Gravitational waves from neutron star - black hole binaries

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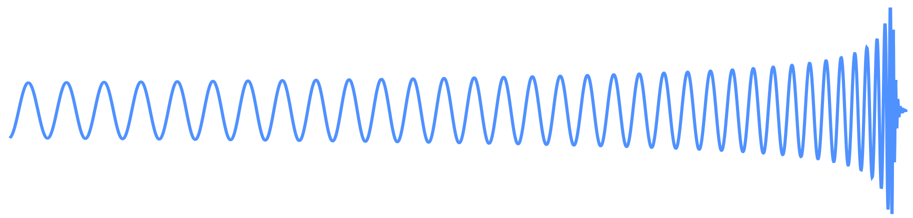
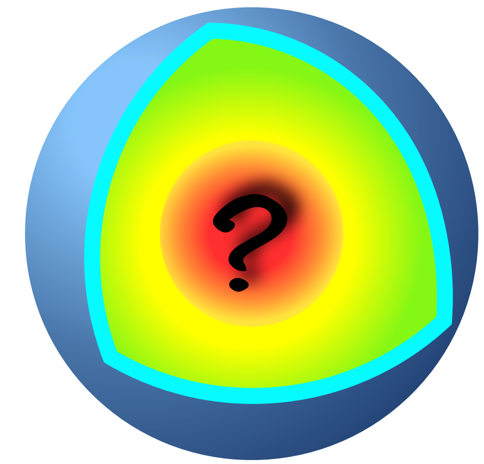
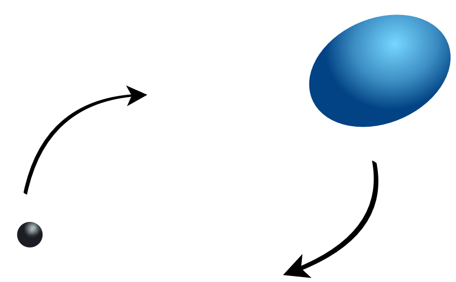
Overview

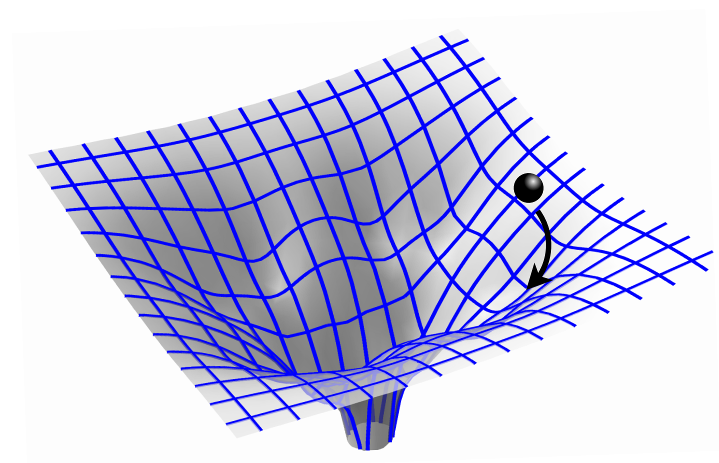
- Motivation



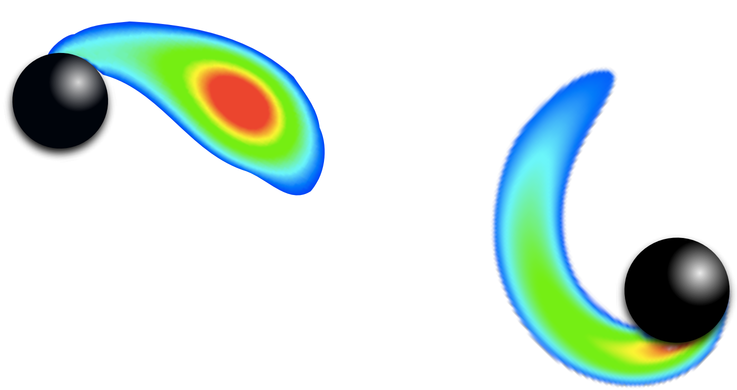


- Challenges for modeling neutron star-black hole binaries
    - mass ratios: *2 (?) - very large*
    - spins: BH *any*, NS *small*
    - NS *matter effects*



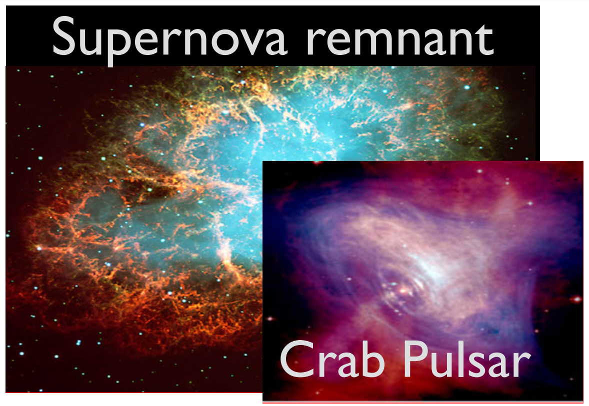


- Tidal effects during inspiral
- Tidal disruption

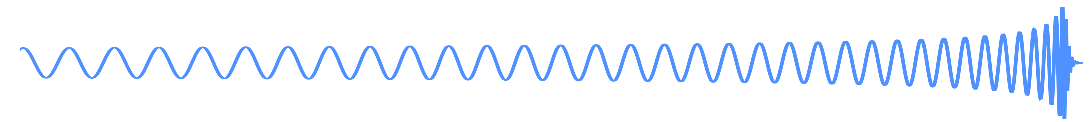


- Conclusions

Why care about neutron stars (NSs)?

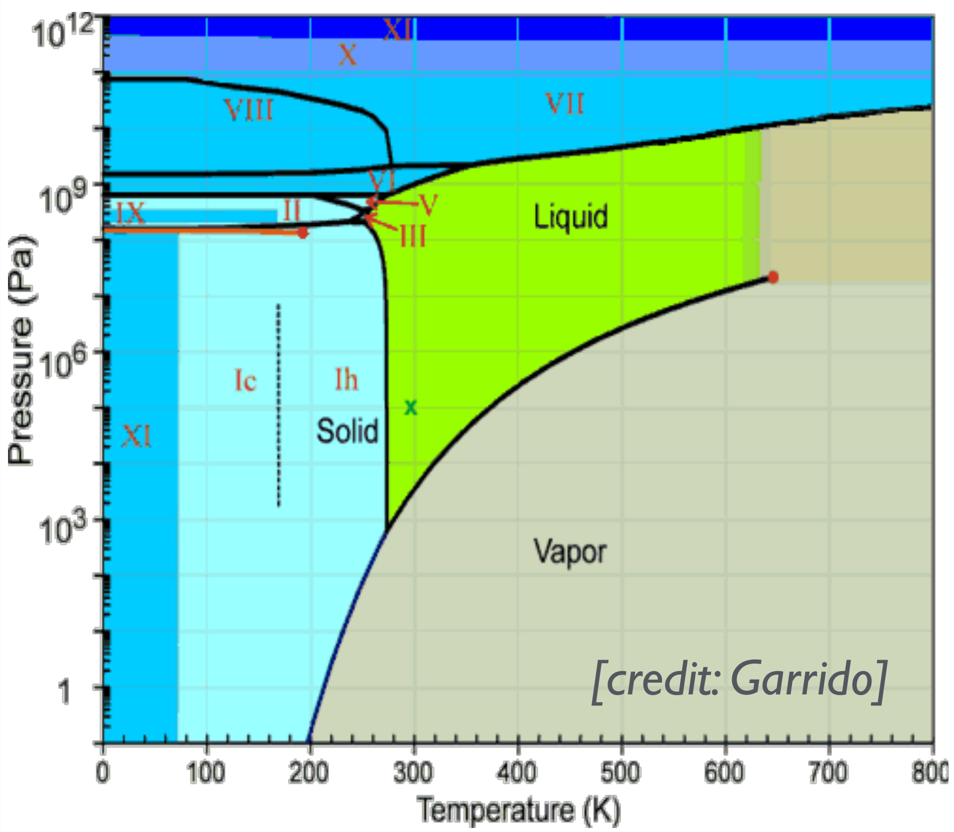


- stellar evolution
- short GRBs
- r-process elements

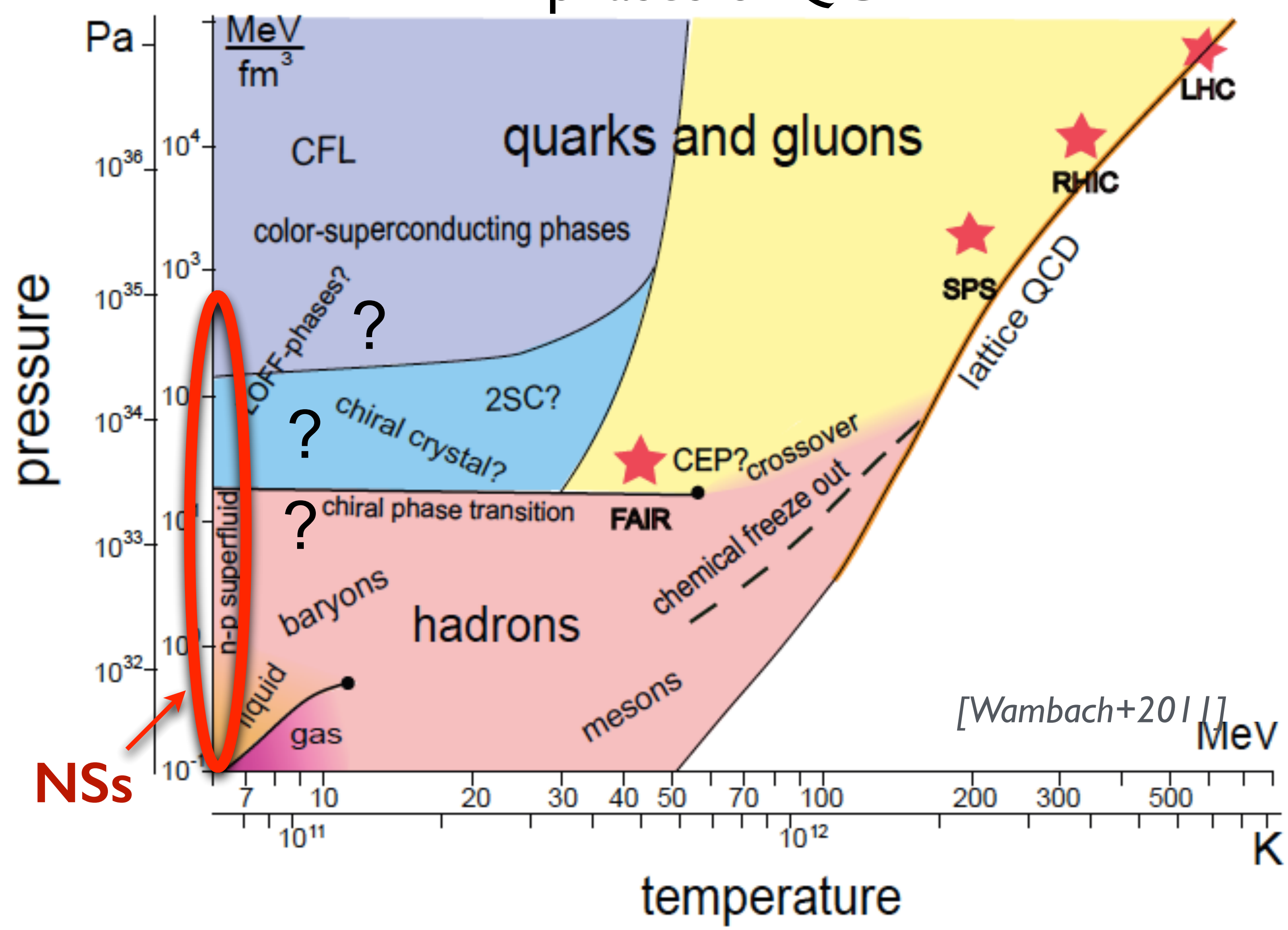


- key GW source: NS binaries
- multimessenger observations
- tests of GR (GWs, pulsars)

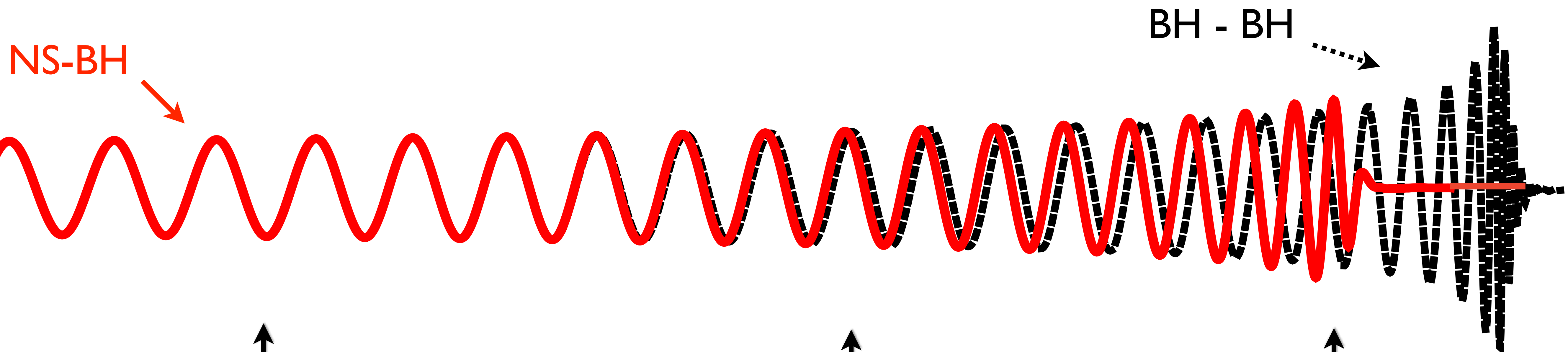
phase diagram for H_2O

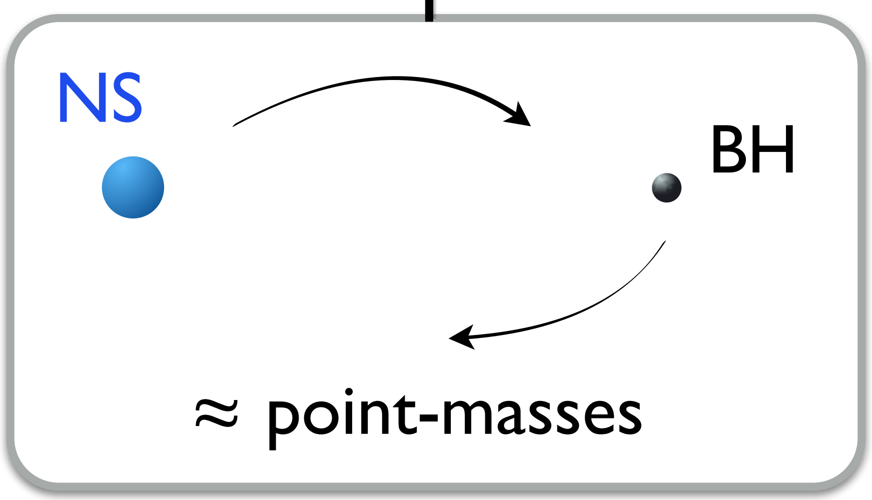


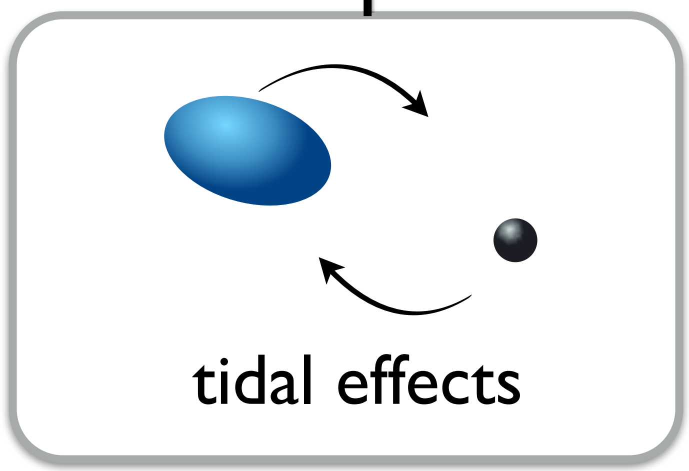
phases of QCD

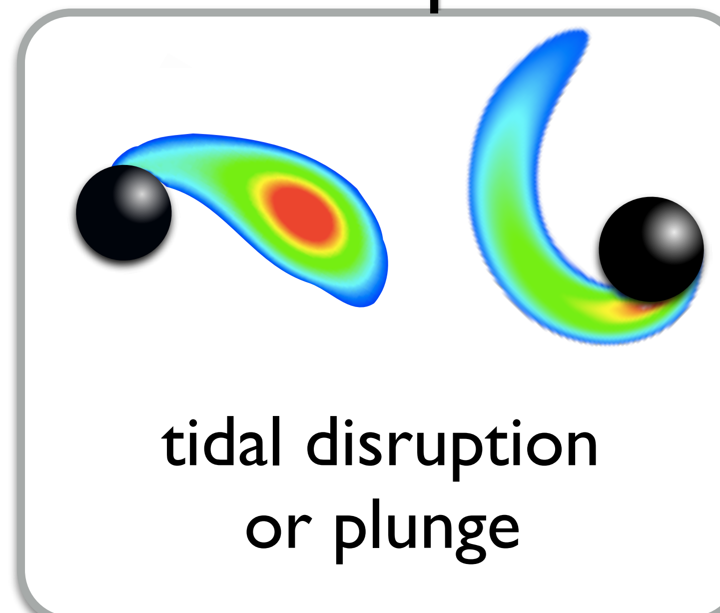


GW signal from NS-BH binaries









larger modeling uncertainty in point-mass GWs than for NS-NS

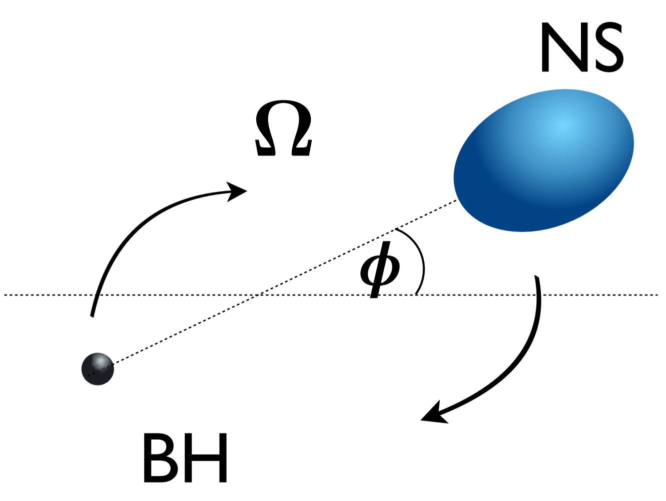
small $\sim \dfrac{1}{(1+q)^5}$

$$q = \frac{m_{\rm BH}}{m_{\rm NS}}$$

GW "shutoff" can be in aLIGO band

[data from F. Foucart]

Adiabatic tidal effects

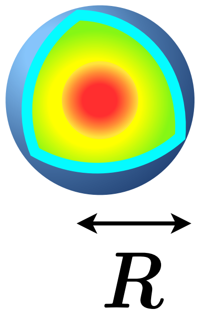


- dominant effect: adiabatic tides (AT)
- induced deformation (fundamental ℓ-modes):

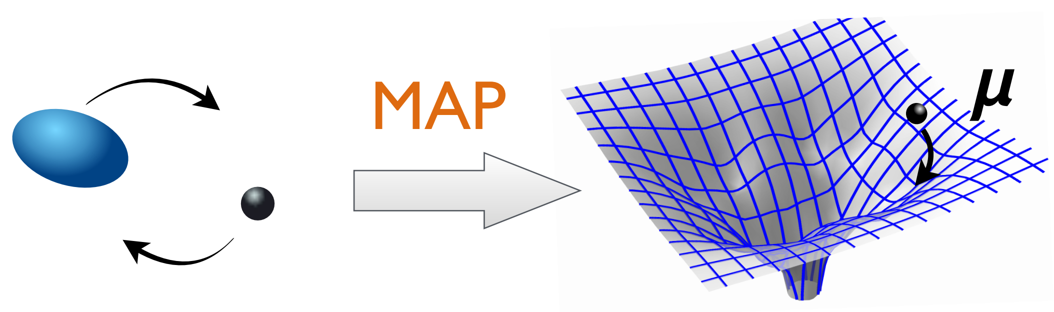
$$Q_{\ell m}^{\mathrm{AT}} = -\lambda_\ell \underbrace{\mathcal{E}_{\ell m} e^{-im\phi}}_{\text{BH's tidal field}}$$

$$\lambda_\ell = \frac{2(\ell-2)}{(2\ell-1)!!} k_\ell R^{2\ell+1}$$

↑ Love number



Adiabatic tides in the EOB Hamiltonian



$$ds^2_{\rm eff} = -A dt^2 + B dr^2 + r^2 d\phi^2$$

$$A = A^{\rm pp}(M,\nu,r) - \lambda_\ell A^{\rm AT}(M,\nu,r)$$

[Damour, Nagar, Bini, Faye, Bernuzzi+2009-2014]

- different possibilities for $A^{\rm AT}$:

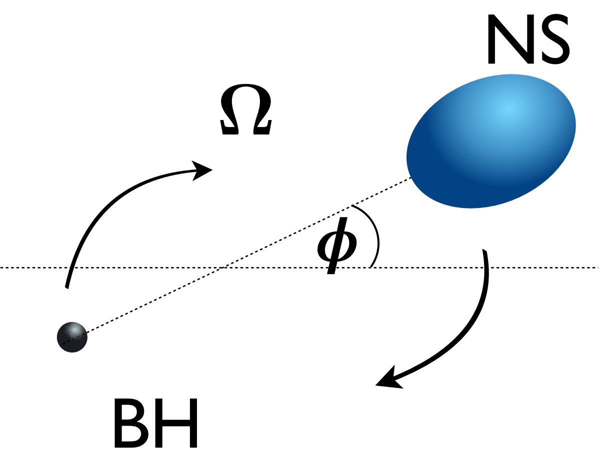
- 2PN, Taylor expanded: $A^{\rm AT}_{\rm PN} = \frac{3q}{r^6}\left[1 + \frac{p_1(\nu)}{r} + \frac{p_2(\nu)}{r^2} + O\left(\frac{1}{r^3}\right)\right]$

- self-force: $A^{\rm AT}_{\rm GSF}(M,\nu,r) = \frac{3q}{r^6}\left[1 + \frac{3}{r^2\left(1-\frac{r_{\rm LR}}{r}\right)} + \frac{g_1(r)}{q\left(1-\frac{r_{\rm LR}}{r}\right)^{7/2}} + O\left(\frac{1}{q^2}\right)\right]$ $r_{\rm LR}$=light ring

- tuned GSF: $A^{\rm AT}_{\rm tGSF}(M,\nu,r) = \frac{3q}{r^6}\left[1 + \frac{3}{r^2\left(1-\frac{r_{\rm LR}}{r}\right)} + \frac{g_1(r)}{q\left(1-\frac{r_{\rm LR}}{r}\right)^{7/2}} + \frac{p_2''(\nu)/2}{q^2\left(1-\frac{r_{\rm LR}}{r}\right)^{p}}\right]$

adjustable: $4 \le p \le 6$

Dynamic tides



- $Q_{\ell m}$ corresponds to the NS's fundamental oscillation modes

$$\omega_f \sim \sqrt{m_{\rm NS}/R^3} \qquad \text{(internal structure - dependent)}$$

- **tidal forcing** frequency: $m\Omega \sim m\sqrt{M/r^3}$

- extended body description: forced harmonic oscillators

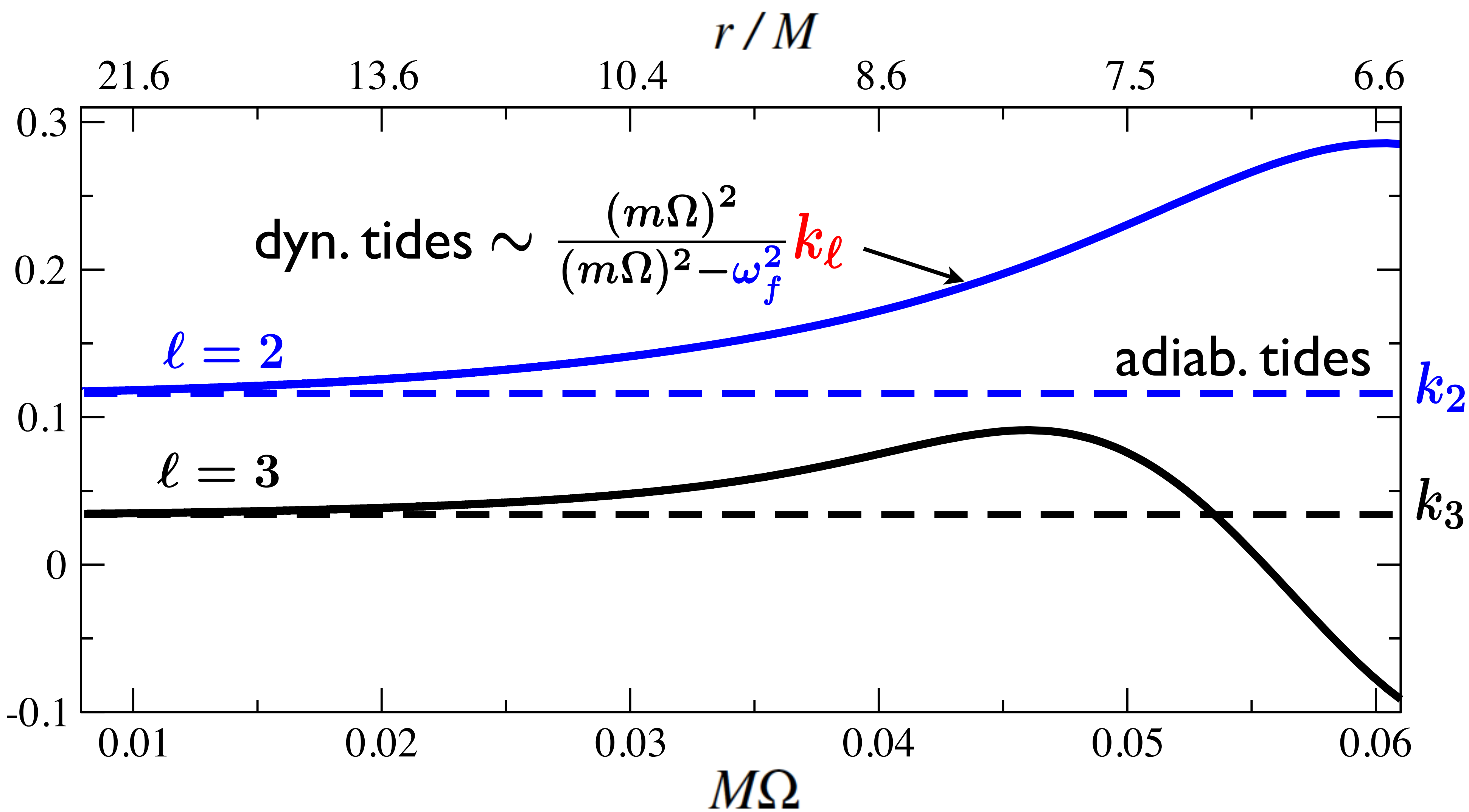
$$L = L_{\rm orbit} + \sum_{m=-\ell}^{\ell} \left[-\frac{z}{2} Q_m E_m e^{-im\phi} + \frac{1}{4\lambda z^2 \omega_f^2} \left(\dot{Q}_m^2 - z^2 \omega_f^2 Q_m^2 \right) + L_{\rm frame} \right]$$

redshift

coupling betw. orbital and Q_{lm}'s angular momentum

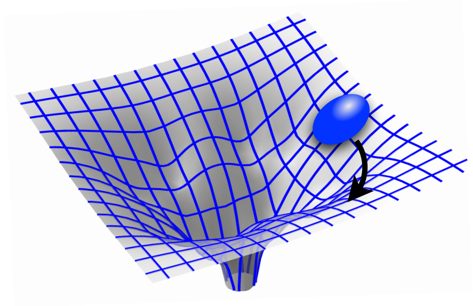
Jan Steinhoff's talk after the coffee break

NS's tidal response during the inspiral



EOB Hamiltonian with dynamic tides

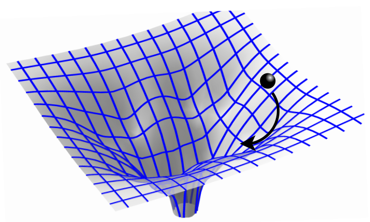
- full evolution: $H_{\rm EOB}(r, p_r, p_\phi, Q_{\ell m}, P_{\ell m}; M, \nu, \lambda_\ell, \omega_f)$



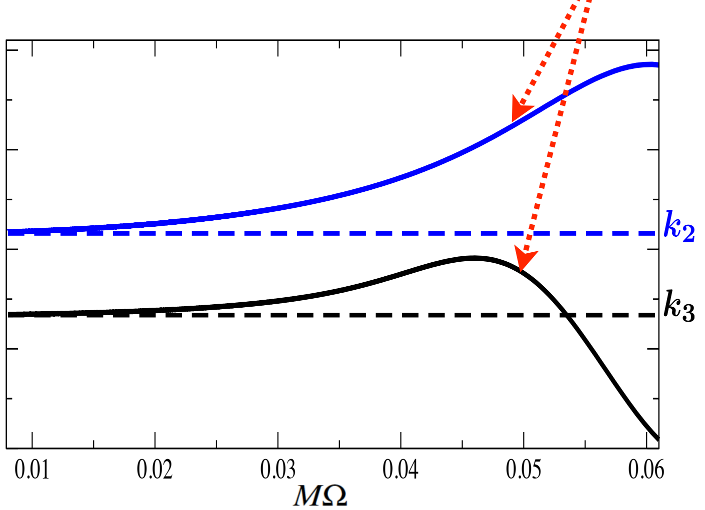
Jan Steinhoff's talk

- effective description from a two-timescale composite expansion for Q_{lm}:

$$A = A^{\rm pp}(M,\nu,r) - \lambda_\ell^{\rm eff} A_{\rm PN}^{\rm AT}(M,\nu,r)$$



$$\frac{\lambda_\ell^{\rm eff}}{\lambda_\ell} \sim \frac{\omega_f^2}{\omega_f^2 - (m\Omega)^2} \;\&\; \frac{\omega_f^2}{(\phi-\phi_f)} \;\&\; \cos\left[(\phi-\phi_f)^2\right] \mathrm{FresnelS}(\phi-\phi_f)$$



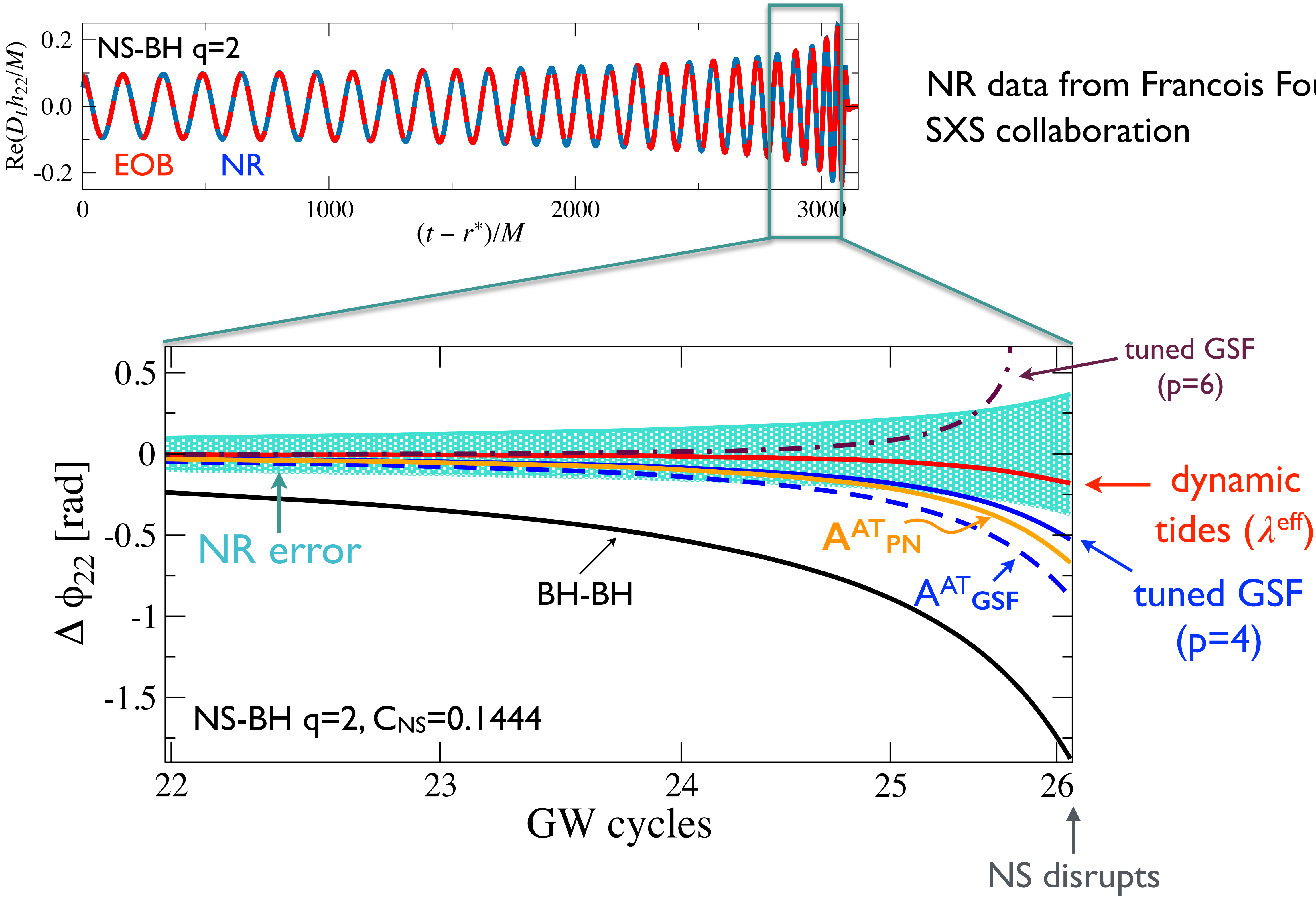
before resonance

— common term

near resonance where $\phi \sim \phi_f$

all fns. of $\{M, \nu, \omega_f, r\}$ using a Newtonian inspiral

Performance of the tidal EOB model



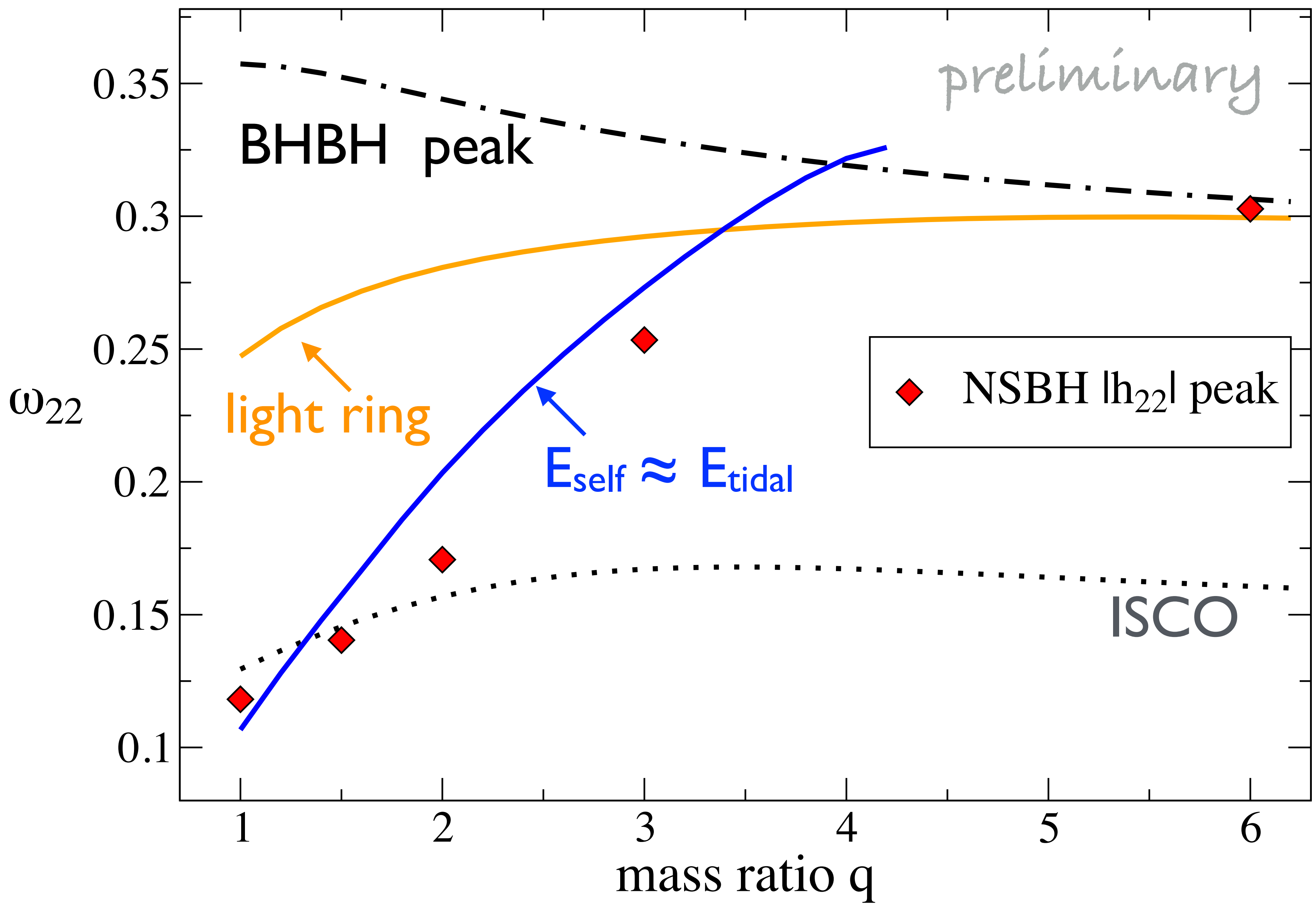
NR data from Francois Foucart, SXS collaboration

- similar results for NS-NS binaries

When to expect tidal disruption

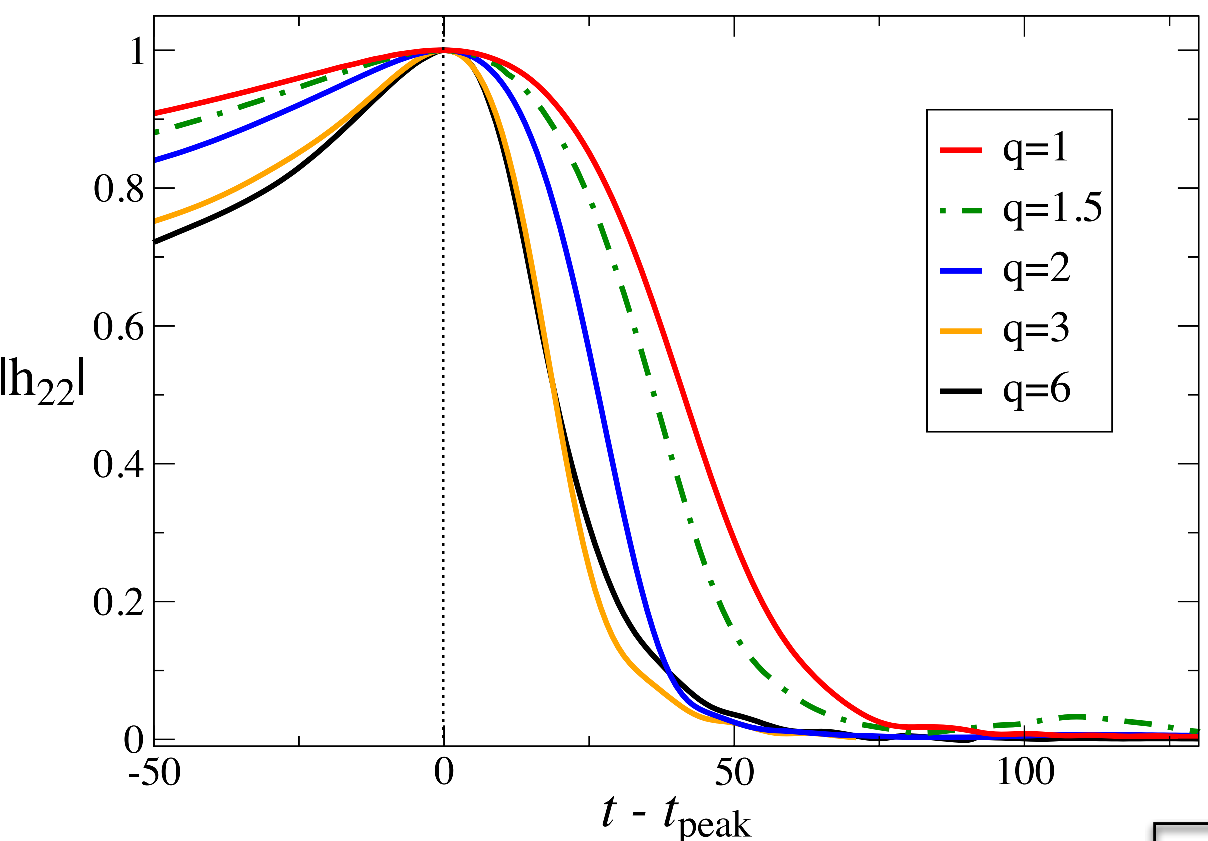
- approximate estimate: $E_{\text{self-gravity}} \approx E_{\text{tidal}}$

$(m_{\text{baryons}} - m_{\text{ADM}})$ $\quad$ $(H_{\text{EOB}}^{\text{PP}} - H_{\text{EOB}}^{\text{tidal}})$

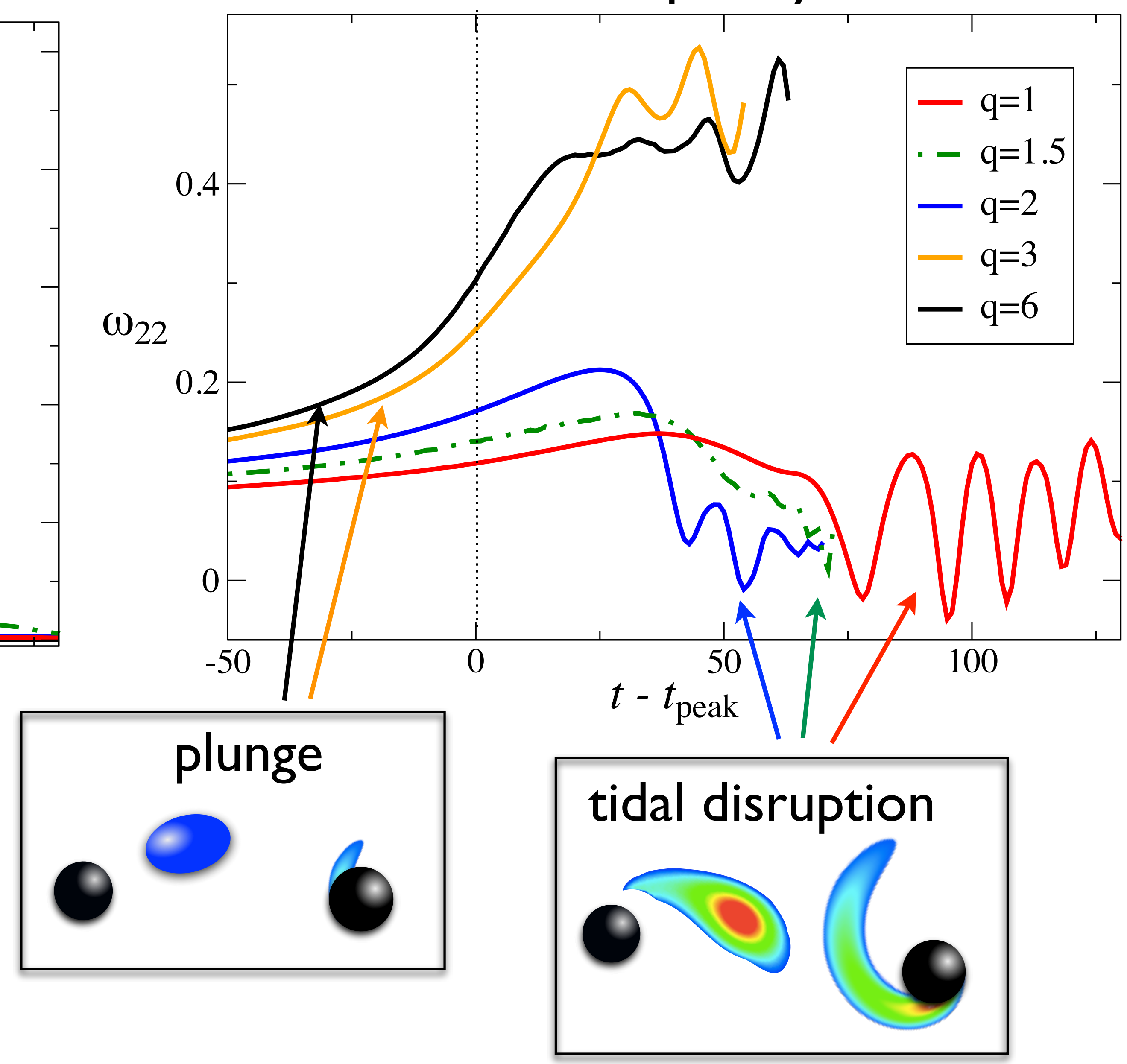


Features in the GWs

GW amplitude

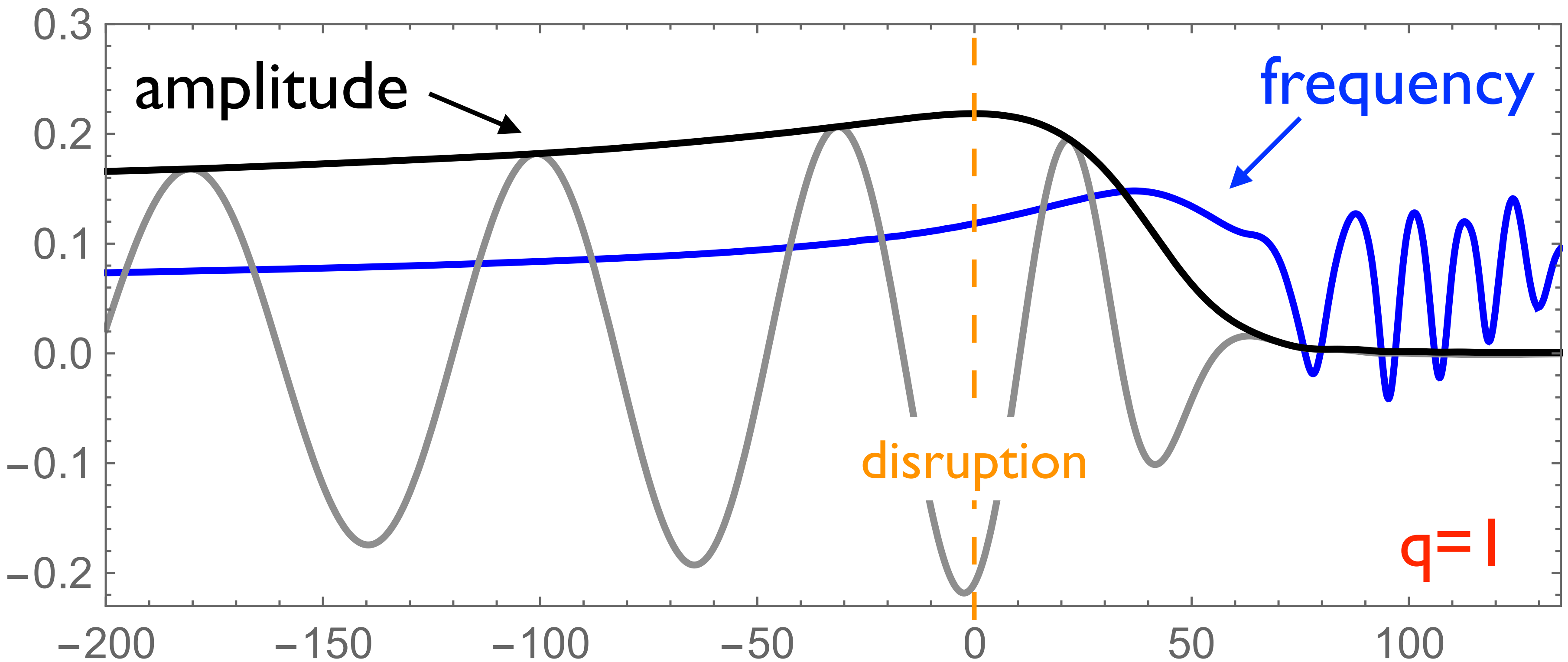


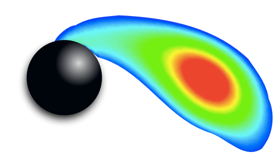
GW frequency

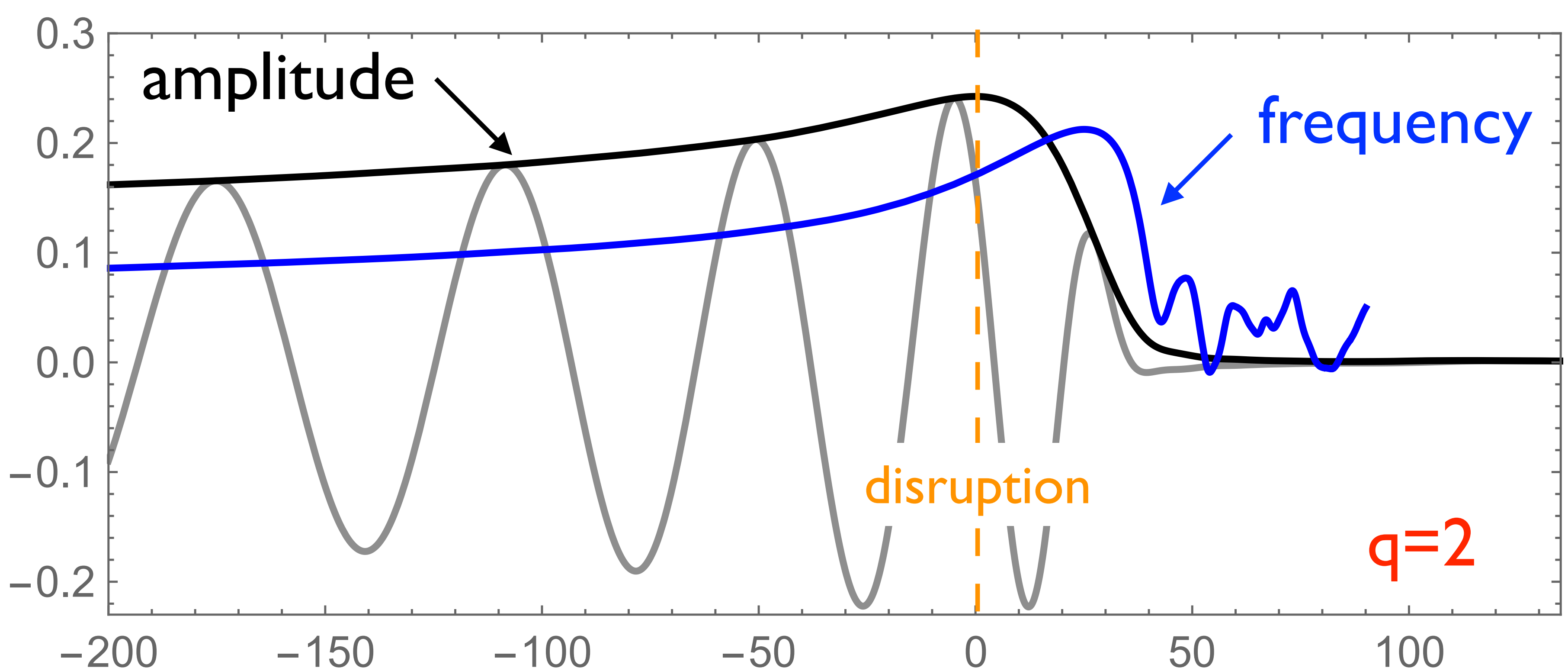


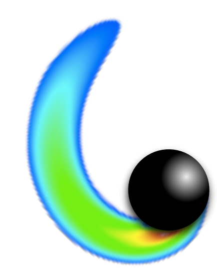
NR data from Francois Foucart,
Matt Duez, SXS collaboration

Features in GWs from tidal disruption









GW emission from dust cloud

- Haugan, Shapiro & Wasserman 1981; Saijo & Nakamura 2000:

frequency domain Teukolsky equation sourced by:

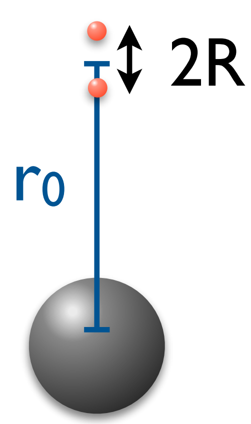
number density of particles

$$T^{\mu\nu}_{\rm blob} = \sum_i T^{\mu\nu}_{\rm one}(x, x_i) \approx \int d^3x'\, T^{\mu\nu}_{\rm one}(x, x')\, n(x', T_0)$$

- result:

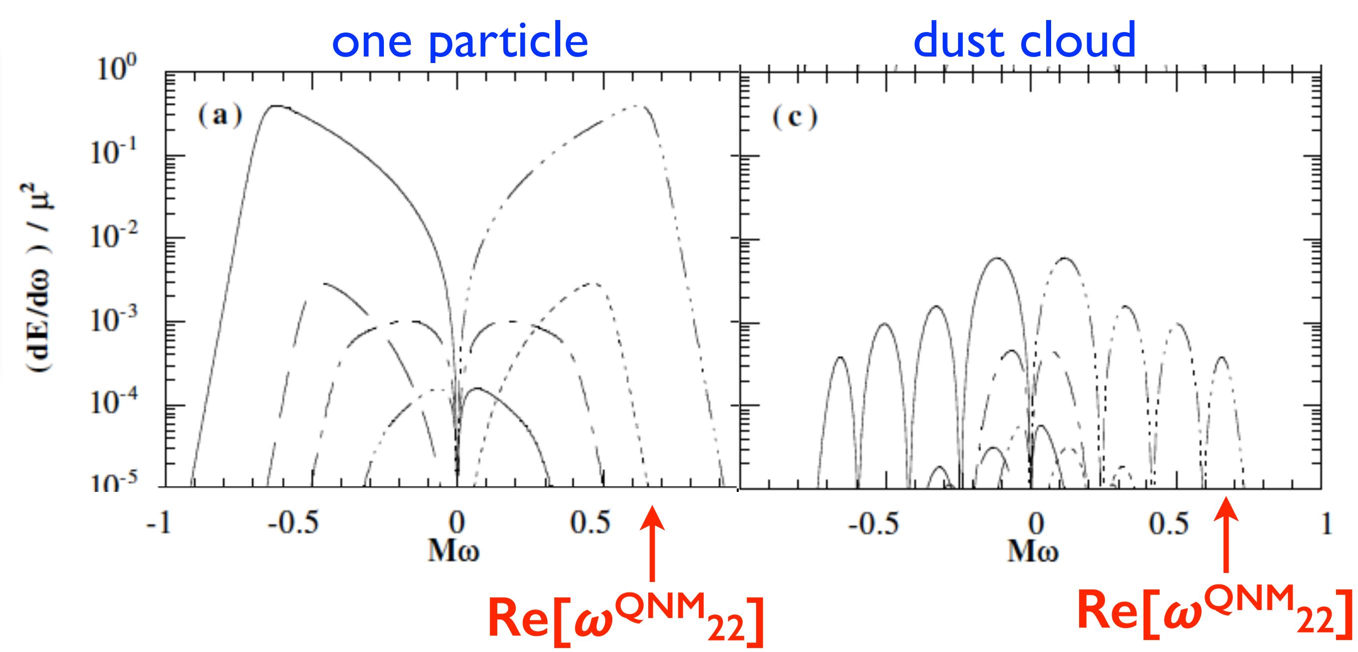
$$\left(\frac{dE}{d\omega}\right)^{(\rm blob)}_{\ell m \omega} = f^2_{\ell m \omega} \left(\frac{dE}{d\omega}\right)^{(\rm one)}_{\ell m \omega}$$

form factor

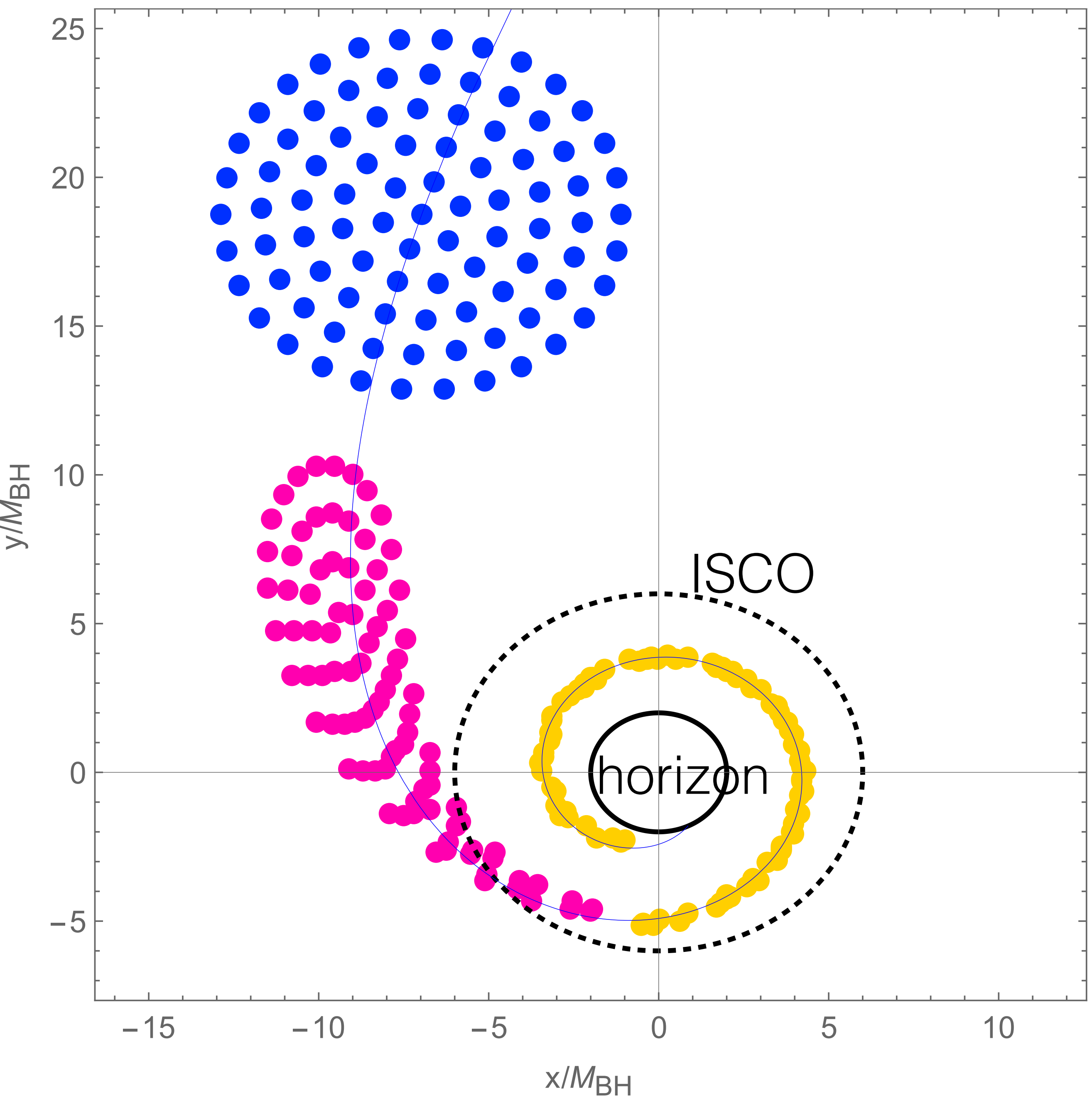


e.g. 2 particles, radial infall, Schwarzschild:

$$f_{\ell m \omega} = \cos\left(\omega R \sqrt{r_0/2M}\right)$$



Towards a toy model for NSBH

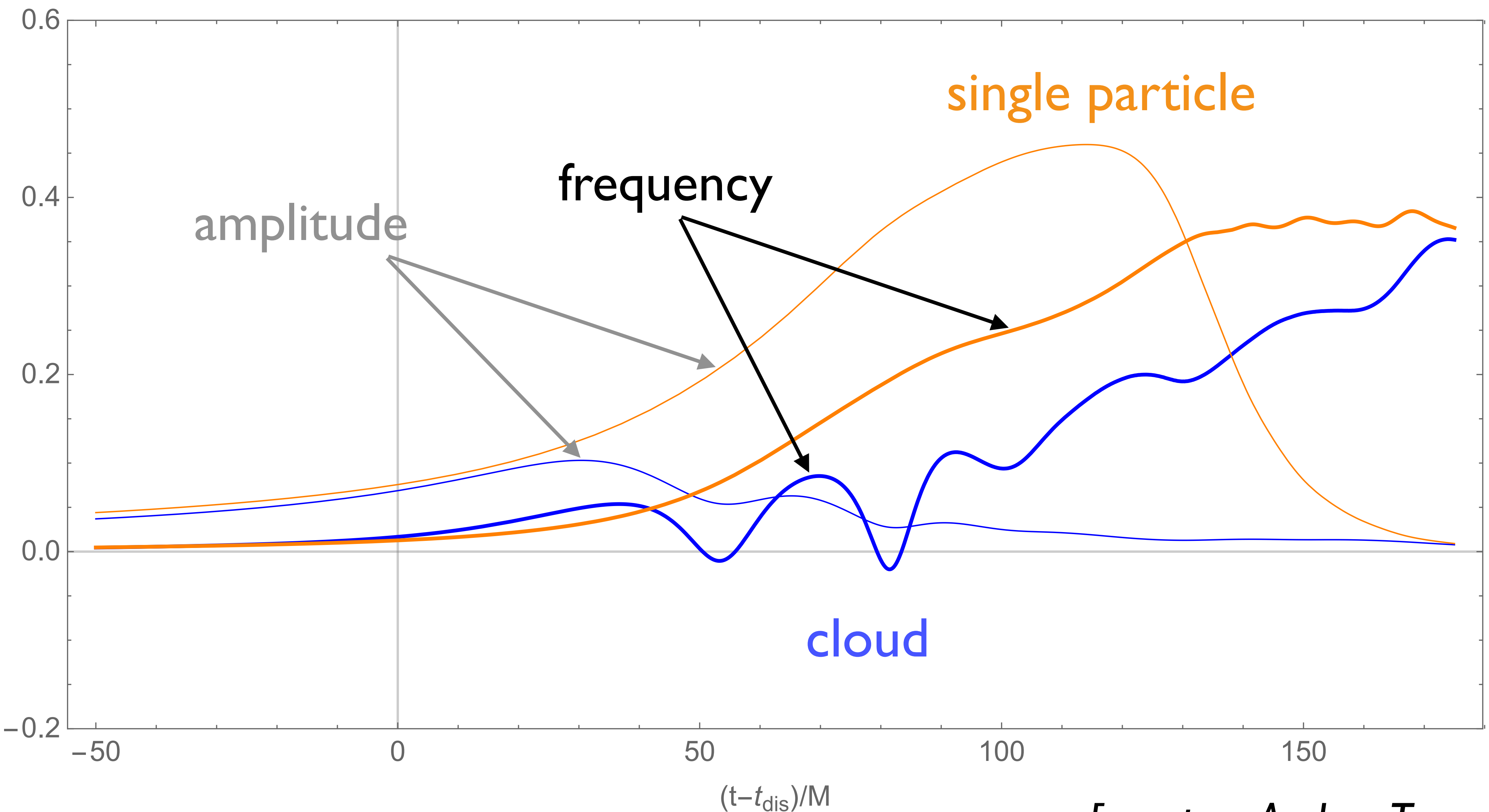


- Cloud of test masses in Kerr
- time-domain Teukolsky eqn.

[Gaurav Khanna]

[courtesy Andrea Taracchini]

Towards a toy model

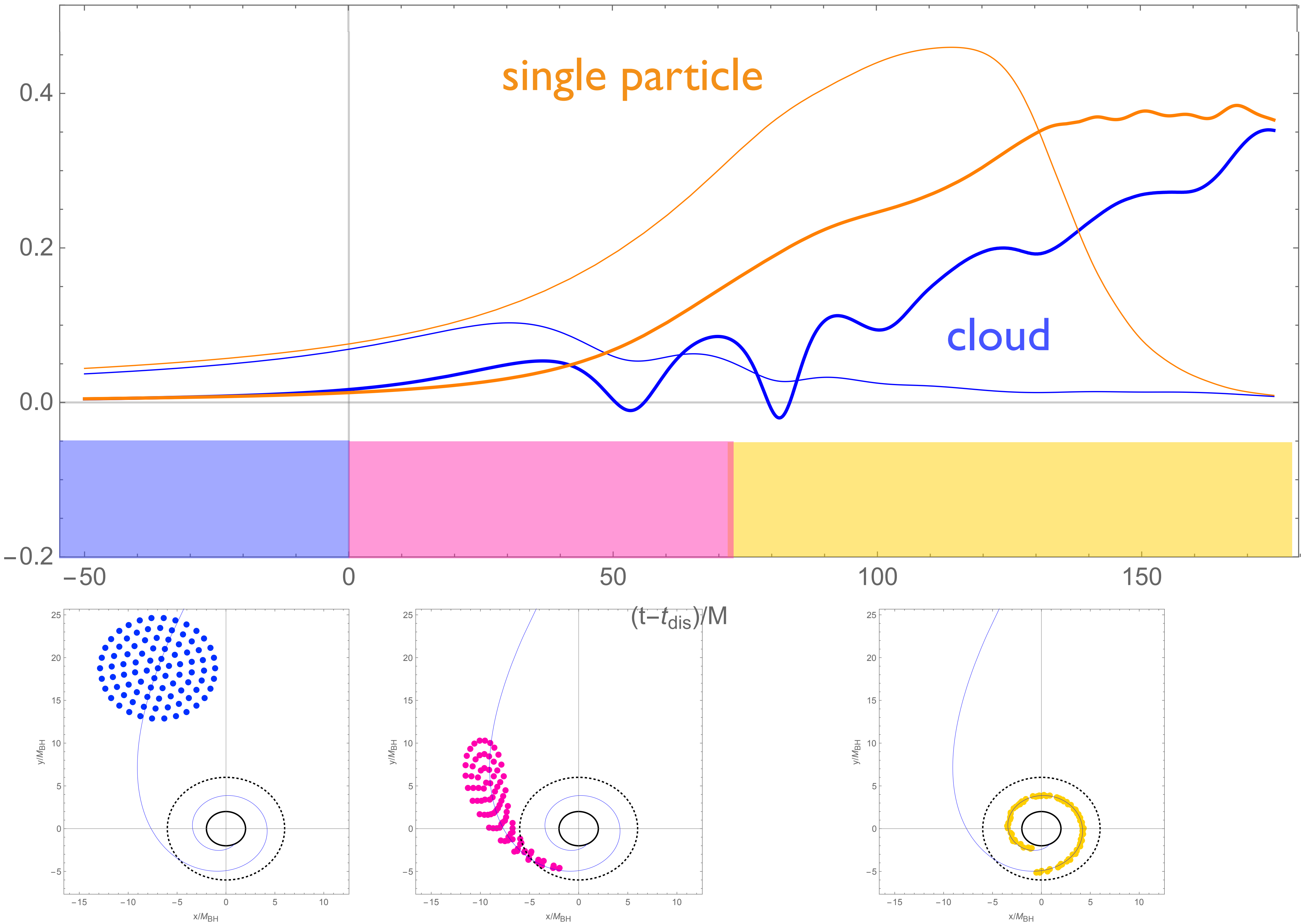


[courtesy Andrea Taracchini]

- Qualitatively similar features to NSBH:

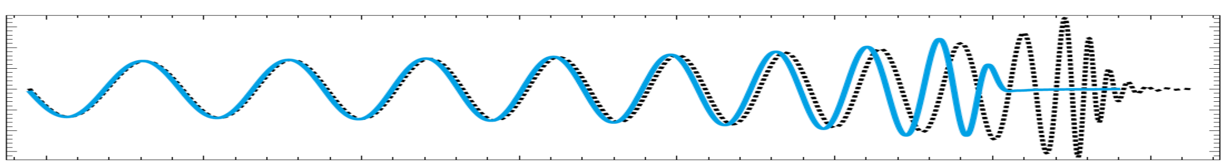
amplitude shut-off, frequency peak, time delay

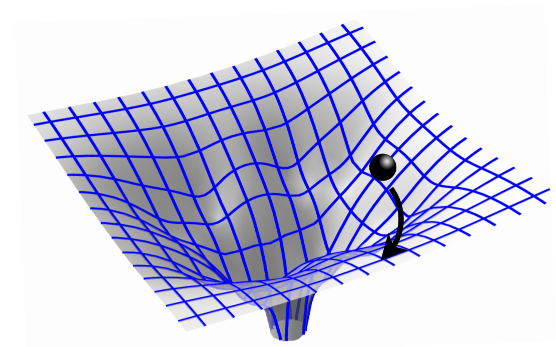
Towards a toy model

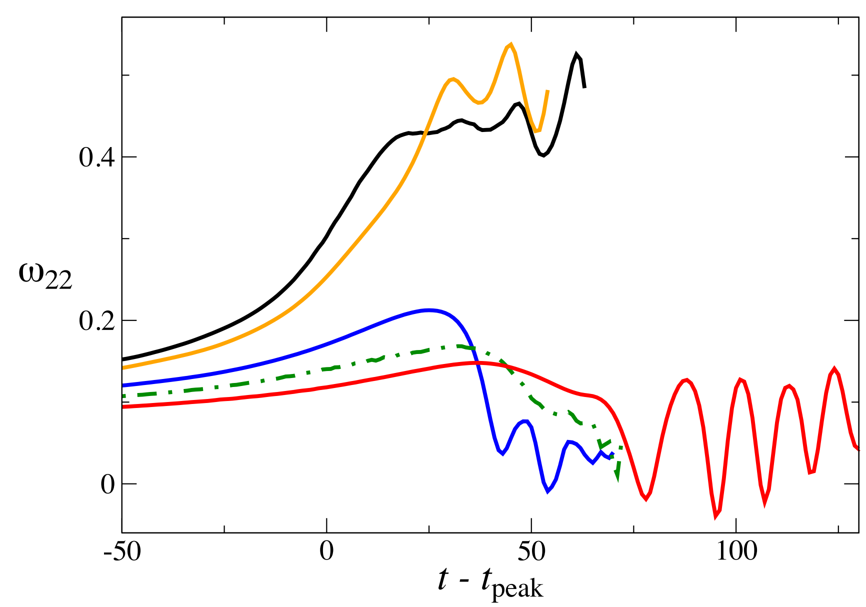


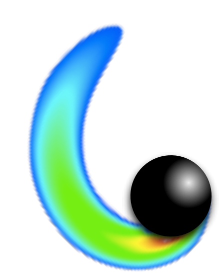
Conclusions

- NS-BH systems are an interesting, rich source of GWs
- Main imprint of NS microphysics in the GWs from inspirals: tidal effects
- Dynamic f-mode tides can be significant, now included in EOB
- Also included: plunge/tidal disruption signal (nonspinning case)



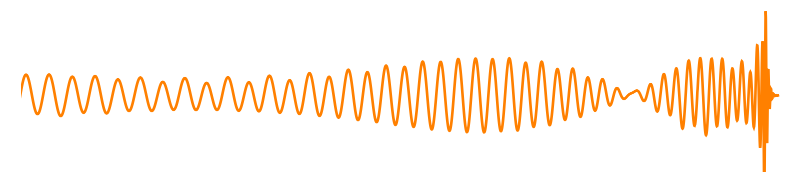




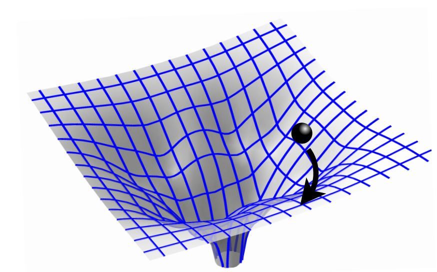


Outlook

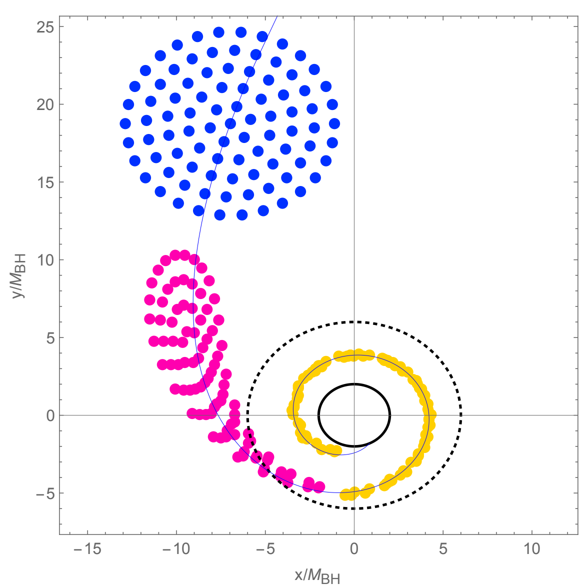
- Further improve models and measurement potential, reduce systematics
- Include more realistic physics (BH spin in progress)

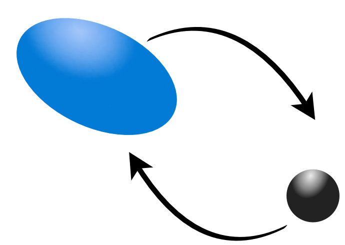


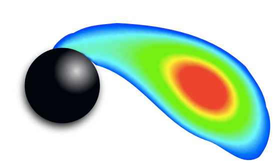
- Improve physical insights to develop more robust models
- Accurate NR simulations are crucial to inform model developments

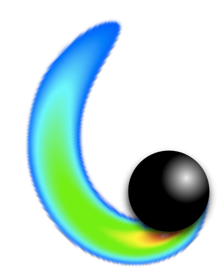


- optimize data analysis strategies (e.g. parameterization)









Thank you