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.

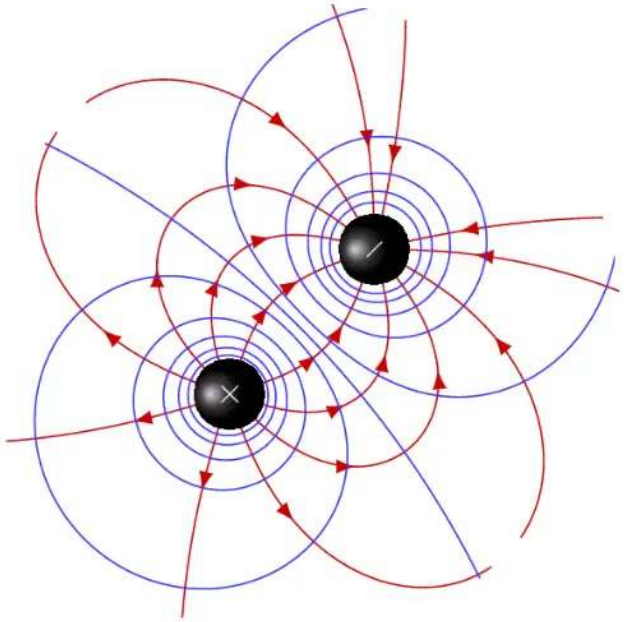
Zoom link: https://pitp.zoom.us/j/93809443805?pwd=bmcvd3NZWjUraERBcGdtL2Y3WTl6QT09

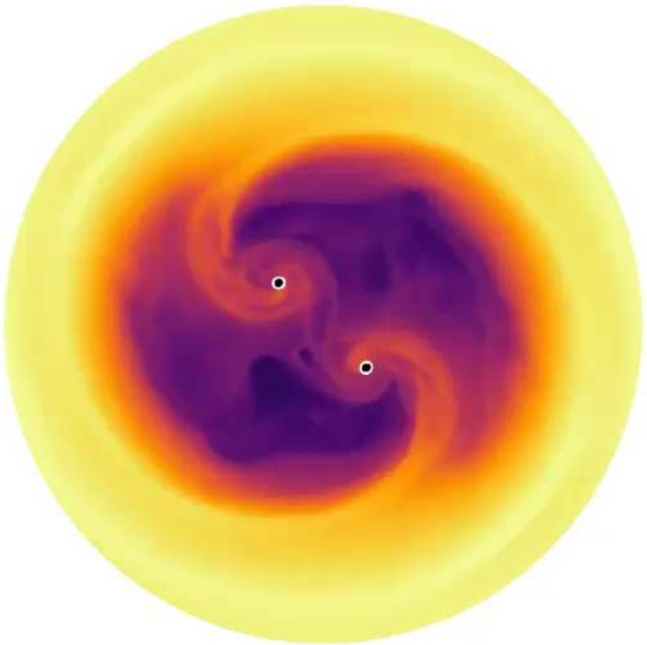
NUMERICAL RELATIVITY, GRAVITATIONAL WAVES, AND FUNDAMENTAL PHYSICS WITH CHARGED BLACK HOLES

December 8, 2022

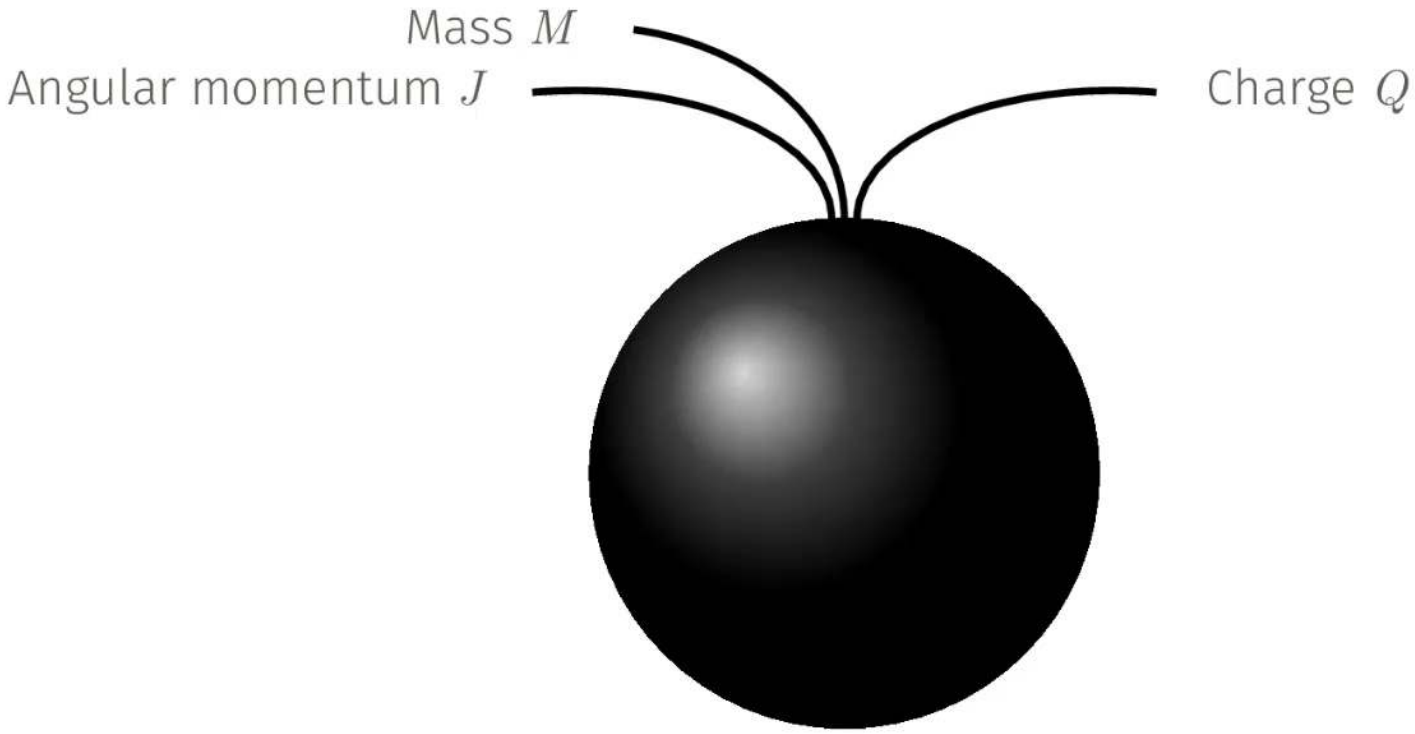
Gabriele Bozzola,
Vasileios Paschalidis

Department of Astronomy,
University of Arizona

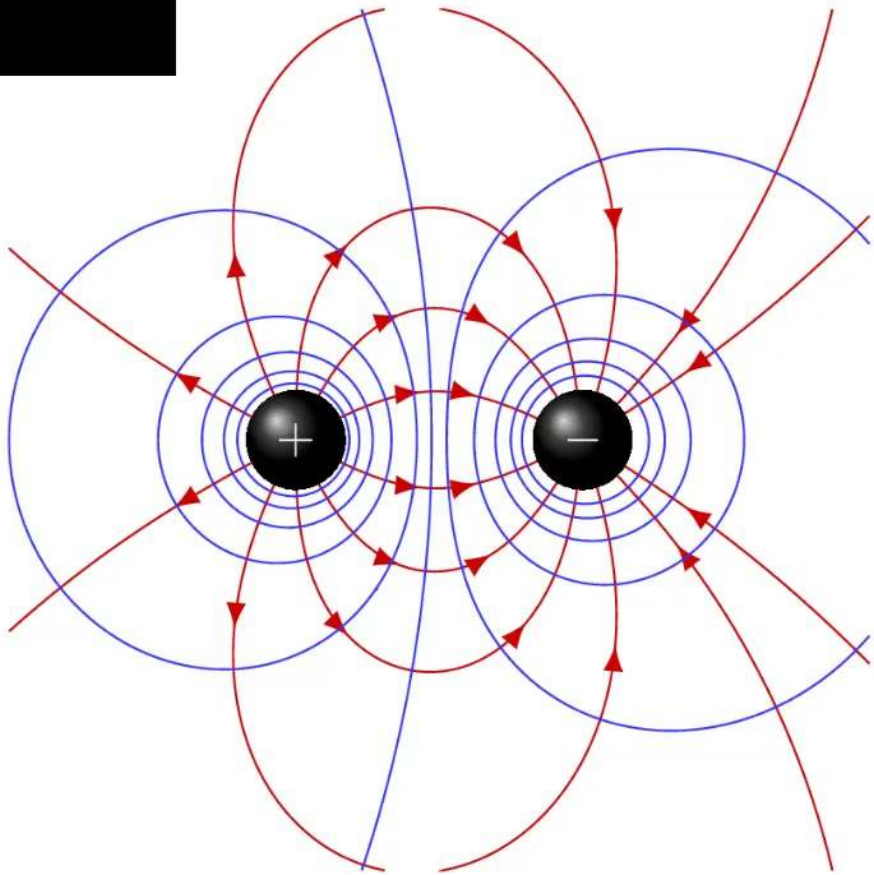




Black holes are simple objects: the *no hair* theorem

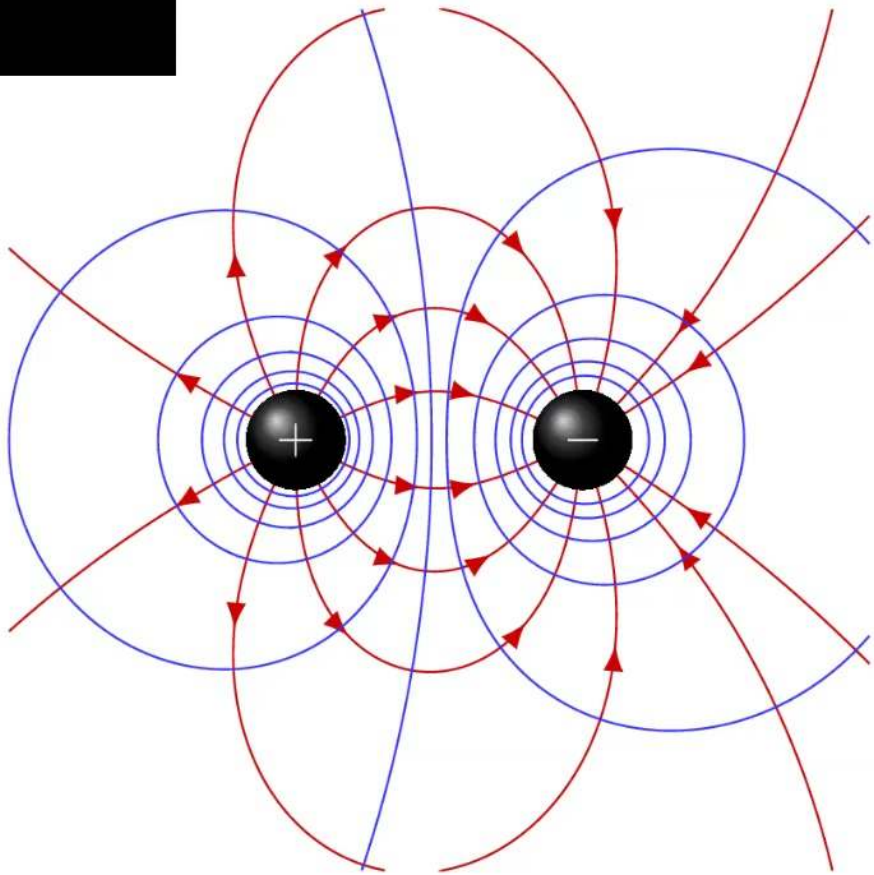


Israel (1967), Israel (1968), Carter (1971), ...



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

Orbits? Emission? ...?



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

Non-linear interaction is important for

Astrophysics ⟷ Constraints on charge
GW templates for LIGO-Virgo

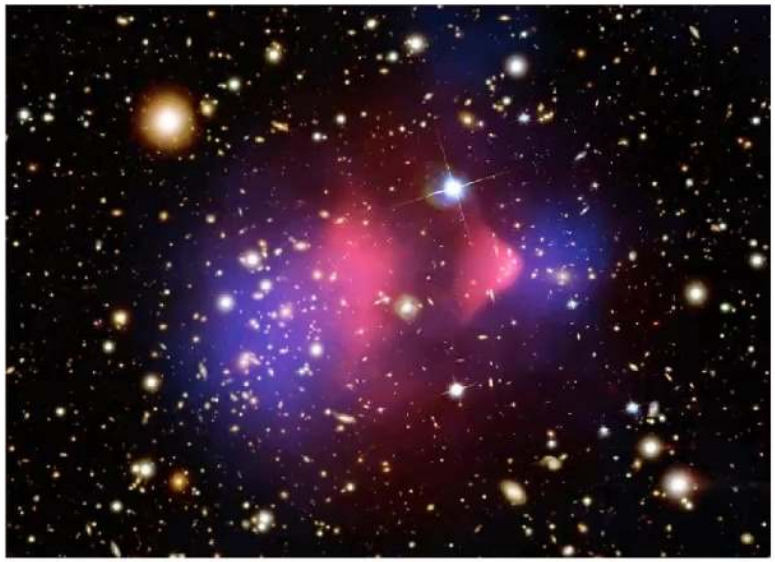
→ BH charge is largely unconstrained

→ GW models do include charge

Much more on this later!

Non-linear interaction is important for

Exotic Astrophysics ⟷ Constraints on charged dark matter and magnetic monopoles

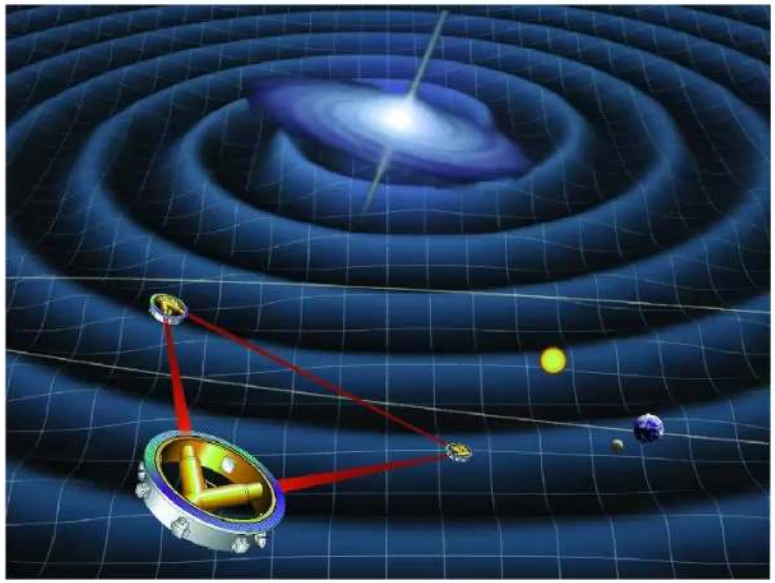


→ Primordial BH could have (electric or magnetic) charge

→ Dark matter could be (darkly) charged

Non-linear interaction is important for

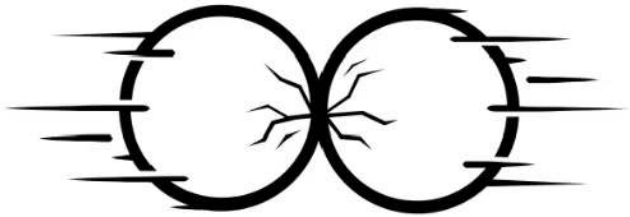
Modified Gravity ⟷ Springboard and proxy for other theories (e.g. Einstein-Maxwell-Scalar)



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

Non-linear interaction is important for

First Principles ⟷ Ultra-relativistic collisions
Scattering
Cosmic censorship

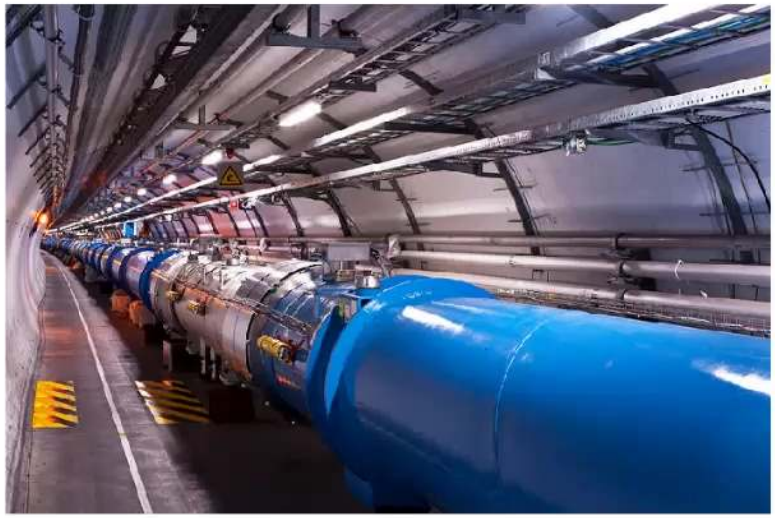


→ Exceptional laboratories for controlled numerical experiments

→ Interplay between extreme electromagnetic and gravitational fields

Non-linear interaction is important for

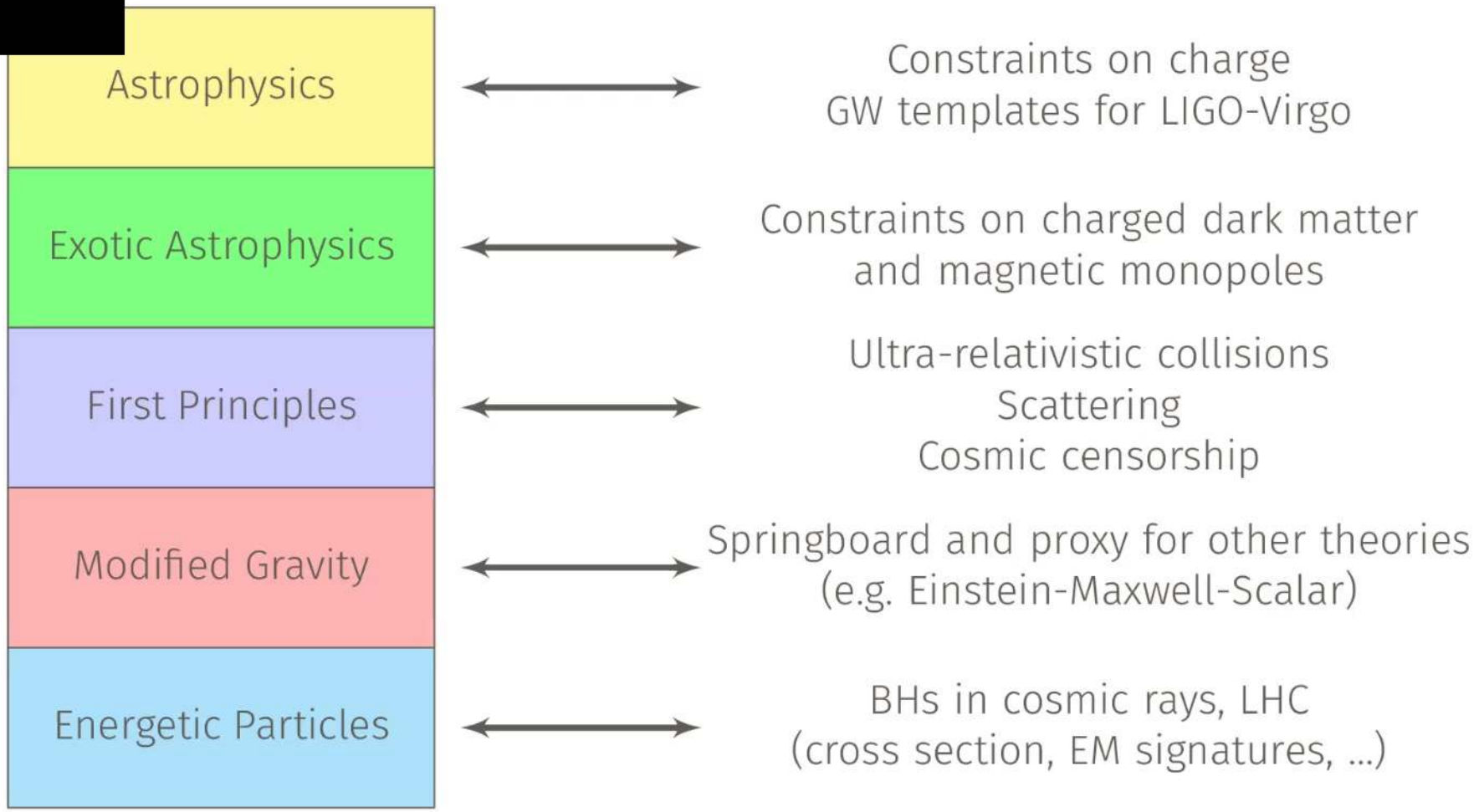
Energetic Particles ⟷ BHs in cosmic rays, LHC (cross section, EM signatures, ...)



→ Microscopic black hole production and detection

→ Tests of specific grand unified theories

Non-linear interaction is important for



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

Einstein-Maxwell

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = 8\pi\, T^{\mathsf{EM}}_{\mu\nu}$$
$$\nabla_\mu F^{\mu\nu} = 4\pi J^\nu$$
$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

for binary black holes

→ No symmetries

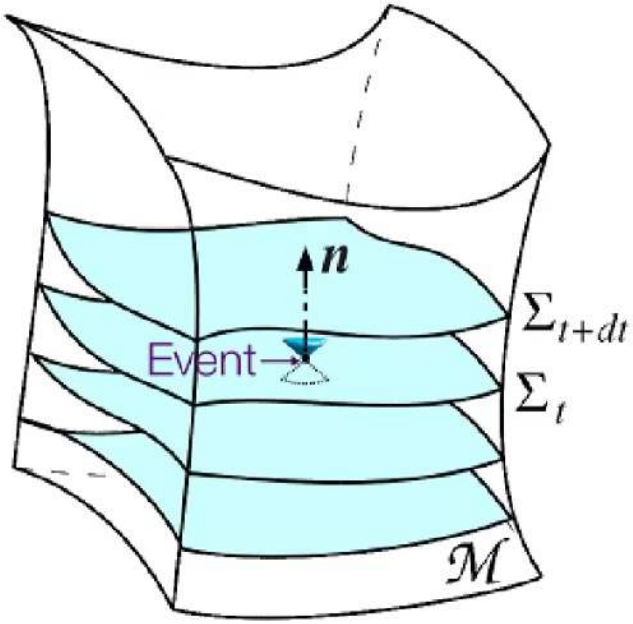
→ Non perturbative

→ Highly non-linear coupled PDEs

⇓

NUMERICAL RELATIVITY

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

Today's talk

Numerical Relativity

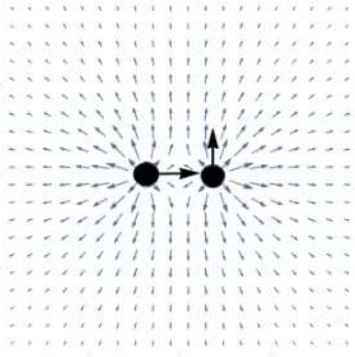
First numerical-relativity simulations of quasi-circular mergers

Astrophysics

First constraints on BH charge from gravitational waves

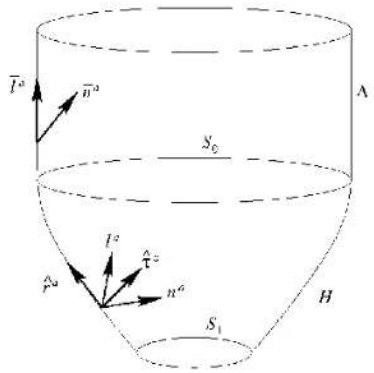
Ask questions or reach out for more!

Novel/improved methods



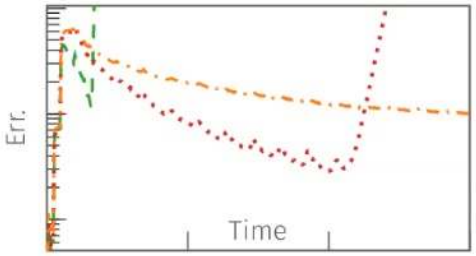
Initial data

`TwoChargedPunctures`



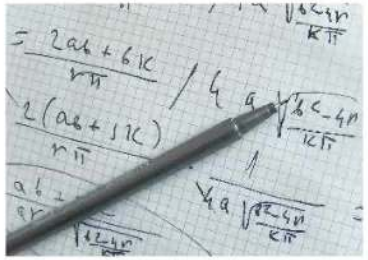
Interpretation

`QuasiLocalMeasuresEM`



Stability

Continuous Dissipation



Analysis

Newman-Penrose

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

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)

- → 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)

Charge of astrophysical black holes

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

q_p, m_p

F_g F_e

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

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

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

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

$\Downarrow$

Accretes opposite charges

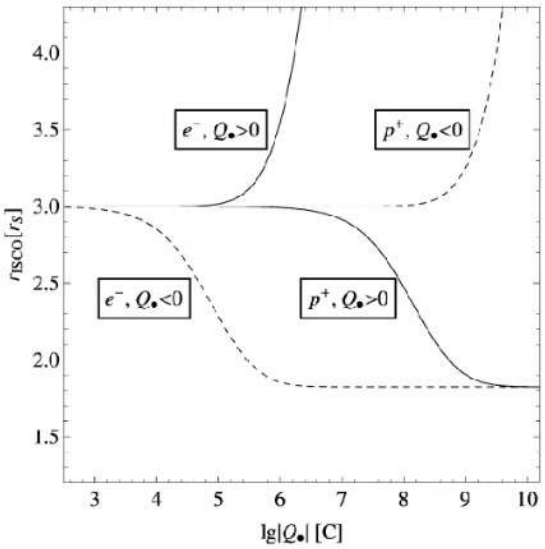
Does not accrete same charge

$\Downarrow$

Discharge

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

Measurements of BH charge are model-dependent



Charge

⇓

Disk structure

⇓

Emission properties

Extensive non-trivial modeling effort

Plot from Zajacek+ (2018)

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

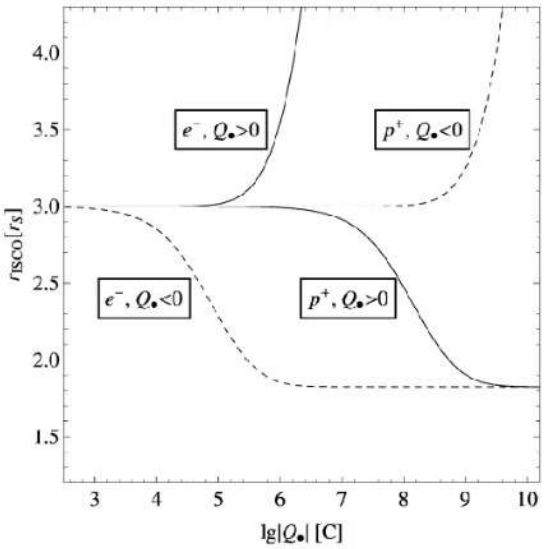
Evaded if:

- → 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), ...

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)

How can we test this?

Charge

⇓

Electromagnetic energy

⇓

Spacetime curvature

Orbital dynamics

⇓

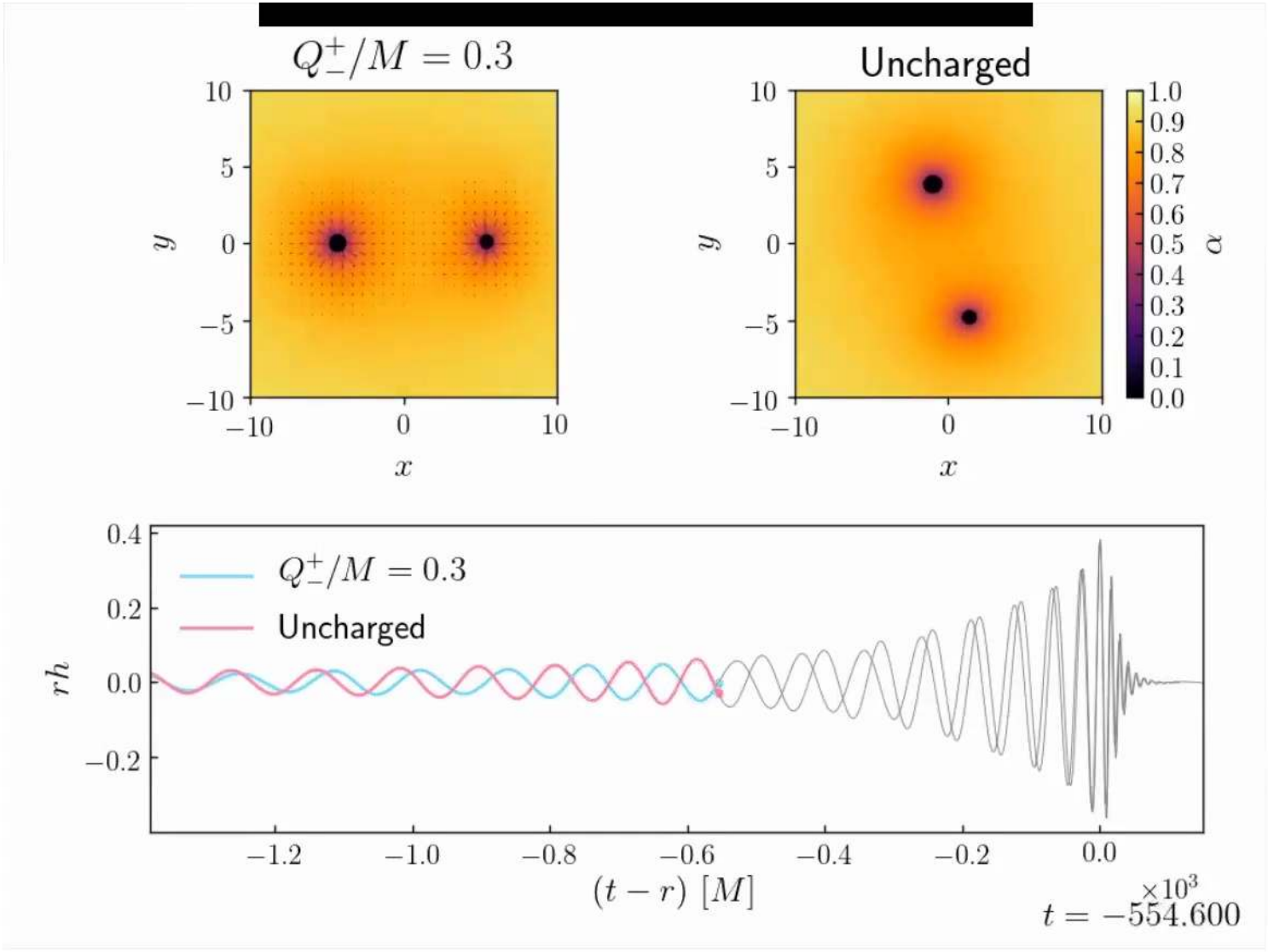
Gravitational waves

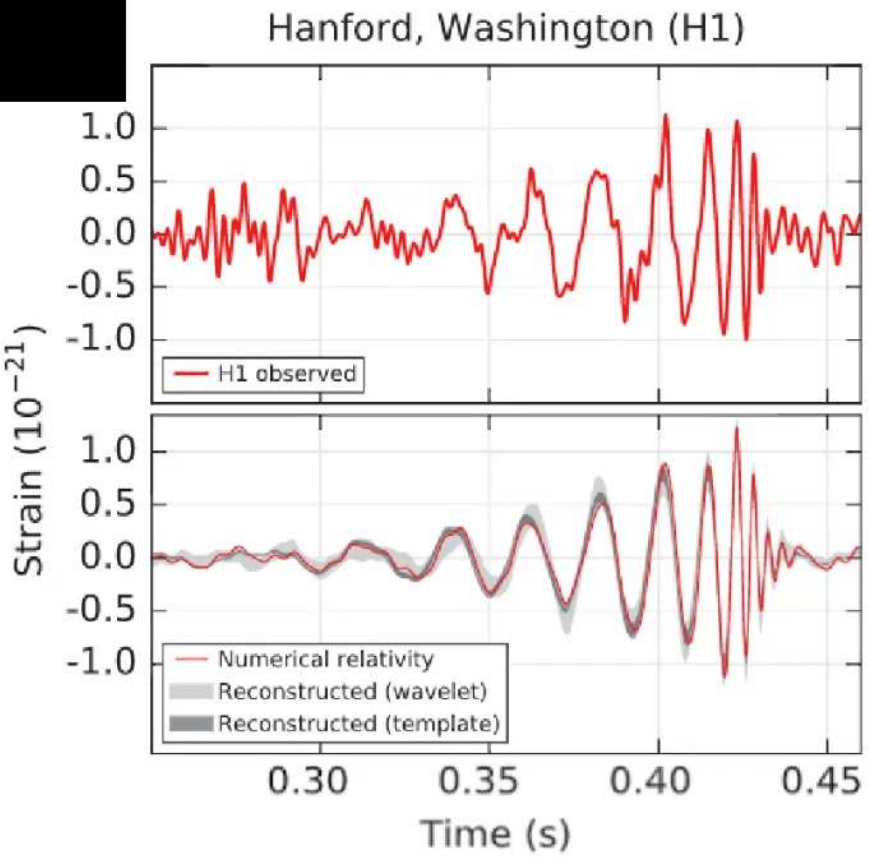
GWs know about charge

Strengths:

→ Little modeling required

→ Applicable to exotic astrophysics


$Q_-^+/M = 0.3$
Uncharged
y
x
α
rh
$Q_-^+/M = 0.3$
Uncharged
$(t-r)\ [M]$
$\times 10^3$
$t = -554.600$



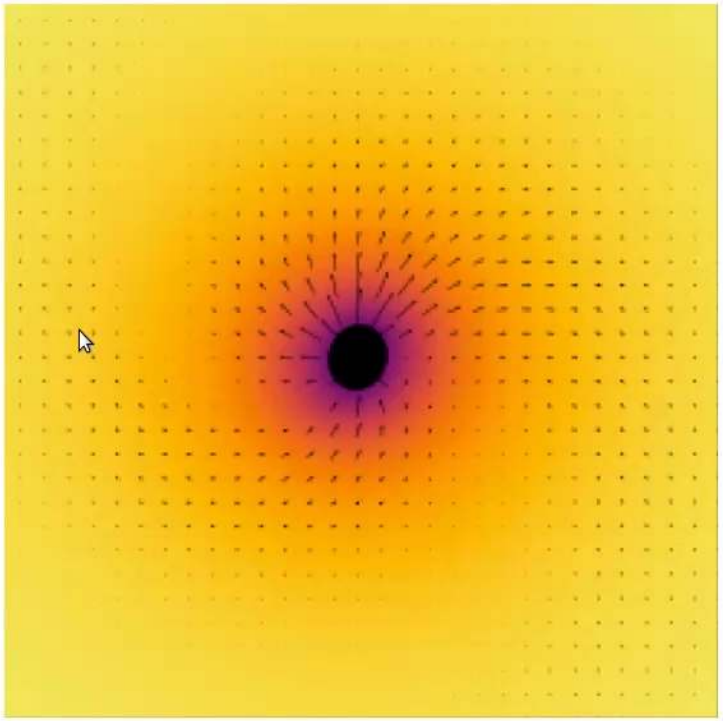
GW150914:

- → 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)

Electromagnetic emission is model dependent

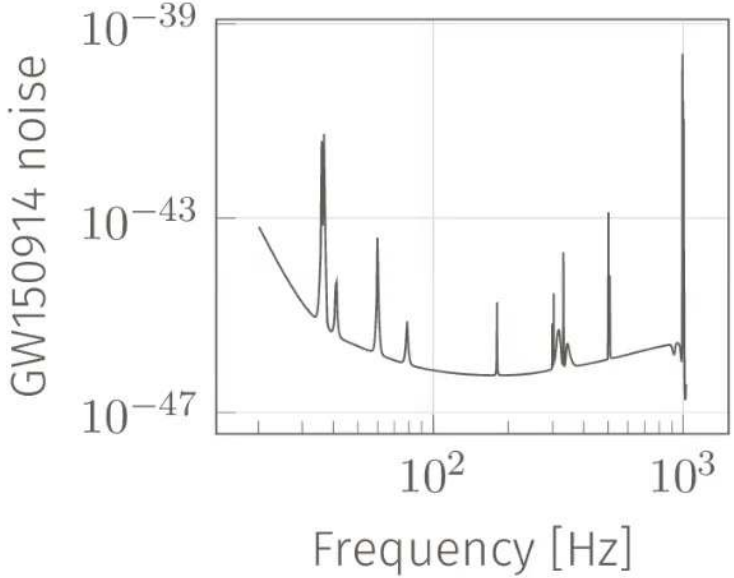


→ Propagation/interaction with plasma

→ Different for non-EM theories

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



First constraints on:

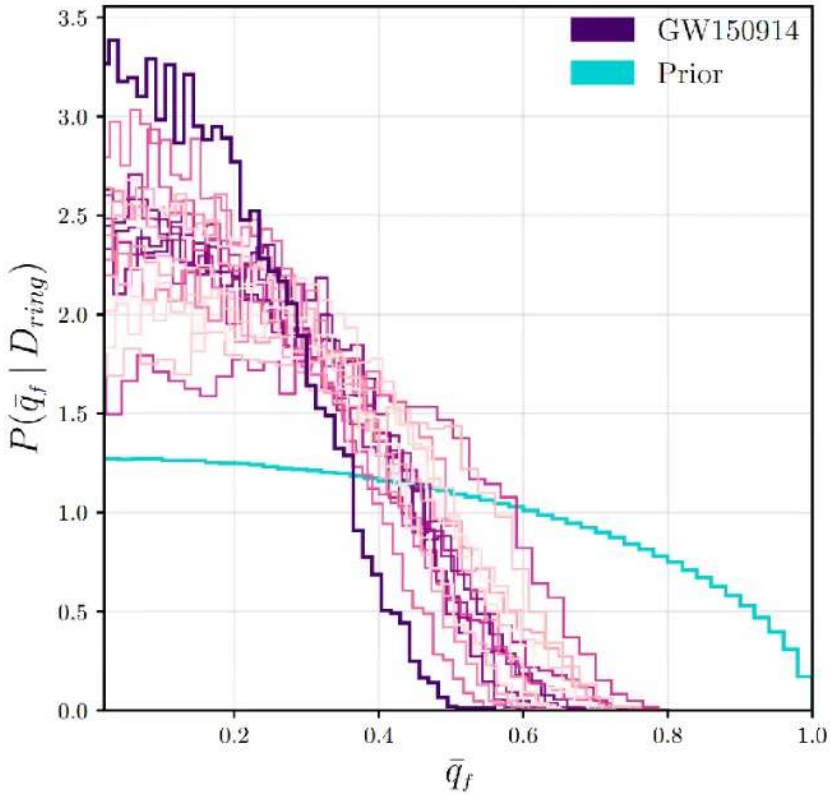
Black hole charge from GW150914:

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 $\alpha \lesssim 9$)

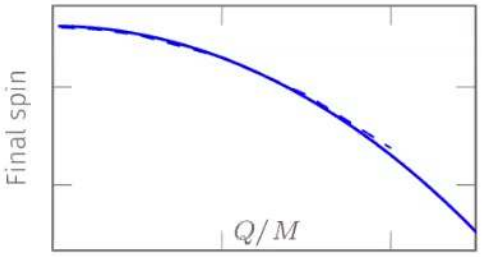
Later confirmed by Carullo+, 2022:



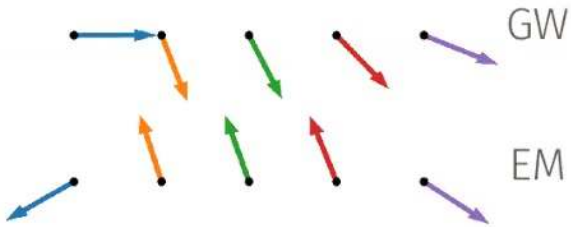
$\bar{q}_f$ =final charge-to-mass-ratio

Bozzola&Paschalidis (PRL 2021)

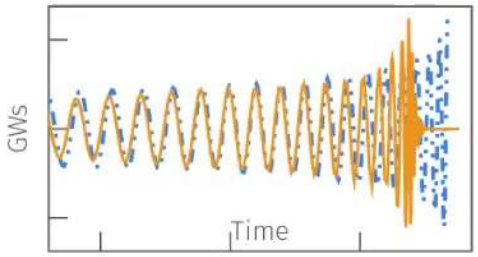
More advancements:



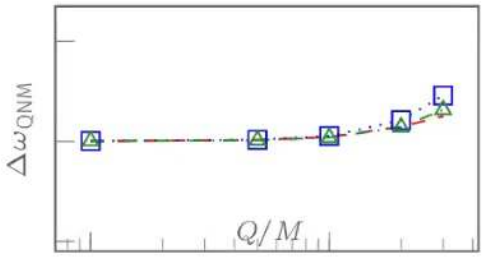
Remnant properties



Kicks



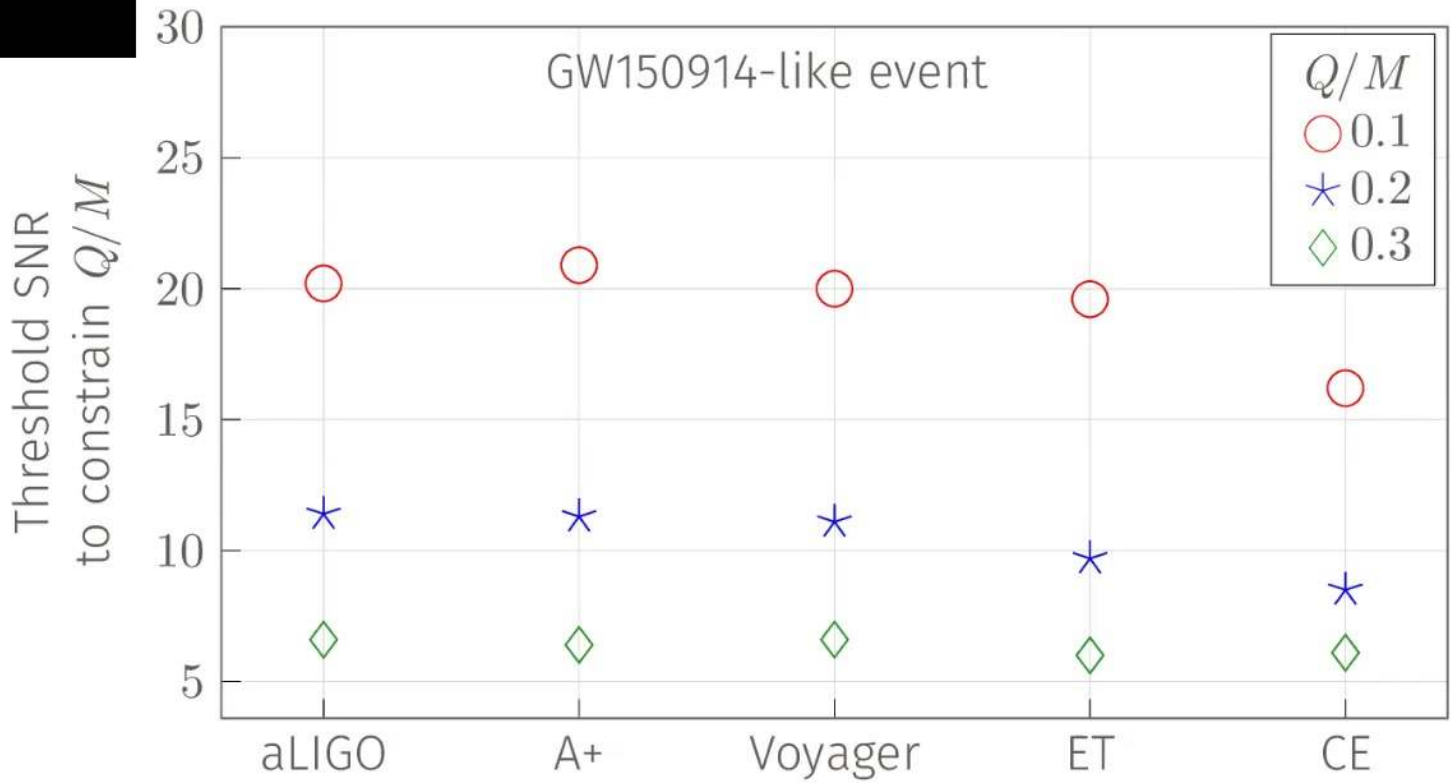
Validation



Quasi-normal modes

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

Expected constraints with future detectors



Bozzola&Paschalidis (2021b)

Expected constraints with future detectors

SNR for 3G $\gg$ 30

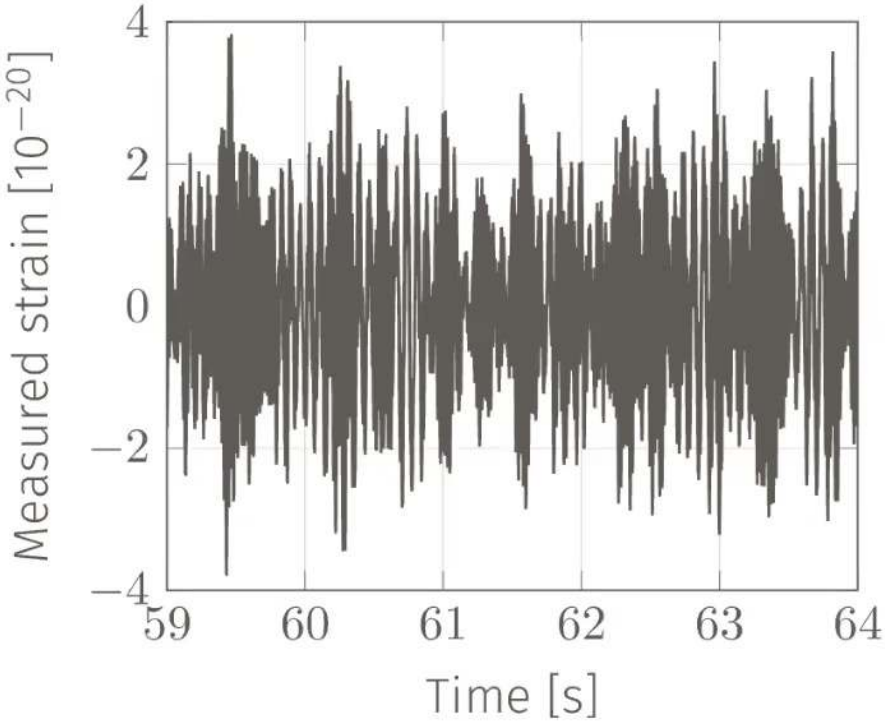
Rough scaling $(Q/M)^{-2}$

LISA will constrain everywhere

Bozzola&Paschalidis (2021b)

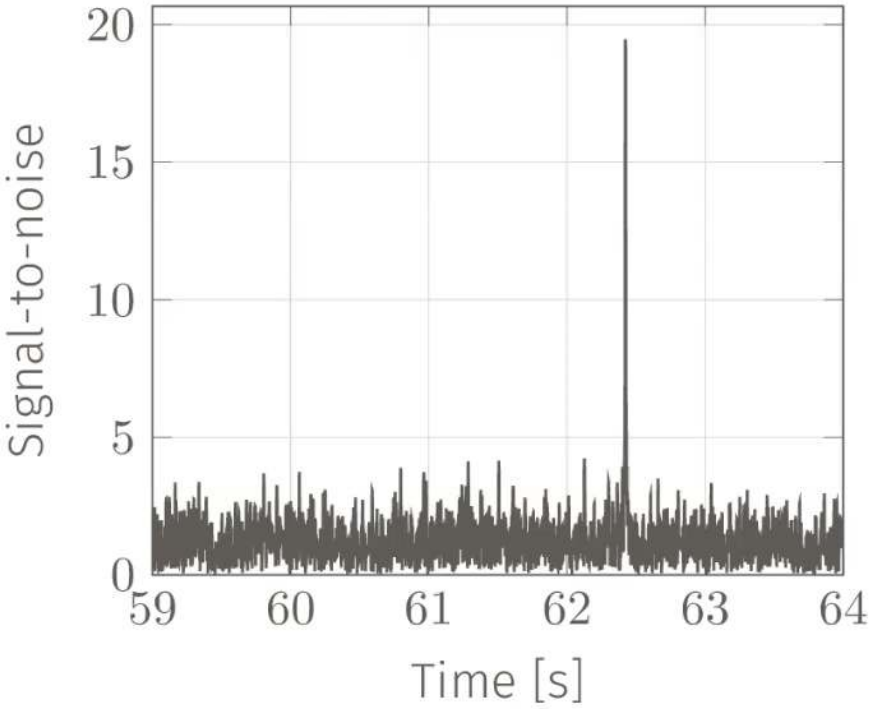
GW detectors look for needles in haystacks

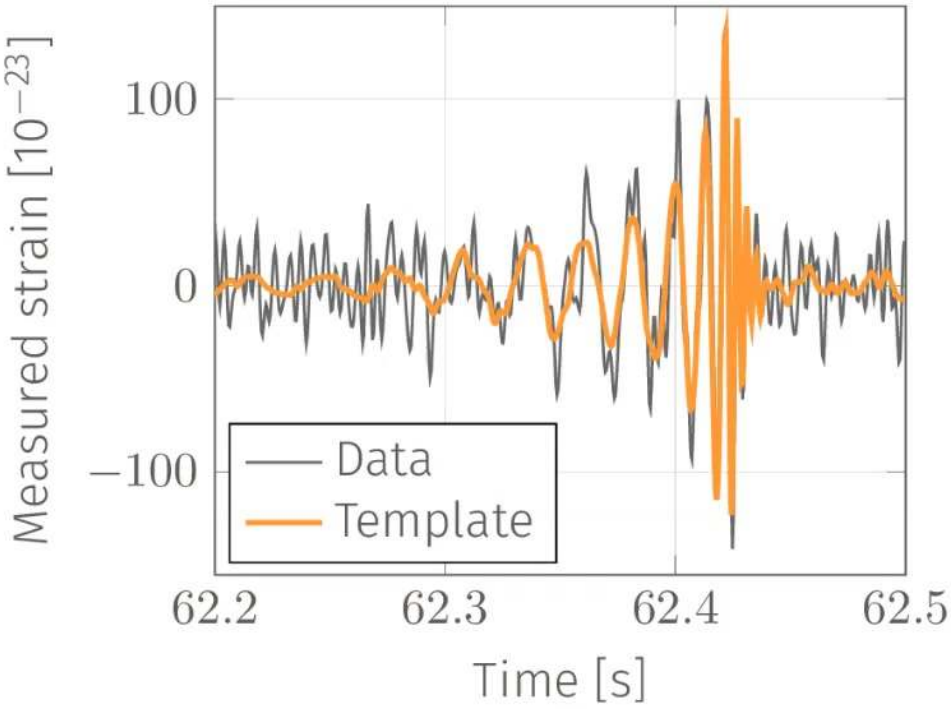
- → Noise ≫ signal
- → GW detection relies on matched filtering



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

Compare NR-calibrated models with data





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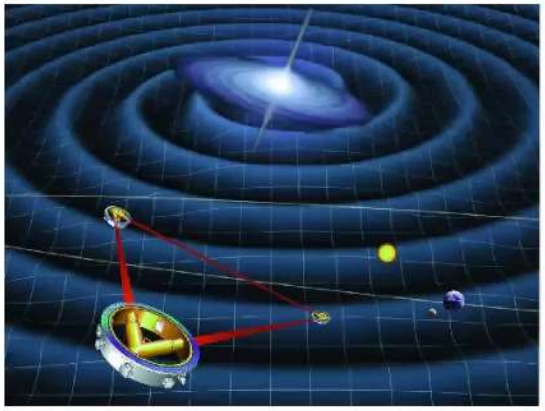
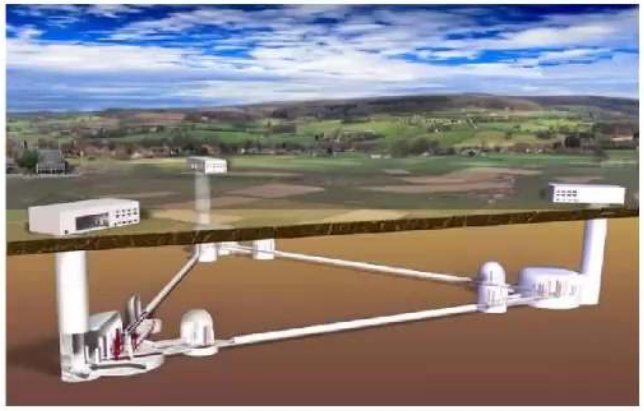
[redacted]re detectors require better and more varied simulations

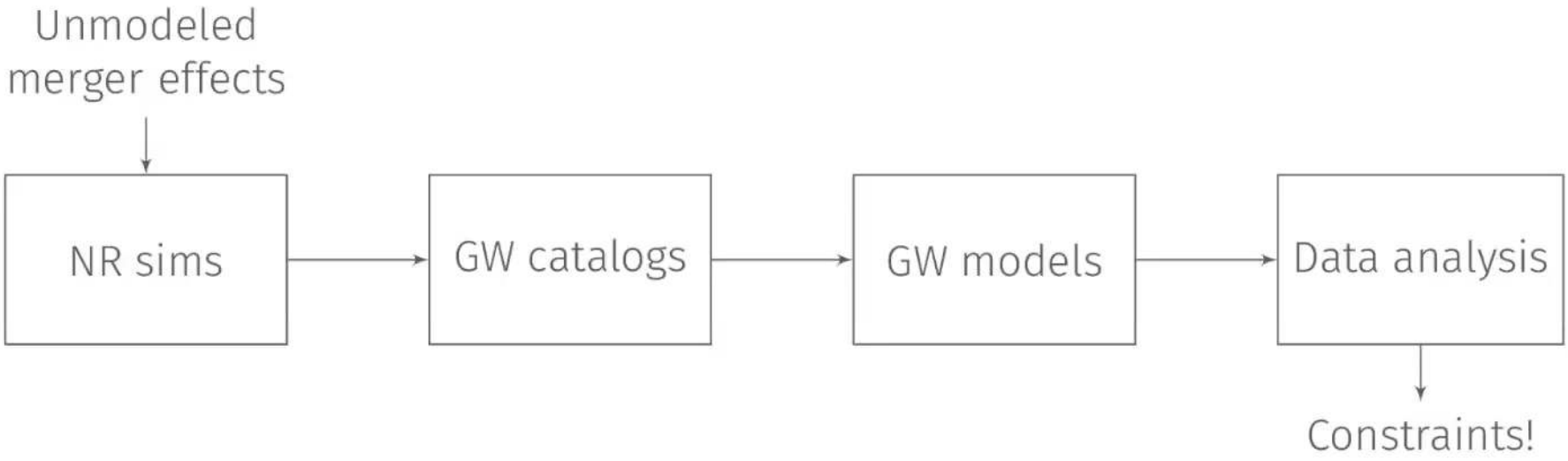



→ Vacuum GR waveforms are not accurate enough

→ 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

I am building...



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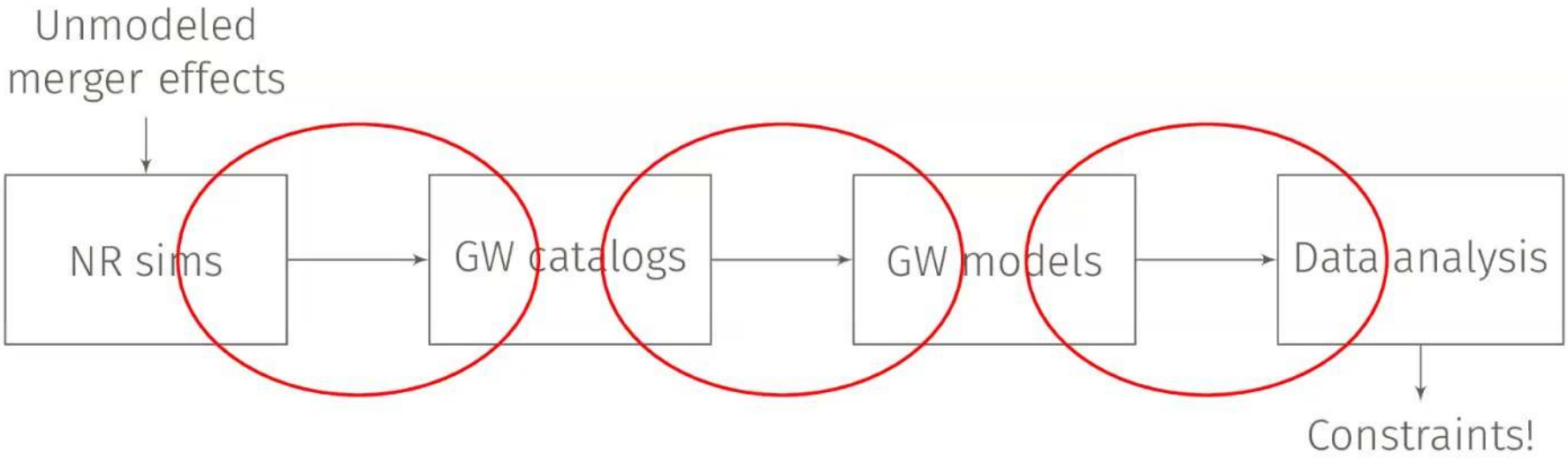
I am building...



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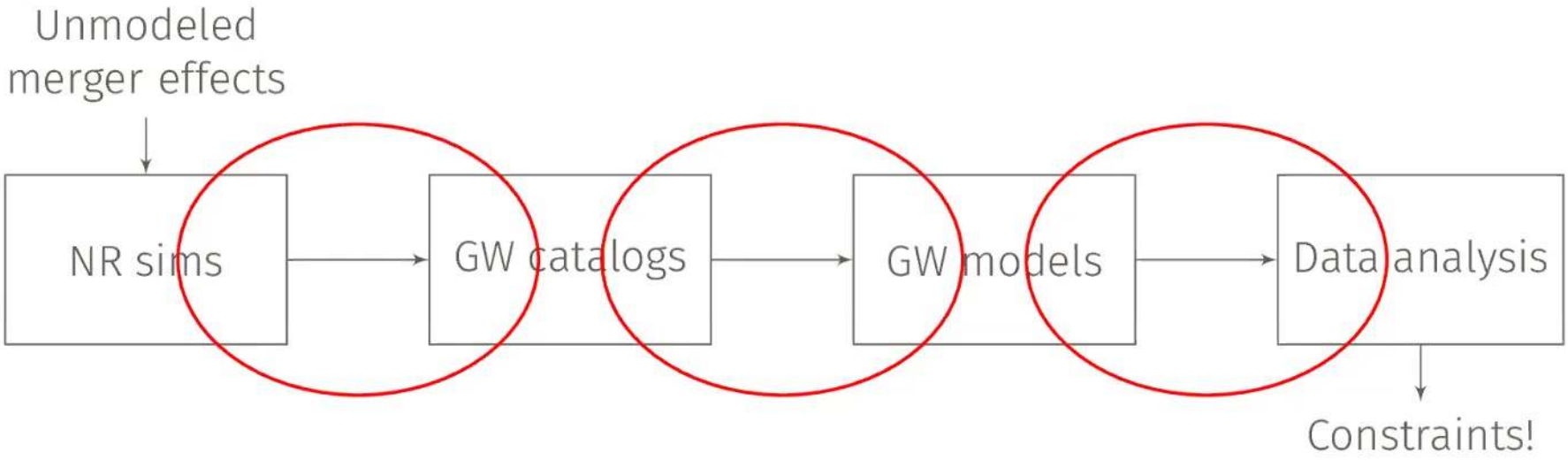
I am building...



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

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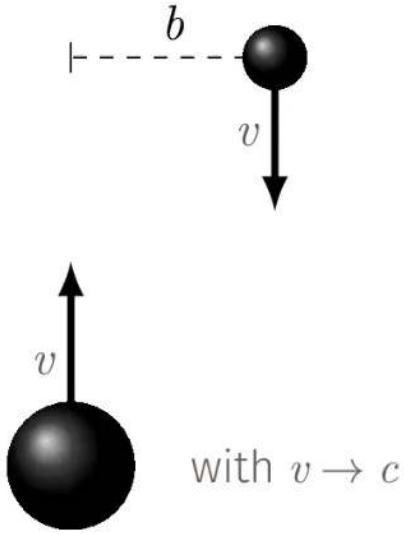
[redacted]rged BHs are optimal laboratories for testing conjectures



Energetic events, a few parameters

$\Downarrow$

Extreme conditions in a **controlled** environment

[redacted]erical Relativity | Astrophysics | Modified Gravity

- → Initial data
- → Stable evolutions
- → New formalisms

- → Full NR waveforms
- → Bounds on Q/M
- → Future bounds

- → 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:

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

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

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

Einstein-Maxwell

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