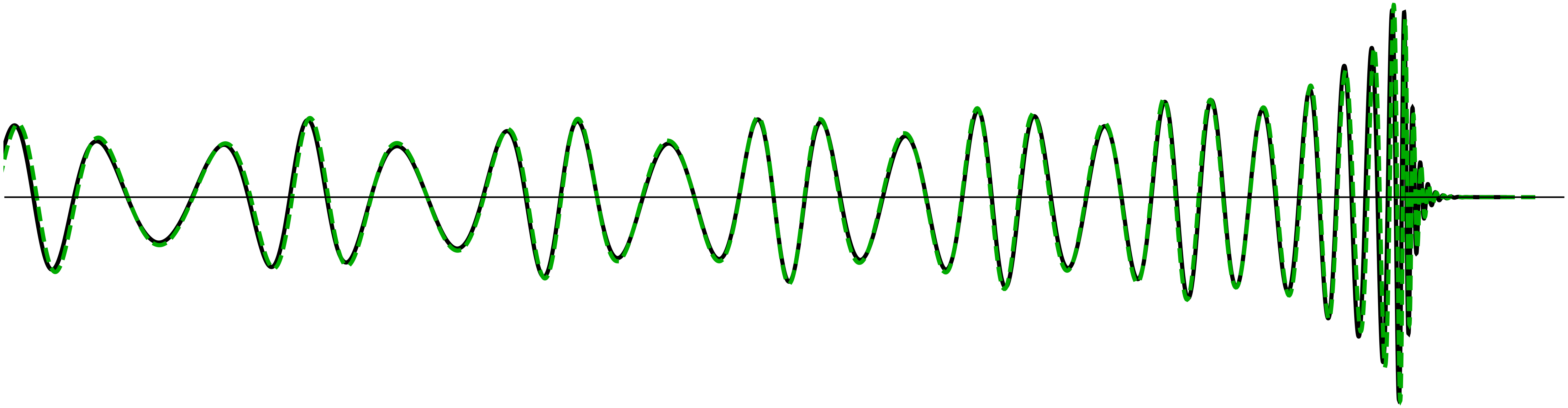

An eccentric binary black hole inspiral-merger-ringdown gravitational waveform model from post-Newtonian and numerical relativity

Ian Hinder

Max Planck Institute for Gravitational Physics
(Albert Einstein Institute)
Potsdam, Germany

Simulating
eXtreme
Spacetimes

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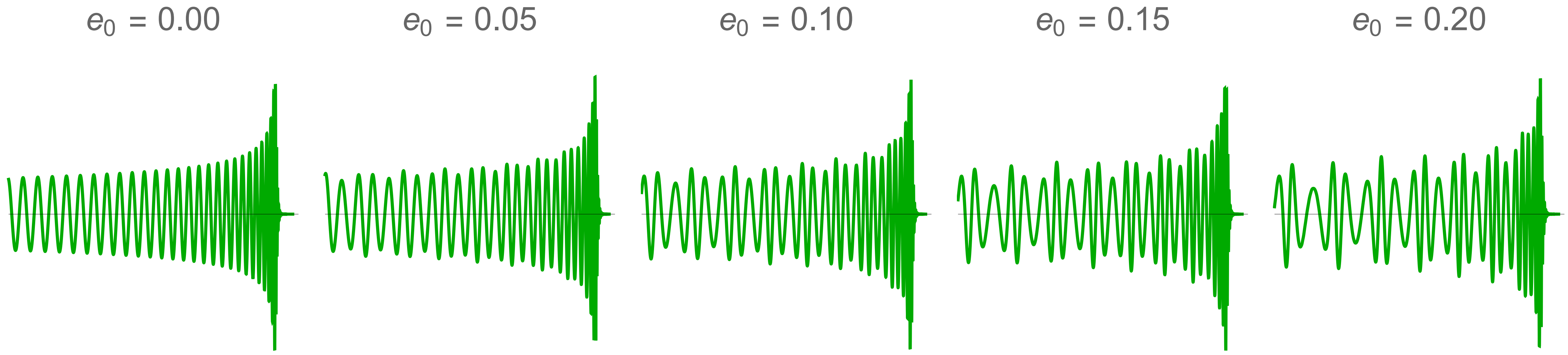
Introduction

- Eccentric binary systems **circularise** as E and L are emitted (Peters 1964)
- Eccentricity of BBH **expected** to be 0 well before merger
- Can we measure (bound) eccentricity of **GW events** such as GW150914?
- **Eccentric waveform model** could be compared with GW data to measure/constrain eccentricity
- Construct and test such a model using **Post-Newtonian** approximation and **Numerical Relativity**
- Only need late inspiral+merger; e.g. **last 5 orbits** for GW150914

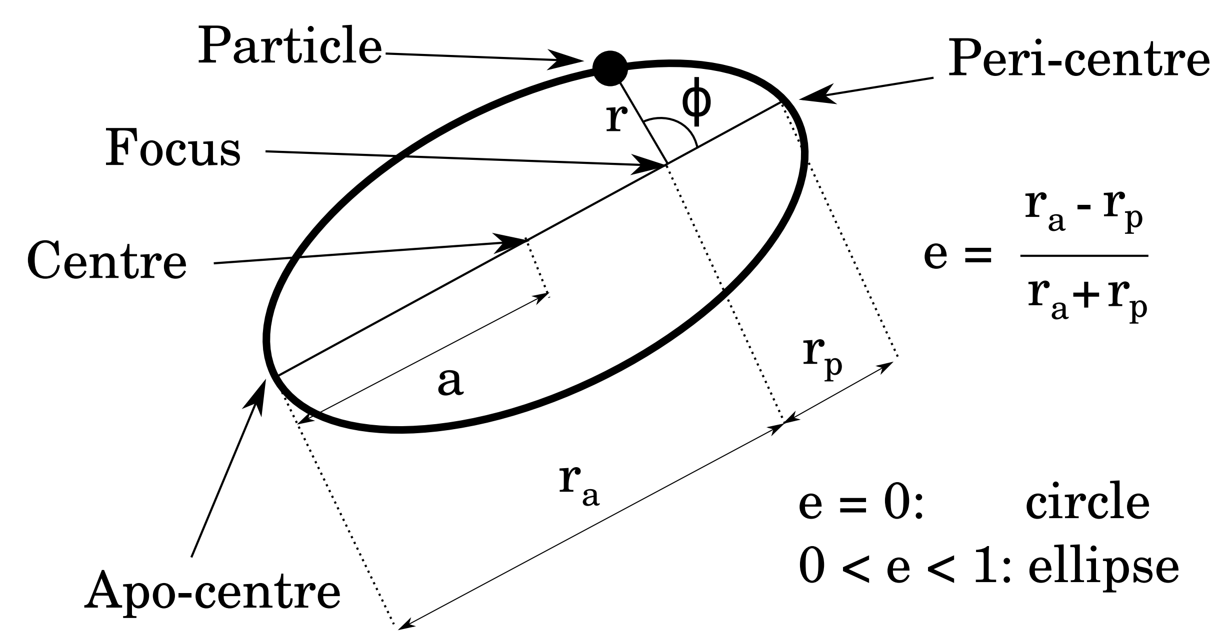
A selection of eccentric NR simulations

- ~12 orbits with the **SpEC** code
- Non-spinning
- Initial eccentricity **$e \leq 0.2$**
- $q = m_1/m_2 \leq 3$



Modelling the inspiral: the building blocks

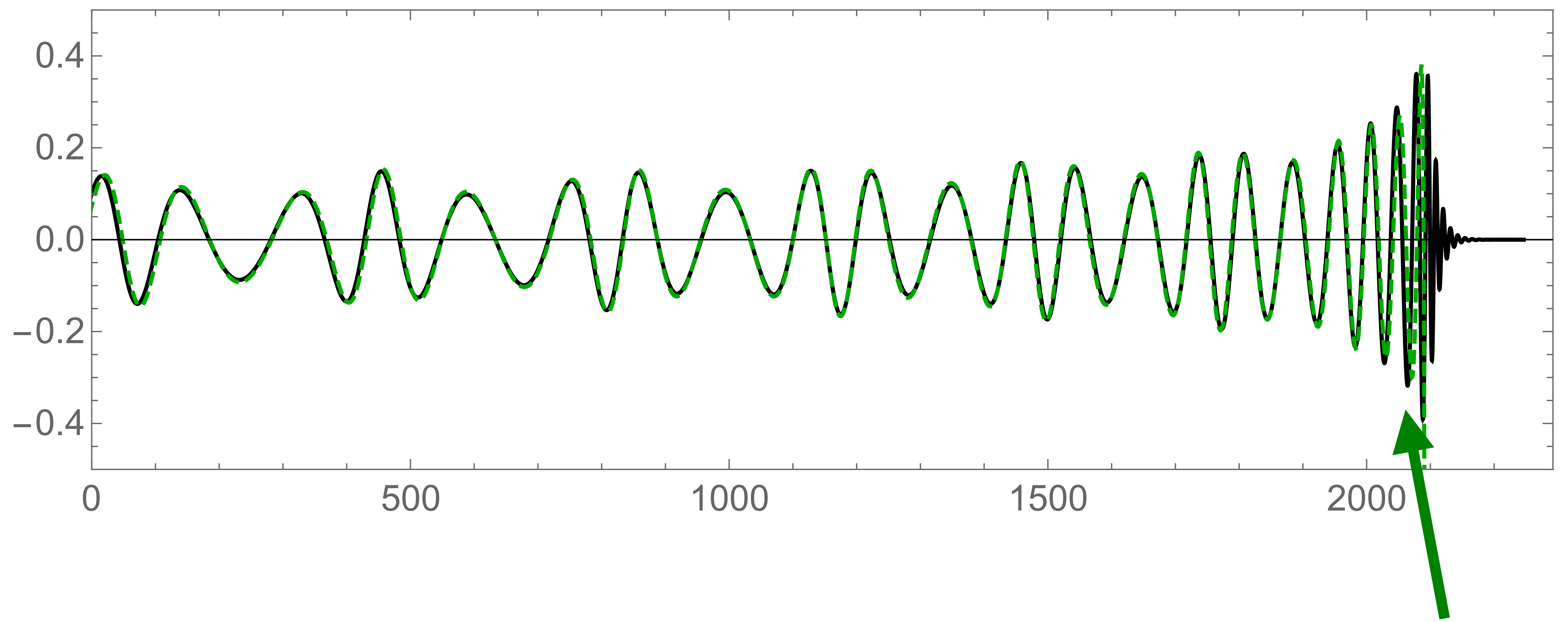
- **Post-Newtonian** model:
  - **Conservative** motion (without inspiral):
    - constant E and L
    - eccentricity **e**, semi-major axis **a**
    - r, ϕ in E and L (**3 PN**)
  - **Radiation reaction**:
    - Adiabatic constants E and L integrated from 2 **PN fluxes**
  - **Waveforms** 0 PN (restricted approximation):
    - h_+, $h_\times$ in r, ϕ



- See Hinder et al. 2010 for details
- Empirically found best agreement with NR for PN expansion variable x (TaylorT4 x when e -> 0)

Validation of PN inspiral against Numerical Relativity

- NR and PN agree well in inspiral for last ~10 orbits



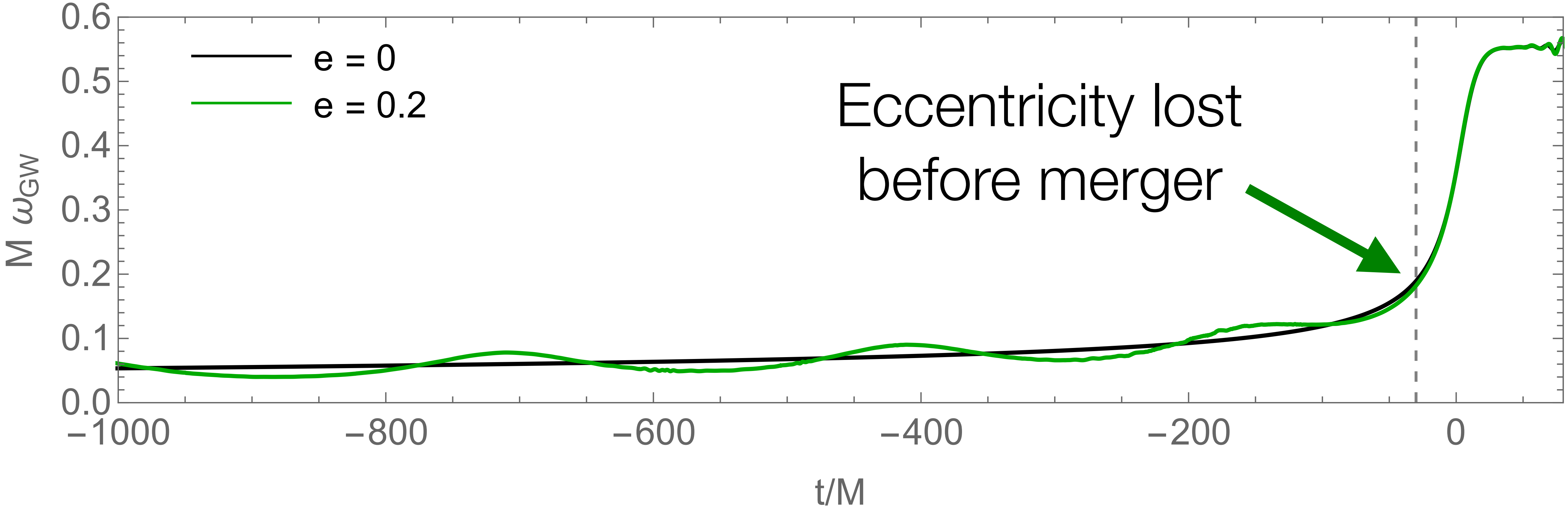
- **Fit** best PN (e,x,l,ϕ) over inspiral

How to model the merger?

- Use an **effective model** based on physical insight
  - Likely to generalise outside calibration parameter space
  - See talk by **Eliu Huerta** on Wednesday in C2 GW session
- Fitting to **NR simulations**
  - Sufficient if NR parameter space **covers region of interest**

What does an eccentric BBH merger look like?

- Eccentric mergers are **circular** (Hinder et al. 2008)

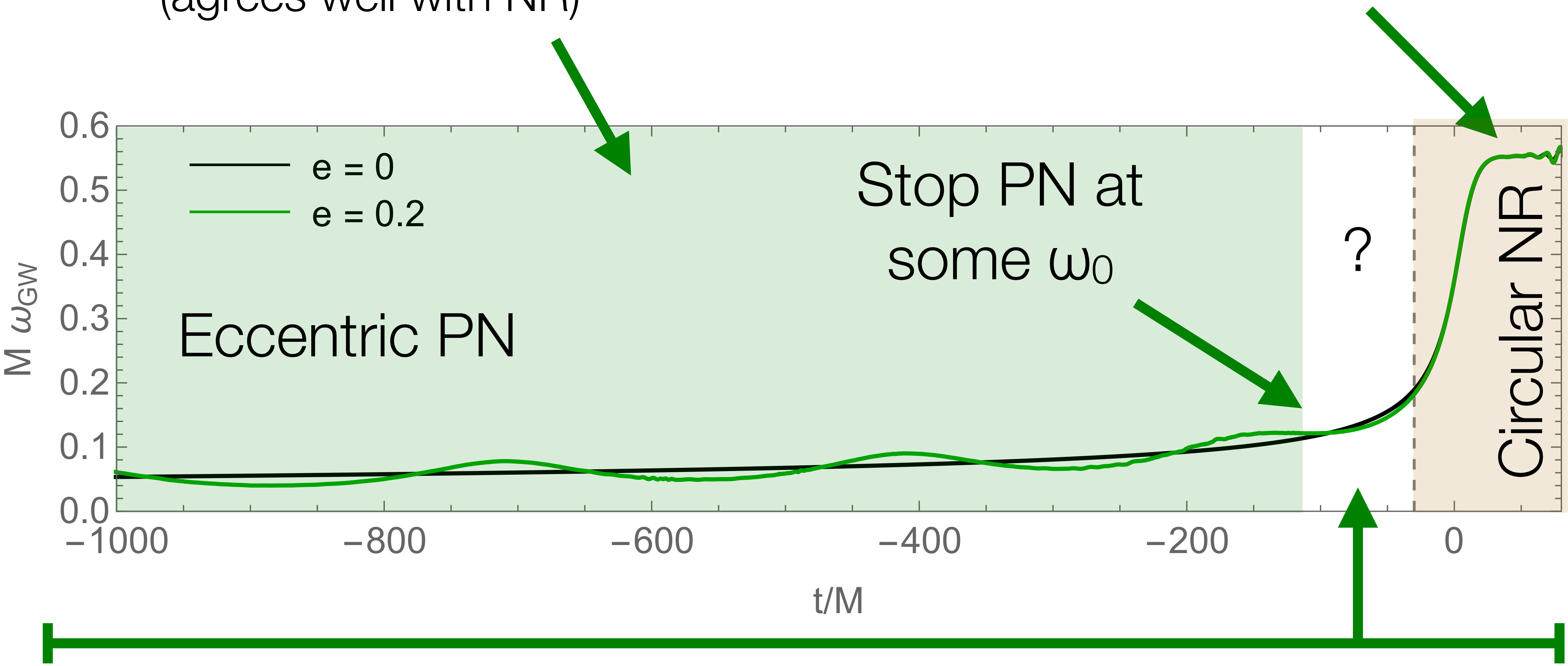


- Circularisation in **frequency** and **amplitude**
- New NR simulations:
  - Circularisation extends at least up to **q=3** for **e ≤ 0.2**

Construct IMR waveform

Use eccentric PN for inspiral (agrees well with NR)

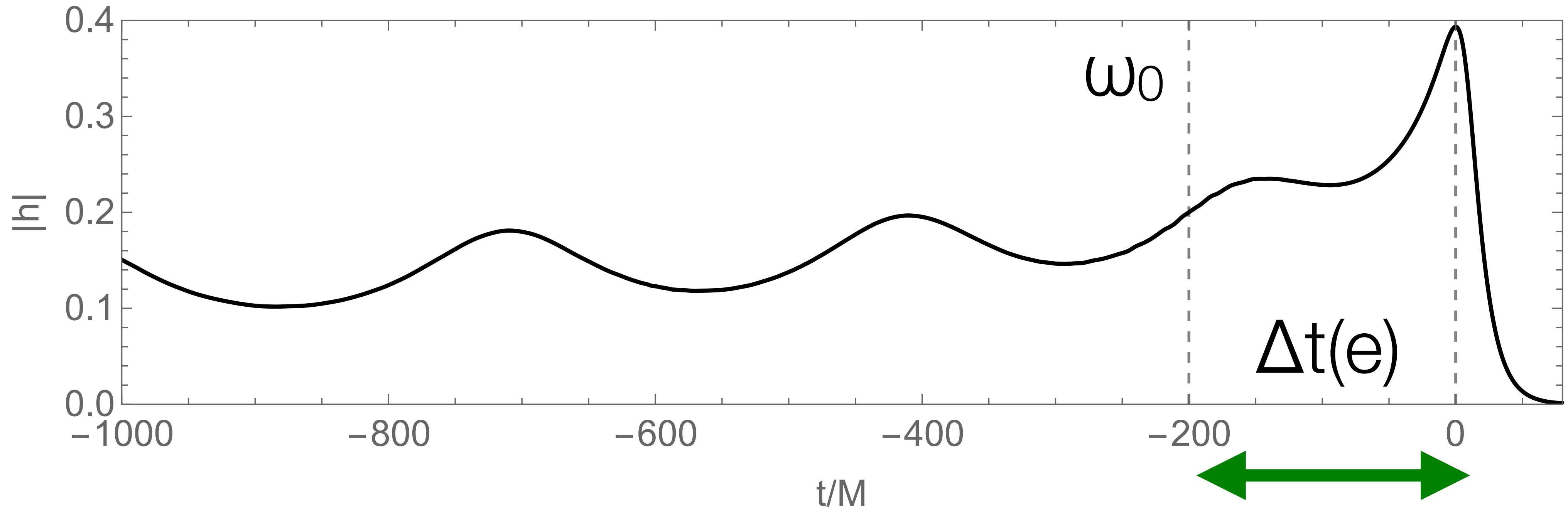
Use a known circular merger (EOB or NR)



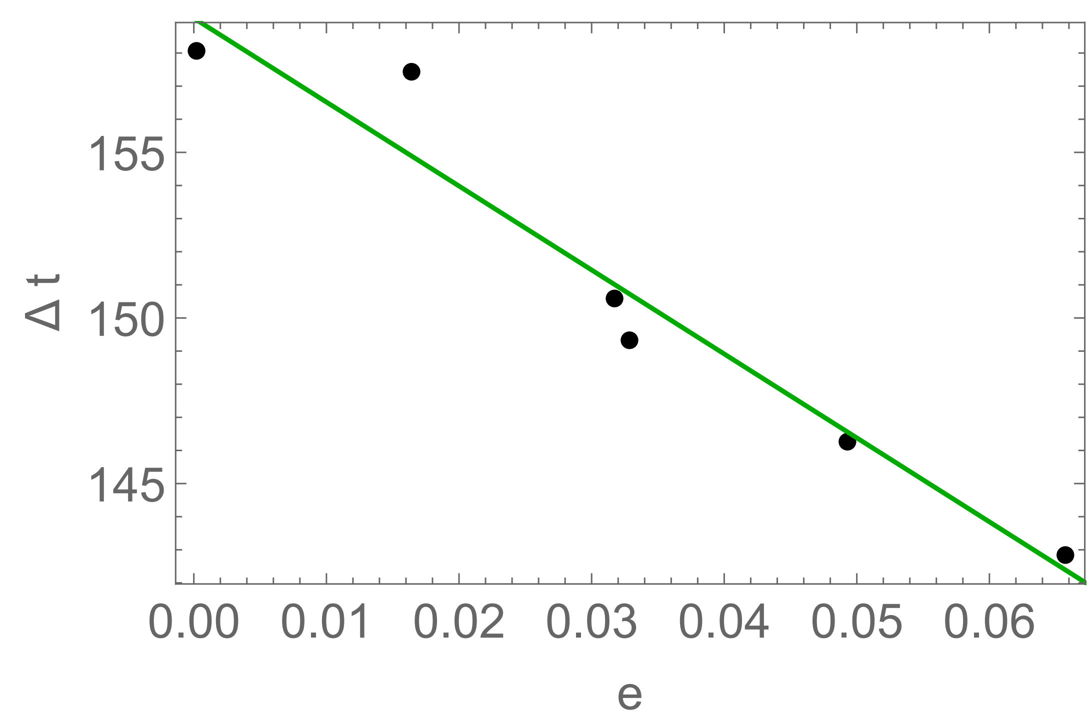
- Make a **best guess**; blend solutions or phenomenological fit
- Blend in **frequency** and **amplitude** of 2,2 mode
- Always validate against NR

Where to attach the merger?

- Need **time offset** from ω_0 to merger peak

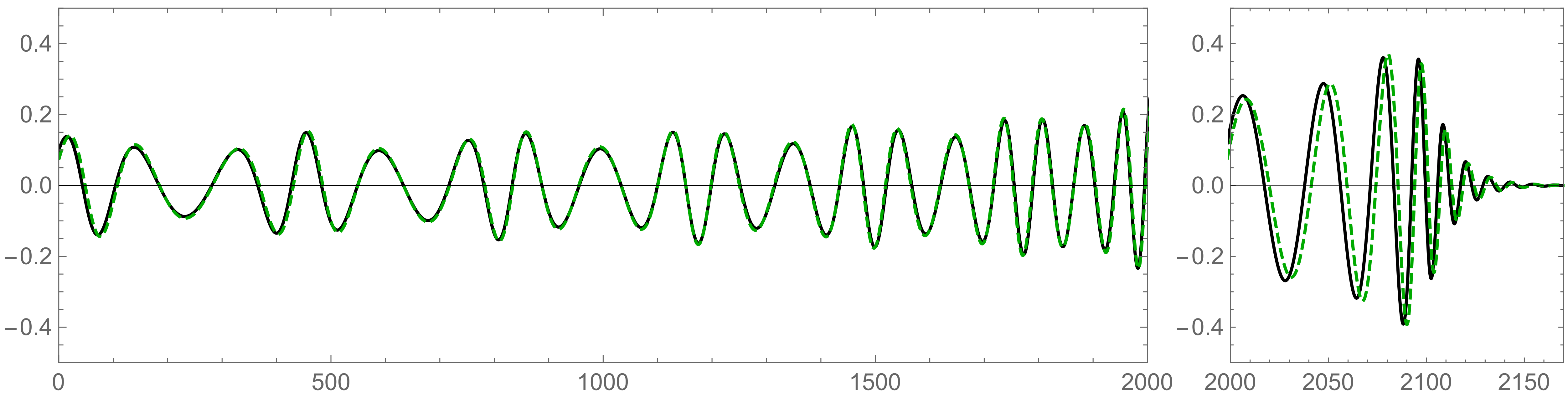


- Calibrate $\Delta t(e)$ from **NR**
- Can predict **merger time** as function of PN $e(\omega_0)$ to within ±2 M



Comparison between NR and IMR waveform

- Depending on choice of ω_0 and **fit window**:
  - Trade-off between dephasing at **merger** and in **early inspiral**
- Example here shows **accurate inspiral** but **dephasing** at merger
- For **short** waveform like GW150914, can instead favour merger

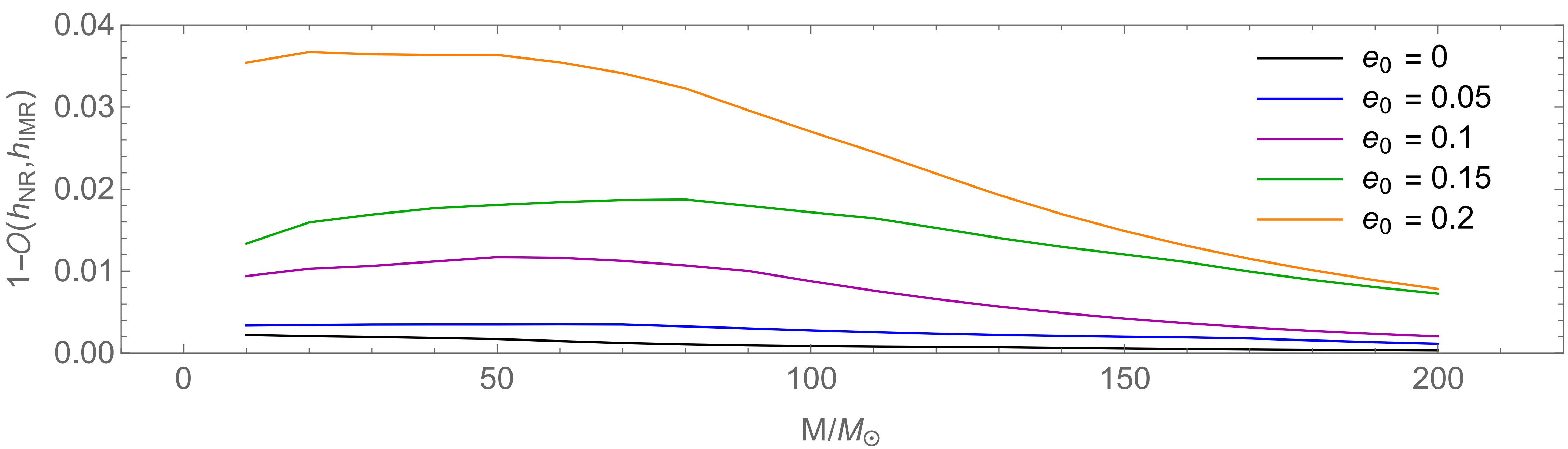


Unfaithfulness

- Compare NR and PN+NR IMR waveforms in the frequency domain

$$\mathcal{O}(h_1, h_2) = \max_{t_0,\phi_0} \frac{4}{||h_1|| \, ||h_2||} \mathrm{Re} \int_0^\infty \frac{\tilde{h}_1(f)\, \tilde{h}_2^*(f)}{S_n(f)} e^{i(2\pi t_0 f + \phi_0)} \, df$$

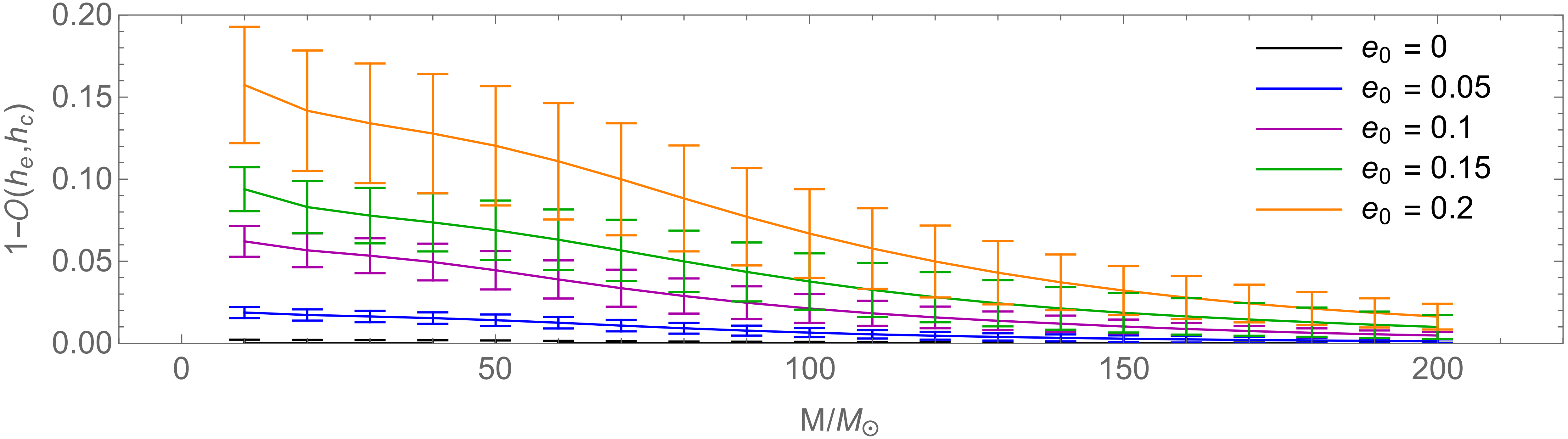
- Rough proxy for how well a GW detector can distinguish waveforms



- NR and IMR agree to **within 4%** unfaithfulness up to **e_0 = 0.2**

How does eccentricity affect unfaithfulness?

- Unfaithfulness between **NR circular** and **NR eccentric**
- Error bars show error in IMR model



- IMR model should be accurate enough to **distinguish eccentricities**

Conclusions and outlook

- **Eccentric inspiral-merger-ringdown BBH waveform model**, non-spinning, $q \lesssim 0.2$ calibrated to and tested against **Numerical Relativity** simulations
- Agreement with NR:
  - < **4% unfaithfulness** for $10\ M_\odot < M < 200\ M_\odot$
  - Model errors smaller than differences between eccentric and circular
- Future:
  - Assess implications for **measurement with LIGO**
  - Higher waveform **modes**
  - Improved **transition** from inspiral to merger
  - Add **spin** to PN model