Gravitational waves beyond general relativity and the standard model

Ulrich Sperhake

M Agathos, C Moore, T Evstafyeva, D Gerosa, C Ott, I Romero-Shaw, R Rosca-Mead

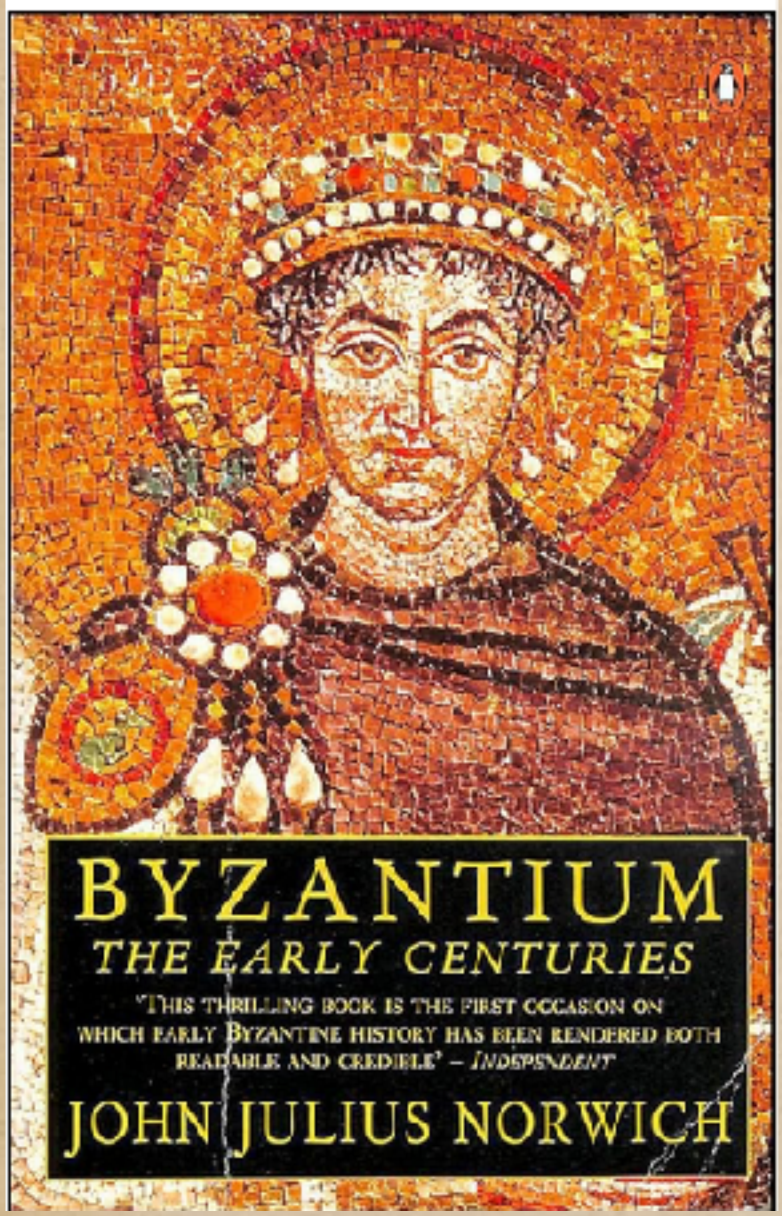
DAMTP, University of Cambridge

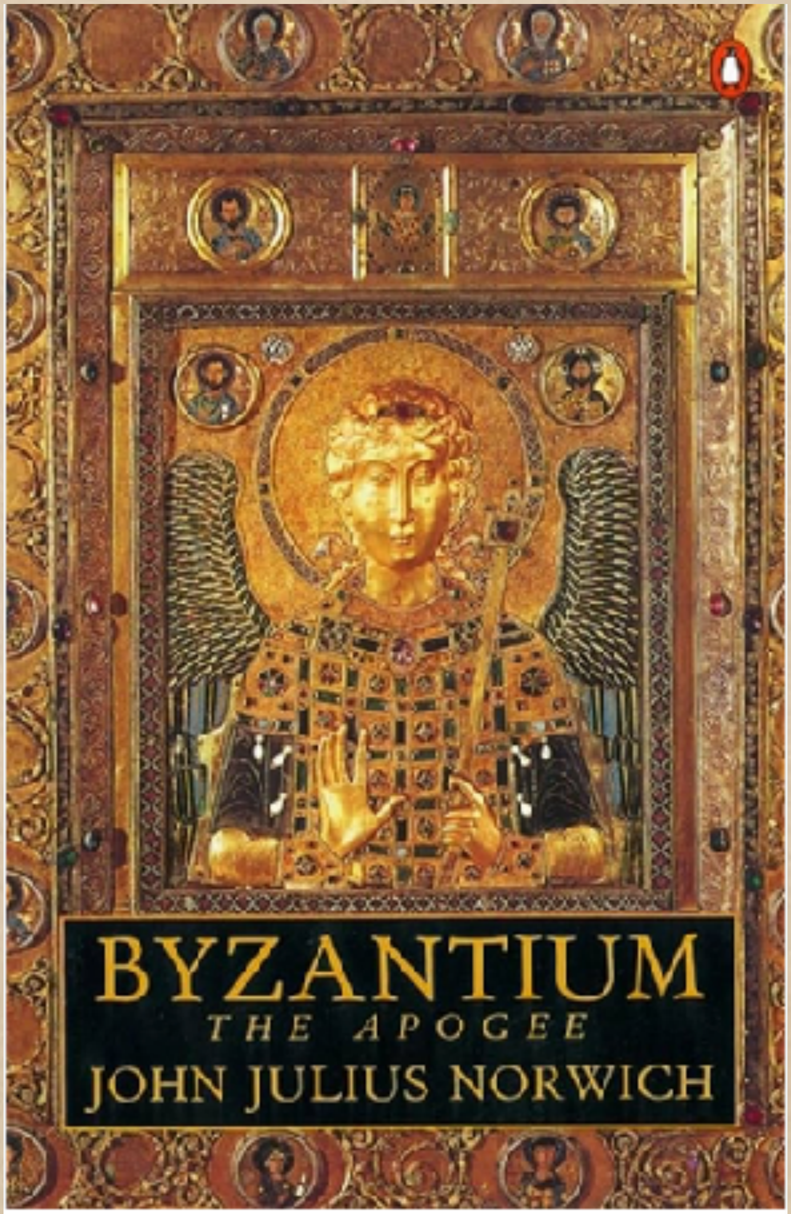
KDK@65, Kostas Fest
Syros, *2 Sep 2024*

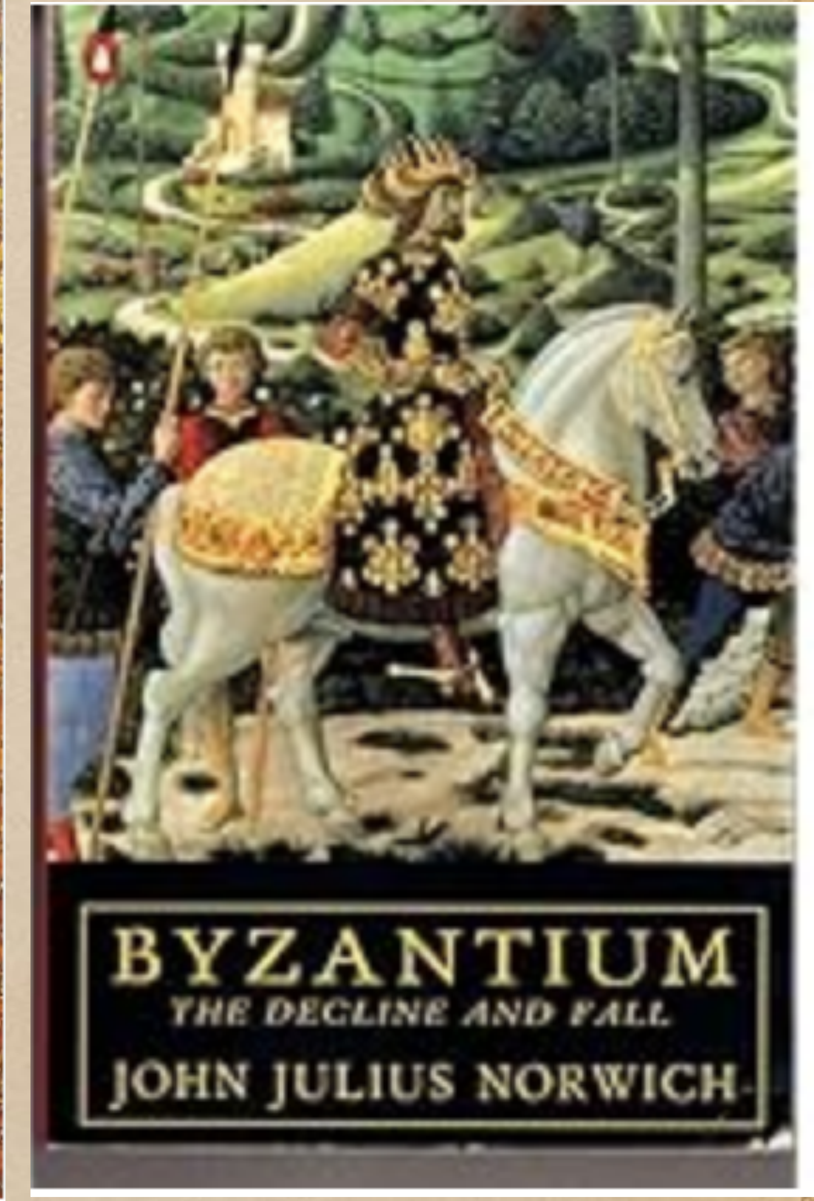
Live Score

W modes	
Teddy bears, Koalas etc	
Middle aged men and Mercedes	
Romantics	
Inappropriate advances	
Moustache	✓

A tale of three eras







Timeline

- Then: 2001/02,

PL.		TEAM	SP.	S	U	N	TORE	DIFF.	PUNKTE
1	—	Olympiakos Piräus (M)	26	17	7	2	69:30	39	58
2	—	AEK Athen	26	19	1	6	65:28	37	58
3	—	Panathinaikos Athen	26	16	7	3	53:25	28	55
4	—	PAOK Saloniki (P)	26	14	6	6	55:45	10	48
5	—	Skoda Xanthi	26	12	6	8	34:26	8	42
6	—	Iraklis Saloniki	26	9	9	8	32:35	-3	36
7	—	Panionios Athen	26	8	11	7	37:33	4	35
8	—	OF Iraklion	26	9	6	11	32:35	-3	33
9	—	Aris Saloniki	26	7	8	11	25:34	-9	29
10	^	AS Aigaleo (N)	26	7	5	14	27:46	-19	26
11	v	Akratitos Ano Liosia (N)	26	6	5	15	29:41	-12	23
12	—	Ionikos Nikea	26	5	7	14	21:47	-26	22
13	^	Panachaiki Patra	26	3	9	14	26:55	-29	18
14	v	Ethnikos Asteras	26	4	5	17	19:44	-25	17

Now: 2024

PL.		TEAM	SP.	S	U	N	TORE	DIFF.	PUNKTE
1	^	PAOK Saloniki	26	19	3	4	66:21	45	60
2	v	AEK Athen (M, P)	26	17	8	1	60:25	35	59
3	^	Olympiakos Piräus	26	18	3	5	58:24	34	57
4	v	Panathinaikos Athen	26	17	5	4	62:21	41	56
5	—	Aris Saloniki	26	12	6	8	39:29	10	42
6	—	PAS Lamia	26	9	7	10	35:44	-9	34
7	—	Asteras Tripolis	26	9	4	13	36:46	-10	31
8	—	Atromitos Athen	26	6	10	10	29:44	-15	28
9	^	Panserraikos (N)	26	6	9	11	28:45	-17	27
10	v	OF Iraklion	26	5	10	11	26:44	-18	25
11	—	AE Kifisias (N)	26	4	9	13	31:56	-25	21
12	—	Panetolikos Agrinio	26	4	8	14	26:46	-20	20
13	—	NFC Volos	26	4	7	15	24:52	-28	19
14	—	PAS Ioannina	26	3	9	14	25:48	-23	18

In the beginning there was a network

Live Score

W modes	
Teddy bears, Koalas etc	✓
Middle aged men and Mercedes	
Romantics	?
Inappropriate advances	
Moustache	✓

2nd order perts. of collapsing NSs

For convenience we will omit the superscript "r" from the perturbation variables in the remainder of this section. The resulting second order field equations for the radiative part are given by

$$\mathrm{eqtt} = \frac{r-2M}{2r}\left\{\bar{Y}_{20}\left[2\bar{H}_{1,t}\frac{2r-3M}{r(r-2M)} - \bar{H}_{0,r}\frac{2r-5M}{r(r-2M)} - \bar{H}_{2,r}\frac{M(r-2M)}{r^3} + 2\bar{K}_{,r}\frac{M}{r^4}\right.\right.$$
$$\left. -4\bar{K}\frac{M}{r^5} - 2\bar{H}_2\frac{M^2}{r^6} - 2\bar{H}_0\frac{M^2}{r^2(r-2M)^2} - \bar{H}_{0,rr} - \bar{H}_{2,tt} + 2\bar{H}_{1,rt} - 2\bar{K}_{,tt}\frac{1}{r(r-2M)}\right] \qquad (8.21)$$
$$\left. +(\cot\theta\partial_\theta + \partial_{\theta\theta})\bar{Y}_{20}\left[(\bar{G}_{,r} - 2\bar{h}_1)\frac{M}{r^4} + (2\bar{h}_{0,t} - \bar{H}_0 - \bar{G}_{,tt})\frac{1}{r(r-2M)} - 2\bar{G}\frac{M}{r^2}\right]\right\}.$$

$$\mathrm{eqtr} = \frac{1}{2}\left\{\bar{Y}_{20}\left[-2\bar{K}_{,tr}\frac{1}{r^2} + 2\bar{K}_{,t}\frac{r-M}{r^3(r-2M)} + 2\bar{H}_{2,t}\frac{r-2M}{r^3}\right] + (\cot\theta\partial_\theta + \partial_{\theta\theta})\bar{Y}_{20}\right. \qquad (8.22)$$
$$\left.\left[\bar{G}_{,t}\frac{r-M}{r^3(r-2M)} - 2\bar{h}_0\frac{M}{r^3(r-2M)} + (\bar{h}_{0,r} - \bar{G}_{,tr} - \bar{h}_{1,t} - \bar{H}_1)\frac{1}{r^2}\right]\right\}.$$

$$\mathrm{eqt}\theta = \frac{1}{2}\partial_\theta\bar{Y}_{20}\left[\left(1-\frac{2M}{r}\right)\left(\bar{h}_{1,tr} - \bar{h}_{0,rr} + \bar{H}_{1,r} - \bar{H}_{2,t} + \frac{2}{r}\bar{h}_{1,t}\right) + \frac{1}{r^2}\left(2M\bar{H}_1 + \bar{G}_{,t} - \bar{K}_{,t} - 4\frac{M}{r}\bar{h}_0\right)\right] \qquad (8.23)$$

$$\mathrm{eqrr} = \frac{1}{r^2(r-2M)}\left\{(\cot\theta\partial_\theta + \partial_{\theta\theta})\bar{Y}_{20}\right.$$
$$\left[-G\frac{r-3M}{r^2} + G_{,r}\frac{2r-5M}{2r} - \bar{h}_1\frac{M}{r} + \bar{h}_{1,t}(r-2M) - \bar{H}_2\frac{r-2M}{2} - \bar{G}_{,rr}\frac{r-2M}{2}\right]$$
$$+\bar{Y}_{20}\left[-2\bar{K}\frac{r-3M}{r^2} + 2\bar{K}_{,r}\frac{2r-5M}{2r} - \bar{H}_{1,t}\frac{Mr^2}{r-2M} - 2M\bar{H}_2\frac{2r-3M}{2r} + \frac{1}{2}r^3\bar{H}_{0,rr} + \frac{r^3}{2}\bar{H}_{2,tt}\right.$$
$$\left.\left. -\bar{H}_{0,r}\frac{Mr^2}{2(r-2M)} + \bar{H}_0\frac{Mr(2r-3M)}{(r-2M)^2} + \bar{H}_{2,r}(r-2M)\frac{2r-3M}{2} - r^3\bar{H}_{1,tr} - \bar{K}_{,rr}(r-2M)\right]\right\}, \qquad (8.24)$$

$$\mathrm{eqr}\theta = \partial_\theta\bar{Y}_{20}\left[-\frac{G}{r^3} + \frac{\bar{K}}{r^3} + \bar{h}_{1,tt}\frac{r}{2(r-2M)} + \frac{1}{2r^2}\bar{G}_{,r} + \bar{H}_2\frac{r-M}{2r^2} - \bar{H}_0\frac{r-M}{2(r-2M)^2}\right. \qquad (8.25)$$
$$\left. +\bar{H}_{0,r}\frac{r}{2(r-2M)} - \frac{\bar{K}_{,r}}{2r^2} - \bar{h}_{0,tr}\frac{r}{2(r-2M)} - \frac{\bar{h}_0}{r^2} + \frac{\bar{h}_{0,t}}{r-2M} - \bar{H}_{1,t}\frac{r}{2(r-2M)}\right]$$

$$\mathrm{eq}\theta\theta = \bar{Y}_{20}A + (B\cot\theta\partial_\theta + C\partial_{\theta\theta})\bar{Y}_{20}, \qquad (8.26)$$

$$\mathrm{eq}\phi\phi = \sin^2\theta\left[A\bar{Y}_{20} + (C\cot\theta\partial_\theta + B\partial_{\theta\theta})\bar{Y}_{20}\right], \qquad (8.27)$$

where

$$A = -r\bar{H}_{1,t} + \bar{H}_2\left(1-\frac{2M}{r}\right)\left(1+\frac{M}{r}\right) - \bar{K}_{,r}\frac{M}{r^3} + \bar{H}_{2,r}\frac{(r-2M)^2}{2r} - \bar{K}_{,rr}\frac{r-2M}{2r}$$
$$+\bar{K}_{,tt}\frac{r}{2(r-2M)} + \frac{1}{2}r\bar{H}_{0,r} - \bar{H}_0\frac{M}{r-2M}, \qquad (8.28)$$

$$B = -\frac{\bar{K}}{2r^2} + \frac{r-2M}{r^2}\left(\bar{h}_1 + \frac{\bar{G}}{r} - \frac{1}{2}G_{,r}\right), \qquad (8.29)$$

$$C = -\bar{G}_{,rr}\frac{r-2M}{2r} - \frac{1}{2r^2}\bar{K} - \bar{h}_{0,t}\frac{r}{r-2M} + \bar{H}_0\frac{r}{2(r-2M)} + \bar{h}_{1,r}\left(1-\frac{2M}{r}\right) - \bar{H}_2\frac{r-2M}{2r}$$
$$+\bar{G}_{,r}\frac{r-4M}{2r^2} + \frac{\bar{h}_1}{r} + \bar{G}_{,tt}\frac{r}{2(r-2M)} + 2\bar{G}\frac{M}{r^3}. \qquad (8.30)$$

The equations for the perturbation functions resulting from Eqs. (8.21)-(8.25) are obtained straightforwardly by using the relation

$$(\cot\theta\partial_\theta + \partial_{\theta\theta})\bar{Y}_{20} = -l(l+1)\bar{Y}_{20}, \qquad (8.31)$$

and/or factoring out the spherical harmonic $\bar{Y}_{20}$. For Eqs. (8.26) and (8.27) we consider the sum and difference of the equations after dividing the latter by $\sin^2\theta$

$$2A\bar{Y}_{20} + (B+C)(\cot\theta\partial_\theta + \partial_{\theta\theta})\bar{Y}_{20} = 0, \qquad (8.32)$$

$$(B-C)(\cot\theta\partial_\theta - \partial_{\theta\theta})\bar{Y}_{20} = 0, \qquad (8.33)$$

which leads to

$$\mathrm{eqAB} = A - l(l+1)B, \qquad (8.34)$$

$$\mathrm{eqBC} = B - C. \qquad (8.35)$$

8.3 The constraint equations

In our formulation we are interested in gauge invariant equations, that is equations that can be formulated in terms of the gauge invariant variables q_1 and q_2 defined in Eqs. (8.16), (8.17). One suitable way of identifying the corresponding linear combinations of the field equations (8.21)-(8.35) is to eliminate the perturbations of the lapse function and the shift vector $\bar{H}_0$, $\bar{H}_1$ and $\bar{h}_0$. Since we have seven field equations and three gauge perturbations to eliminate we may expect to find four gauge independent linear combinations. I have found three so far and we shall see whether I need to find another one or not. First we consider the gauge invariant constraint which is given in terms of the field equations by

$$\mathrm{constraint} = -\frac{r^4}{2(r-2M)^2}\frac{\mathrm{eqtt}}{\bar{Y}_{20}} - \frac{r^2}{2}\frac{\mathrm{eqrr}}{\bar{Y}_{20}} - \frac{r}{r-2M}\mathrm{eqAB} - \frac{3r}{r-2M}\mathrm{eqBC}. \qquad (8.36)$$

Wouldn't it be easier to do NR?

Inspired by Kostas 1

Rapidly rotating neutron stars in scalar-tensor theories of gravity

Daniela D. Doneva,[1,2,*] Stoytcho S. Yazadjiev,[3,1]
Nikolaos Stergioulas,[4] and Kostas D. Kokkotas[1,4]

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[2]*INRNE - Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria*
[3]*Department of Theoretical Physics, Faculty of Physics, Sofia University, Sofia 1164, Bulgaria*
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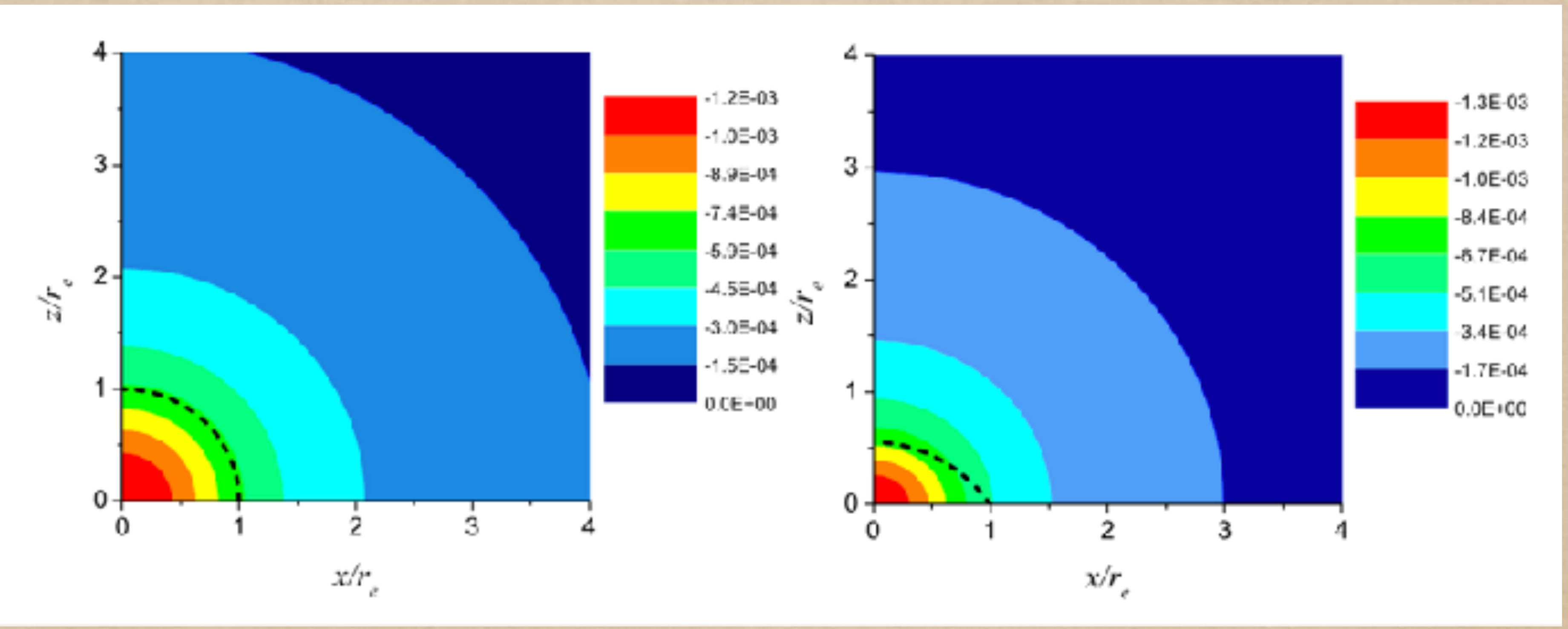
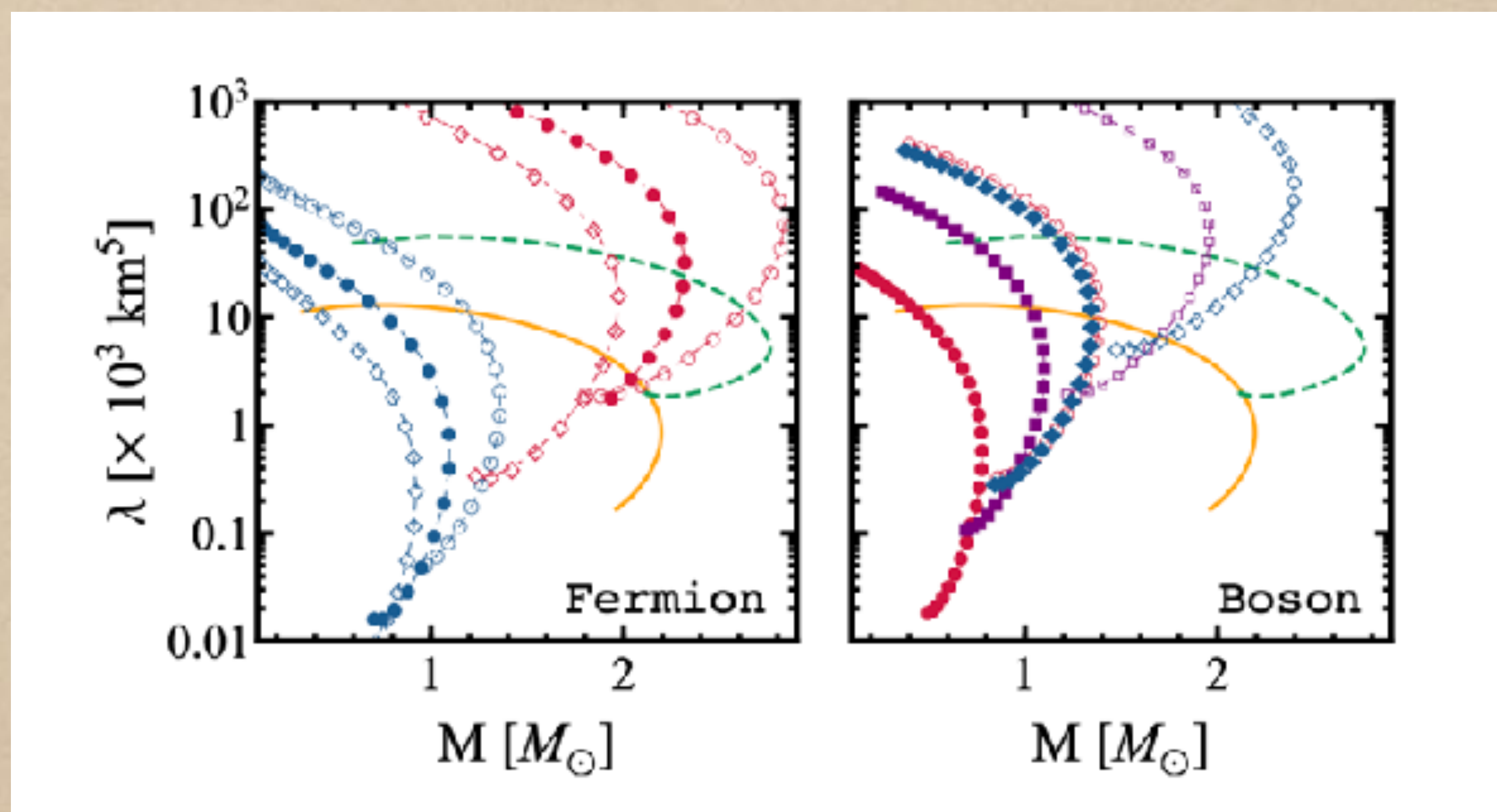


- Scalar field for non-rotating and rotating NSs 1309.0605

Inspired by Kostas 2

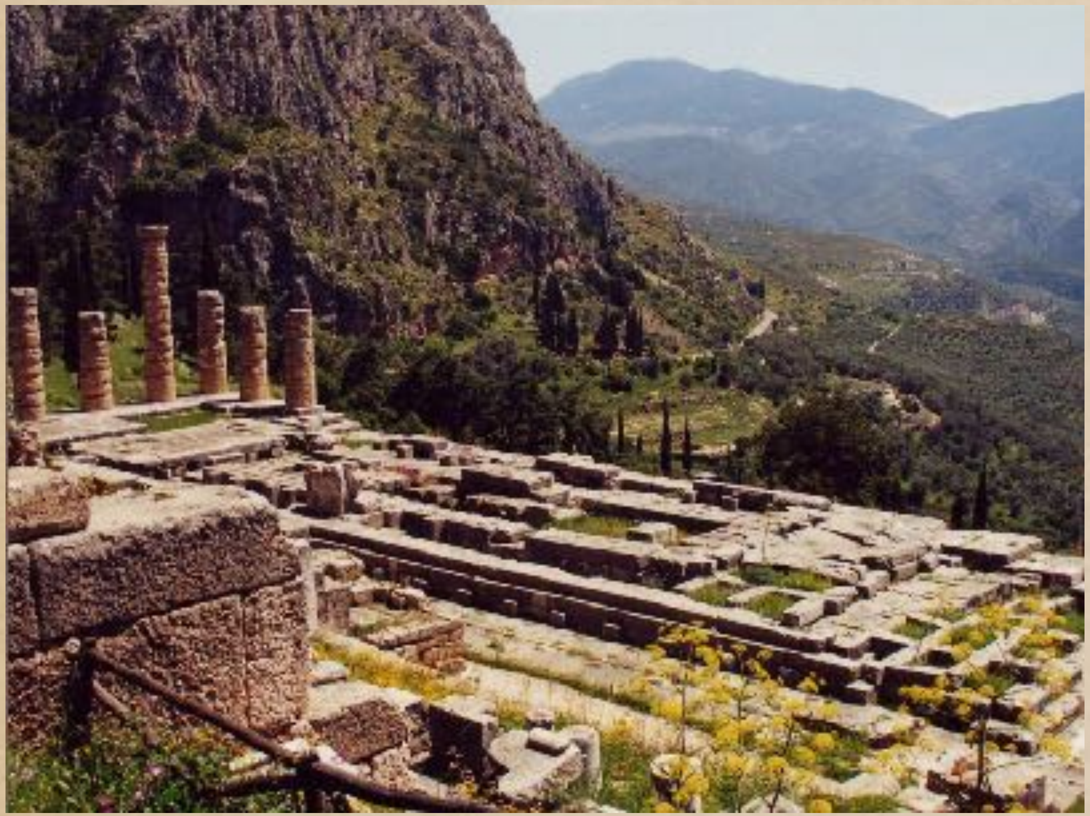
Dark stars: gravitational and electromagnetic observables

Andrea Maselli,[1,*] Pantelis Pnigouras,[1,†] Niklas Grønlund Nielsen,[2,‡] Chris Kouvaris,[2,§] and Kostas D. Kokkotas[1,¶]
[1] *Theoretical Astrophysics, IAAT, University of Tüebingen, Tüebingen 72076, Germany*
[2] *CP^3-Origins, Centre for Cosmology and Particle Physics Phenomenology*
University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
(Dated: April 25, 2017)



- Tidal deformability of fermionic and bosonic dark stars 1704.07286

Inspired by Kostas 3



Inspired by Kostas 4

Spring 2003

Sep 2005

What's wrong about middle aged men and Mercedes Sports Cars ?

Live Score

W modes	
Teddy bears, Koalas etc	✓
Middle aged men and Mercedes	✓
Romantics	?
Inappropriate advances	
Moustache	✓

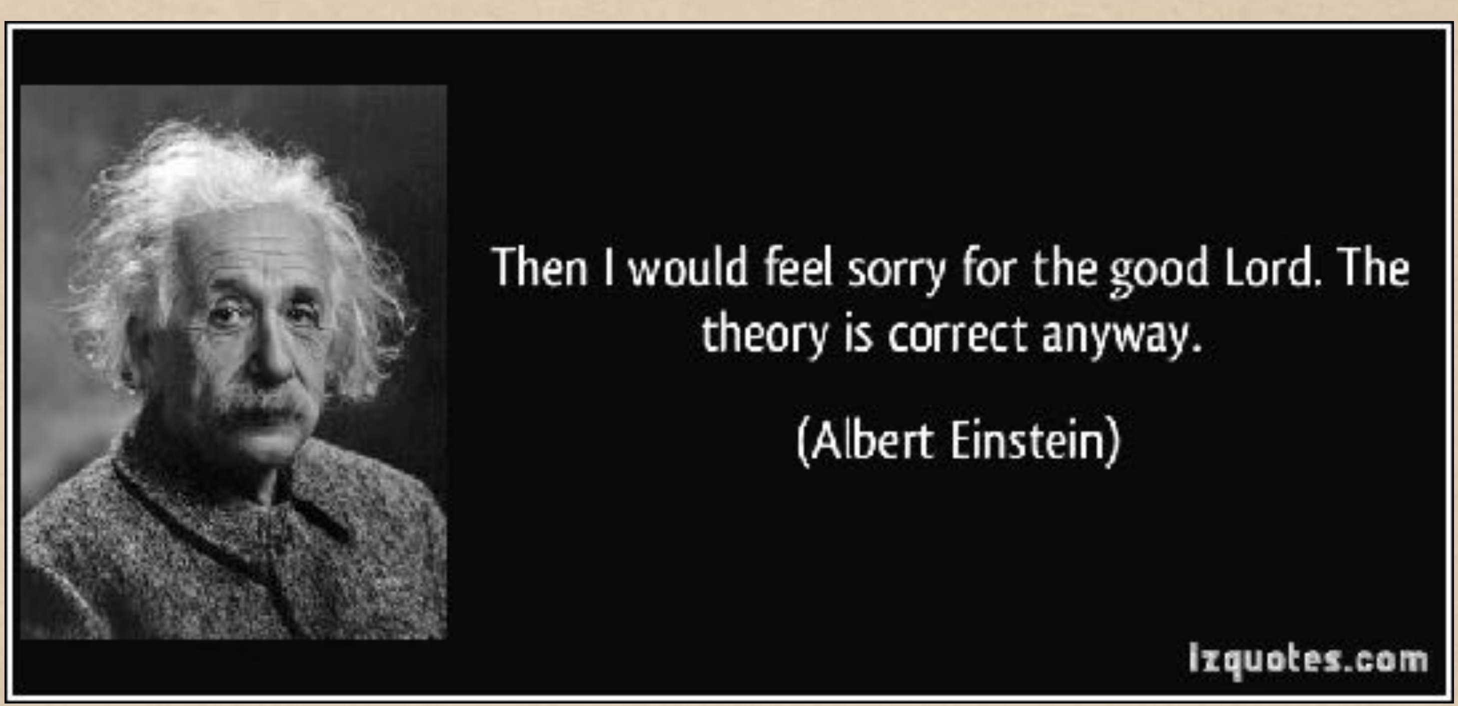
Part 1

Core Collapse in ST theory

US, Moore, Rosca-Mead, Agathos, Gerosa, Ott 1708.03651,
Rosca-Mead, US, C Moore, M Agathos, D Gerosa, C Ott 2005.09728
cf also 1903.09704, 2007.14429, 2302.04495

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: "Neptun" 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: $M_{\rm ZAMS} = 8 \ldots 100\ M_\odot$
- Core compressed from $\sim 1\,500$ km to ~ 15 km
  $\sim 10^{10}$ g/cm^3 to $\gtrsim 10^{15}$ g/cm^3
- Released gravitational energy: $\mathcal{O}(10^{53})$ erg
  ~ 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
- Star's life 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: $d\bar{s}^2 = \bar{g}_{\mu\nu} dx^\mu dx^\nu = -F\alpha^2 dt^2 + F X^2 dr^2 + r^2 d\Omega^2$

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

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

  $\partial_t\partial_t\varphi = \dots$

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

  GR1D code   O'Connor & Ott CQG 2009

Equation of state

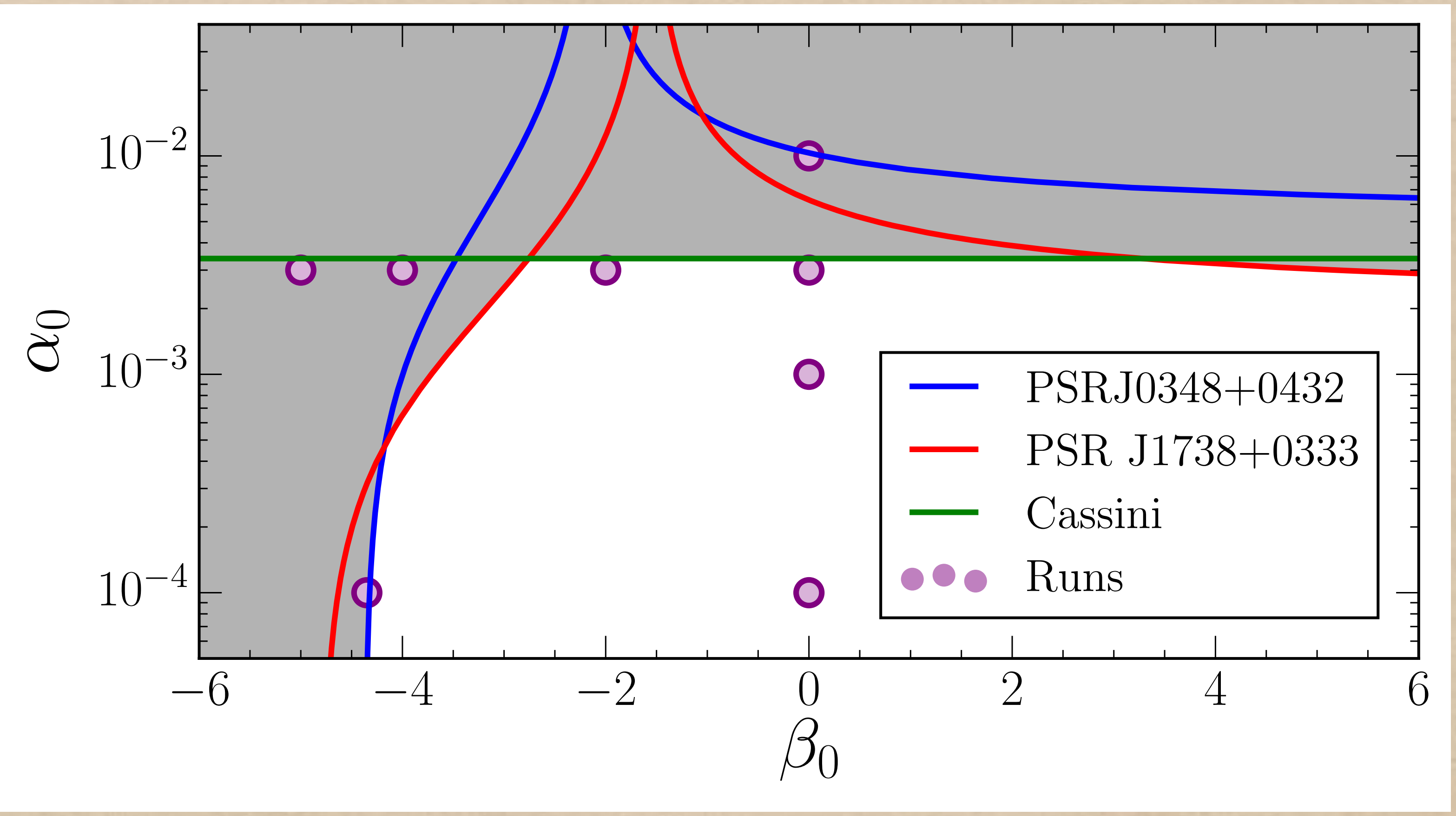
- Pressure: "cold" + "thermal" contribution: $P = P_{\rm c} + P_{\rm th}$
- Hybrid EOS for cold part: $P_c = \begin{cases} K_1 \rho^{\Gamma_1} & \text{if} \quad \rho \le \rho_{\rm nuc} \\ K_2 \rho^{\Gamma_2} & \text{if} \quad \rho > \rho_{\rm nuc} \end{cases}$
- Internal energy from 1st law: $\epsilon_c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

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

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

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

Ramazanoglu & Pretorius PRD 2016

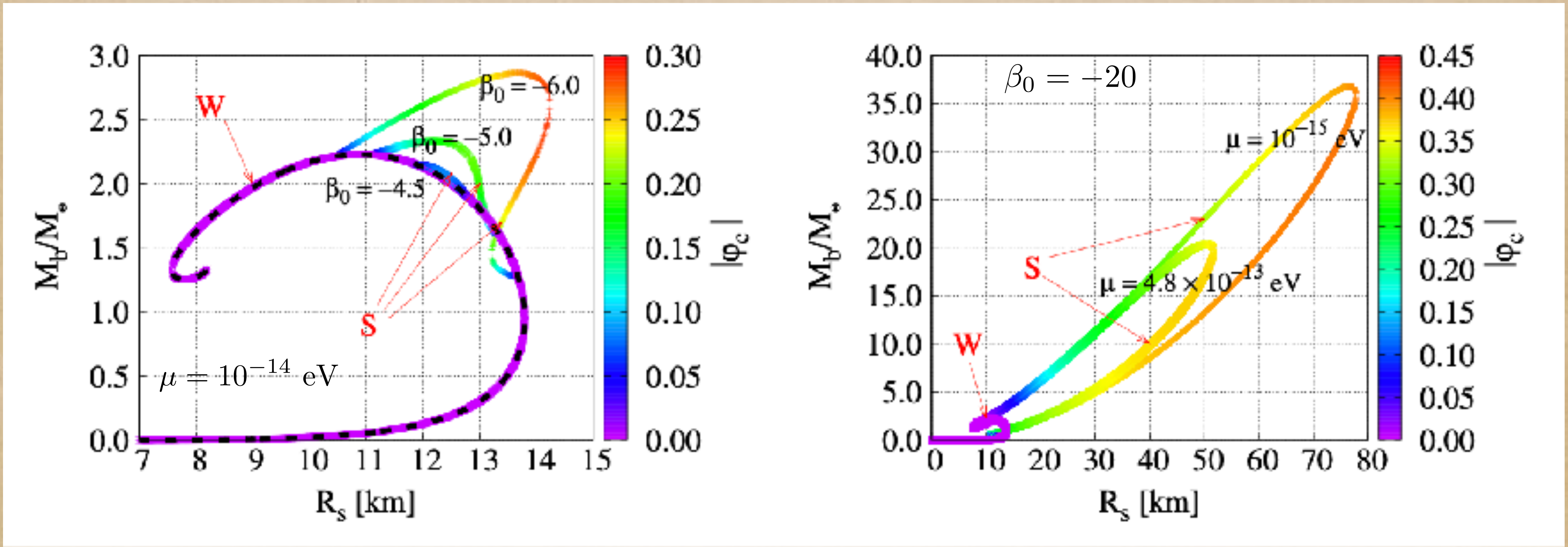
- Free parameters: $\mu,\ \alpha_0,\ \beta_0,\ \Gamma_1,\ \Gamma_2,\ \Gamma_{\rm th}$ + progenitor $M_{\rm ZAMS},\ \zeta$

Spontaneous scalarization

- Phase transition in the solution space as we vary β_0

  Damour & Esposito-Farese PRL 1993

- $\beta_0 \lesssim -4.35 \quad \Rightarrow$ New families of solutions



- Lots of substructure   Rosca-Mead+ Symmetry 2020
- Scalarized stars often energetically favored!

Time evolutions cooking book recipe

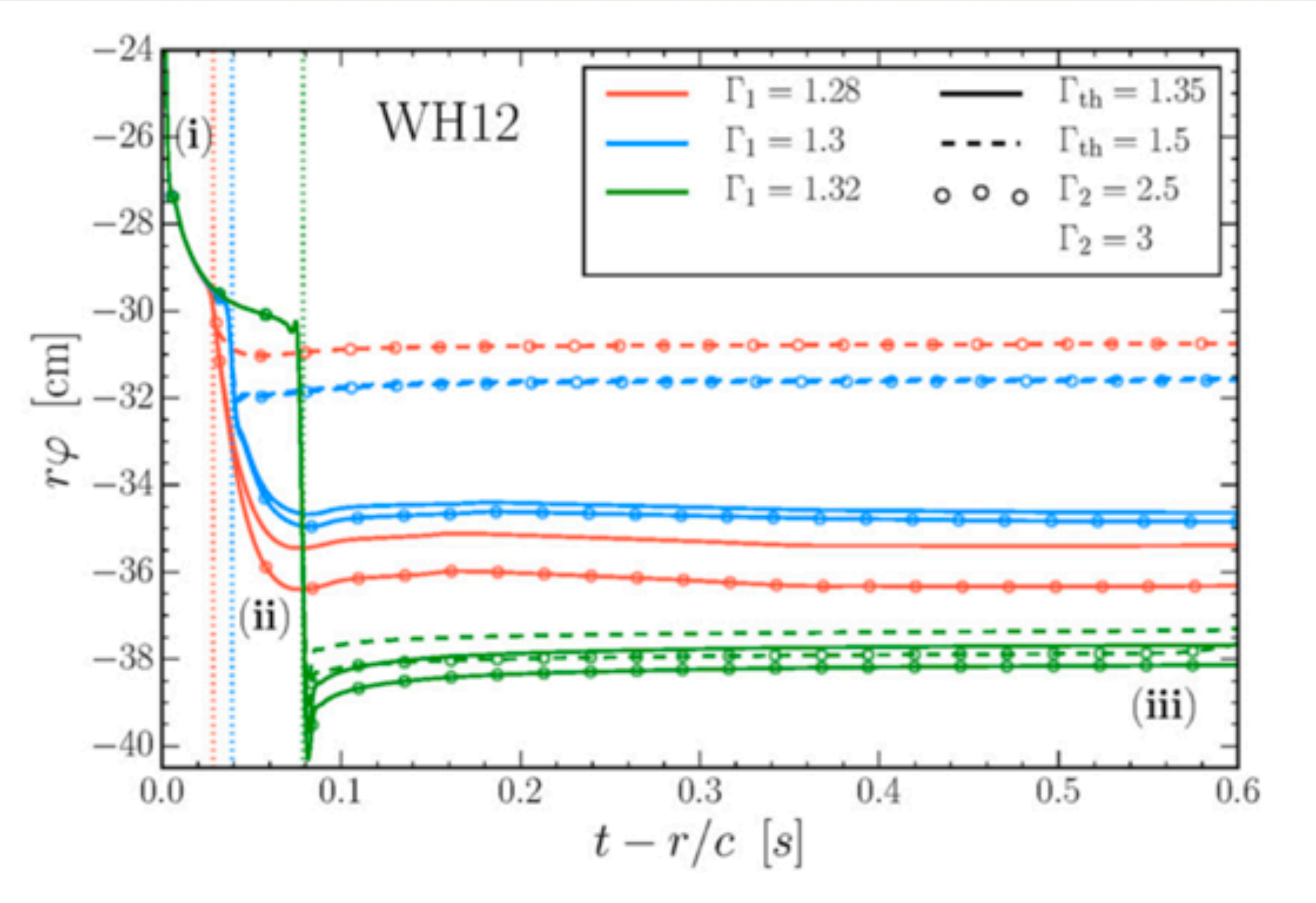
- Choose your Woosley-Heger progenitor $M_{\rm ZAMS},\ \zeta$
- Specify parameters $\mu,\ \alpha_0,\ \beta_0,\ \Gamma_1,\ \Gamma_2,\ \Gamma_{\rm th}$
- Specify the grid
- Run (may need checkpointing, but no Parallelization)
- Extract GW signals at $R_{\rm ex} \sim \mathcal{O}(1)$ light second
- Propagate signal to astrophysical distances;

  easy if $\mu = 0$, not easy if $\mu \neq 0$

Core collapse in massless ST theory

- Here: $\mu = 0 \quad \Rightarrow \quad V(\varphi) = 0$

  $\alpha_0 = 10^{-4}, \quad \beta_0 = -4.35$

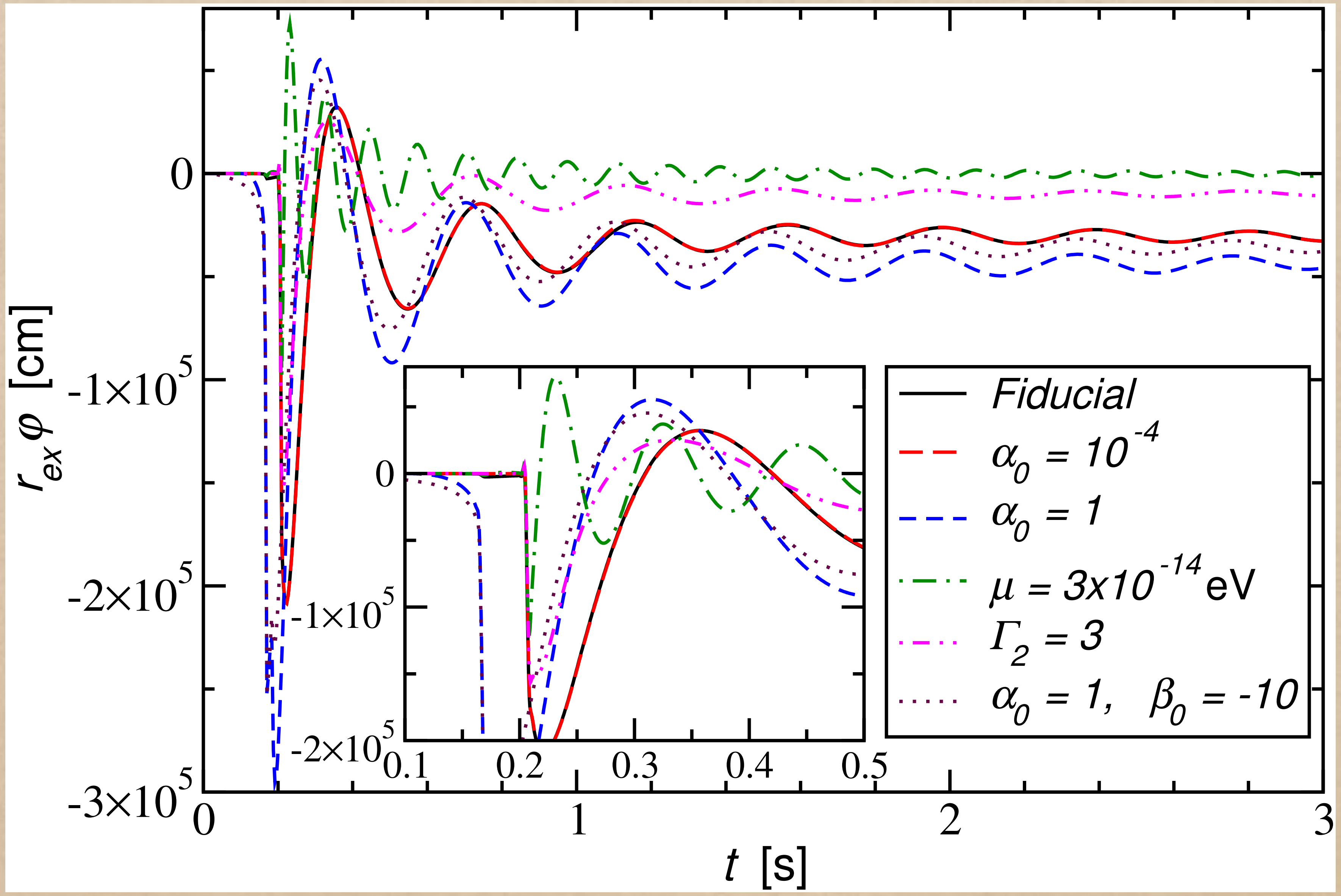


Gerosa, US, Ott CQG 2016

- Weak signals (β_0 constraints!), Heaviside like

Waveforms "close to" the source

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



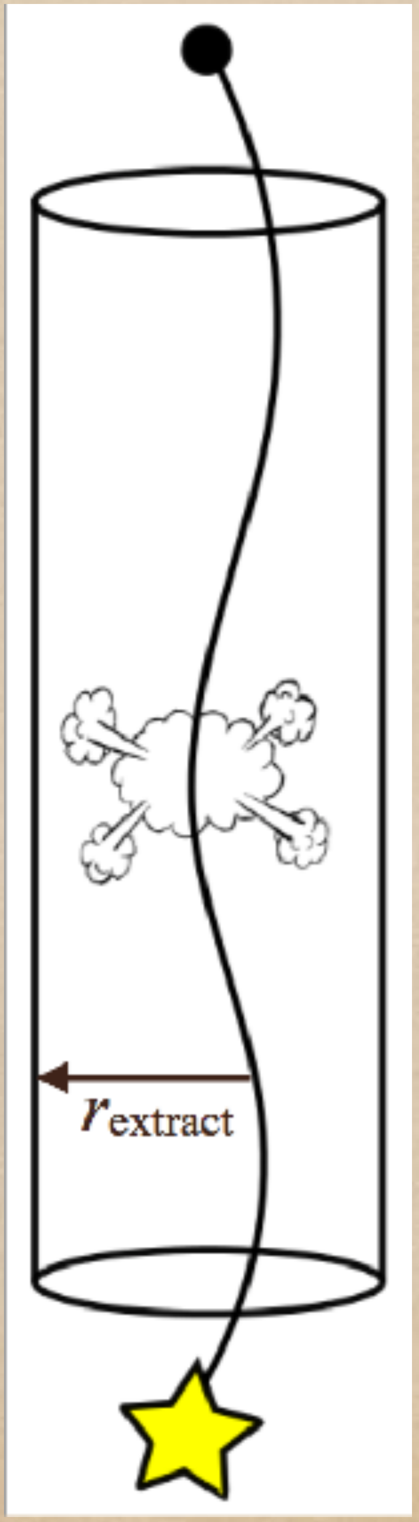
- $r\varphi \gg$ massless case; fairly insensitive to parameters; dispersion!

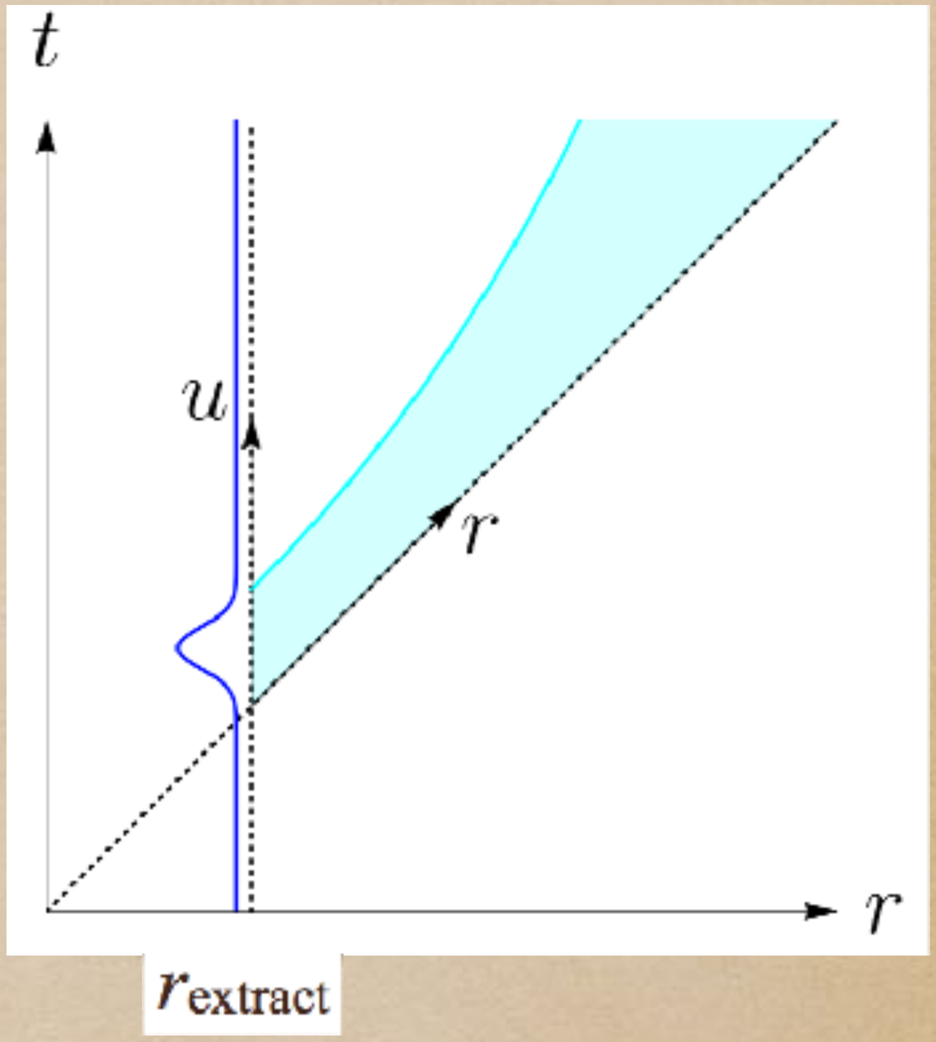
Waveforms "far from" the source

- 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 ***dispersion***

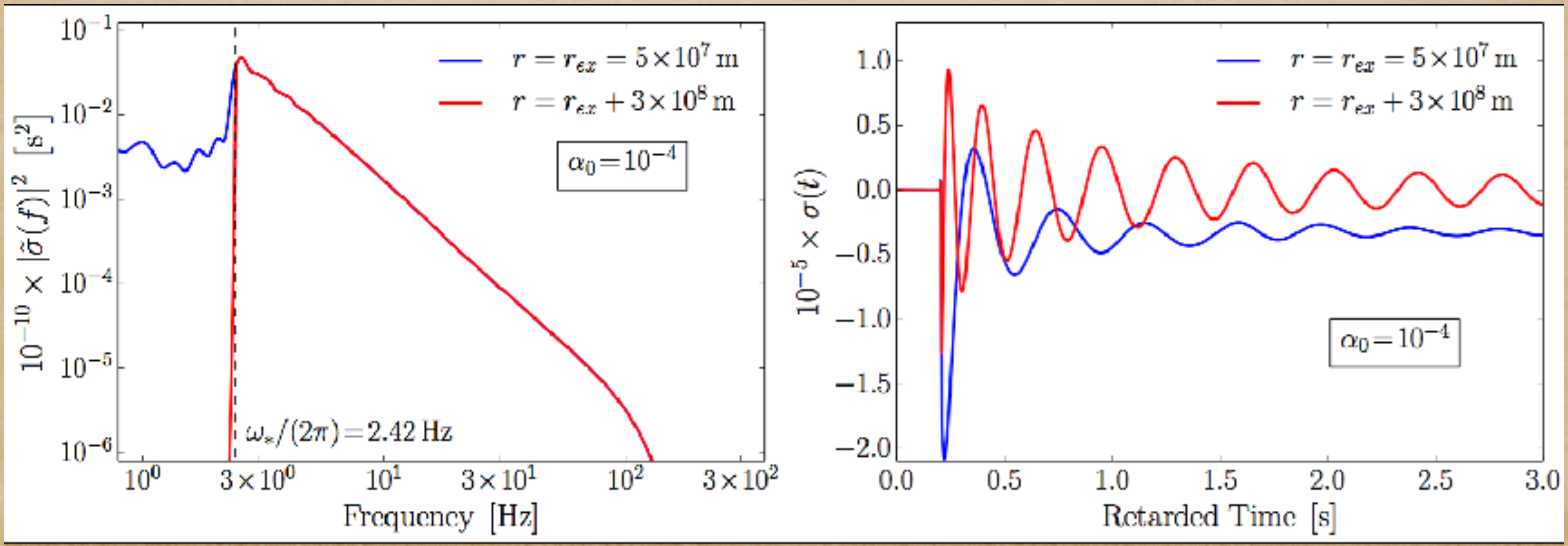




Waveforms "far from" the source

- 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 $\omega_* = c^2\mu/\hbar$



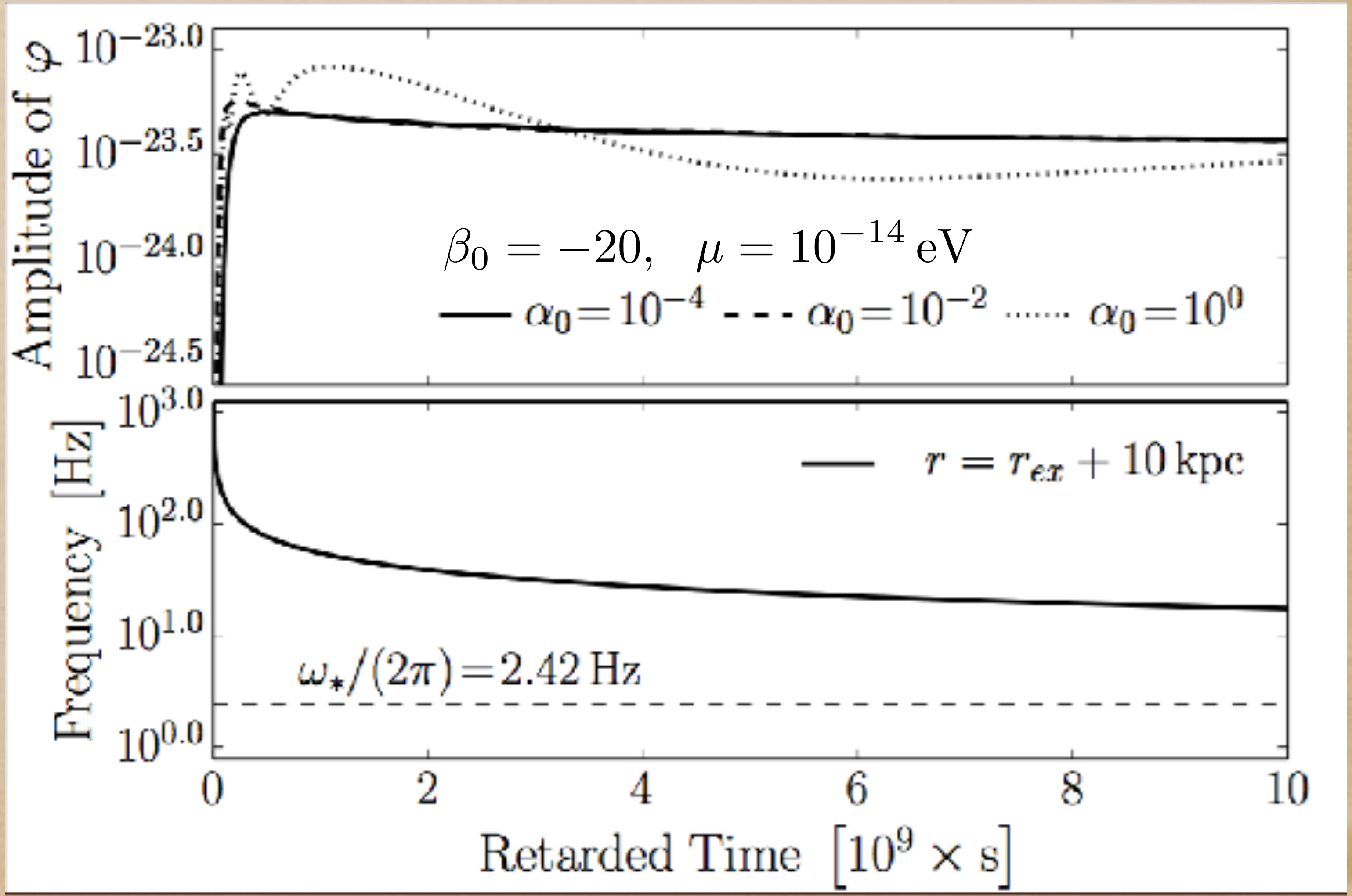
Waveforms "far from" the source

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



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 $\sim \omega_*$

Rosca-Mead, Agathos, Moore & US PRD 2023

Conclusions

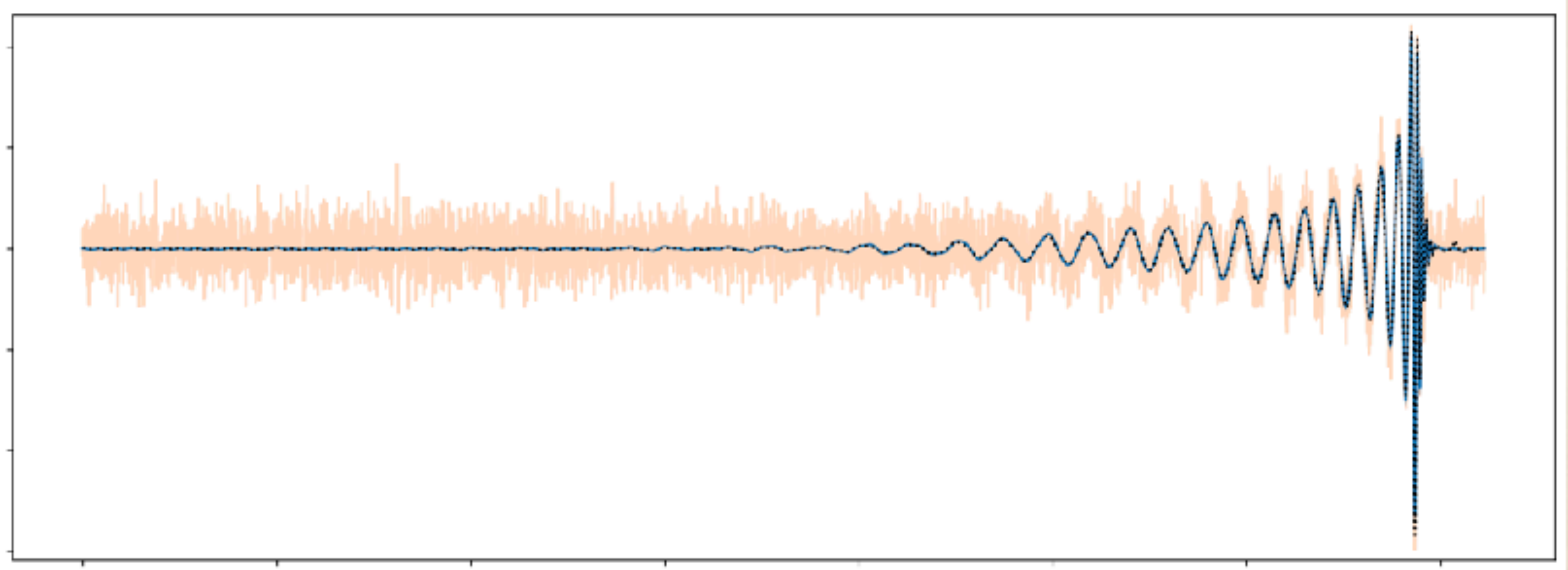
- Spontaneous scalarization occurs as in massless case, but effect can be more dramatic because the scalar mass "screens" the effect of the scalar, allowing larger values of $\alpha_0,\ \beta_0$ to be compatible with binary pulsar observations
- Signals propagate with dispersion, signals can last for years to centuries at kpc distances
- Signals can show up in LIGO/Virgo burst, CW or stochastic searches

Part 2

GWs from Boson-star binaries

T Evstafyeva, US, I Romero-Shaw, M Agathos 2406.02715,
cf also 2108.11995, 2212.08023

Motivation



- Test nature of compact objects: BHs, NSs, ECOs?
- Dark-matter candidates: Ultralight, axion-like fields
- Bosonic fields can form equilibrium configurations:

  Boson stars   Kaup 1968
- Properties: Compactness 0 to > NSs,   any Mass
- Use BSs as proxy for not BHs in GR

Questions and work plan

- Can we observe boson stars with LIGO-Virgo-KAGRA?
- If yes, what does PE with current approximants yield?
- Can we simulate BS binaries with sufficient accuracy?

- Perform high-precision NR simulations of BSs
- Inject resulting waveforms into LIGO detector noise
- Recover signals and parameters with Binary BH/NS approximants
- Test residuals

Theory and Numerical Modelling

- Massive complex scalar field + GR

$$S = \int \frac{\sqrt{-2}}{2} \left\{ \frac{R}{8\pi G} - [g^{\mu\nu} \nabla_\mu \bar{\varphi} \nabla_\nu \varphi + V(\varphi)] \right\} \mathrm{d}^4 x$$

$\Rightarrow$ Einstein-Klein-Gordon equations

- Space-time (3+1) formulation: CCZ4

Alic et al 2012

- Use two numerical relativity codes

GRChombo Radia et al 2021

Lean US 2006

- Technical details:

$\mathrm{d}x = \frac{1}{48} \ldots \frac{1}{32}$, domain size ~ 1024, 8 refinement levels

BS binaries

We simulate 5 BS binaries through inspiral, merger and ringdown.

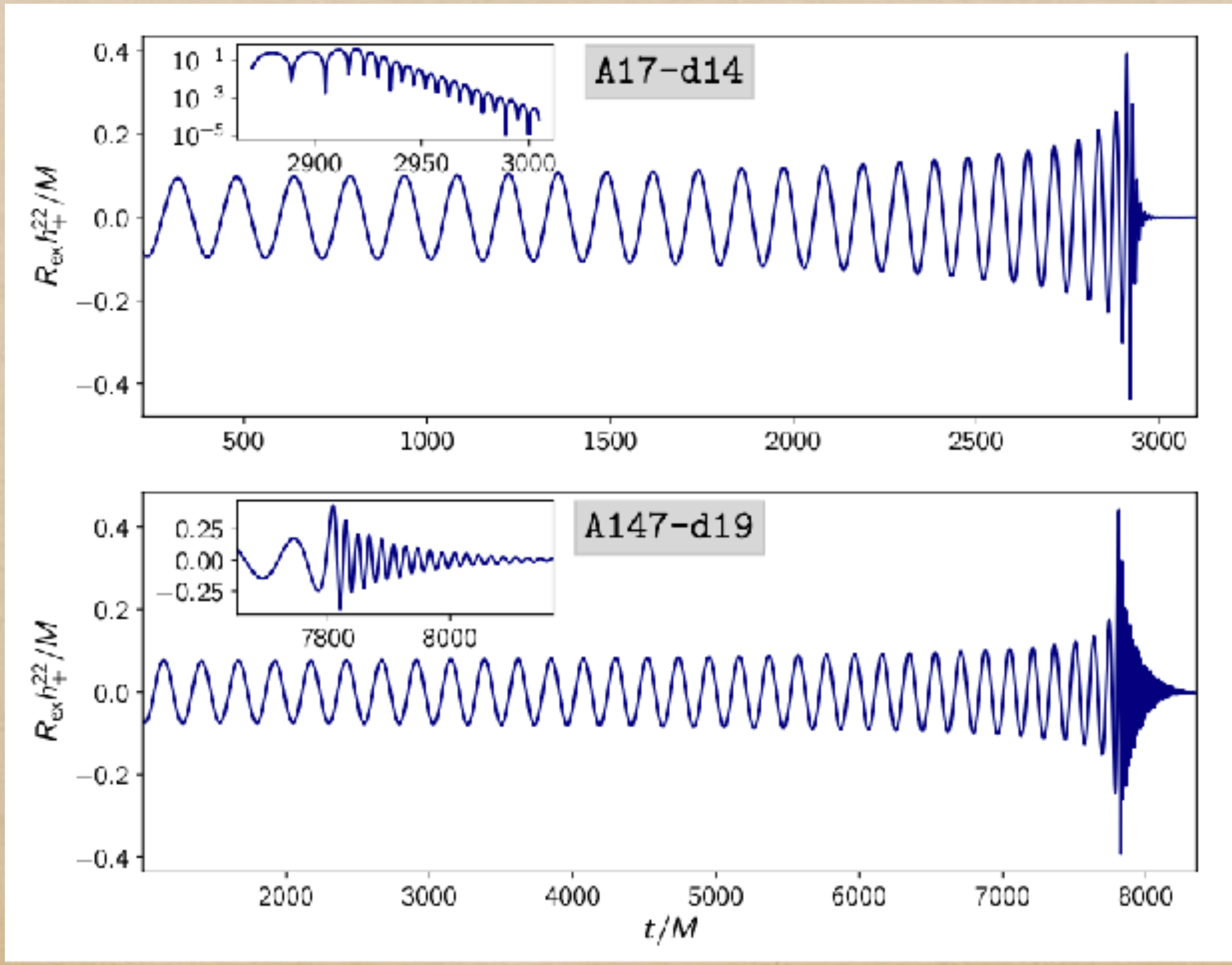
Characterized by

- Quasi-circular, non-spinning, equal-mass: $e \approx 0,\ \boldsymbol{S}_{1,2} = 0,\ q = 1$
- Number of orbits N
- Compactness 0.1 or 0.2
- Scalar dephasing $\delta\phi \in [0, \pi]$
- BS-BS or BS-anti BS binary?
- Total mass: Any by trivial rescaling of the scalar mass

Name	Nickname	Compactness	N (orbits)	$\delta\phi$	BS or ABS
A17-d14, -d12	*standard*	0.2	14, 11	0	BS-BS
A17-d15-p090	*dephased*	0.2	16	$\pi/2$	BS-BS
A17-d15-p180	*anti-phase*	0.2	16	π	BS-BS
A17-d12-e1	*anti-BS*	0.2	11	0	BS-ABS
A147-d19	*fluffy*	0.1	18	0	BS-BS

BS binaries

- Phase error $\approx 0.1 \ldots 0.2$
- Amplitude error $\lesssim 3\,\%$



Waveform approximants

- Parameter estimation performed with `Bilby` Ashton et al 2019

- `IMRPhenomXP`: Frequency domain Pratton et al 2021
    - Quasi-circular, spin-precessing black-hole binaries
    - Quadrupole modes

- `IMRPhenomPv2_NRTidal`: Frequency domain Dietrich et al 2017, 2019
    - Quasi-circular, spin-precessing neutron-star binaries
    - Tidal deformability parameters $\Lambda_{A,B}$

- We have tested more with similar results.

Injections and parameter estimation

- Inject BS signals with specified parameters:

  Fixed: sky location, incliation, initial phase, time etc

  Variable: total mass, luminosity distance

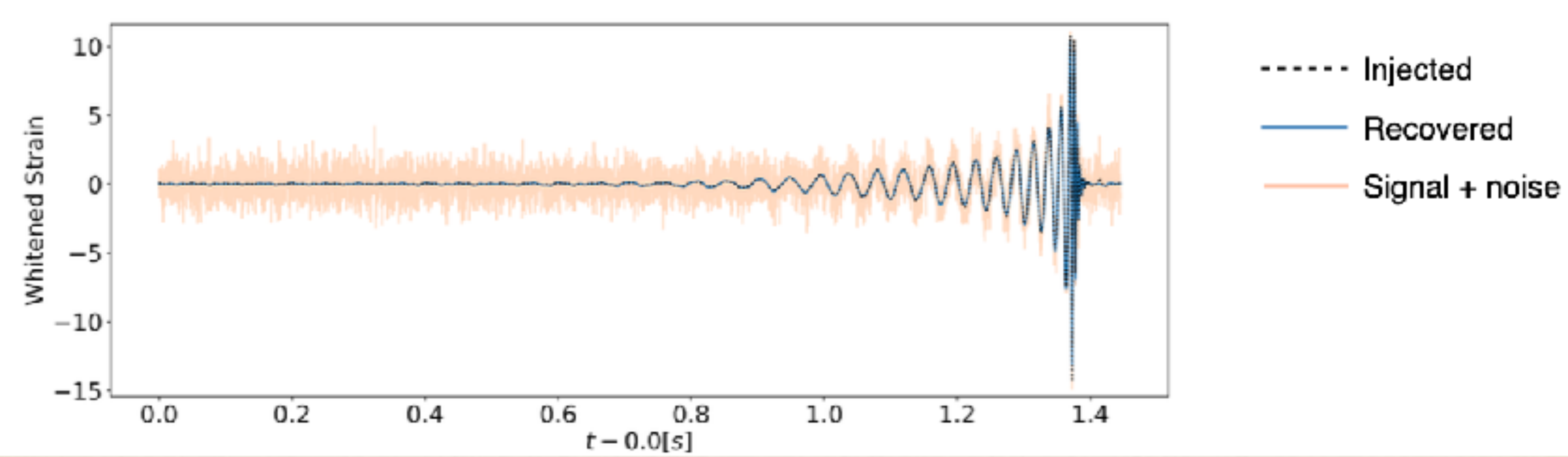
- 2 Approaches: (1) Allow spins to vary in the analysis

  (2) Spins fixed to zero throughout analysis

- Main diagnostics:
  - Recovered masses, spins
  - Recovered SNR, Log Bayes factor
  - Test residual for Gaussianity

Results using IMRPhenomXP

- Injections often recovered but with biased parameters!
- Example `A17-d15` with $M_{\rm tot} = 77\, M_\odot,\ d_L = 200\,{\rm Mpc}$ in the analysis



- Recovered: $M_1 = 37.8 \pm 1.1\, M_\odot,\ M_2 = 25.4 \pm 1.2\, M_\odot,\ d_L = 236 \pm 20\,{\rm Mpc},$

  $a_1 \approx 0.95,\ a_2 \approx 0.15$

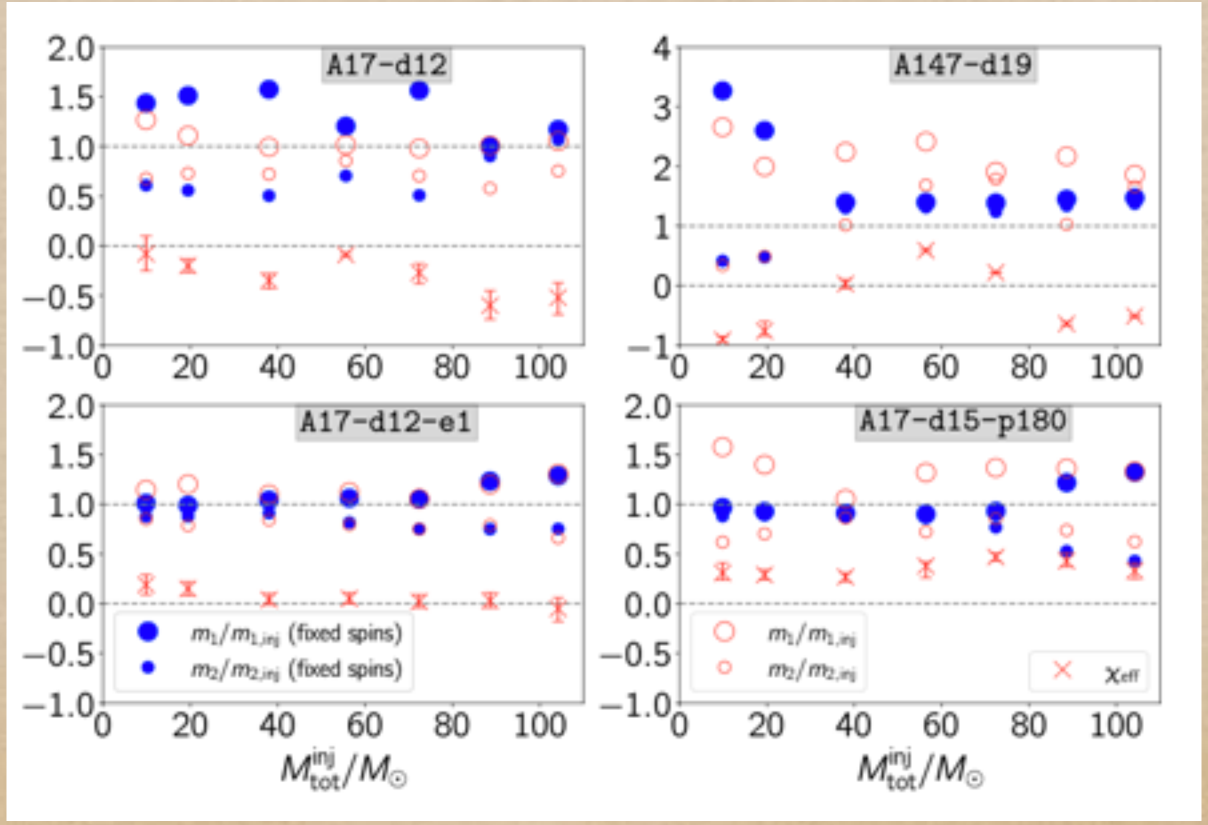
  Recovered SNR $\approx$ injected SNR

  $\log \mathscr{B}^{\rm S}_{\rm N} = 5392$

- Parameter bias not random!

Results using IMRPhenomXP

- Fixing spins to zero:
  - poor m_1, m_2 for *standard* BBS
  - decent m_1, m_2 for *anti-phase* BBS
- Variable spins:
  - decent m_1, m_2 and anti-aligned spins for *standard* BBS
  - poor m_1, m_2 and aligned spins for *anti-phase* BBS

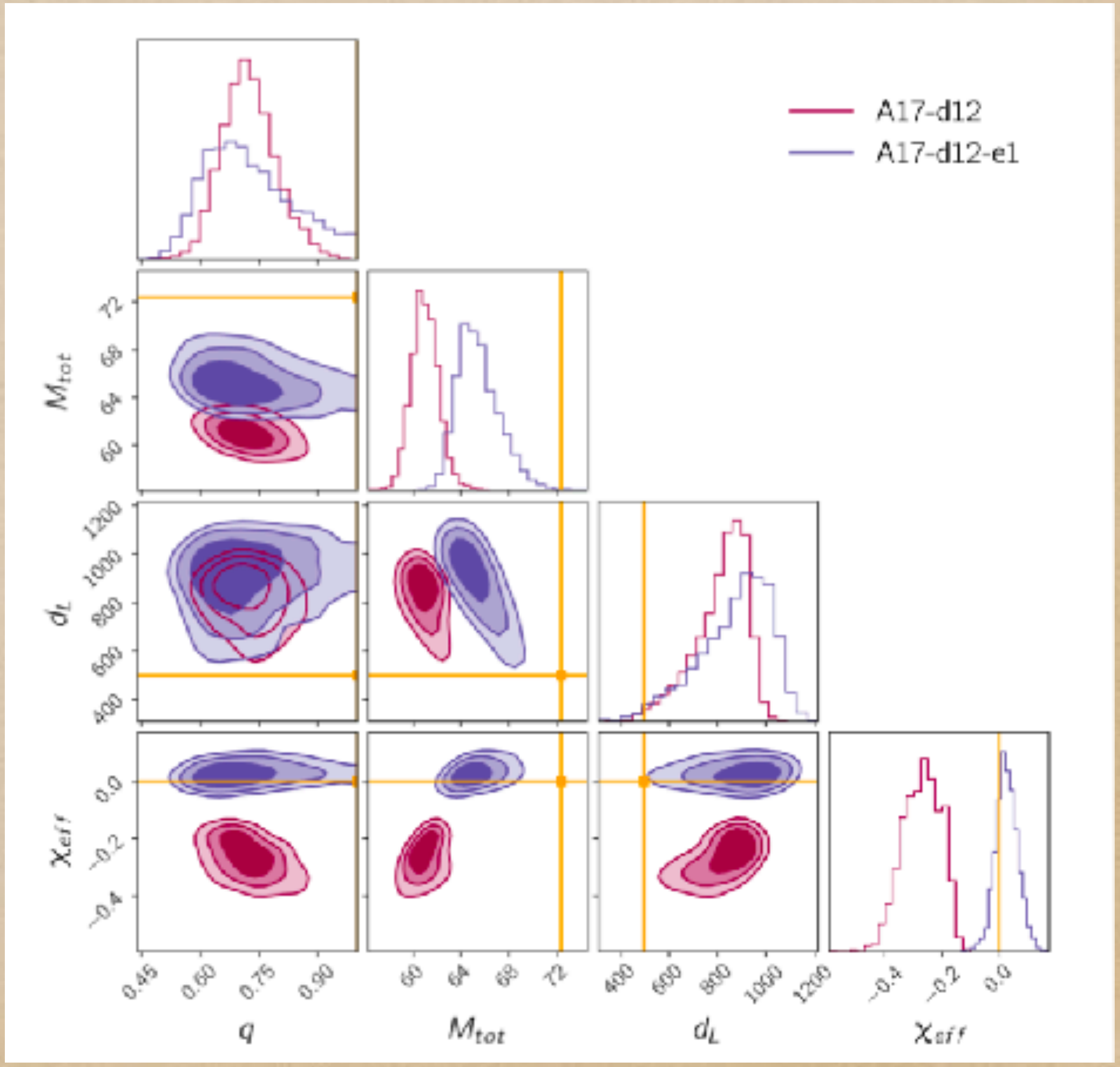


Results using IMRPhenomXP

- Paramerer estimation always erratic for *fluffy* BBS
- BBH approximants recover parameters best for *anti-BS* !!

Corner plot:

A17-d12-e1 vs. A17-d12



- These features can be explained with the chirp strength

Conclusions

- NR simulations of BS binaries about as accurate as for BHs
- BS binaries recovered well with BH approximants $\rightarrow$ degeneracy
- But systematic bias in parameter estimation

Live Score

W modes	✓
Teddy bears, Koalas etc	✓
Middle aged men and Mercedes	✓
Romantics	?
Inappropriate advances	✗
Moustache	✓

Many thanks Kosta!