Title: Growing Black-Hole Hair in Extensions of General Relativity

Date: Nov 10, 2017 02:20 PM

URL: http://pirsa.org/17110099

Abstract:

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Output: SDI - 1920x1080i@60Hz

UNIVERSITAT DE BARCELONA

ICCUB Institute of Cosmos Sciences

EXCELENCIA MARÍA DE MAEZTU

MARIE CURIE ACTIONS

Growing Black-Hole Hair – binaries in Einstein-dilaton Gauss-Bonnet gravity

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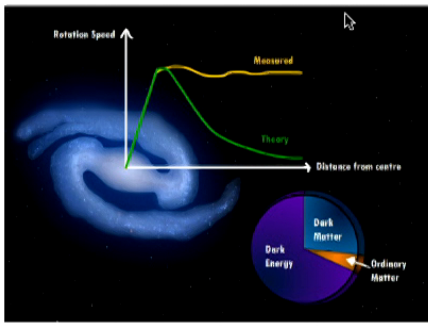
Universitat de Barcelona

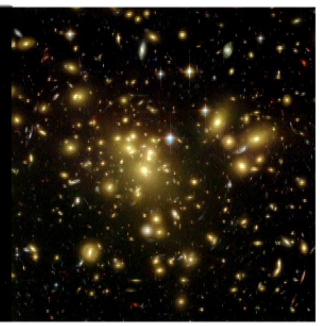
work in progress with L. Gualtieri, P. Pani, T. Sotiriou

Workshop "Quantum black holes in the sky?", Perimeter Institute, 10 November 2017


Workshop "Quan
H. Witek (Universitat de B

Why modify General Relativity?





Cosmology

- observational evidence for dark matter/energy
- cosmological constant problem
- evolution of the universe

High-energy physics

- general relativity is non-renormalizable
- UV completion and quantum gravity?
- curvature singularities

GR is well tested – but where?

(for details see Kent Yagi's and Katerina Chatziioannou's talks on Wednesday)

(credit: LIGO / Virgo Scientific Collaborations)

- so far: little theoretical knowledge about merger regime in extensions of GR

  (scalar-tensor theory [Healy et al '11, Berti '13, Barausse et al '12, Shibata et al '13], dynamical Chern-Simons [Okounkova et al '17], Einstein-Maxwell-dilaton [Hirschmann et al '17])
- needed to calibrate parametrized models, e.g., extensions of EoB, ppN, ppE, ...
- no parametrized numerical models → choose most promising candidates

Here:

Einstein-dilaton Gauss-Bonnet gravity

action of EdGB gravity (e.g. Kanti et al '95)

$$S = \frac{1}{16\pi} \int \mathrm{d}^4x \sqrt{-g} \left({}^{(4)}R + \alpha_{\rm GB} f(\Phi) \mathcal{R}_{\rm GB} - \frac{1}{2} (\nabla\Phi)^2 \right)$$

$$G_{ab} = 8\pi T^{\Phi}_{ab} - 16\pi\alpha_{\rm GB} \mathcal{G}^{\rm GB}_{ab} \,,$$
$$\Box\Phi = -\alpha_{\rm GB} f'(\Phi) \mathcal{R}_{\rm GB}$$

[1]

- $\mathcal{R}_{\rm GB} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$
- $f(\Phi) \sim e^{\Phi}$ or $f(\Phi) = \Phi$

[1] use geometric units $c = 1 = G$

Why EdGB gravity?

High-energy physics

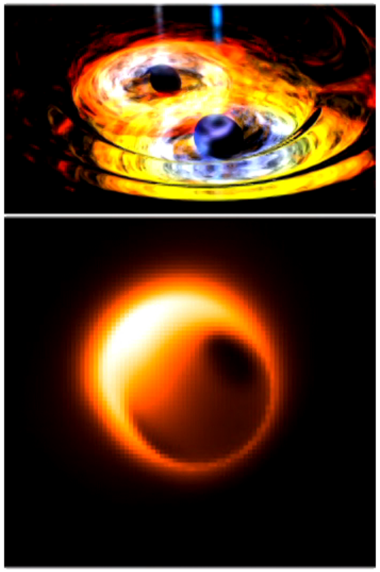
- higher curvature corrections
  relevant in strong-curvature regime
- low-energy limit of some string theories
  (Gross & Sloan '87, Kanti et al '95, Moura & Schiappa 06)
- compactification of Lovelock gravity (Charmousis '14)

Mathematical relativity

- field equations at most second order
  $\Rightarrow$ potential for well-posed PDE system?
  - in generalized harmonic gauge only weakly hyperbolic (Papallo & Reall '17, Papallo '17)
  - good chances as effective field theory (Choquet-Bruhat '88, Delsate et al '14)

Why EdGB gravity?

- in standard scalar-tensor theory:
  - no-hair theorems for BHs
    (Bekenstein '95, Heusler '96, Sotiriou & Faraoni '11)
  - neutron stars can have scalar hair
    (Damour & Esposito-Farese '93, '96, ...)
- BUT: reverse in quadratic gravity!
  - BHs can have hair!
    (Hui & Nicolis '12, Sotiriou & Zhou '14)
  - monopole scalar charge for neutron star vanishes (Yagi et al '15)



(www.eventhorizontelescope.org)

$\Rightarrow$ modified dynamics and extra polarizations, e.g,

- induced scalar dipole & quadrupolar radiation
  $\Rightarrow$ increased inspiral rate
- shift in binding energy
  $\Rightarrow$ correction to orbital phase
- change in ISCO: $r_{\rm ISCO}/M \sim 6 - \frac{16297}{9720}\alpha_{\rm GB}^2$
- spin can exceed Kerr bound (Kleihaus et al '11)
- ...

EdGB as effective field theory

- $g_{\mu\nu} = g^{(0)}_{\mu\nu} + \epsilon g^{(1)}_{\mu\nu} + \mathcal{O}(\epsilon^2)$, $\Phi = \epsilon\Phi^{(1)} + \mathcal{O}(\epsilon^2)$ and take $\epsilon \sim \alpha_{\rm GB}$

$$\alpha^0_{\rm GB}: \quad G^{(0)}_{ab} = 0\,,$$
$$\alpha^1_{\rm GB}: \quad \Box\Phi^{(1)} = -\mathcal{R}^{(0)}_{\rm GB}\,, \quad \mathcal{R}^{(0)}_{\rm GB} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$$

- rotating black holes with $\chi = \frac{J}{M^2}$ in small coupling approximation

(Kanti et al '95, Pani et '09, '11, Stein & Yunes '11, Sotiriou & Zhou '14, Ayzenberg & Yunes '14, Maselli et al '15, Kleihaus et al '11, '14, ...)

  - $\alpha^0_{\rm GB}$: no modification to GR solution

$$ds^2 = ds^2_{\rm Kerr}\,, \quad \Phi = const = 0$$

  - $\alpha^1_{\rm GB}$: no modification to metric, but scalar charge (hair of second kind)

  (courtesy of Kent Yagi)

$$\Phi = \sum_{l\geq 0,{\rm even}} \mathcal{P}_l \frac{M^{l+1}}{r^{l+1}} P_l(\cos\theta)\left[1 + \mathcal{O}\left(\frac{M}{r}\right)\right]$$

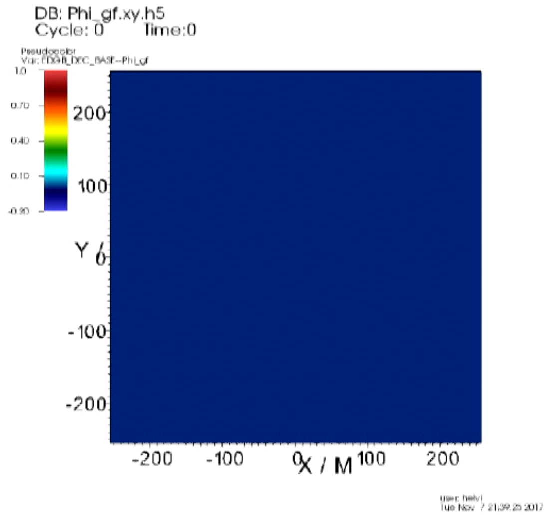
$$\mathcal{P}_0 = 4\frac{\alpha{\rm GB}}{M^2}\frac{\sqrt{1-\chi^2} - 1 + \chi^2}{\chi^2} \qquad \mathcal{P}_2 \sim -\frac{28}{15}\frac{\alpha_{\rm GB}}{M^2}\chi^2\left(1 - \frac{5\chi^2}{98}\right) + \mathcal{O}(\chi^6)$$

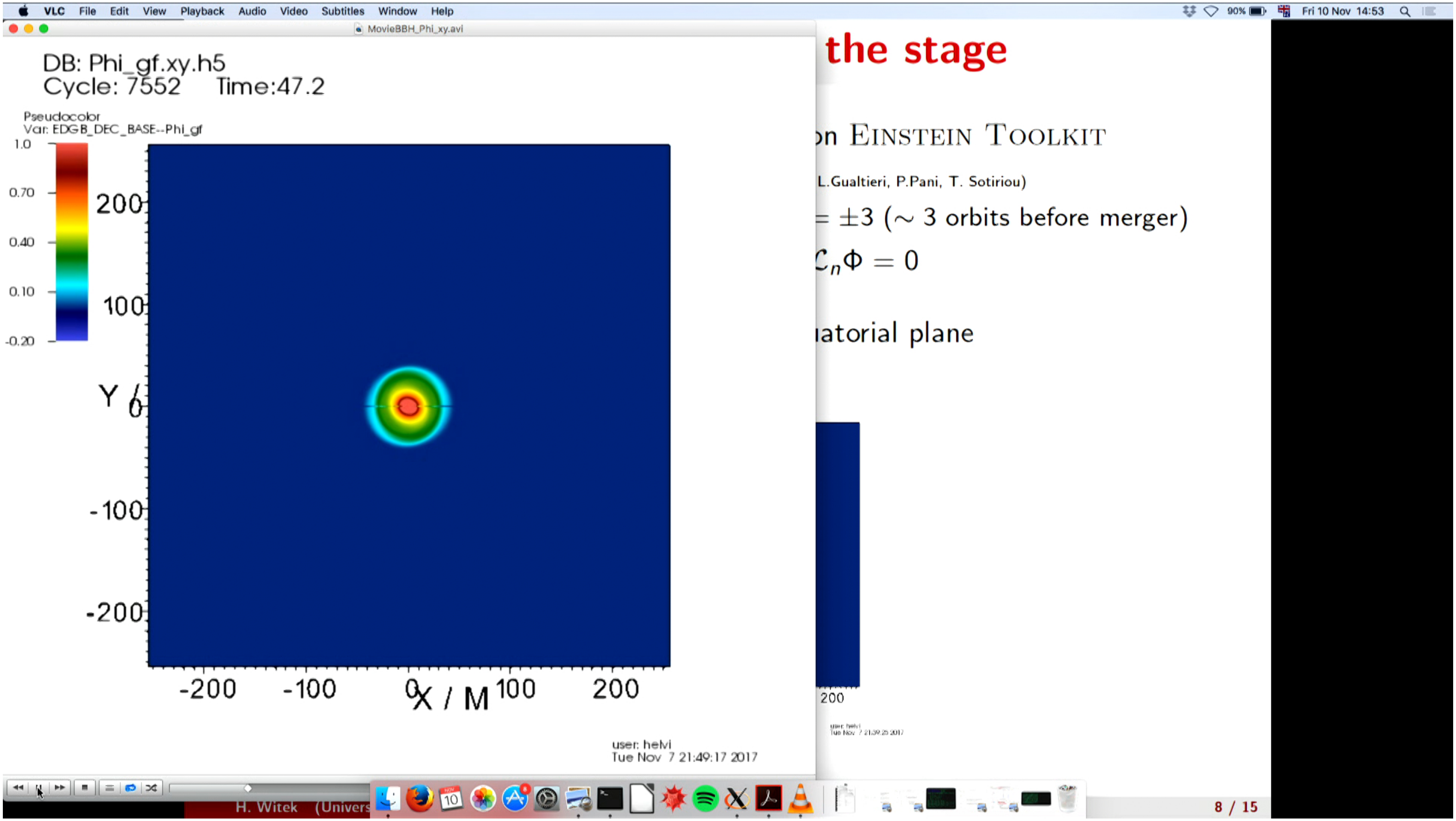
BH binaries in EdGB – setting the stage

Time evolution in 3+1 dimensions, code based on EINSTEIN TOOLKIT

- Background: black-hole binary (work in progress with L.Gualtieri, P.Pani, T. Sotiriou)
  - equal-mass, non-spinning binary with $x_{\pm} = \pm 3$ ($\sim$ 3 orbits before merger)
- zero initial scalar field $\Phi_{t=0} = 0, \Pi_{t=0} = -\mathcal{L}_n \Phi = 0$

Scalar field evolution – equatorial plane

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the stage
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L.Gualtieri, P.Pani, T. Sotiriou)
= ±3 (∼ 3 orbits before merger)
$\mathcal{L}_n\Phi = 0$
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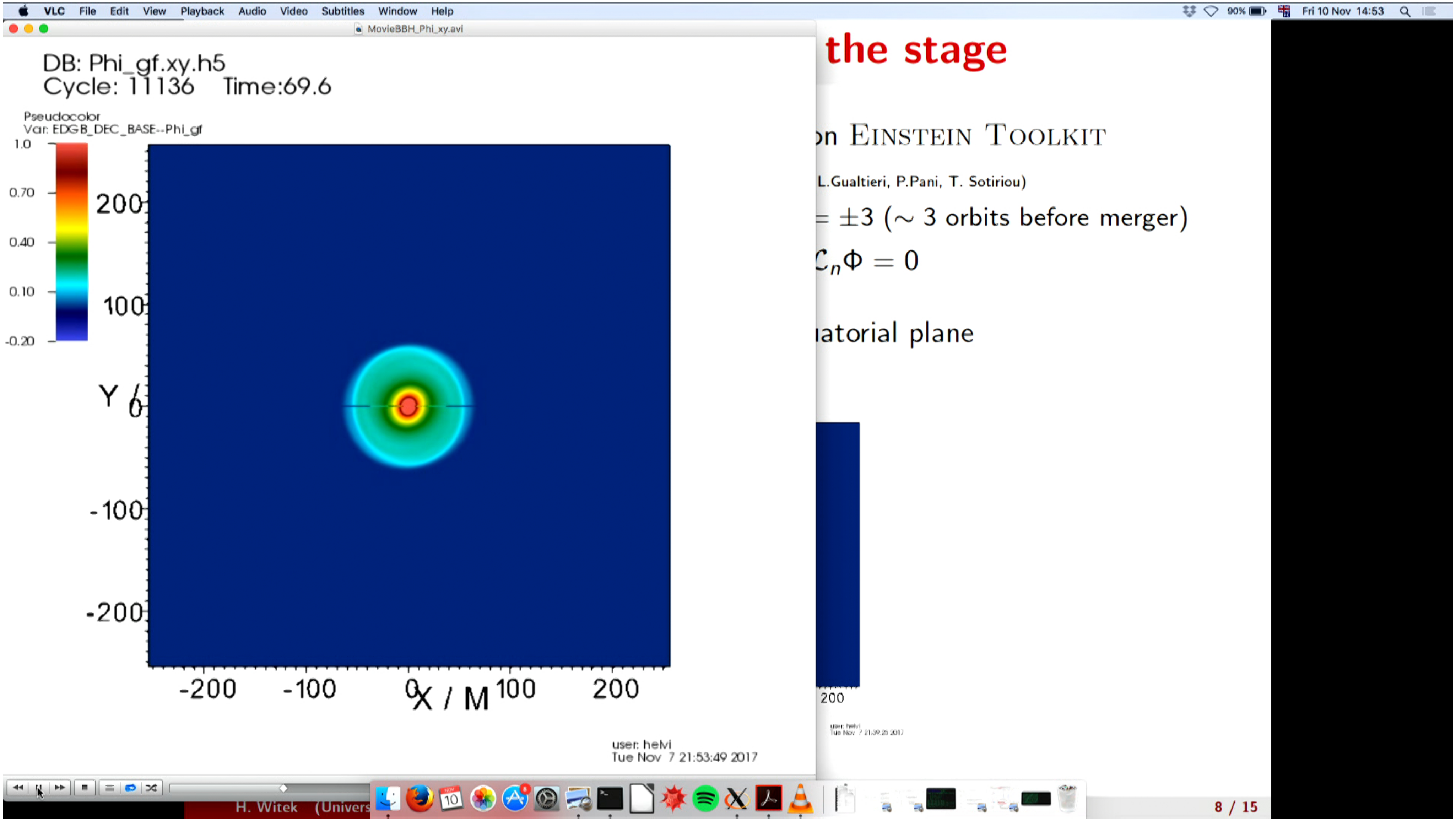
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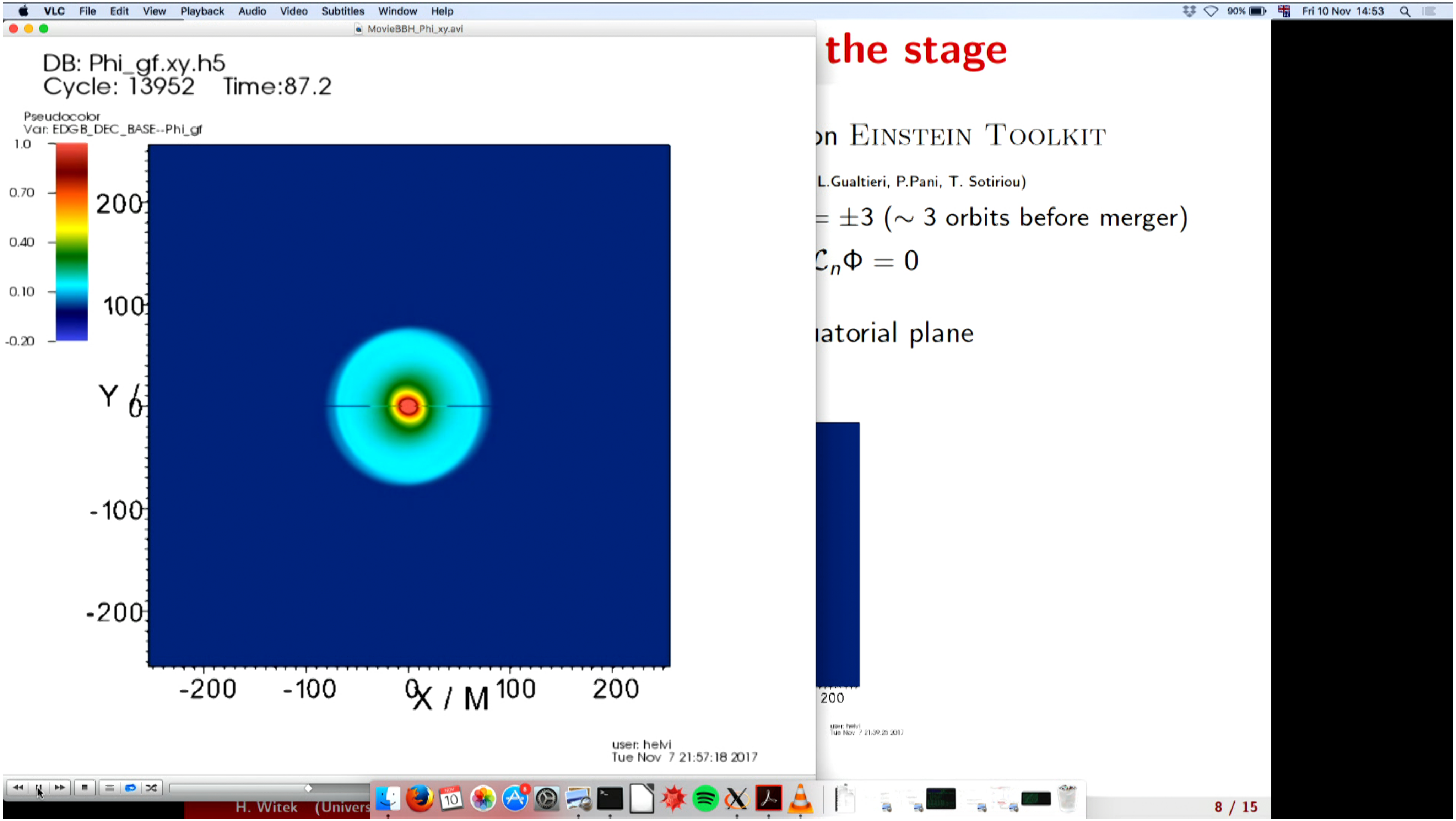
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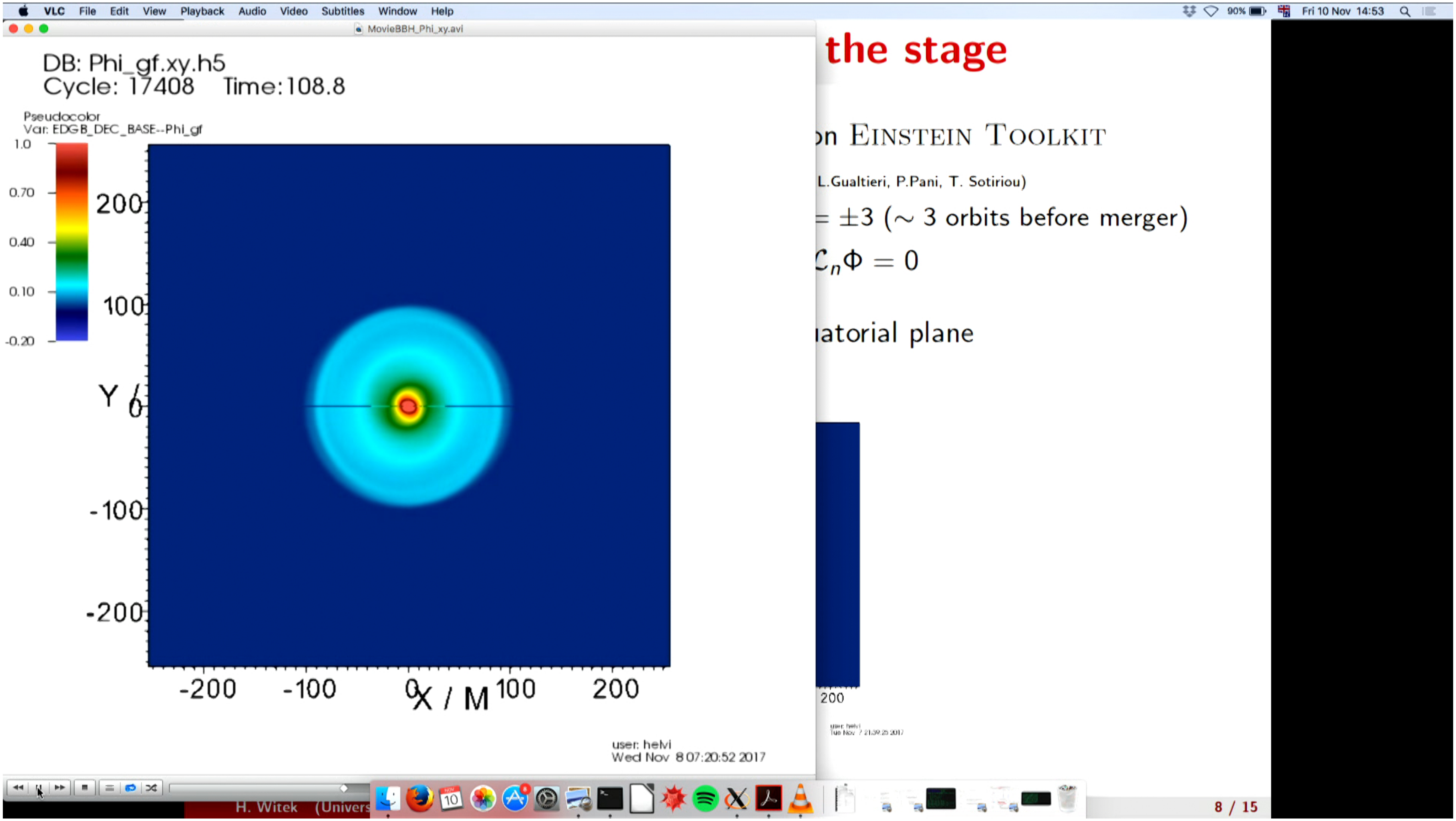

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= ±3 (∼ 3 orbits before merger)
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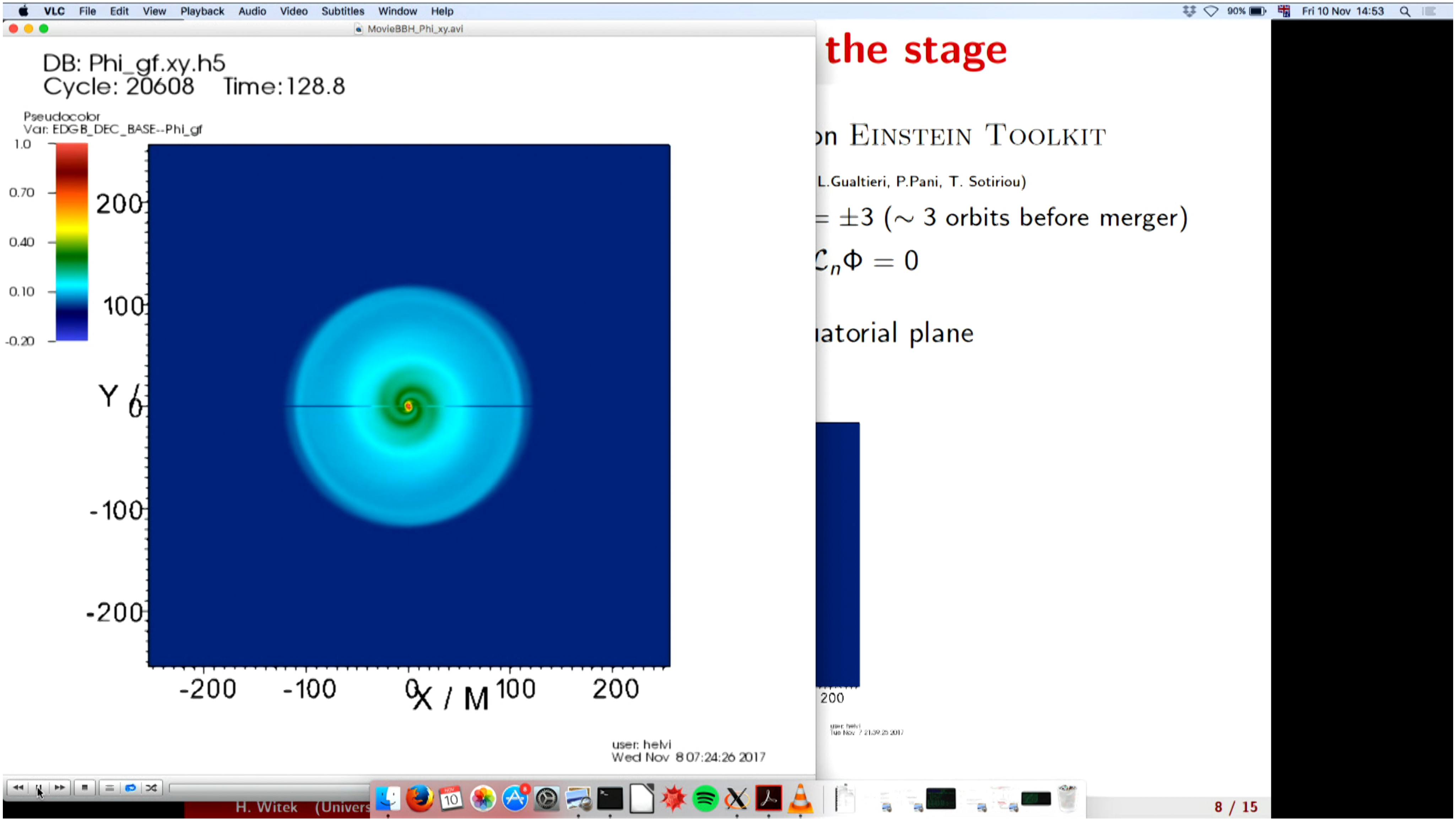
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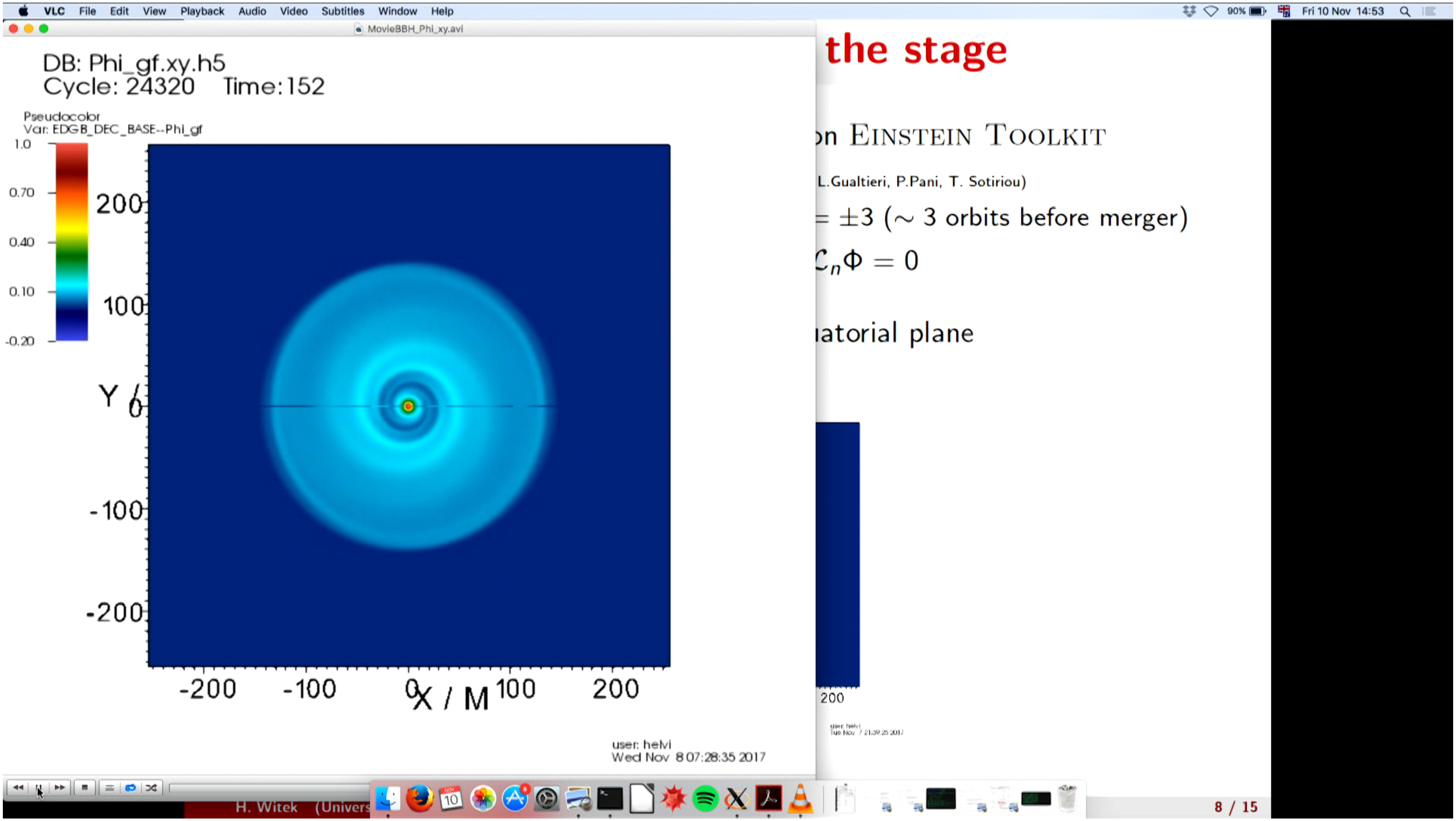
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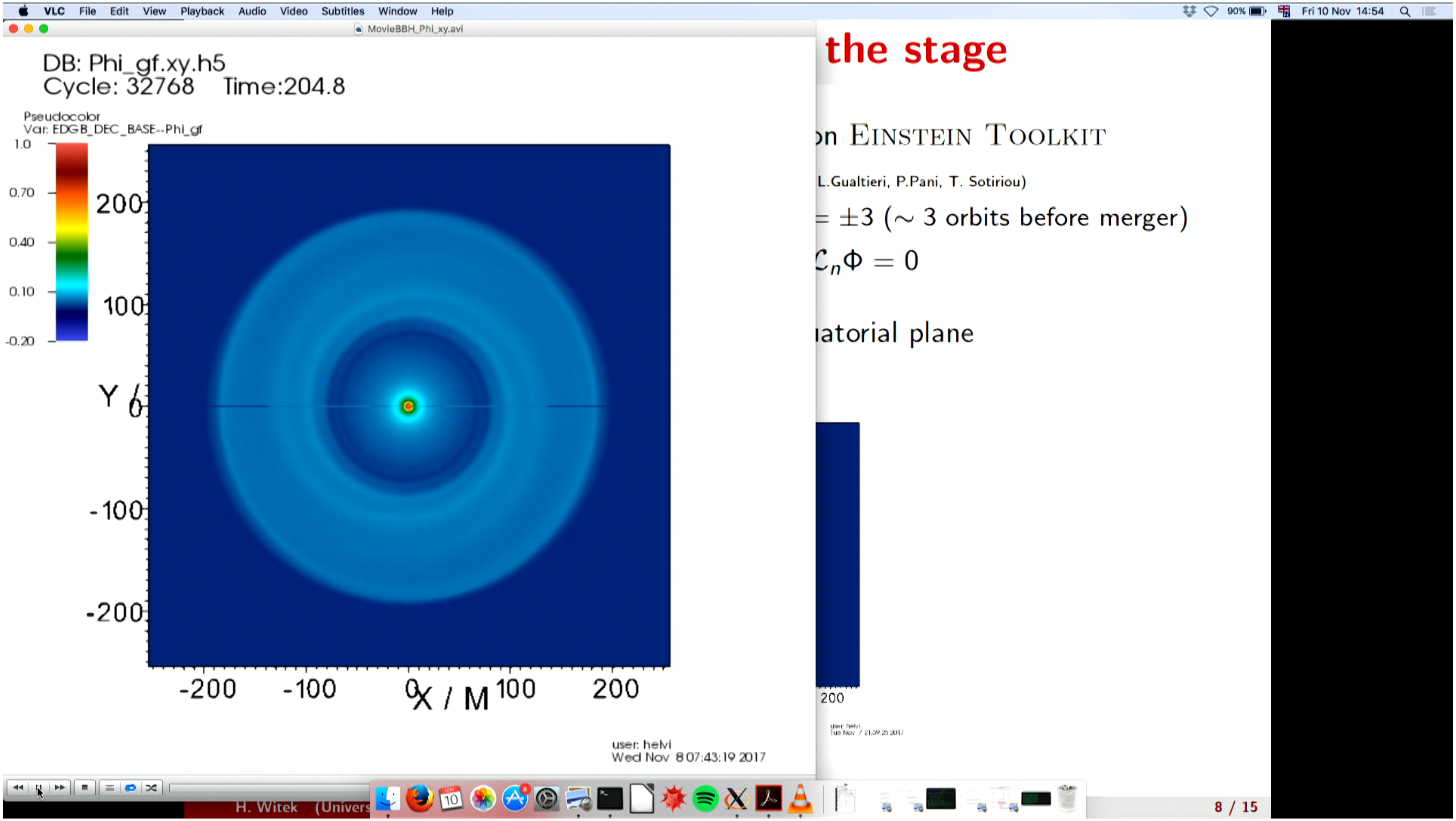
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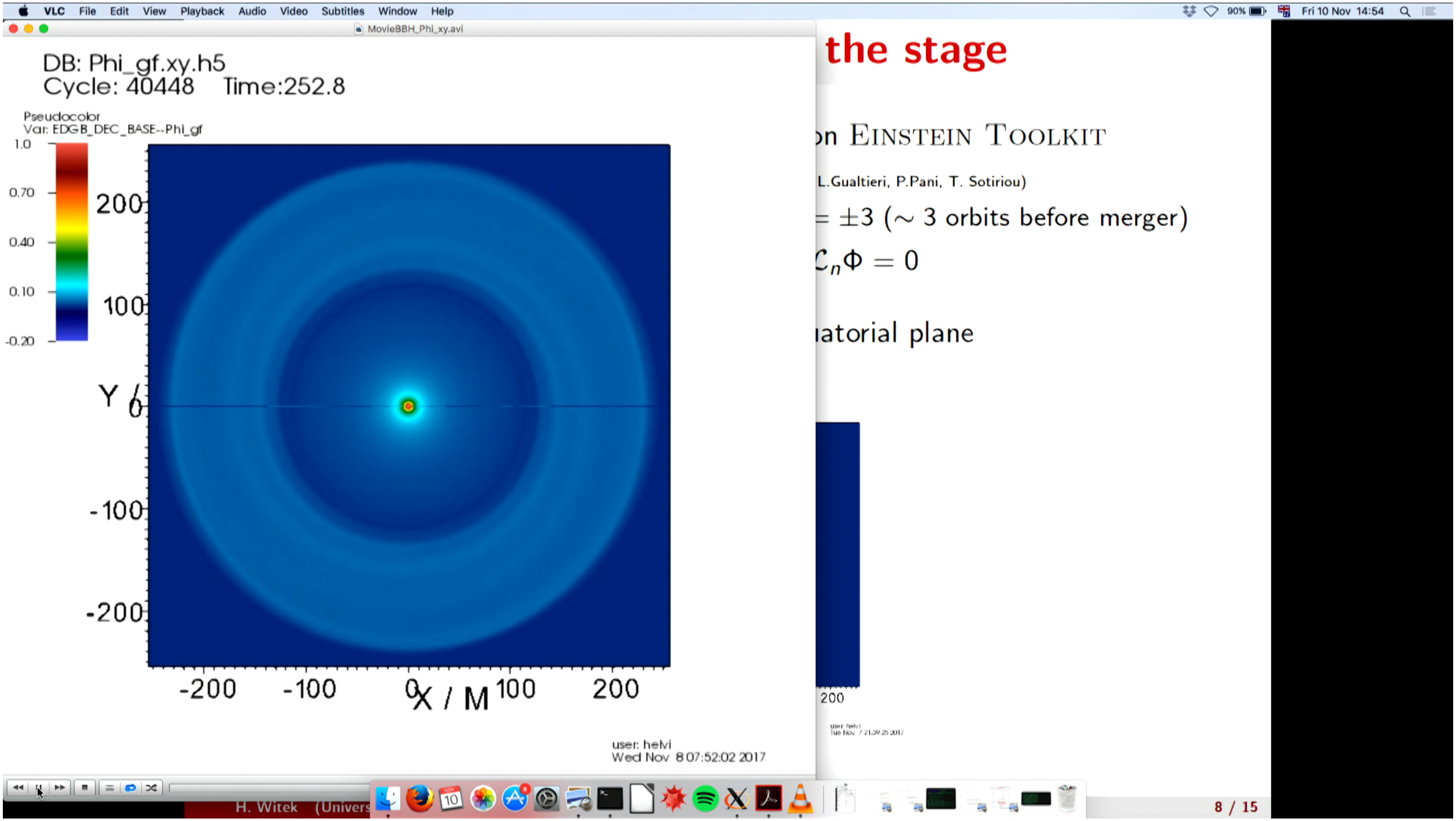

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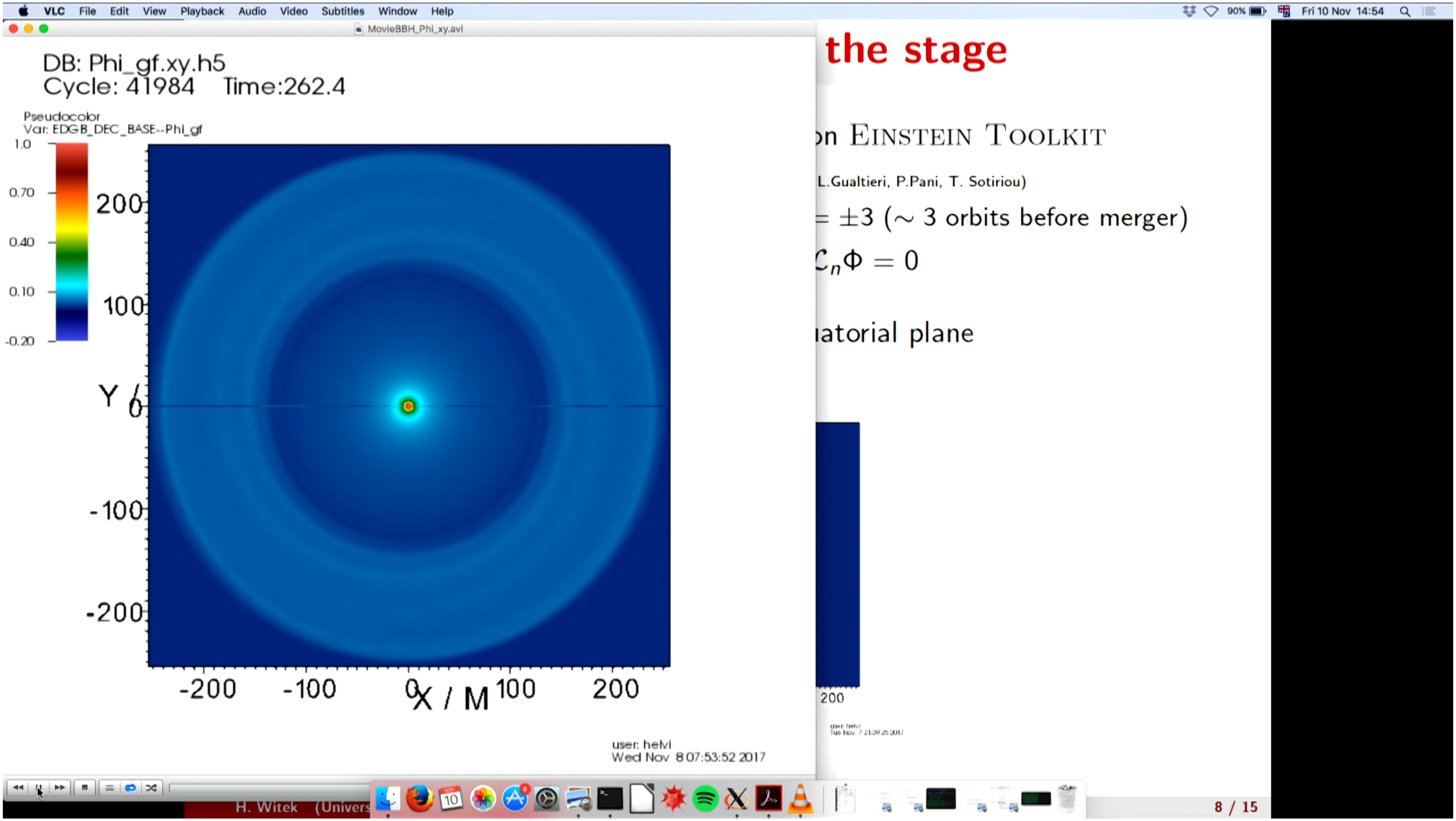
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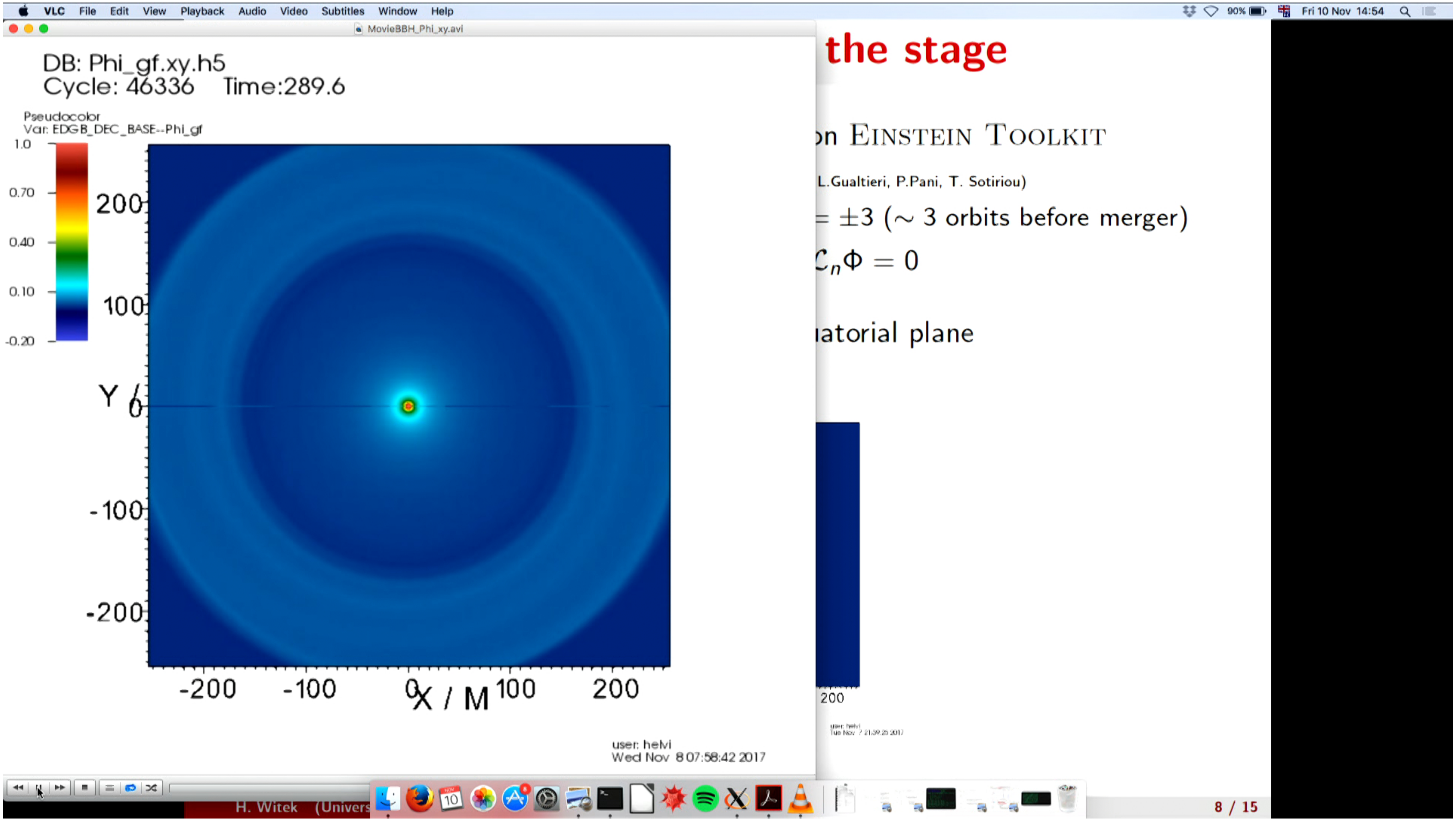
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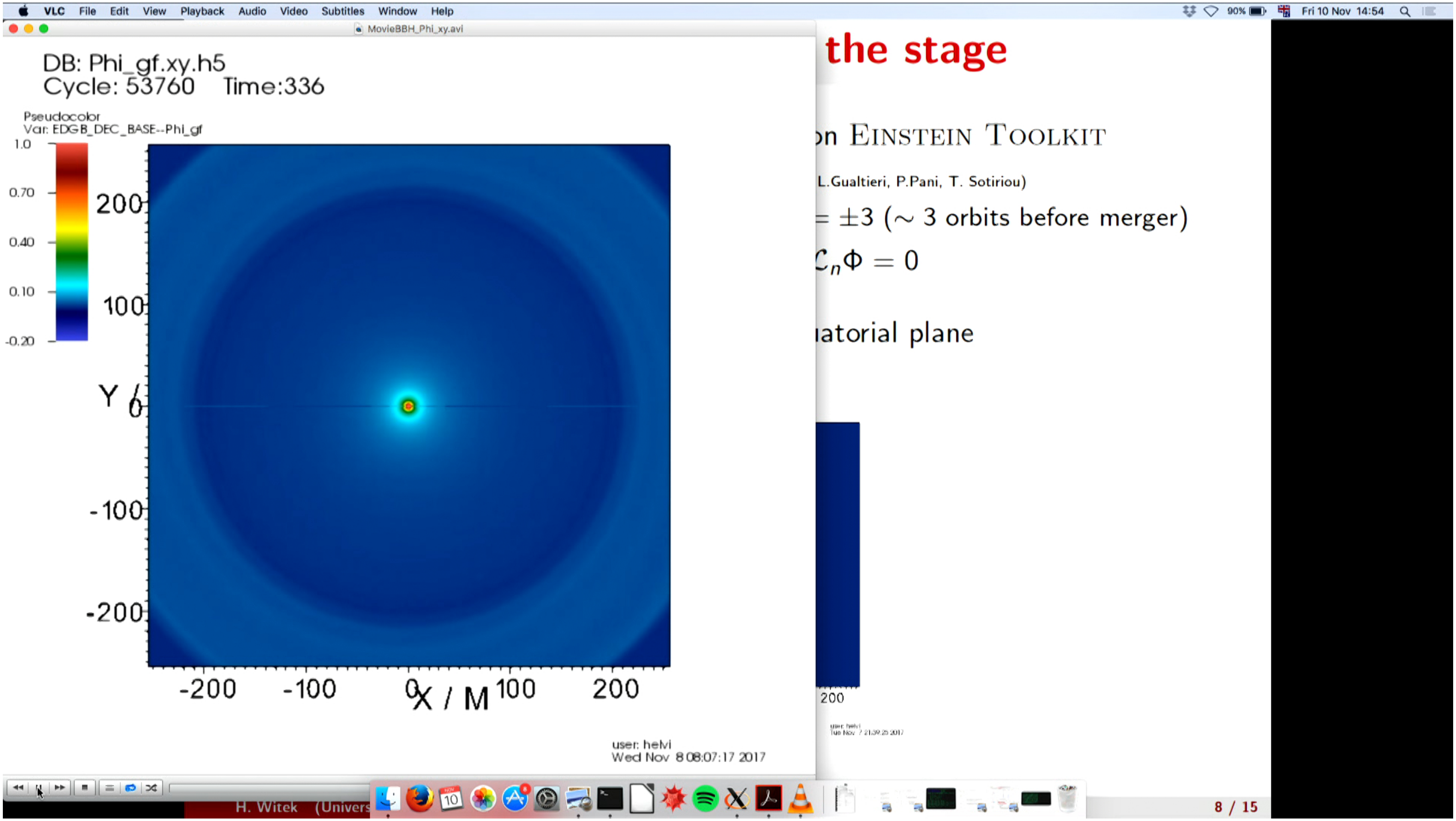
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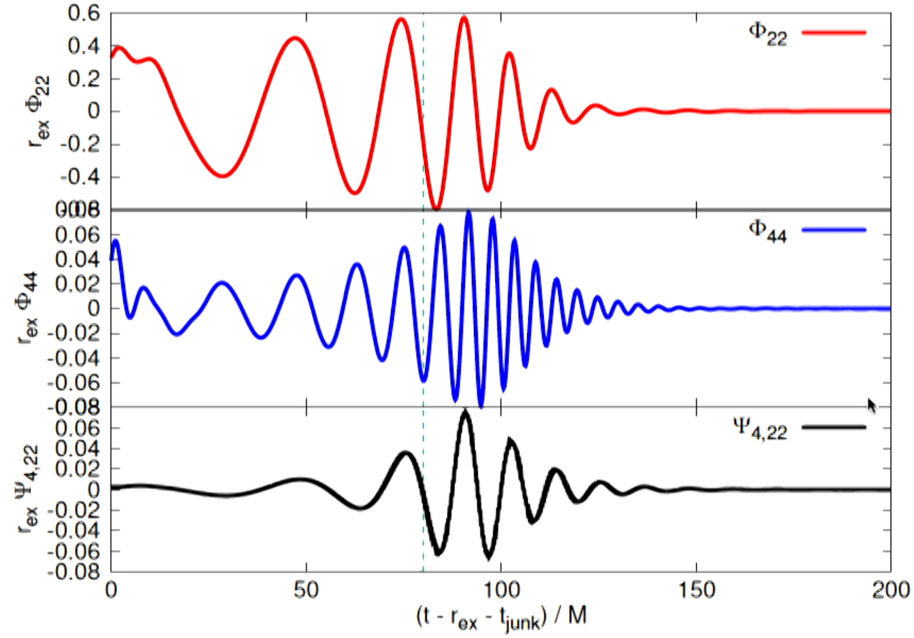
Results

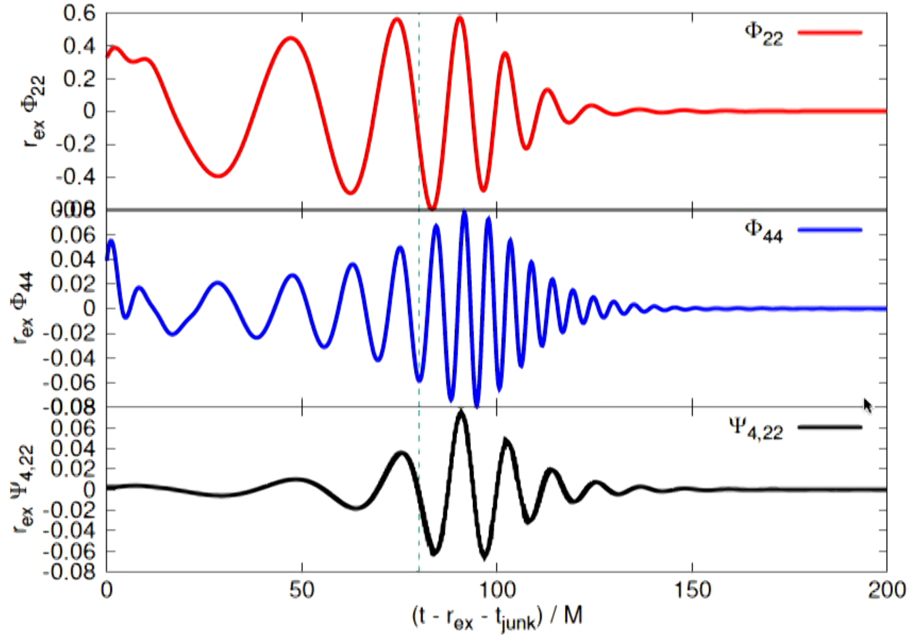
Scalar radiation measured at $r_{\rm ex}/M = 40$



- burst of scalar radiation in $l = m = 2$ and $l = m = 4$ *before* merger
- post-merger ringdown

Results

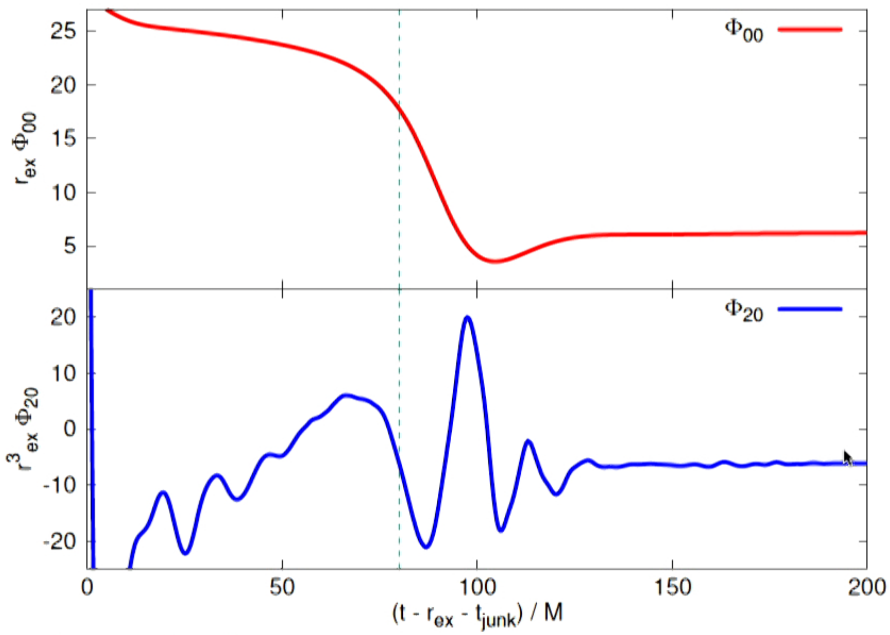
Scalar radiation measured at $r_{\rm ex}/M = 40$



- burst of scalar radiation in $l = m = 2$ and $l = m = 4$ *before* merger
- post-merger ringdown

Results

Scalar field waveforms with $m = 0$, measured at $r_{\rm ex}/M = 40$



- non-trivial scalar excitation
- at late times: approach to analytic solution

$$\Phi \sim \mathcal{P}_0 \frac{M}{r} + \mathcal{P}_2 \frac{M^3}{r^3} Y_{20} \quad \mathcal{P}_0 \sim \frac{2\alpha_{\rm GB}}{M^2} \quad \mathcal{P}_2 \sim -\frac{\alpha_{\rm GB}}{M^2}\chi^2$$

Summary and Outlook

Take home message:

- modifications to GR may be unavoidable on a quest for a theory of quantum gravity
- compact objects & binaries unique probes for strong-gravity regime
- here: focus on Einstein-dilaton Gauss-Bonnet theory
  - motivated from "stringy" models
  - black holes have hair – fundamentally different from GR
  - first nonlinear study of BH binaries (up to $\mathcal{O}(\alpha_{\rm GB}^{(1)})$)
    $\rightarrow$ burst of scalar radiation excited in late inspiral & merger
    $\rightarrow$ settling down to hairy, rotating solution at late times

Outlook

- extension to $\mathcal{O}(\alpha_{\rm GB}^{2})$ within EFT approach
  $\rightarrow$ include deformation of metric and GW signal
- modelling as full theory?
  Understand PDE structure within BSSN+puncture gauge approach
- construct inspiral-merger-ringdown signal for GW searches

Thank you!