Gravitational Wave Afterglow of Stellar Collapse in Massive Scalar-Tensor Gravity

Ulrich Sperhake

C Moore, M Agathos, R Rosca, D Gerosa, C Ott

DAMTP, University of Cambridge
LIGO Scientific Collaboration

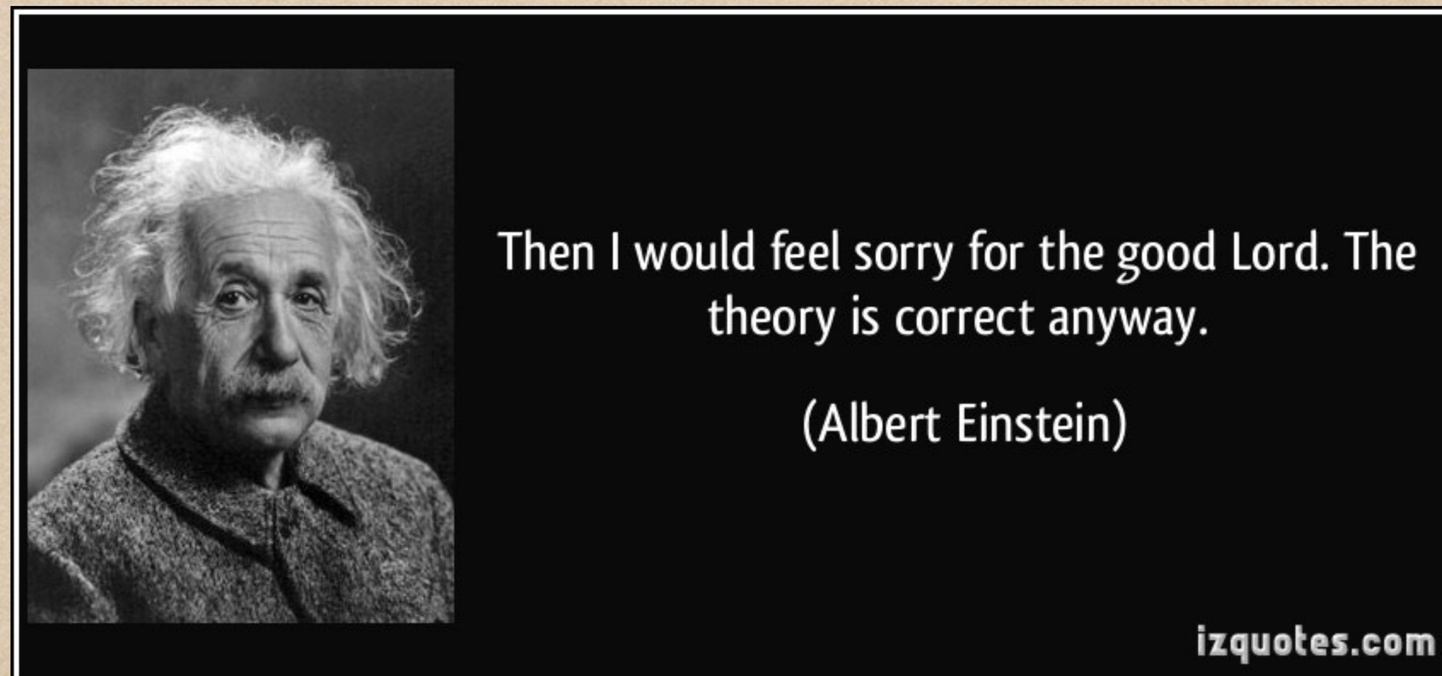
LIGO-P1700218, P1900083

GR22 & Amaldi 13
Valencia, *10 Jul 2019*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 690904, from H2020-ERC-2014-CoG Grant No. "MaGRaTh" 646597, from NSF XSEDE Grant No. PHY-090003 and from STFC Consolidator Grant No. ST/L000636/1.

Do we need a theory beyond GR?

- When asked what he would do if Eddington's mission failed…



- But we have reasons to search for "beyond GR"
  - Renormalization: Requires, e.g., higher curvature terms.

    $\rightarrow$ GR is low-energy limit of more fundamental theory
  - Dark energy: Why is Λ so small and why $\rho_{\rm dark} \sim \rho_{\rm mat}$
  - Dark matter: "Neptune" or "Vulcan" ?

Scalar tensor theory of gravity

- Scalars appear naturally in extra-dimensional theories
- Scalars prominent in cosmology
- ST theory well-posed; fairly well understood mathematically
- No-hair theorems limit potential of black-hole spacetimes

  $\Rightarrow$ Matter: Neutron stars, core-collapse
- Best example of smoking gun to date:

  Spontaneous scalarization   Damour & Esposito-Farese PRL 1993
- Collapse studies in massless case

  Novak PRD 1998/1999

  Novak & Ibanez ApJ 2000,

  Gerosa+ CQG 2016

Core-collapse scenario to 0th order

- Massive stars: $M_{\rm ZAMS} = 8 \ldots 100\ M_\odot$
- Core compressed from $\sim 1\,500$ km to ~ 15 km

  $\sim 10^{10}\ {\rm g/cm^3}$ to $\gtrsim 10^{15}\ {\rm g/cm^3}$
- Released gravitational energy: $\mathcal{O}(10^{53})$ erg

  $\sim 99\ \%$ in neutrinos, $\sim 10^{51}$ erg in outgoing shock, explosion
- Explosion mechanism: still uncertainties...
- Failed explosions lead to BH formation

  "Collapsar": possible engine for long-soft GRBs
- All of this handled for us by Woosley & Heger Phys.Rept. 2007

  $\rightarrow$ Initial pre-collapse profile

Theoretical framework

Einstein frame: conformal metric $\bar{g}_{\mu\nu} = F(\varphi)\, g_{\mu\nu}$

- Action

$$S = \frac{1}{16\pi} \int dx^4 \sqrt{-\bar{g}}\, [\bar{R} - 2\bar{g}^{\mu\nu} \partial_\mu \varphi\, \partial_\nu \varphi - 4V(\varphi)] + S_m[\psi_m, \bar{g}_{\mu\nu}/F(\varphi)]$$

- Energy momentum tensor: $T_{\alpha\beta} = \rho h u_\alpha u_\beta + P g_{\alpha\beta}$

- Spherical symmetry: $d\bar{s}^2 = \bar{g}_{\mu\nu} dx^\mu dx^\nu = -F\alpha^2 dt^2 + FX^2 dr^2 + r^2 d\Omega^2$

$$u^\alpha = \frac{1}{\sqrt{1-v^2}} [\alpha^{-1},\ vX^{-1},\ 0,\ 0]$$

- Equations (gravity): $\partial_r \alpha = \ldots\,, \qquad \partial_r X = \ldots$

  $\partial_t \partial_t \varphi = \ldots$

- Equations (matter): $(\rho,\, h,\, v) \leftrightarrow (D,\, S^r,\, \tau) \quad \Rightarrow$ HRSC

  GR1D code O'Connor & Ott CQG 2009

Theoretical framework

Coupling function

Einstein frame: conformal metric $\bar{g}_{\mu\nu} = F(\varphi)\, g_{\mu\nu}$

Potential

- Action

$$S = \frac{1}{16\pi}\int dx^4\sqrt{-\bar{g}}\,[\bar{R} - 2\bar{g}^{\mu\nu}\partial_\mu\varphi\,\partial_\nu\varphi - 4V(\varphi)] + S_m[\psi_m, \bar{g}_{\mu\nu}/F(\varphi)]$$

Equation of state

- Energy momentum tensor: $T_{\alpha\beta} = \rho h u_\alpha u_\beta + P g_{\alpha\beta}$

- Spherical symmetry: $d\bar{s}^2 = \bar{g}_{\mu\nu}dx^\mu dx^\nu = -F\alpha^2 dt^2 + FX^2 dr^2 + r^2 d\Omega^2$

$$u^\alpha = \frac{1}{\sqrt{1-v^2}}[\alpha^{-1},\ vX^{-1},\ 0,\ 0]$$

- Equations (gravity): $\partial_r\alpha = \dots\,,\qquad \partial_r X = \dots$

$$\partial_t\partial_t\varphi = \dots$$

- Equations (matter): $(\rho,\, h,\, v) \leftrightarrow (D,\, S^r,\, \tau) \quad \Rightarrow$ HRSC

GR1D code O'Connor & Ott CQG 2009

The coupling function and potential

- Coupling function: $F(\varphi) = e^{-2\alpha_0\varphi - \beta_0\varphi^2}$

  $\alpha_0, \ \beta_0$ determine all modifications at 1st PN order

- Potential:

  (1) Massive non-interacting case $V(\varphi) = \frac{1}{2}\mu^2\varphi^2$

  (2) Interacting field

$$V(\varphi) = \frac{1}{2}\mu^2\varphi^2\left(1 + \lambda_1\frac{\varphi^2}{2} + \lambda_2\frac{\varphi^4}{3} + \ldots + \lambda_n\frac{\varphi^{2n}}{n+1}\right), \quad \lambda_n > 0$$

- All λ_i are dimensionless.

  Mass μ introduces characteristic frequency $\omega_* = \dfrac{\mu}{\hbar}$

  Here $\mu = 10^{-14}\ \mathrm{eV} \quad \Leftrightarrow \quad \omega_* = 15.2\ \mathrm{s}^{-1}$

Equation of state

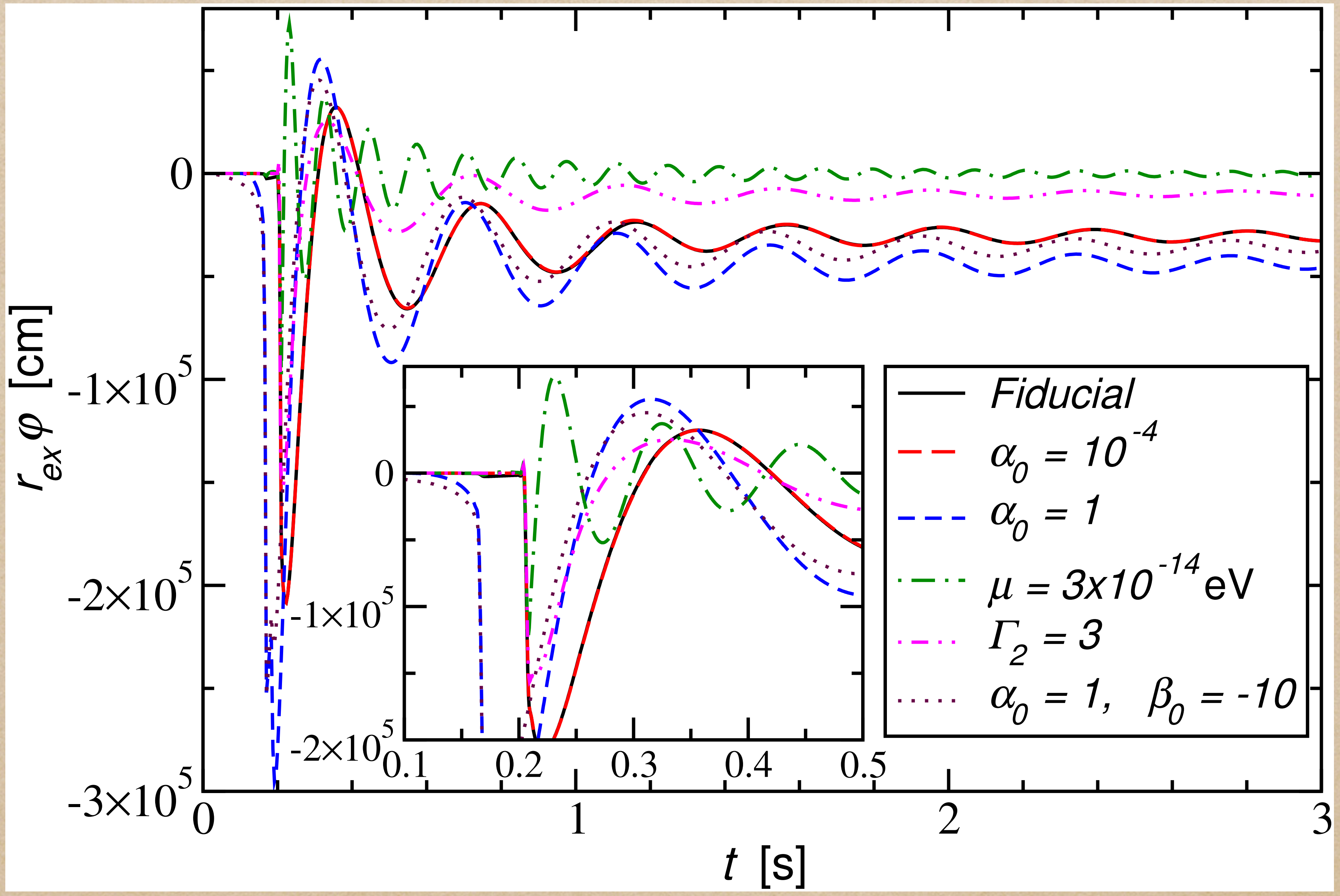
- Pressure: "cold" + "thermal" contribution: $P = P_c + P_{th}$
- Hybrid EOS for cold part: $P_c = \begin{cases} K_1 \rho^{\Gamma_1} & \text{if} \quad \rho \leq \rho_{nuc} \\ K_2 \rho^{\Gamma_2} & \text{if} \quad \rho > \rho_{nuc} \end{cases}$
- Internal energy from 1st law: $\epsilon_c = \begin{cases} \frac{K_1}{\Gamma_1 - 1} \rho^{\Gamma_1 - 1} & \text{if} \quad \rho \leq \rho_{nuc} \\ \frac{K_2}{\Gamma_2 - 1} \rho^{\Gamma_2 - 1} + E_3 & \text{if} \quad \rho > \rho_{nuc} \end{cases}$
- Thermal pressure: $P_{th} = (\Gamma_{th} - 1)\rho(\epsilon - \epsilon_{th})$
- Parameters: $\Gamma_1 = 1.3\,, \quad \Gamma_2 = 2.5\,, \quad \Gamma_{th} = 1.35$

  $K_1 = 4.9345 \times 10^{14}\ [\text{cgs}]\,, \quad \rho_{nuc} = 2 \times 10^{14}\ \text{g}\,\text{cm}^{-3}$

  $K_2\,, \quad E_3$ from continuity at $\rho = \rho_{nuc}$

Waveforms "close to" the source

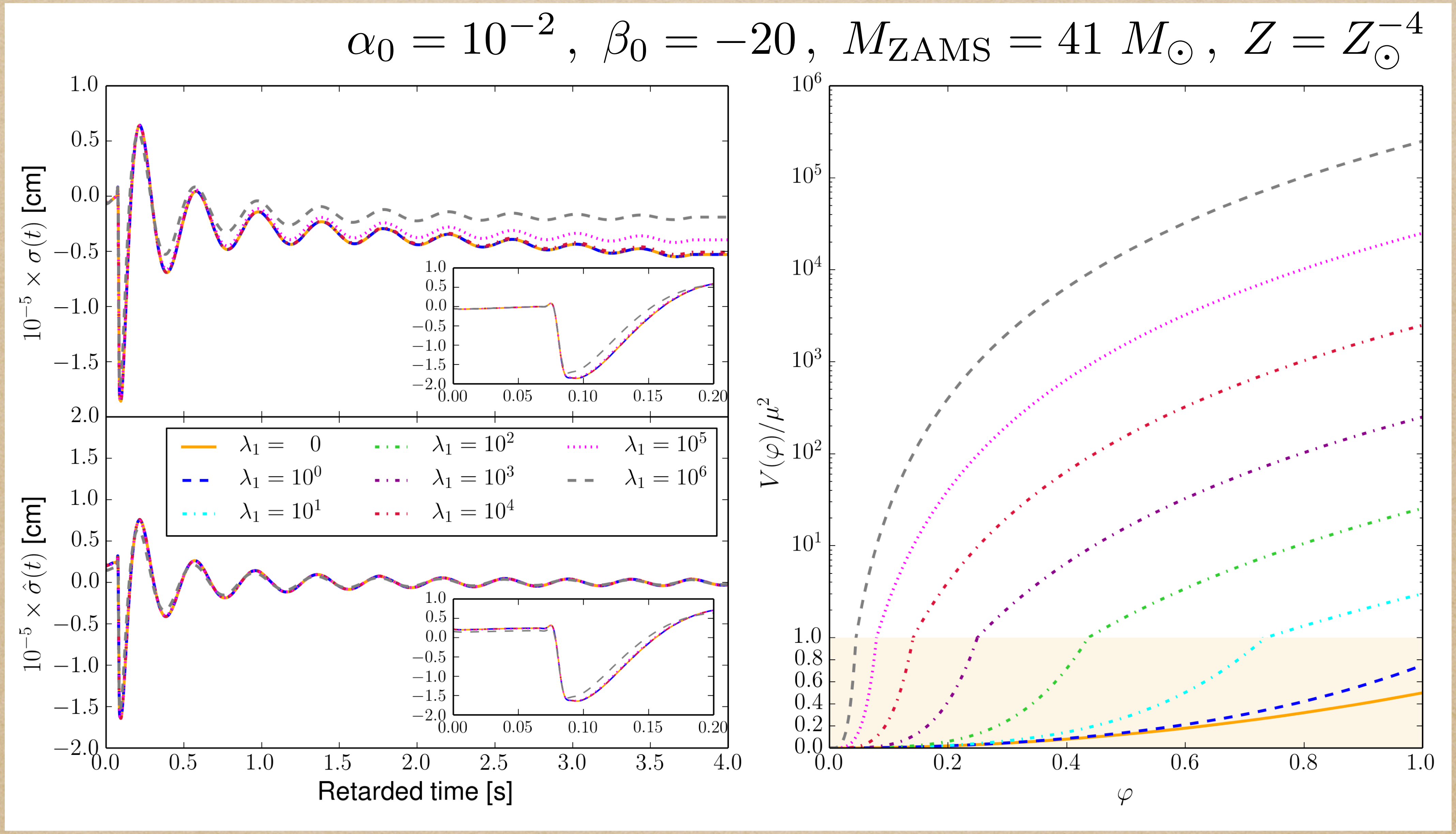
- For $\mu = 10^{-14}\,\mathrm{eV}, \quad \alpha_0 = 10^{-2}, \quad \beta_0 = -20$
  $\Gamma_1 = 1.3, \quad \Gamma_2 = 2.5, \quad \Gamma_{\rm th} = 1.35$



- $r\varphi \gg$ massless case; fairly insensitive to parameters; dispersion!

With self interaction

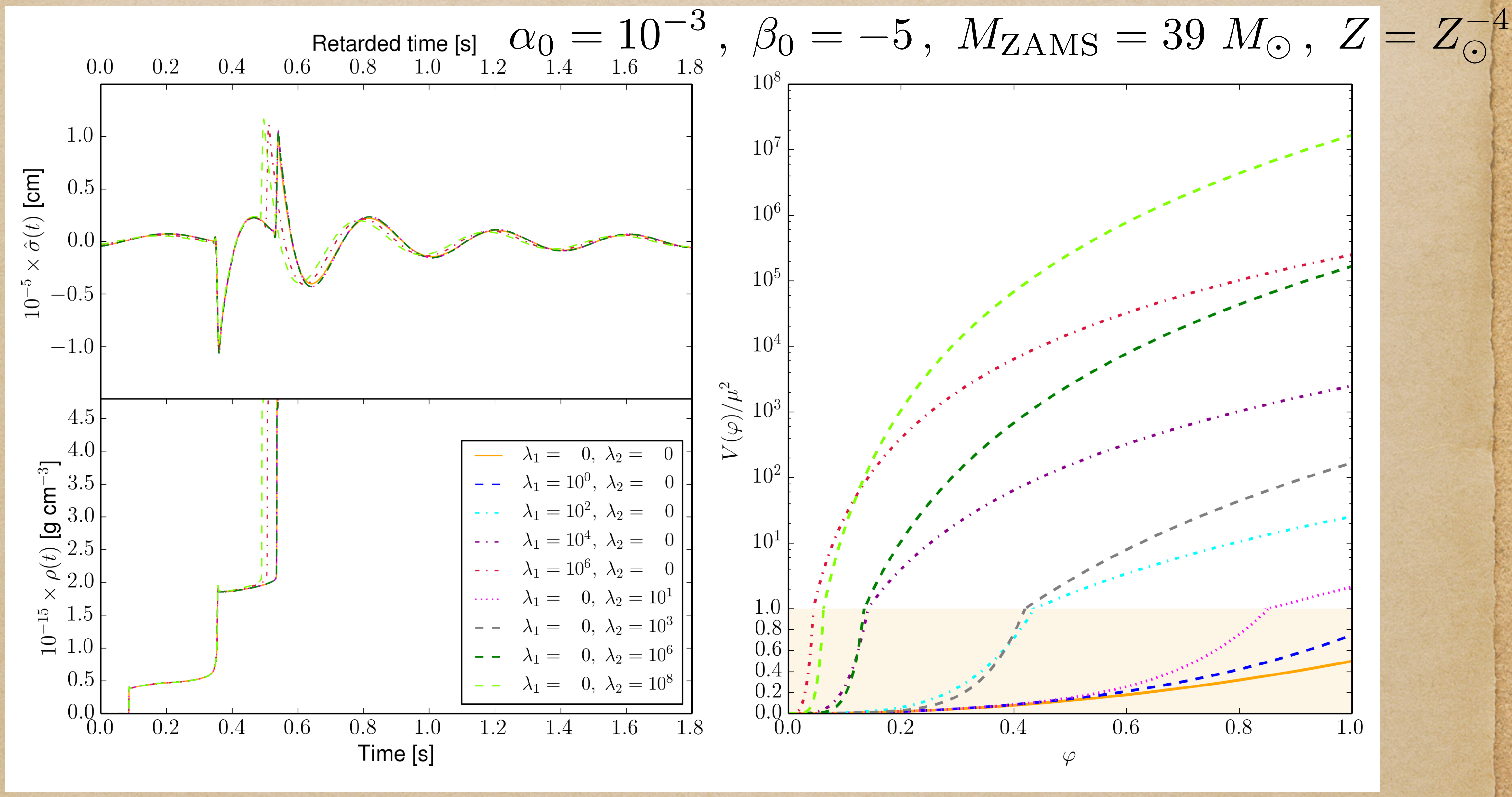
- Varying quartic term $\lambda_1 = 0 \ldots 10^6$: Wave signal highly robust!



- Same observation for $\lambda_2,\ \lambda_3$

BH formation

- Varying quartic term $\lambda_1 = 0 \ldots 10^6$: Wave signal highly robust!



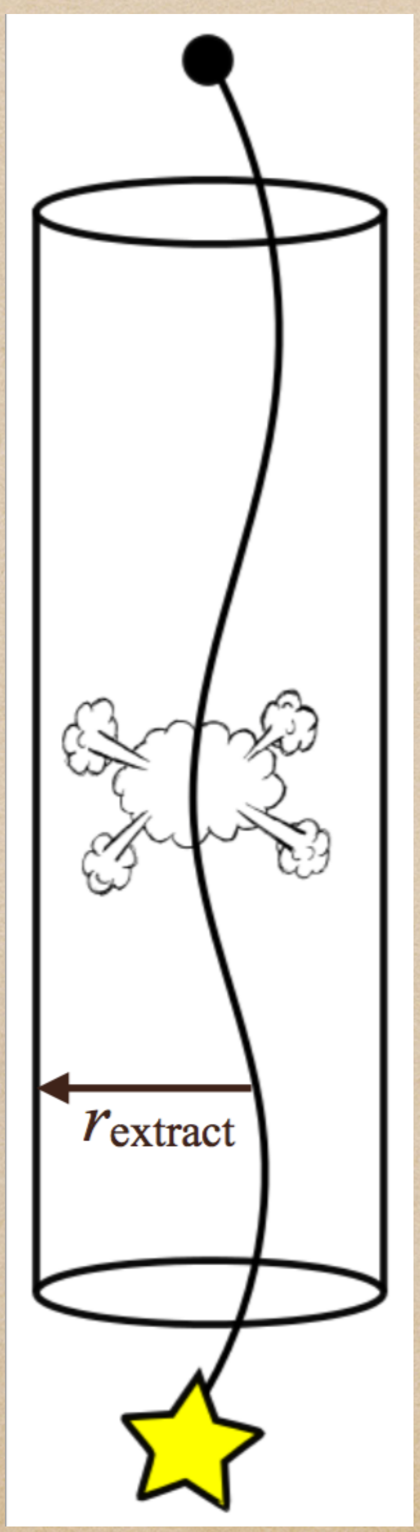
- Same observation for $\lambda_2,\ \lambda_3$

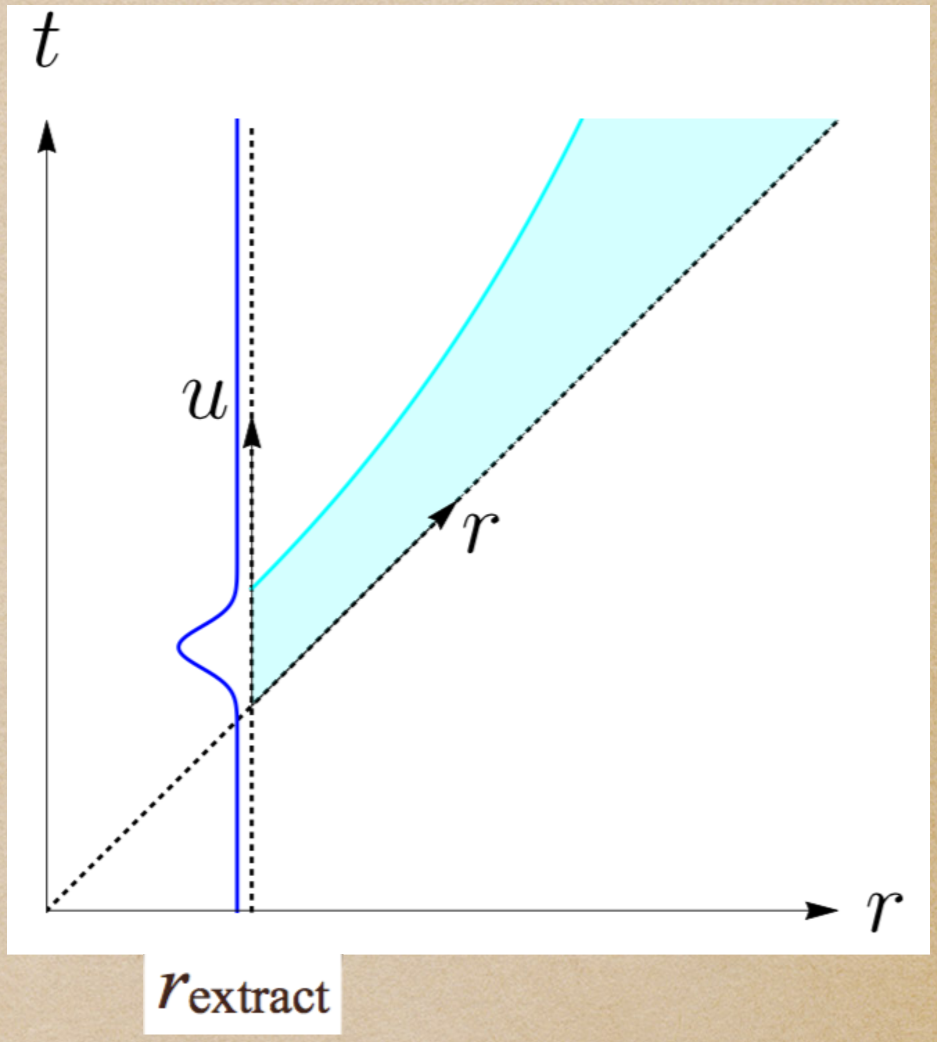
Waveforms ``far from" the source

- LIGO will observe the above scalar profiles after they propagate to large distances
- In the massless case this is almost trivial

$$\varphi(t;r) = \frac{1}{r}\varphi(t-r; r_{\text{extract}})$$

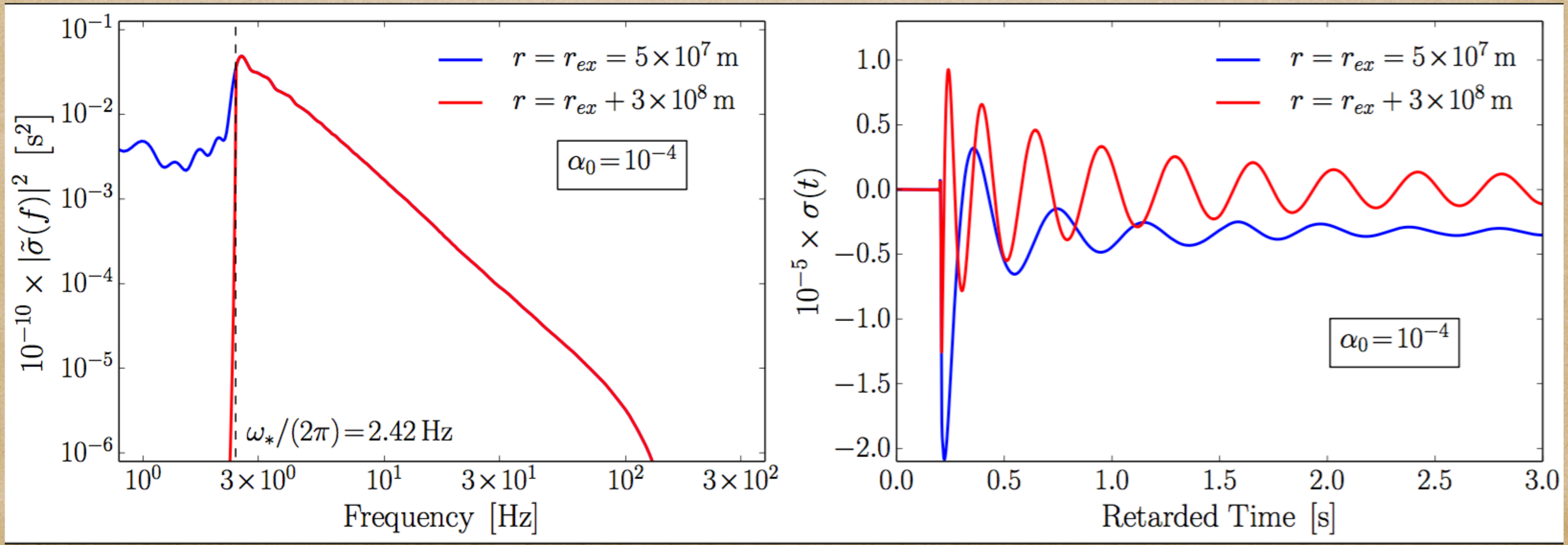
- In the massive case things are more complicated: signals propagate with ***dispersion***





Waveforms "far from" the source

- Far from the source, scalar dynamics are governed by the flat-space Klein-Gordon wave equation $\partial_t^2\varphi - \nabla^2\varphi + \omega_*^2\varphi = 0$
- Easier to work with the radially rescaled field $\sigma \equiv r\varphi$
- As the signal propagates outwards:
  - Low frequencies are suppressed
  - High frequency power spectrum is unaffected
  - Signal spreads out in time
  - High frequencies arrive earlier than low frequencies
  - Signal becomes increasingly oscillatory



Waveforms "far from" the source

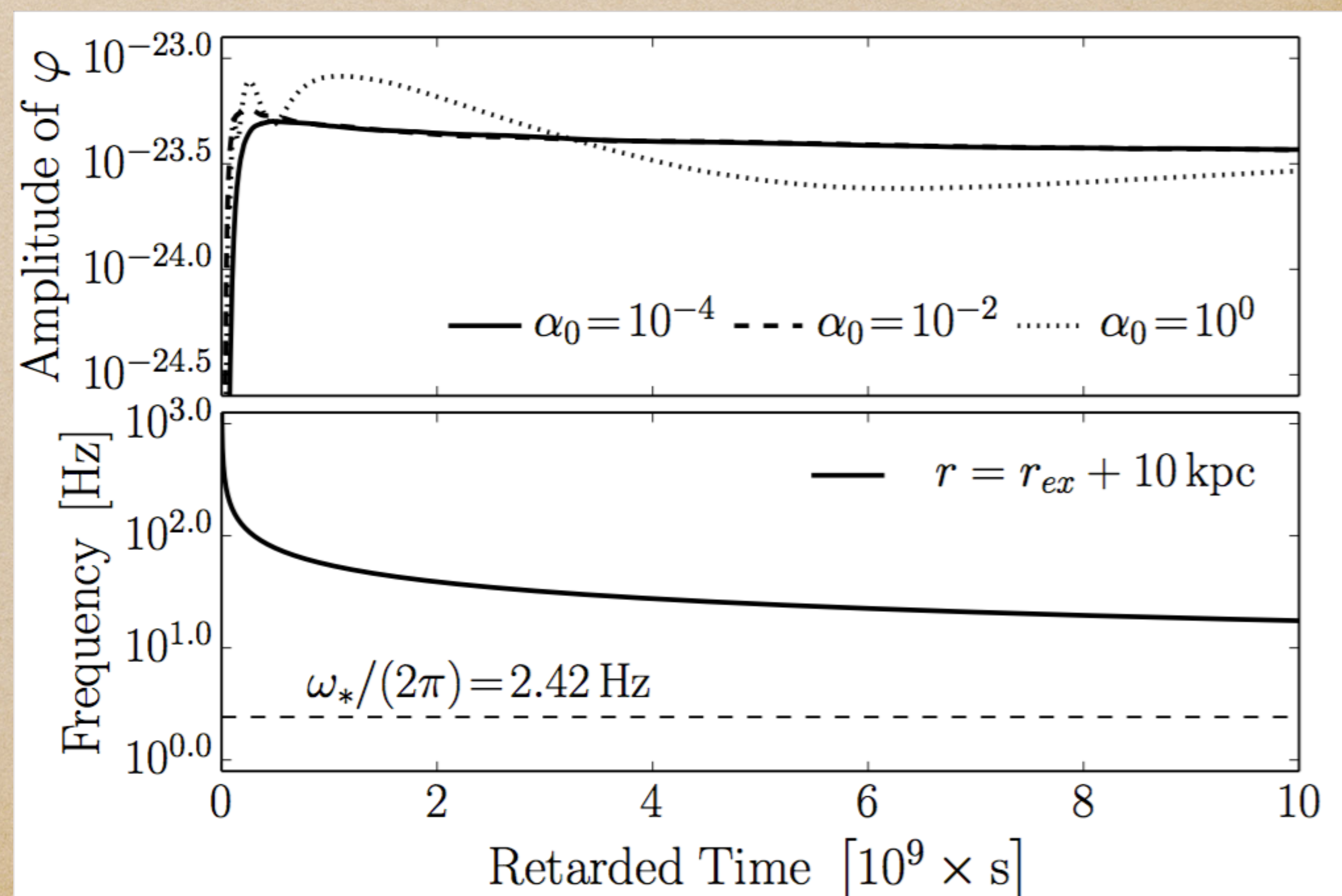
- Signals become more oscillatory as they propagate outwards
- In the large-distance limit the stationary phase approximation applies $\rightarrow$ analytic expression for the time domain signal
- Signals have a characteristic "inverse chirp" lasting many years

SPA frequency as function of time (Inverse Chirp)

$$F(t) = \frac{\omega_*}{2\pi}\frac{1}{\sqrt{1-(d/t)^2}}$$

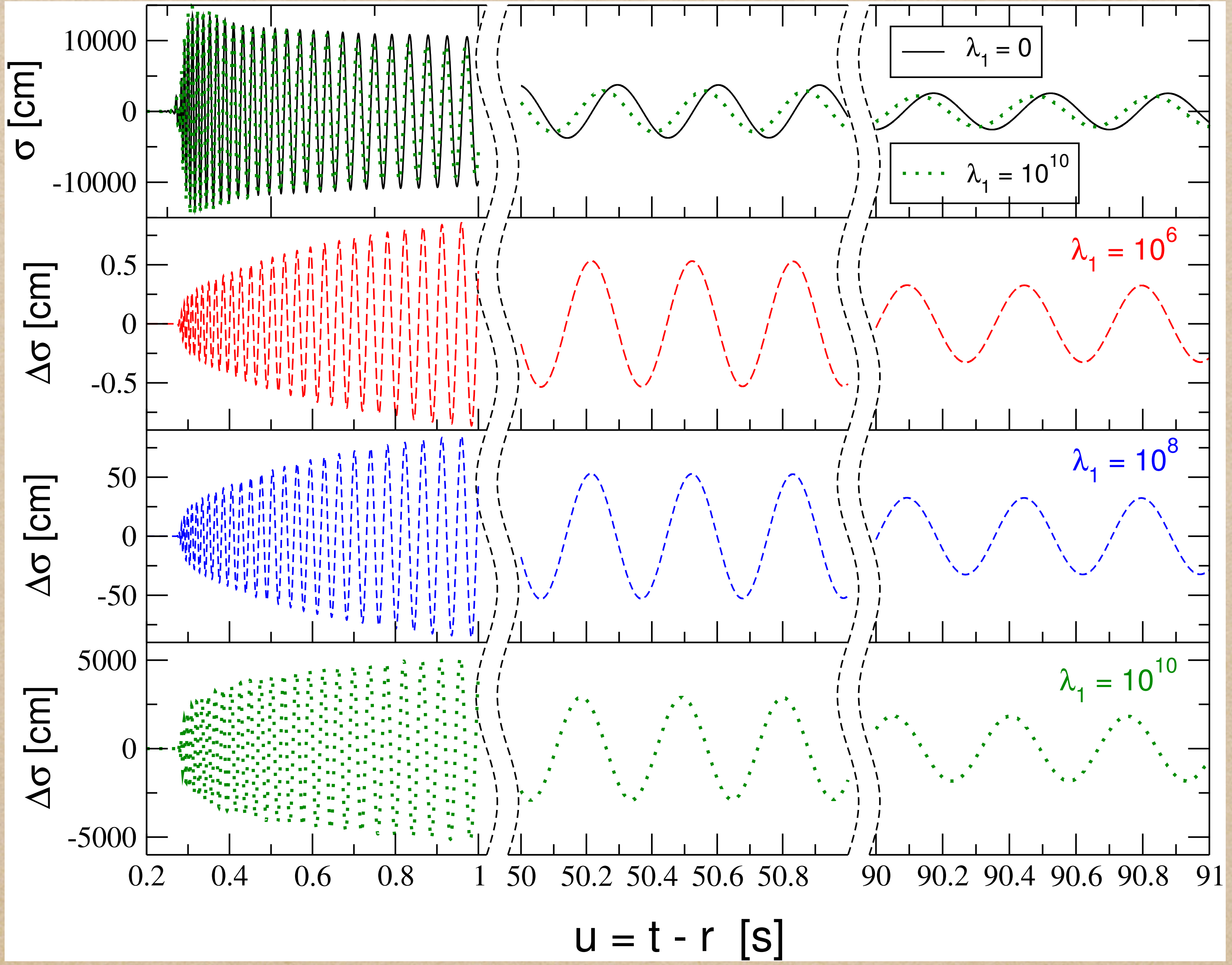
Distance to source

$$d = 10\,\mathrm{kpc}$$



With self interaction

- Far-field wave equation is now non-linear: SPA no longer applicable
- Numerically evolve signal to $\mathcal{O}(10^2)$ light seconds with $\lambda_i \neq 0$



- Need $\lambda_1 = 10^{10}$ to see non-negligible effects!!

Detection with LIGO-Virgo

GWs from core-collapse in ST gravity may fall into 3 classes:

- Burst signals: For light scalars $(\mu < 10^{-20}\,\mathrm{eV})$ and short distances $(10\,\mathrm{kpc})$, the pulse does not disperse significantly; will look like a $< 1\,\mathrm{s}$ burst
- Continuous wave signal: for heavier scalars, long dispersion turns pulse into a quasi-monochromatic signal
  $\rightarrow$ capture using standard directed CW searches, assuming EM counterpart; e.g. SN1987A, Kepler1604
- Stochastic background:
  - Many quiet sources $+$ very long duration (superposed)
  - Cosmological redshift $+$ mass variation $\rightarrow$ smeared low-f cutoff
  - Characteristic "bump" in background, peaking at $\sim \omega_*$
  - Well in reach for aLIGO/AdVirgo stochastic searches

Conclusions

- We have simulated stellar core collapse in massive ST theory
- Spontaneous scalarization occurs as in massless case, but effect can be more dramatic because the scalar mass "screens" the effect of the scalar, allowing larger values of $\alpha_0, \ \beta_0$ to be compatible with binary pulsar observations
- Signals propagate with dispersion, signals can last for years to centuries at kpc distances
- Signals can show up in LIGO/Virgo burst, CW or stochastic searches
- GW generation + propagation very robust to self interaction terms