Title: Gravitational-wave astronomy and fundamental physics with charged black holes

Speakers: Gabriele Bozzola

Series: Strong Gravity

Date: December 08, 2022 - 1:00 PM

URL: https://pirsa.org/22120059

Abstract: Charge (electric, magnetic, or any U(1) charge) is a parameter often neglected in simulations of black holes. As a result, little is known about the dynamics of charged binaries. In this talk, I will highlight the importance of understanding the non-linear interaction of charged black holes for astrophysics and fundamental physics. I will show results from fully self-consistent general-relativistic simulations of merging black holes, touching upon the challenges faced in performing such calculations and the improvements that enabled successful long-term evolution. I will discuss general features of quasi-circular inspirals, and present constraints on the charge of astrophysical black holes and deviation from general relativity obtained from the gravitational-wave event GW150914. Finally, I will highlight the relevance of this line of research in the context of the upcoming gravitational-wave detectors.

Zoom link: https://pitp.zoom.us/j/93809443805?pwd=bmcvd3NZWjUraERBcGdtL2Y3WTl6QT09

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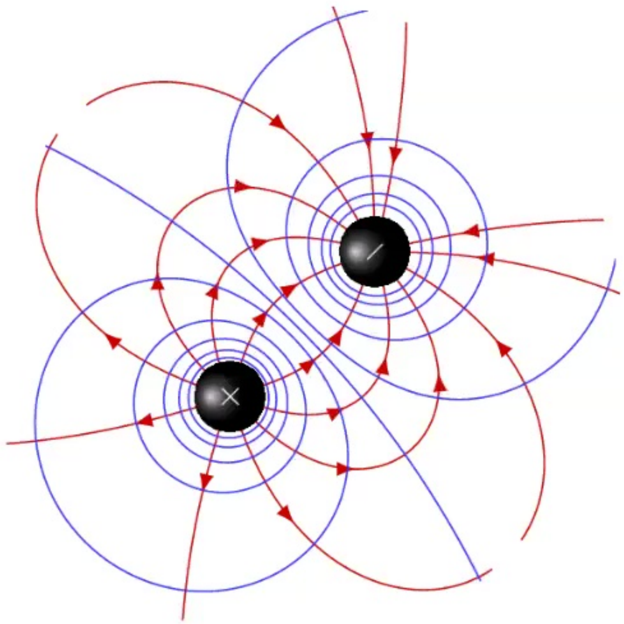
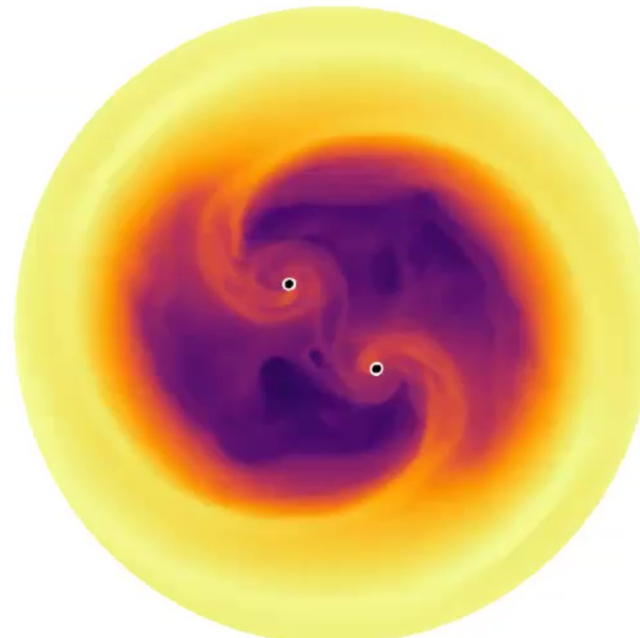
NUMERICAL RELATIVITY, GRAVITATIONAL WAVES, AND FUNDAMENTAL PHYSICS WITH CHARGED BLACK HOLES

December 8, 2022

Gabriele Bozzola,
Vasileios Paschalidis

Department of Astronomy,
University of Arizona





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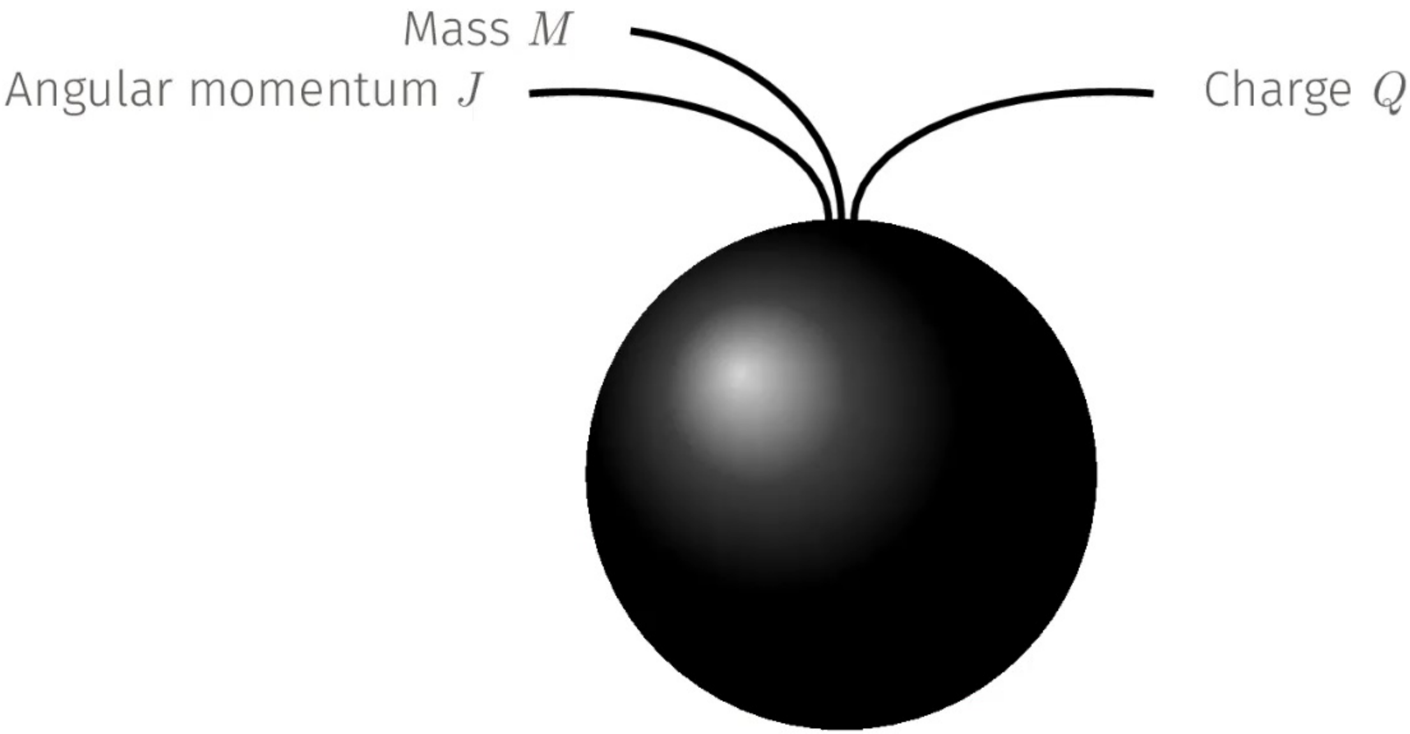
Black holes are simple objects: the *no hair* theorem



Israel (1967), Israel (1968), Carter (1971), ...

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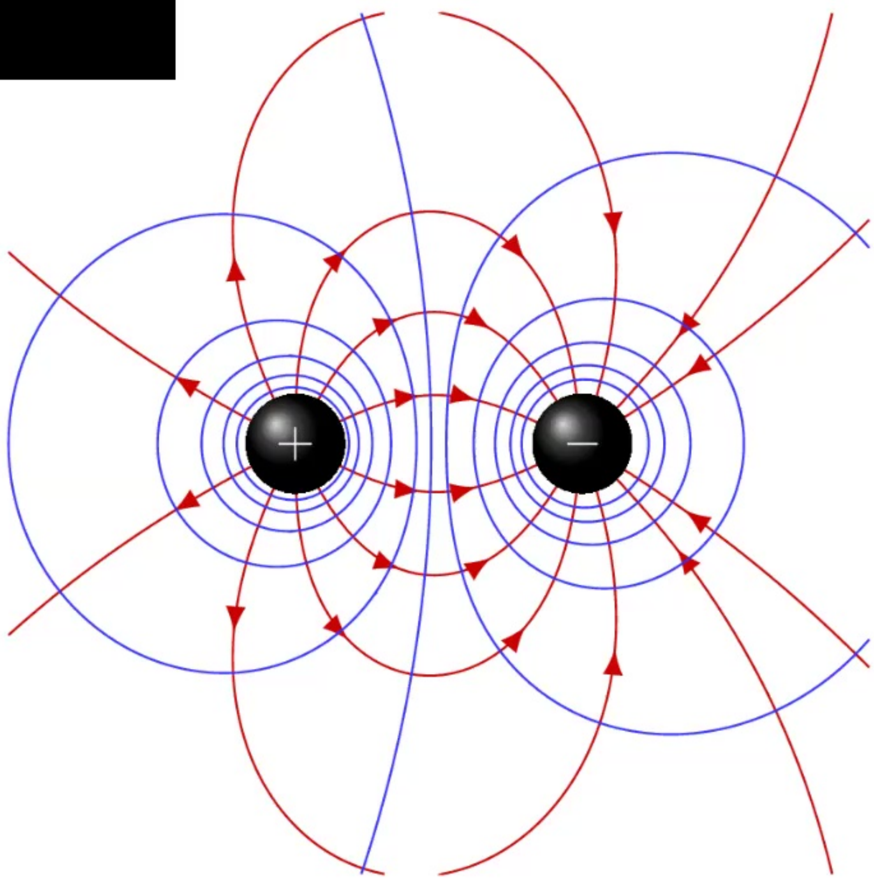

The nonlinear interaction between charged binary black holes is **unexplored**

Orbits? Emission? ...?

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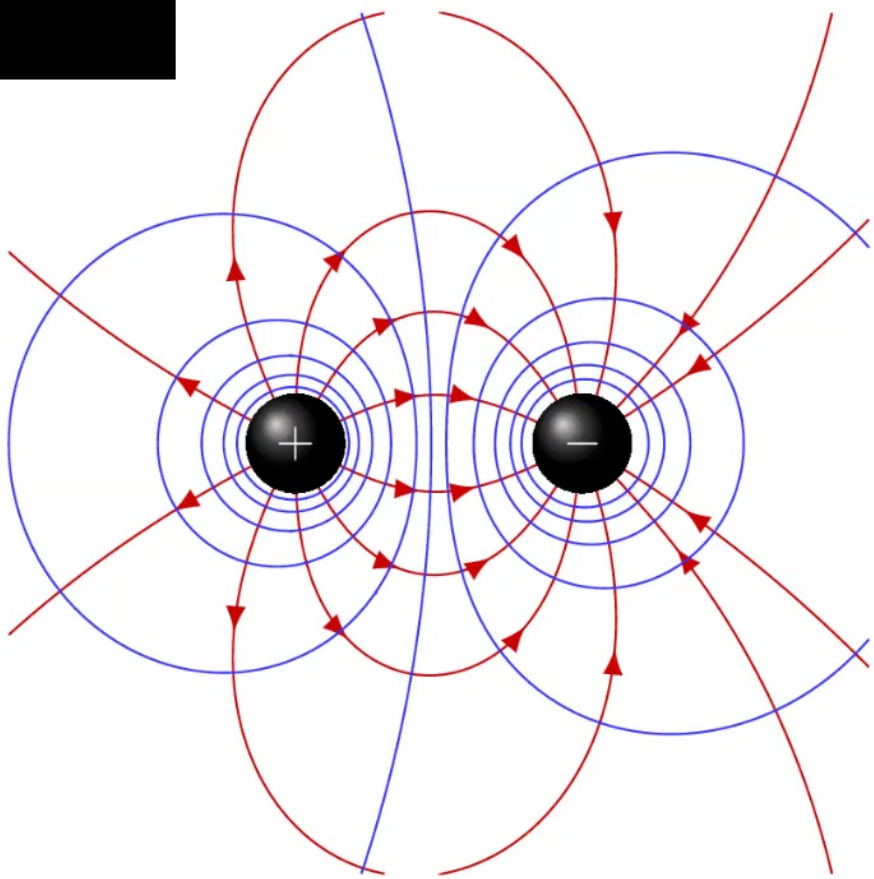

The nonlinear interaction between charged binary black holes is **unexplored**

Orbits? Emission? ...?

We assume

$$G = c = (4\pi\varepsilon_0)^{-1} = 1$$

$$(q_{\text{proton}}/m_{\text{proton}} \approx 10^{18})$$

1. Results apply to stellar-mass, supermassive, and microscopic BHs
2. Charge does not have to be electromagnetic

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Non-linear interaction is important for

Astrophysics ⟷ Constraints on charge
GW templates for LIGO-Virgo

→ BH charge is largely unconstrained
→ GW models do include charge

Much more on this later!

[redacted]

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Non-linear interaction is important for

Exotic Astrophysics ⟷ Constraints on charged dark matter and magnetic monopoles

→ Primordial BH could have (electric or magnetic) charge

→ Dark matter could be (darkly) charged

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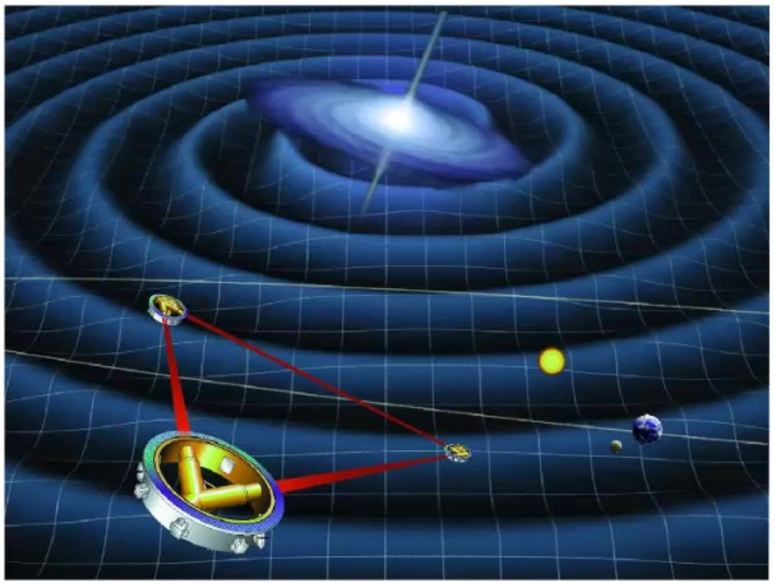
Non-linear interaction is important for

Modified Gravity ⟷ Springboard and proxy for other theories (e.g. Einstein-Maxwell-Scalar)



- → Well defined way to go beyond GR
- → Some theories are mathematically identical in specific limits
- → Better understanding for future facilities

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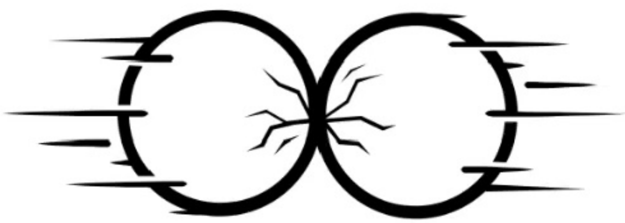
Non-linear interaction is important for

First Principles ⟷ Ultra-relativistic collisions
Scattering
Cosmic censorship



- → Exceptional laboratories for controlled numerical experiments
- → Interplay between extreme electromagnetic and gravitational fields

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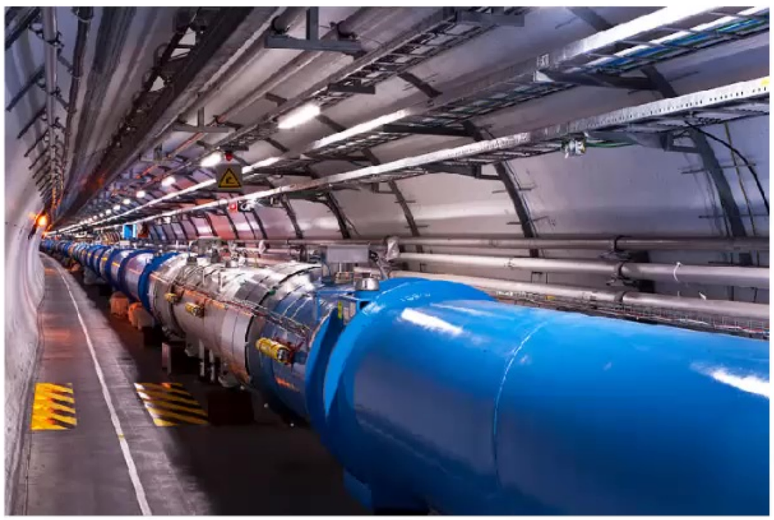
Non-linear interaction is important for

Energetic Particles ⟷ BHs in cosmic rays, LHC
(cross section, EM signatures, ...)



→ Microscopic black hole production and detection

→ Tests of specific grand unified theories

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Non-linear interaction is important for

Astrophysics	Constraints on charge GW templates for LIGO-Virgo
Exotic Astrophysics	Constraints on charged dark matter and magnetic monopoles
First Principles	Ultra-relativistic collisions Scattering Cosmic censorship
Modified Gravity	Springboard and proxy for other theories (e.g. Einstein-Maxwell-Scalar)
Energetic Particles	BHs in cosmic rays, LHC (cross section, EM signatures, ...)

This list is incomplete; you can help by expanding it.

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Einstein-Maxwell

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T^{\text{EM}}_{\mu\nu}$$

$$\nabla_\mu F^{\mu\nu} = 4\pi J^\nu$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

for binary black holes

→ No symmetries

→ Non perturbative

→ Highly non-linear coupled PDEs

$\Downarrow$

NUMERICAL RELATIVITY

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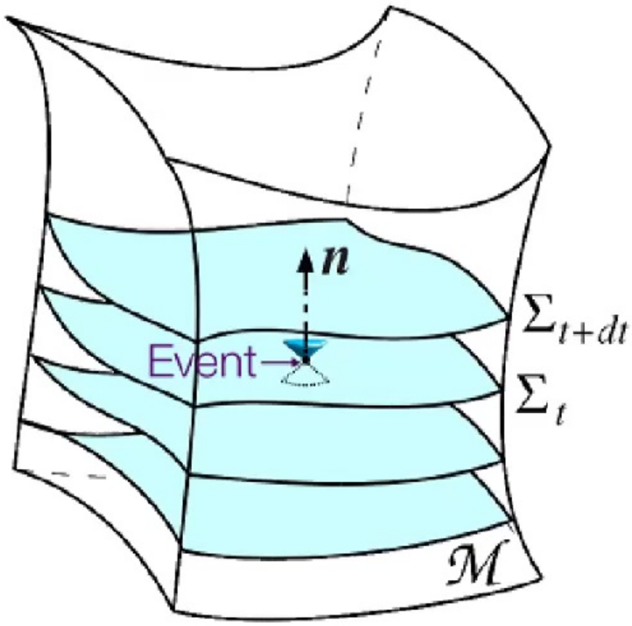
How to solve Einstein-Maxwell's equations



Numerical solution of Einstein-Maxwell's equations as initial-value-problem

Issues with stability, gauge, initial data, ...

HARD PROBLEM!

Numerical relativity = *know-how* to be successful in this feat

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Today's talk

Numerical Relativity	Astrophysics
First numerical-relativity simulations of quasi-circular mergers	First constraints on BH charge from gravitational waves

Ask questions or reach out for more!

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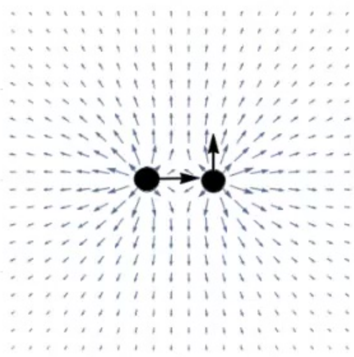
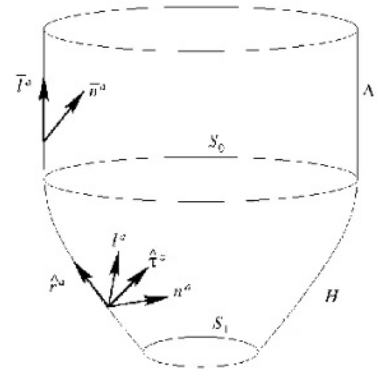
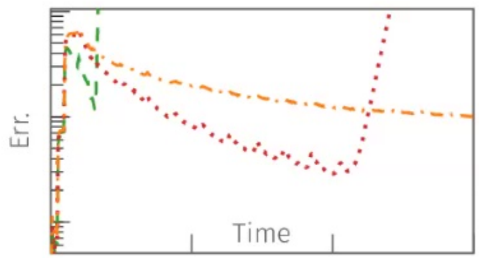
Novel/improved methods



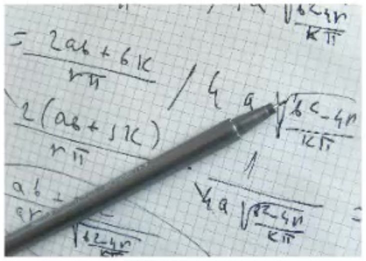
Initial data
`TwoChargedPunctures`



Interpretation
`QuasiLocalMeasuresEM`



Stability
Continuous Dissipation



Analysis
Newman-Penrose

Bozzola&Paschalidis (2019, 2021b), Luna&Bozzola+ (2022)

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Full non-linear simulations with the `Einstein Toolkit`

Initial data	`TwoChargedPunctures`
Adaptive mesh refinement	`Carpet`
Evolution	`ProcaEvolve` + `Lean`
Diagnostics	`ProcaConstraints` `ProcaDiagnostics`
Wave extraction	`Proca_NPScalars`
Horizons properties	`AHFinderDirect` + `QuasiLocalMeasuresEM`
Postprocessing	`kuibit`

KUIBIT

Bozzola&Paschalidis (2019, 2020, 2021a, 2021b) Bozzola (2021) Sperhake (2006)
Thornburg (2003) Dreyer et al (2002) Schnetter (2003) Zilhão et al (2015)

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→ Mostly multi-resolution Cartesian grids
→ (Non-)linear elliptic and hyperbolic PDEs
→ Pseudo-spectral solvers, finite differences, method of the lines
→ Volume/surface integrals with Lagrange/Hermite interpolations
→ C, C++, Fortran, OpenMP, MPI (no GPU)
→ Weeks/months on supercomputers

KUIBIT

Bozzola&Paschalidis (2019, 2020, 2021a, 2021b) Bozzola (2021) Sperhake (2006) Thornburg (2003) Dreyer et al (2002) Schnetter (2003) Zilhão et al (2015)

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Astrophysics

Charge of astrophysical black holes

$Q_{\text{BH}}, M_{\text{BH}}$

Accretion $\Leftrightarrow$ $F_e + F_g < 0$

$$\frac{q_p Q}{r^2} - \frac{m_p M}{r^2} < 0$$

$$\boxed{\frac{Q_{\text{BH}}}{M_{\text{BH}}} < \frac{m_{\text{proton}}}{q_{\text{proton}}} \sim 10^{-18}}$$

BH with $Q/M > 10^{-18}$

$\Downarrow$

Accretes opposite charges

Does not accrete same charge

$\Downarrow$

Discharge

Press+ (1975), Wald (1984), Cardoso+ (2016), ...

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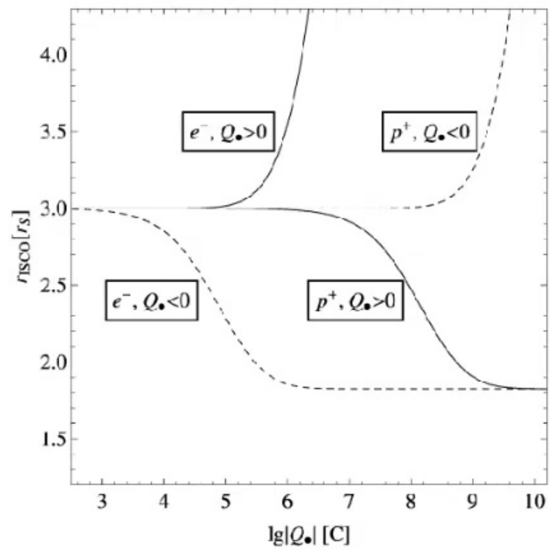
Measurements of BH charge are model-dependent



Charge

⇓

Disk structure

⇓

Emission properties

Extensive non-trivial modeling effort

Plot from Zajacek+ (2018)

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Discharge limits rely on $\frac{Q_{\text{BH}}}{M_{\text{BH}}} < \frac{m_{\text{proton}}}{q_{\text{proton}}} \sim 10^{-18}$

Evaded if:

- → Mini-charged dark matter ($m/q \sim 1$)
- → Dark electromagnetism (different EM coupling)
- → Magnetic monopoles (no discharge)
- → Gravitational charge (STVG*, $Q/M = \sqrt{\alpha/(1+\alpha)}$, with α coupling)

* = Scalar-Tensor-Vector Gravity

Preskill+ (1984), Moffatt (2006), Feng+ (2009), Cardoso+ (2016), ...

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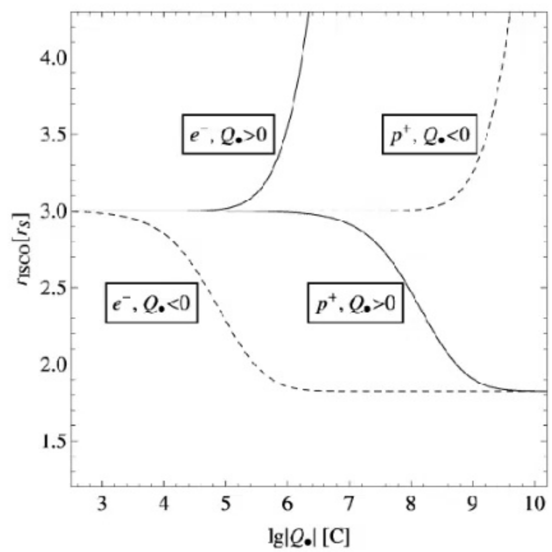
Measurements of BH charge are model-dependent



Charge
⇓
Disk structure
⇓
Emission properties

Extensive non-trivial modeling effort

Non-zero charge would challenge current understanding of BH formation and environments

Plot from Zajacek+ (2018)

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How can we test this?

Charge

⇓

Electromagnetic energy

⇓

Spacetime curvature

Orbital dynamics

⇓

Gravitational waves

GWs know about charge

Strengths:

→ Little modeling required

→ Applicable to exotic astrophysics

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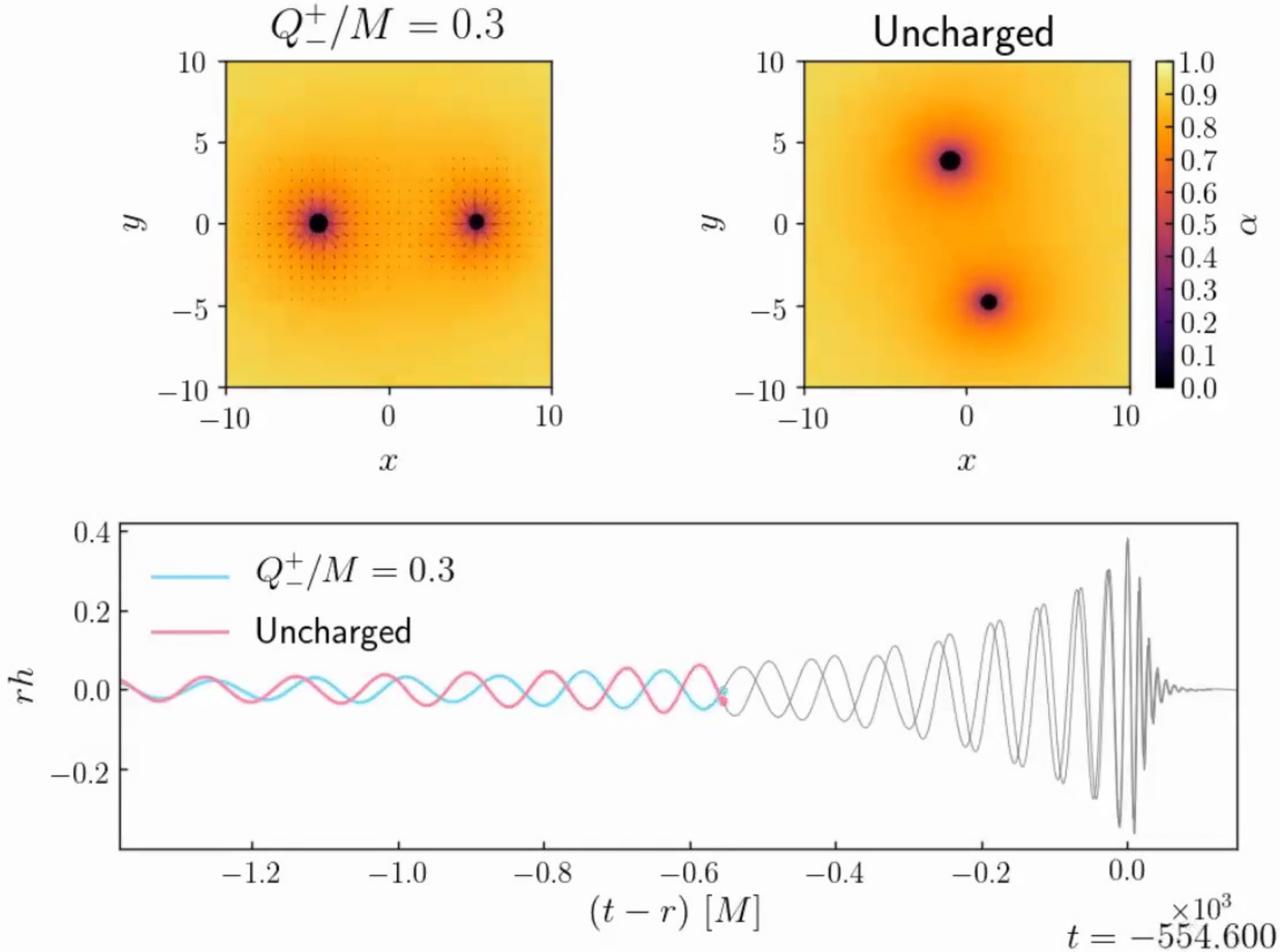

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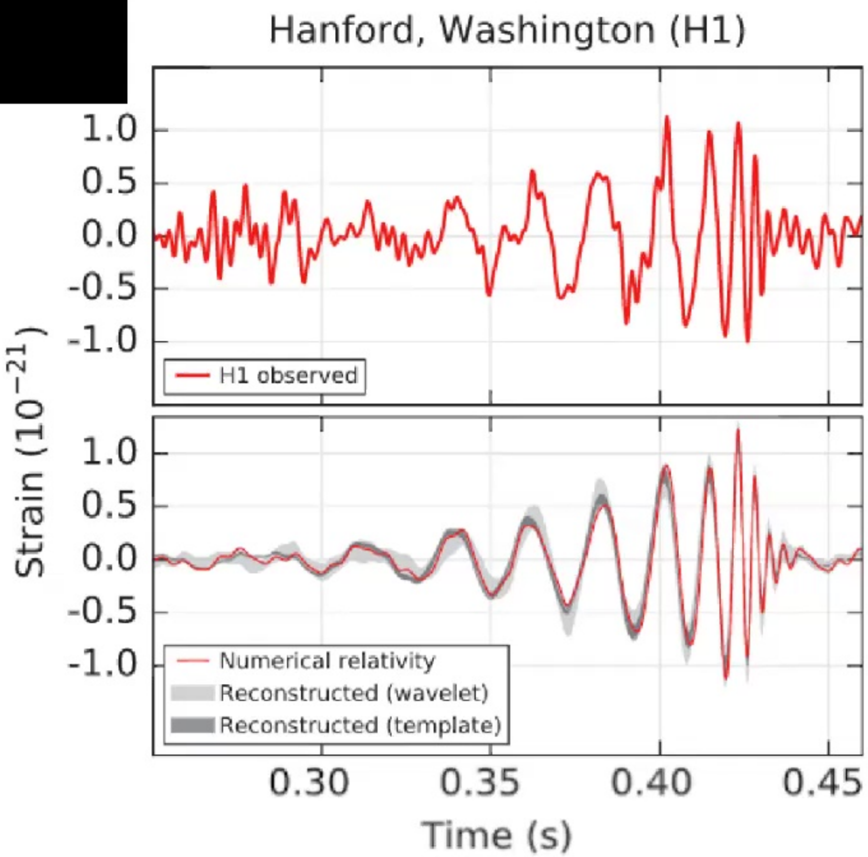

GW150914:

- → First confirmed GW event
- → Loud and well-characterized (SNR = 25)
- → Mass-ratio $29/36$
- → (Disputed) coincident EM observations

Full Bayesian analysis requires GW templates (= *currently impossible*)

Plot from LIGO (2016)

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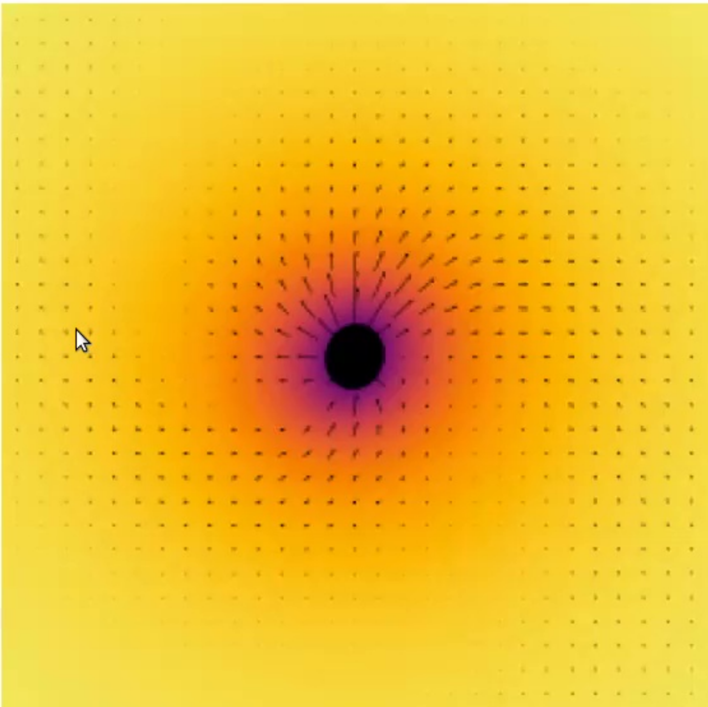
Electromagnetic emission is model dependent



→ Propagation/interaction with plasma

→ Different for non-EM theories

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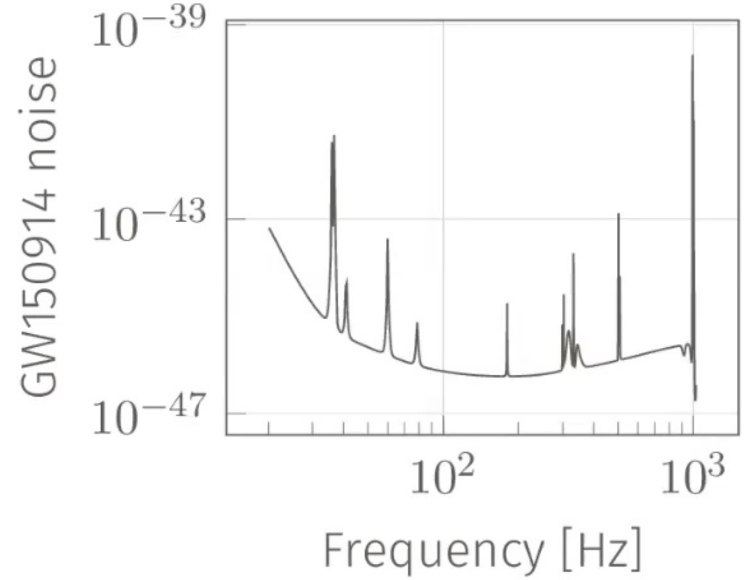
Constraint from mismatch analysis

1. Perform array of charged simulations
2. Compute SNR needed to distinguish them from GW150914
3. If SNR marginalized over time, phase, and mass < 25 →ruled out
4. Find maximum charge still compatible



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First constraints on:

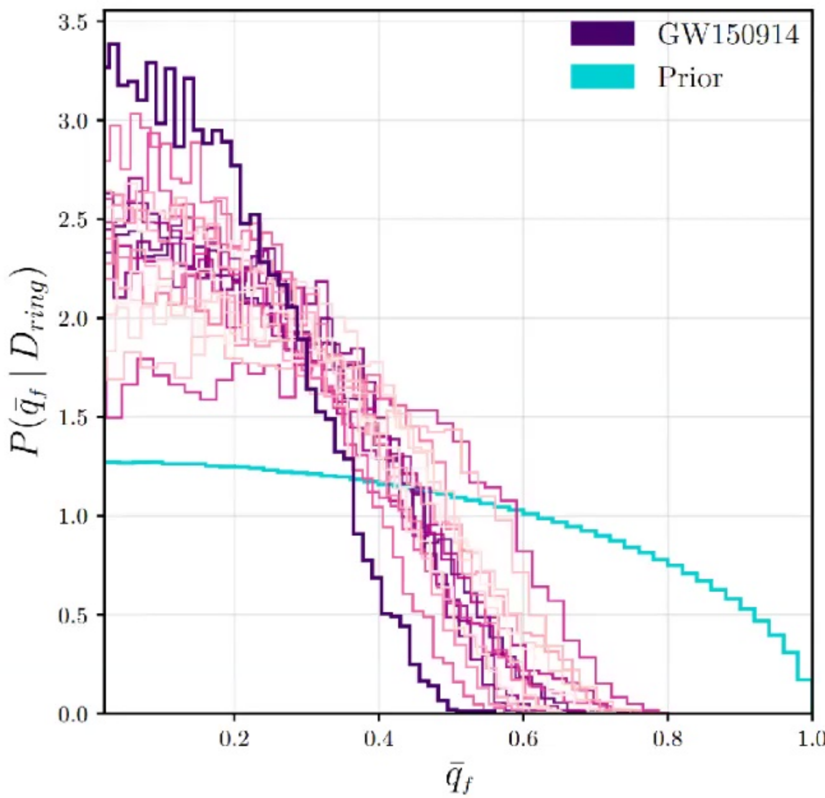
Black hole charge from GW150914:

Opposite charge: $\mathbf{Q/M < 0.2}$
Single charge: $\mathbf{Q/M < 0.35}$
Same charge: $\mathbf{Q/M < 0.4}$
(charge imbalance $< 10^{-17}\ M_\odot$)

Tightest constraint on STVG
(Scalar-Tensor-Vector Gravity)
in strong-field:

$\alpha < \mathbf{0.19}$ (before $\alpha \lesssim 9$)

Later confirmed by Carullo+, 2022:



$\bar{q}_f$ =final charge-to-mass-ratio

Bozzola&Paschalidis (PRL 2021)

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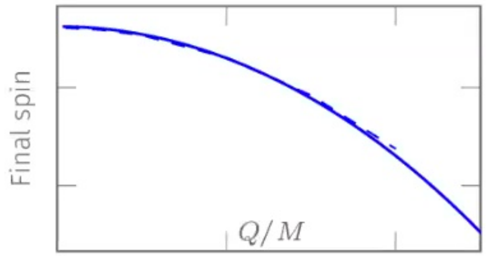
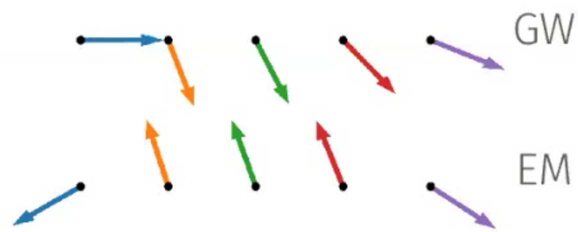
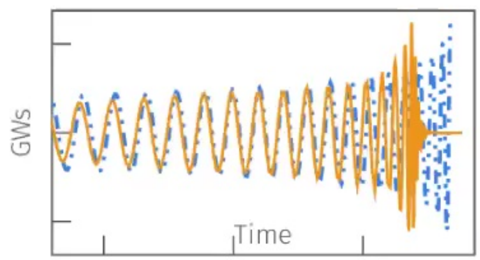
More advancements:



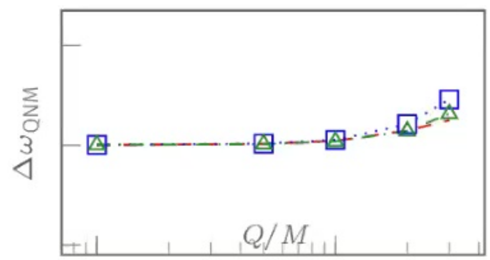
Remnant properties



Kicks



Validation



Quasi-normal modes

Bozzola&Paschalidis (2019, 2021b, in prep), Luna&Bozzola+ (2022)

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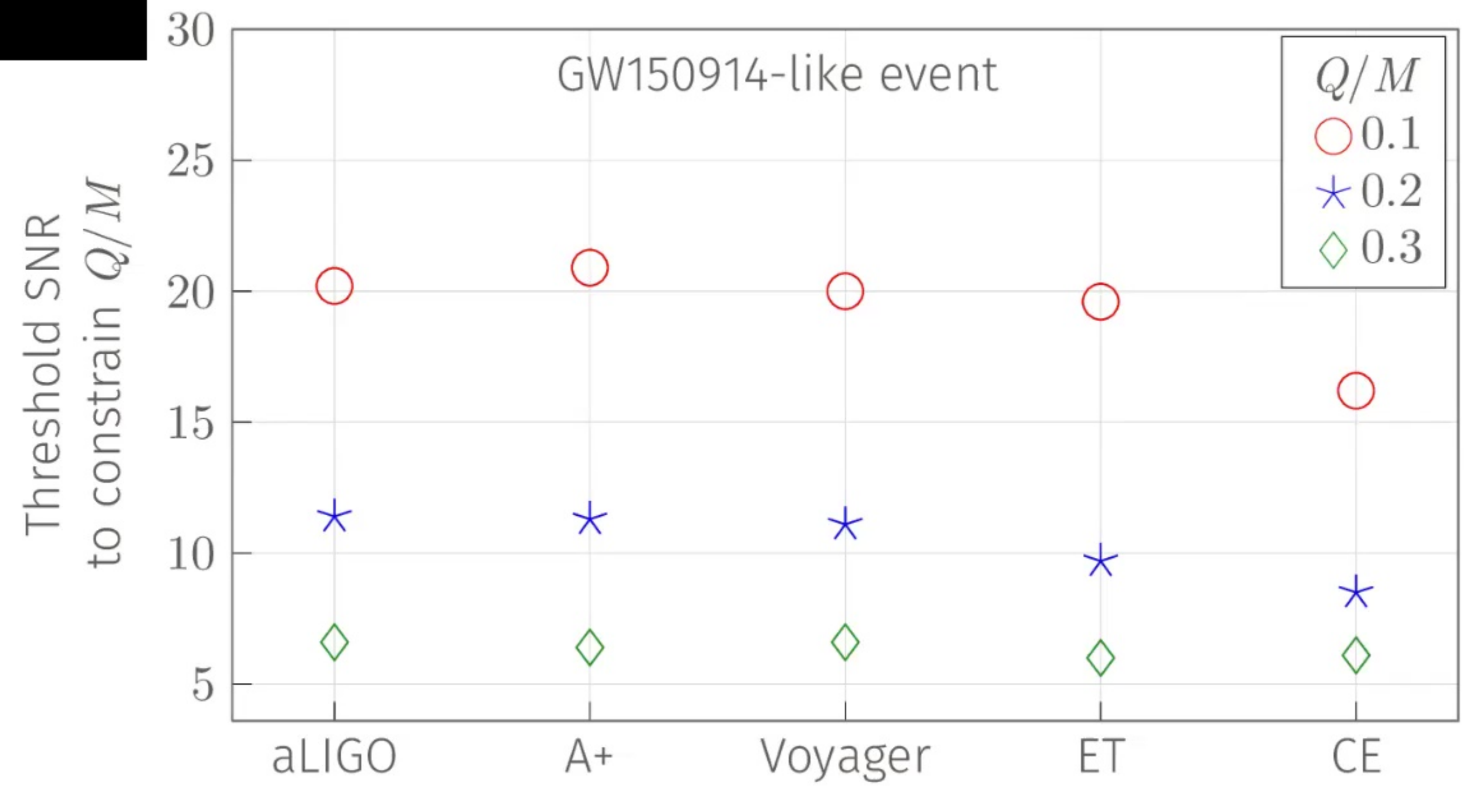
Expec[redacted]ectors



Bozzola&Paschalidis (2021b)

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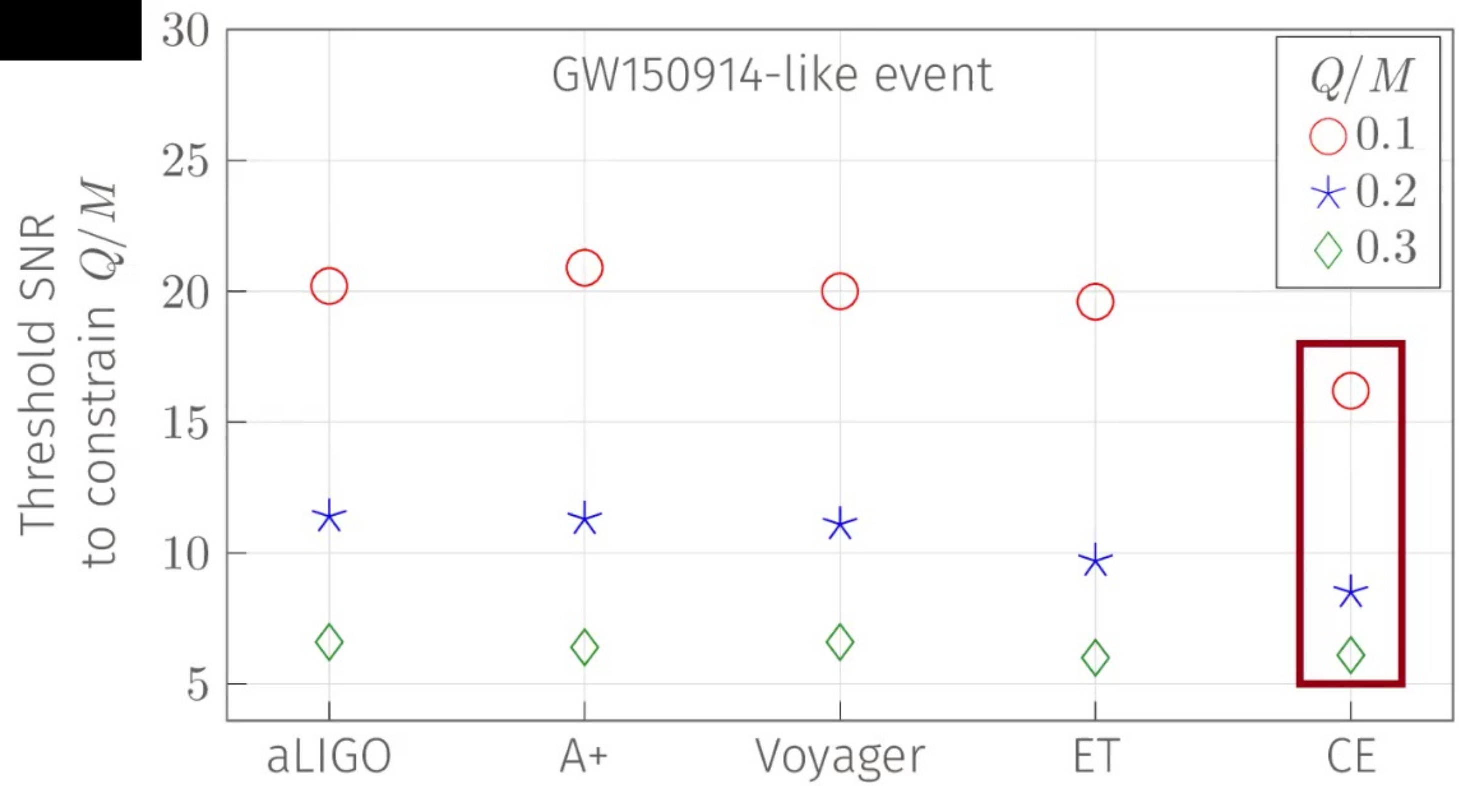
Expected constraints with future detectors



SNR for 3G $\gg 30$

Rough scaling $(Q/M)^{-2}$

LISA will constrain everywhere

BETTER CONSTRAIN REQUIRE BETTER SIMULATIONS

Bozzola&Paschalidis (2021b)

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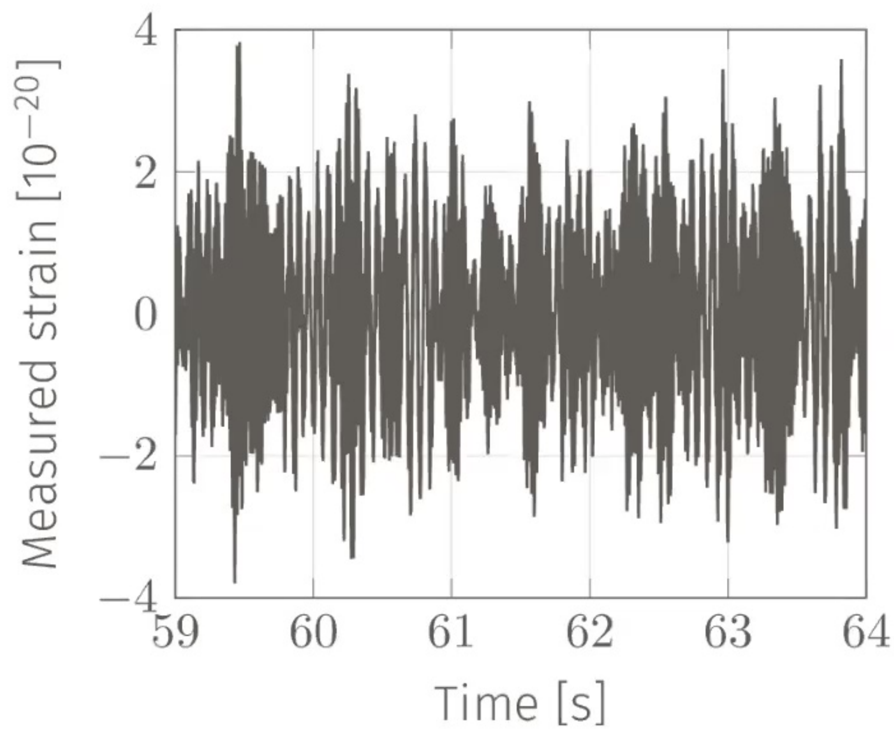
GW detectors look for needles in haystacks

- → Noise $\gg$ signal
- → GW detection relies on matched filtering



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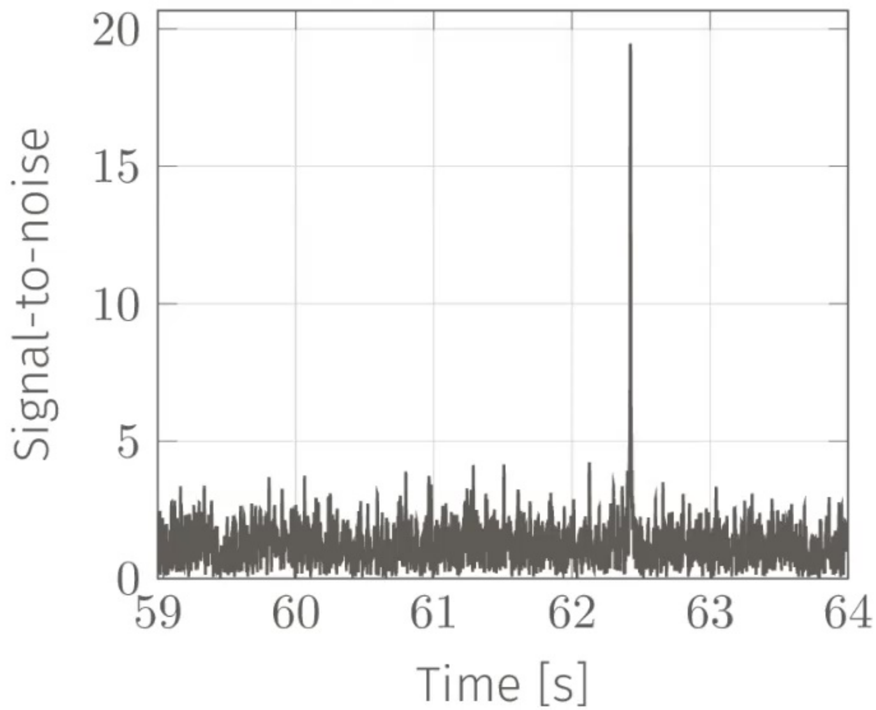
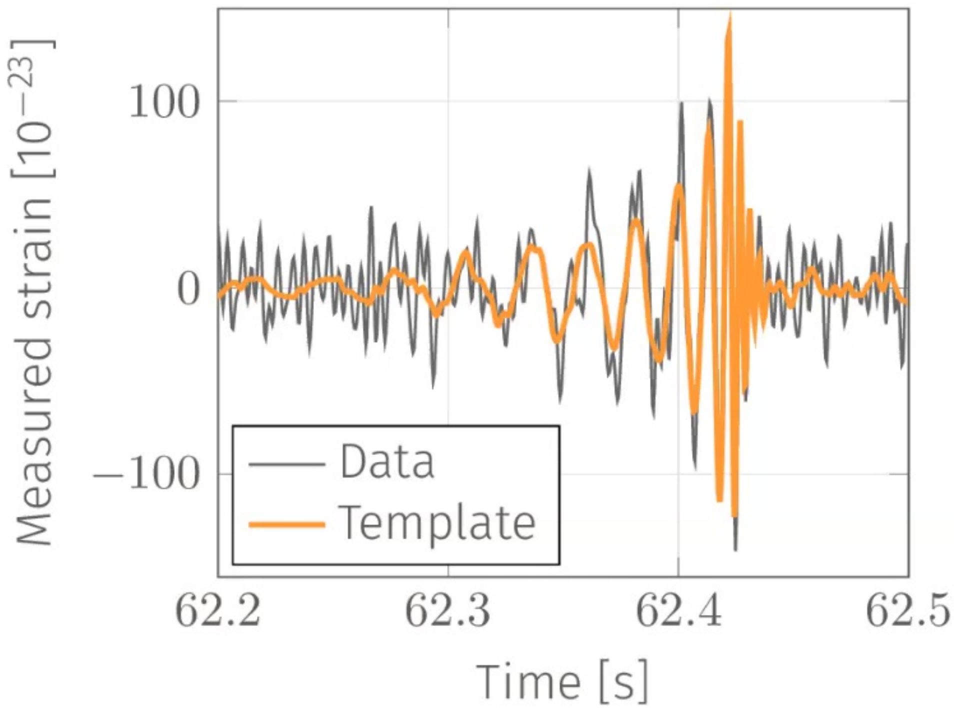
[redacted]W models are critical for detection and interpretation!

Compare NR-calibrated models with data





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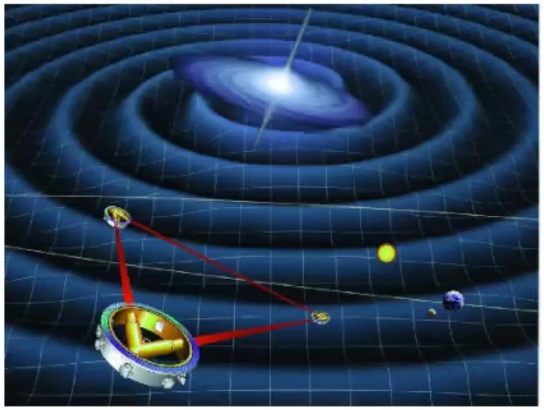
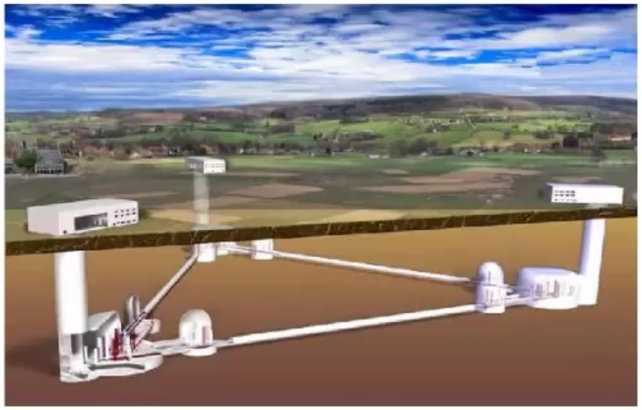
[redacted]re detectors require better and more varied simulations


- → Vacuum GR waveforms are not accurate enough
- → Going off the beaten path to understand biases and degeneracies
- → Einstein-Maxwell is a great way to develop tools and techniques for gravitational-wave astronomy beyond vacuum GR

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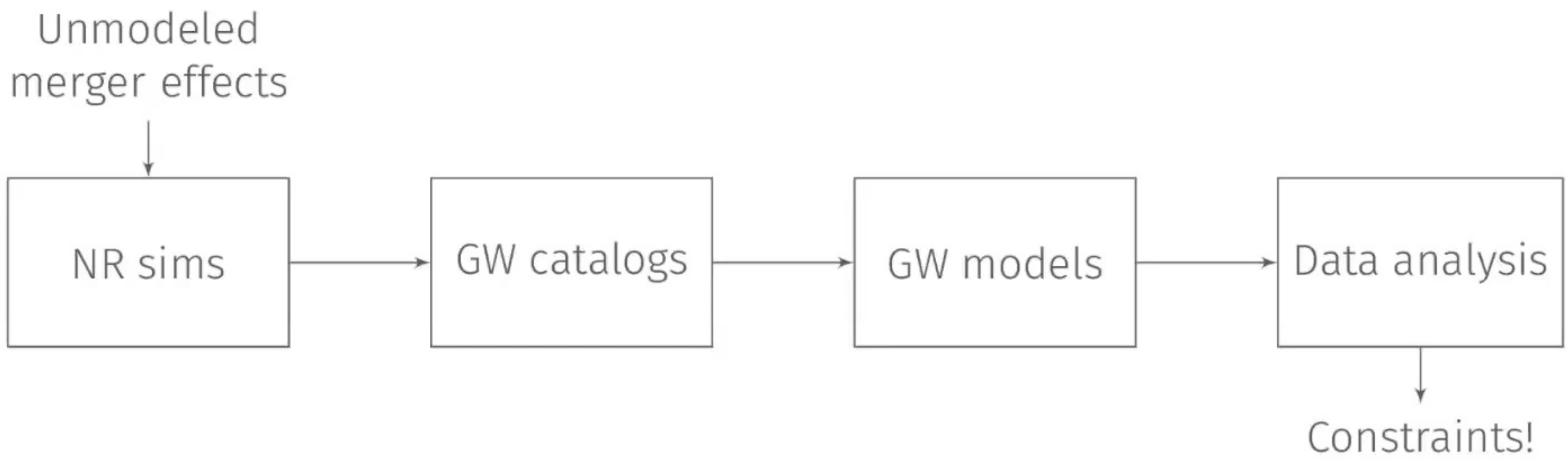
I am building...



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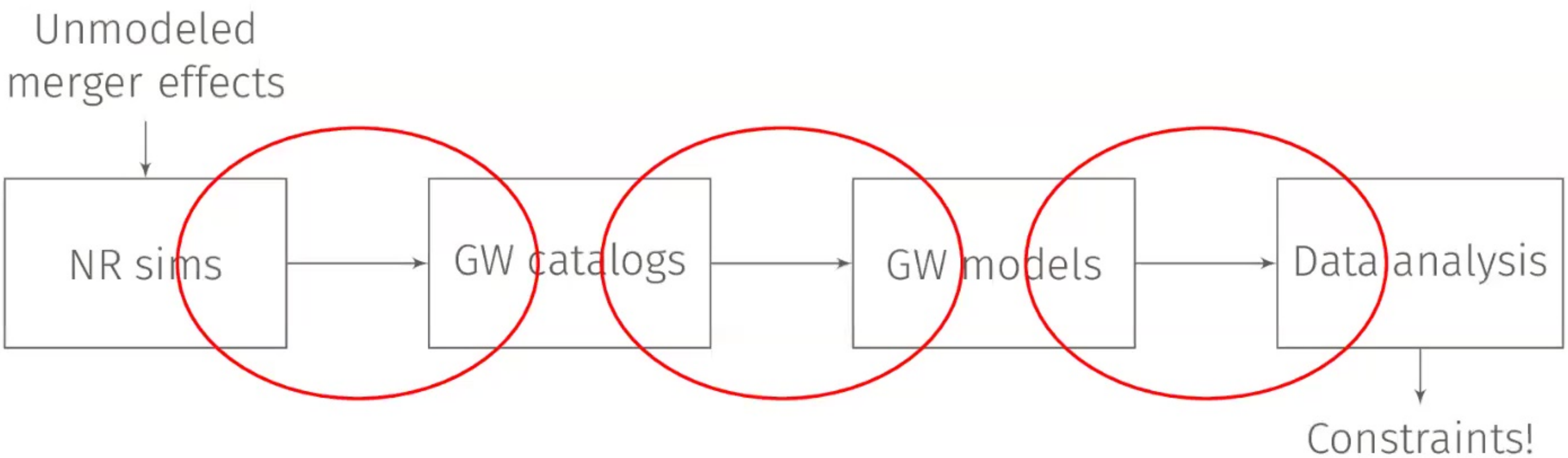
I am building...



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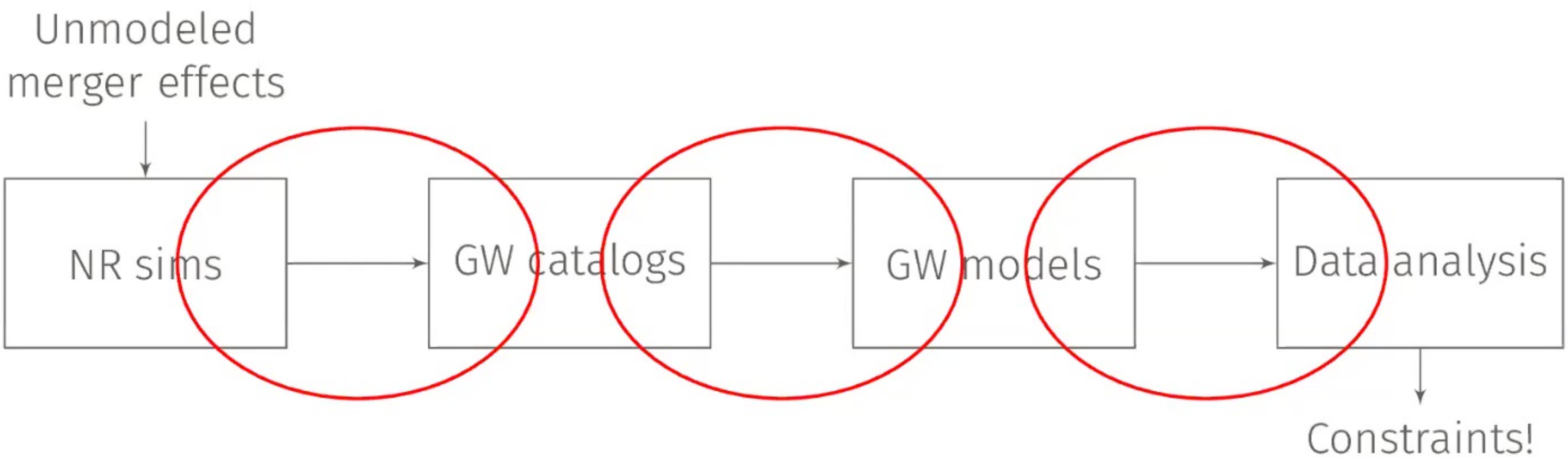
I am building...



and **theoretical/numerical experiments**...

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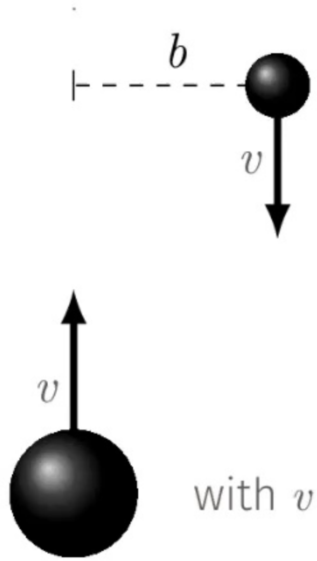
[redacted]rged BHs are optimal laboratories for testing conjectures



with $v \to c$

Energetic events, a few parameters

$\Downarrow$

Extreme conditions in a **controlled** environment

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[redacted]erical Relativity	Astrophysics	Modified Gravity

[redacted]erical Relativity

→ Initial data

→ Stable evolutions

→ New formalisms

Astrophysics

→ Full NR waveforms

→ Bounds on Q/M

→ Future bounds

Modified Gravity

→ Bound on STVG α

Current work

→ GW pipeline beyond vacuum GR

→ Cosmic censorship in quasi-circular mergers (+ C. Worley)

→ Quasi-normal-modes and 3G detectors (+ G. Carullo, M. de Amicis, V. Cardoso)

→ Hyperbolic encounters (+ M. Smith)

→ Effects of plasma (+ R. Luna, M. Zilhão, V. Cardoso)

Ask me about:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T^{\text{EM}}_{\mu\nu}$$

$$\nabla_\mu F^{\mu\nu} = 4\pi J^\nu$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

Einstein-Maxwell

NSF NASA THE UNIVERSITY OF ARIZONA TACC TEXAS ADVANCED COMPUTING CENTER

Bozzola&Paschalidis (2019, 2021, 2021b, in prep), Bozzola (2021, 2022), Luna&Bozzola+ (2022)