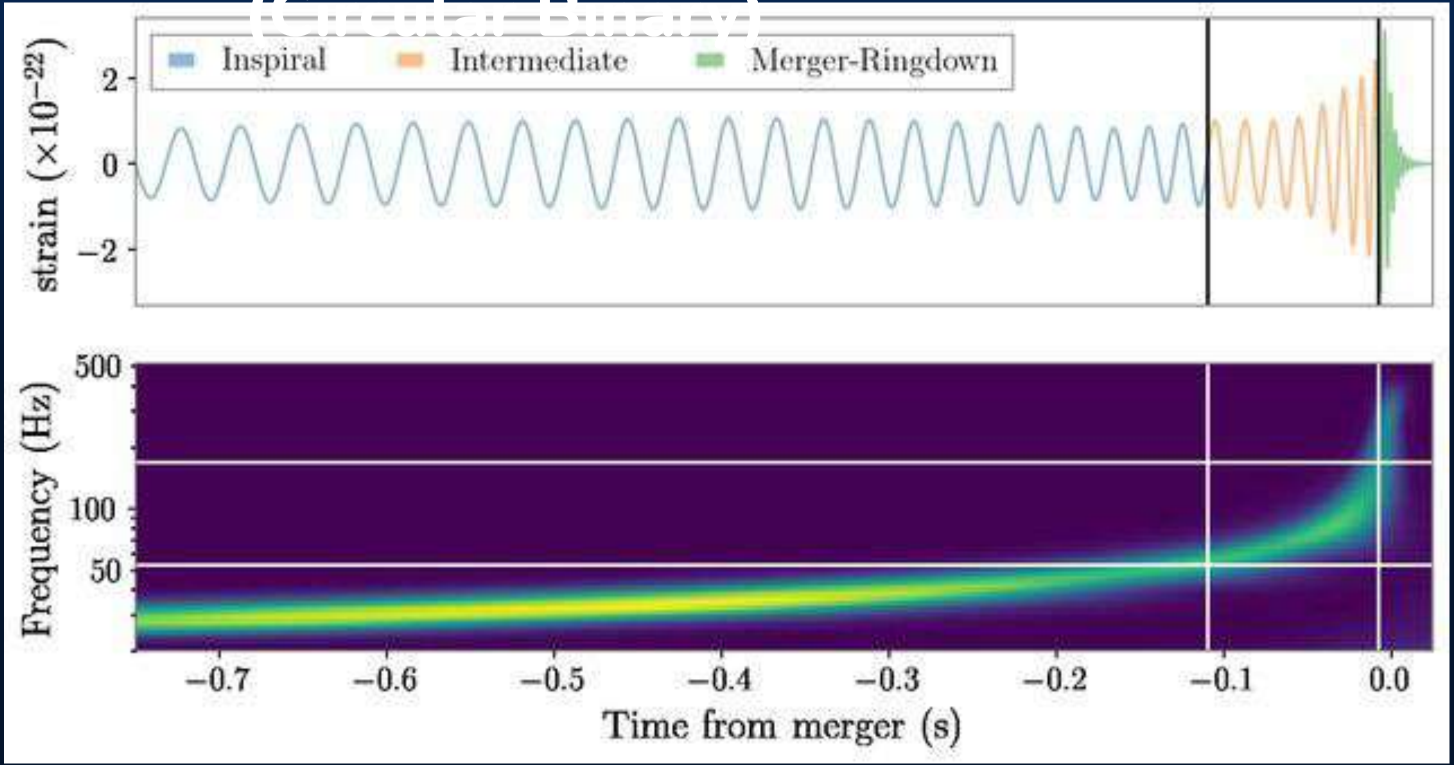
GW Luminosity

$$L_{GW} = -\frac{dE}{dt} = \frac{1}{5}\frac{G}{c^5}\langle \frac{\partial^3 Q_{ij}}{\partial t^3}\frac{\partial^3 Q_{ij}}{\partial t^3}\rangle$$

Energy carried away by GWs per second ~ Peak luminosity @ BH merger : **10^{50} watts!!!**

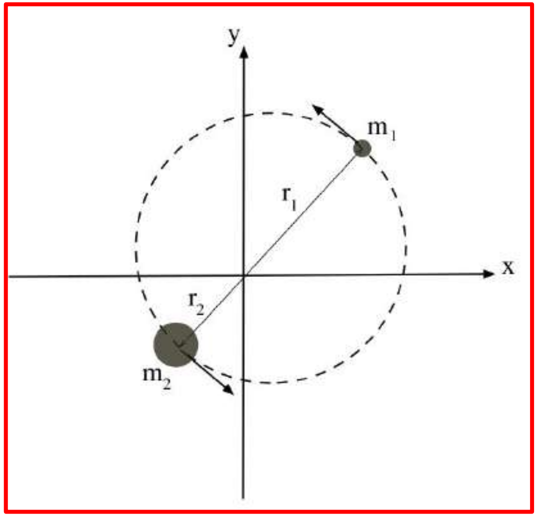
Gravitational Waveform: Time Domain vs Freq Domain

(Circular Binary)



"Chirp/ćwierkanie" Signal

GWs from binary system in Circular orbit

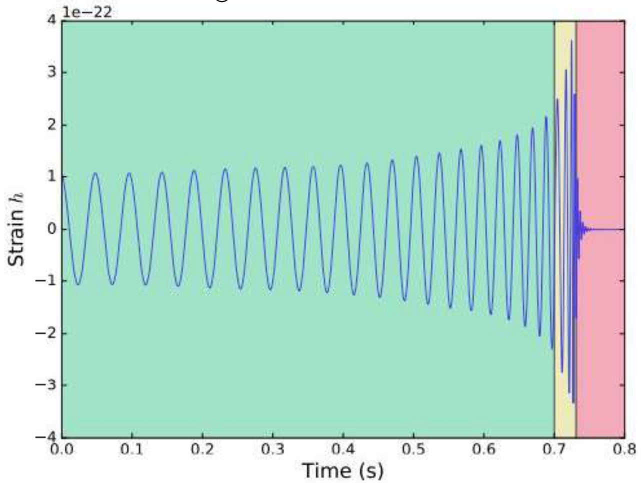


Radiated power:
Evaluated from Reduced Quadrupole Moment

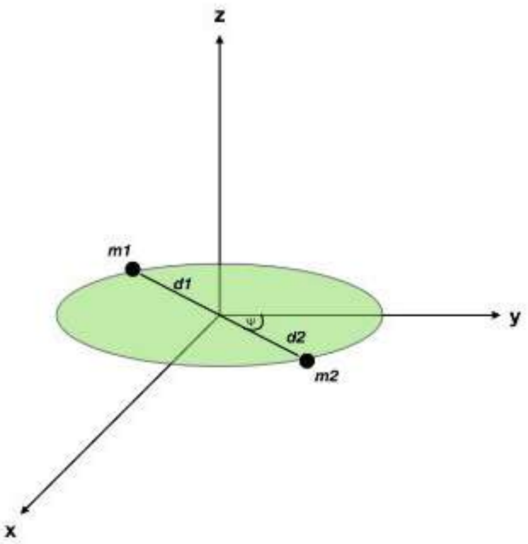
$$< E_{GW} > \approx < \dot{h}_{+}^{2} + \dot{h}_{\times}^{2} >$$

$$< E_{GW} > = \frac{32}{5} \frac{G^4}{c^5} \frac{m_1^2 m_2^2 (m_1 + m_2)}{a}$$

35-30 $M_\odot$: quasi circular case



GWs from binary system in Eccentric orbit

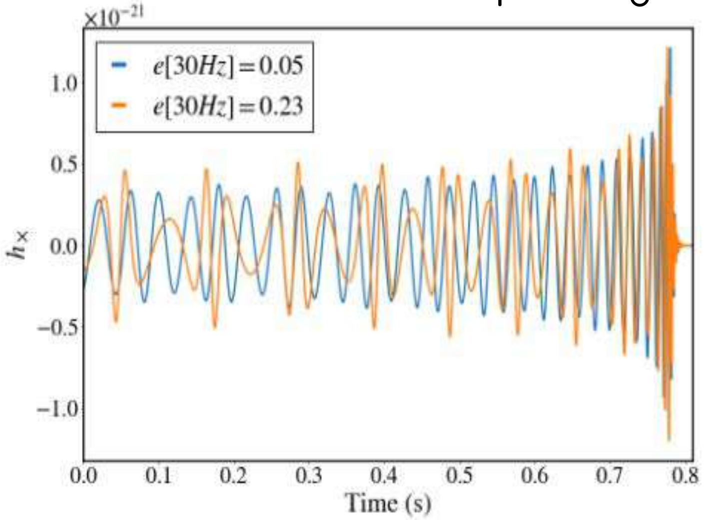


Radiated power:
Evaluated from Reduced Quadrupole Moment

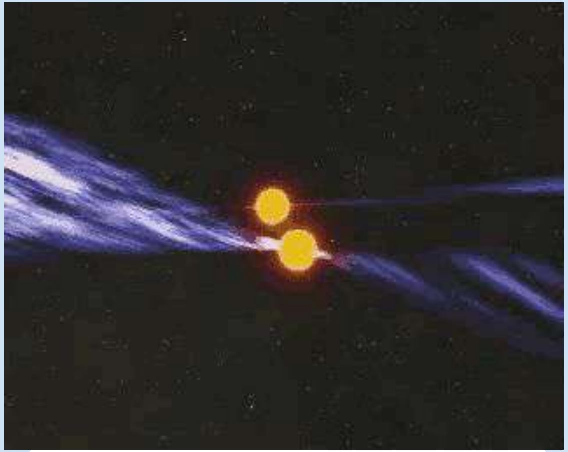
$$< E_{GW} > \approx < \dot{h}_{+}^{2} + \dot{h}_{\times}^{2} >$$

$$< E_{GW} > = \frac{32}{5}\frac{G^4}{c^5}\frac{m_1^2 m_2^2 (m_1 + m_2)}{a} f(e)$$

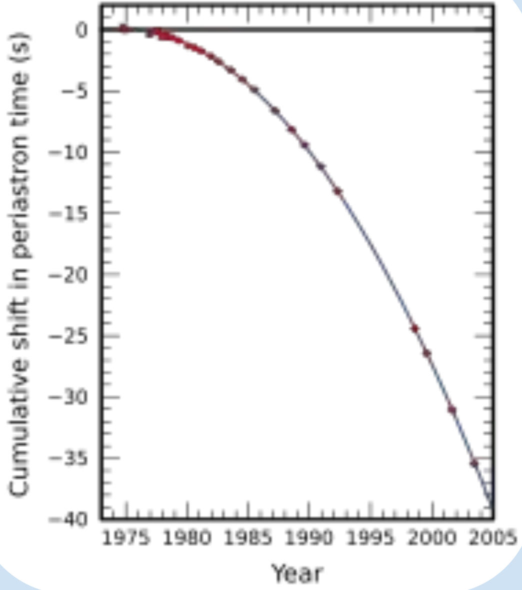
Non-spinning, eccentric, $M_T = 50M_{\odot}$



First Indirect GW detection: Hulse–Taylor binary pulsar (PSR 1913+16)



- Discovered in 1974; binary neutron-star system: one star is a millisecond pulsar
- Orbital period: ~7.75 hours
- Eccentric orbit → strong relativistic effects
- Provided the first evidence that gravitational waves carry energy



PSR 1913+16

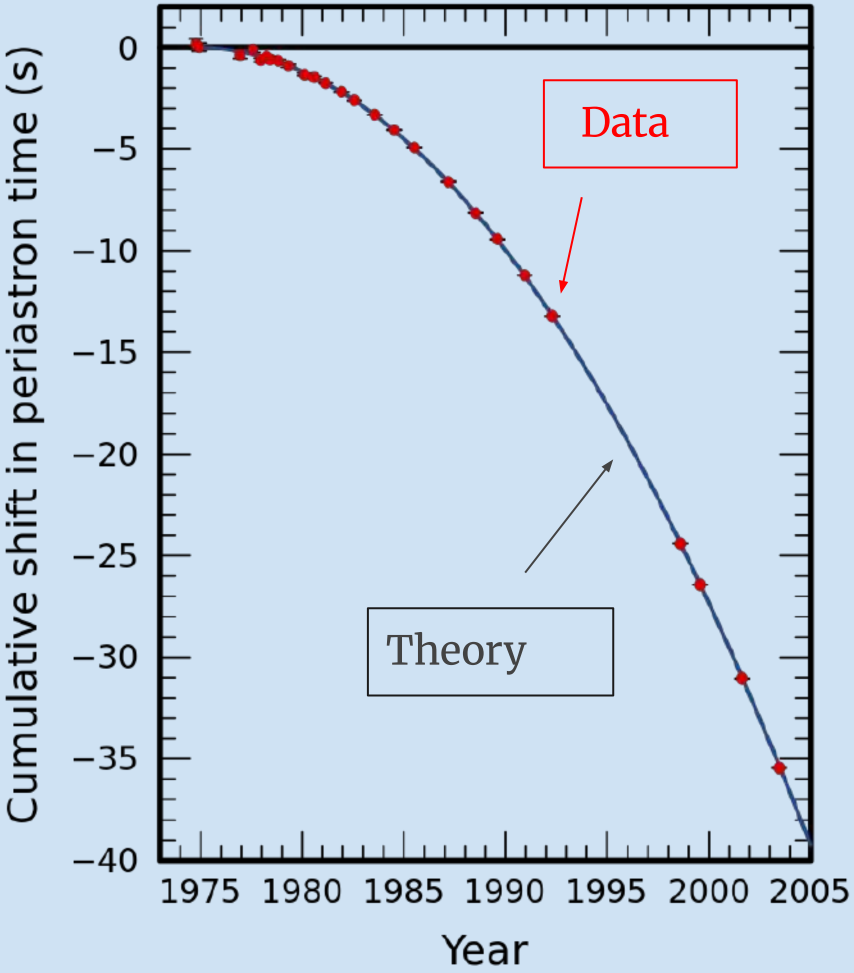
$$l_0 \sim 10^{11} cm$$

$$\nu_{GW} \sim 10^5 Hz$$

$$\lambda_{GW} = \frac{c}{\nu_{GM}} \sim 10^{14} cm$$

$$(\lambda_{GW} >> l_0)$$

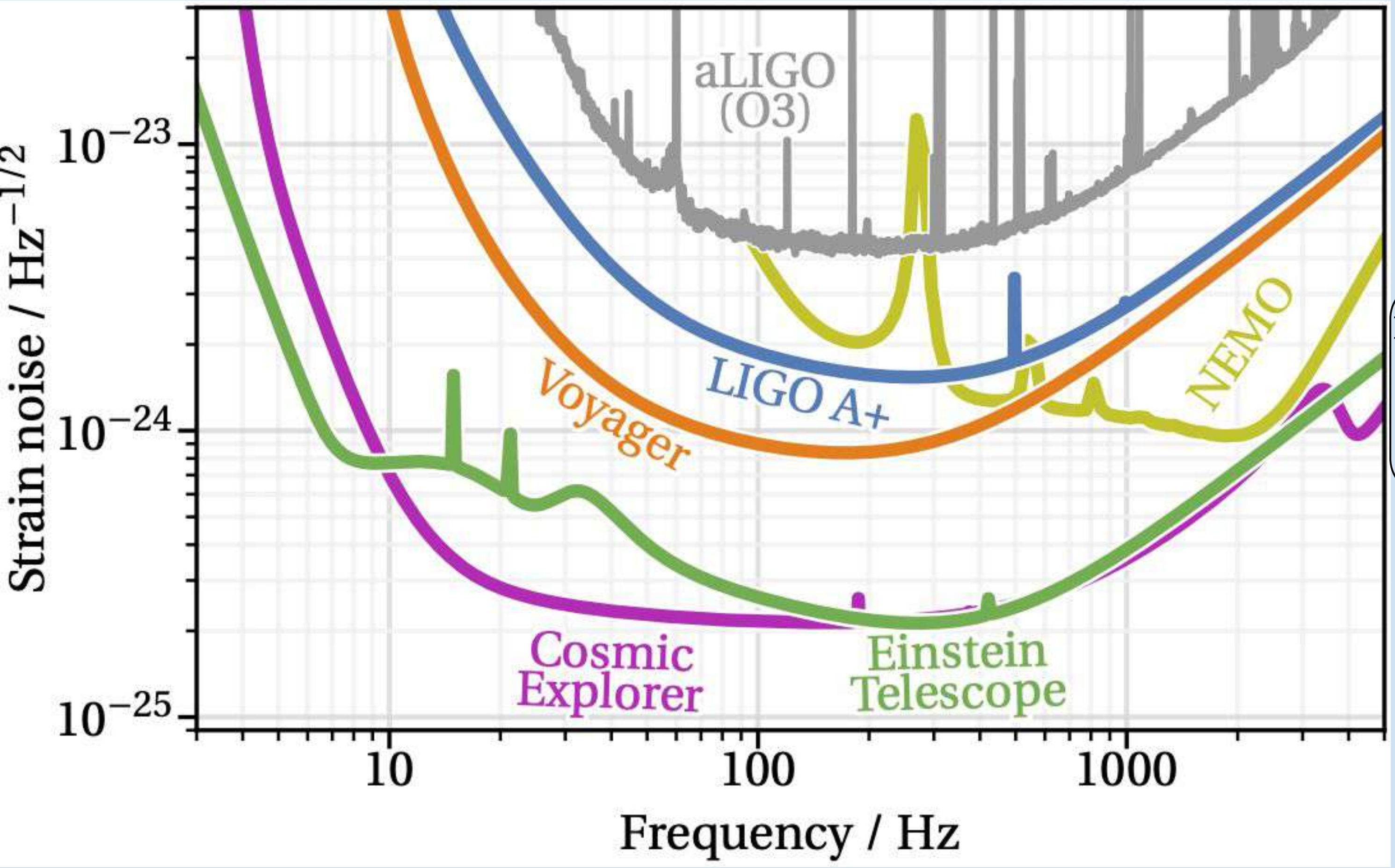
(slow-motion approximation,
on which the quadrupole formalism is based)



Hulse-Taylor binary pulsar
e_o ~ 0.617 and $f(e_o)$ ~ 0.184,

Time to coalescence
shorter by a factor $l/f(e_o)$ ~ 5.4, compared
to a binary on a circular
orbit with the same period.

Future of GWs : A new window to the universe



Lower freq sensitivity (1Hz)=> O(10^5-10^6/yr) + longer-duration signals

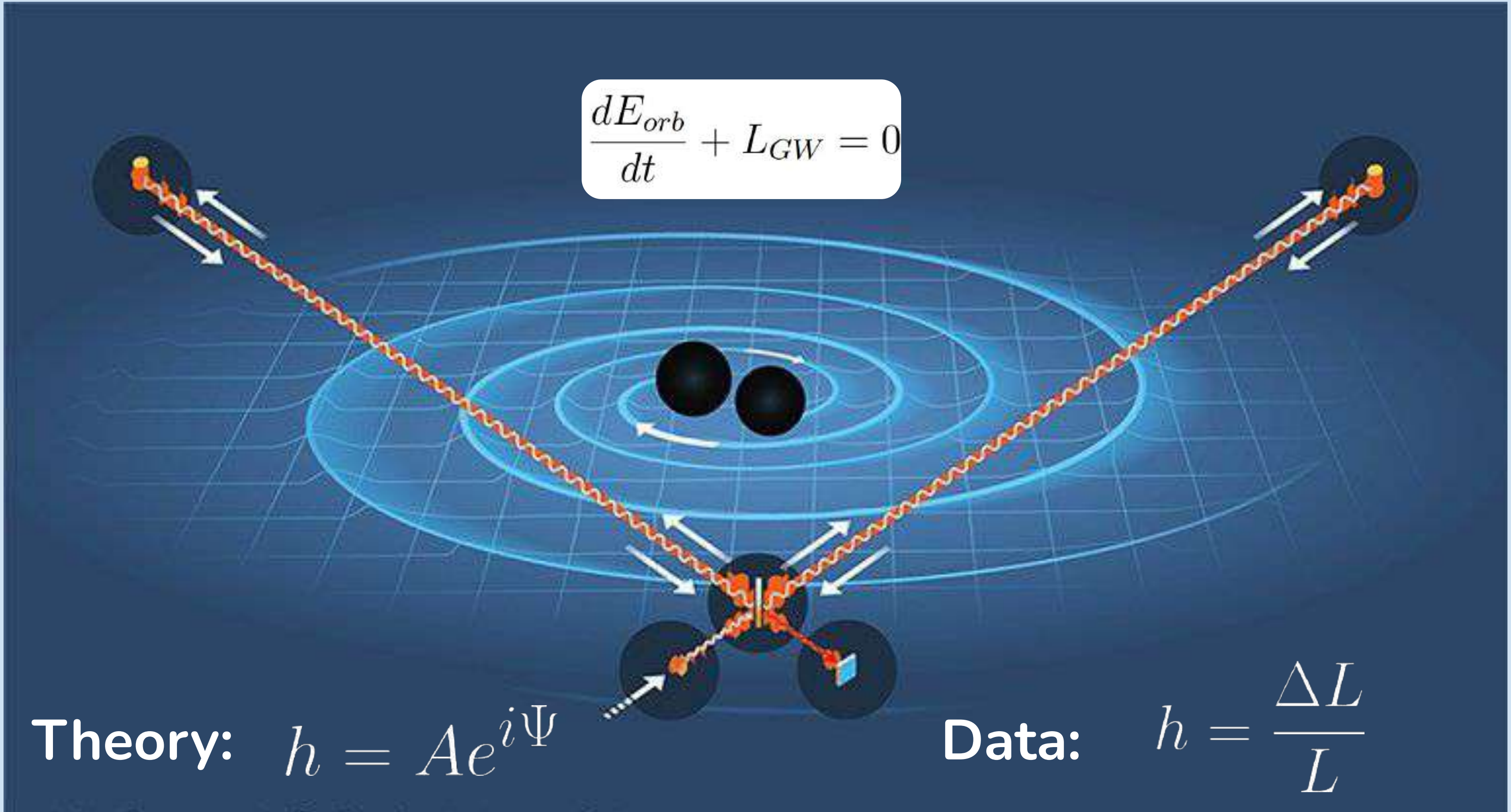
Improved reach vs. 2G:

- SNR → 10×
- Redshift horizon z → 20×
- Detection rate → 100×

Our Group Goal

- **Neutron Stars**
- **oscillations of compact stars**
- **stochastic GWs**

Detecting Gravitational



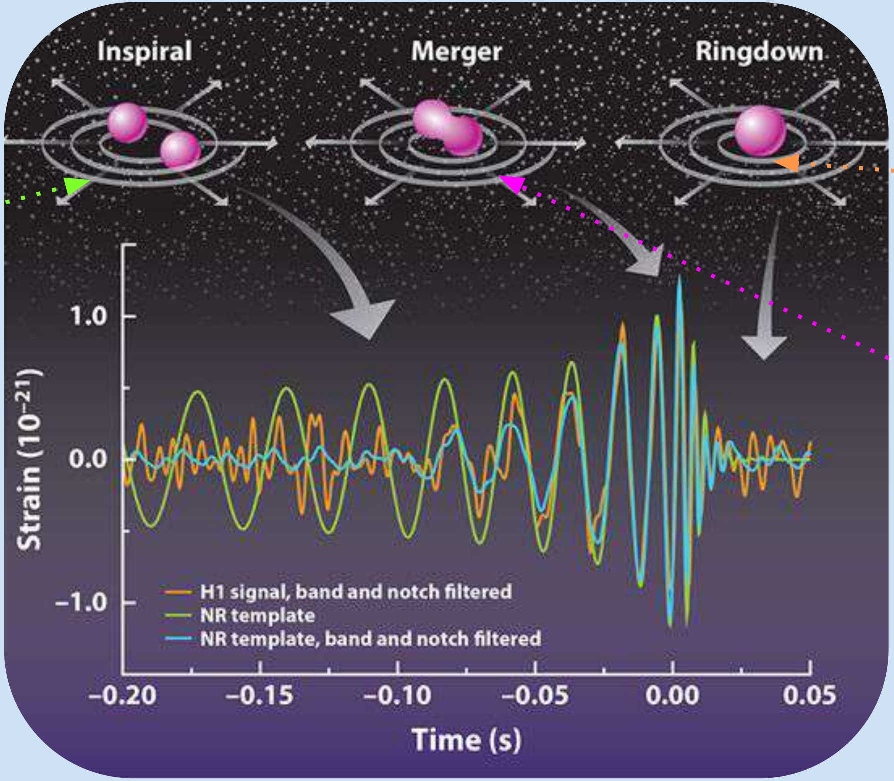
$$\frac{dE_{orb}}{dt} + L_{GW} = 0$$

Theory: $h = Ae^{i\Psi}$

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

Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

GWs : Methods to compute templates



Post-Newtonian Theory

BH Perturbation Theory

Numerical Rel.

$$h = Ae^{i\Psi}$$

the correct template/needle!

Gravitational Waves and the Effort to Detect them By Peter Shawhan

Post-Newtonian Theory: Small Intro

Rewrite Einstein Equations in terms of flat-space wave eqn:

$$\left.\begin{aligned} G_{\mu\nu} &= 8\pi T_{\mu\nu} \\ g_{\alpha\beta} &= \eta_{\alpha\beta} + h_{\alpha\beta} \end{aligned}\right\} \Box h_{\mu\nu} = 16\pi T_{\mu\nu} + \Lambda_{\mu\nu}(h,h)$$

(least quadratic in h and its space-time derivatives)

Expand quantities in terms of small parameter ε

$$\left\{ \varepsilon \sim \frac{v_{orb}}{c} \sim \sqrt{\frac{GM}{c^2 r}} << 1 \right\}$$

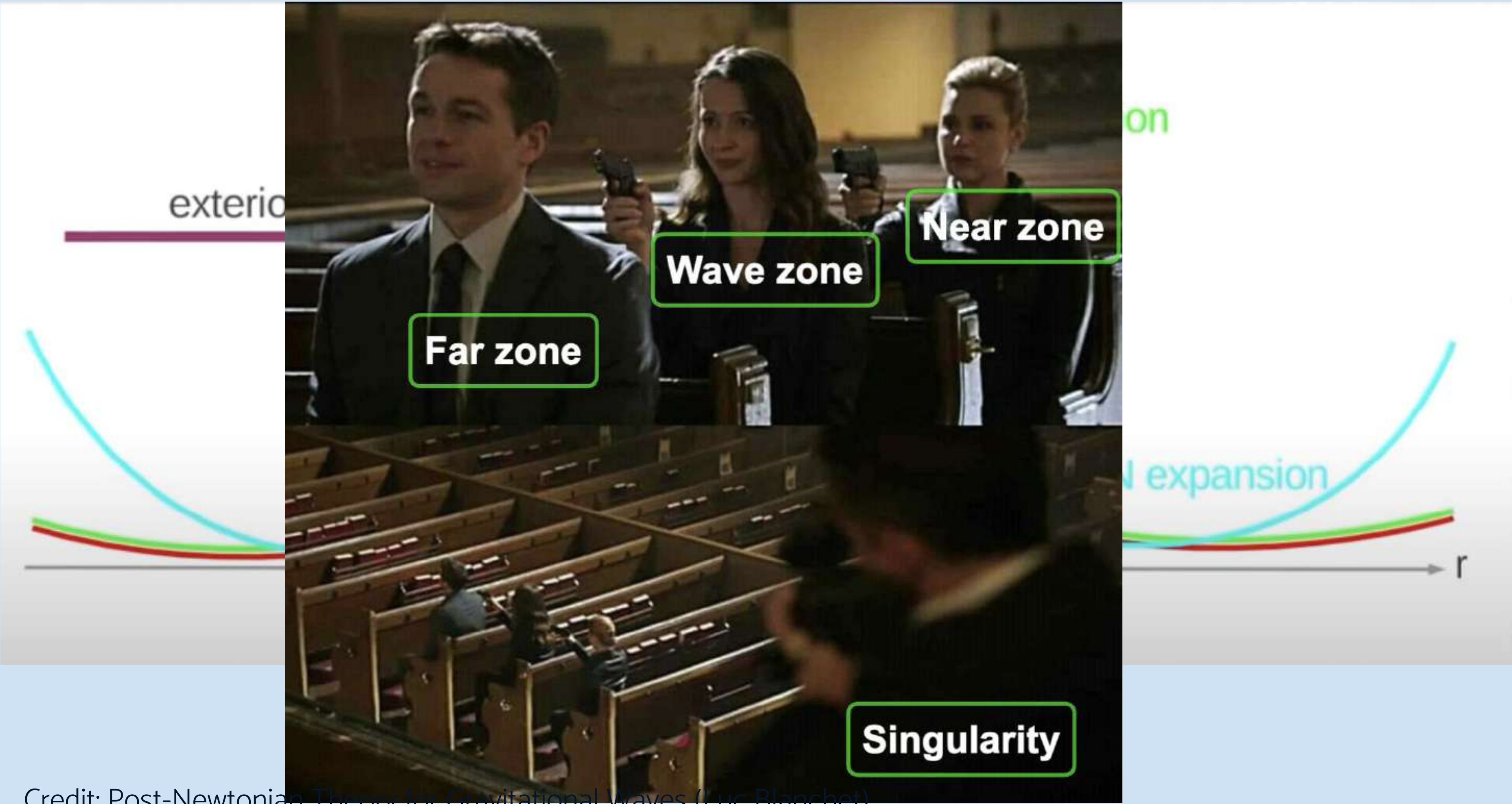
$$h_{\alpha\beta} = \varepsilon h^{(1)}_{\alpha\beta} + \varepsilon^2 h^{(2)}_{\alpha\beta} + \ldots$$

$$T_{\alpha\beta} = \varepsilon T^{(1)}_{\alpha\beta} + \varepsilon^2 T^{(2)}_{\alpha\beta} + \ldots$$

Plug expansion back into equations and solve iteratively at each order ε

$$\varepsilon^1 : \Box h^{(1)}_{\mu\nu} = 16\pi T^{(1)}_{\mu\nu} \qquad \varepsilon^2 : \Box h^{(2)}_{\mu\nu} = 16\pi T^{(2)}_{\mu\nu} + \Lambda_{\mu\nu}(h^{(1)}, h^{(1)})$$

(i) Near the source : metric determines the EoM (ii) Far from source: EoM determine the radiated GWs



Credit: Post-Newtonian Theory for Gravitational Waves (Luc Blanchet)

GWs : Data-Analysis

Parameter Estimation

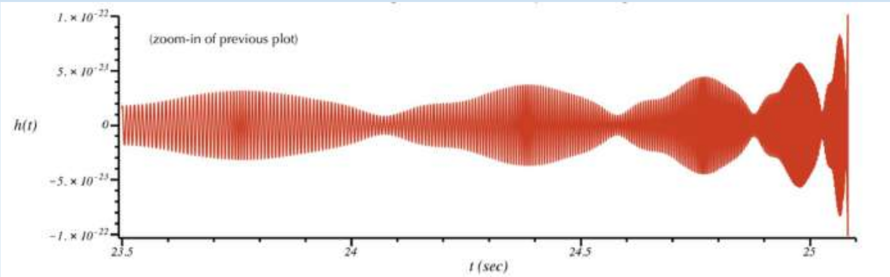
$$h = Ae^{i\Psi}$$

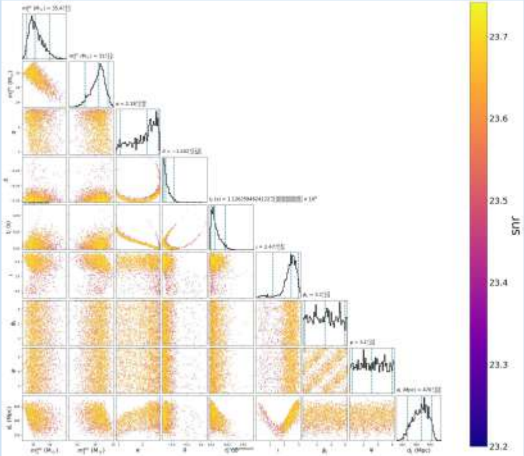
Gravitational Wave Search Pipelines

Modeled Searches

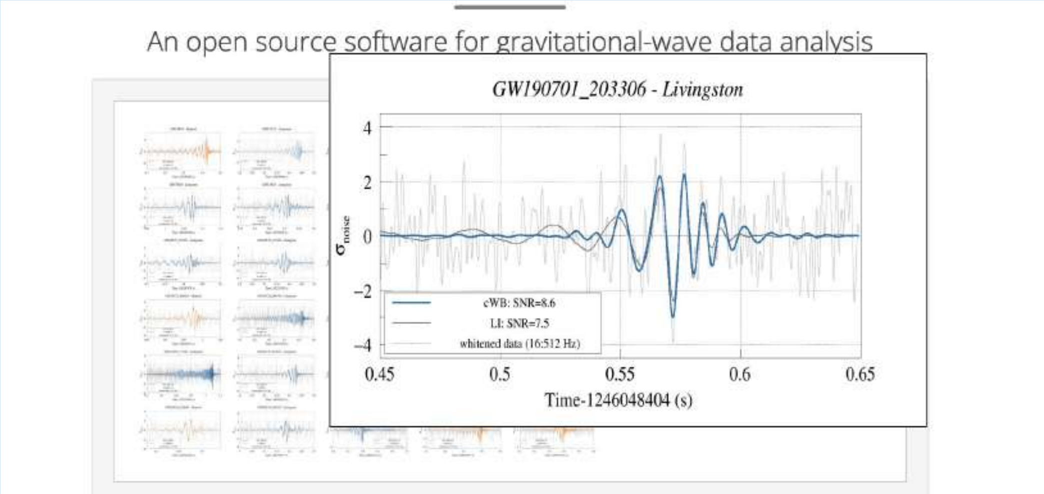
- specifically look for signals from compact binary mergers of neutron stars and black holes (BNS, NSBH, and BBH systems).
- Eg : GstLAL, MBTA, PyCBC Live and SPIIR
- use discrete banks of waveform templates to cover the target parameter space of compact binaries + match-filtering

PyCBC





Gravitational Wave Search Pipelines



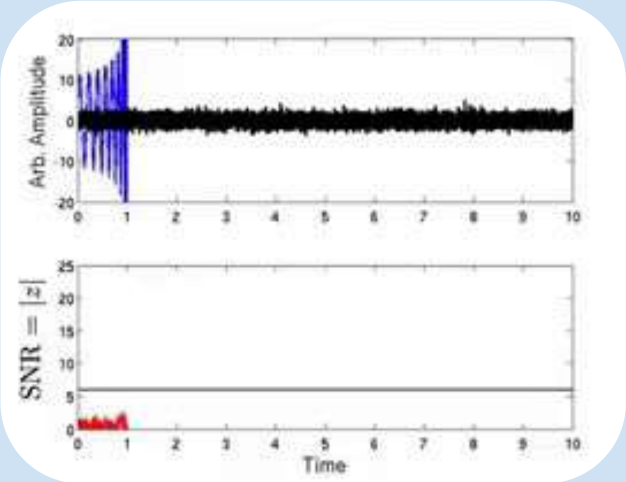
Un-Modeled Searches

- searches for and reconstructs gravitational-wave transient signals without relying on a specific waveform model.
- Identify coherent excess power across detectors Example: cWB (coherent WaveBurst)
- Best for unknown / unexpected sources

GW Data-analysis => Matched Filtering

$$d(t) = h(t) + n(t)$$

$$z = \langle d|\hat{h}\rangle = 4\int_{\mathrm{f_{low}}}^{\mathrm{f_{high}}} \frac{\tilde{d}(f)\hat{h}^*(f)}{S_n(f)}df$$



- <u>Cross–correlate with detector data:</u> d(t) using the noise-weighted inner product → Signal-to-Noise Ratio (SNR)

- <u>Template bank:</u> Covers a grid of masses, spins, orientations
  Search = “scan over templates” to find the best match

- Noise is non-Gaussian and non-stationary → **Need ranking statistics & likelihood**

Aaron Zimmerman talk: <u>Link</u>
Designing a template bank to observe compact binary coalescences, Canton and Harry (arxiv:1705.01845)

GW
Parameter Estimation

Bayesian Analysis:
Comprehensive, reliable for realistic data, especially when the likelihood is non-Gaussian.

Given the detector data,:
What is the probability that the observed strain was produced by an astrophysical signal rather than by noise?

Fisher Analysis:
Quick, approximate, best for high SNR and gaussian noise

*References:
- *Post-Newtonian theory for gravitational waves, Living Reviews in Relativity, Luc Blanchet 2024*
- *Sources of Gravitational Waves: Theory and Observations, Alessandra Buonanno and B.S. Sathyaprakash*

Bayesian Analysis: Given the data, inferring parameters

Posterior: prob. distn. of param (**θ**)

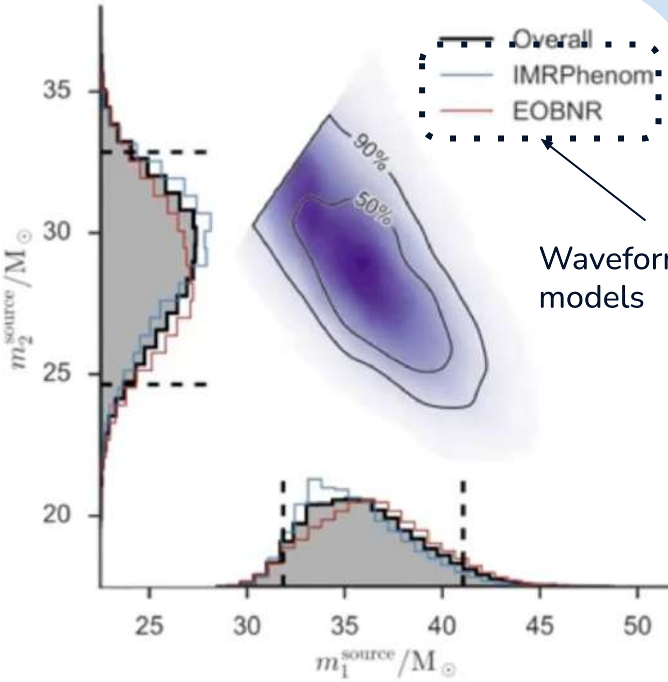
$$p(\theta|\vec{d}, M) = \frac{p(\vec{d}|\theta, M)\,p(\vec{\theta}, M)}{p(d|M)}$$

Likelihood: measures how well the data fits param

$$\Lambda(\mathcal{H}_1|s) = \frac{p(s|\mathcal{H}_1)}{p(s|\mathcal{H}_0)} = e^{(s,h)} e^{-(h,h)/2}$$

Prior: encodes our knowledge about param

Evidence: normalization



Waveform models

Fisher Analysis: Main Ingredients

- Fisher Information Matrix (PSD:) $S_n(f)$
  ET, CE

$$\Gamma_{\mathbf{ij}} = 4 \int \frac{\overbrace{\partial_i \tilde{h}(f)\, \partial_j \tilde{h}^*(f)}^{\text{Waveform Sensitivity}}}{\underbrace{S_n(f)}_{\text{Detector Noise}}} \, \mathbf{df}$$

- Error on each parameter is given by the square root of the diagonal entries of the covariance matrix.

$$\sigma_{\kappa_{\mathbf{s}}} = \sqrt{\underbrace{(\Gamma^{-1})_{\kappa_s \kappa_s}}_{\text{Marginalized Covariance}}}$$

- **Parameter Space** $\theta_i = \{t_c, \phi_c, \mathcal{M}_{\text{chirp}}, \eta, \chi_1, \chi_2, \kappa_s, \mathrm{e0}\}$

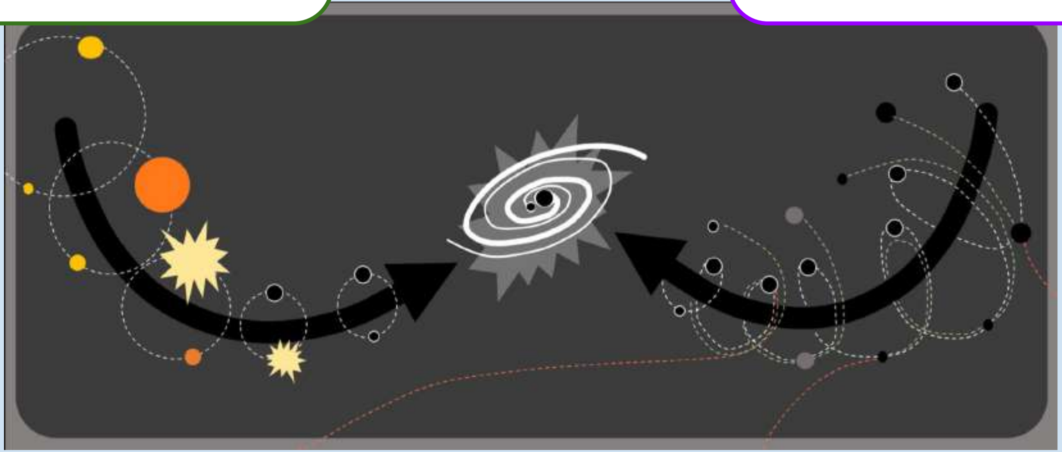
GWs: The case for Eccentricity

Isolated Binary Evolution

- Shed their formation eccentricity
- Circularise when entering detector

Dynamically formed Binaries

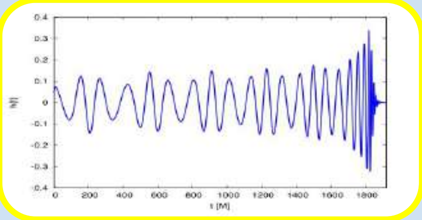
- Retain eccentricity
- In globular clusters, AGN...



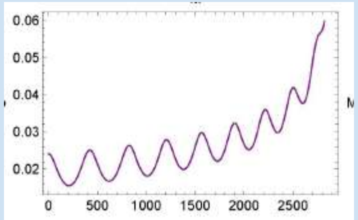
*issue of model uncertainties + lack of GW statistics : BBH formation scenarios ???

Searching for eccentricity: Isobel M Romero-Shaw, 2019

Mapelli, Binary Black Hole Mergers: Formation and Populations



GWs: The case for Eccentricity in PN theory



• **Eccentricity fundamentally alters the PN expansion**: the phase evolution gains additional harmonics $\propto e^n$, so standard quasi-circular PN templates under-estimate signal duration and miss power in higher modes.

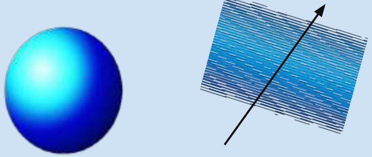
• Higher eccentricity accelerates periastron precession and GW emission bursts, **pushing more cycles into the detector band** and changing the required PN order for a given accuracy.

• Ignoring e **injects systematic biases:** $\gtrsim$ 10 % errors in chirp mass and symmetric mass ratio even at moderate $e \approx 0.1$ for LIGO sources.

$$\Psi_{\rm ecc}(f) \;=\; \Psi_{\rm circ}(f) \;+\; e_0^2\,\Psi_{\rm ecc}(f)$$

Constraining the orbital eccentricity of inspiralling compact binary systems with Advanced LIGO, Favata 2022
Blind spots and biases: the dangers of ignoring eccentricity in gravitational-wave signals from binary black holes, Divyajyoti et al 2024

GWs: The case for SIQM



The spinning motion of companion A creates a distortion in its mass distribution => creates a distortion in the gravitational field outside the star, measured by $(Q_A)^{ij}$

The quadrupole term, $(Q_A)^{ij}$, in the gravitational potential affects the orbital motion of the companions, and it affects also the emission of GWs.

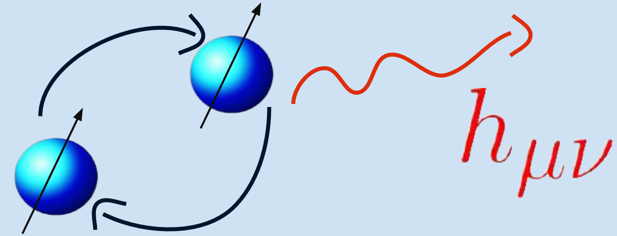
Poisson ’98, Kidder ’95

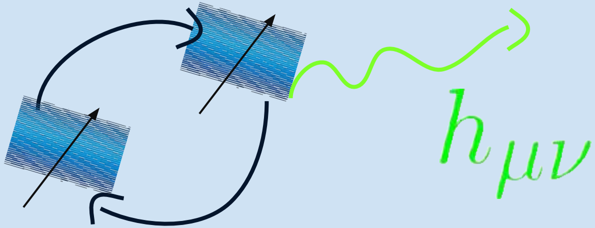
$$\left\{ Q_A = -\kappa \chi_A^2 m_A^3 \right\}$$

$\kappa = 1$, BH

$\kappa \neq 1$, N.S etc

Kappa: Spin-induced moment constant





PN Waveform: General overview + where **SIQM** Enters

GW Waveform (Freq. Domain)

$$\tilde{h}(f) = A\psi(f)$$

$$\Psi(f) = \frac{3}{128\eta v^5}\left\{1 + v^2\left[\text{1 PN}\right] + v^3\left[\text{1.5PN } (\beta)\right] + v^4\left[\text{2 PN } (\sigma)\right] + v^5(\ldots)\right.$$

$$v = (\pi M f)^{1/3}$$

$$\eta = \mu/M$$

{ M = Total Mass
η = symm mass-ratio }

Spin-Orbit: $\beta \sim \sum_A \hat{\mathbf{L}}.\chi_{\mathbf{A}}$

Spin-Spin: $\sigma = \sigma_{ss} + \sigma_{qm}$

$(\sigma_{ss} \sim \chi_{\mathbf{1}} \cdot \chi_{\mathbf{2}})$

$\{\kappa$ **appears at 2PN, 3PN, 3.5PN**$\}$

$$\left\{Q_A = -\kappa \chi_A^2 m_A^3\right\}$$

SIQM - quasi circular binaries

Why is it imp?

- Probing mass gap bw massive NS and lightest BH
- Existence of BH mimickers (boson stars, $\kappa \sim$ 10-100), gravastars
- Test of GR (Krishnendu 2022, arxiv:2201.05418)

Earlier Studies

- Krishnendu et al 2017, 2018: semianalytical P.E for κ (2PN Amplitude and **4PN** phase)
- Divyajyoti et al 2024: Bayesian param. est. for spin-precession + higher order
- Lyu et al 2024: compare SIQM for precc + non-precess

Future Studies

SIQM for eccentric binaries ?

Inspiral Waveform: Adding Kappa-Ecc Terms*

- Inspiral Waveform : an update to the 3PN eccentric phasing (**Moore et al**)
- **Omkar et al** aligned-spin effects to the small eccentricity expanded time and freq domain phases
- Valid for max e0=0.3.

κ_1, κ_2

$$\Psi = \frac{3}{128\nu y^5}\left\{\Psi_{\rm circ} + \frac{650}{731} e_0^2 \left(\frac{y_0}{y}\right)^{19/3} \right. \Psi_{\rm ecc+kappa} + e_0^4(\ldots) + e_0^8(\ldots..)$$

Aim

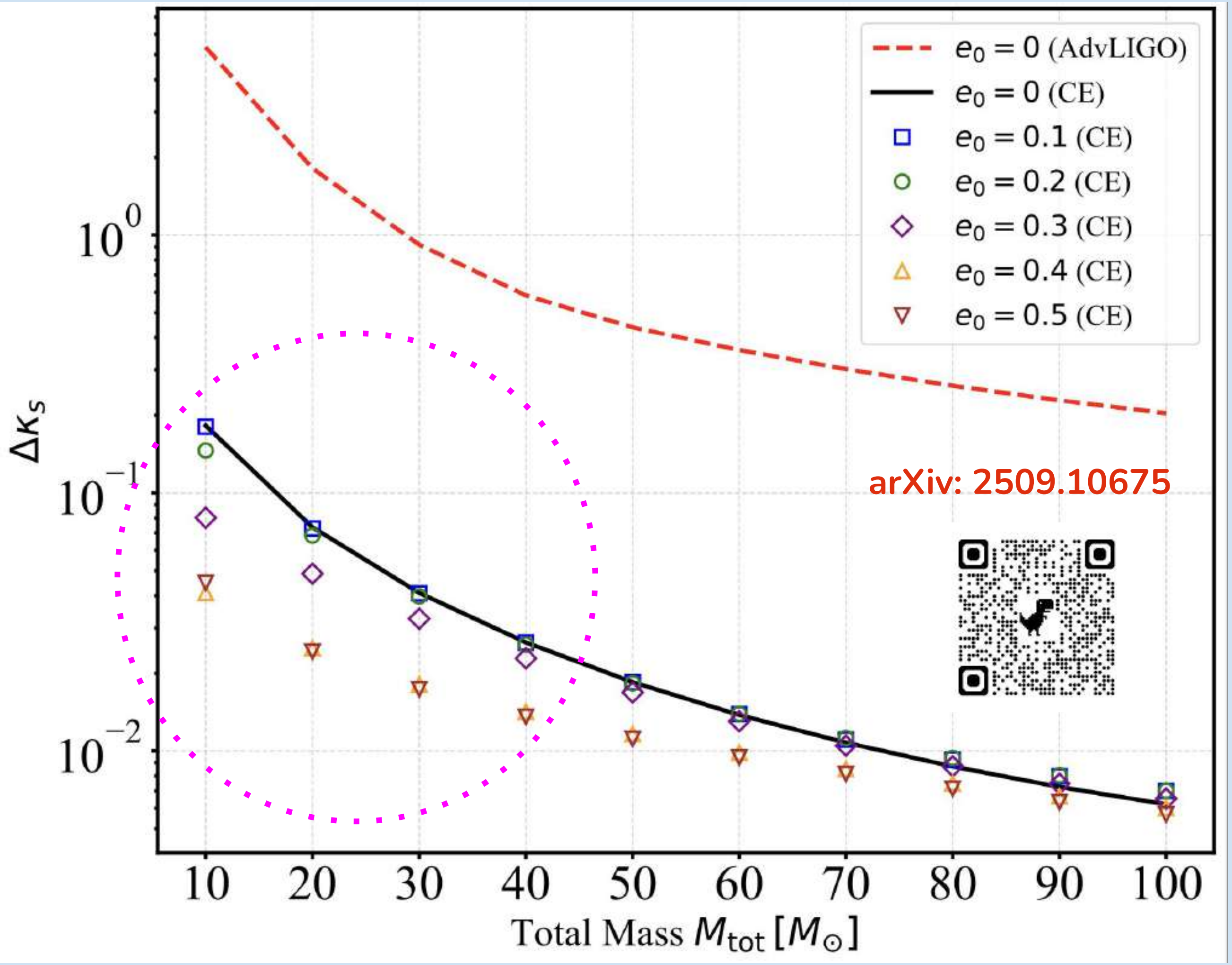
- Kappa errors for ET and Cosmic Explorer and compare with adv. LIGO
- Define symmetric and anti-symm combination: $\kappa_S = (\kappa_1 + \kappa_2)/2$
  (For BBH: κ_S=1, κ_A=0)

*Credit: Omkar, Soham Kaushik 2024

SIQM-Ecc Waveform: e0 8 for CE vs advLIGO

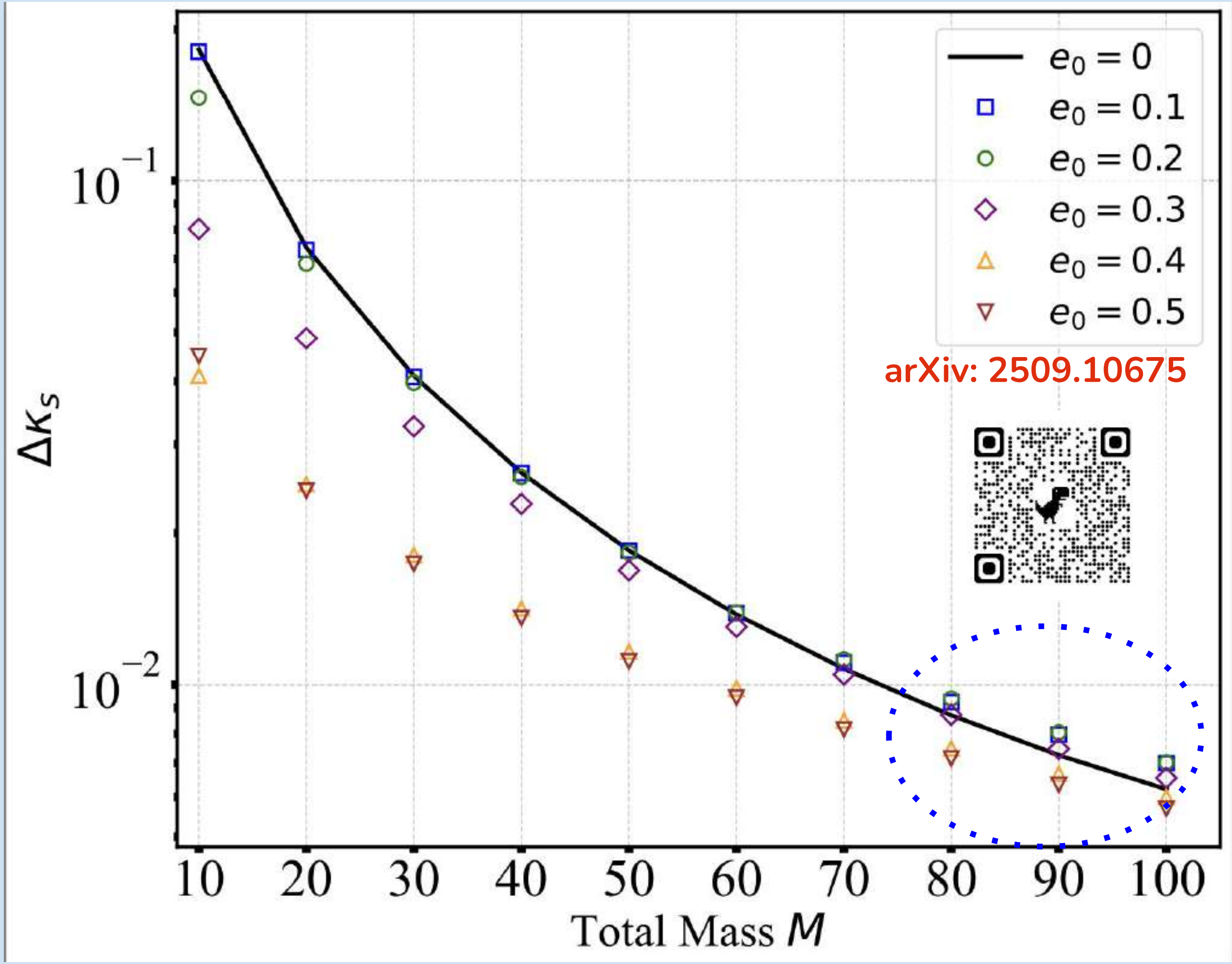
For higher eccentric case: Large number of PN cycles => allows eccentric binaries to imprint additional harmonics over many cycles.

Additional phase information, leading to slightly smaller uncertainties compared to the circular case.



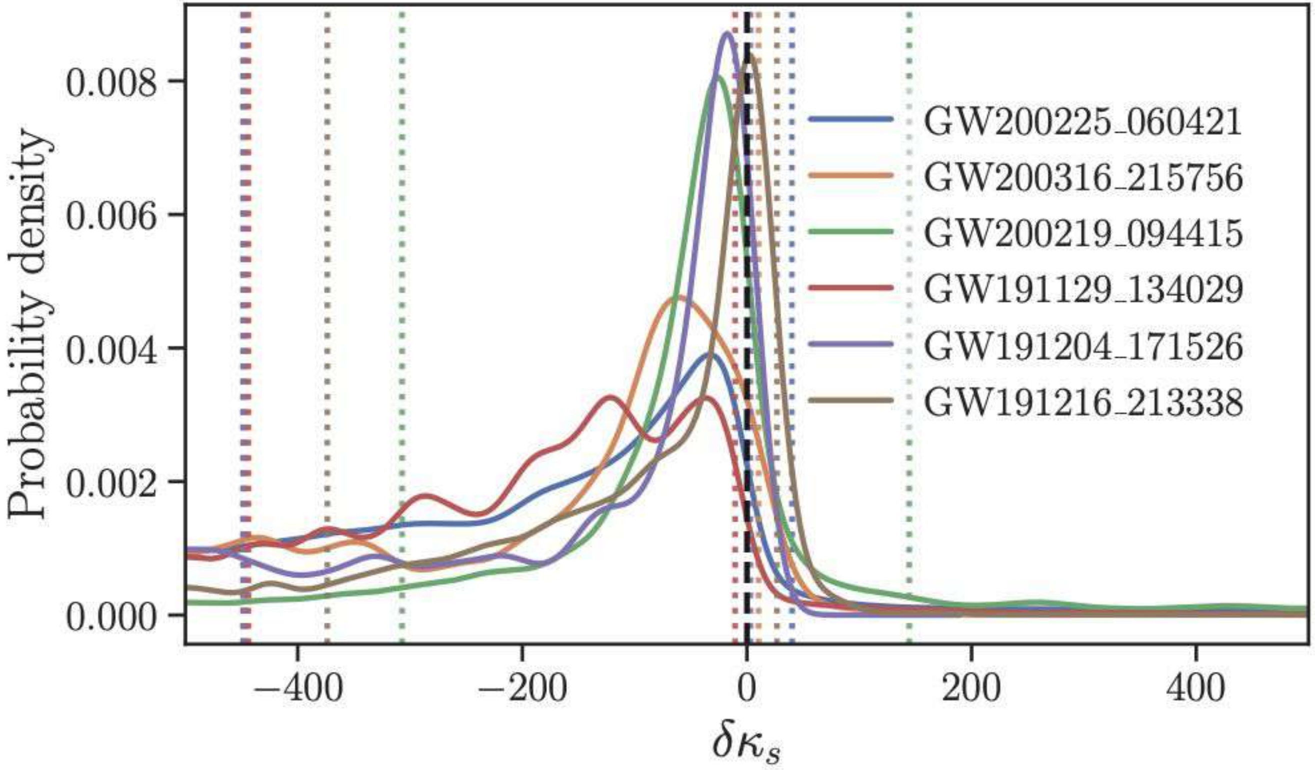
SIQM-Ecc Waveform: e0^8 for CE

Inspiral contributes only a few PN cycles before merger, leaving little opportunity for eccentricity-driven harmonics to accumulate in the waveform.



Constrain on kappa GWTC 3 : Waveform IMRPhenomPv2

Parameterised deviations $\kappa_s = 1 + \delta\kappa_s$ assuming $\kappa_a = 0$.



Tests of General Relativity with GWTC-3. LVK 2021

The Astrophysical Journal Letters, 993:L21 (45pp), 2025 November 1 https://doi.org/10.3847/2041-8213/ae0d54

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GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences

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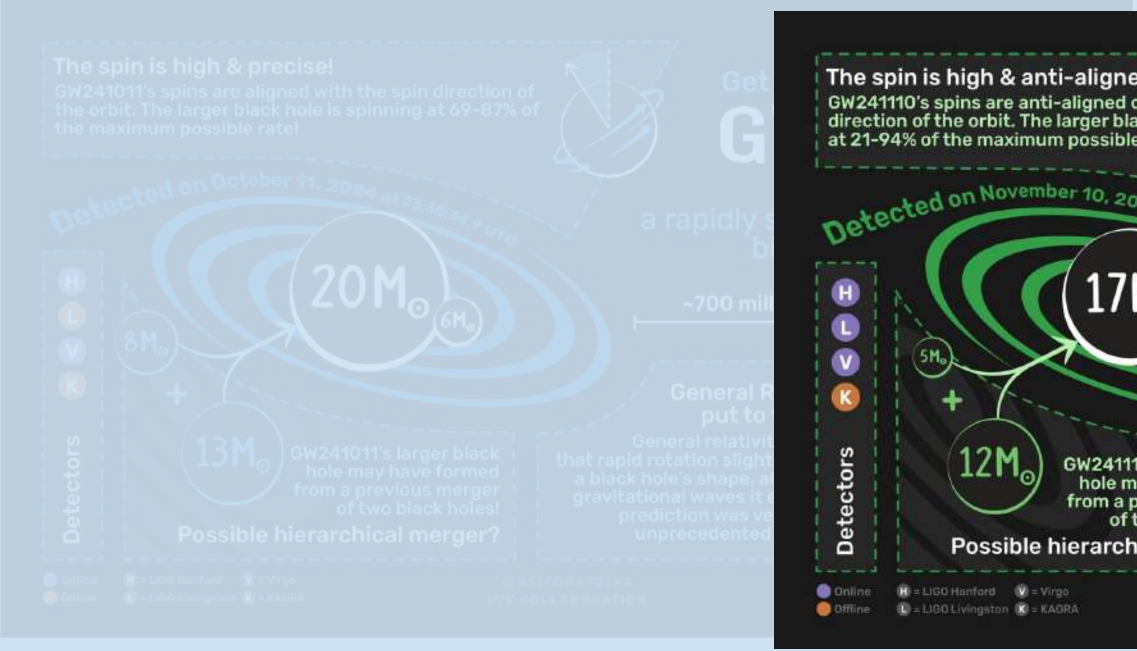

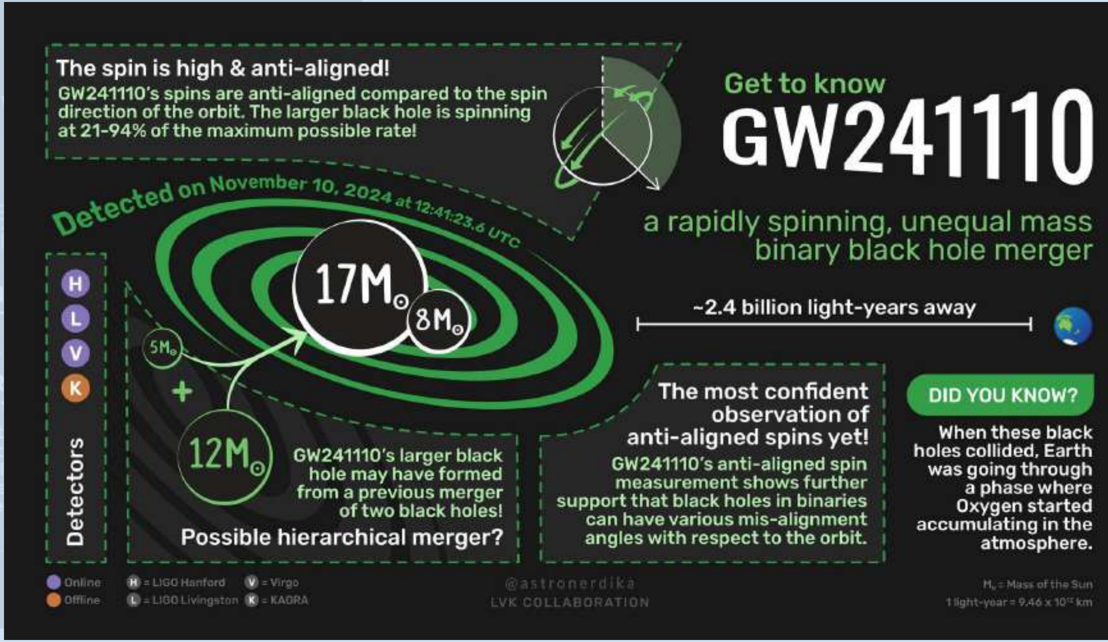

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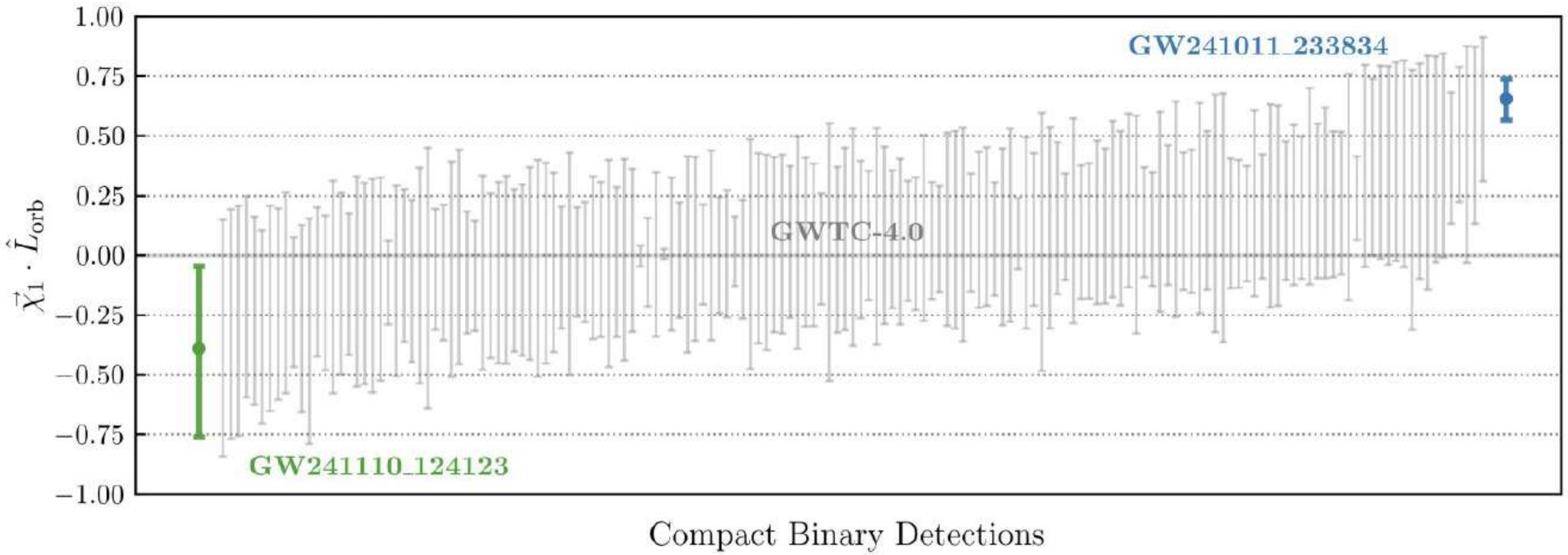

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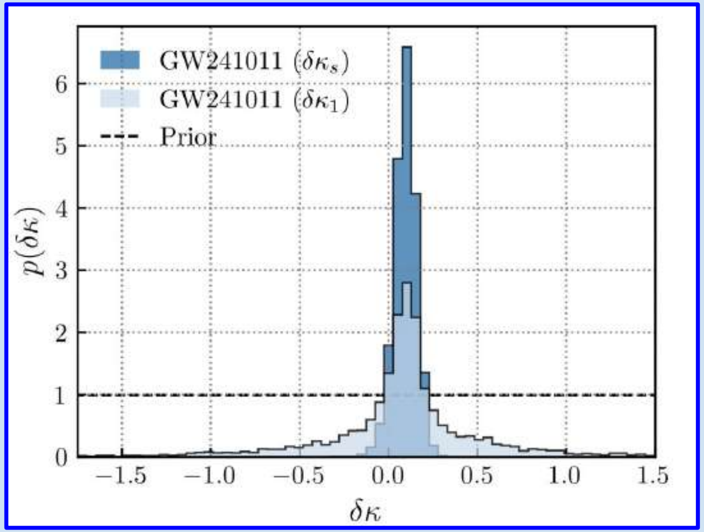
GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences

$

Test fundamental physics

Black Hole Spin-induced Quadrupole Moment



Define $\kappa_1 = 1 + \delta\kappa_1$ and $\kappa_2 = 1 + \delta\kappa_2$ as the spin-induced quadrupole coefficients of each compact object in GW241011's source binary.

Repeat parameter estimation with a modified IMRPHENOMXPHM waveform model allowing for nonzero $\delta\kappa1$ and $\delta\kappa2$

Implications of GW241011 for rotating exotic compact objects

arxiv:2511.17341

N. V. Krishnendu, Tamara Evstafyeva, Aditya Vijaykumar, William E. East, Rimo Das, Sayantani Datta, Nils Siemonsen, Nami Uchikata, Poulami Dutta Roy, Anuradha Gupta, Ish Gupta, Syed U. Naqvi, Manuel Piarulli, Muhammed Saleem, Elise M. Sänger, Pratyusava Baral, Sajad A. Bhat, Thomas A. Callister, Mattia Emma, Carl-Johan Haster

(Krishnendu et al.) Consider GW241011 posterior from paper \$

Question: Given this event, what does it imply for rotating exotic compact objects?
It maps the κ measurement onto ECO model space and derives the compactness bounds.

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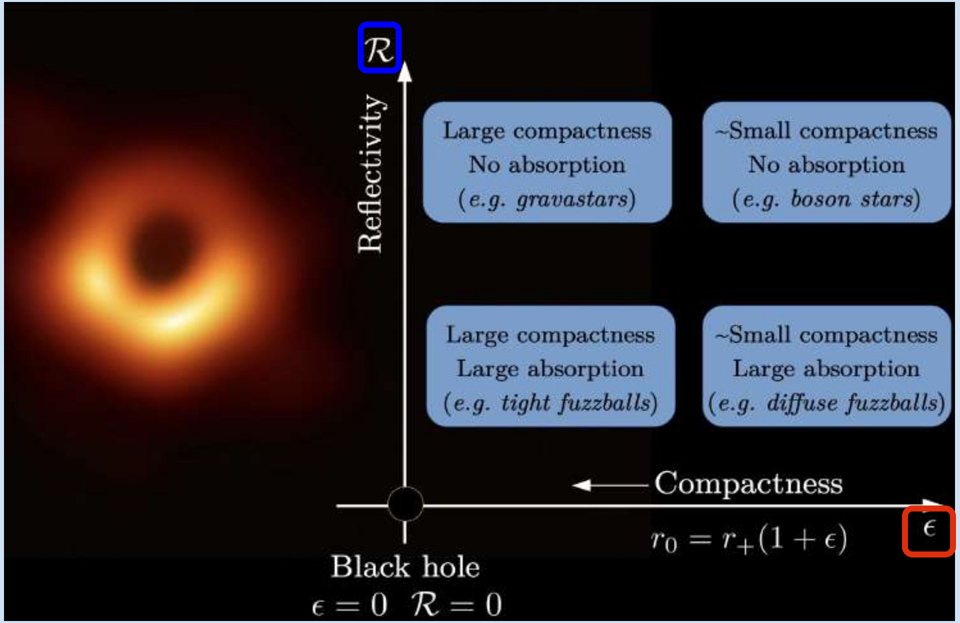
Taxonomy diagram for Exotic Compact Objects (ECOs)

- compactness (ϵ = how close the surface is to the horizon)
- reflectivity ($\mathcal{R}$ = what fraction of infalling radiation bounces back).

Slide: Paolo Pani talk



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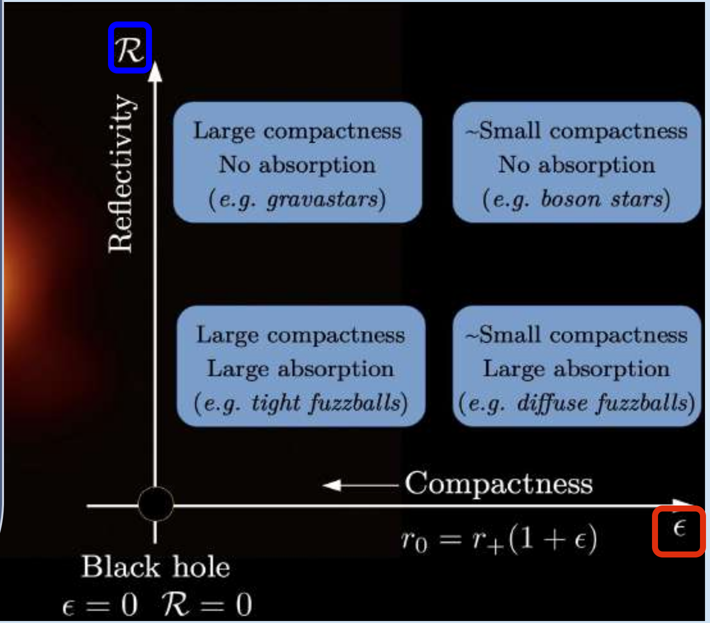
- **Black holes at the origin** ($\varepsilon = 0$, $\mathfrak{R} = 0$): perfectly compact and perfectly absorbing. All ECOs => deviations from this corner.

- **Two independent axes of "non-blackholeness"**: ECO can differ from a BH by having a

  i) surface outside the horizon (small compactness, large ε),
  ii) by reflecting radiation instead of absorbing it (large $\mathfrak{R}$),
  iii) or both simultaneously.

Slide: Paolo Pani talk



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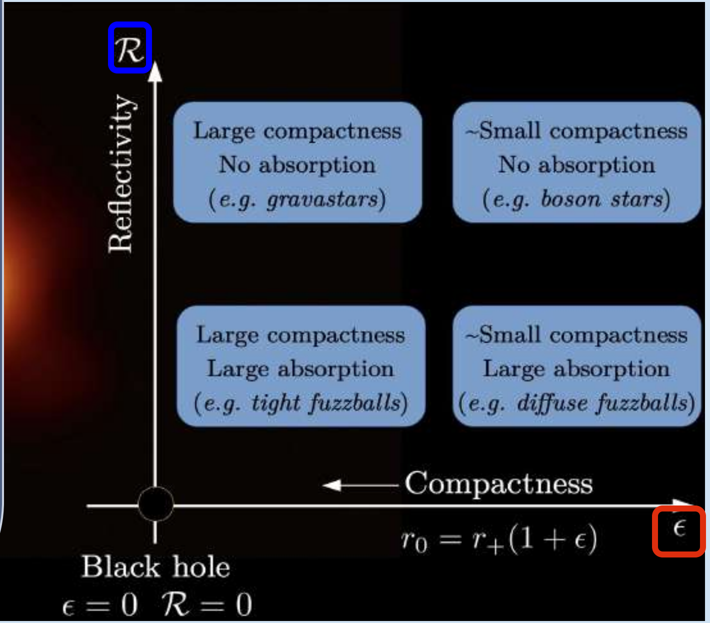
κ probes only compactness — the spin-induced quadrupole moment is sensitive to how concentrated the mass is (C = M/R)

GW241011 sets a compactness threshold — the κ_1 measurement places a lower bound C ≳ 0.24.

A compact ECO with C ≳ 0.24 — whether a gravastar or a thin-wall solitonic star — remains viable.
Not all boson stars are equal — whether a boson star survives depends entirely on its potential: some are fully excluded, some partially.

Slide: Paolo Pani talk



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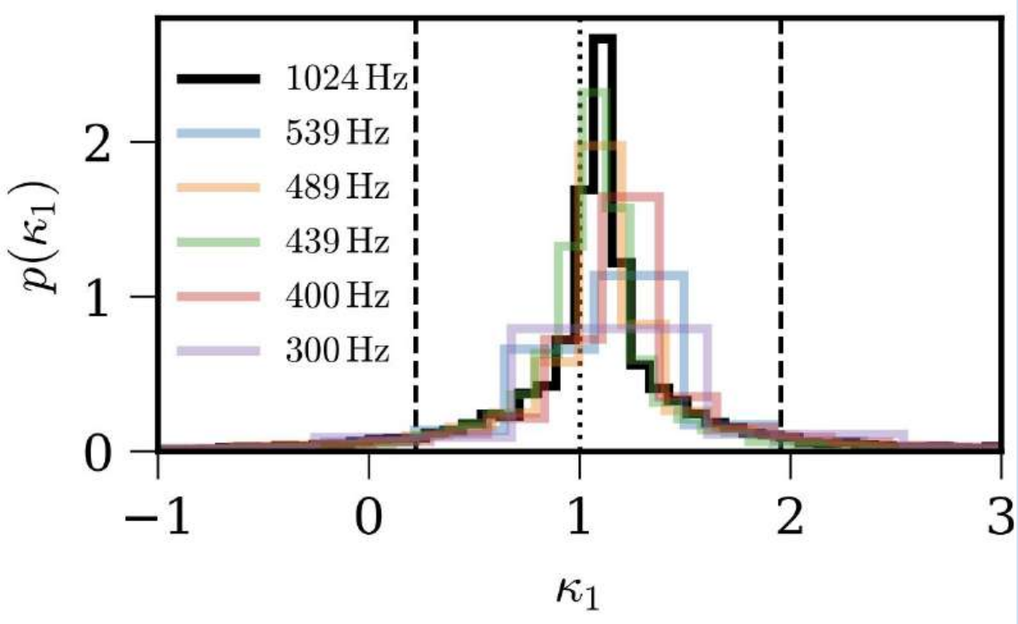
- **GW241011 is an ideal ECO laboratory:** highly spinning primary ($\chi_1 \sim 0.78$) with a 3:1 mass ratio, giving strong SIQM sensitivity — the κ measurement is among the tightest from any single event.



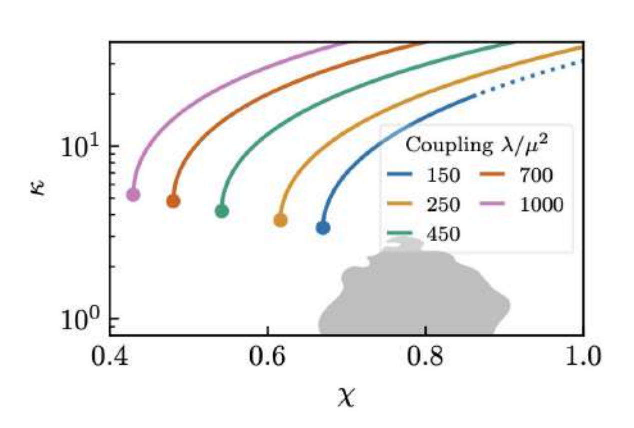
Implications of GW241011: Two Boson stars case

- **Compactness (C=M/R) is the surviving knob:** only models with C ≳ 0.24 remain viable — compactness is now the key parameter separating allowed from excluded ECO models.
- (The gray shaded region denotes the κ–χ measurement (at 95% credible level).)

{λ, σ} :coupling constants (self-interactions)

$$V_{\mathrm{rep}}(|\Phi|) = \underbrace{m^2|\Phi|^2}_{\text{mass term}} + \underbrace{\lambda\,|\Phi|^4}_{\substack{\text{repulsive}\\ \text{self-interaction}\\ \lambda>0}}$$

Repulsive stars



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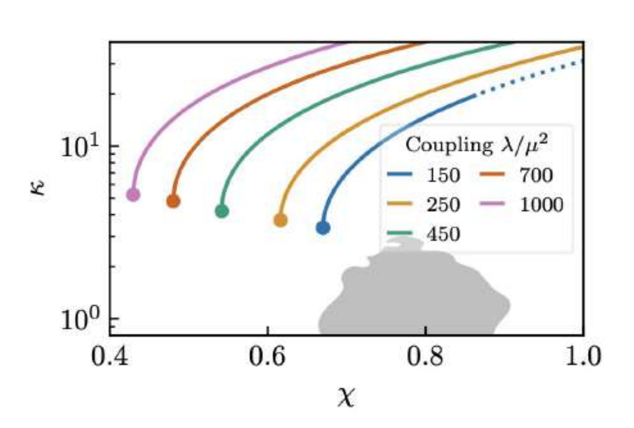
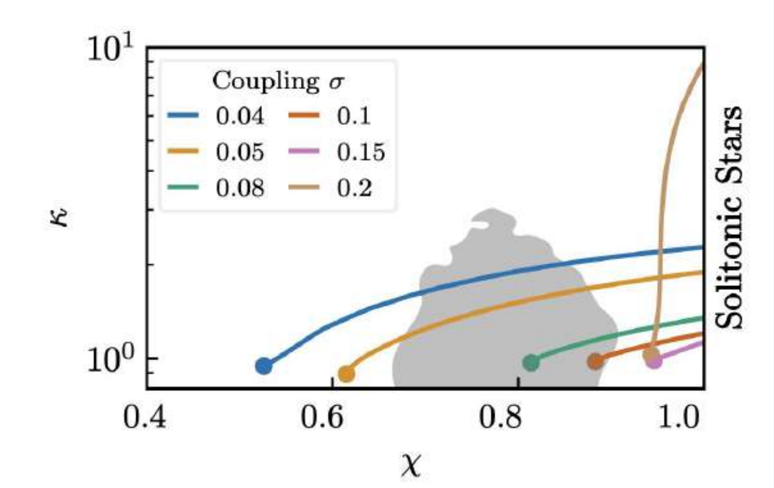
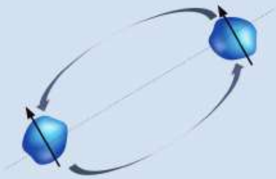
Repulsive stars

$$V_{\rm sol}(|\Phi|) = m^2|\Phi|^2\left(1 - \frac{|\Phi|^2}{\sigma^2 m_{\rm Pl}^2/4\pi}\right)^2$$

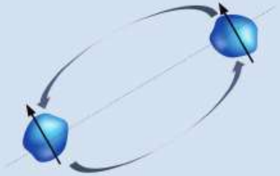
Solitonic stars







Conclusion



SIQM Eccentric

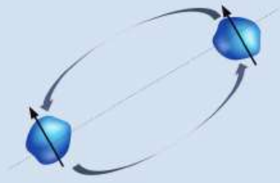
arXiv:2511.1734 1

➢ SIQM-Ecc Fisher analysis:

- Go beyond single-event studies → statistical constraints from many detections
- Quantify how well we can measure κ□ (spin-induced quadrupole moment) at the population level
- Test how including eccentricity (e_0) affects parameter estimation

➢ SIQM-Ecc e0 ^{2} : Bayesian Analysis

- Terms coded in LALSuite => injection and recovery study
- Are κs - e0 degenerate?
- Does eccentricity broaden the κs posterior?



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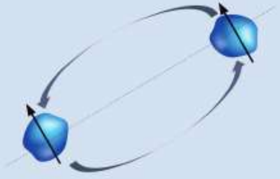

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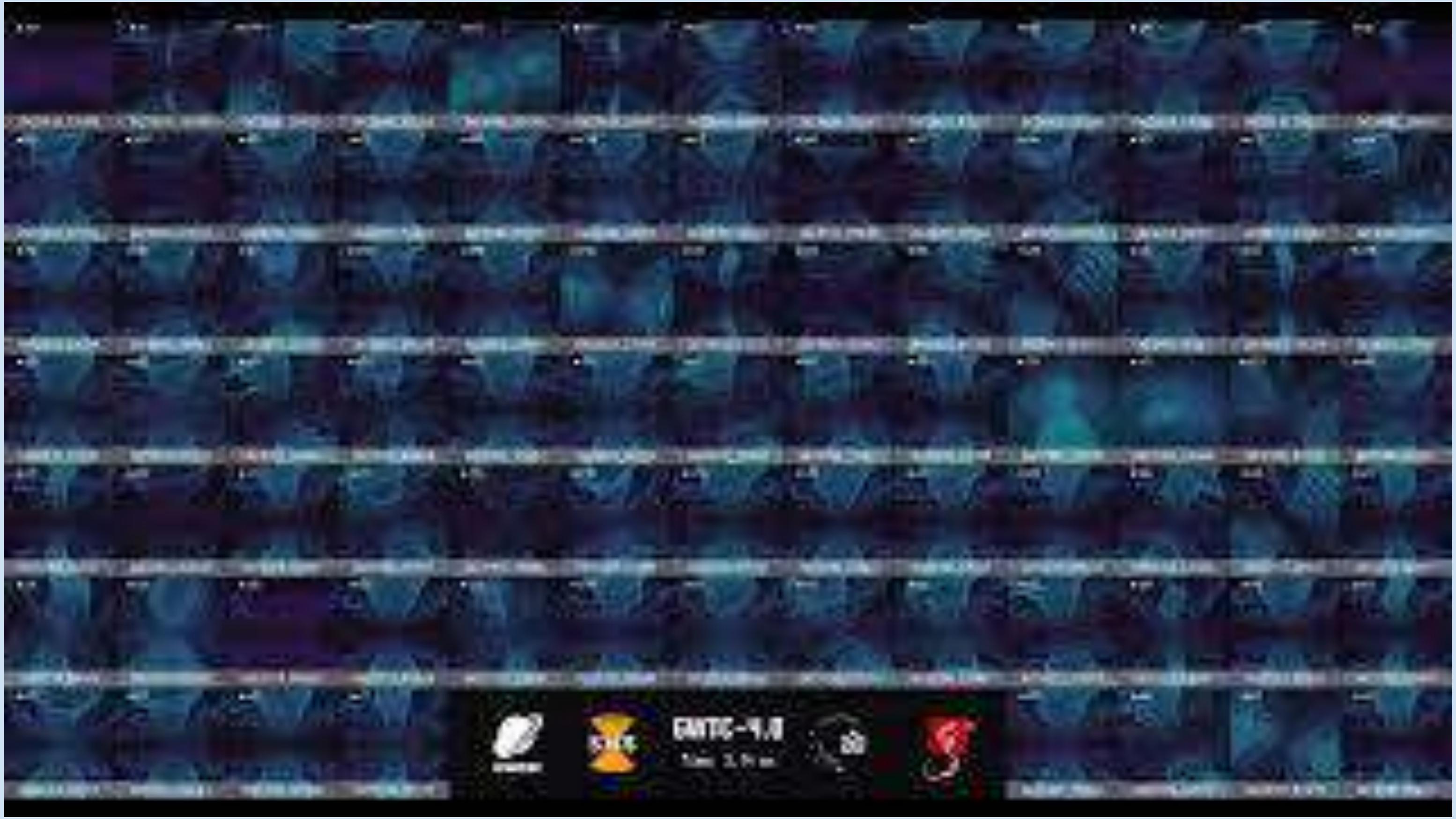
- Does eccentricity broaden the κs posterior?

GW241011: Heisenberg "what we observe is not nature itself, but nature exposed to our method of questioning"—Analysis tests for one specific finite-size effect relating to SIQMs, and by construction does not account for other possible effects, such as tidal deformability...

Conclusion

Numerical relativity simulations of the black hole mergers provided by the Simulations of Extreme Spacetimes (SXS) waveform database



Thank You!


A TRAUTMAN
58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