GW of Boson Stars mergers

Eugene A. Lim

2nd UHFGW workshop via the Internet, 2021

w/ T. Helfer, K. Clough, B. Ge, U. Sperhake, M. Radia, R. Croft

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GW of Exotic Compact Objects mergers

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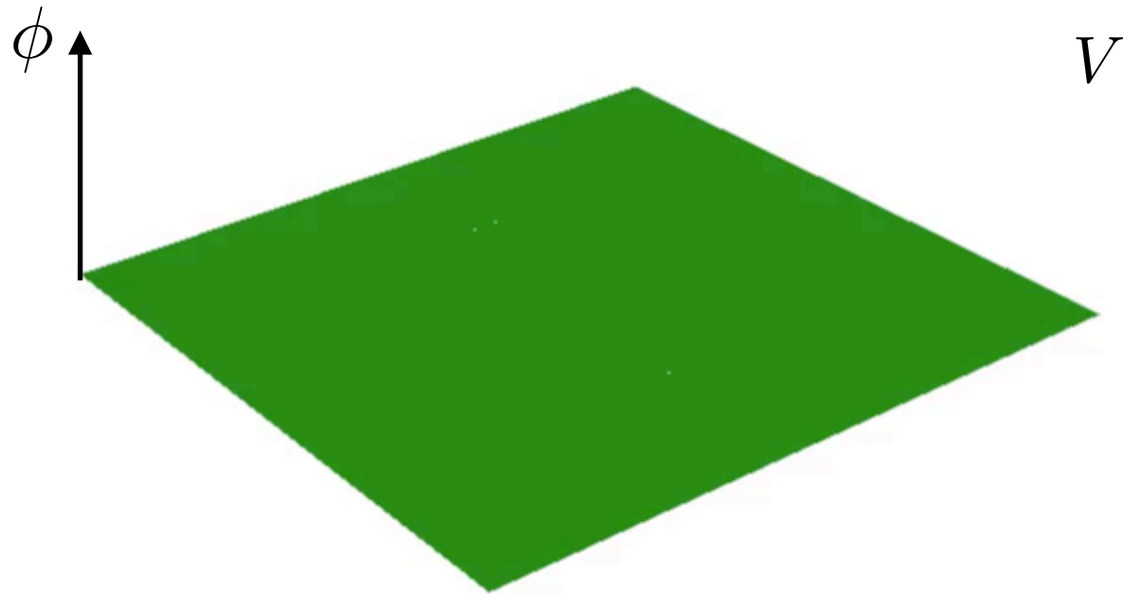
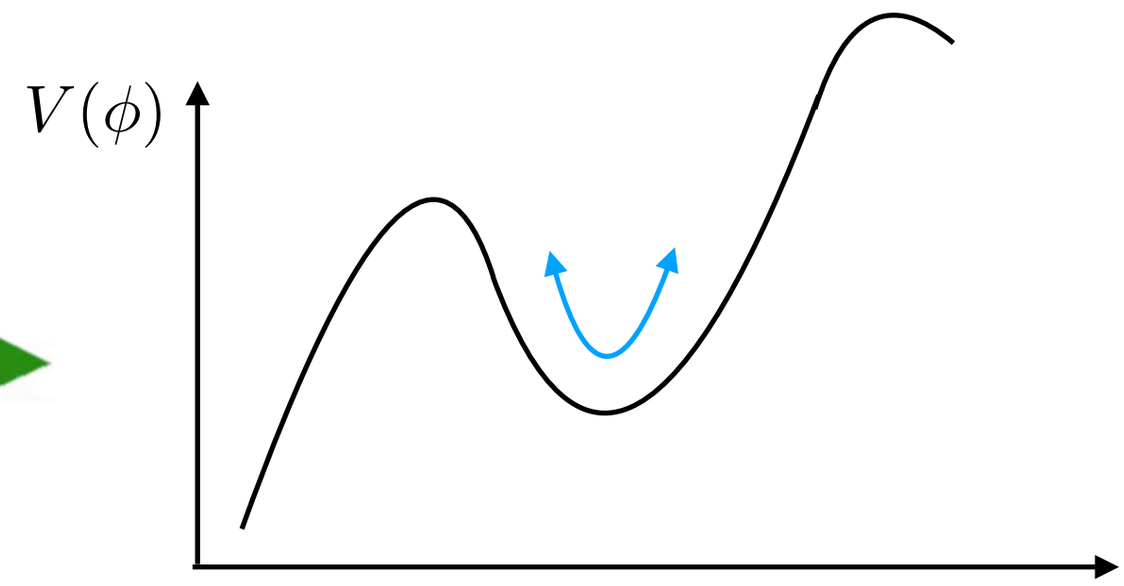
Exotic Compact Objects

Self-gravitating coherent fundamental boson fields

aka. boson stars, oscillations, solitonic stars etc
(nobody agrees on nomenclature!)





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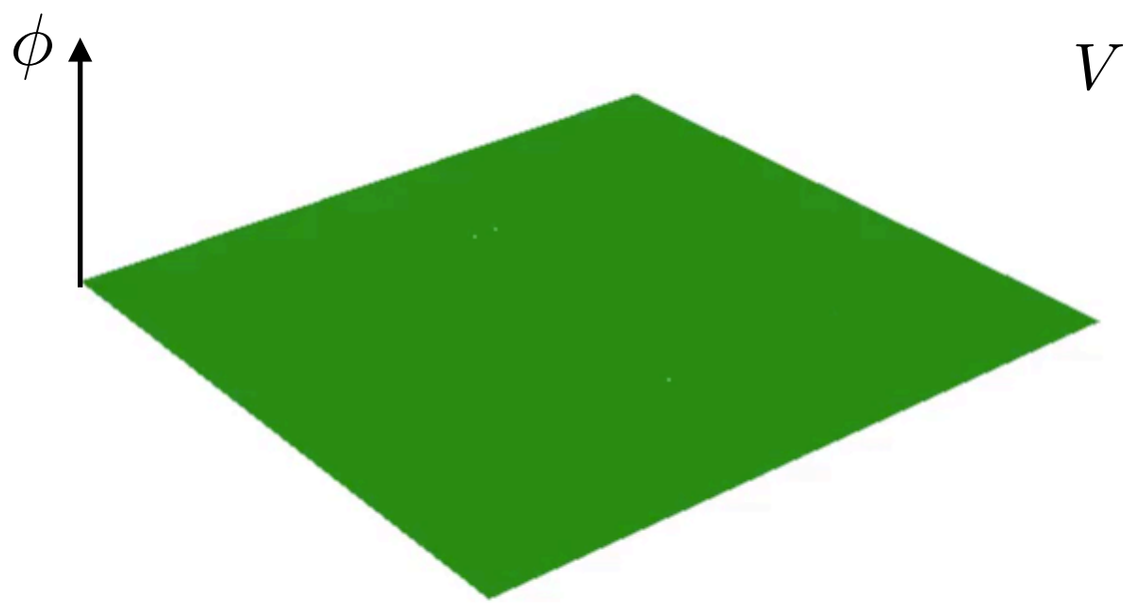

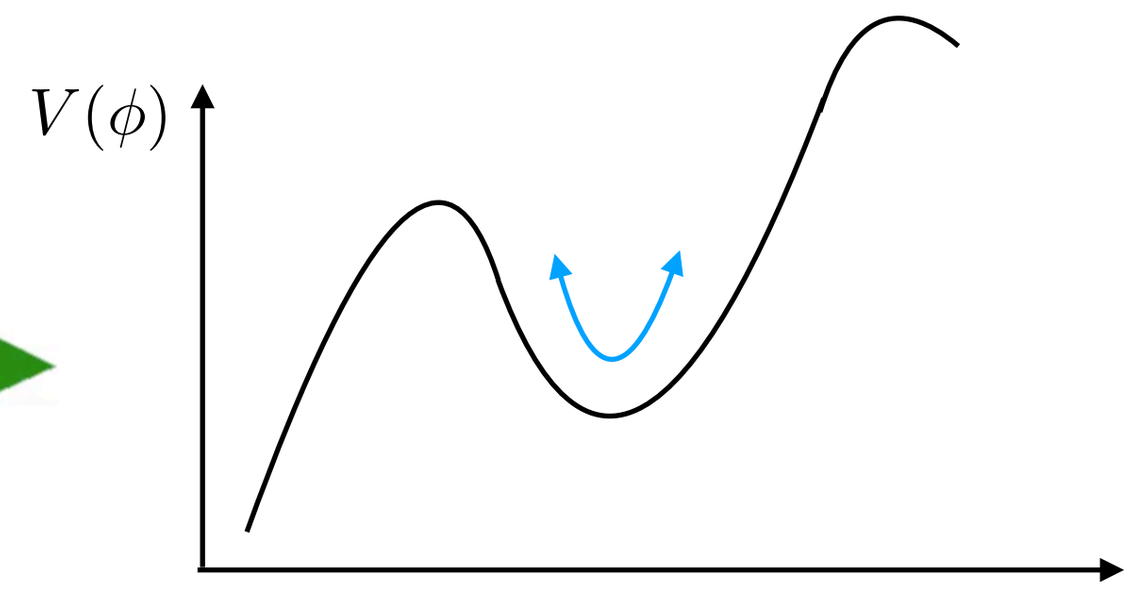

Can be diffused (galaxies cluster sized) or highly (~neutron star) compact.

High Compactness = lots of GW in collisions/formation

Basic Features of ECO

Bosonic : large occupation numbers so described by coherent classical fields (scalar, vector etc)

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Bosonic : large occupation numbers so described by coherent classical fields (scalar, vector etc)

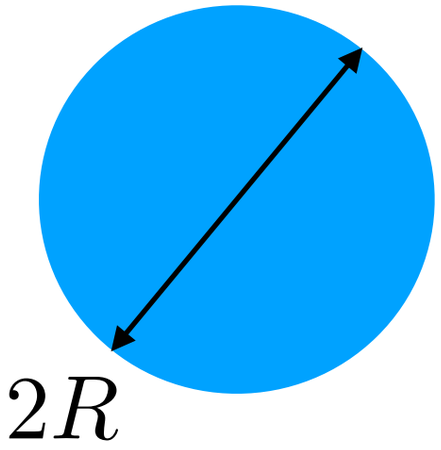
Two broad classes : charged (more compact/stable) or uncharged.

For $V(\phi) = \frac{1}{2}m^2\phi^2$ mass of ECO $M \sim \frac{M_p^2}{m}$

In general, depends on higher order interactions.

ECO Compactness

Compactness $$\mathcal{C} = \frac{GM}{R}$$



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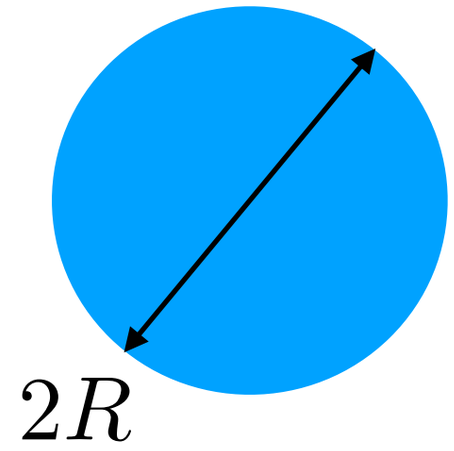


$$\mathcal{C}_{BH} = 0.5 \ , \ \mathcal{C}_{NS} \sim 0.2$$

Non-relativistic $0 \leq \mathcal{C} < 0.5$ **relativistic**

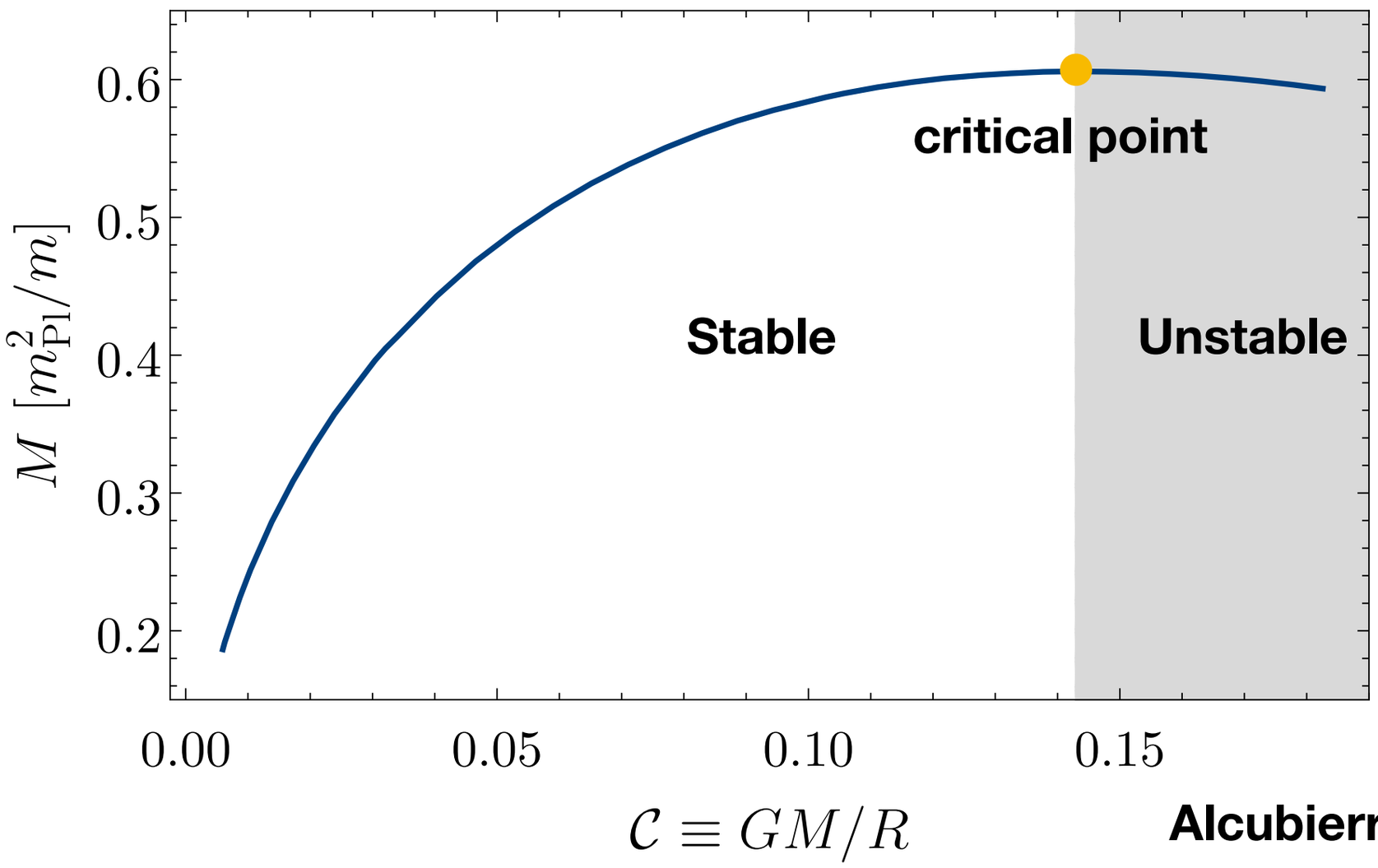
Most models become unstable around $\mathcal{C} \sim 0.1 - 0.3$

Open Question : can we get to 0.5? (I suspect no.)

Stability of ECOs

Stable up to high compactness : Become unstable at some critical compactness.

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

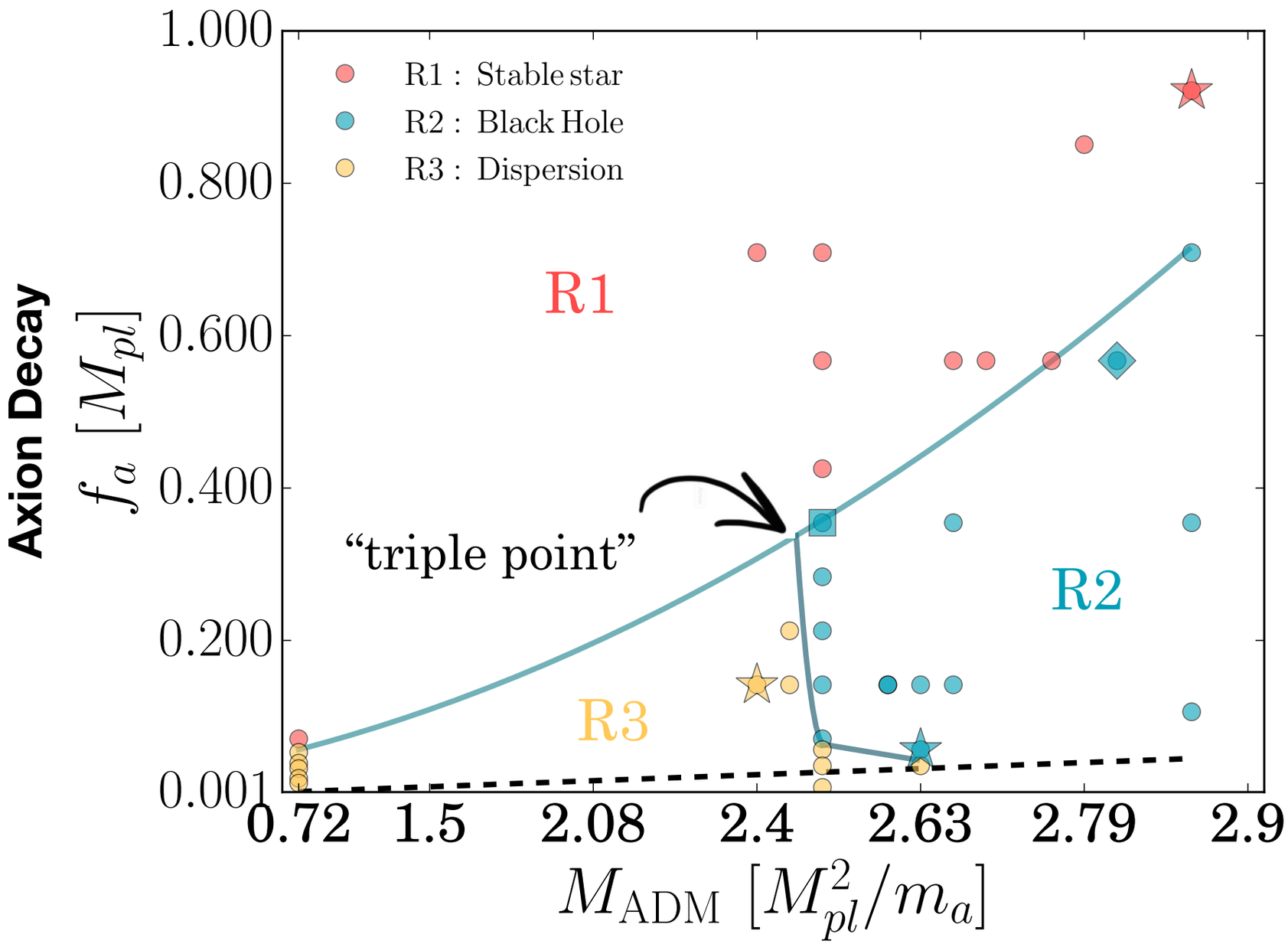


Alcubierre (2003)

Stability of ECOs

More complicated potentials have more structure.

Axions Like Particles



(Helfer, Clough, Marsh, Lim, Fairbairn, Becceril 2016)

Why we care?

Dark Matter candidates : ultra light scalars (axions)

Black hole mimics :“did we see BH or some other exotic things?”

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Dark Matter candidates : ultra light scalars (axions)

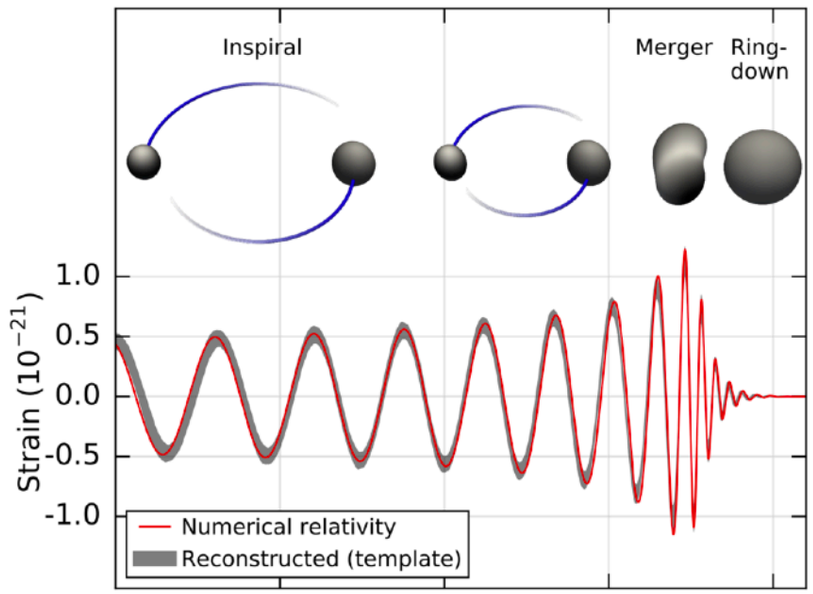
Black hole mimics :"did we see BH or some other exotic things?"

In general, they are "practice problems" or placeholder for new physics.

Observations in the future we know not, prepare we must to deal. *(Katy Clough)*

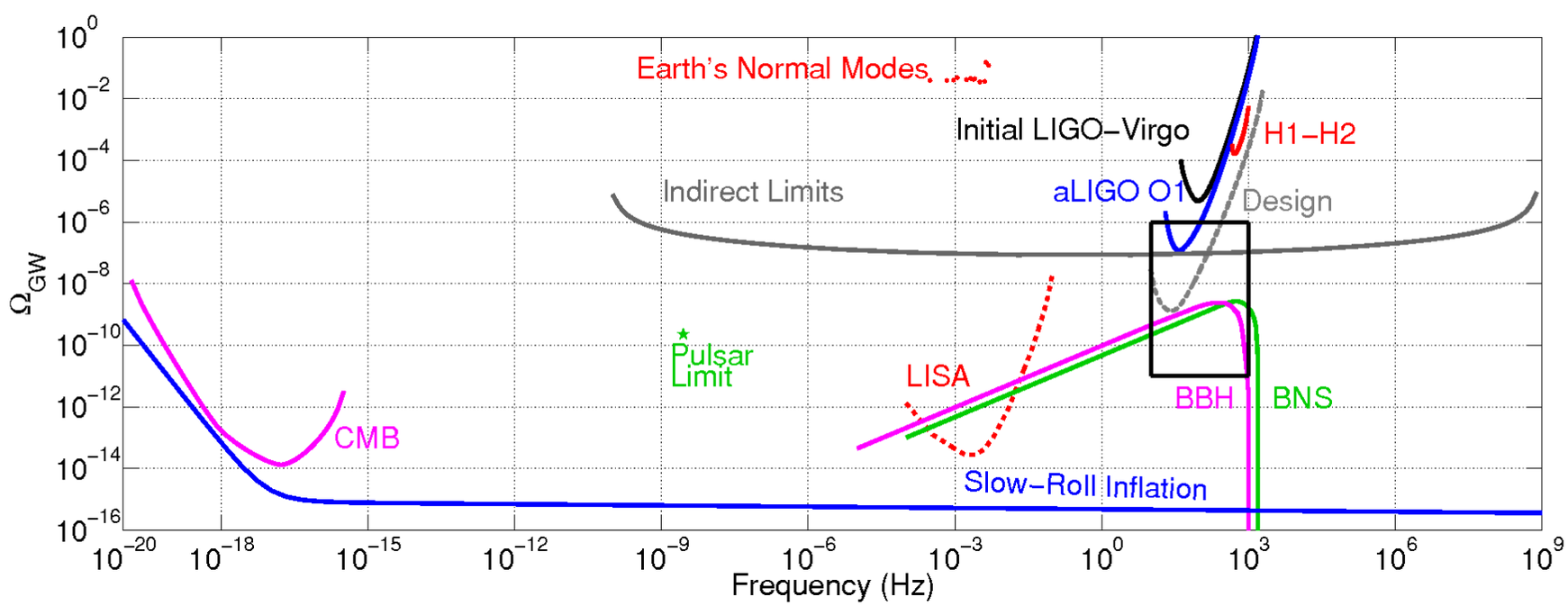
GW signatures

Coherent signatures of individual events (strain vs time)

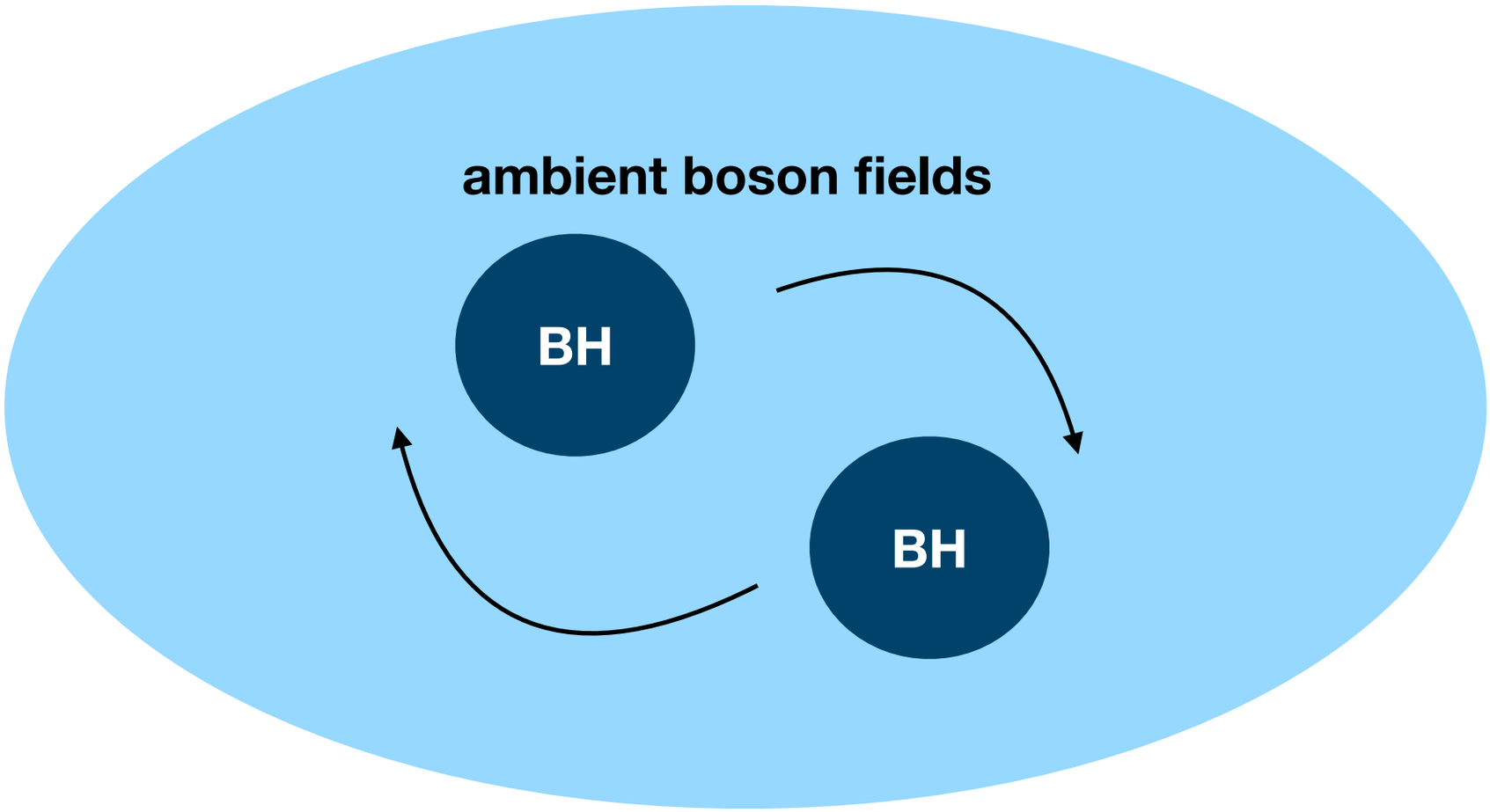


Stochastic signatures of many accumulated events

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{\partial \rho_{\rm GW}}{\partial \ln f},$$



GW from ambient sources



I won't talk about GW from interaction of BH with ambient boson fields (e.g. super radiance etc). See Masha's Talk!

GW frequency range

Peak frequency of binary ECO merger

$R_{ISCO} \approx \frac{3GM}{\mathcal{C}}$ so the peak frequency is $f \sim \sqrt{\frac{GM}{R_{ISCO}^3}}$

$$f \approx 0.3 \frac{\mathcal{C}^{3/2}}{GM} \approx \mathcal{C}^{3/2} \left(\frac{6 \times 10^{-3} M_\odot}{M} \right) 10^6 \text{ Hz}$$

(Giudice, McCullough, Urbano 2016, UHFGW working paper)

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For UHF GW, $f_{UHF} > 10^6 \text{Hz}$ then $M < 10^{-3} M_\odot$

=> constraints $m > 10^{-6} \text{eV}$

BS vs BH/NS mergers

Squishiness : BH/NS are very rigid, BS are "squishy" — they deform a lot more from tidal forces : more GW!

(Helfer, Lim, Amin, Garcia et al 2018)

QNM spectra : Different from BH/NS, can be excited.

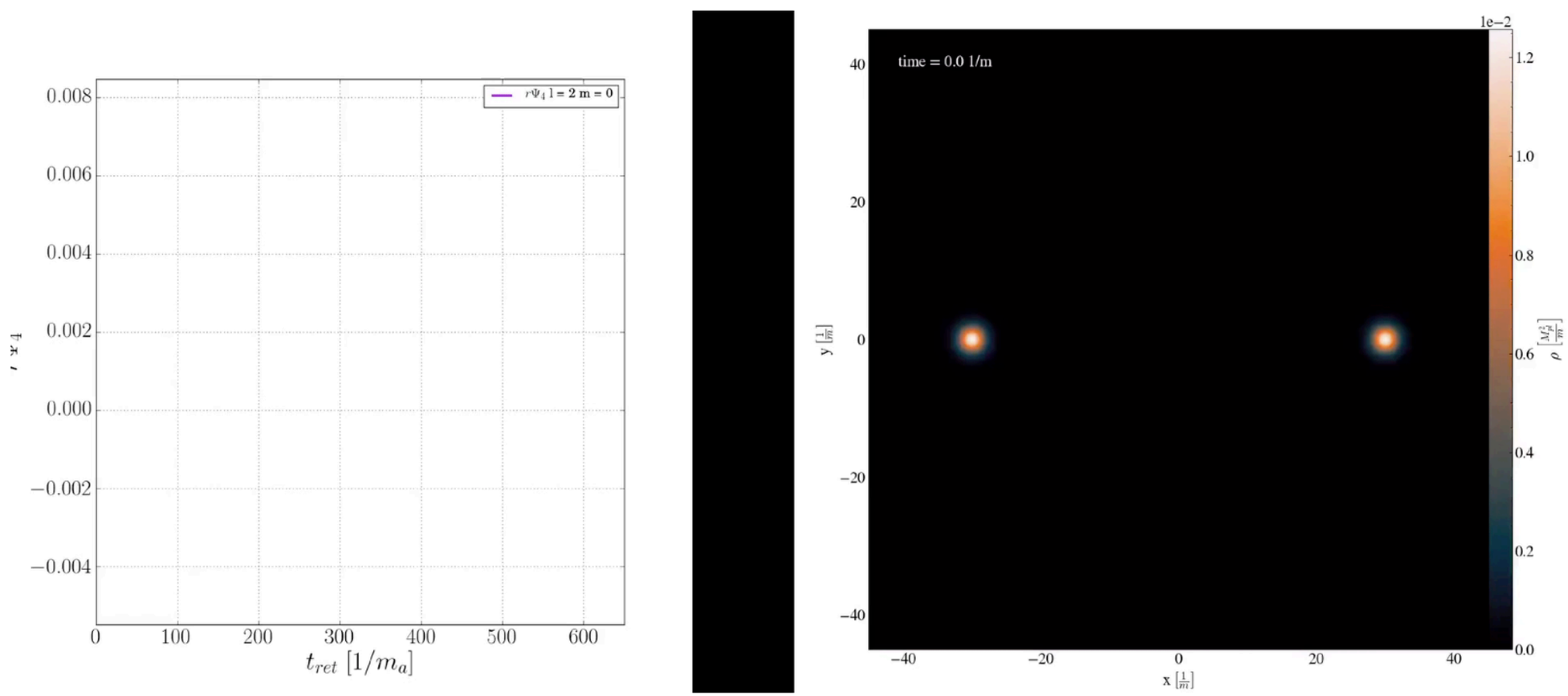
(Macedo et al 2013, 2016)

Extended objects : BS has no "surface", and additional attractive/repulsive scalar force mediator.

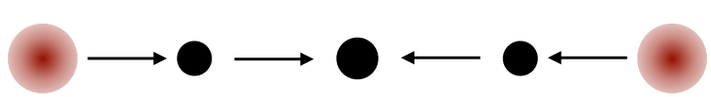
Not a fluid : BS has anisotropic "pressure", hence cannot be modeled as a fluid (like NS or star).

BS vs BH/NS mergers

Instability at high compactness : BS can collapse to BH before merger due to tidal perturbations — unique signature!



(Helfer et al 2018)



Head-on case as illustration.

All good but…

Physics problems : formation history? population distribution? can ECOs spin?

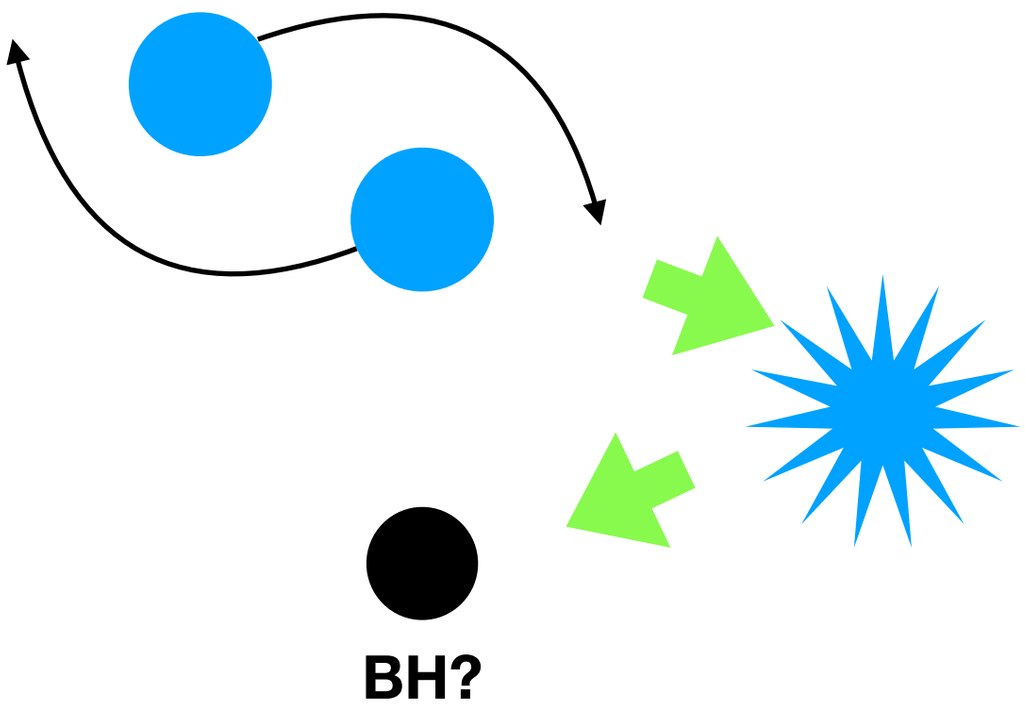
Technical challenges : initial conditions for binaries? relativistic cosmological simulations?

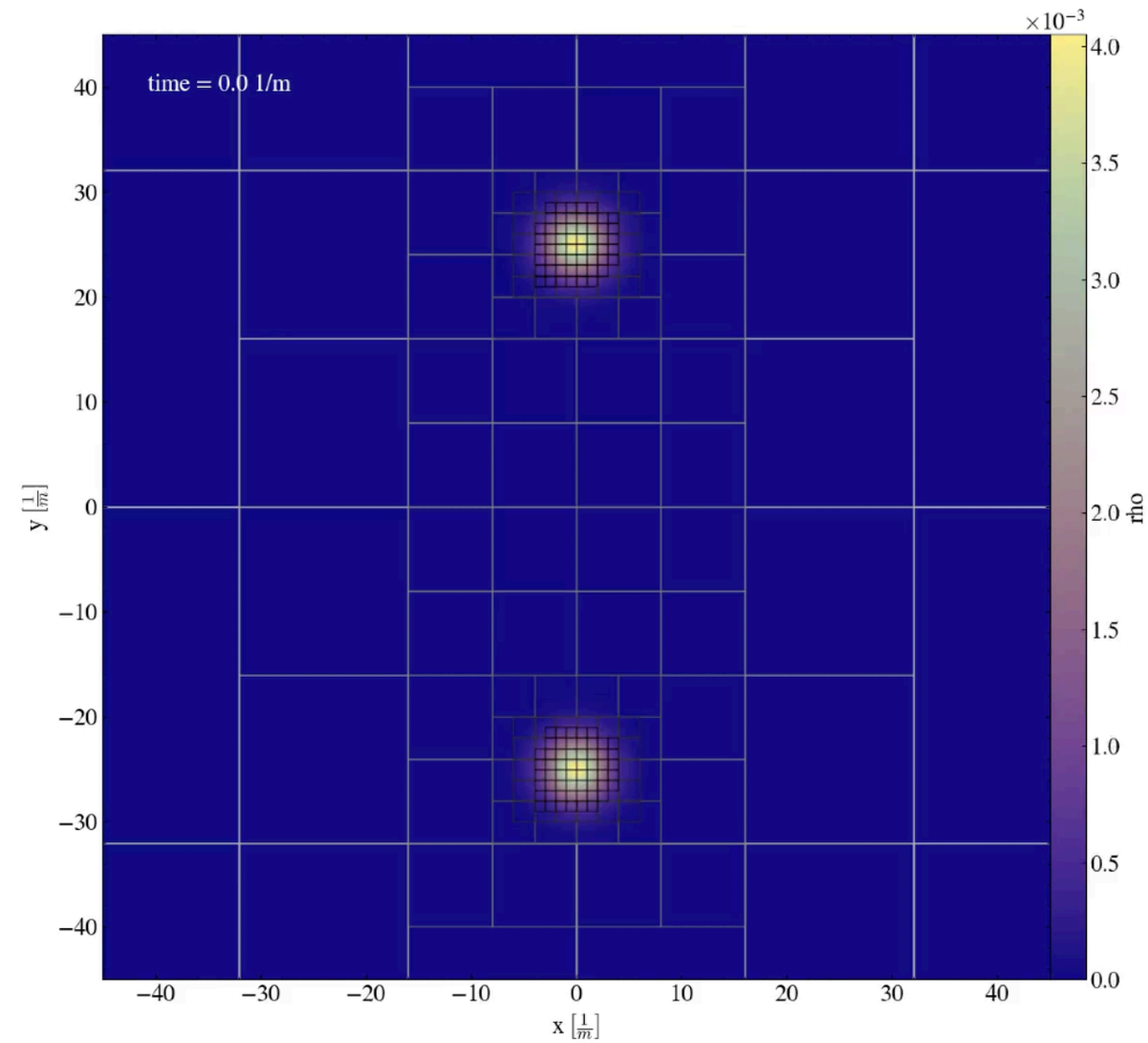
Problems :

Coherent GW : Initial Conditions

Stochastic GW : Formation history and populations

GW from ECO Inspirals

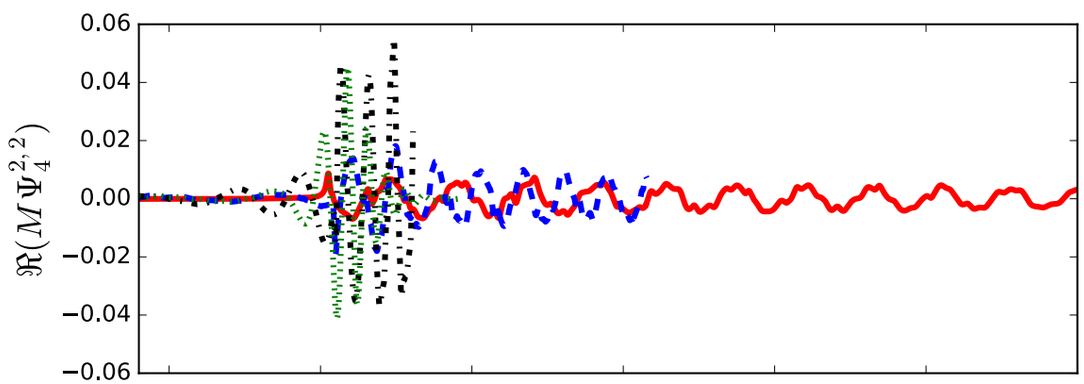




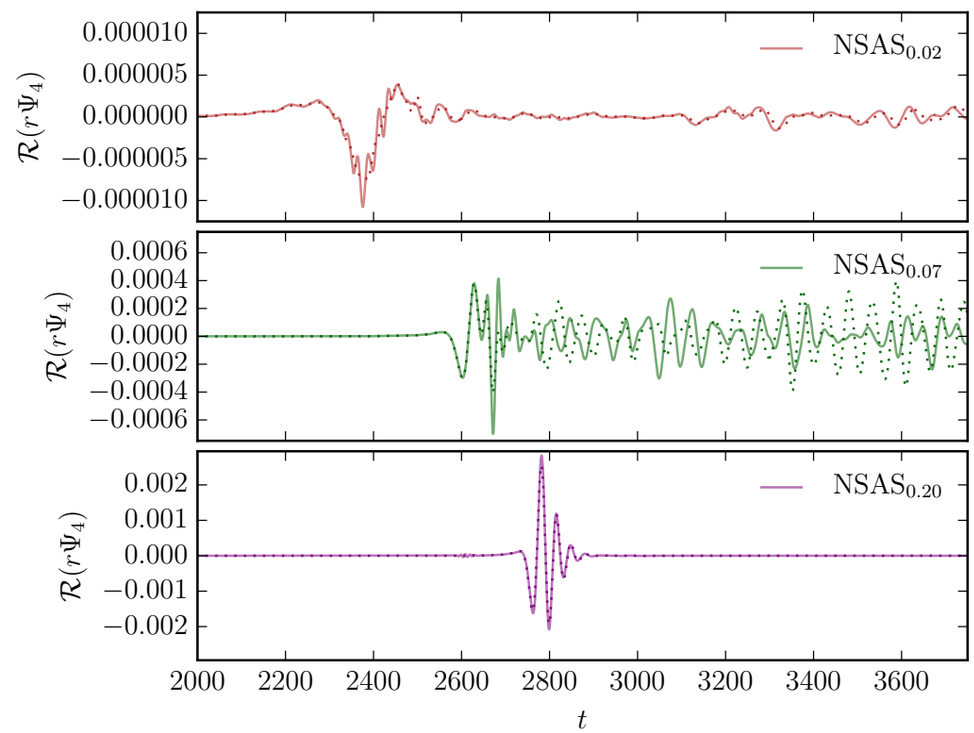
(Work in progress!)

GW from ECO Inspirals

Some "early" attempts to get NR GW templates….



Binary Boson star mergers (Palenzuela et al 2017)

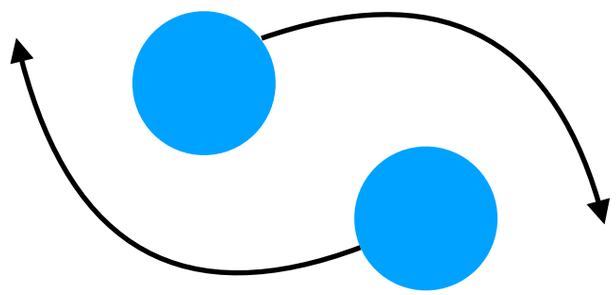


GW from head on merger of ECO and NS (Clough, Dietrich, Ossokine 2018)

Turns out that this is much more difficult than BH-BH!

Initial Conditions

Getting initial conditions we can *control* is very difficult.



Need to control for

(1) Compactness/Mass

(2) Orbital AM

(3) ECO state (excited/non-excited?)

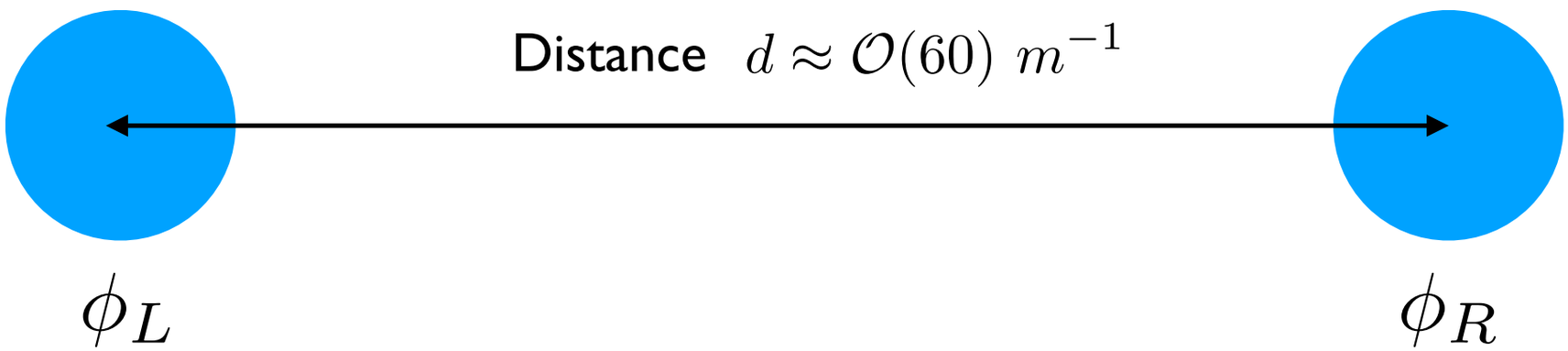
Satisfying constraints necessary but not sufficient!

Linear superposition ?

"Even linear superposition is hard in GR!!!" **Thomas Helfer**

A popular strategy : linear superposition of two independent solutions.

many recent papers : 1705.01071, 1710.09432, 1808.10732, 1608.08637, 1807.06959 etc.



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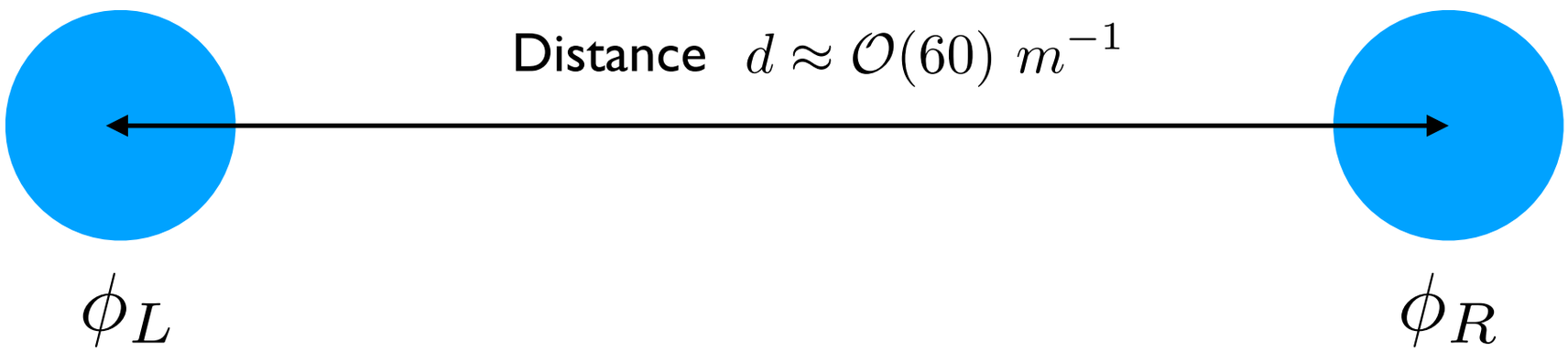


3-metric $\gamma_{ij,tot} = \gamma_{ij,L} + \gamma_{ij,R} - \delta_{ij}$

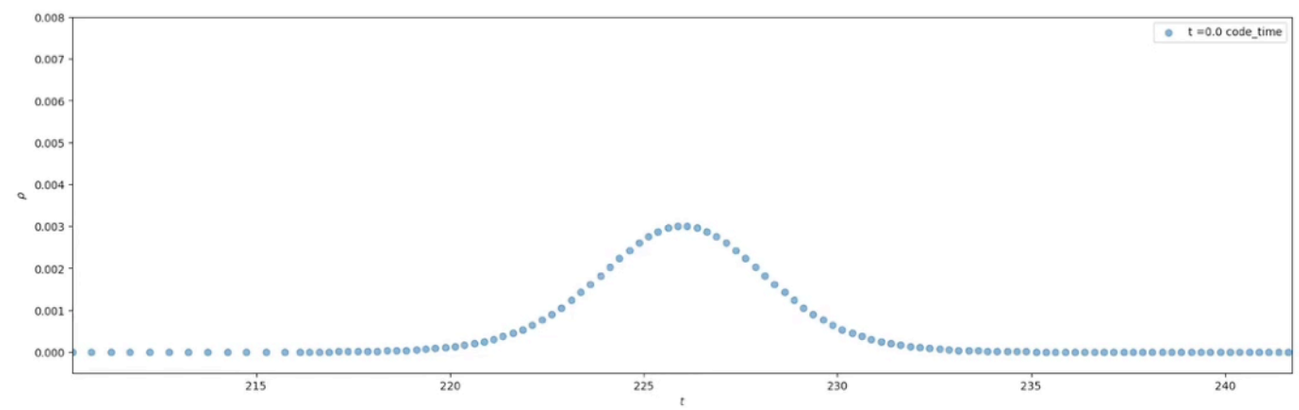
Assume $ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$

then volume element $\sqrt{\det \gamma_{ij}} = \sqrt{(1 - 2GM/d)^{-1}} \approx 1.01$

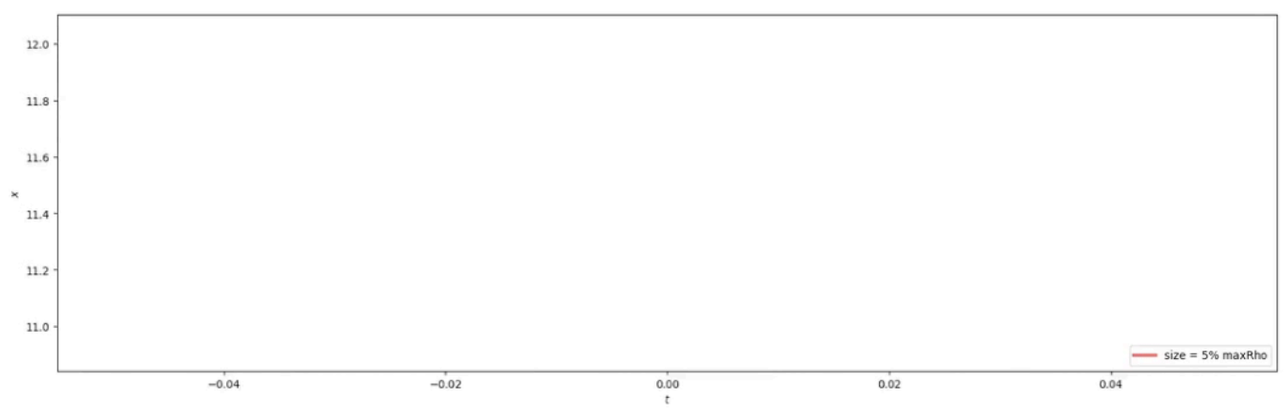
$\Rightarrow$ ECO is "puffed up" by 1% initially.

Linear superposition ?

Radial "breathing" mode due to 1% volume difference

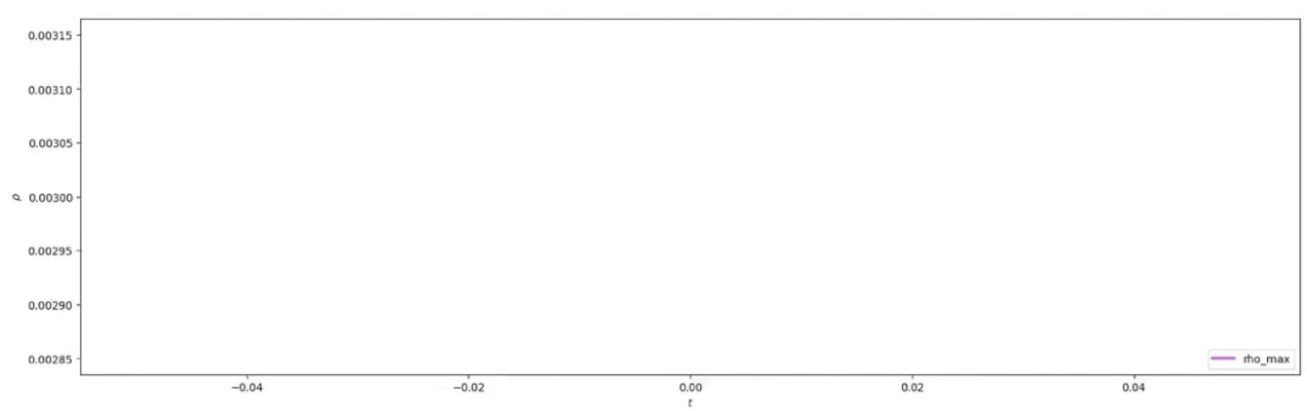


ρ profile



Radius

$\Delta R \sim 10\%$



Central density

$\Delta \rho_c \sim 100\%$

Real scalar ECO, linear superposition (Helfer, Lim, Amin, Garcia, 2018)

A quick and dirty fix

(Helfer + Lim et al 2018,
Helfer, Sperhake, Lim, Radia, Croft, Ge 2021)

Solution : Choose h_{ij} such that metric values is conserved at the center

3-metric $\gamma_{ij,tot} = \gamma_{ij,L} + \gamma_{ij,R} - \cancel{\delta_{ij}}$ $h_{ij}(x_0)$

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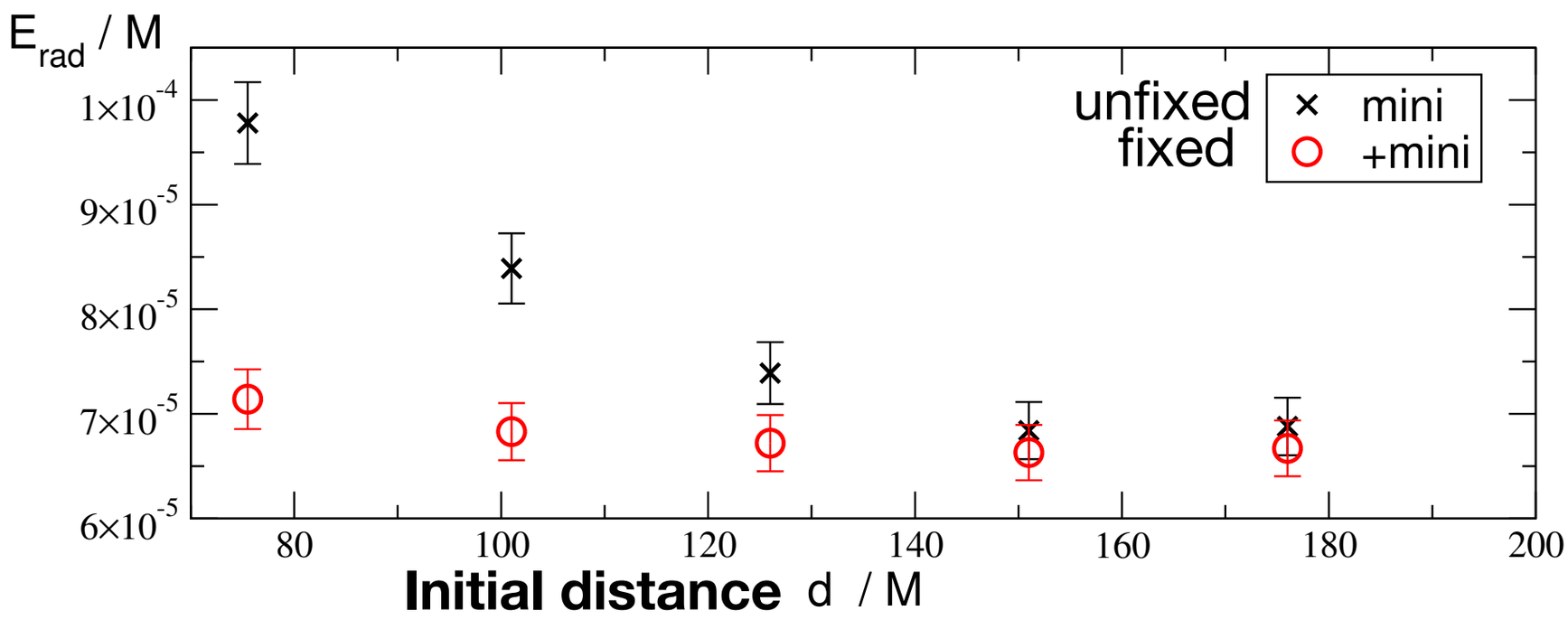

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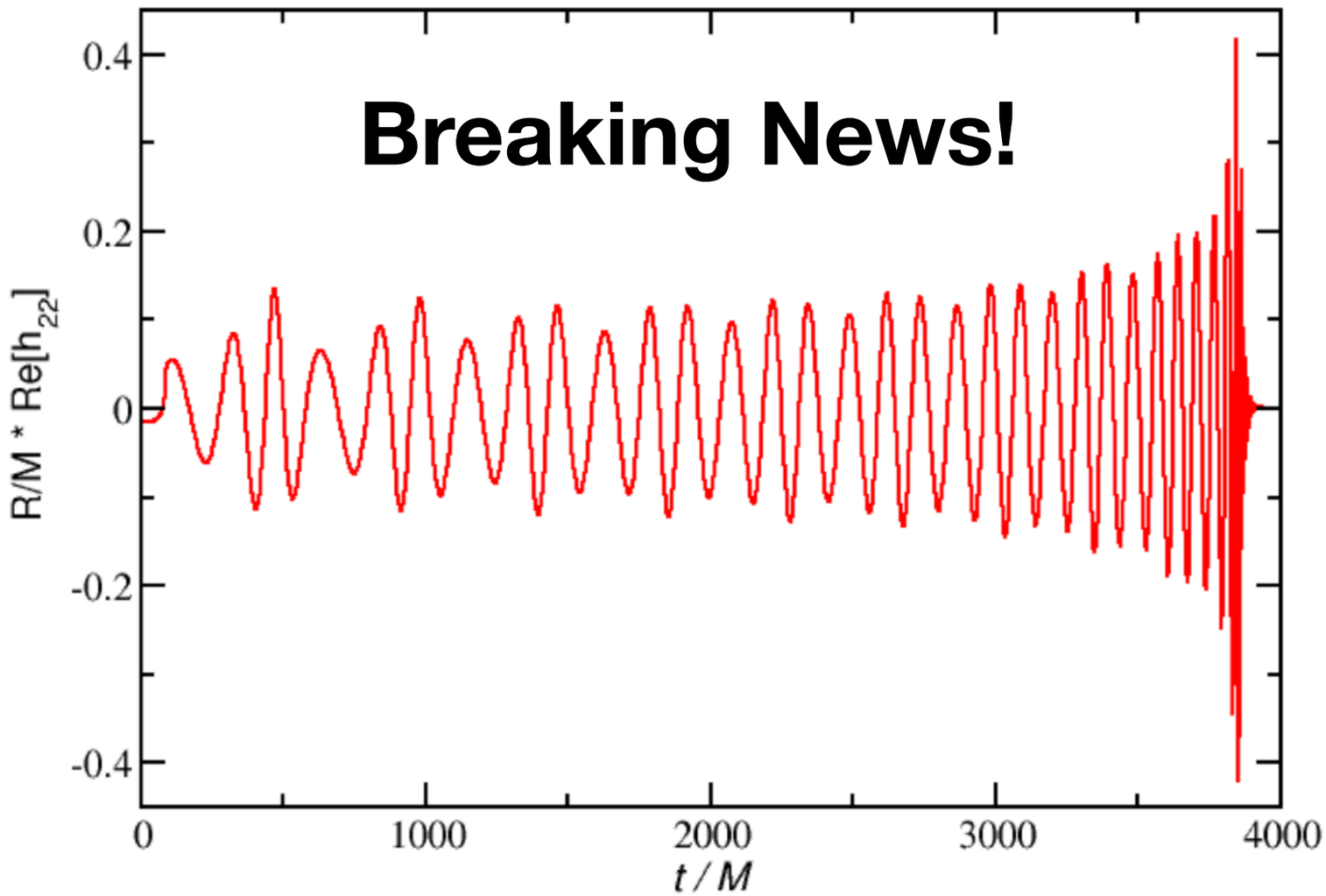


(Helfer, Radia, Sperhake, Lim, Ge, Croft, *work in progress*)

GW template from inspiral BS with 30+ orbits!

(Still problems to solve, but we are getting there…)

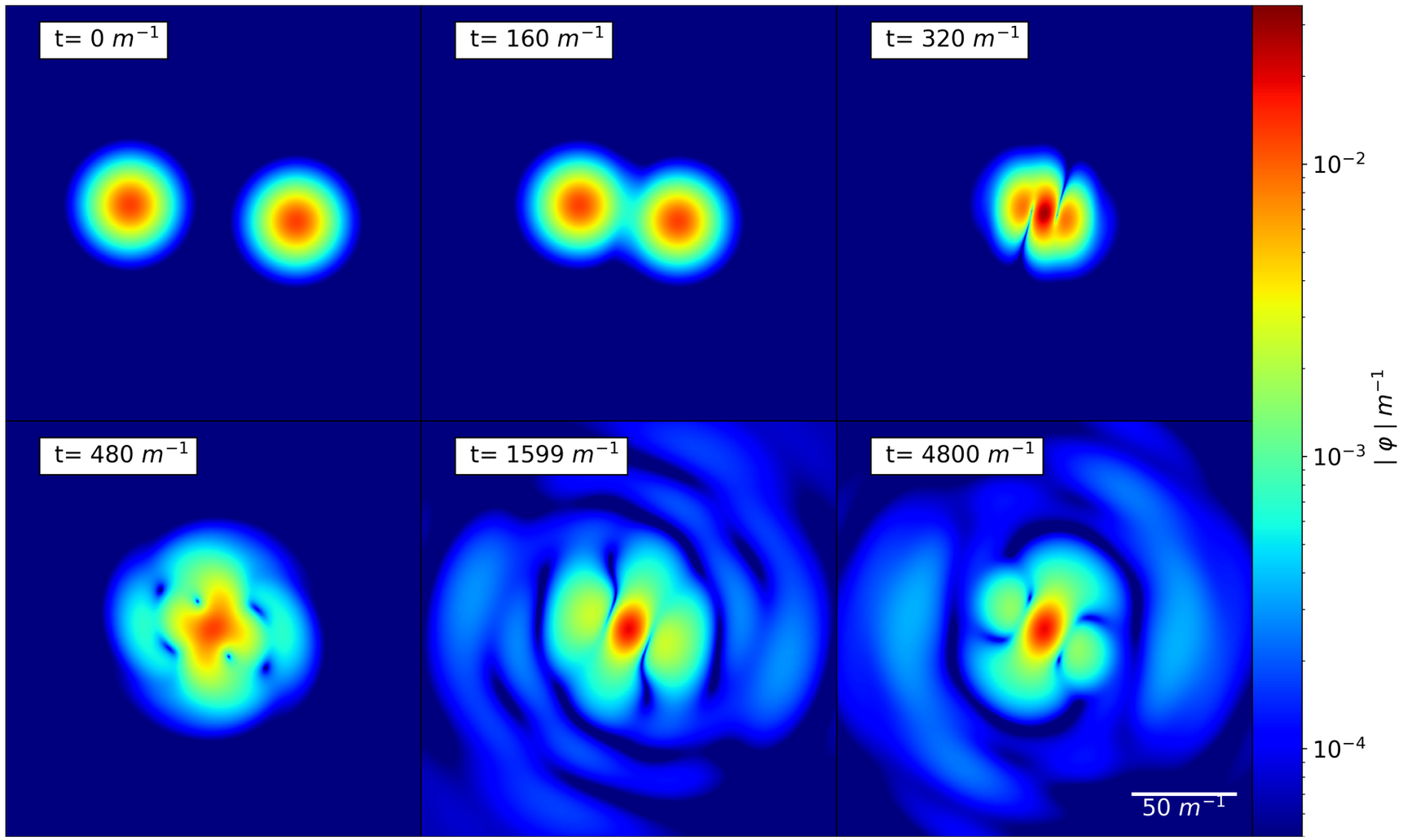
Can ECOs have Stable Spin?

No….? **Sanchis-Gual 2019, Siemonsen 2020, Di Giovanni 2020 etc**

Can ECOs have Stable Spin?

No….? **Sanchis-Gual 2019, Siemonsen 2020, Di Giovanni 2020 etc**

But can hold spin for terrestrial observation timescales!



Helfer, Ge, Lim, Croft, Sperhake, Radia, Clough (very soon now!)

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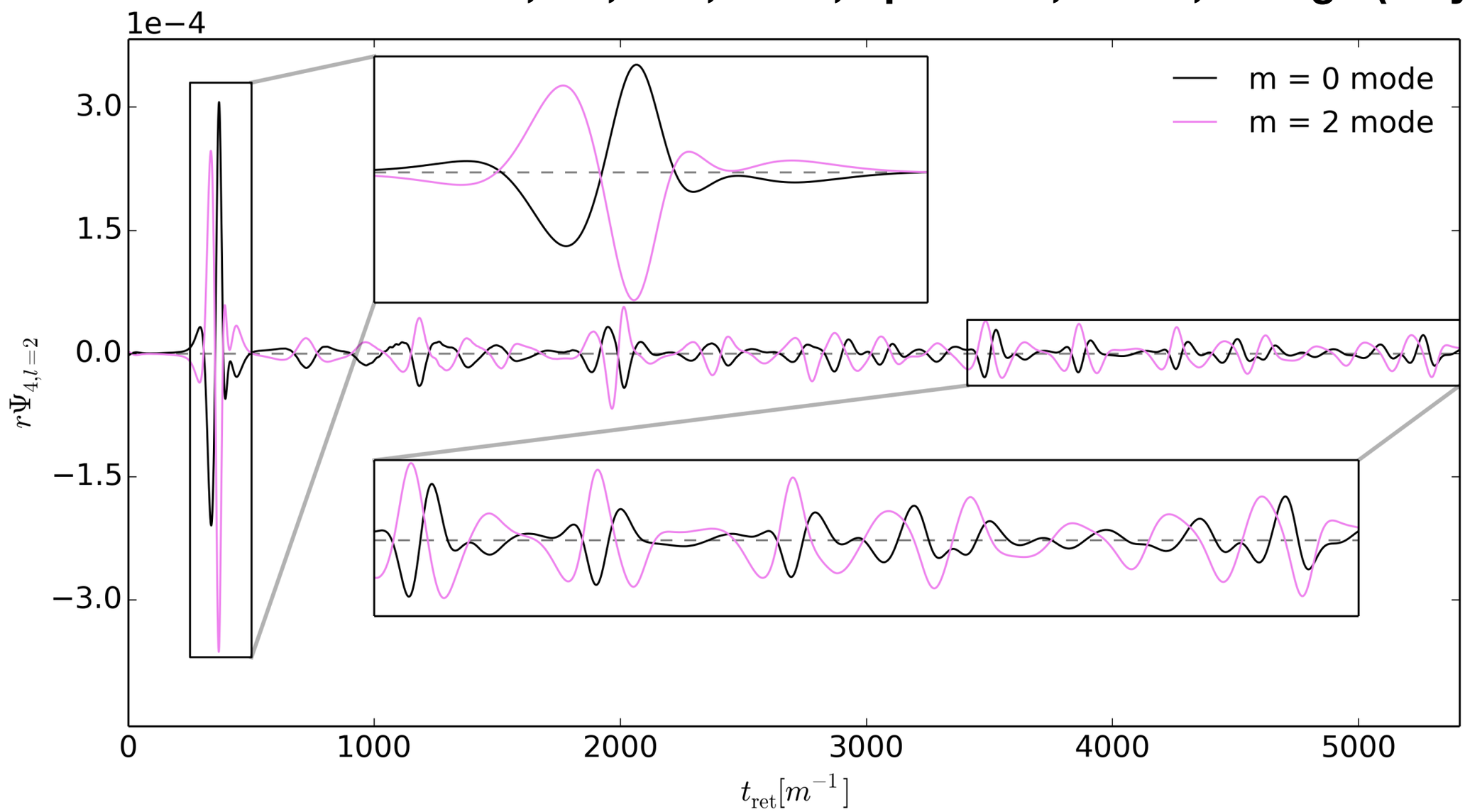

$$f = 8.0 \cdot 10^{-2}\ \mathrm{Hz}\left(\frac{m}{10^{-14}\ \mathrm{eV}}\right) \quad \Rightarrow \quad m > 10^{-6}\mathrm{eV}$$ **for UHFGW**

GW signatures for *post-collision* BS with spin.

Stochastic GW from ECOs

There should be also a background stochastic GW from ECO populations.

Problem : we don't know how to calculate this population as yet.

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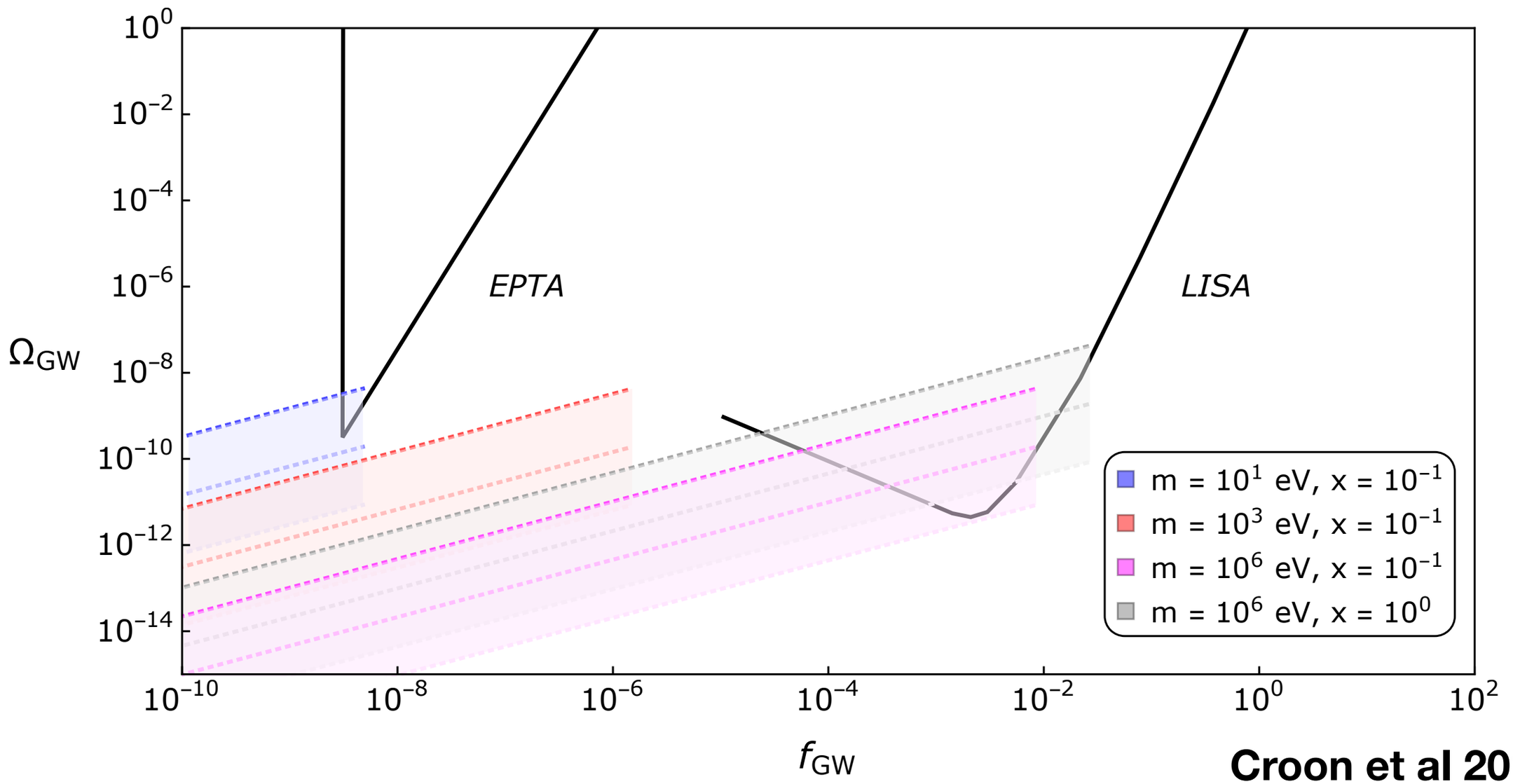
Problem : we don't know how to calculate this population as yet.

Good(?) news : large mass range for ECO models => SGW can be very different frequencies from compact binaries, including at high frequency ranges.

Stochastic GW from ECOs

Croon et al. assumes ECO formation track star formation



Croon et al 2018

Also : early universe populations ?
(e.g see Evangelos Sfakianakis's talk)

Formation and populations

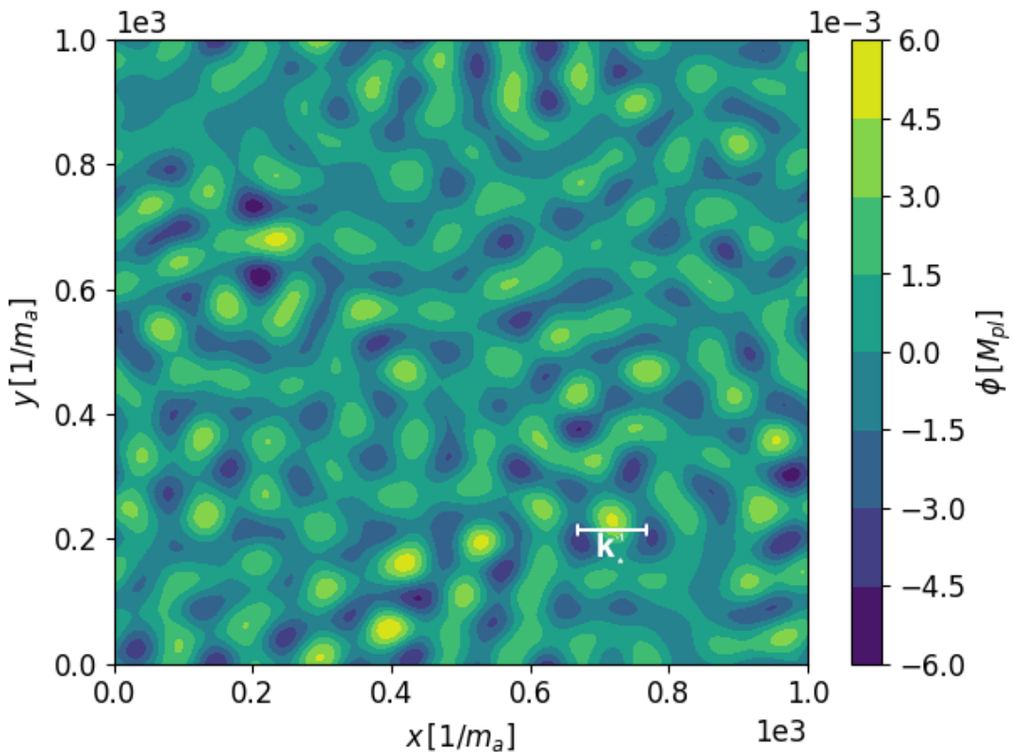
We *can* form relativistic ECOs from collapse of cosmological perturbations.

Widdicoombe, Helfer, Lim, Marsh (2019)

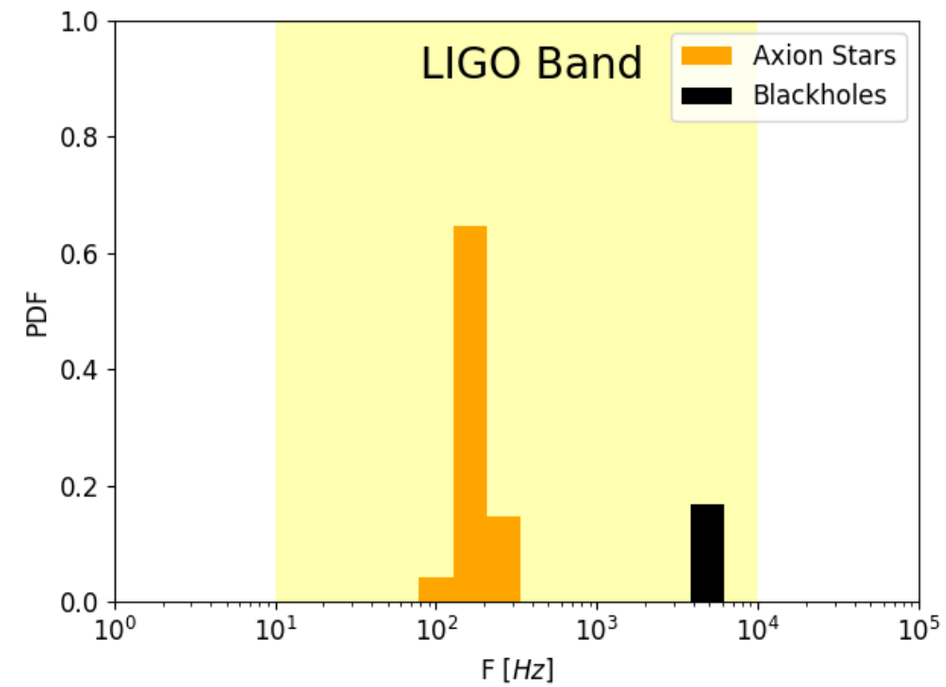
Formation and populations

But no large scale simulation of relativistic formation thus far (too expensive!)

Relativistic populations can be inferred from small scale simulations.



simulated over density field



Widdicoombe, Helfer, Lim, Marsh (2019)

Much more work needed!

Summary

ECOs are much more complicated and richer objects than BH — ECOs have plenty of hair!

But much more difficult objects to simulate in numerical relativity — lots of technical problems.

Good progress in solving ECO mergers — not there yet!

Much more work needed to study of population/ formation of relativistic ECOs to understand stochastic GW.

Thanks!