The stochastic GW background from core collapse SNe in massive ST gravity

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Rosca-Mead et al 2212.?????, 2007.14429, 2005.09728, 1903.09704;

US et al 1708.03651, Gerosa et al 1602.06952

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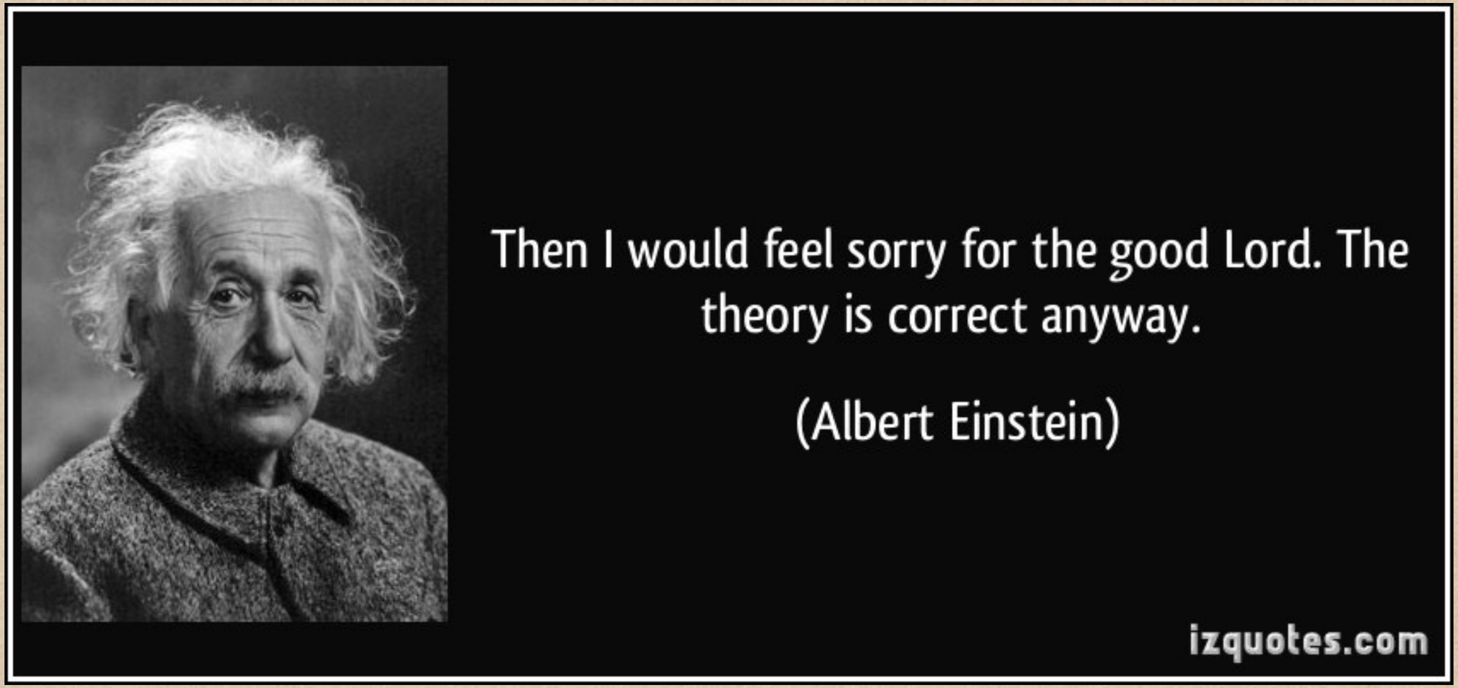
Do we need a theory beyond GR?

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



Then I would feel sorry for the good Lord. The theory is correct anyway.

(Albert Einstein)

izquotes.com

- 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 $\rho_{\mathrm{dark}} \sim \rho_{\mathrm{mat}}$
  - Dark matter: “Neptun” or “Vulcan” ?

Scalar tensor gravity (DEF theory)

- Generalization of Brans-Dicke theory

  Gravity mediated by metric + scalar field

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

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

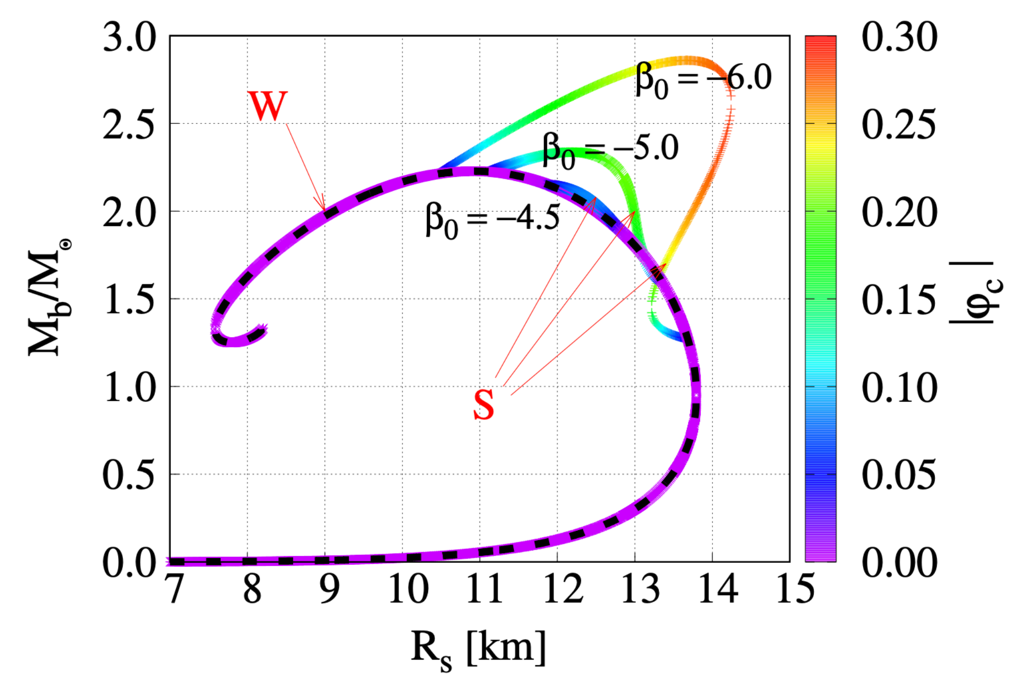
- No-hair theorems

  ⇒ BHs (in general) like in GR

- Neutron stars:

  Spontaneous scalarization

  Damour & Esposito-Farese PRL 1993



Core-collapse scenario to 0th order

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

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

  $\sim 99\ \%$ in neutrinos, $\sim 10^{51}\ {\rm erg}$ in outgoing shock, explosion
- All of this handled for us by Woosley & Heger Phys.Rept. 2007
- We evolve the WH data using a GR1D extended to ST gravity

  O'Connor & Ott CQG 2009,

  Gerosa et al CQG 2016,

  Rosca-Mead PRD 2020

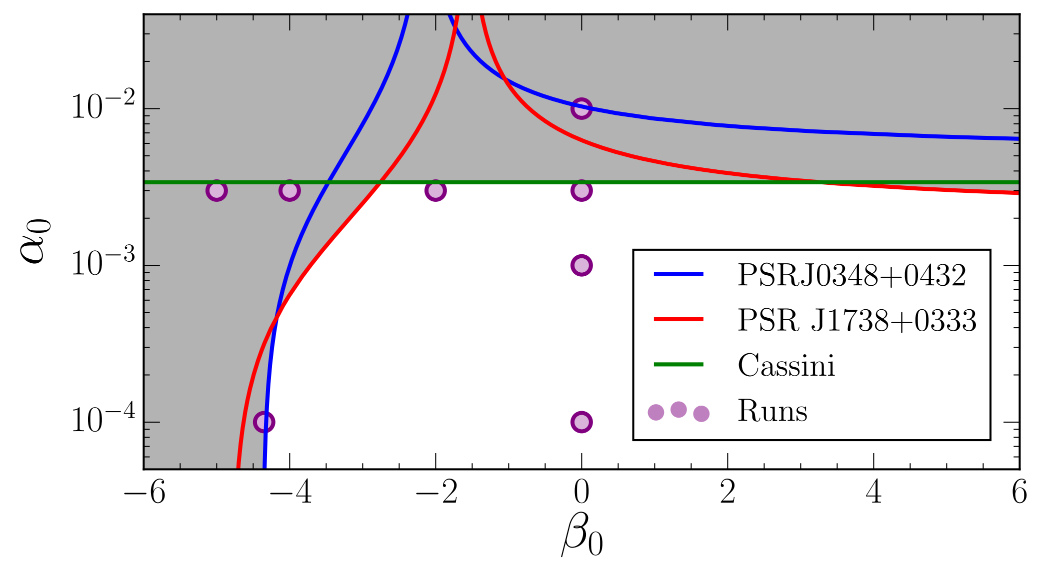
Scalar GWs in massless ST gravity

- Coupling function, potential:

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

$$\boxed{V(\varphi) = 0}$$

- Binary pulsar constraints

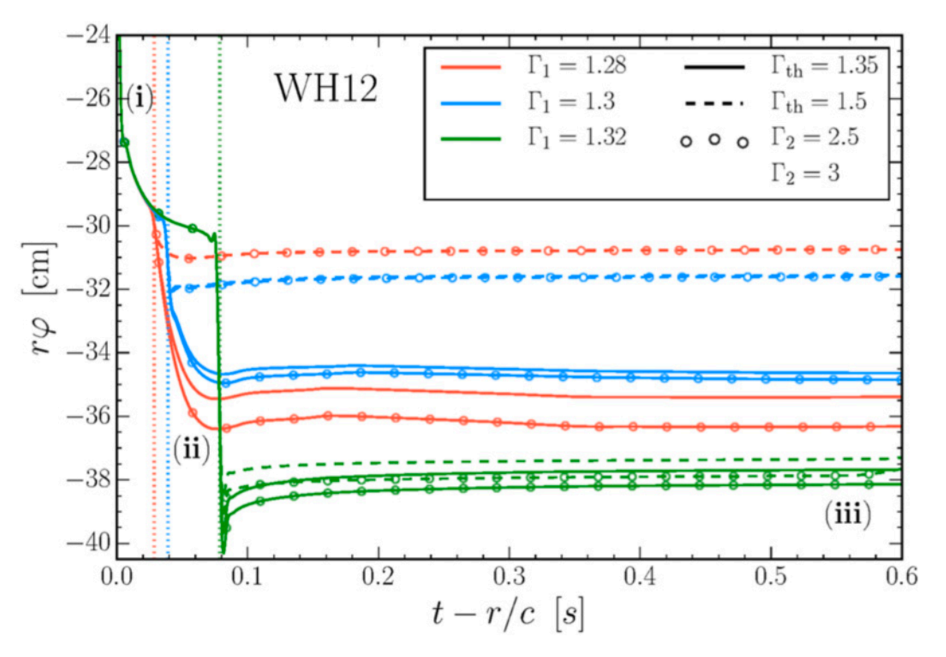


- Scalarized NSs often energetically prefered over GR like models!

- Physical scenario: unscalarized normal star → scalarized NS / BH

  Sudden creation of a scalar charge

  → Heaviside signal



The coupling function and potential

- Coupling function, potential: $\boxed{F(\varphi) = e^{-2\alpha_0\varphi - \beta_0\varphi^2}}$ $\boxed{V(\varphi) = \frac{1}{2}\mu^2\varphi^2}$

- Pulsar constraints only apply to $\mu \lesssim 10^{-16}$ eV

  Ramazanoglu & Pretorius PRD 2016

- Here: $\mu[\mathrm{eV}] \in [10^{-15}, 10^{-12}]$

- Free parameters:
  - ST gravity: $\mu,\ \alpha_0,\ \beta_0$
  - EOS: $\Gamma_1,\ \Gamma_2,\ \Gamma_{\mathrm{th}}$
  - Progenitor $M_{\mathrm{ZAMS}},\ \zeta$

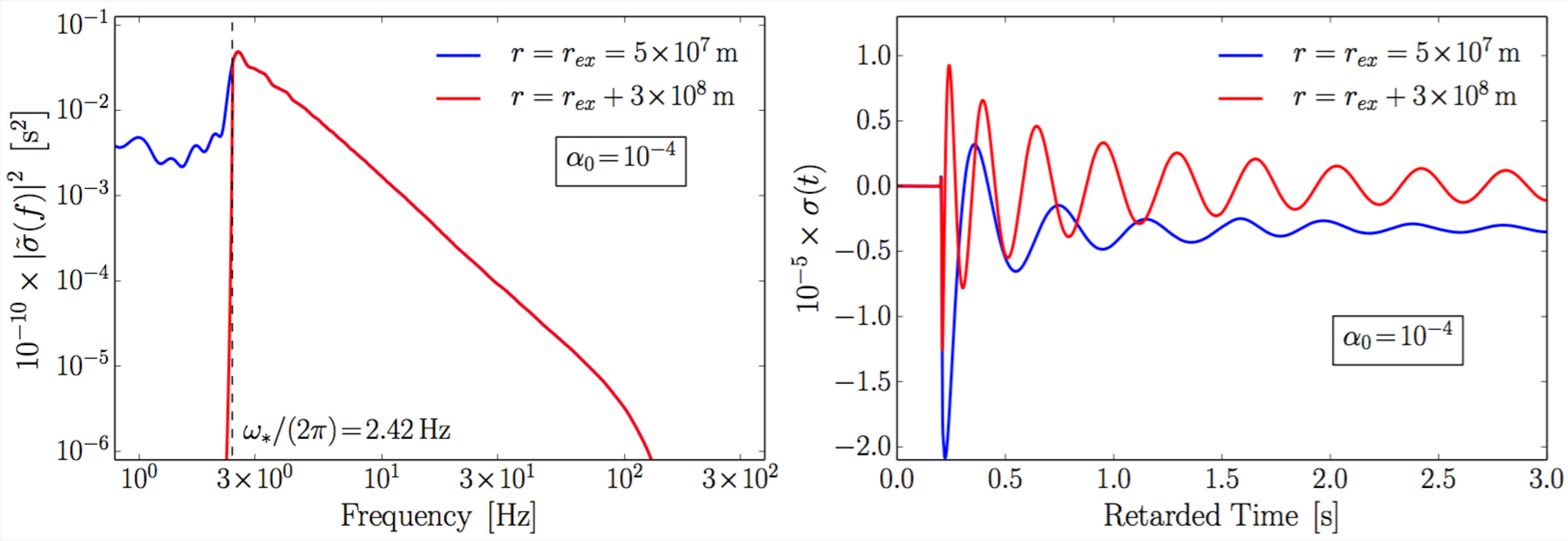
Waveforms "close to" the source

$$\mu = 10^{-14}\,\mathrm{eV}, \quad \alpha_0 = 10^{-2}, \quad \beta_0 = -20$$

$$\Gamma_1 = 1.3, \quad \Gamma_2 = 2.5, \quad \Gamma_{\mathrm{th}} = 1.35\,, \quad M_{\mathrm{ZAMS}} = 39\,M_\odot, \quad \mathcal{Z} = 10^{-4}\mathcal{Z}_\odot$$

- High-frequency modes: Unaffected

  Low-frequency modes: Exponentially damped



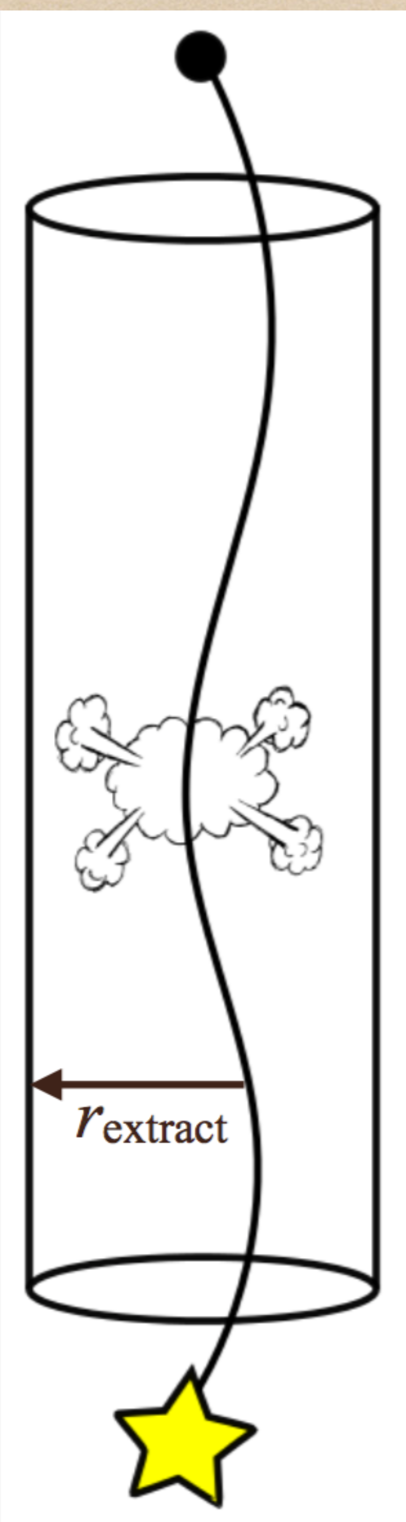
- $r\varphi \gg$ massless case; fairly insensitive to parameters; dispersion!

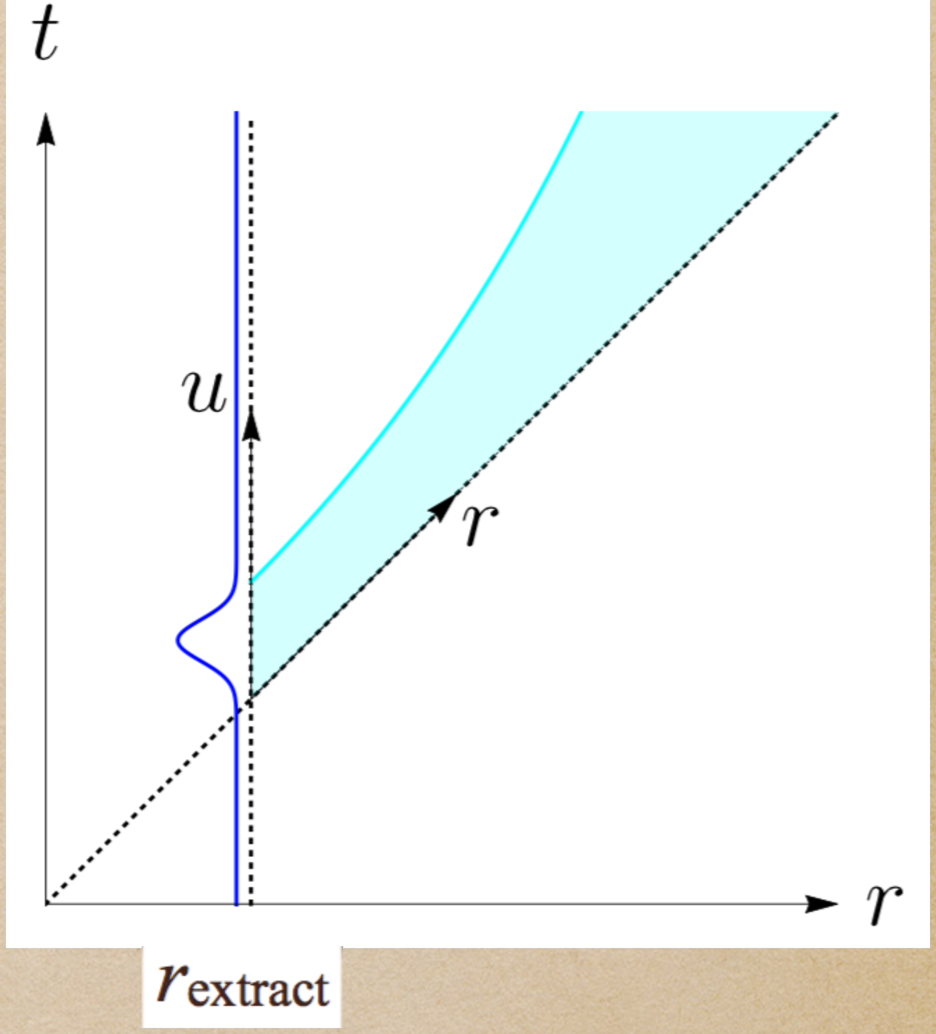
Waveforms ``far from" the source

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

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

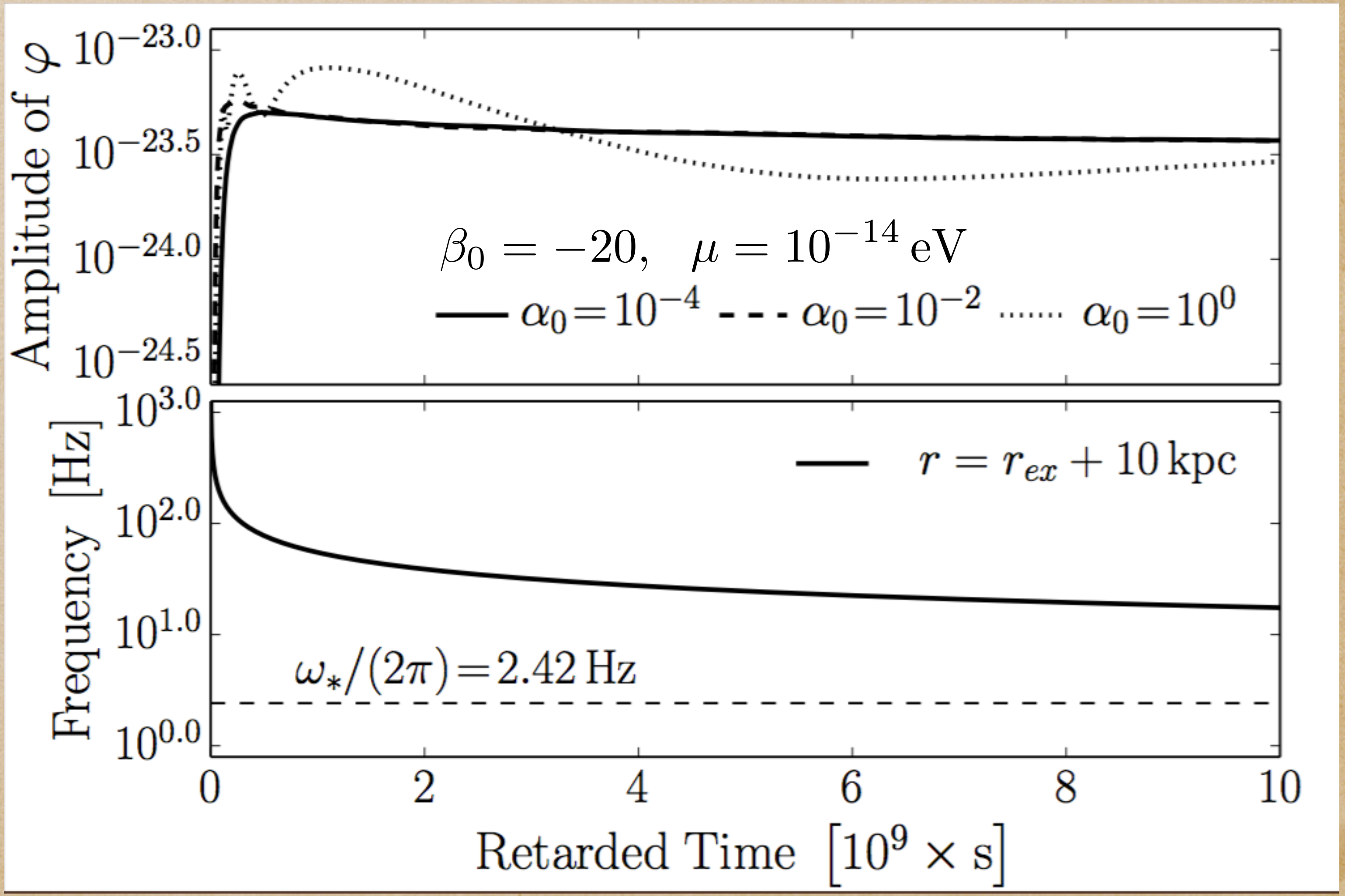
- In the massive case things are more complicated: signals propagate with ***<u>dispersion</u>***





Waveforms "far from" the source

- Signals become more oscillatory as they propagate outwards
- In the large-distance limit the stationary phase approximation applies → analytic expression for the time domain signal
- Signals have a characteristic "inverse chirp" lasting many years
- Strain $h \propto \alpha_0 \varphi$



SPA frequency as function of time (Inverse Chirp)

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

Distance to source

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

Stochastic background

- Events are stronger in GR and long-lived

  $\Rightarrow$ signals from the local universe overlap

- Task list:
  - Waveform catalog for parameters

    $\mu,\ \alpha_0,\ \beta_0,\ \Gamma_1,\ \Gamma_2,\ \Gamma_{\rm th},\ M_{\rm ZAMS},\ \zeta$
  - SN event rate in local Universe
  - Wave propagation in expanding cosmos
  - Integrate all events in frequency space

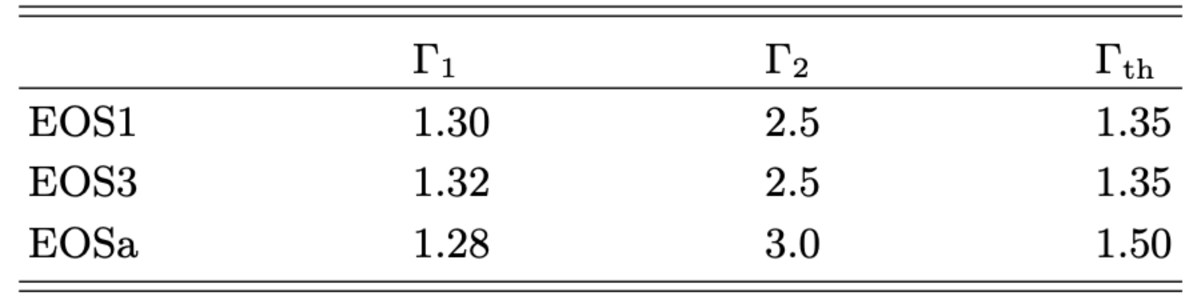
Rosca-Mead, Agathos, Moore, US arXiv:2210.?????

Catalog

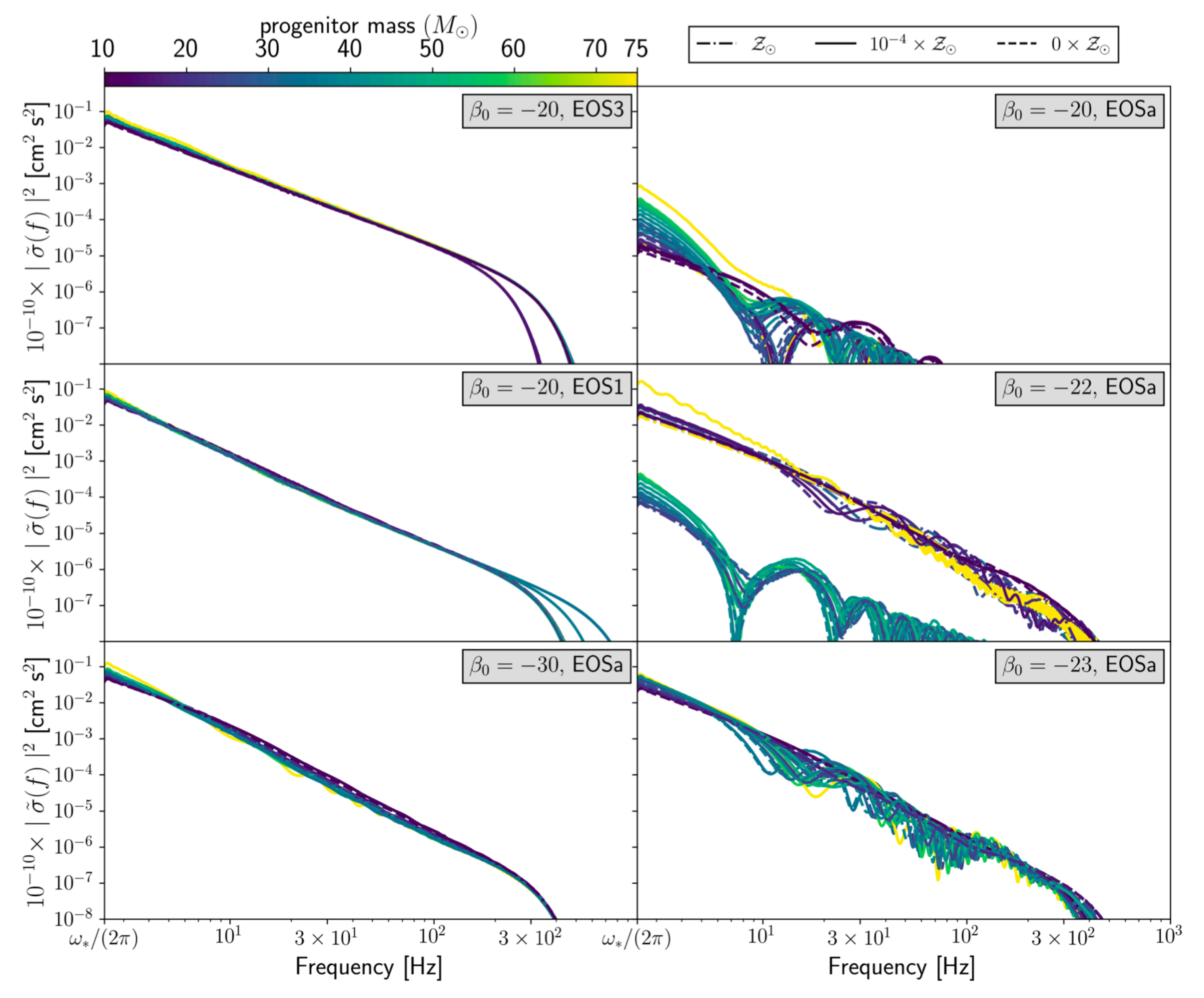
- EOS: soft —> stiff
- ST: $\alpha_0 = 10^{-2}$
- Approximate

  Universality!
- Only exception:

  $\beta_0 \approx \beta_{0,\mathrm{thr}}$
- Focus on EOS1

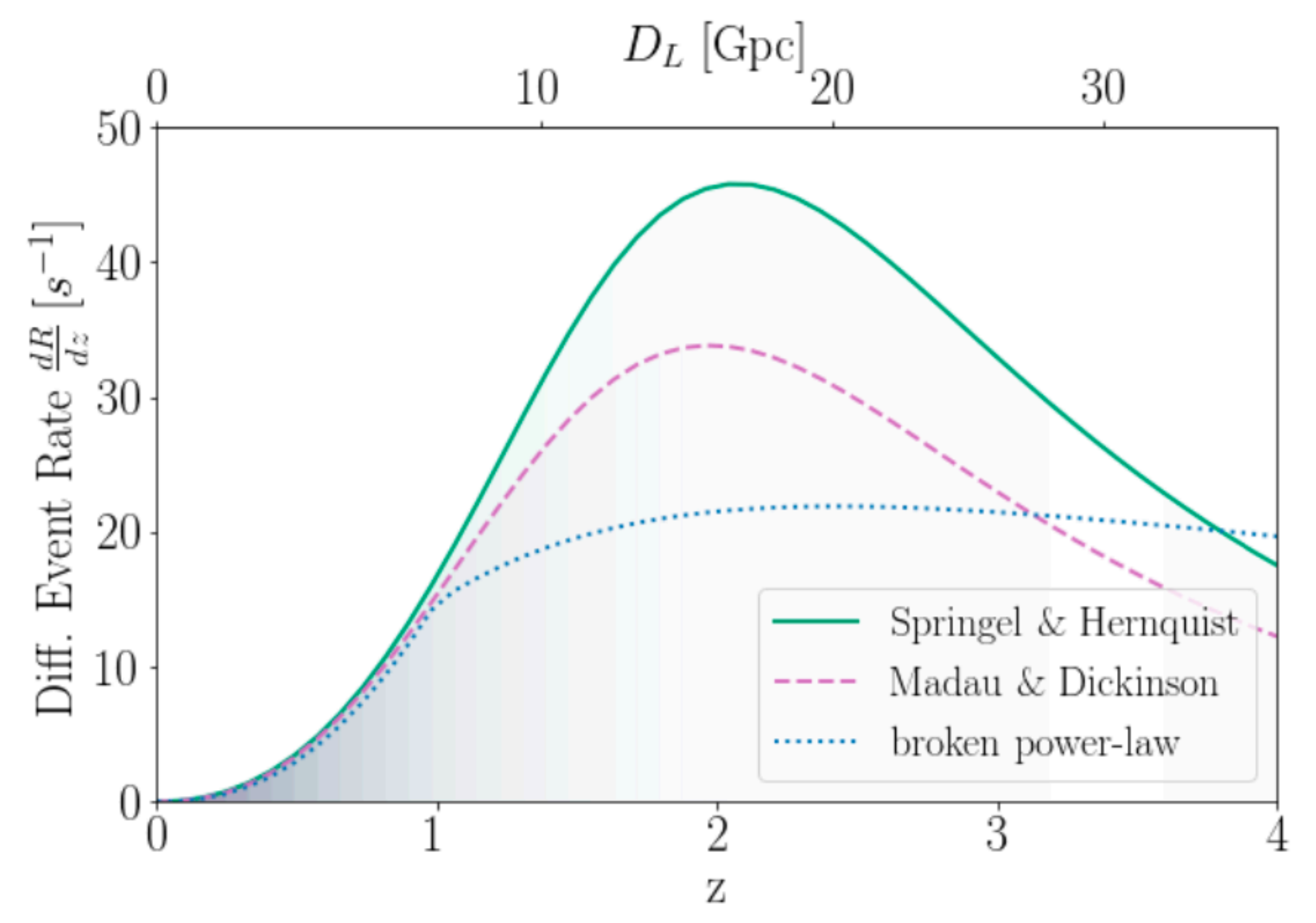


	Γ_1	Γ_2	Γ_{th}
EOS1	1.30	2.5	1.35
EOS3	1.32	2.5	1.35
EOSa	1.28	3.0	1.50



Astrophysical population statistics

- Need the even rate $\frac{\mathrm{d}R(z)}{\mathrm{d}\theta}$ in the $\theta = (M_{\mathrm{ZAMS}},\ \zeta)$ parameter space
  - Broken power law Buonanno et al astro-ph/0412277
  - Springel, Hernquist astro-ph/0206395, 0209183, 1409.2462
  - Madau, Dickinson astro-ph/1403.0007



Integration of events

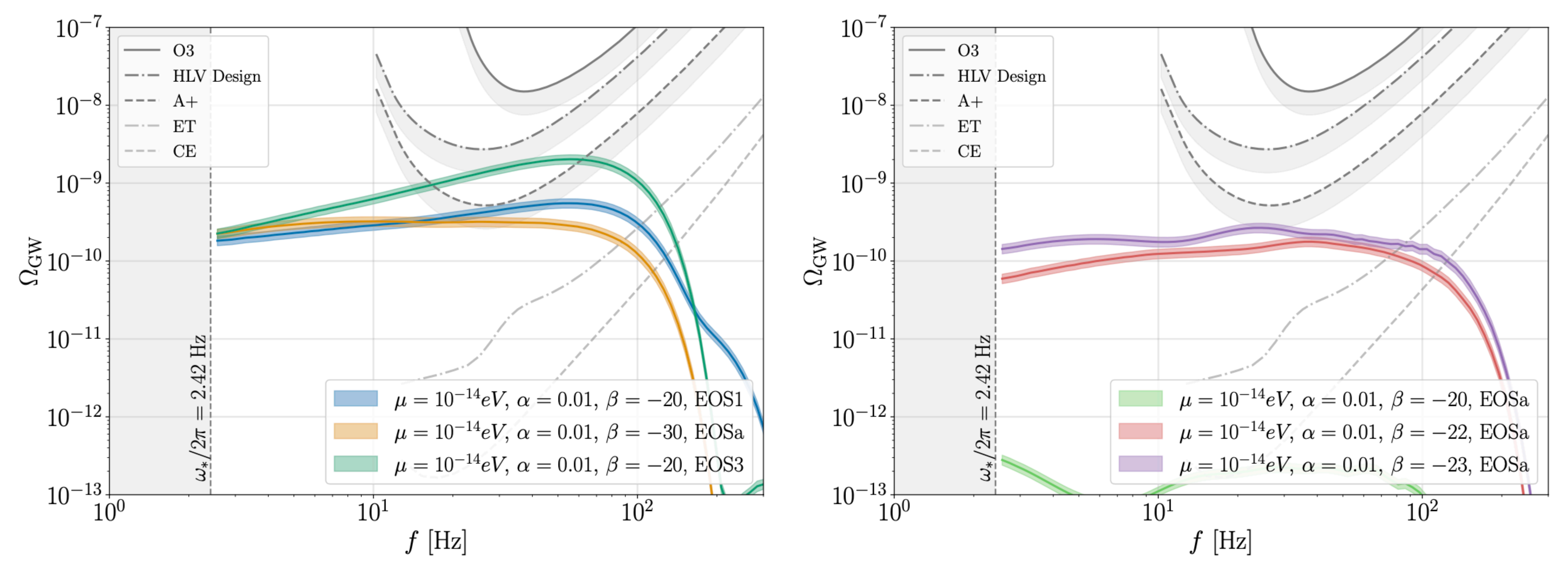
- Energy density frequency space:

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f_s} = \frac{c^3(2\pi f_s)^2}{16\pi G}\int \left\langle (\tilde{h}_+^{\mathrm{TT}})^2 + (\tilde{h}_\times^{\mathrm{TT}})^2 + (\tilde{h}_S^{\mathrm{TT}})^2 \right\rangle \mathrm{d}\Omega$$
$$= \frac{c^3\pi^2 f_s^2}{G}\left\langle \left(\tilde{h}_S^{\mathrm{TT}}(f_s)\right)^2 \right\rangle$$

$$H_0 = 67.4\ \mathrm{km/s}$$
$$\Omega_m = 0.315$$
$$\Omega_\Lambda = 0.68$$

- Cosmology $H_0 = 67.4\ \mathrm{km/s}$ Aghanim et al 1807.06209

$$\Omega_m = 0.315\,, \quad \Omega_\Lambda = 0.68$$



Conclusions

- 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
- Stochastic background $\Omega_{\mathrm{GW}} = 10^{-10}...10^{-9}$ for strong scalarization

Wave propagation and event rate

- Very similar to flat space; wave equation in $k = 0$ cosmology:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2(\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2)$$; conformal time $$\frac{\mathrm{d}\eta}{\mathrm{d}t} = \frac{1}{a}\,, \quad \sigma = ar\varphi$$

$$\Rightarrow \boxed{\partial_\eta^2\sigma - \partial_r^2\sigma - a^2H^2(1-q)\sigma + \mu^2a^2\sigma = 0}$$

- Stationary phase approximation:

Frequency $$F(t) = \frac{\omega_*}{2\pi}\frac{1}{\sqrt{1-(D_L/\tau)^2}}\,, \quad \omega_* = (1+z)\mu$$

- That’s no blueshift!!!

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 around $\sim \omega_*$