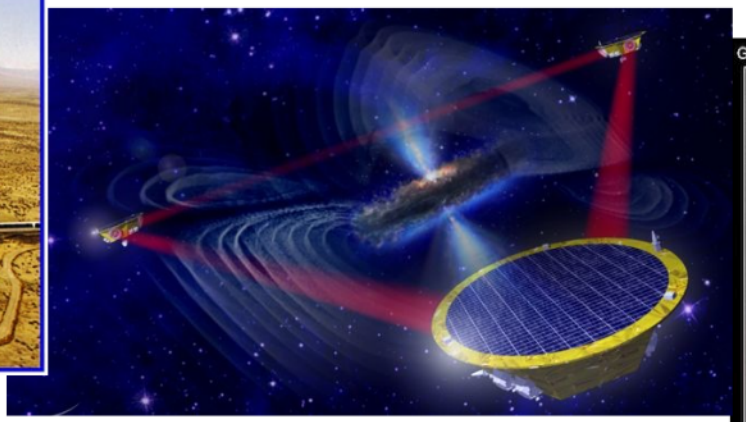
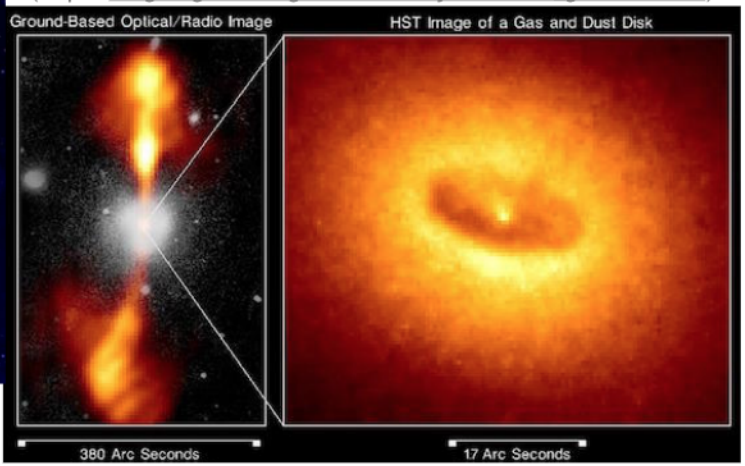
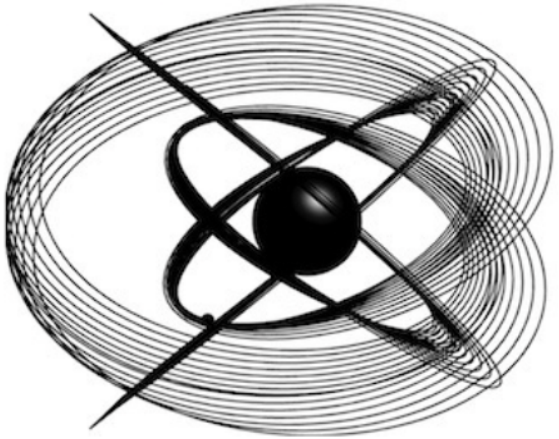
First Trieste Meeting on the Physics of Gravitational Waves: Environmental Effects on Binary Black Holes

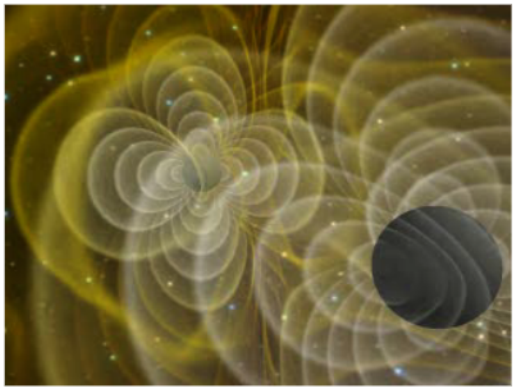


NGC4261

(http://imagine.gsfc.nasa.gov/science/objects/active_galaxies1.html)







Why are we here? (Answer 1)

Email from Barausse to Hughes, 6 August 2019:

> Discovery that there is a program supporting collaborations between MIT and the Friuli Venezia Giulia region

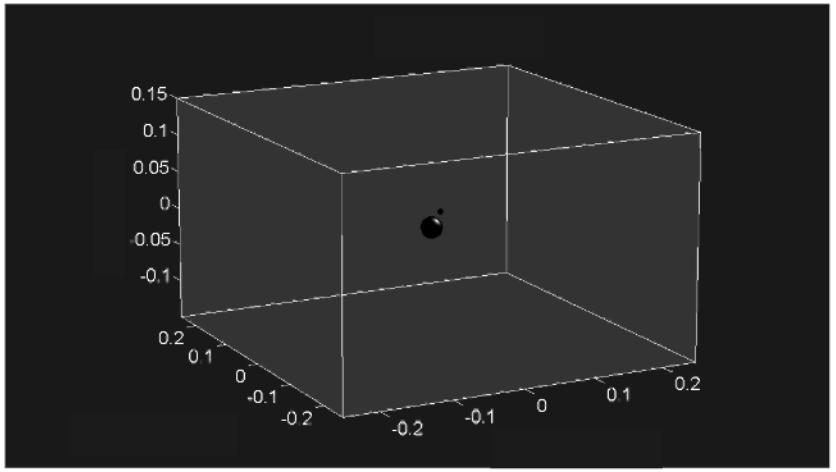
Leads to developing a proposal to explore various issues in the measurement of EMRI wave parameters … funds awarded in Spring 2020 supporting travel and a workshop.

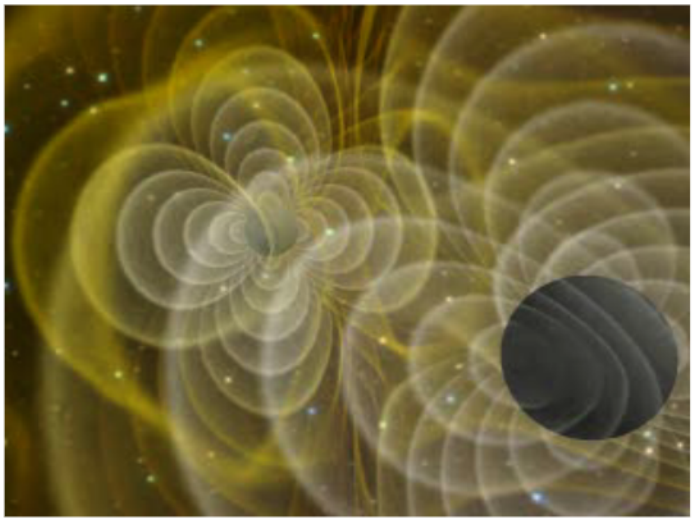
Early March 2020: Conferences start getting canceled due to some weird virus in circulation.

March 13 2020: MIT shuts all in-person operations and informs all staff that travel is verboten. Many colleagues' institutions introduce a similar edict.

Why are we here?

To date, the most commonly measured sources are binary black holes … a solution to $G_{\mu\nu} = 0$.





Models often constructed as a "Platonic ideal" binary system: the entire universe consisting of binary member 1 and binary member 2 … plus a distant observer who has no effect on the system.

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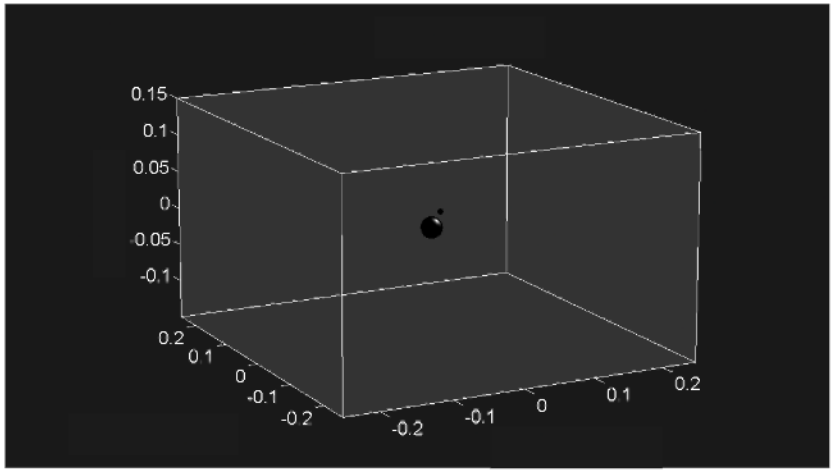
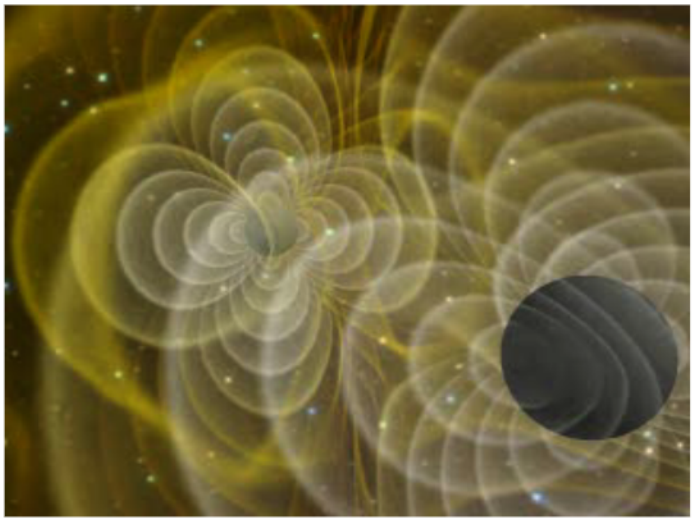




"There are more things in binary spacetimes than are dreamt of in your philosophy."

William Shakespeare, *Hamlet*, Act 1, scene 5 [general relativity edition]

Why are we here?

We **know** black holes exist in environments with lots of other matter … matter interacts with the black hole, backreacts on the environment.

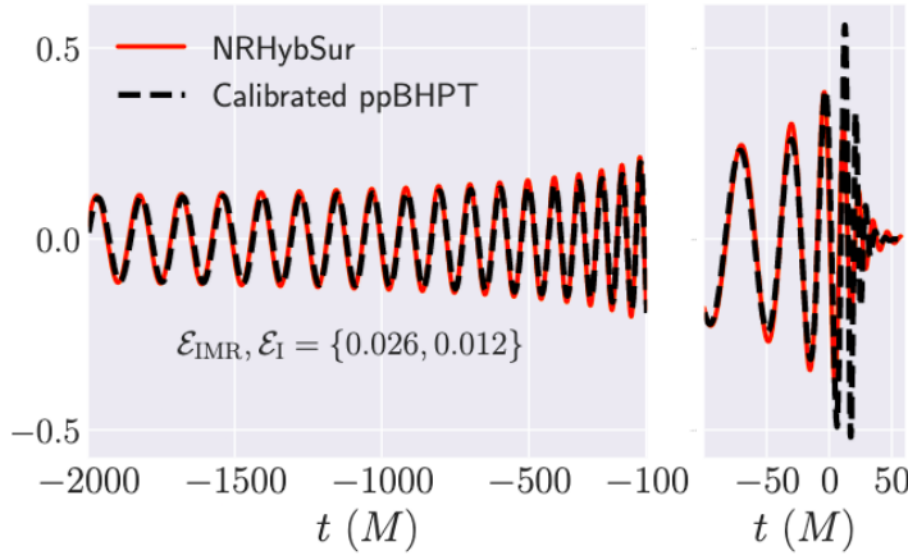
Binary black holes **must** exist in environments that affect them … we cannot find the gravitational waves that these systems generate unless we know how to model how the environment affects their dynamics and their gravitational waveforms.

Extreme mass ratio inspirals (EMRIs) major focus: Dynamics governed by Kerr perturbations; have framework for modeling waves, assessing accuracy.

Waveforms and accretion

Immediate focus: How accurate must waveforms be to meet data analysis needs of future detectors? (Task item for LISA waveform working group.)

Template fitting: cross correlate data with theoretical model, model that best matches data used to infer properties of source which generated wave.



Example is actually comparison of different surrogate waveform models, but nicely illustrates core idea of template match (Fig 11 of arXiv:2204.01972)

Crucial for EMRIs, for which instantaneous *h* expected to be roughly 100 x smaller than noise.

Waveforms and accretion

Immediate focus: How accurate must waveforms be to meet data analysis needs of future detectors? (Task item for LISA waveform working group.)

Detection vs measurement (following Finn 1992): Different accuracy needs depending on analysis goal.

Detection: "Just" need to know confidently whether a signal is present or not, do not need to determine its characteristics.

Useful rule of thumb: Need model that can hold phase with signal to within $\Delta\Phi < 1$ radian over signal's duration.

NB: Can break data into segments, coherently integrate each segment, then combine into a single statistic.

Waveforms and accretion

Immediate focus: How accurate must waveforms be to meet data analysis needs of future detectors? (Task item for LISA waveform working group.)

Detection vs measurement (following Finn 1992): Different accuracy needs depending on analysis goal.

Measurement: Need a model that accurately characterizes source parameters. Want to coherently match phase over duration of event.

Statistical errors due to noise must be smaller than systematic errors (mismodeling). Crude rule of thumb: Must hold phase to $\Delta\Phi < 1/\mathrm{SNR}$.

Waveform modeling: Birds' eye view

Much effort over past decade has gone into making waveform models … crucial physics essentially enforces $\nabla_a T^{ab} = 0$ for a body moving in a curved spacetime:

1. T_{ab} = monopole mass + BH spacetime. Enforce conservation: Geodesic equations emerge; see your favorite GR textbook.
2. T_{ab} = monopole mass + BH spacetime + correction due to that mass. Enforce conservation: Self force emerges. Excellent progress; see talk(s) that follow.
3. T_{ab} = monopole mass + dipolar current + BH spacetime (+ correction due to that mass & current). Enforce conservation: Mathison-Papapetrou-Dixon equations of motion (plus dipolar self force terms). Getting a lot more attention in recent years; mentioned in talk that follows.

Waveform modeling: Birds' eye view

Summary: **Tons** of modeling of gravitational physics, very detailed analysis of the relativistic two-body problem and its associated GW emission.

Much less analysis of how environment — especially accretion — affects binaries!

Kocsis, Yunes, Loeb PRD 2011

Perhaps the most detailed "recent" analysis of how accretion affects EMRI systems:

- Uses Shakura-Sunyaev α-disk models.
- Examines only circular and equatorial inspiral, using effective-one-body model.

Examined a range of possible effects … most significant is *migration* driven by perturbations in the disk due to the secondary's tidal field.

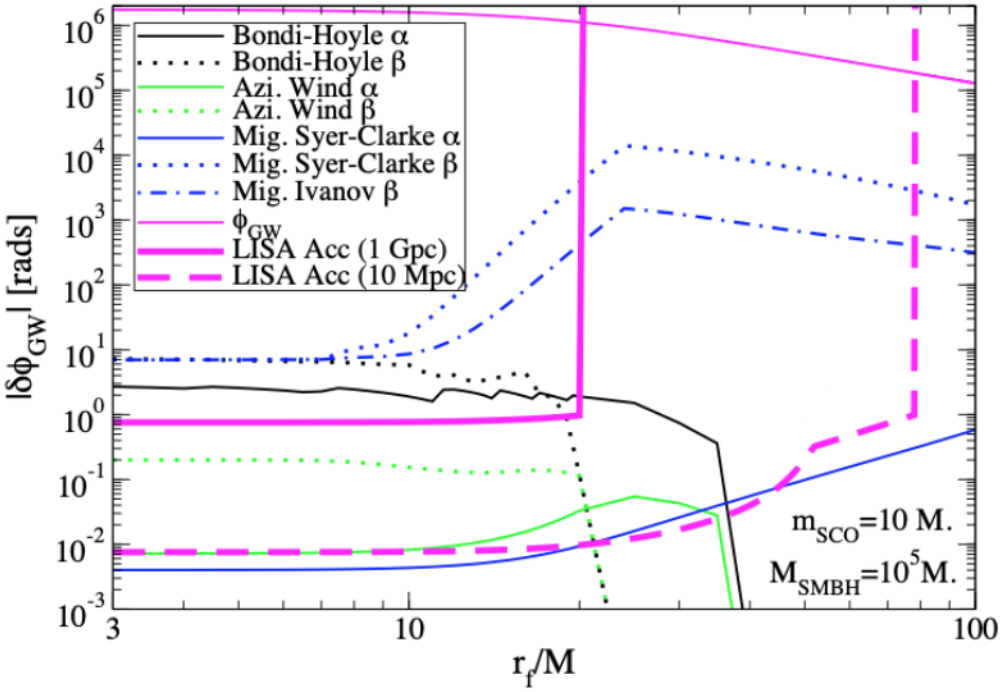


Figure 1 from Kocsis, Yunes, Loeb

Kocsis, Yunes, Loeb PRD 2011

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Demonstration that accretion's impact can be observationally significant … at least in principle.

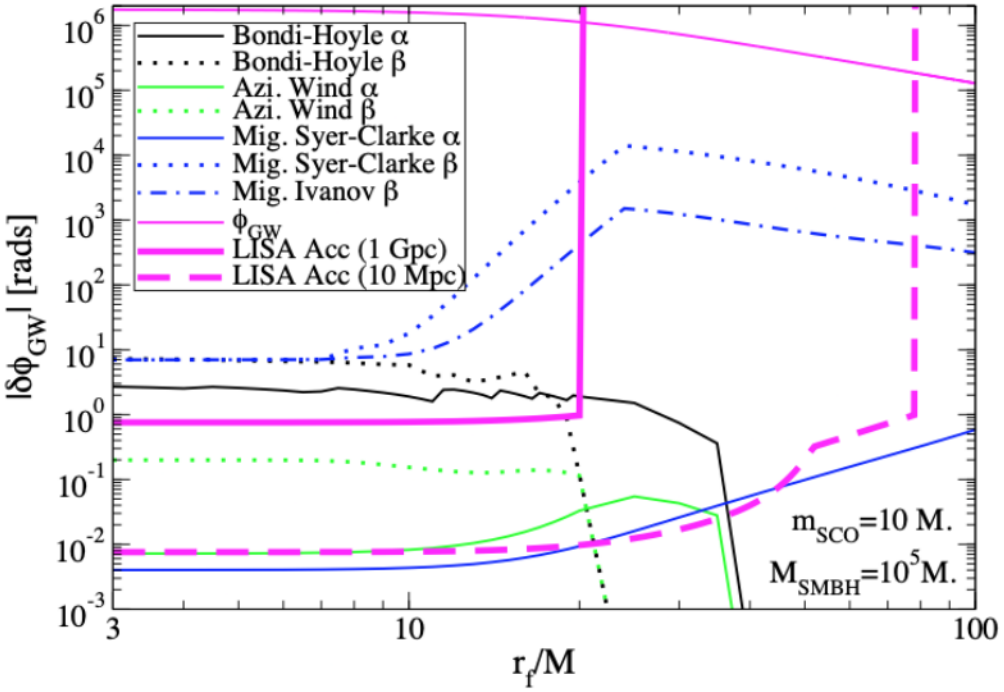

Figure 1 from Kocsis, Yunes, Loeb

What next? What do we need to do?

In my opinion, several key issues we need to address:

- ***Accretion model*:** Can we do better than the α-disk model, perhaps maintaining a reasonably easy-to-use prescription?
- ***Waveform models*:** Can we go beyond the limit of circular equatorial inspiral of most previous studies? In particular, can we make such a model including the effect of accretion?
- ***When do accretion effects "matter"? What does this really mean?*** Need to go beyond phase counting … can imagine a hierarchy of importance:
  - Negligible accretion: Vacuum models work fine.
  - Non-negligible accretion: Vacuum models find signals, but systematically finds wrong parameters
  - Strong accretion: Vacuum models miss signals entirely.
- ***Learning about accretion*:** Can we learn about accretion flow from the waveform?