Gravitational Waves from theory to detection (non-perturbative regime)

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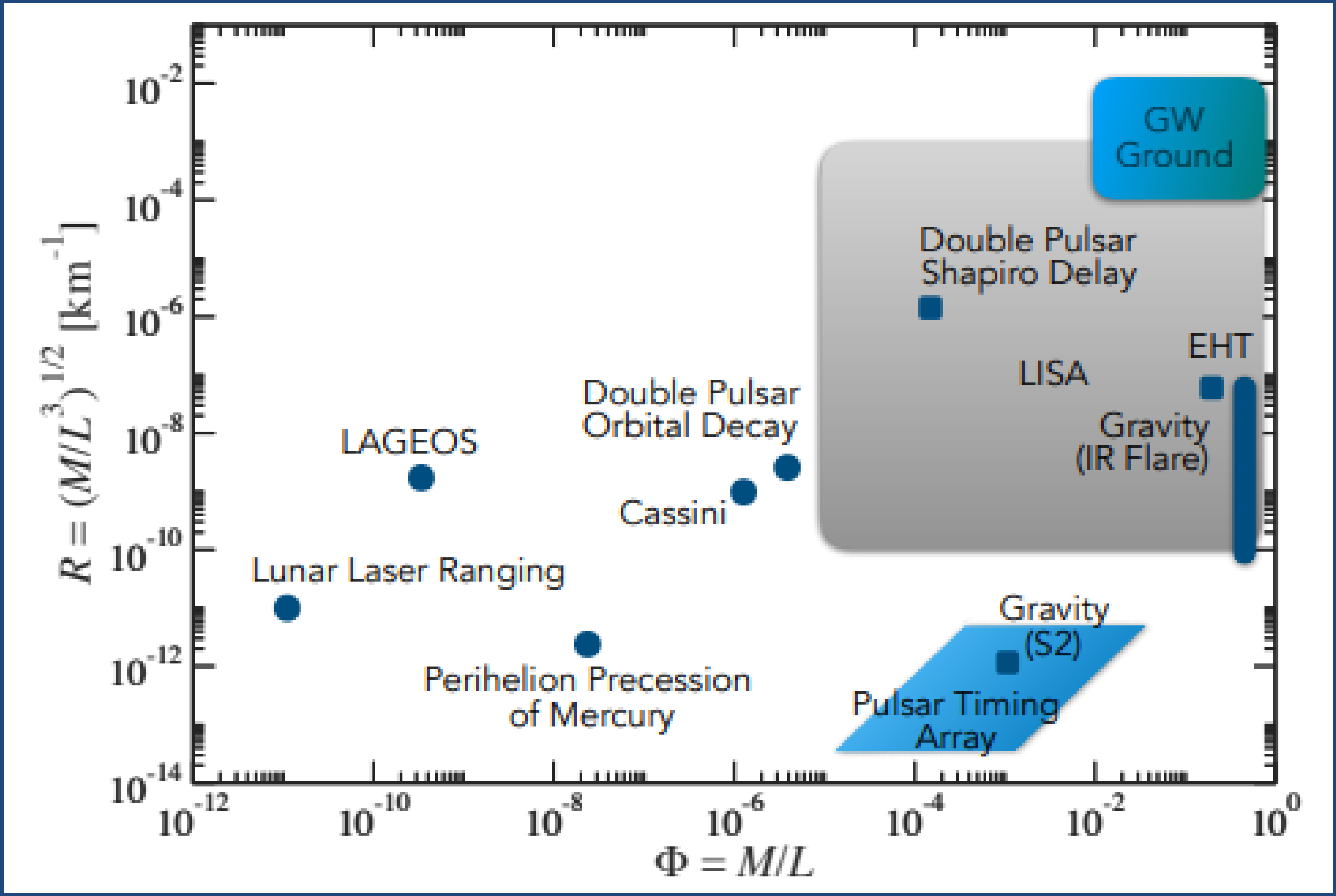


GW Ground
Double Pulsar Shapiro Delay
EHT
LISA
Gravity (IR Flare)
Double Pulsar Orbital Decay
LAGEOS
Cassini
Lunar Laser Ranging
Gravity (S2)
Perihelion Precession of Mercury
Pulsar Timing Array
$R = (M/L^3)^{1/2}$ [km^{-1}]
$\Phi = M/L$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

(some) motivating questions

- Regime: d~M, t ~ M, v~c, Φ ~ 1, R ~$10^{-10\,..-2}$ km^{-1}
- 'fundamental'
  - Is gravity described by GR?
  - How do: BHs relax? Respect Kerr bound as they merge? Collapsing/merging compact objects satisfy the 'ultimate state conjecture'?
  - Evidence for alternative compact objects? Guide for potential deviations of GR?
  - Constraints for potential DM models?
  - SURPRISES?

(some) motivating questions II

- Regime: $t \sim M$, $v \sim c$, $\Phi \sim 1$, $R \sim 10^{-10..-2}$ km^{-1}
- ‘practical’
  - populations
  - Connection with sGRBs and other energetic phenomena
  - Origin of heavy elements?
  - What else can compact objects do to ‘shine’?
  - SURPRISES?

Tackling this regime: Vacuum case & in GR

- A priori: No ‘weak field or slow’ approximation valid, or perturbation wrt to a given soln valid. horizon, strong dragging and radiation-reaction
- -> face Einstein equations ‘head-on’
- Issues:
  - – Mathematical: structure of underlying PDE
  - – Physical: coordinate conditions, initial data
  - – Computational: model disparate scales (M, wave zone 100s M, boundary location ~1000s M) [AMR, HPC]
  - – Practical: coverage of physical parameter space

Tackling this regime: non-vac case & in GR

- -> face matter model ‘head-on’
- Issues:
  - Mathematical: largely a different beast wrt type PDE
  - Physical: magnetized matter, EoS, microphysics, plasma…
  - Observational: compute corresponding lightcurves
  - Computational: even more scales (10s meters, longer times, higher dimensionality) [AMR, HPC and beyond]
  - Practical: what can really be done? What can be off-loaded to separate efforts?

Tackling this regime: beyond standards

- What alternative compact object? (Boson stars…and ‘the rest’)
- What alternative gravity theory? (scalar tensor, EMD, and ‘the rest’)

- Mathematical qns: ‘the rest’ is generically ill defined
- Practical qns: even resolving the above… which one and why? And even with a preferred subset.. Why would nature care? What general conclusions can be drawn in spite of uncertainties?

The ‘big’ picture

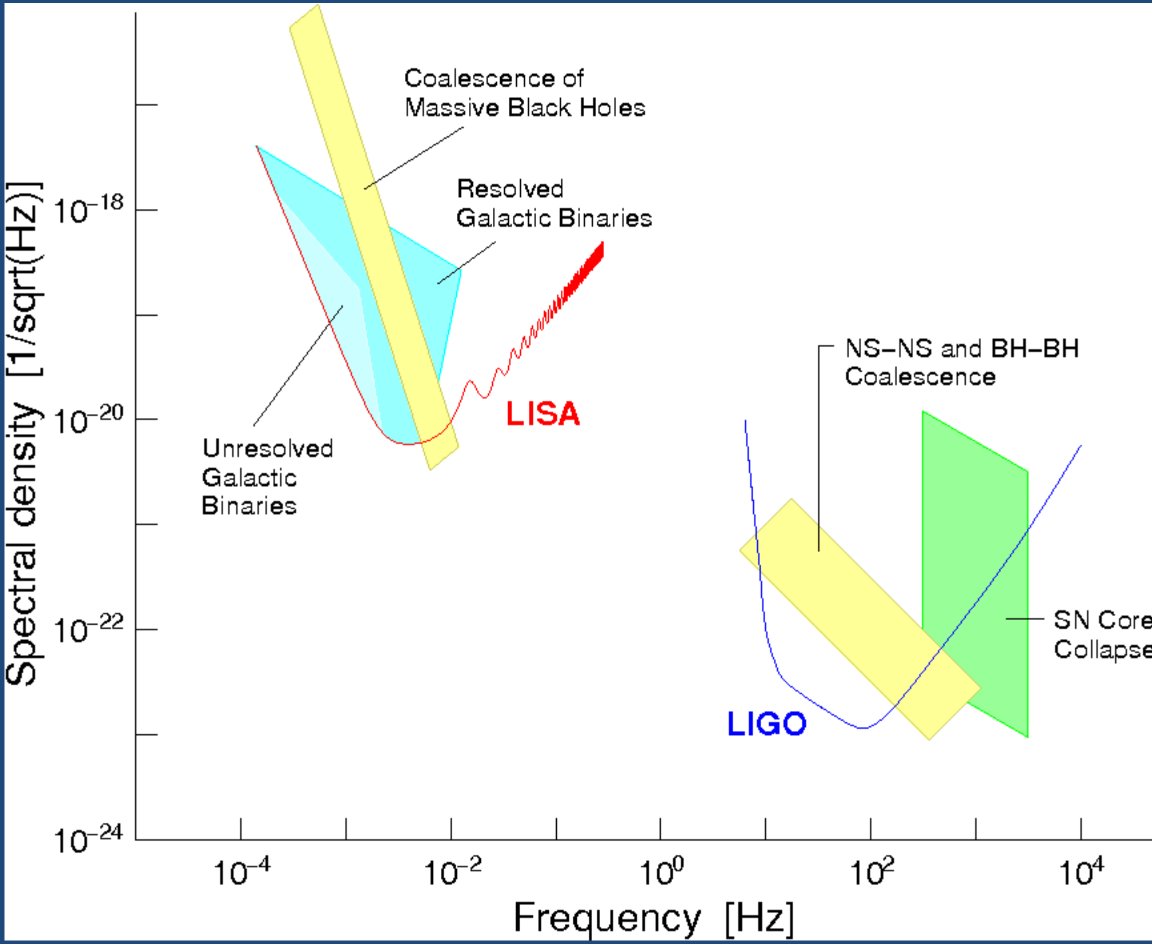
strain freq $\sim M^{-1}$

Redshift dependence can be exploited for cosmo qns

different regimes do not scale in the same way

There is lots of work! Can only skim through some aspects of this topic: Gravity, Astro, Cosmo, PP

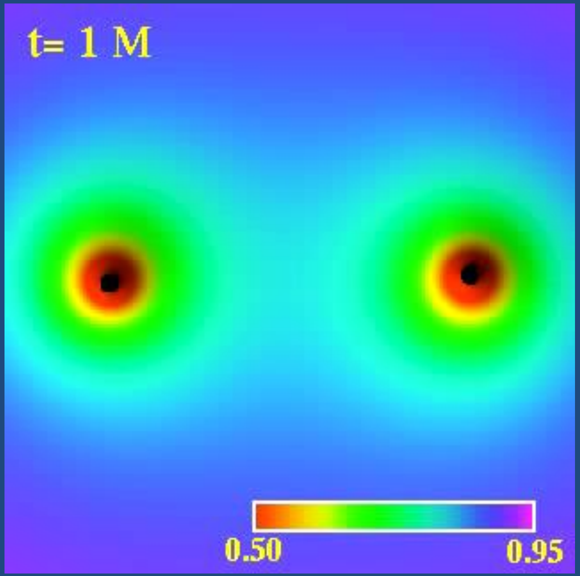
[see: Blanchet, Mayer, Nardini, Besancon, Shoemaker]



[see: Gonzalez – Petiteau talks]

BBHs: since ’05
By now: multiple codes, 2 formulations of EEs
Comparable mass case significantly covered.

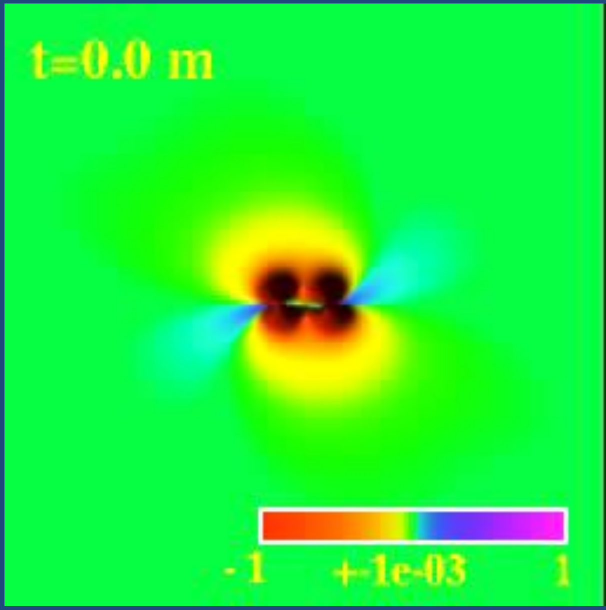
Results informing efficient ways to encode inspiral-merger-ringdown (e.g. EOB, Phenomenological approach, ReducedOrder methods, ML)



[Pretorius ‘05]

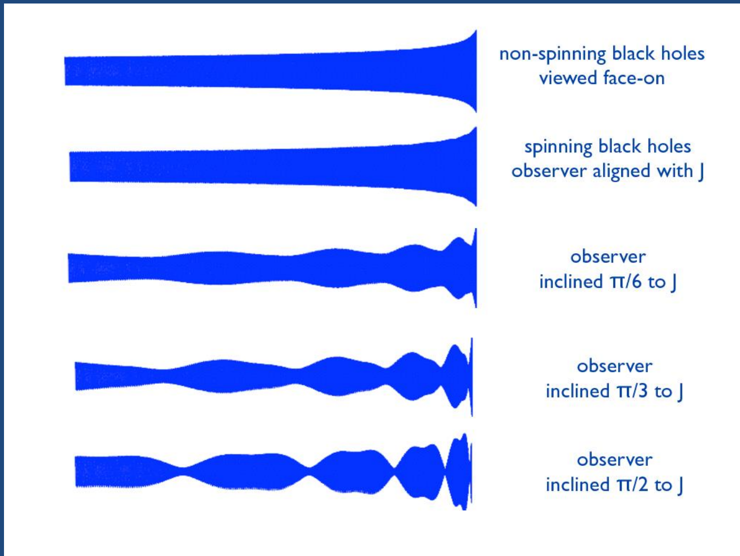
On the fundamental side:

- ‘higher’ net angular momentum →later (higher freqn) merger & higher spin in final BH
- Merged object, relaxes as predicted by perturbations off Kerr for fundamental mode (measured), argued also some of its overtones.



Richness of observations

- Aligned (+,-) with orbital ang. Momentum → higher/lower final spin. Rather smooth transition from inspiral to ringdown
- Asymmetry of radiation → net recoil or merged object, which can be as high has 1000s km/s! [RIT,+..]
- Misaligned spins -> waveform modulation (spin-orbit and spin-spin coupling) but strong dependence on observation direction… there is a price to pay in 'range' (SNR)



[Colpi etal 1610.05309]

- Much fun with data. e.g. Tying different regimes and first tests of GR

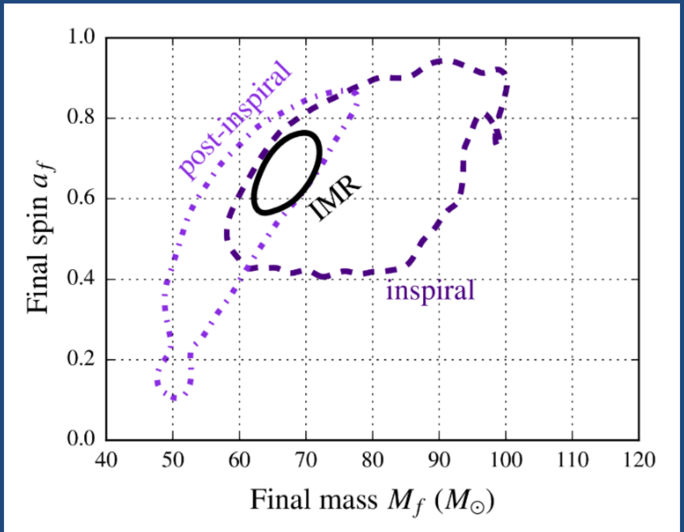
- Determining further modes require higher SNR in a single detection (statistical arguments argue one might need to wait for LISA or 3G detectors for doing so in a single event, [Berti+])

- *However*, 'stacking' can be employed

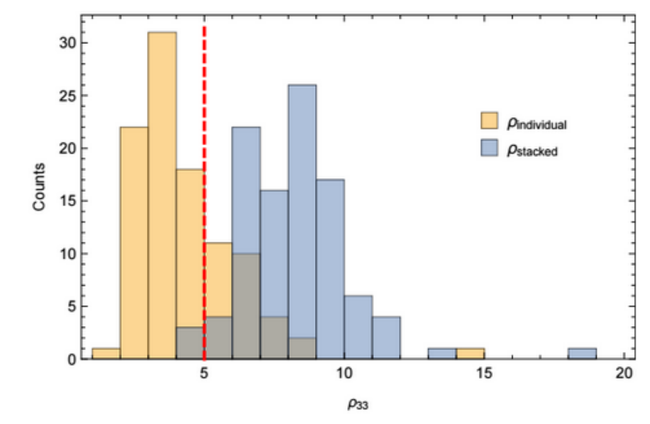
To dig for further modes

To dig fundamental modes in low SNR events

To search for any mapable feature in GWs



[LSC]



[Yang,Yagi,Blackman,LL, Paschalidis,Pretorius,Yunes '17]

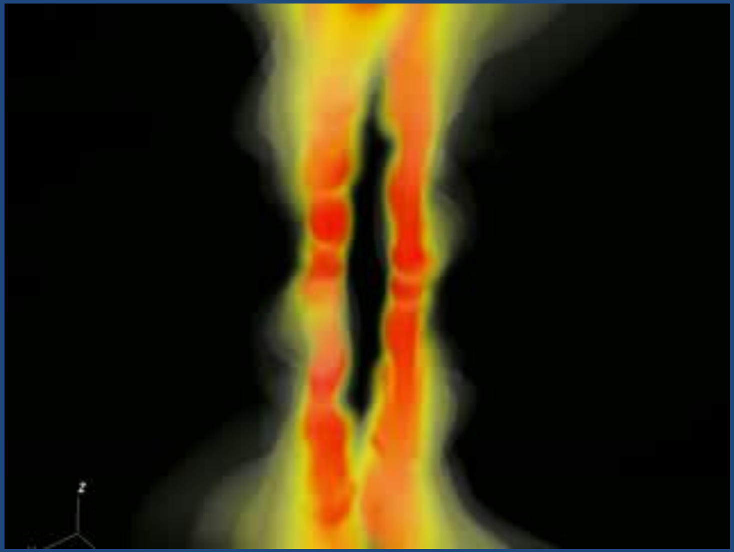
- *BH 'kinematics'/perturbations and interesting possibilities*
  - In a rotating BH, superradiance if $0< \omega < m\,\Omega_{BH}$

- Energy extracting in spinning black holes → can condense an axion cloud around BHs [Arvanitaki+]
  - Pseudo-monochromatic emission of GWs tied to axion (or bosonic field) at freqn given by its mass

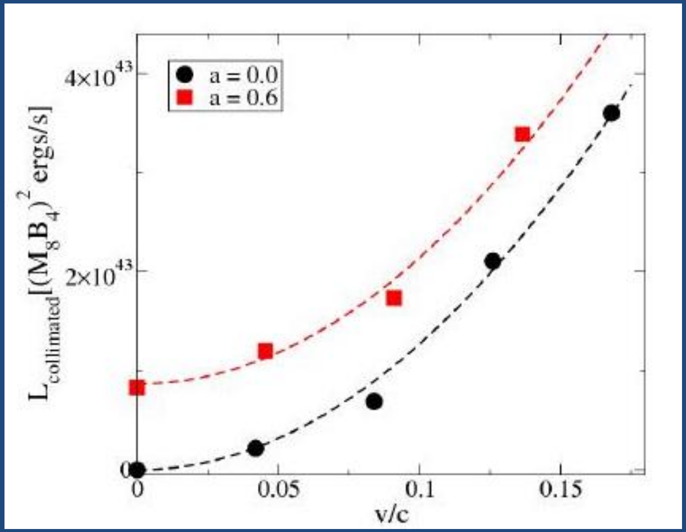
- Sims of the full nonlinear process:
  - Mass/angular momentum of the cloud ~6% / 18% [East '19]
  - This can, in turn, impact the merger! [Bauman+, 19] (LISA)

BBHs with a 'twist' *[LISA]*

- Rotating BH + plasma (energy extraction) → jet (Blandford-Znajek)
- For the BH case, invoking 'negative' energy arguments does not work if BH does not spin



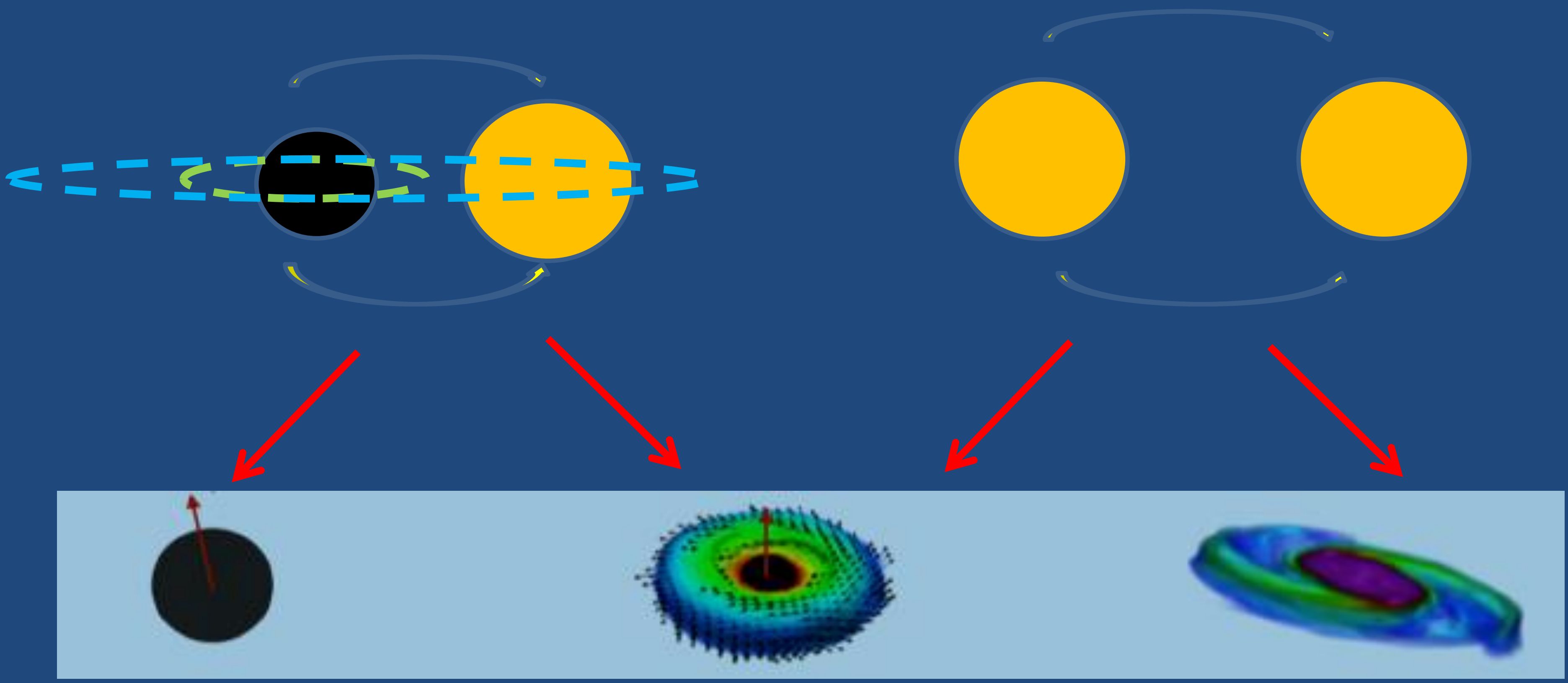
[Palenzuela,LL,Liebling, Science '10]



[Garret,Neilsen,LL,Paenzuela,Liebling '11]

- However, *diffusion* + reconnection, as in solar flare models, can take place with the BH 'pulling together' field lines at an efficient pace ~ (v/c) → $L \sim B^2 v^2$

Non-vacuum binary mergers: possible outcome?

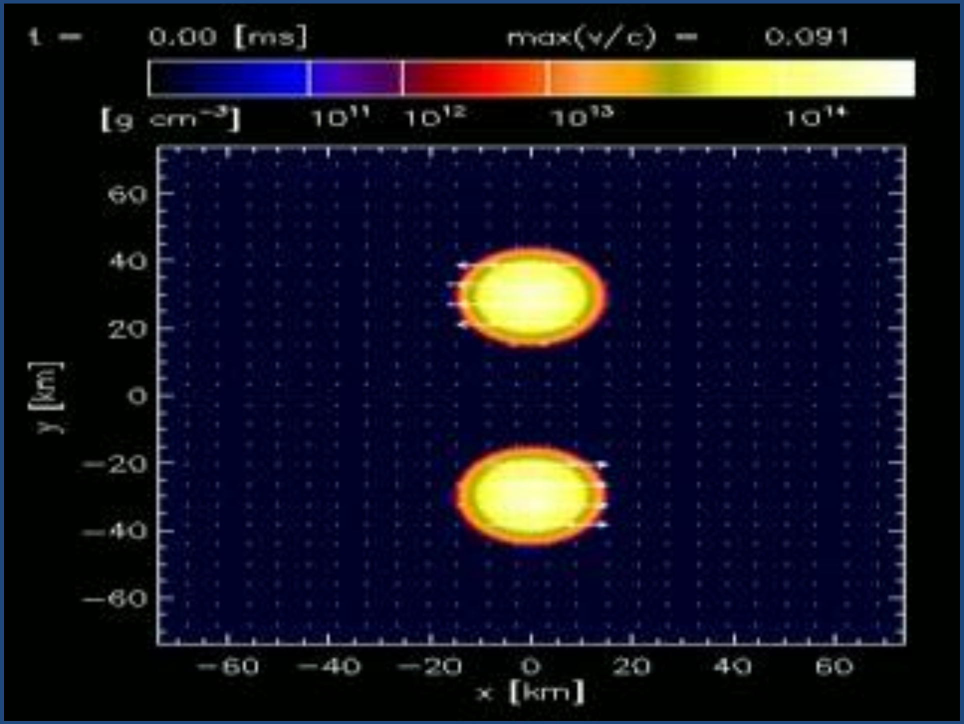


Low spin/high mass, small radius → direct plunge.
No sGRB, but could still shine?

BHNS: High spin/low mass, large radius → disruption.
NSNS: $M_{tot} > 1.3\text{-}1.5\ M_{max}$
'comfortable' disk mass
GW: with a clear cutoff

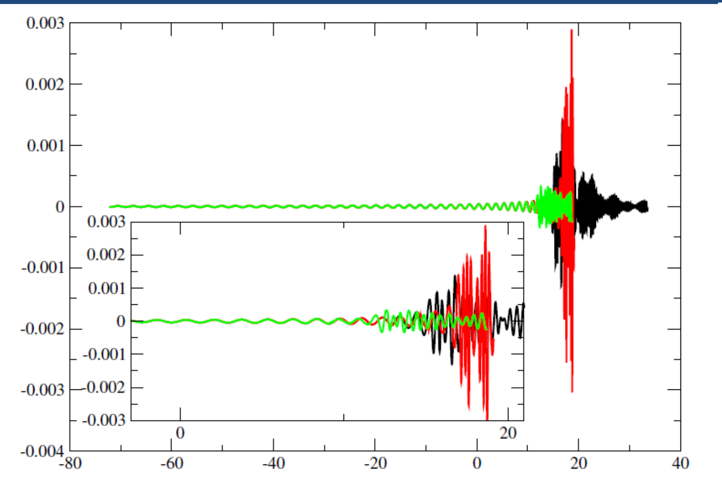
NSNS: $M_{tot} < 1.3\text{-}1.5\ M_{max}$
GW: postmerger signal
sGRB from 'sufficiently' magnetized MNS?

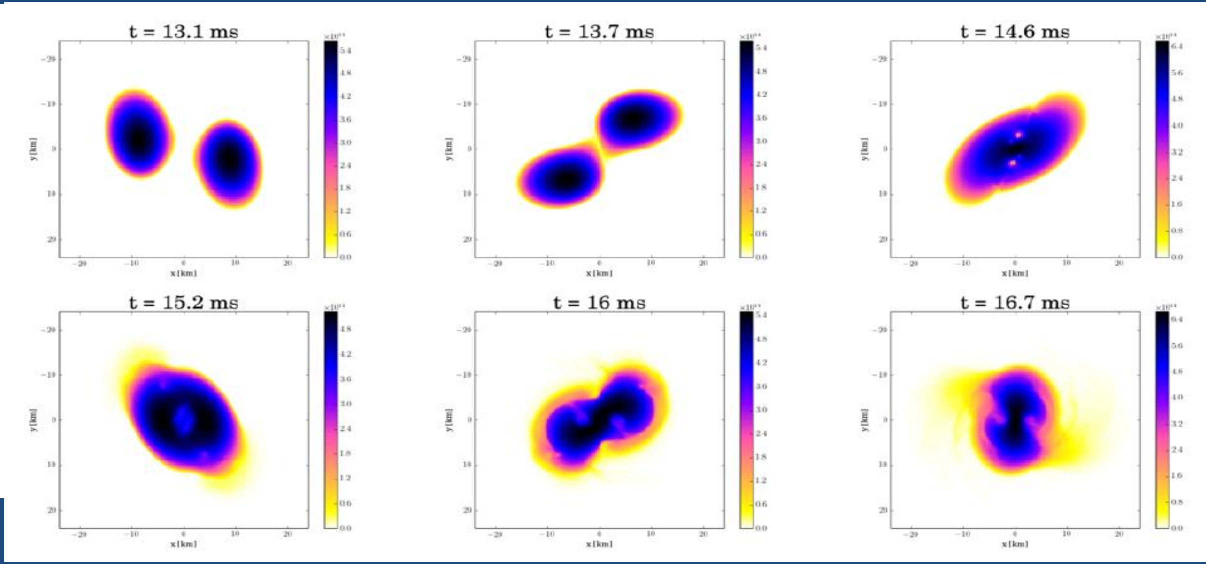
- NS described by unknown EoS.
- Cold during and lowly magnetized during inspiral
- going through a violent collision which can pump magnetic field strength induce nuclear reactions and produce copious amounts of neutrinos

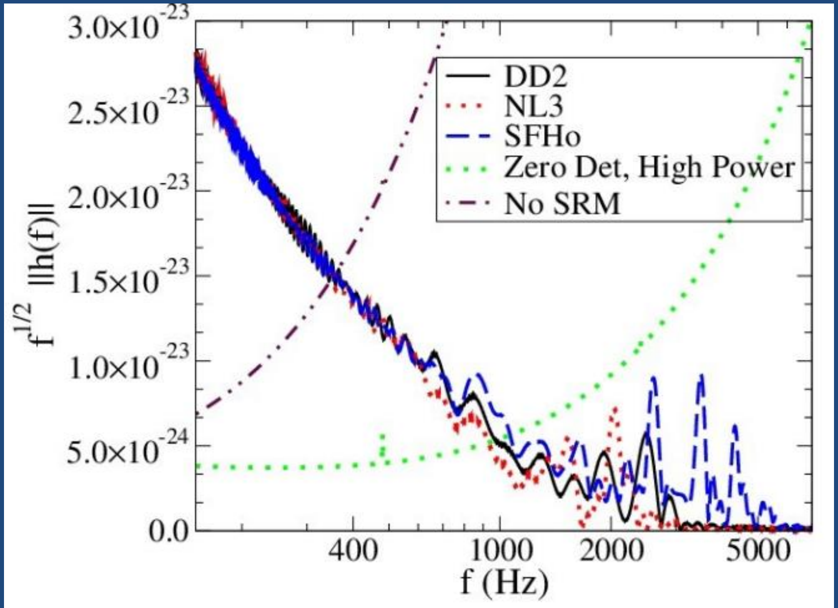


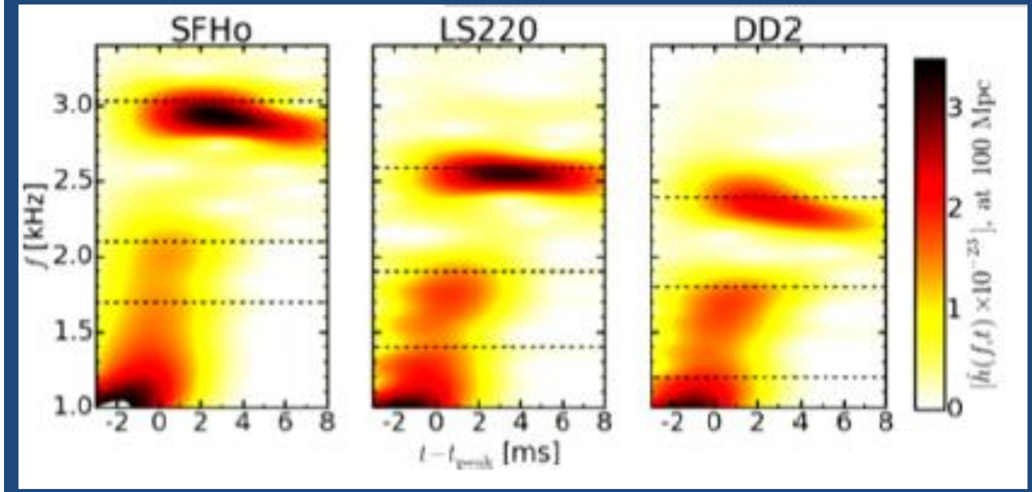
- Early regime PN, but then?
- What happens with ejecta? And central 'engine'
- Characteristics of merger and post-merger waveforms?

BNS & EoS?...







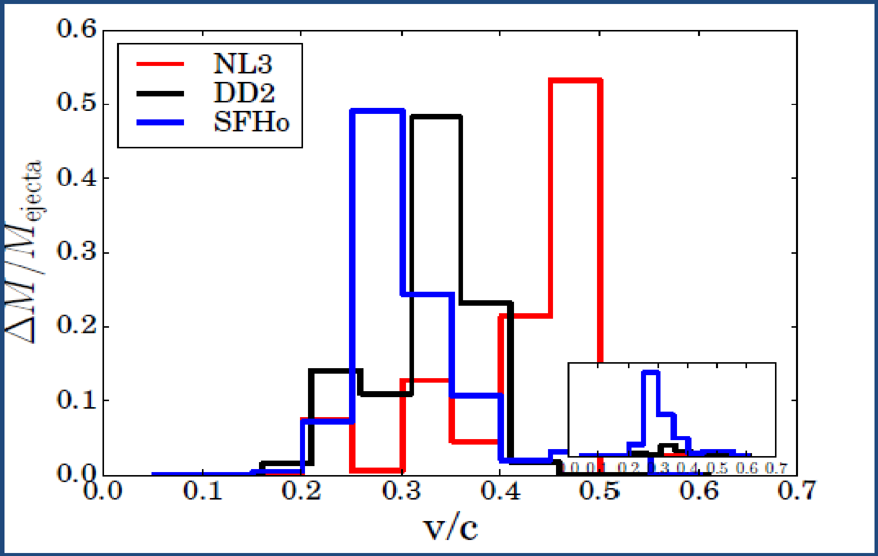


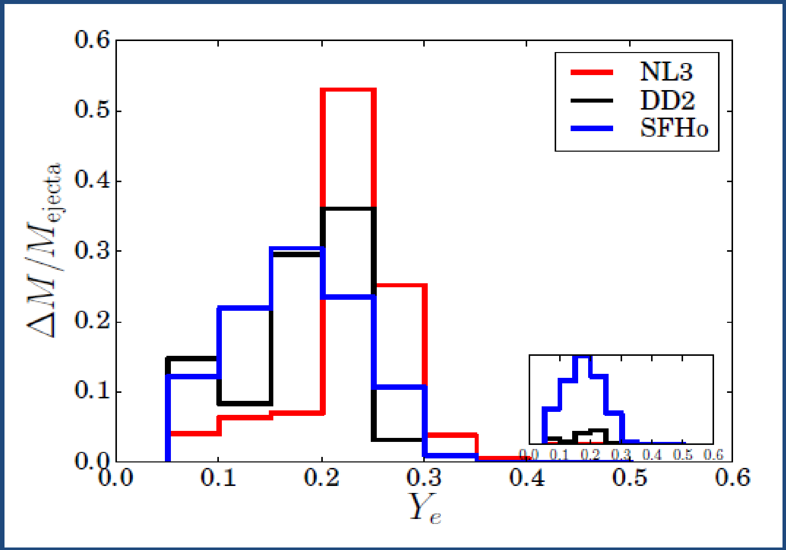
[Foucart etal ’15]

[Palenzuela,LL,Liebling,Neilsen,Caballero ‘15]

- EOS info, encoded in 5PN order of inspiraling behavior through ‘tidal deformability parameter’.
  - $\Lambda \sim k_2\, C^{-5}$ (k_2=0 for BHs)
  - For low (stiff) EOS and at sufficiently high frequencies, impact on waveforms, as C grows, effect reduces significantly
  - Further, at high frequencies, LIGO/VIRGO sensitivity degrades considerably → Future detectors for after-merger frequency [*which scales ‘proportionally’ with mass!*]
  - For now…unless ‘observational’ evidence (bias?) is taken into account, telling NSs from BHs is delicate from gravitational waves alone [Yang,East,LL ‘17]

Come disk & ejecta physics





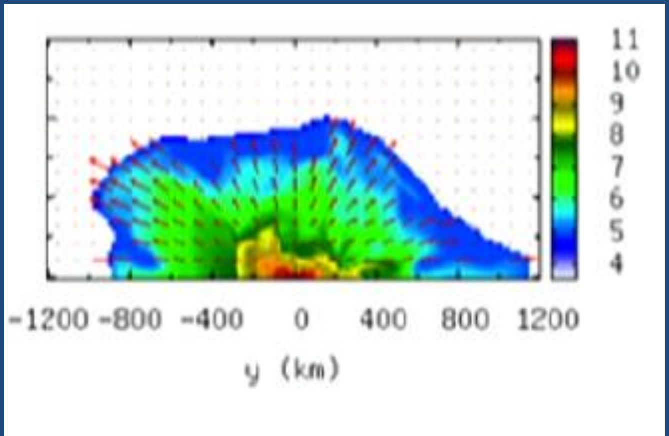


Image: Hotokezaka et al 2013

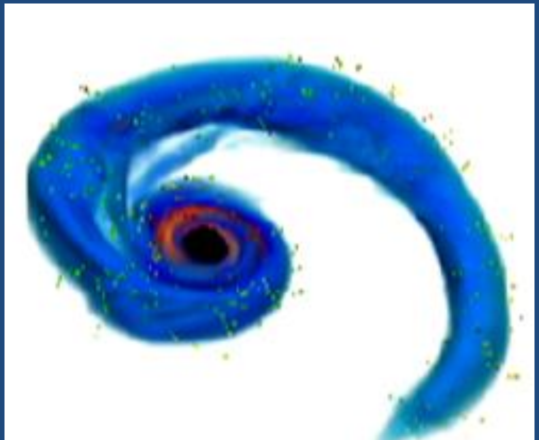
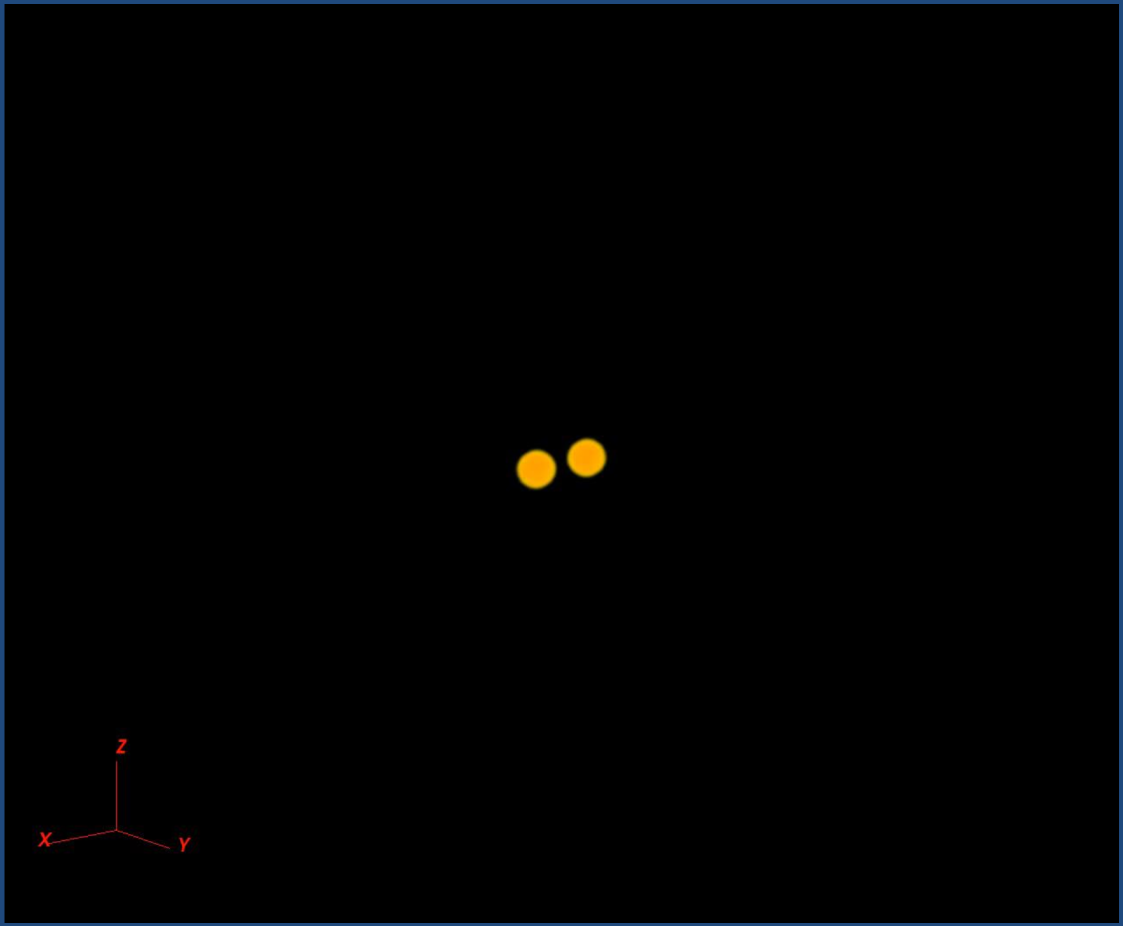


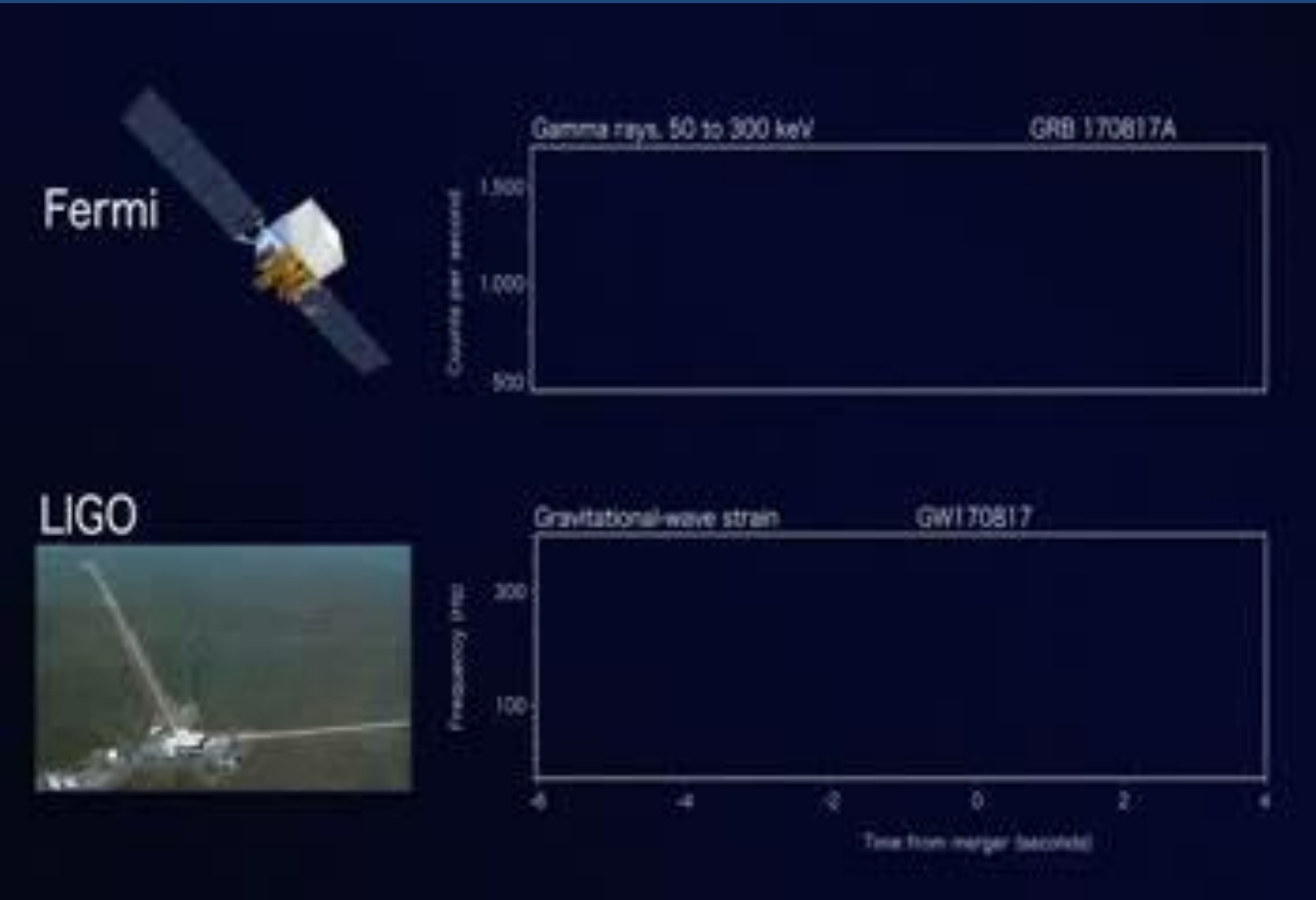
Image: Foucart et al 2015

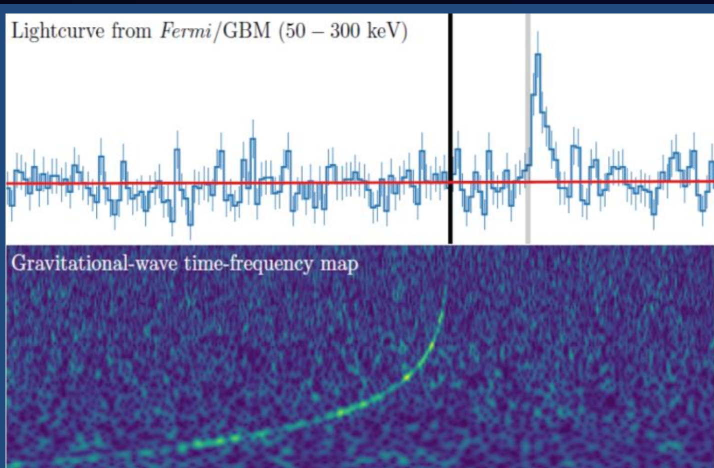
- Also, other ejecta from winds driven by the eventual accretion disk is possible, though this is less neutron rich [Fernandez etal '15] and expected signal would be in the optical.

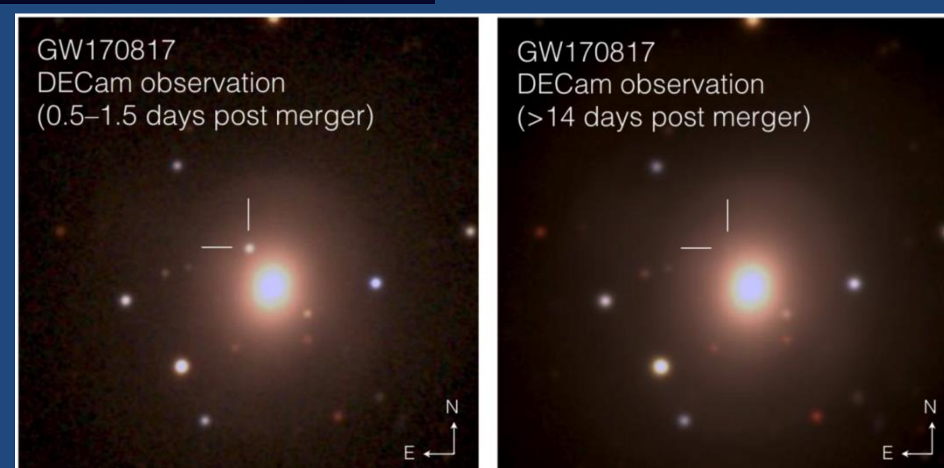
More on the ‘energy output’ budget



GW170817


Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
1,500
1,000
500
LIGO
Gravitational-wave strain
GW170817
200
100
-6
-4
-2
0
2
4

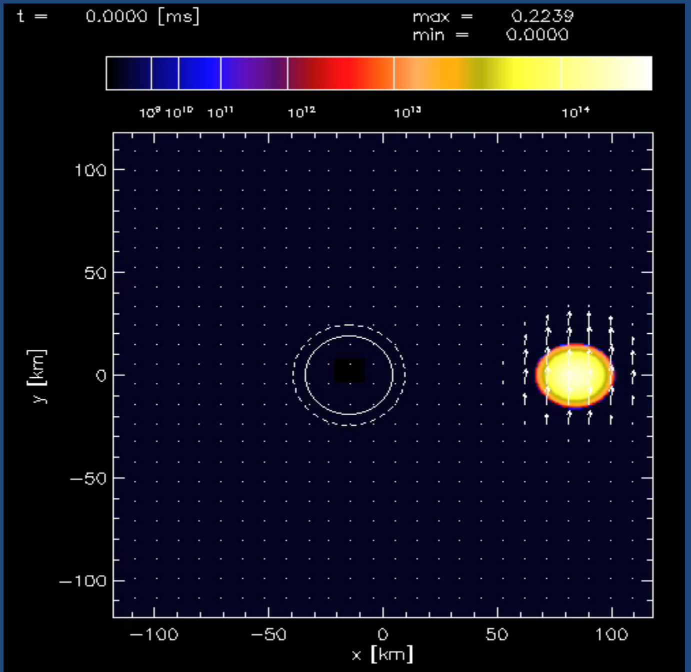

Lightcurve from *Fermi*/GBM (50 – 300 keV)
Gravitational-wave time-frequency map

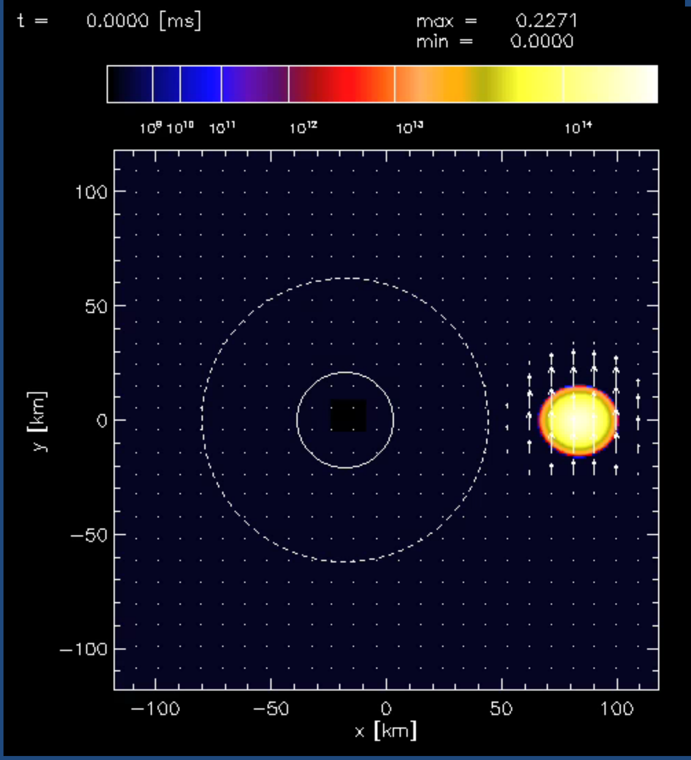

GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
GW170817
DECam observation
(>14 days post merger)
N
E

- Signals from radio to gamma-rays → matter was present
  - No tidal effects → rules out a number of stiff EOS [LSC,+++]
  - 'long shot' : no signal from assumption of no collapse to a BH (and simplistic waveform model) [LSC,++]
  - No BH with low mass → further constraints on Λ (otherwise, BH-NS can reproduce much of what is seen [Yang,East,LL])
  - Characteristics of 'red' kilonovae → re-radiation from disk decreasing neutron richness of ejecta → BH collapse [Metzger,Fernandez,Siegel…]
  - sGRB (at an angle) →(?) BH + 'sufficiently massive' disk. Assuming 'standard' picture for sGRB [LSC+AstroComm]
  - BNS inferred rates + KN constraints -> origin of heavy elements [though may be not the main source Siegel+]

BHNS

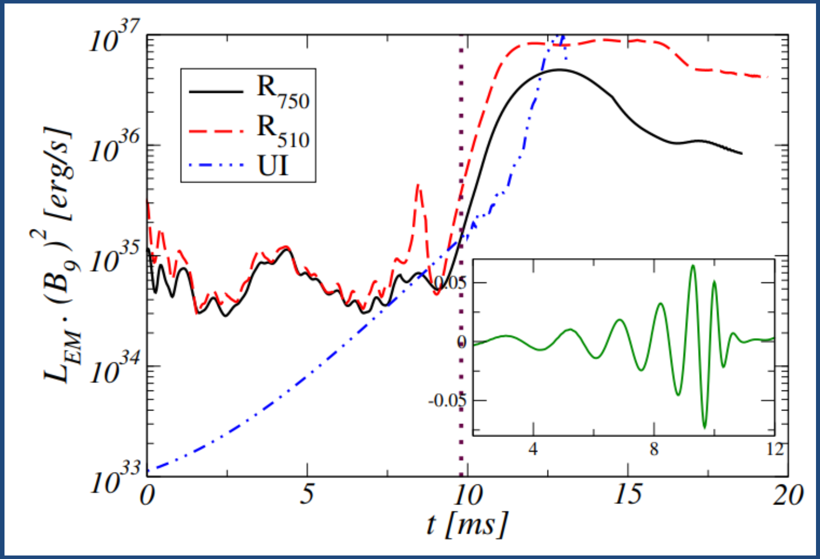
- For low mass ratios, (and/or high BH spins), significant disruption [tidal radius > ISCO]
- Observations of LMXBs seemingly disfavoring this option, BBH mass detections as well…
- BUT… not so fast: GW200105, GW200115 [~5:1 -> ~2:1]!

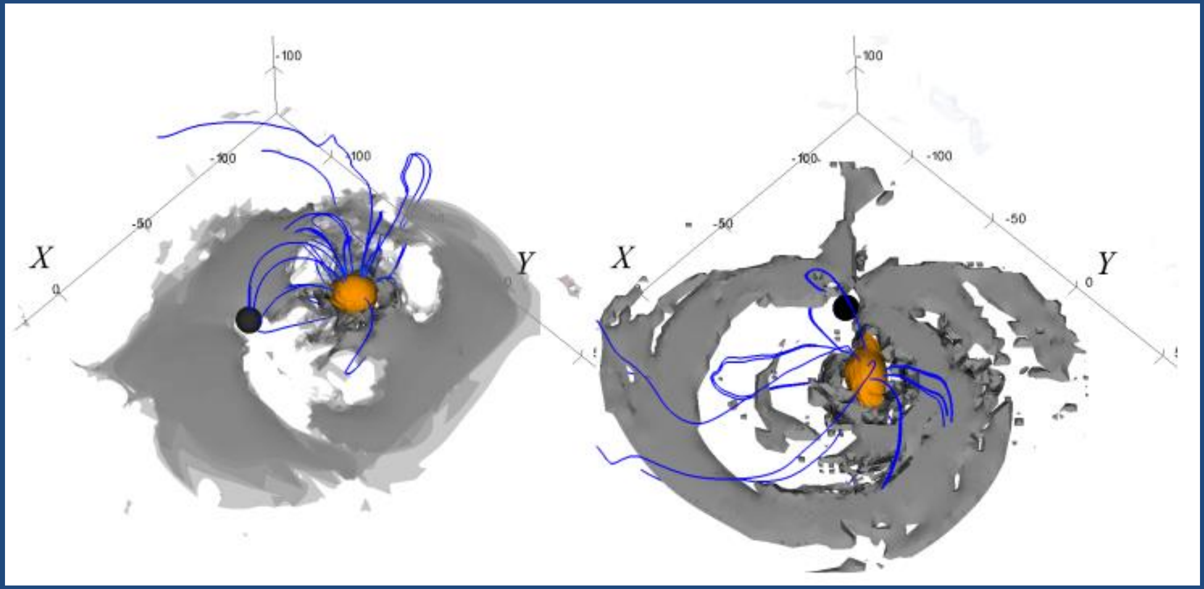




For higher mass ratios, are we out of luck?

- But now we know EM options from BHs (even without spin) interacting with magnetic fields/plasma can shine





[East,LL,Liebling,Palenzuela '21]

Beyond GR?

Options?

- *Model Building:* specific theories built from key assumptions of new physics. E.g. Brans-Dicke, Horndenskii

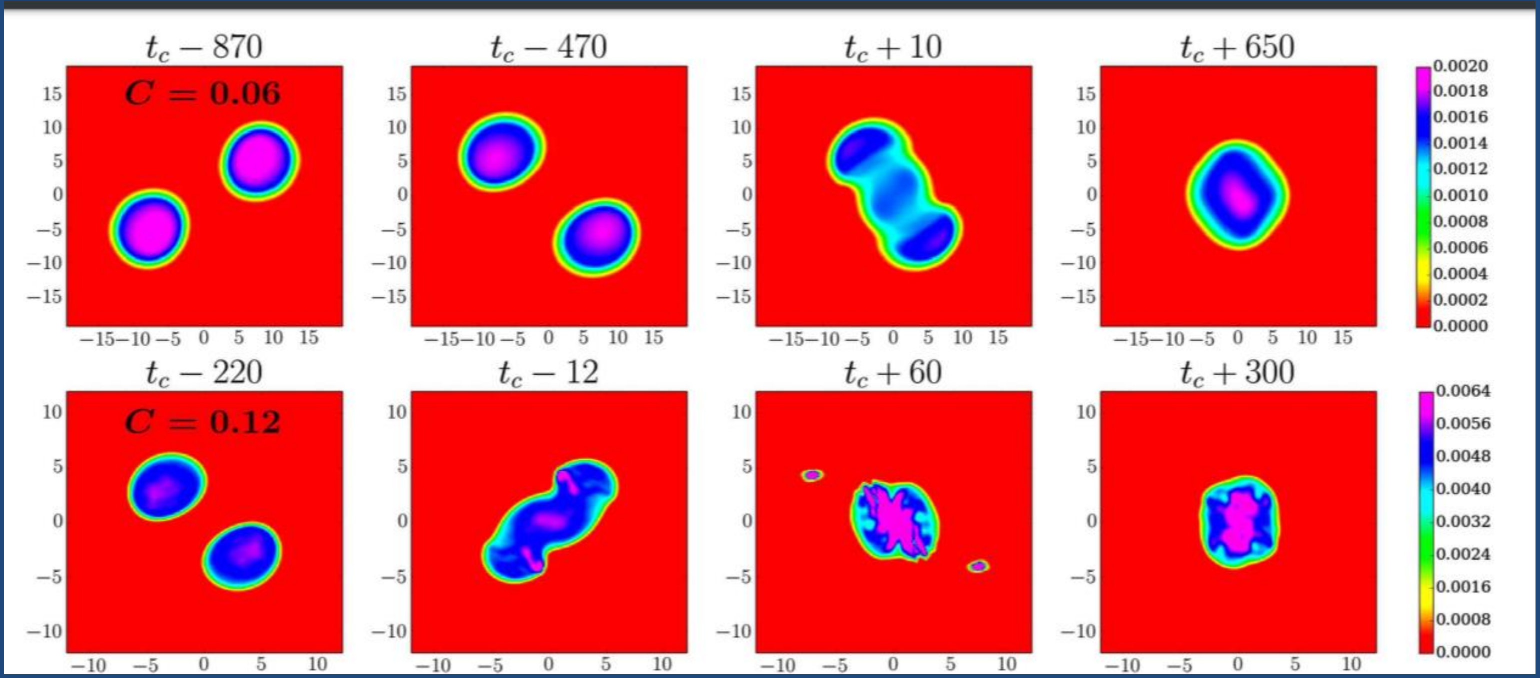
- *Effective Field Theories (EFTs):* no ‘new’ degrees of freedom (as they are integrated out), and new phenomena arises through short scale interactions organized in higher derivatives

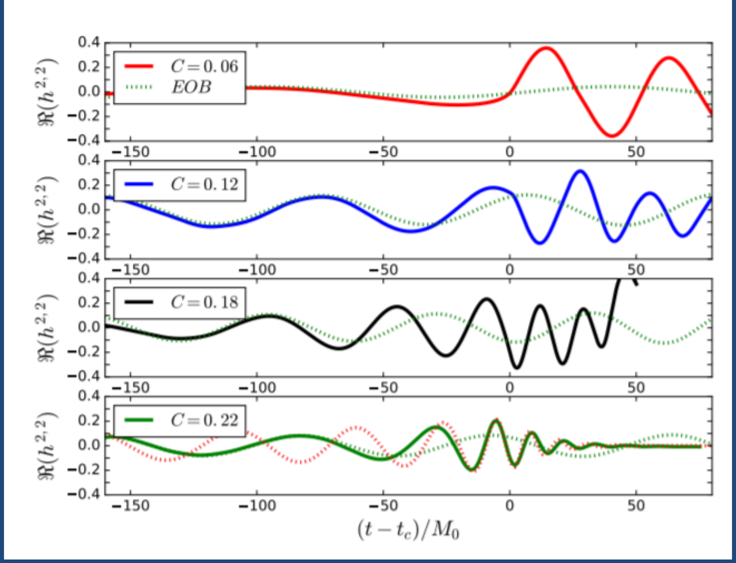
Many options, most incomplete

Beyond BH/NS as compact objects?

- Nature can provide extra fields, e.g. scalar fields: Higgs, DM, inflaton…
- Could interact with standard ones and endow them of further structure
- Could condensate and form an alternative compact object? E.g. Boson stars, proca stars…
- Arguments for potential way out of information paradox → horizons dressed with further structure
- Many options, most incomplete

Bin Boson stars 'vs' BBHs/BNSs: can they be confused?





- inspiral : can be degenerate with both
- merger: could be degenerate with NS
- post-merger: could again mimic the 'wrong' BH or the 'wrong' NS

[Palenzuela+,1710.09432]

beyond GR

- Restricting to theories known to allow for well-posed problems. I.e. those that guarantee: existence, uniqueness and ‘continuous dependence on initial/boundary data’

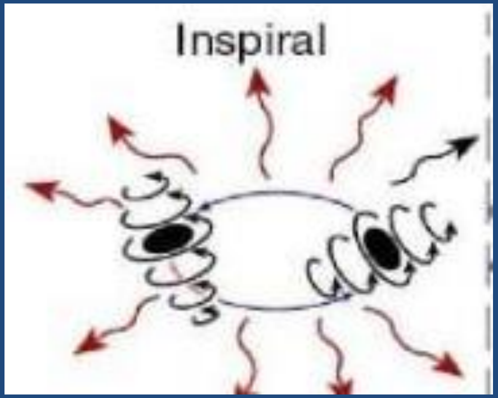
- Few options known to be amenable to well defined initial (boundary) value problems. Examples: Scalar-Vector-Tensor theories.

  Scalar-Tensor (ST) *{many incarnations}*

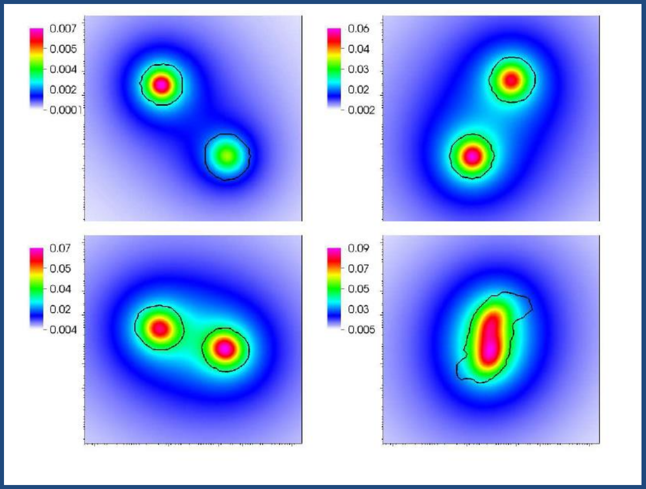
$$S = \int d^4x \frac{\sqrt{-g}}{2\kappa} \left[\phi R - \frac{\omega(\phi)}{\phi} \partial_\mu \phi \partial^\mu \phi \right] + S_M [g_{\mu\nu}, \psi]$$

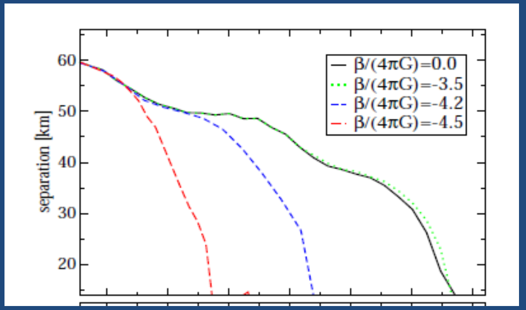
- Isolated case well understood: e.g. dipole radiation, mass renormalization, etc. and quite constrained by binary pulsar observations

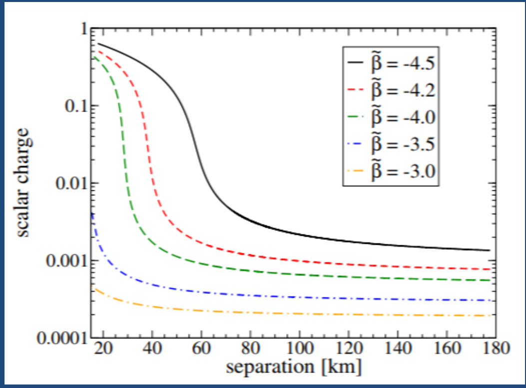
Close inspiral/merger



- Induced/dynamical scalarization can endow further structure absent in isolation. And, even 'take it away' as merger approaches







[Barausse+,Palenzuela+]

  - Behavior can be captured with PN or PPE like approaches, but must take into account effects need not be monotonic in freqn
  - Final outcome strongly affected by coupling values

2^{nd} (PDE) order theories: Horndenski

- Much work to can for full range of options
  - Analytical work to study and understand what would take for (local) well posednes: [Kovacs-Papallo-Real]
  - Numerical simulations and complementary analytical work identifying pitfalls for global arguments: Depending on ID & coupling strength → character change in equations of motion (Rippley-Pretorius, Bernard+)
  - As well, for sufficiently small couplings: single black holes [Ripley-Pretorius], binary black hole mergers [Witek+, East-Ripley], gravitational collase [Bezares+, Figueras-Franca]

  - Potential methods for ‘controlling’ pitfalls: [J. Cayuso, R. Cayuso ,Ortiz,LL]. And illustration in [Bezares+ ‘21] in ‘K-essence’

Higher order theories (EFT)

- Higher order PDE terms introduce significant mathematical roadblocks
- 'Iteration' of corrections evaluated by GR solution [akin but extending "reduction of order" methods] explored in dCS theories [Okounkova+]. Preliminary further improvements [Galvez-Stein]
- 'Fixing' method illustrated in $L \sim R + k\,(\text{Rieman})^4$ for single BHs [R. Cayuso-LL], and ongoing in binaries [Franca+]

- So… some potential ways to deal with mathematical roadblocks… but what theory? Do we care?

Final words

- Rich geometric & kinematic explorations of General Relativity in the 20th centure, amazing overarching results obtained.
- Perturbation studies provided much exciting insights which fueled many interesting results
- Ability to explore the theory in the nonlinear/highly dynamical regime in the 21st century opening a number of exciting (and in cases unexpected) new fronts
- And, of course, ever improving data (quantity & quality!) from GW detectors and connections with EM observations the most exciting scenario going forward