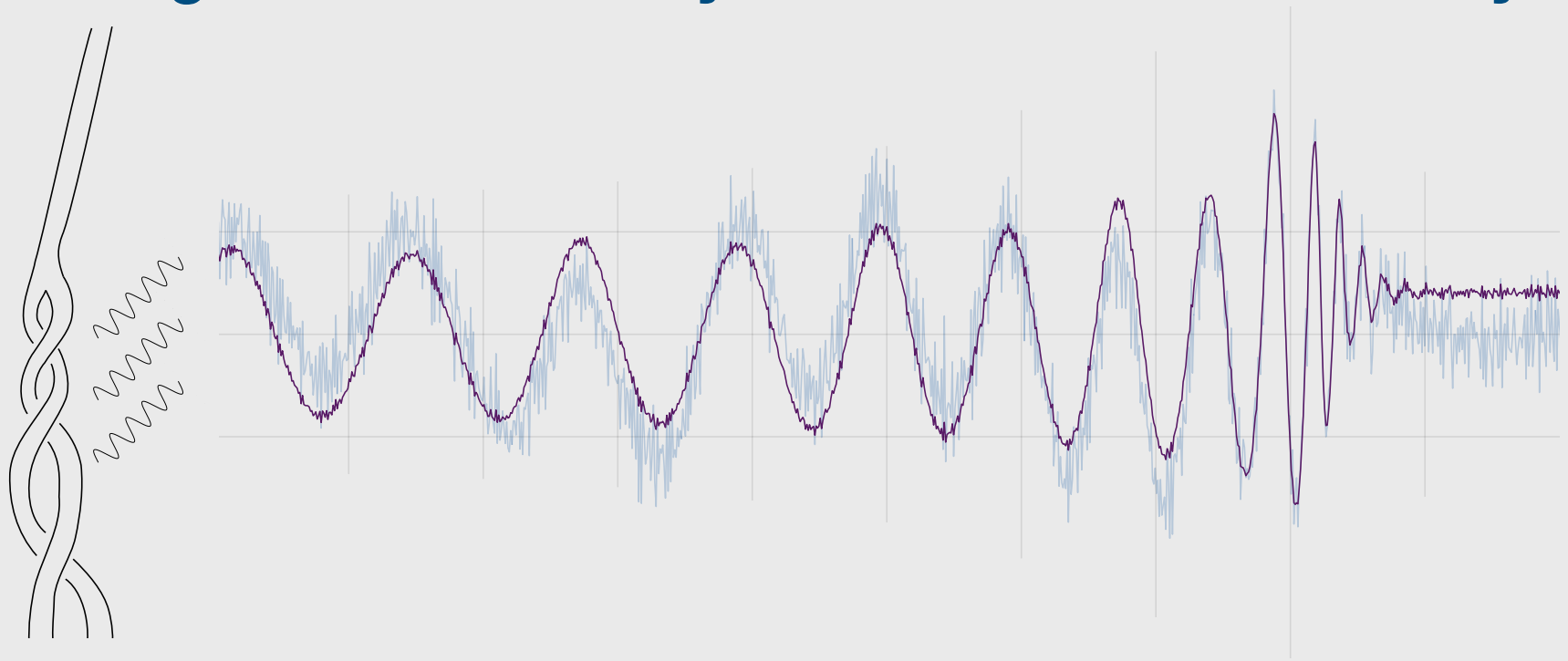
The Universe Never Forgets:

pushing Einstein's theory to the limits with memory effects



Keefe Mitman,
NHFP Symposium,
September 17th, 2024

Caltech → Cornell University

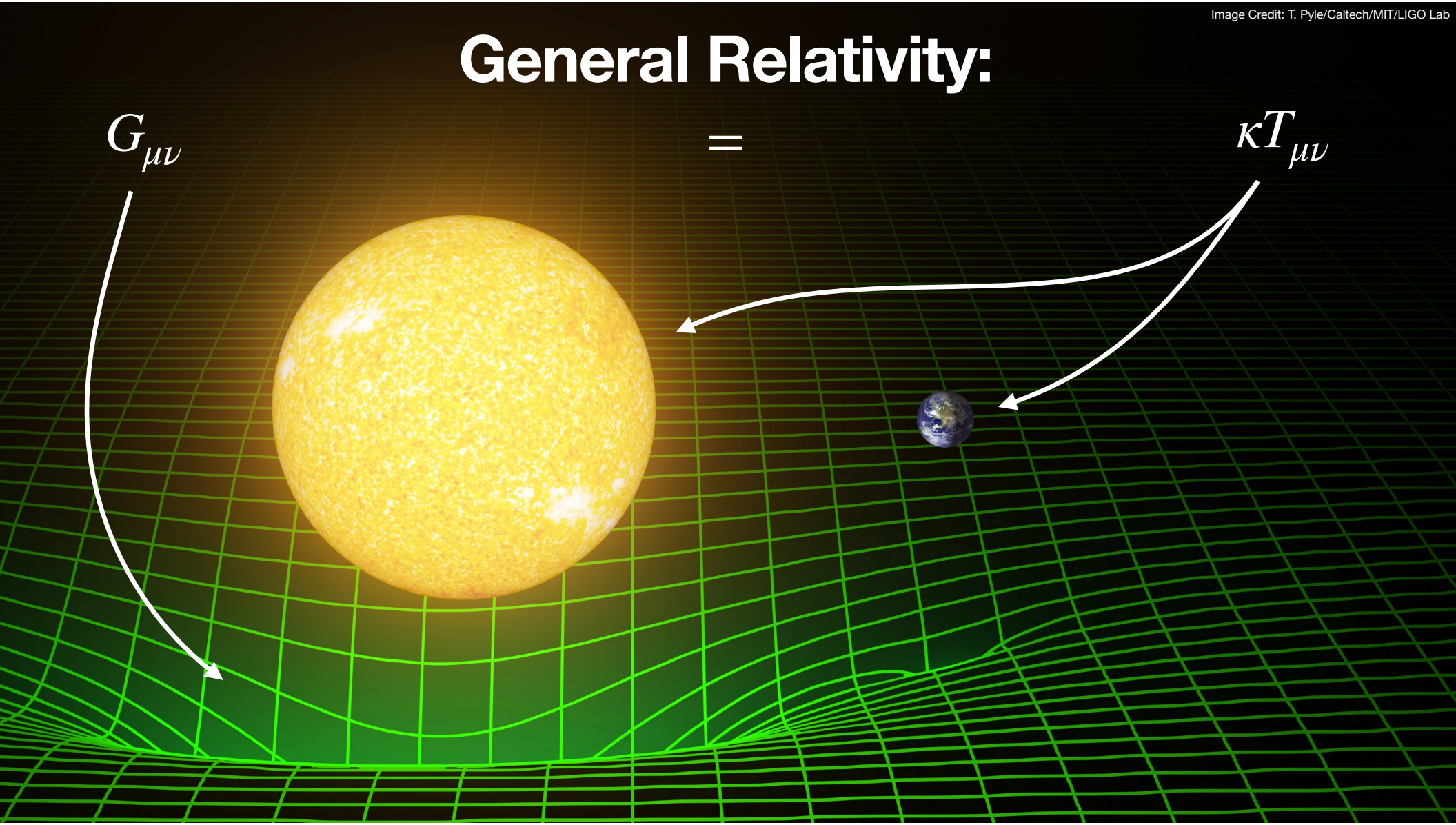
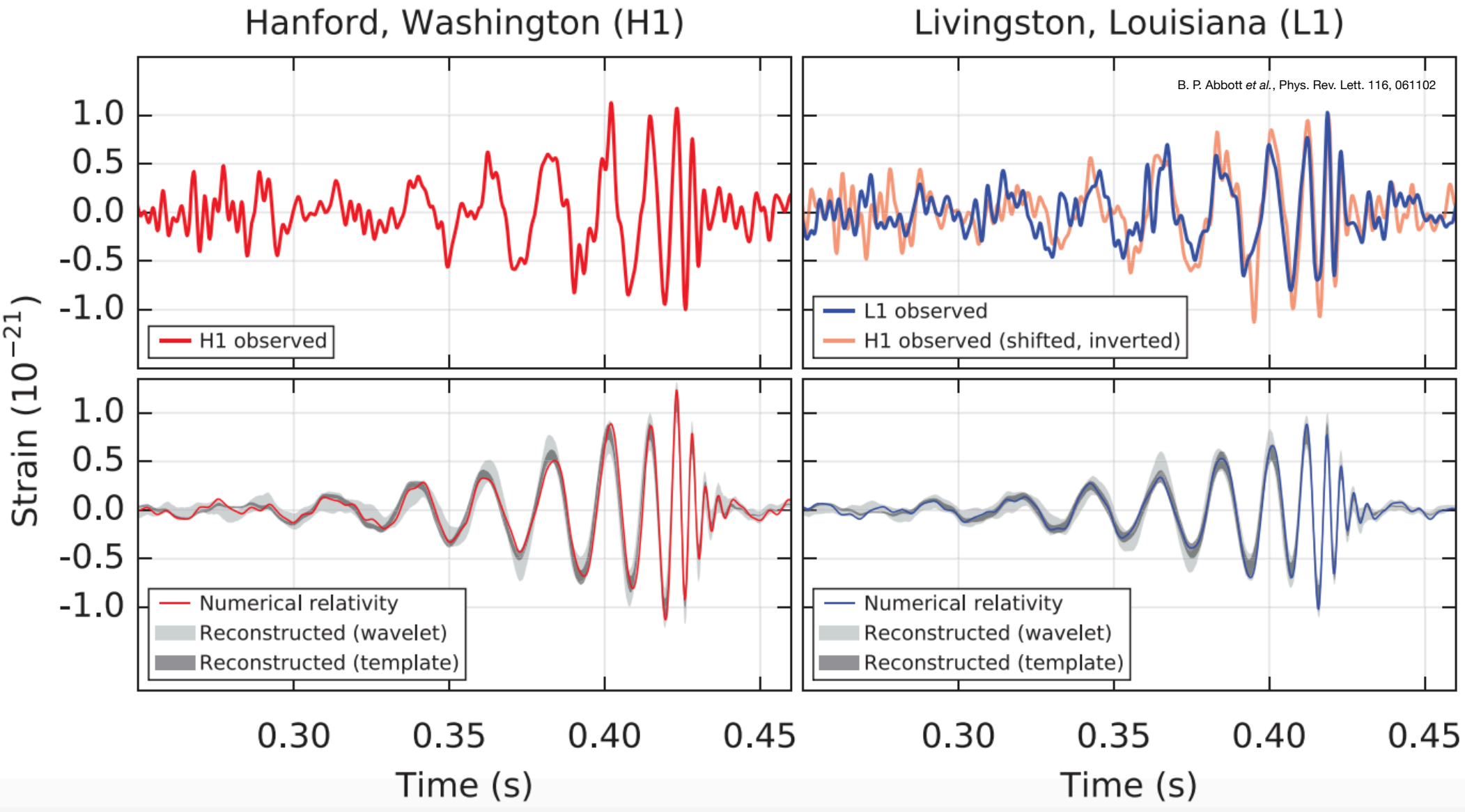


Image Credit: T. Pyle/Caltech/MIT/LIGO Lab
General Relativity:
$G_{\mu\nu}$
=
$\kappa T_{\mu\nu}$


Hanford, Washington (H1)
Livingston, Louisiana (L1)
B. P. Abbott et al., Phys. Rev. Lett. 116, 061102
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
0.30
0.35
0.40
0.45
Time (s)

Numerical Relativity

Evolving Binary Black Holes

- Write Einstein's equations in 3 + 1 form
- Obtain constraint and evolution equations
  - constraint ⇒ initial data
  - evolution ⇒ evolve initial data
- Yields the spacetime "metric" at some finite radius—the "world tube"

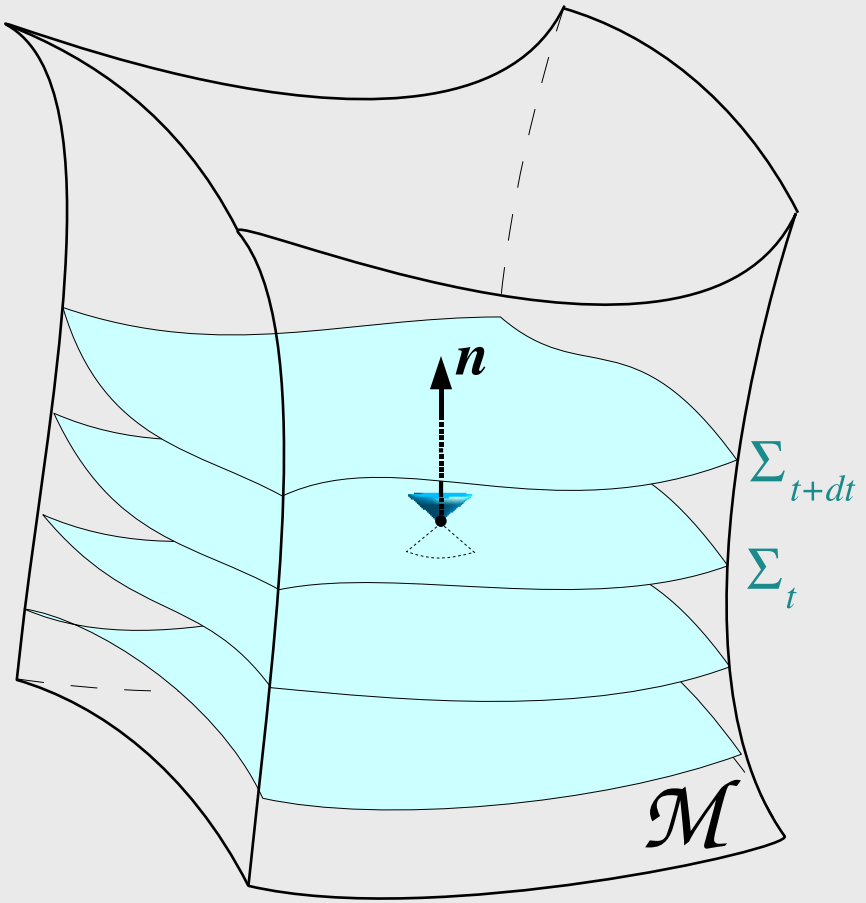
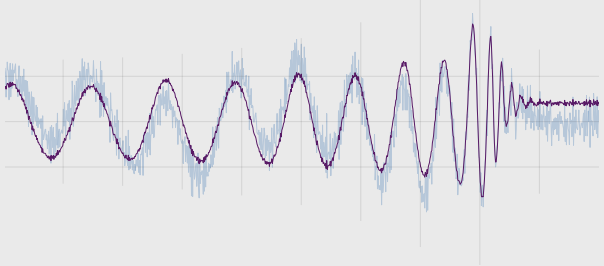


Image Credit: E. Gourgoulhon, (2007)

What about waveforms?



?

Waveforms in Numerical Relativity

Extracting Gravitational Waves

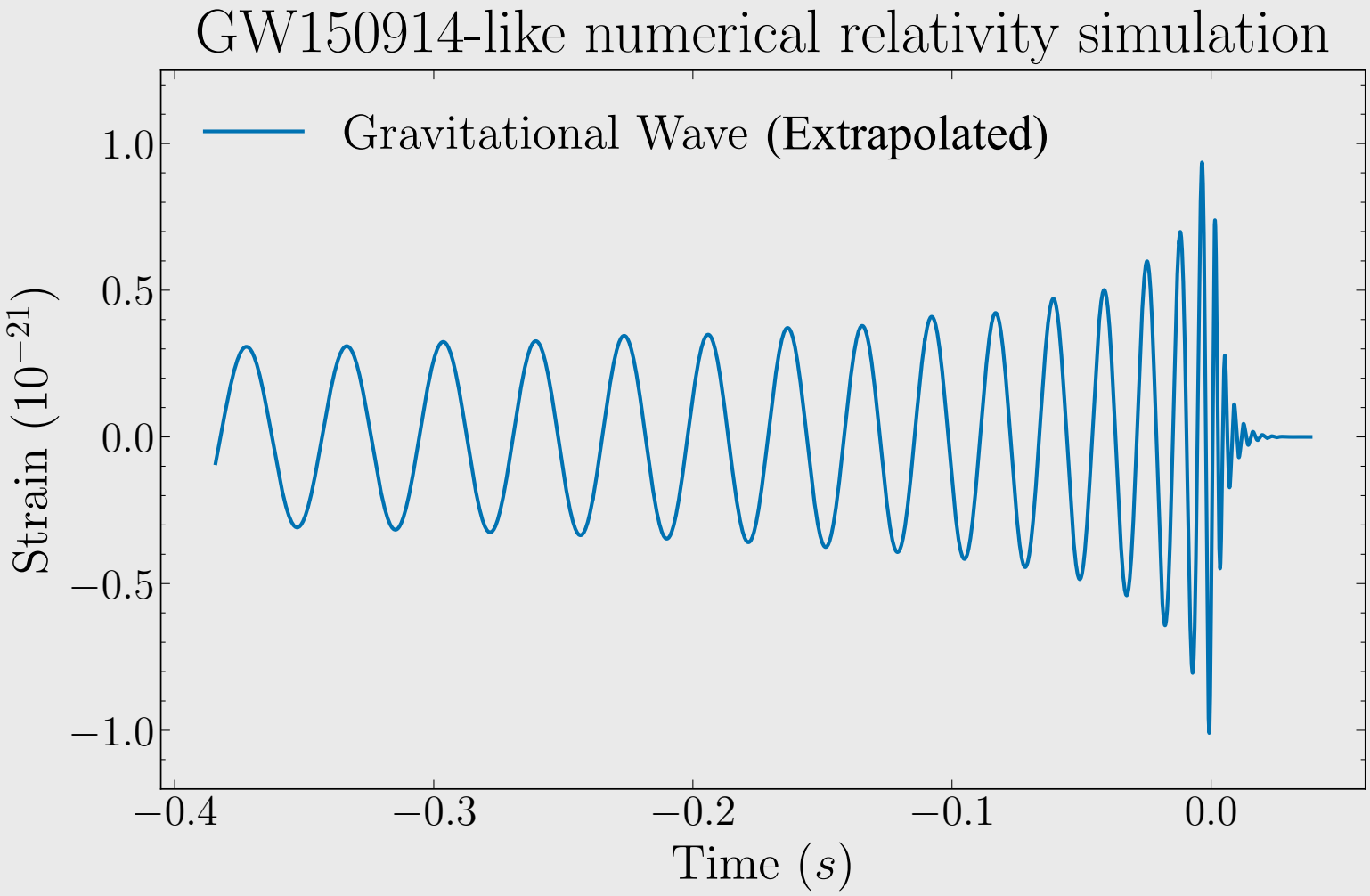
- Can compute the correction to the background metric at any finite-radius position within the simulated volume… not generalizable!
- Compute the waveform data at future null infinity! Generalizable!
- $$ds^2 = -Ue^{2\beta}du^2 - 2e^{2\beta}dudr + r^2\gamma_{AB}\left(d\theta^A - \mathcal{U}^A du\right)\left(d\theta^B - \mathcal{U}^B du\right);$$

$$\gamma_{AB} = h_{AB} + \frac{1}{r}C_{AB} + \frac{1}{r^2}D_{AB} + \cdots$$

"Gravitational wave strain"

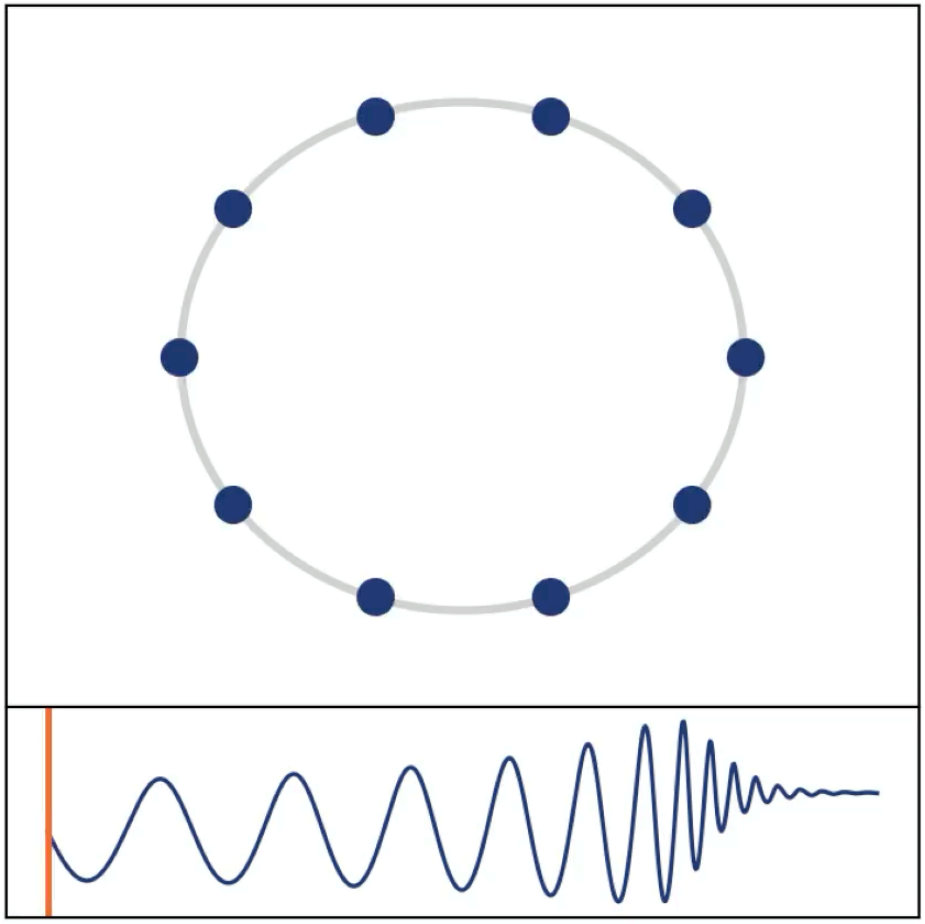
"$\mathcal{O}(10^{-20})$ correction (for LVK events)"

What Gravitational Waves Look Like



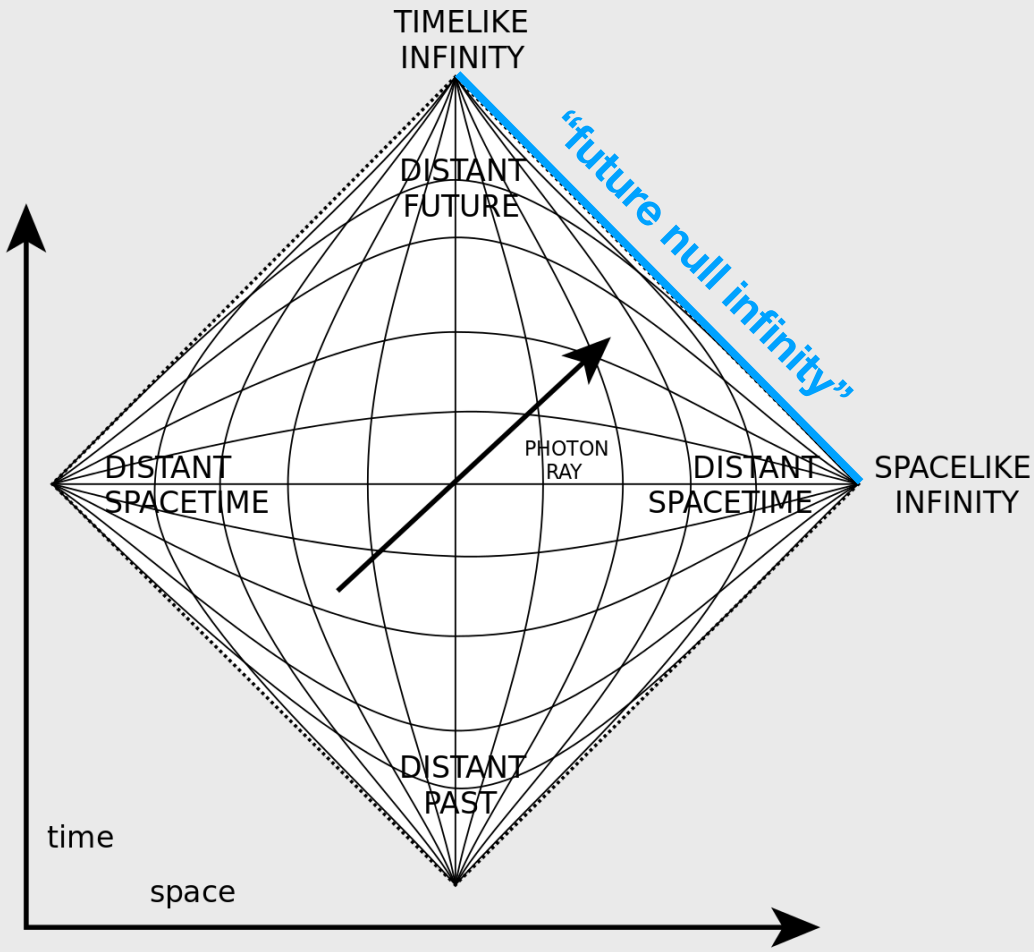
Gravitational Wave Memory Effect

- **What is it?**
  - Permanent, net displacement between two initially comoving observers
  - Nonlinear* prediction of general relativity
- **Why do we care?**
  - Not yet observed!
  - Intriguing and unique way to test Einstein's theory at low-frequencies
  - Intimately connected to the symmetries of future null infinity
    - Think celestial holography or AdS/CFT



Why We Want to Observe It

- **Noether's theorem:**
  - For every symmetry of a system, there is a corresponding conserved charge
  - E.g., time translation invariance $\Longrightarrow$ energy conservation
  - More generally, 0 = "charge" + "flux"
- **Asymptotic symmetries:**
  - Extra symmetries at "future null infinity"
  - Connected to memory!
  - "strain" = "charge" + "flux"



Concluding Remarks

Numerical Relativity

- Provides the only exact solution to Einstein's equations for BBHs
- But needs to be understood to be used correctly!

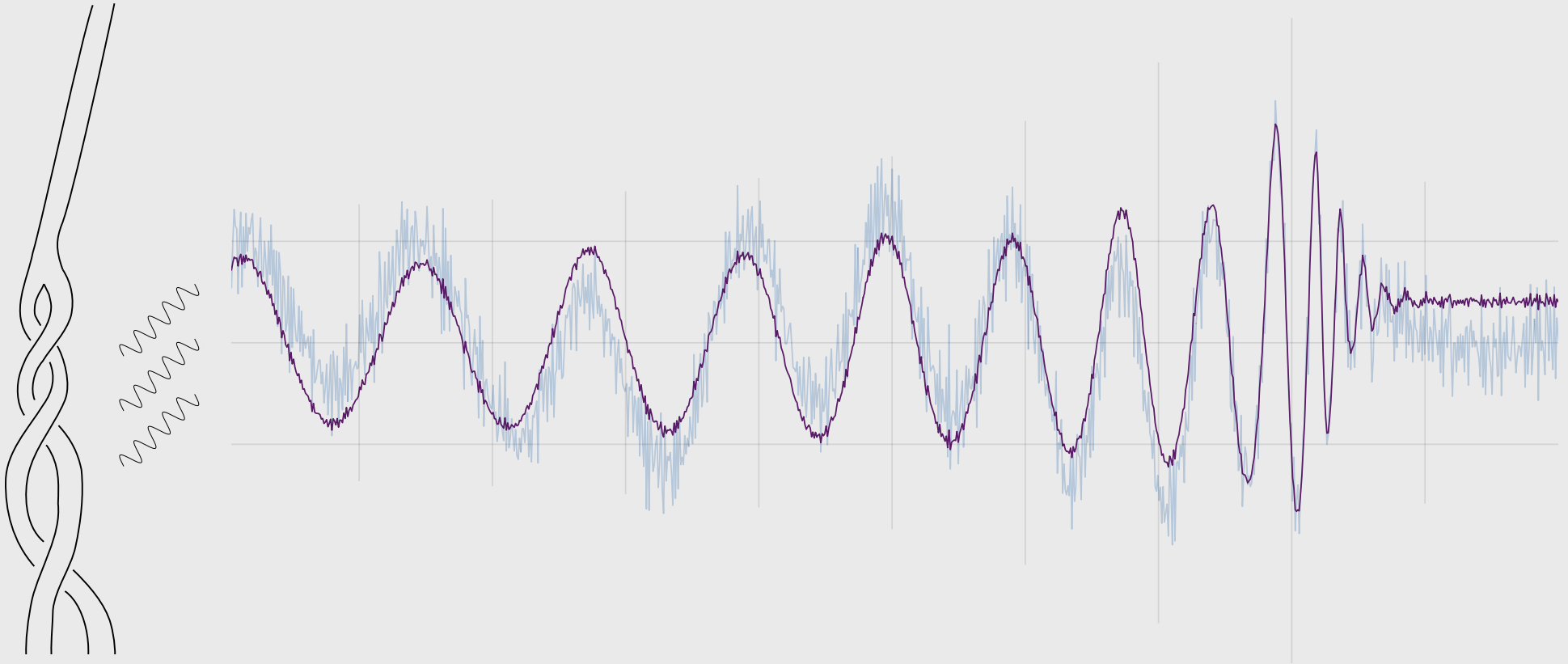
Memory Effects

- Permanent, net displacement experienced by initial comoving observers
- Nonlinear and intimately related to asymptotic symmetries / soft theorems
- One limited waveform model exists, but more to come!

Pushing Einstein's theory to the limits

- Detect memory!
- Alternative theories of gravity? Asymptotic symmetries? Quantum effects?

Thank you!



Why We Haven't Observed It (Yet!)

- **Ground-based:**
  - LIGO:
    $\mathcal{O}$(2,000) events*
    arXiv:1911.12496
    arXiv:2105.02879
    arXiv:2210.16266
    arXiv:2404.11919
  - CE/ET:
    $\mathcal{O}$(1) event per year
    arXiv:2210.16266
- **LISA:** $\mathcal{O}$(10) per 4 years!
  - arXiv:1906.11936,
    arXiv:2406.09228