Title: Dynamical Capture Compact Binary Mergers

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Abstract:

Dynamical Capture Compact Binary Mergers

William East

Princeton University

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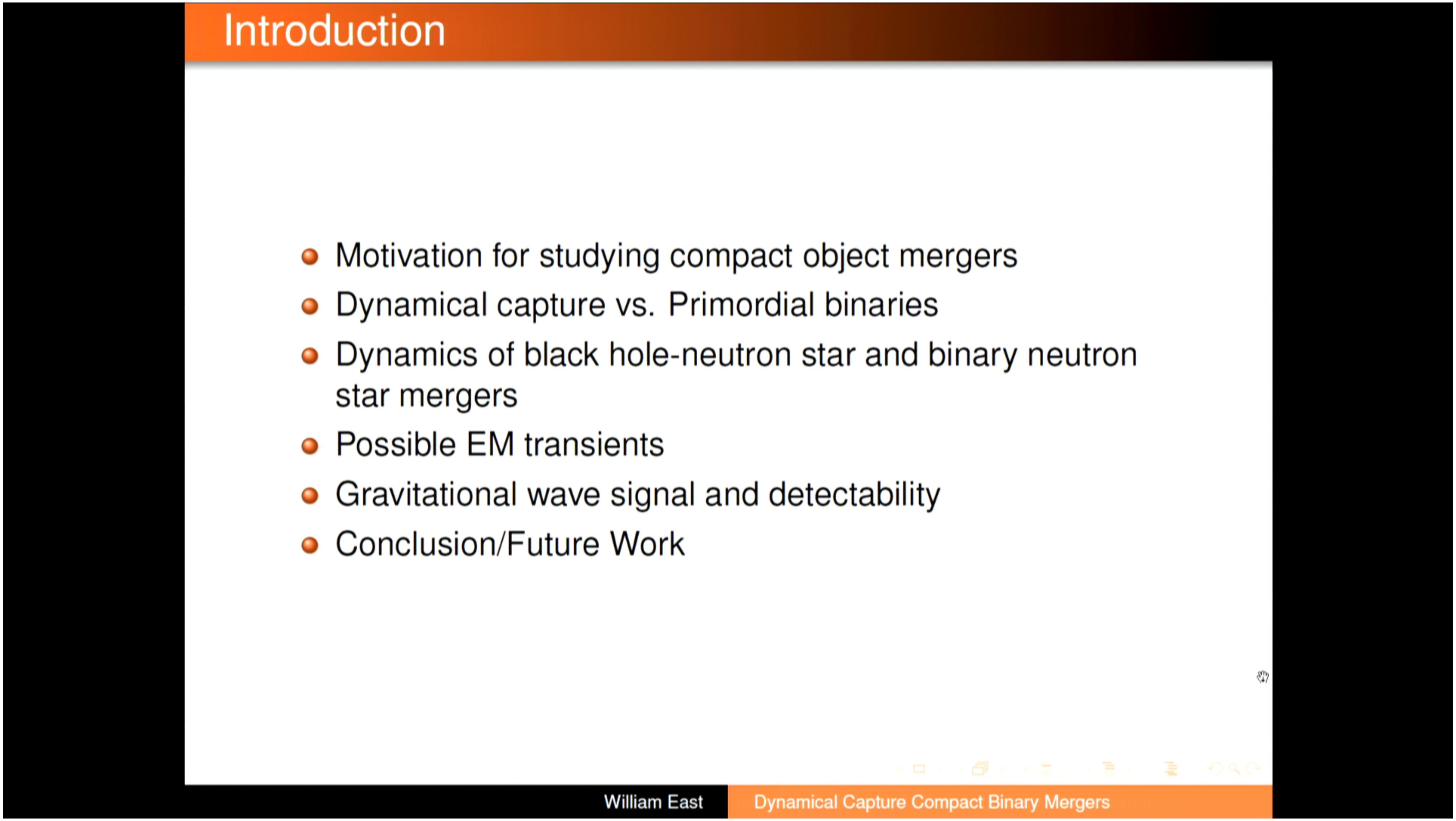
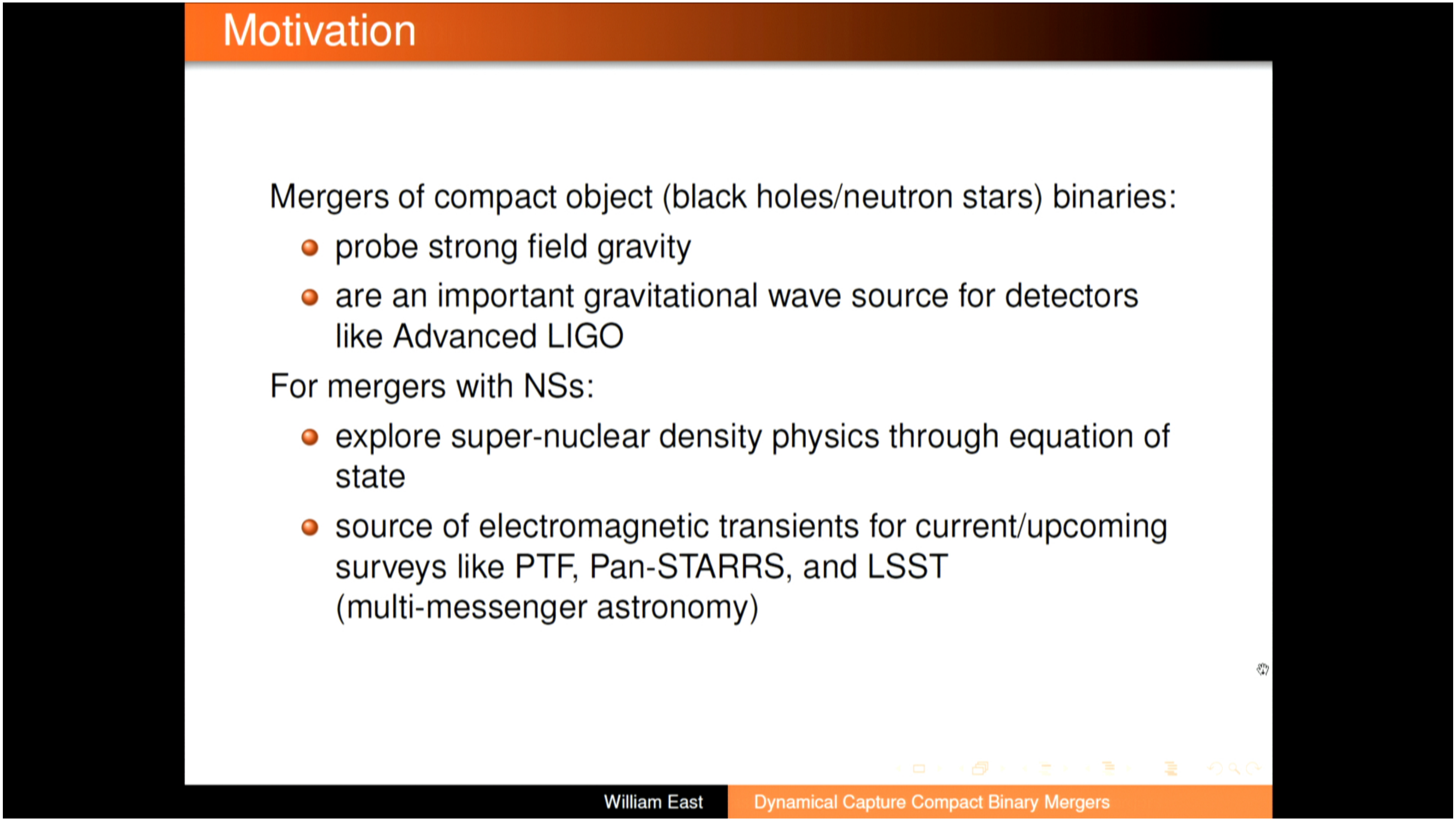


Introduction

- Motivation for studying compact object mergers
- Dynamical capture vs. Primordial binaries
- Dynamics of black hole-neutron star and binary neutron star mergers
- Possible EM transients
- Gravitational wave signal and detectability
- Conclusion/Future Work



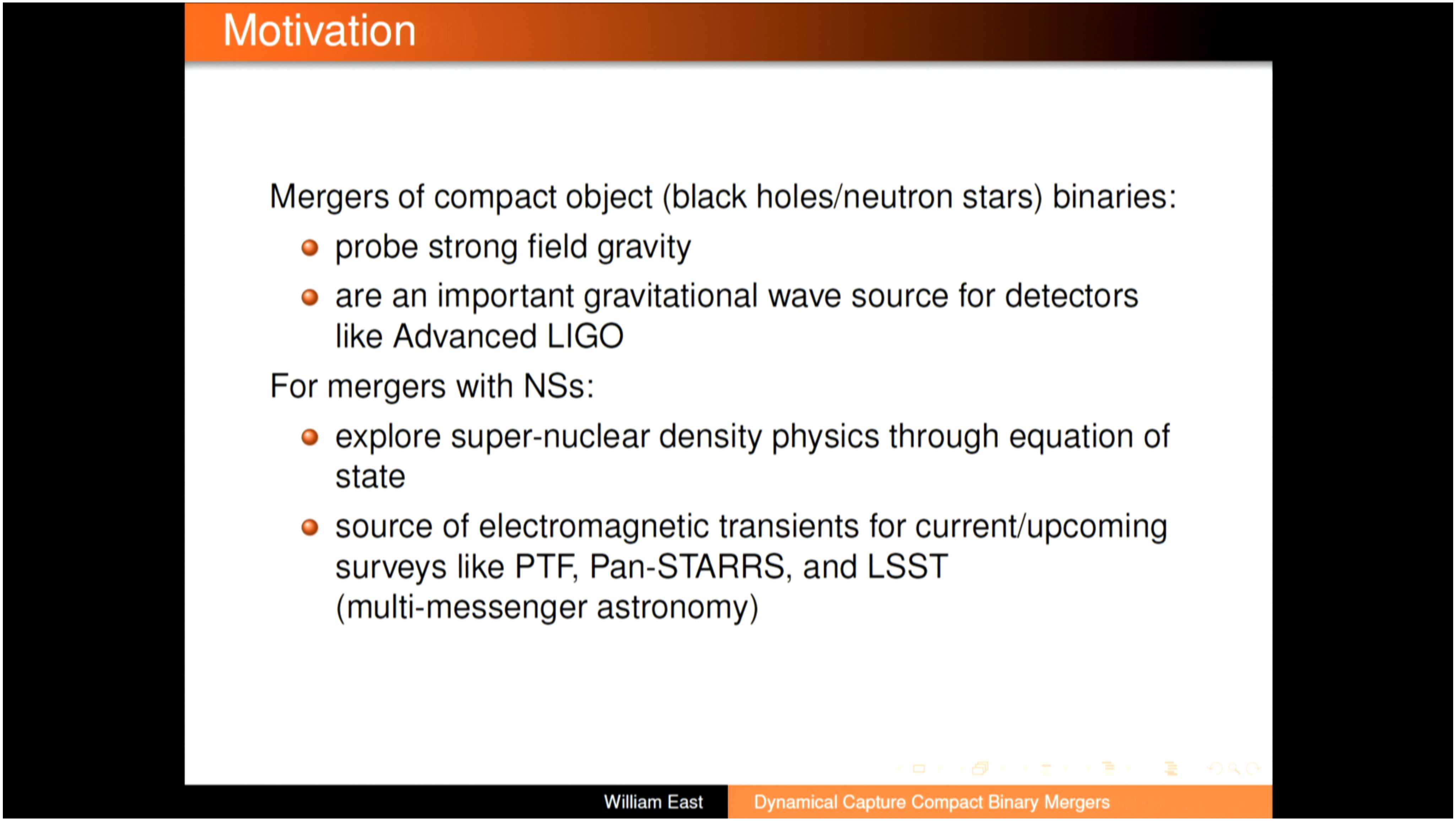
Motivation

Mergers of compact object (black holes/neutron stars) binaries:

- probe strong field gravity
- are an important gravitational wave source for detectors like Advanced LIGO

For mergers with NSs:

- explore super-nuclear density physics through equation of state
- source of electromagnetic transients for current/upcoming surveys like PTF, Pan-STARRS, and LSST (multi-messenger astronomy)



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Primordial vs. dynamical capture binaries

Primordial binaries:

- Born in bound system
- Are expected to have negligible eccentricity (i.e. quasi-circular) when detected
- Event rates for Advanced LIGO (*Abadie et al 2010*):
  NS-NS: 0.4-400 (40) /yr,
  NS-BH: 0.2-300 (10) /yr,
  BH-BH 0.4-1000 (20) /yr

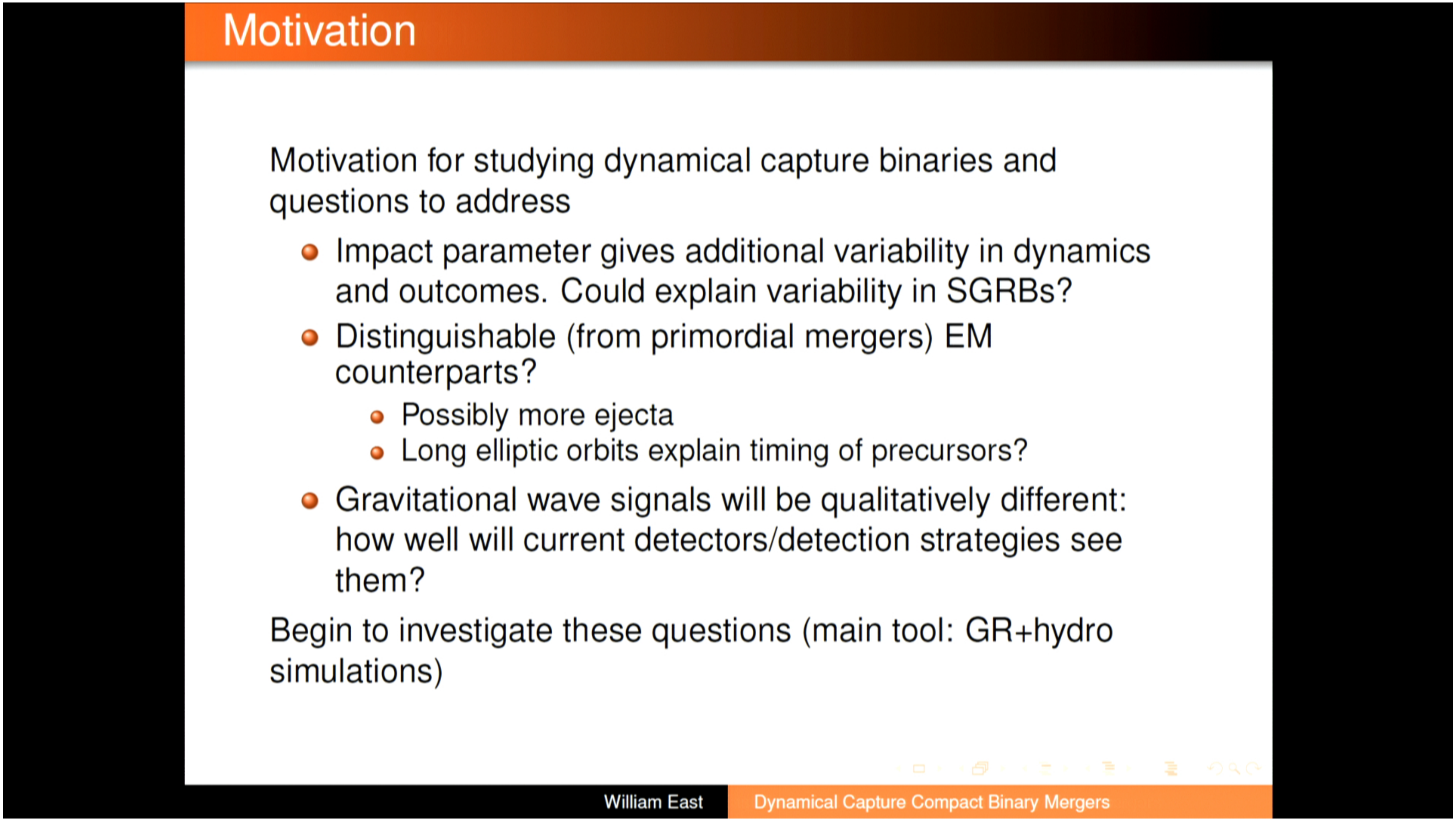
Dynamical-capture binaries:

- Arise in dense regions, e.g. globular cores undergoing core collapse. Orbital energy lost to gravitational waves and tidal effects.
- Subset will merge with large orbital eccentricities
- Event rates less well understood

Event rates for dynamical capture binaries

- For BH-BH systems in galactic nuclei *O'Leary, Kocsis, Loeb (2009)* estimate AdLIGO rate of 1 – 100/yr
- For BH-NS and NS-NS systems in globular clusters *Lee, Ramirez-Ruiz, and van de Ven, 2010* estimate global rates of 10 – 100/yr/Gpc^3 (c.f. SGRB rate: 8-30/yr/Gpc^3)
- For BH-NS observable with AdLIGO to 200-300 Mpc (*Kocsis & Levin 2011*), even excluding strong-field close encounters, merger, given rates of a 0.3-10/yr.

Not that well understood: scatter in BH number densities, NS retention rates in GCs, three body interactions (Kozai mechanism?), . . .

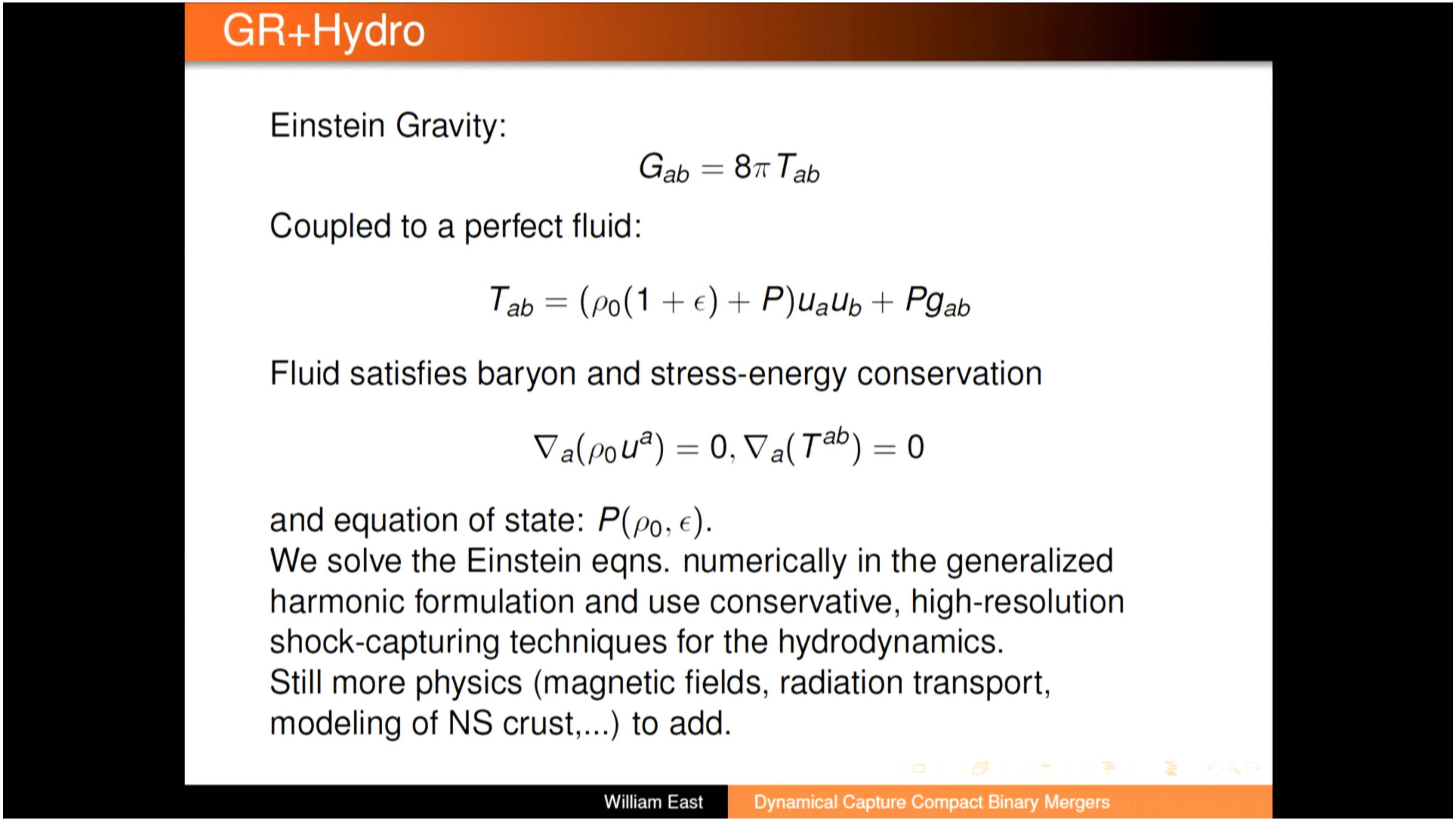


Motivation

Motivation for studying dynamical capture binaries and questions to address

- Impact parameter gives additional variability in dynamics and outcomes. Could explain variability in SGRBs?
- Distinguishable (from primordial mergers) EM counterparts?
  - Possibly more ejecta
  - Long elliptic orbits explain timing of precursors?
- Gravitational wave signals will be qualitatively different: how well will current detectors/detection strategies see them?

Begin to investigate these questions (main tool: GR+hydro simulations)



GR+Hydro

Einstein Gravity:

$$G_{ab} = 8\pi T_{ab}$$

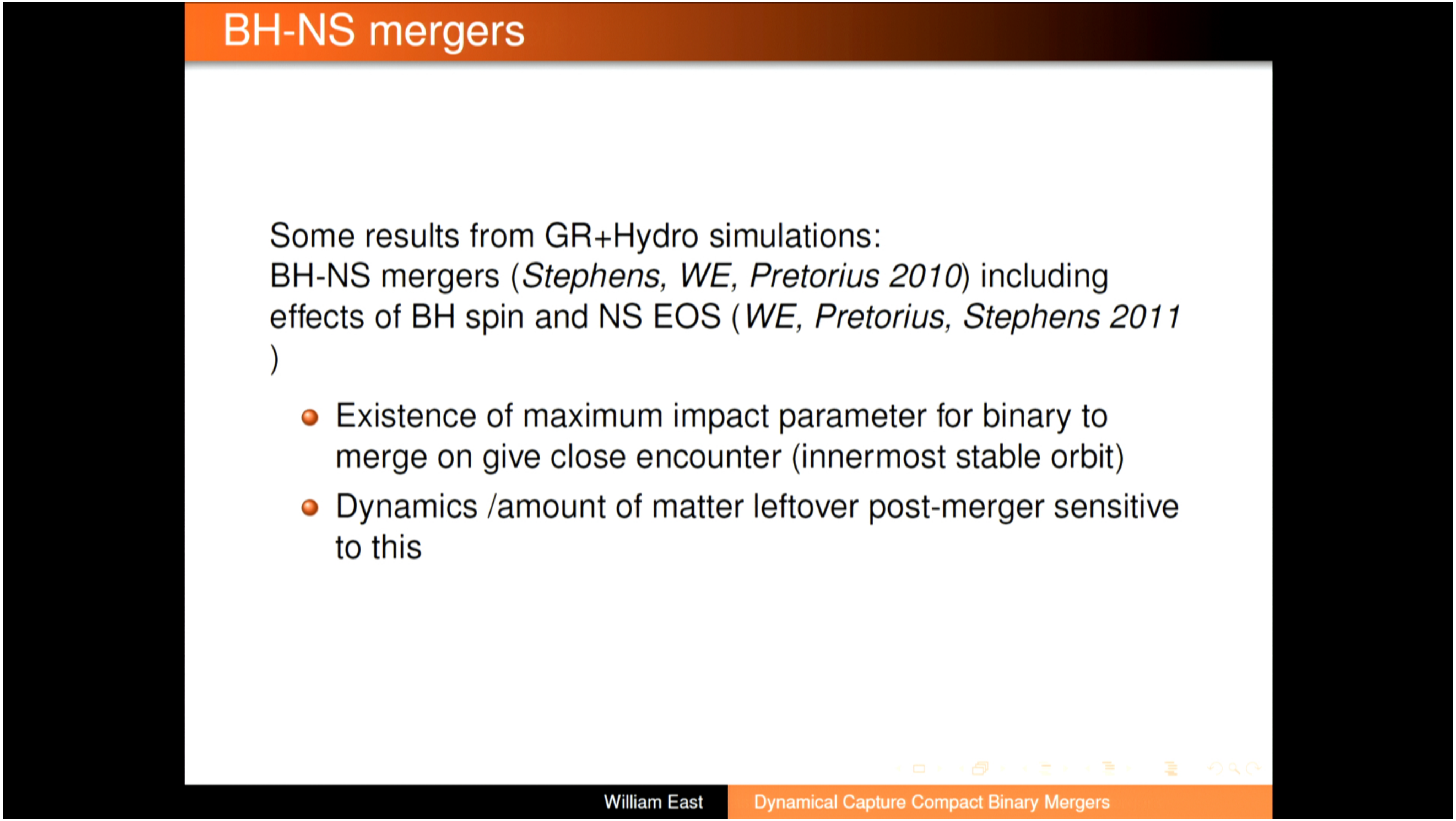
Coupled to a perfect fluid:

$$T_{ab} = (\rho_0(1+\epsilon) + P)u_a u_b + P g_{ab}$$

Fluid satisfies baryon and stress-energy conservation

$$\nabla_a(\rho_0 u^a) = 0, \nabla_a(T^{ab}) = 0$$

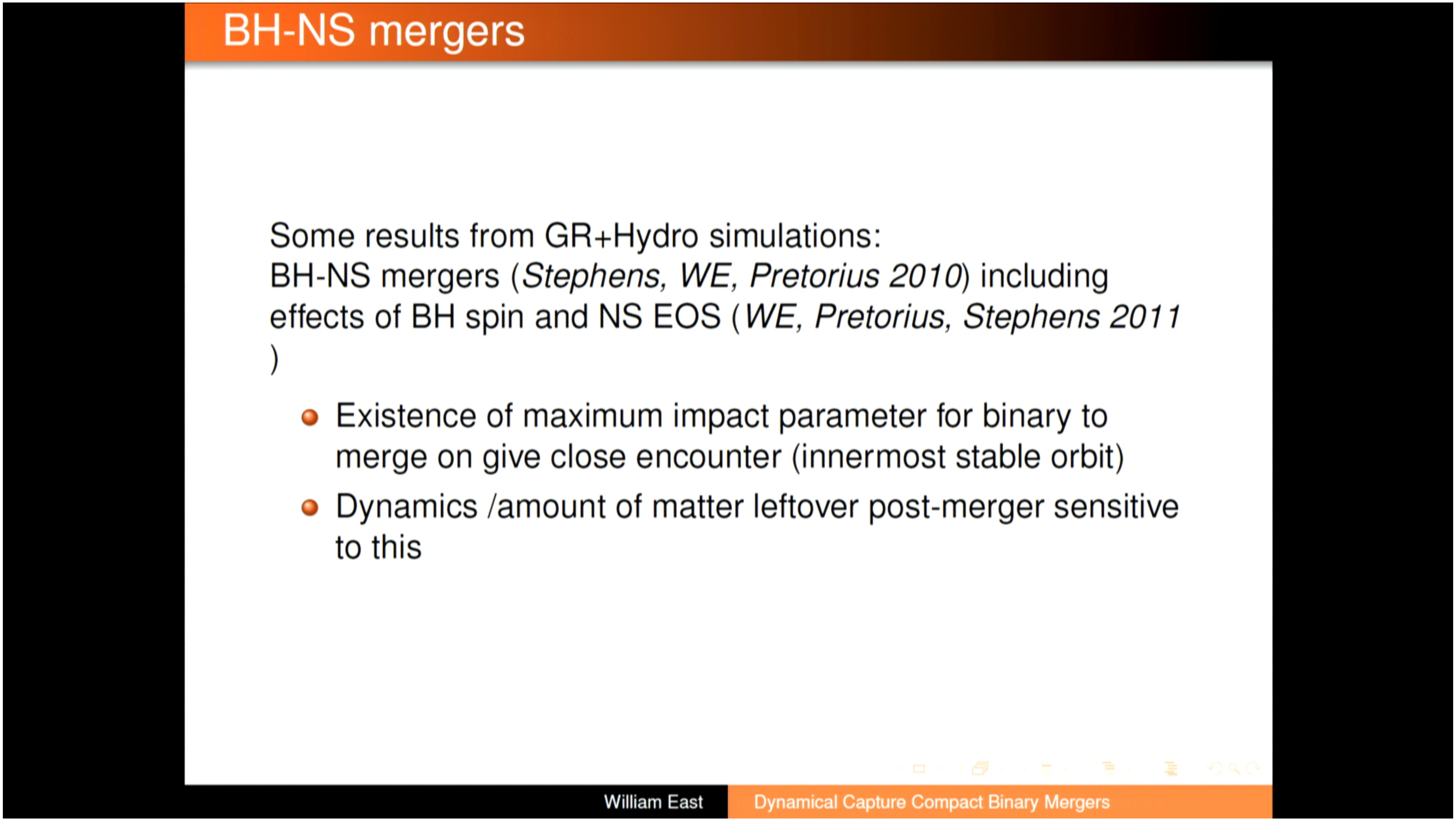
and equation of state: $P(\rho_0, \epsilon)$.
We solve the Einstein eqns. numerically in the generalized harmonic formulation and use conservative, high-resolution shock-capturing techniques for the hydrodynamics.
Still more physics (magnetic fields, radiation transport, modeling of NS crust,...) to add.



BH-NS mergers

Some results from GR+Hydro simulations:
BH-NS mergers (*Stephens, WE, Pretorius 2010*) including effects of BH spin and NS EOS (*WE, Pretorius, Stephens 2011*)

- Existence of maximum impact parameter for binary to merge on give close encounter (innermost stable orbit)
- Dynamics /amount of matter leftover post-merger sensitive to this



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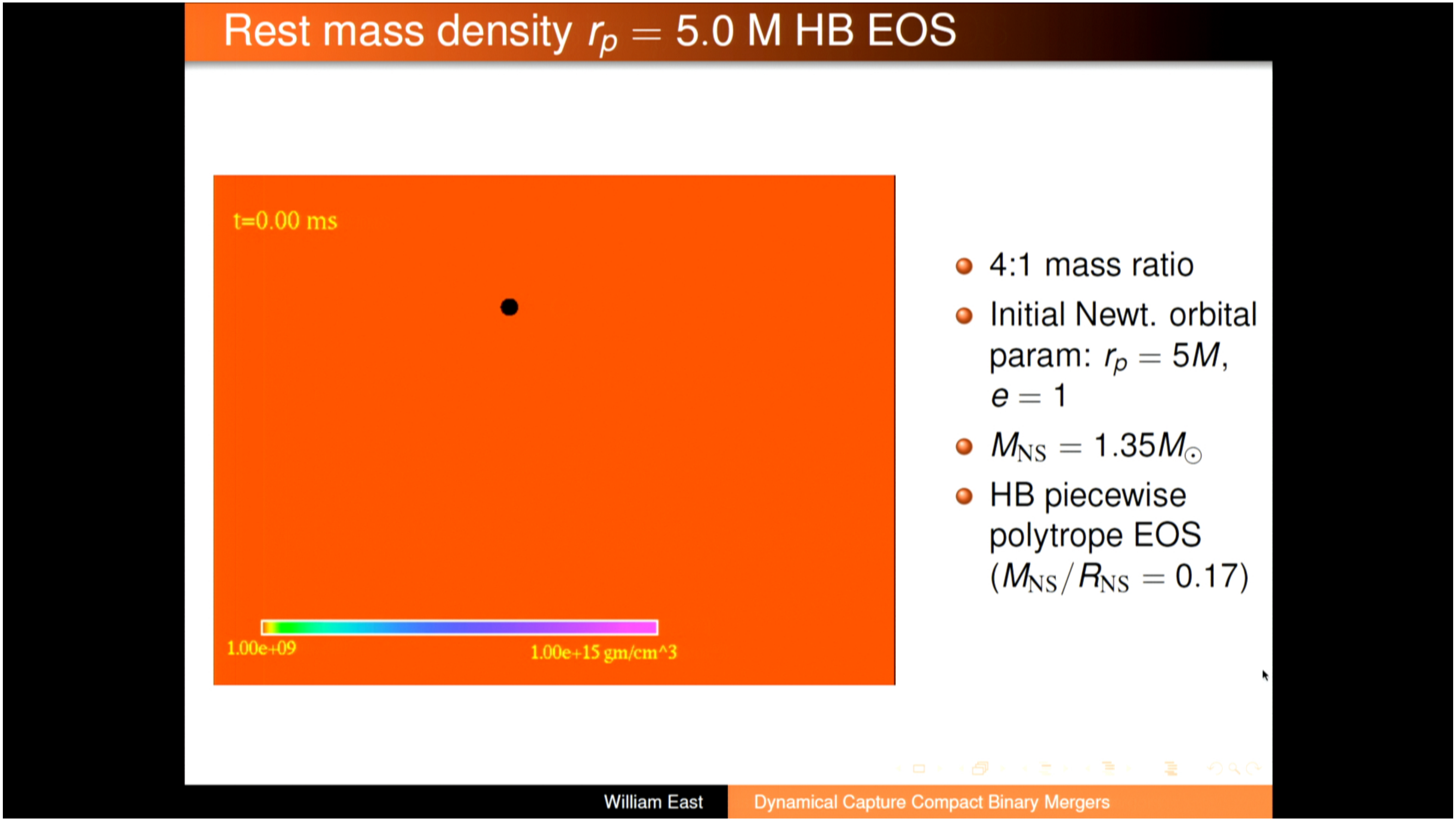
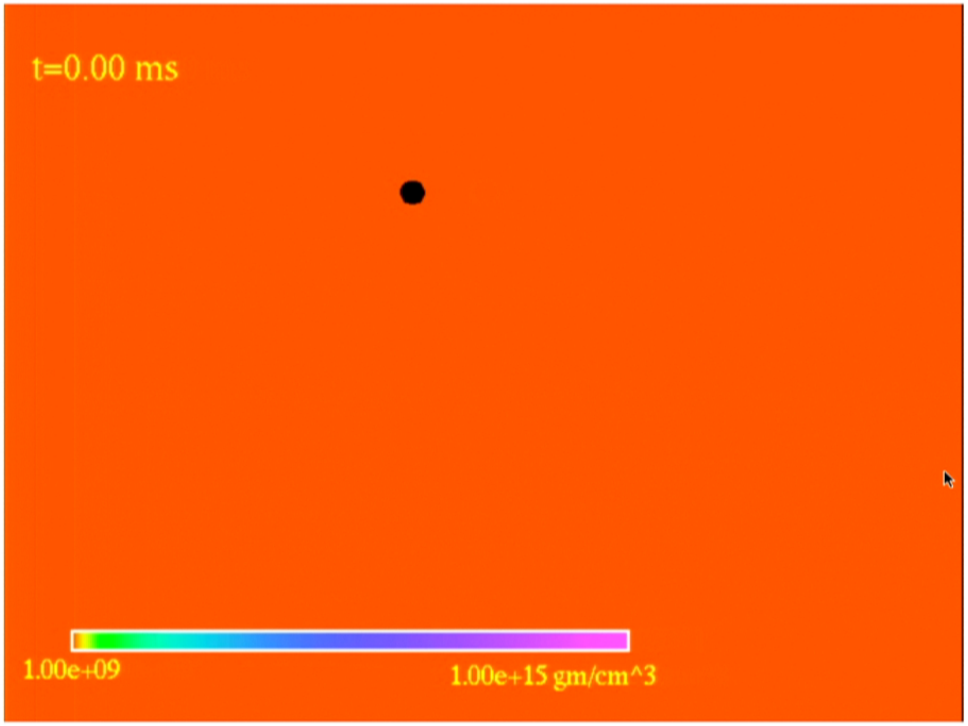


Rest mass density $r_p = 5.0$ M HB EOS

- 4:1 mass ratio
- Initial Newt. orbital param: $r_p = 5M$, $e = 1$
- $M_{\rm NS} = 1.35 M_\odot$
- HB piecewise polytrope EOS ($M_{\rm NS}/R_{\rm NS} = 0.17$)

Rest mass density $r_p = 6.81$ M HB EOS



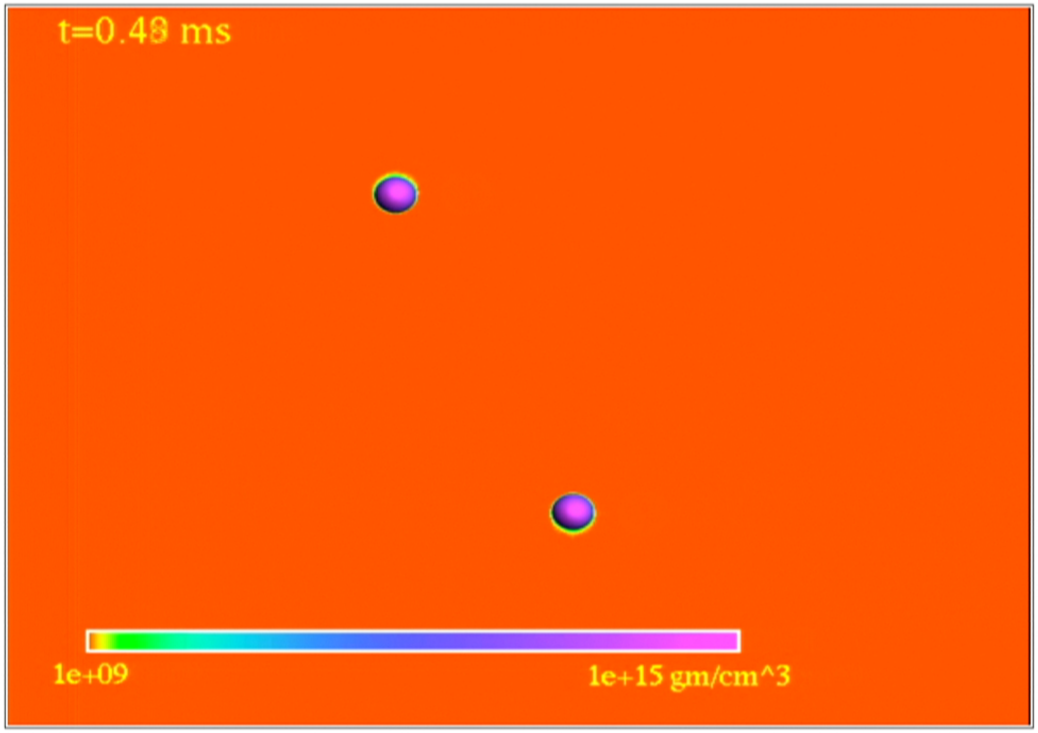
- 4:1 mass ratio
- Initial Newt. orbital param: $r_p = 6.8M$, $e = 1$
- $M_{\mathrm{NS}} = 1.35 M_\odot$
- HB piecewise polytrope EOS ($M_{\mathrm{NS}}/R_{\mathrm{NS}} = 0.17$)

BH-NS mergers

- Greatest amount of leftover matter for r_p just below threshold for merger. E.g. for $r_p = 6.81 \approx 20\%$ while $\lesssim 0.1\%$ $M_{\rm NS}$ for $r_p = 5$
- In some cases approximately half of material is unbound.
- In extreme cases there are episodes of significant mass transfer and f-mode excitation.

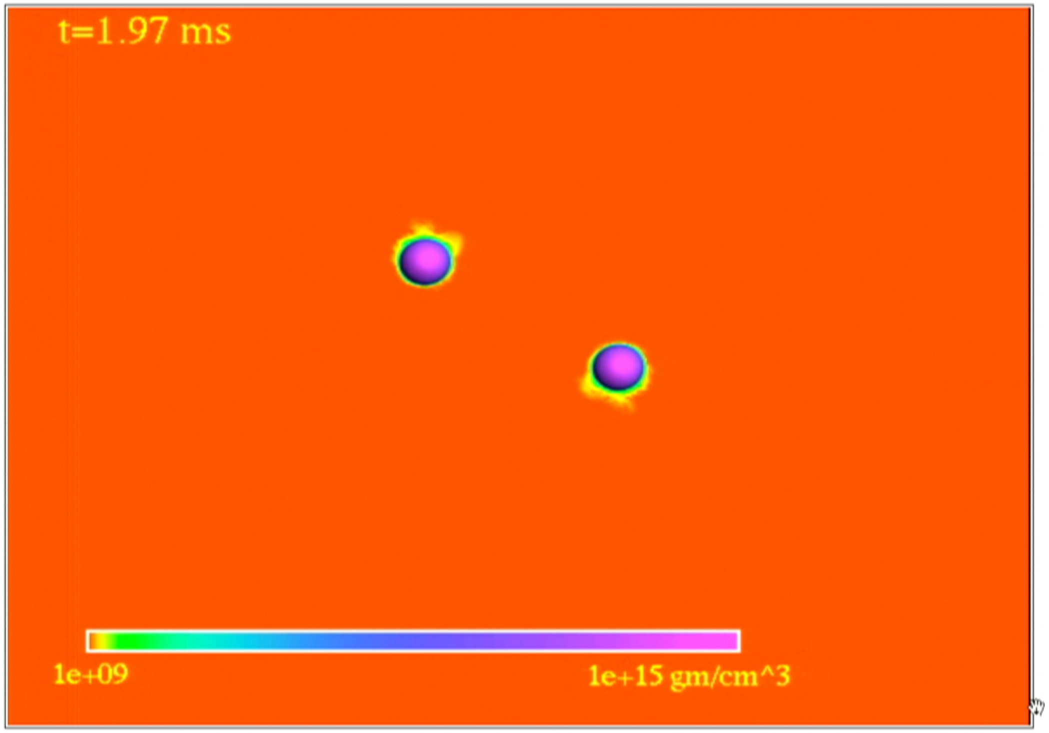
For retrograde spin, innermost stable orbit (ISO) is farther out, for prograde ISO is closer in. Stiffer EOS will give more tidal disruption.

Hypermassive NS case



- $M_1 = M_2 = 1.35M_\odot$
- Initial Newt. orbital param: $r_p = 7.5M$, $e = 1$
- HB piecewise polytrope EOS ($M_{\rm NS}/R_{\rm NS} = 0.17$, $M_{\rm max} = 2.12M_\odot$)

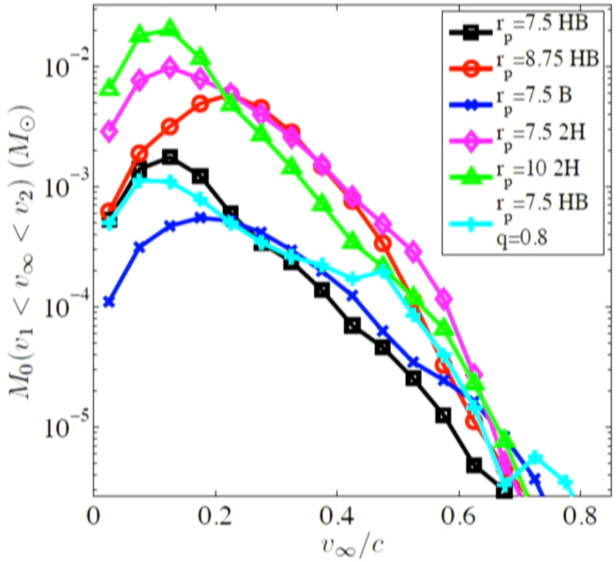
Non-merger close encounter



- $M_1 = M_2 = 1.35M_\odot$
- Initial Newt. orbital param: $r_p = 7.5M$, $e = 1$
- HB piecewise polytrope EOS ($M_{\rm NS}/R_{\rm NS} = 0.17$, $M_{\rm max} = 2.12M_\odot$)

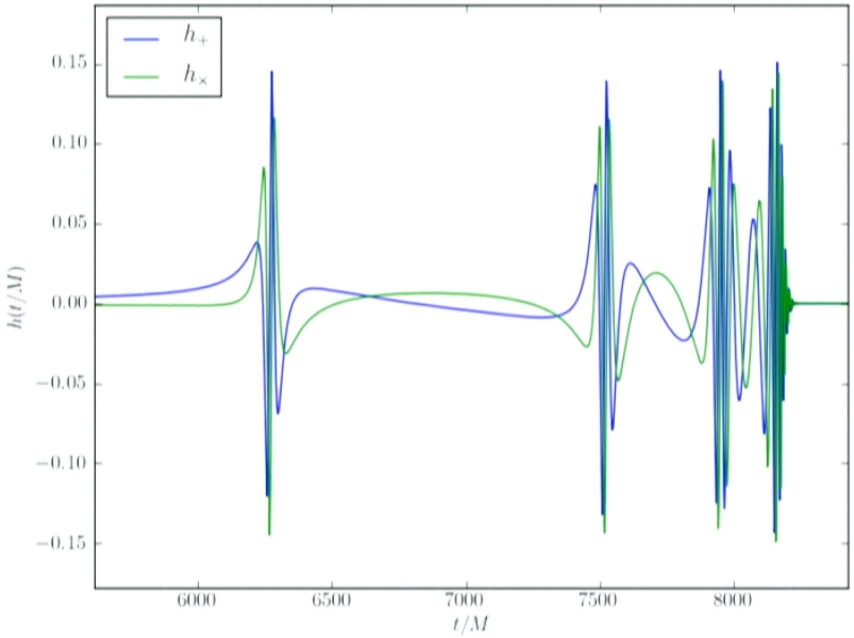
Possible electromagnetic transients

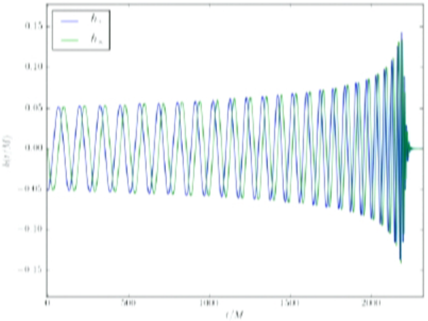
- Flaring from NS crust cracking ($\sim 10^{46}$ erg in elastic energy *Thompson & Duncan 1995*)
- Strong B-fields during HMNS collapse (*Lehner et al. 2011*)
- Short gamma-ray burst
- Kilonovae from ejecta (*Li & Paczynski 1998, Kulkarni 2005, Metzger 2010*) peaks $\sim$ day, $L \sim 4 \times 10^{42}$ erg/s in optical/near UV
- Radio waves from ejecta colliding with ISM (*Nakar & Piran 2011*), peaks in weeks with $F(\nu_{\rm obs}) \approx 0.4(\nu_{\rm obs}/{\rm GHz})^{-3/4}(d/100{\rm Mpc})^{-2}$ mJy



Gravitational wave signal

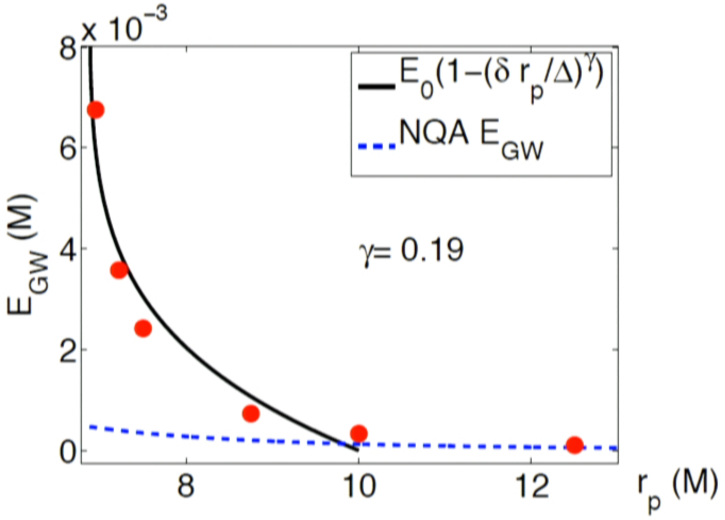
Series of bursts from close encounters followed by merger ringdown signal

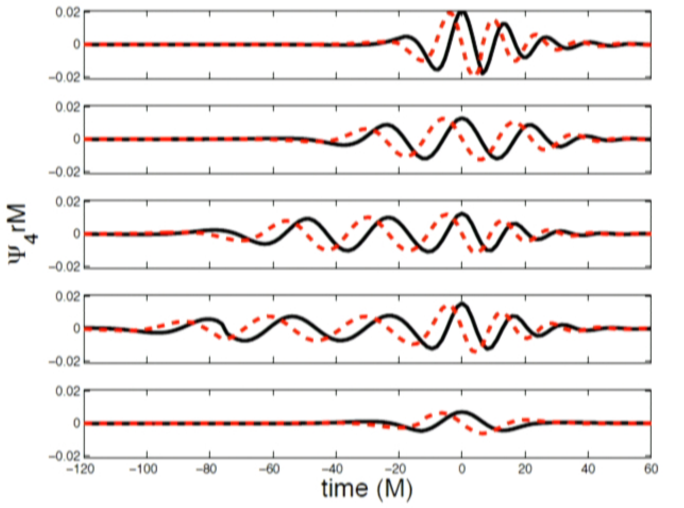




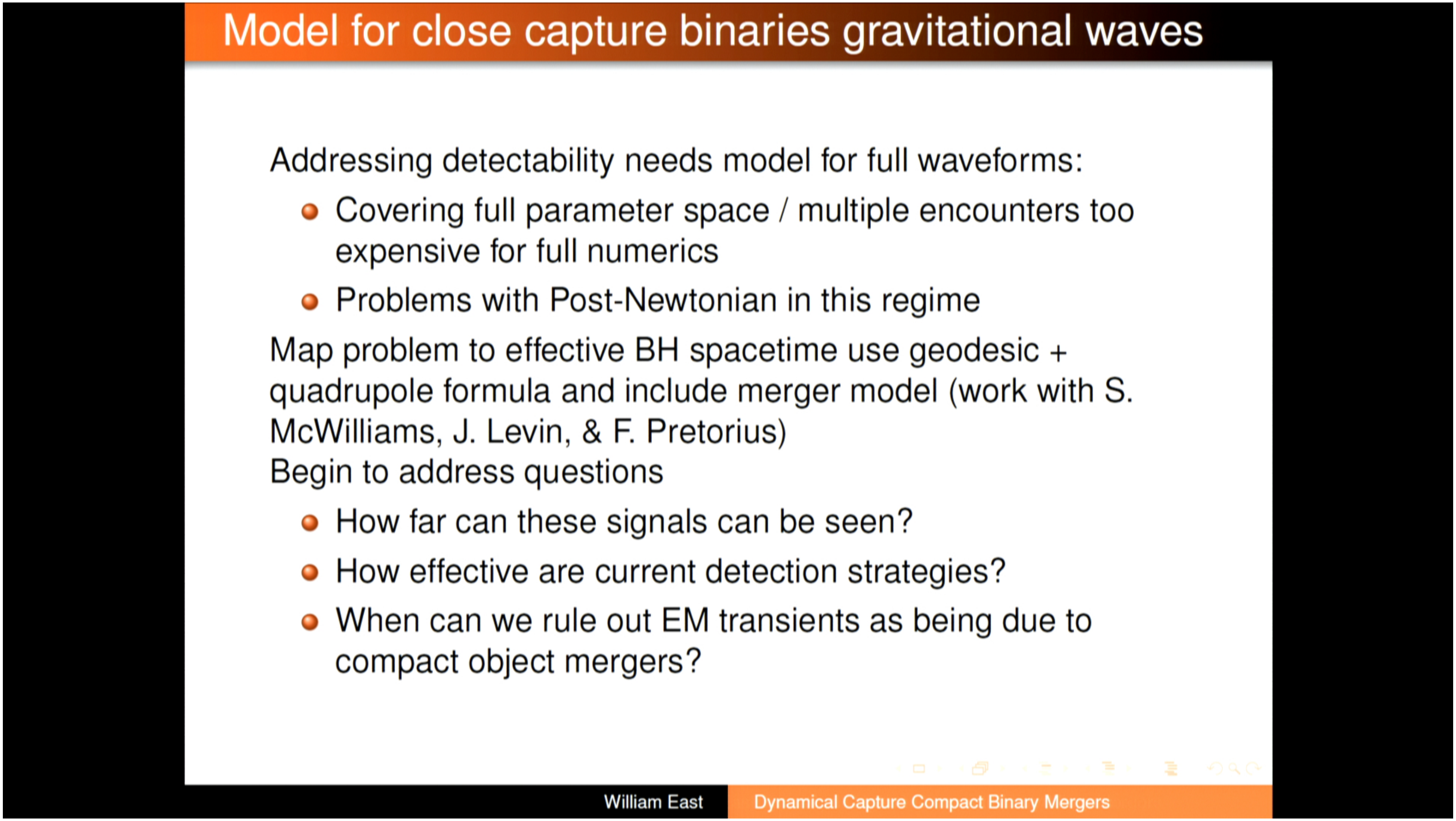
quasicircular for comparison

Strong-field gravitational wave signal





(top to bottom) $r_p = 5$ HB, $r_p = 6.81$ HB, $r_p = 7.5$, $e = 0.75$ HB, $r_p = 8.13$, $a = -0.5$ HB, and $r_p = 7.0$ 2H



Model for close capture binaries gravitational waves

Addressing detectability needs model for full waveforms:

- Covering full parameter space / multiple encounters too expensive for full numerics
- Problems with Post-Newtonian in this regime

Map problem to effective BH spacetime use geodesic + quadrupole formula and include merger model (work with S. McWilliams, J. Levin, & F. Pretorius)

Begin to address questions

- How far can these signals can be seen?
- How effective are current detection strategies?
- When can we rule out EM transients as being due to compact object mergers?

Detectability Results - Example

LIGO S5 run: Ruling out coincident gravitational waves to GRBs (using QC templates and burst searches)

GRB051103: candidate soft gamma repeater associated with M81/M82

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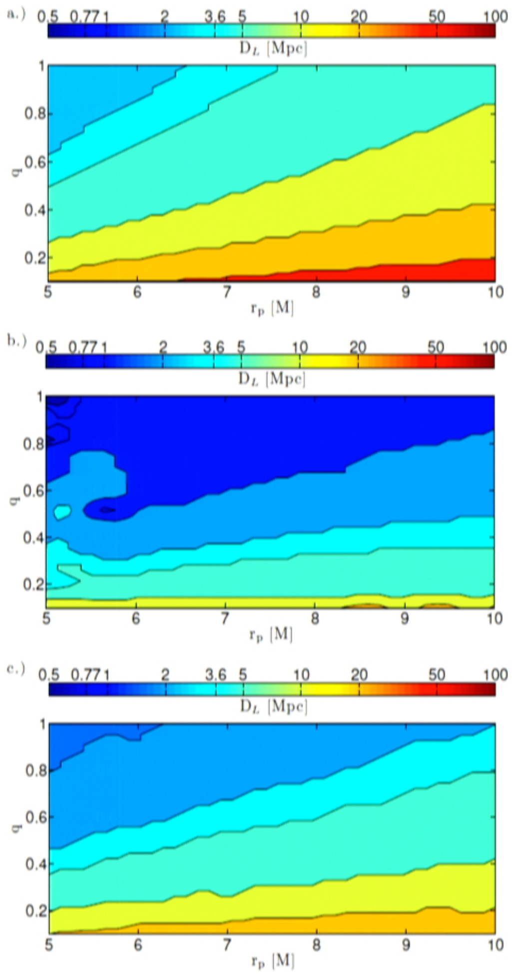
Detectability Results - Example



For initial LIGO, binary with 1.4 $M_\odot$ NS contours of luminosity distance with SNR=8 as function of mass ratio and initial periastron distance for:

a) ideal templates

b) sine-gaussian

c) incoherent stacking (mock-up)

$D_L = 3.6$ Mpc GRB051103

Conclusion

- Dynamical capture binaries show large variability in dynamics probing strong field gravity
- Possibility of large accretion disks, amounts of ejecta, crust cracking etc.
- However gravitational wave detection will require searches with methods designed for these signals