

Long-Lived Inverse Chirp Signals from Core-Collapse in Massive Scalar-tensor Gravity

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C Moore, M Agathos, R Rosca, D Gerosa, C Ott [arxiv:1708.03651](https://arxiv.org/abs/1708.03651)



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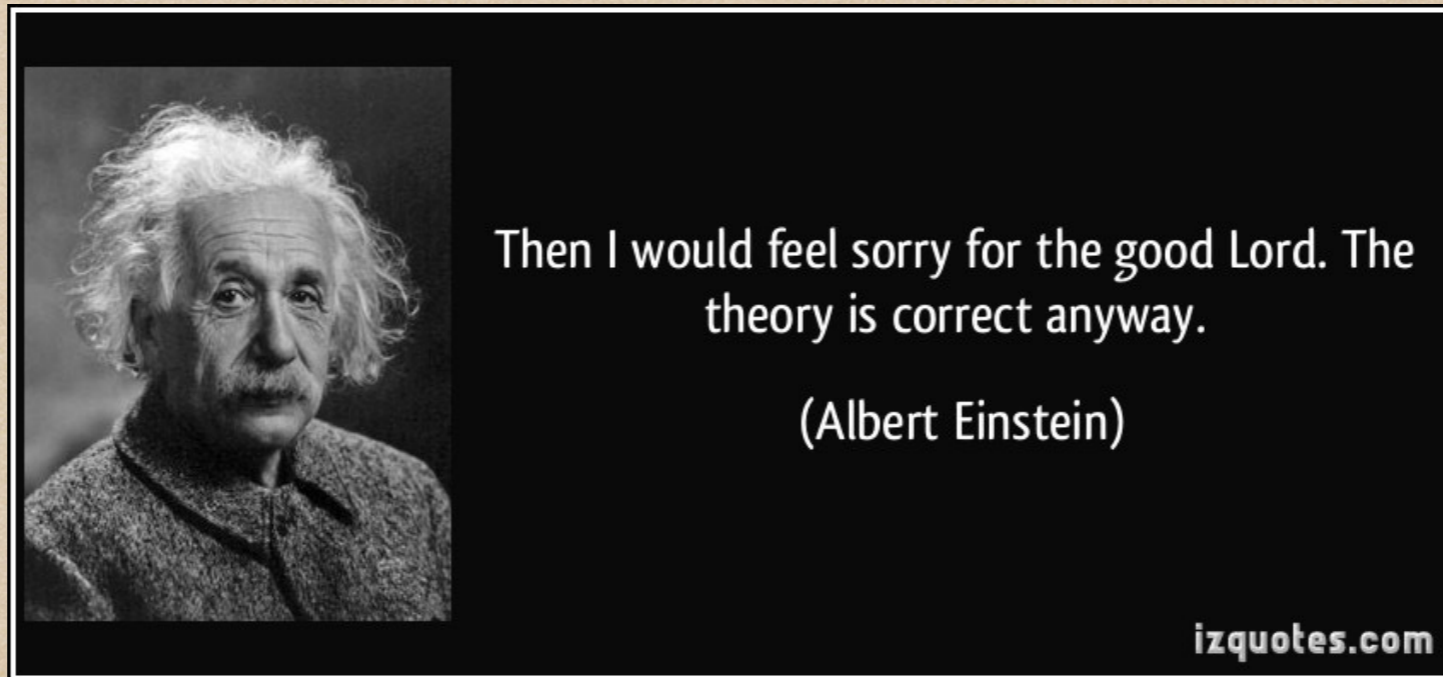
New Horizons for Gravity
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Do we need a theory beyond GR?

- 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.
 - GR is low-energy limit of more fundamental theory
 - **Dark energy:** Why is Λ so small and why $\rho_{\text{dark}} \sim \rho_{\text{mat}}$
 - **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

⇒ 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: $M_{\text{ZAMS}} = 8 \dots 100 M_{\odot}$
- Core compressed from $\sim 1500 \text{ km}$ to $\sim 15 \text{ km}$
 $\sim 10^{10} \text{ g/cm}^3$ to $\gtrsim 10^{15} \text{ g/cm}^3$
- Released gravitational energy: $\mathcal{O}(10^{53}) \text{ erg}$
 $\sim 99 \%$ in neutrinos, $\sim 10^{51} \text{ erg}$ 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
→ 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): $\partial_r \alpha = \dots, \quad \partial_r X = \dots$

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

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

GR1D code O'Connor & Ott CQG 2009

Equation of state

- Pressure: "cold" + "thermal" contribution: $P = P_c + P_{th}$
- Hybrid EOS for cold part:
$$P_c = \begin{cases} K_1 \rho^{\Gamma_1} & \text{if } \rho \leq \rho_{nuc} \\ K_2 \rho^{\Gamma_2} & \text{if } \rho > \rho_{nuc} \end{cases}$$
- Internal energy from 1st law:
$$\epsilon_c = \begin{cases} \frac{K_1}{\Gamma_1 - 1} \rho^{\Gamma_1 - 1} & \text{if } \rho \leq \rho_{nuc} \\ \frac{K_2}{\Gamma_2 - 1} \rho^{\Gamma_2 - 1} + E_3 & \text{if } \rho > \rho_{nuc} \end{cases}$$
- Thermal pressure: $P_{th} = (\Gamma_{th} - 1)\rho(\epsilon - \epsilon_{th})$
- Parameters: $\Gamma_1 = 1.3, \quad \Gamma_2 = 2.5, \quad \Gamma_{th} = 1.35$
$$K_1 = 4.9345 \times 10^{14} \text{ [cgs]}, \quad \rho_{nuc} = 2 \times 10^{14} \text{ g cm}^{-3}$$

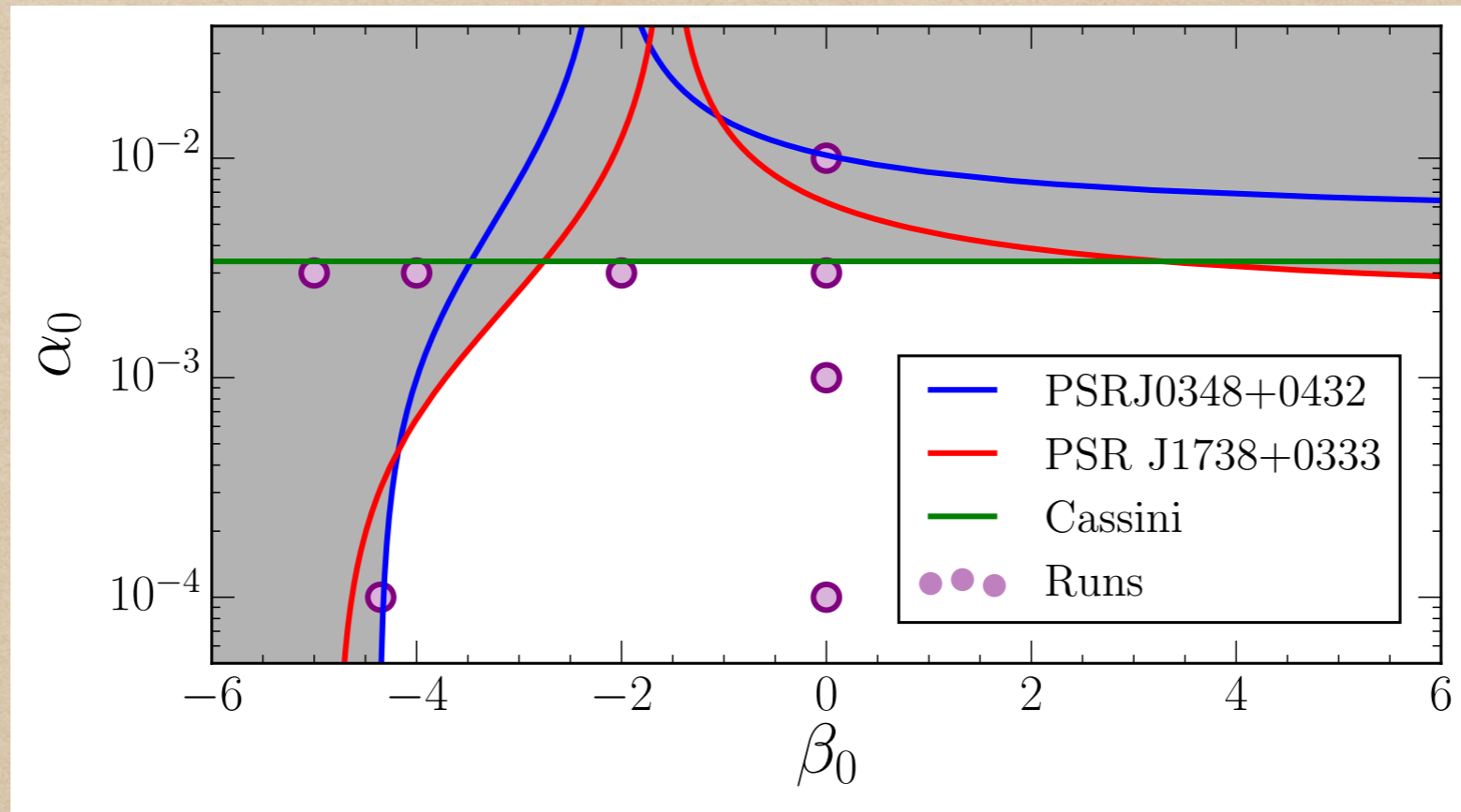
$$K_2, \quad E_3 \text{ from continuity at } \rho = \rho_{nuc}$$

The coupling function and potential

- Coupling function, potential:

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

$$V(\varphi) = \frac{1}{2}\mu^2\varphi^2$$



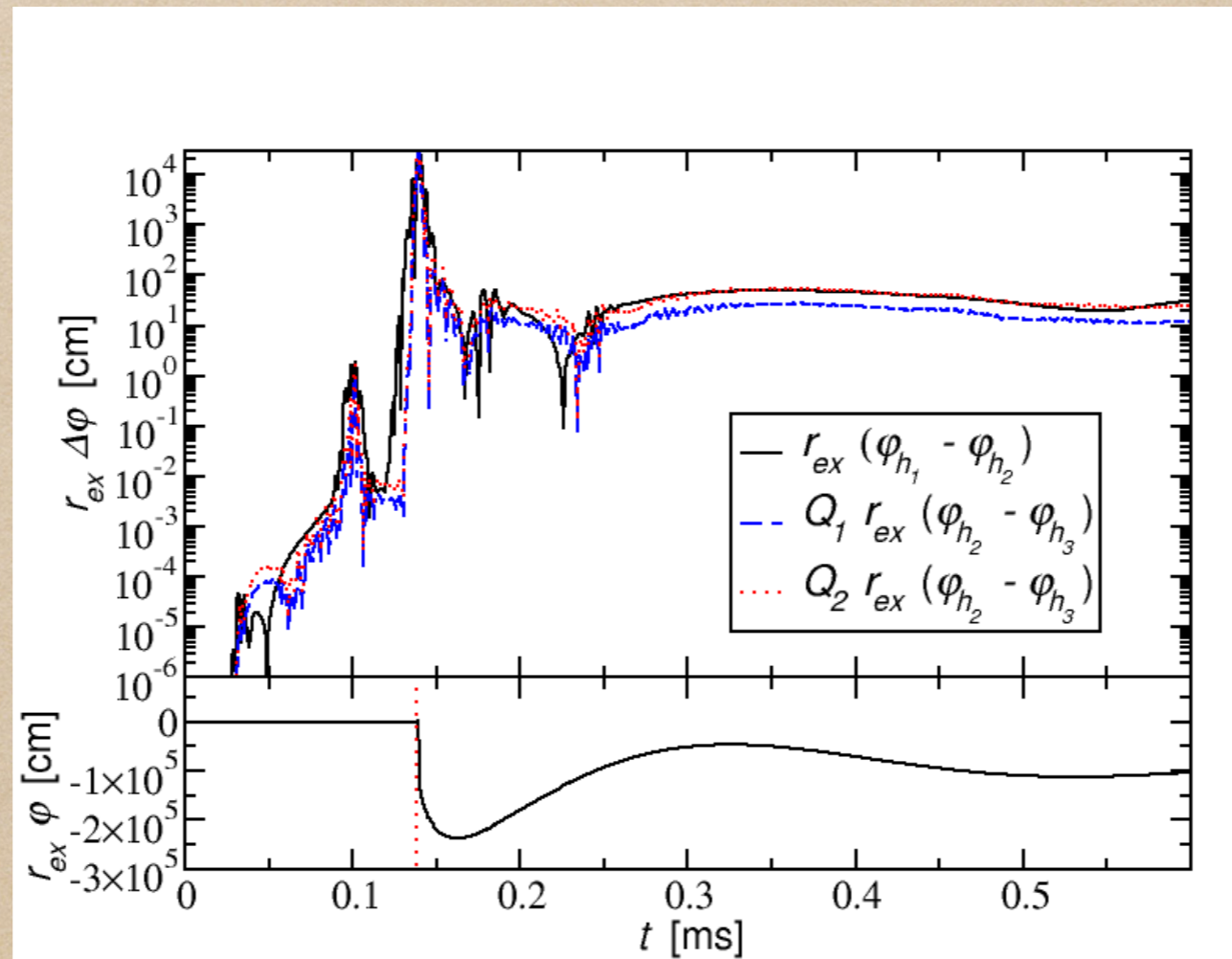
- Only for $\mu \lesssim 10^{-19}$ eV !! Here: $\mu[\text{eV}] \in [10^{-15}, 10^{-12}]$

Ramazanoglu & Pretorius PRD 2016

- Free parameters: $\mu, \alpha_0, \beta_0, \Gamma_1, \Gamma_2, \Gamma_{\text{th}}$

Convergence test

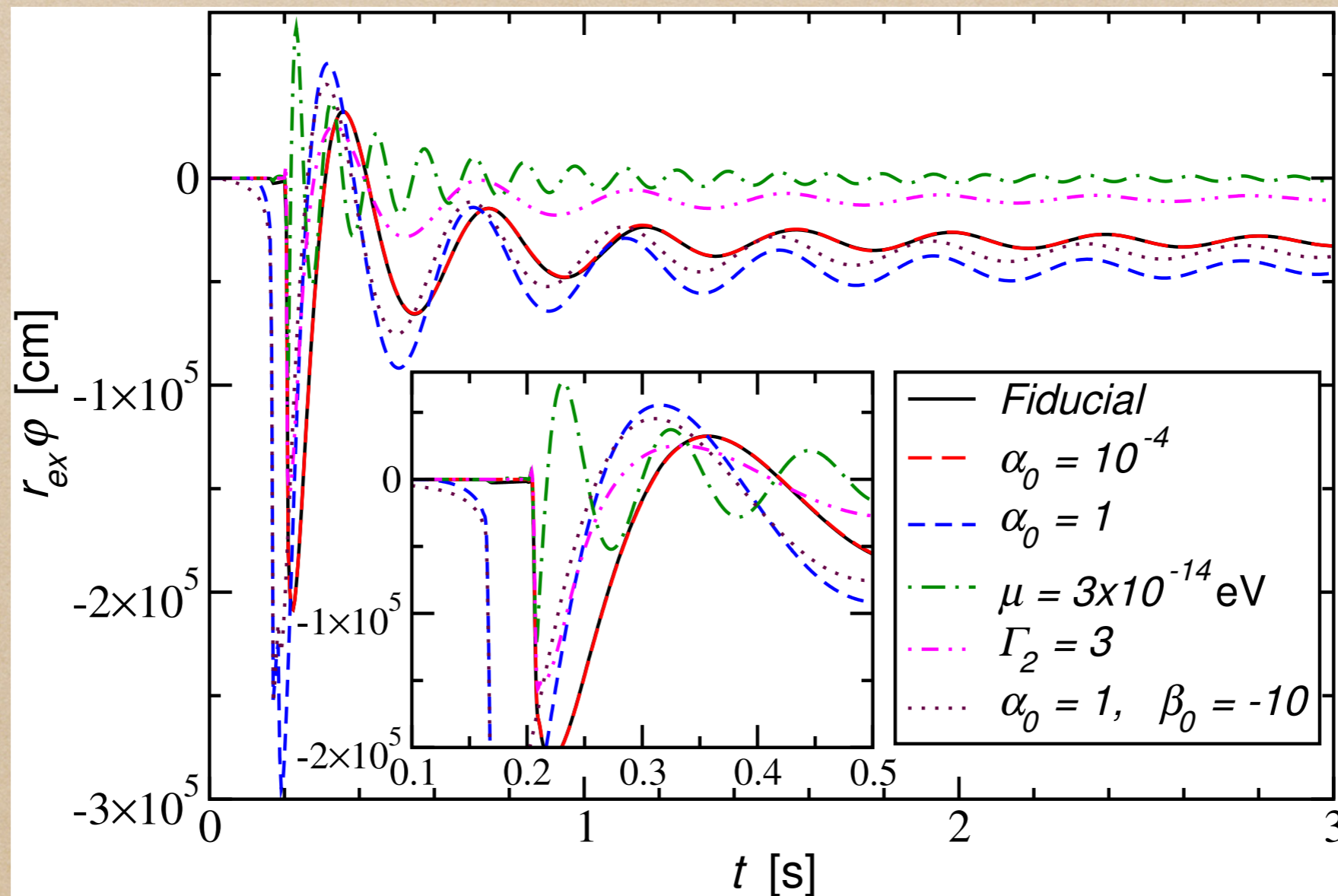
- For $\mu = 10^{-14}$ eV, $\alpha_0 = 10^{-4}$, $\beta_0 = -20$
 $\Gamma_1 = 1.3$, $\Gamma_2 = 2.5$, $\Gamma_{th} = 1.35$
- Using $N_1 = 5000$, $N_2 = 10000$, $N_3 = 20000$ points



- Discretization error: $\sim 5\%$

Waveforms "close to" the source

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



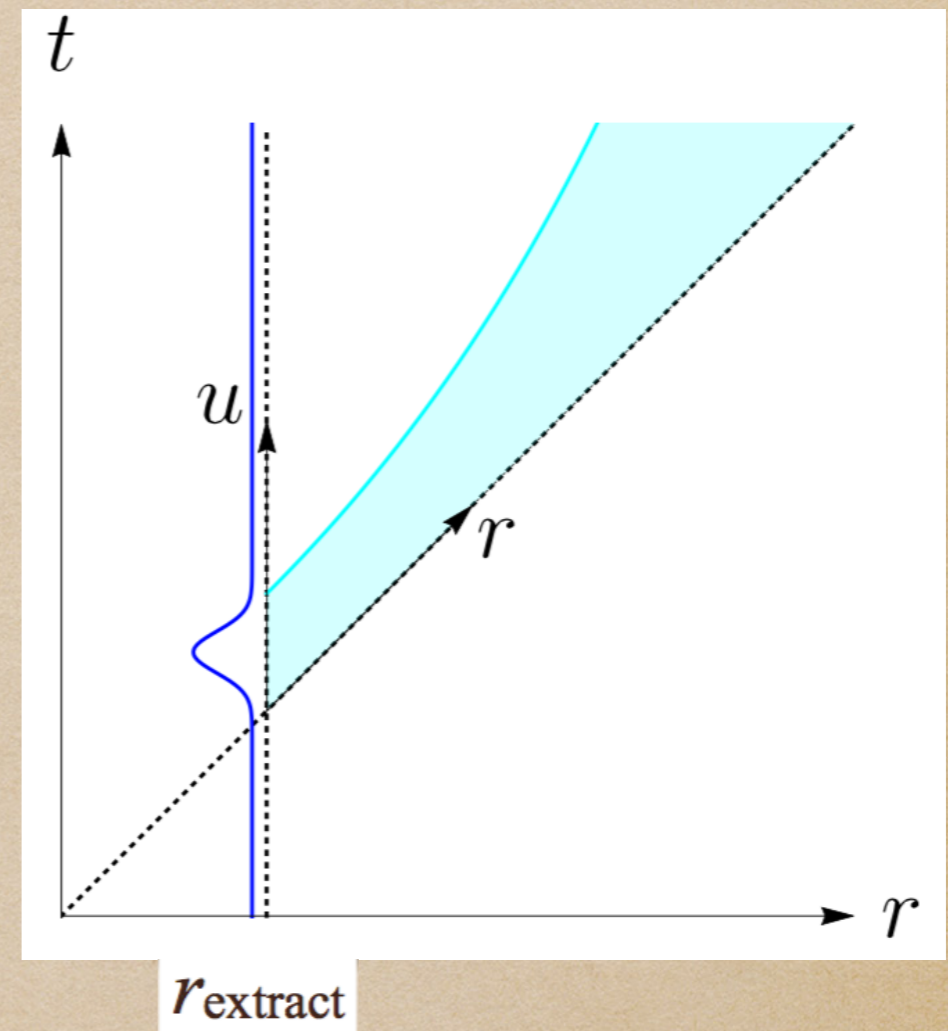
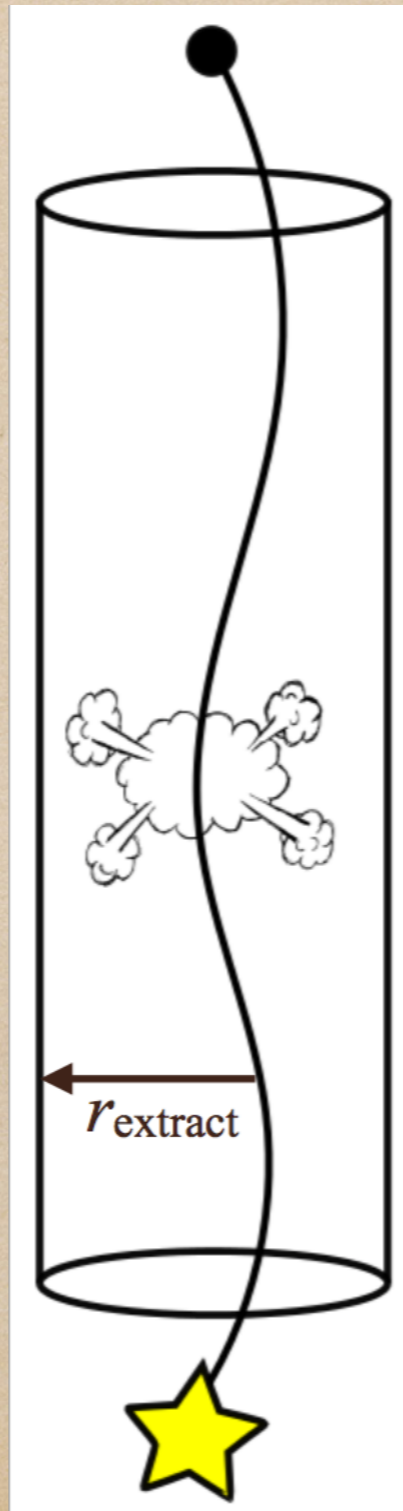
- $r_{\text{ex}} \phi \gg$ massless case; fairly insensitive to parameters; dispersion!

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

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

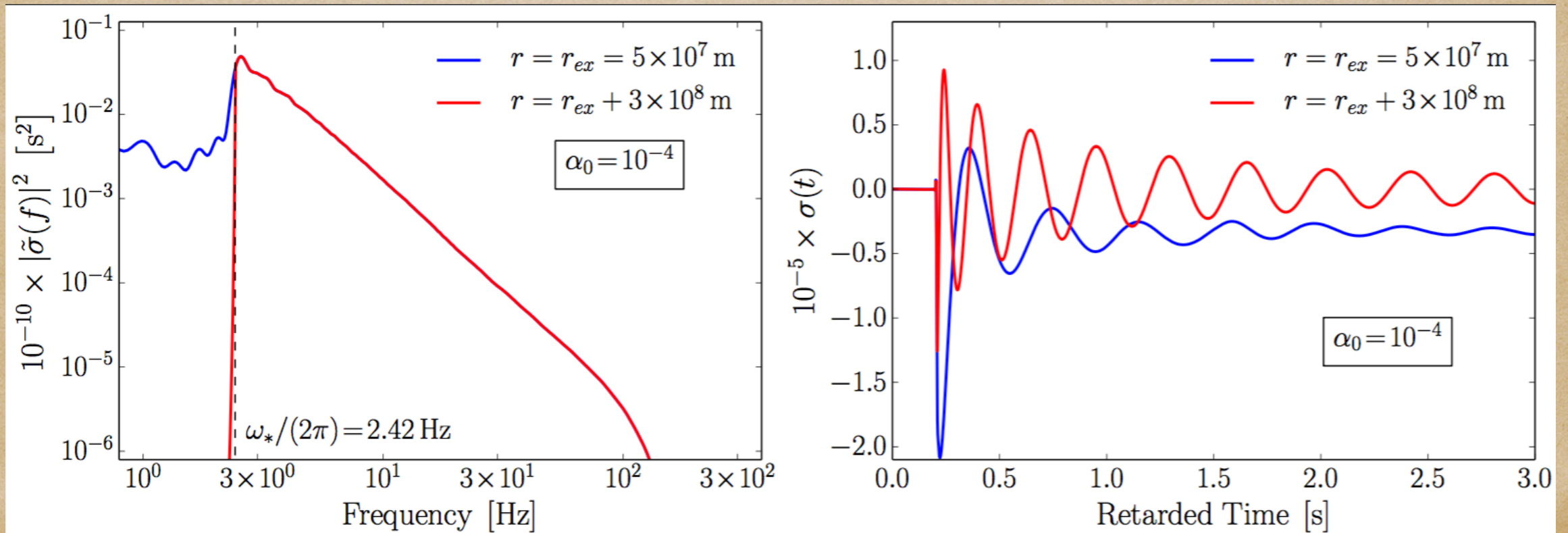
- In the massive case things are more complicated: signals propagate with **dispersion**



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

The scalar field mass has a natural frequency $\omega_* = c^2 \mu / \hbar$



Waveforms “far from” the source

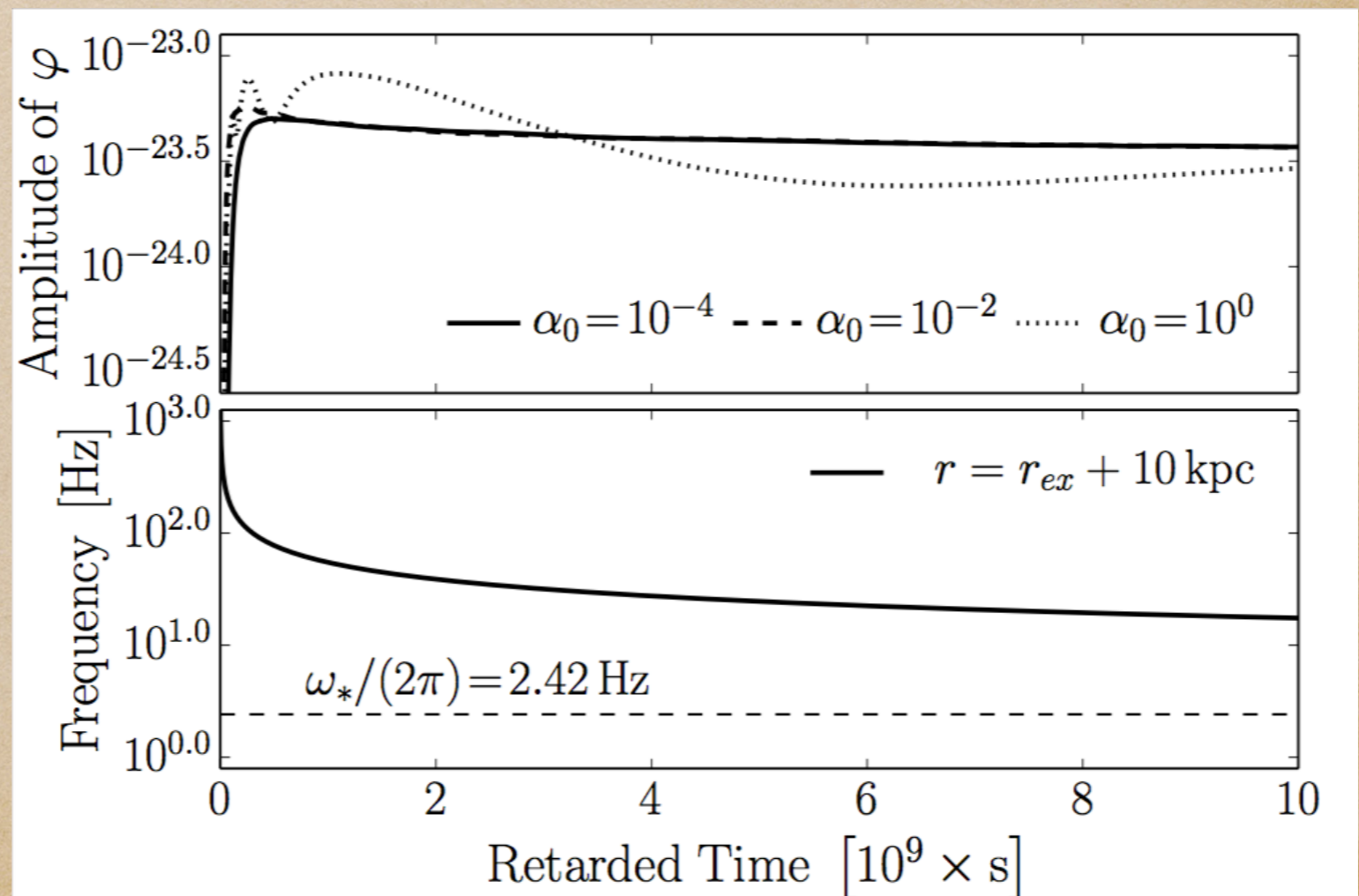
- Signals become more oscillatory as they propagate outwards
- In the large-distance limit the stationary phase approximation applies \rightarrow analytic expression for the time domain signal
- Signals have a characteristic “inverse chirp” lasting many years

SPA frequency as
function of time
(Inverse Chirp)

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

Distance to source

$$d = 10 \text{ kpc}$$



Detection with LIGO-Virgo

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

- **Burst signals:** For light scalars ($\mu < 10^{-20}$ eV) and short distances (10 kpc), the pulse does not disperse significantly; will look like a < 1 s burst
- **Continuous wave signal:** for heavier scalars, long dispersion turns pulse into a quasi-monochromatic signal
→ 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 → 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
- Explored combined parameter space of EOS and ST theory parameters
- 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 α_0, β_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