Rattle and shine by compact binaries mergers

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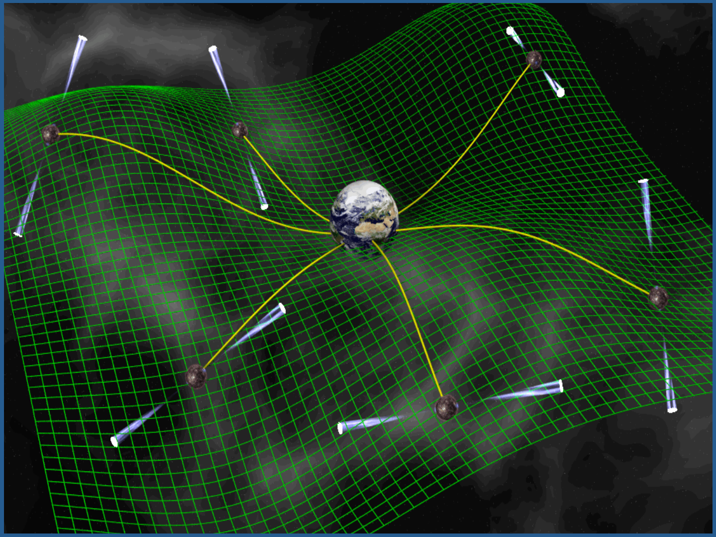
Compact objects have long been focus of attention as they:

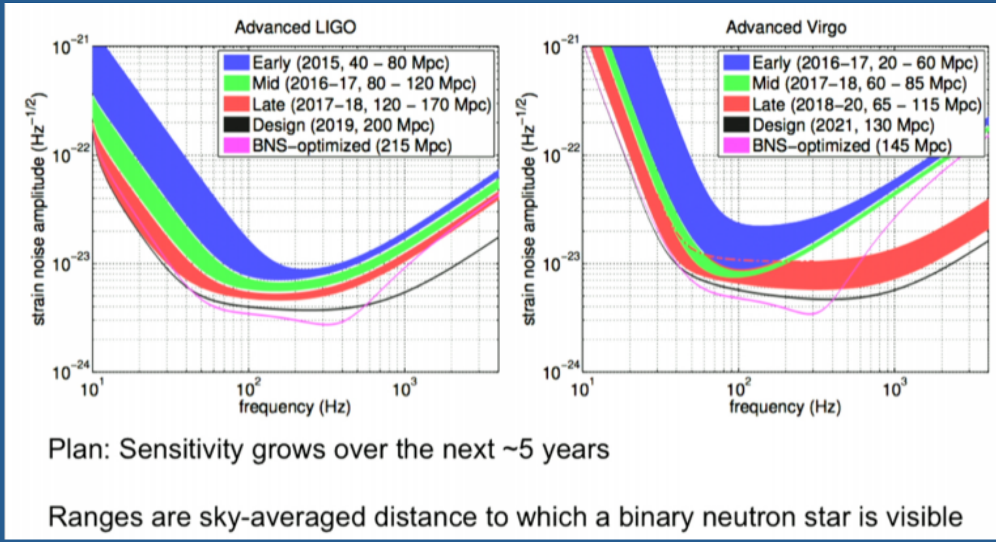
- Rattle the spacetime → gravitational waves (e.g. binary pulsar)
  - Is GR correct? And if not what might the correct theory be?
  - Inform population of BHs & NSs
  - Extract EoS (or at least a bound)
  - *Trigger EM counterpart searches*

- Help systems to shine brightly → EM waves (e.g. AGNs)
  - Binary connection with sGRB? (typically: do they give rise to a BH + disk with the right properties? Or a long-lived highly magnetized star?)
  - what else? E.g. help extract EoS? What else & how can shine?
  - *Trigger GW counterpart searches*

Quality of information

- On the grav wave front. In pple clean but freqn limited!



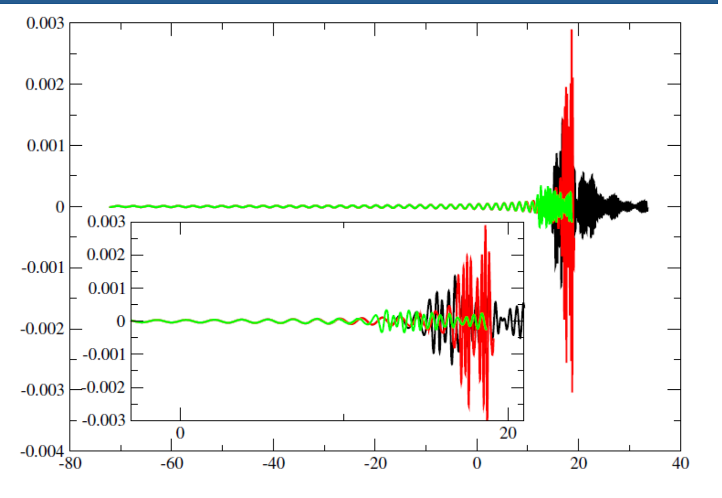


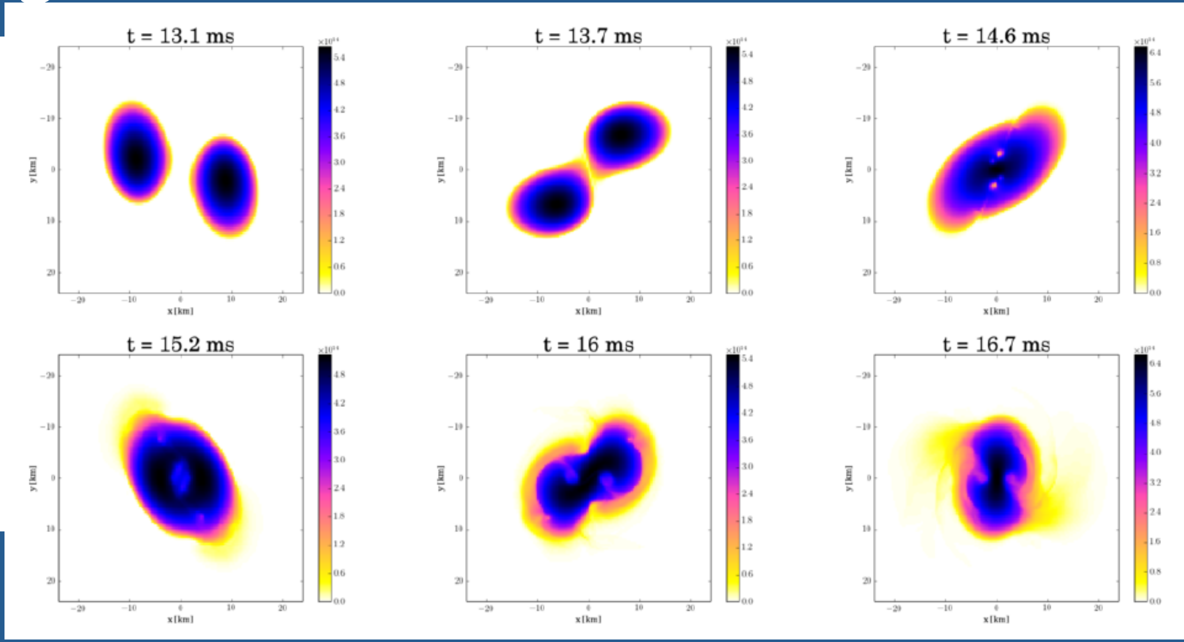
- On the EM front. Largely quite messy, relatively few 'clean smoking guns'

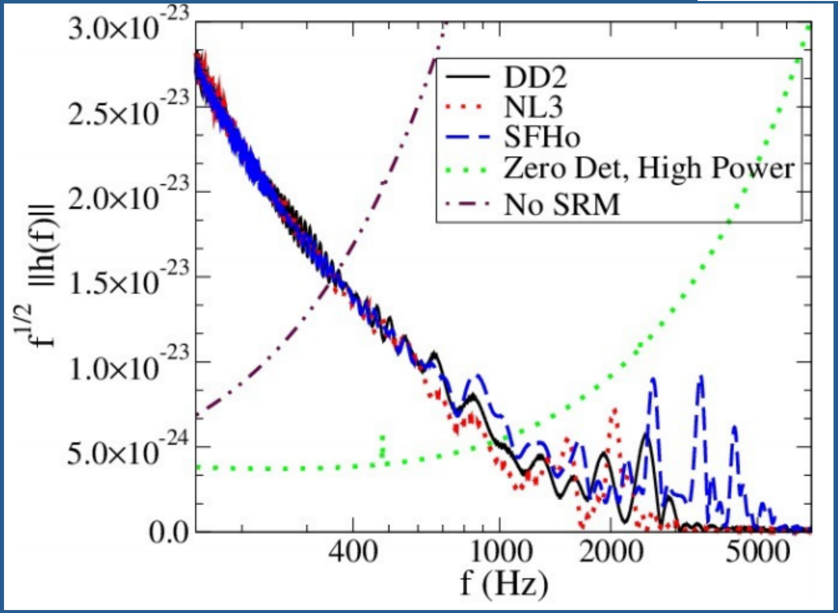
→ Combined information will be required to answer even some of the fundamental questions. For this, of course, comprehensive knowledge of the system is required

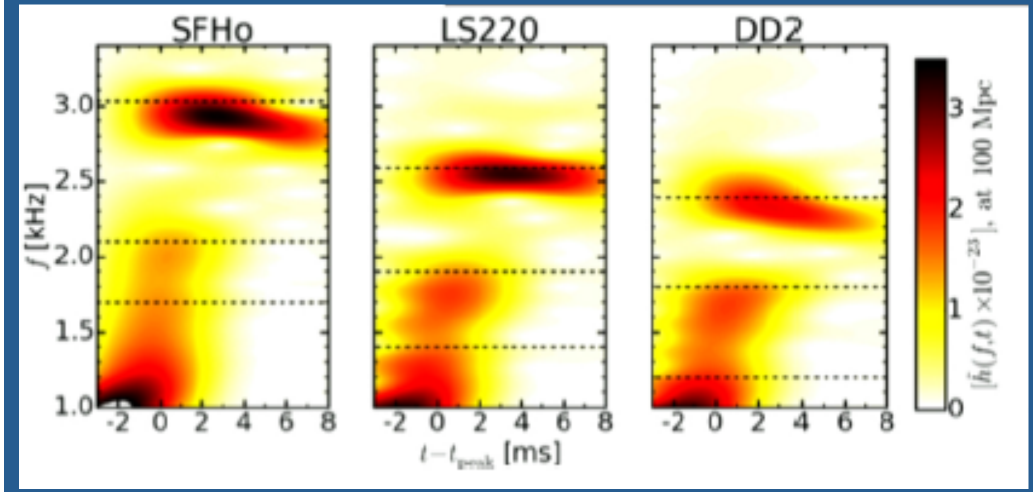
"group"	EOS (P: piecewise polytrope, T: tabulated)	MHD (I:Ideal, P:pasive R:Resistive)	Plasma (ForceFree)	Sub-grid model for mag. field effects or direct studies	Neutrino (E:effective C:Cooling, L:Leakage,M: Moment)	Alt. gravity
Shibata,Hotozekaka,Sekiguchi,Kiuchi,Kyutoku..	T,P	I		Direct Sims	M	✓
LL,Palenzuela,Liebling,Neilsen …	T	R	✓	Sub-grid (direct sims)	L	✓
Rezzolla,Giacommazzo,Alic,Baiotti,Moesta..	P	R	✓	Sub-grid (direct sims)	L	
Shapiro,Paschalidis,Etienne,Gold,Ruiz..	P	P	✓		E	
Duez,Foucart,Pfeiffer,Haas,…	T	I	✓		M	
Pretorius,Will, Stephens,Ramazanoglou..	P		✓			
Bruegmann,Bernuzzi,Dietrich, Markakis…	P					

‘First’ 2 qns: grave waves & BH-disk…









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

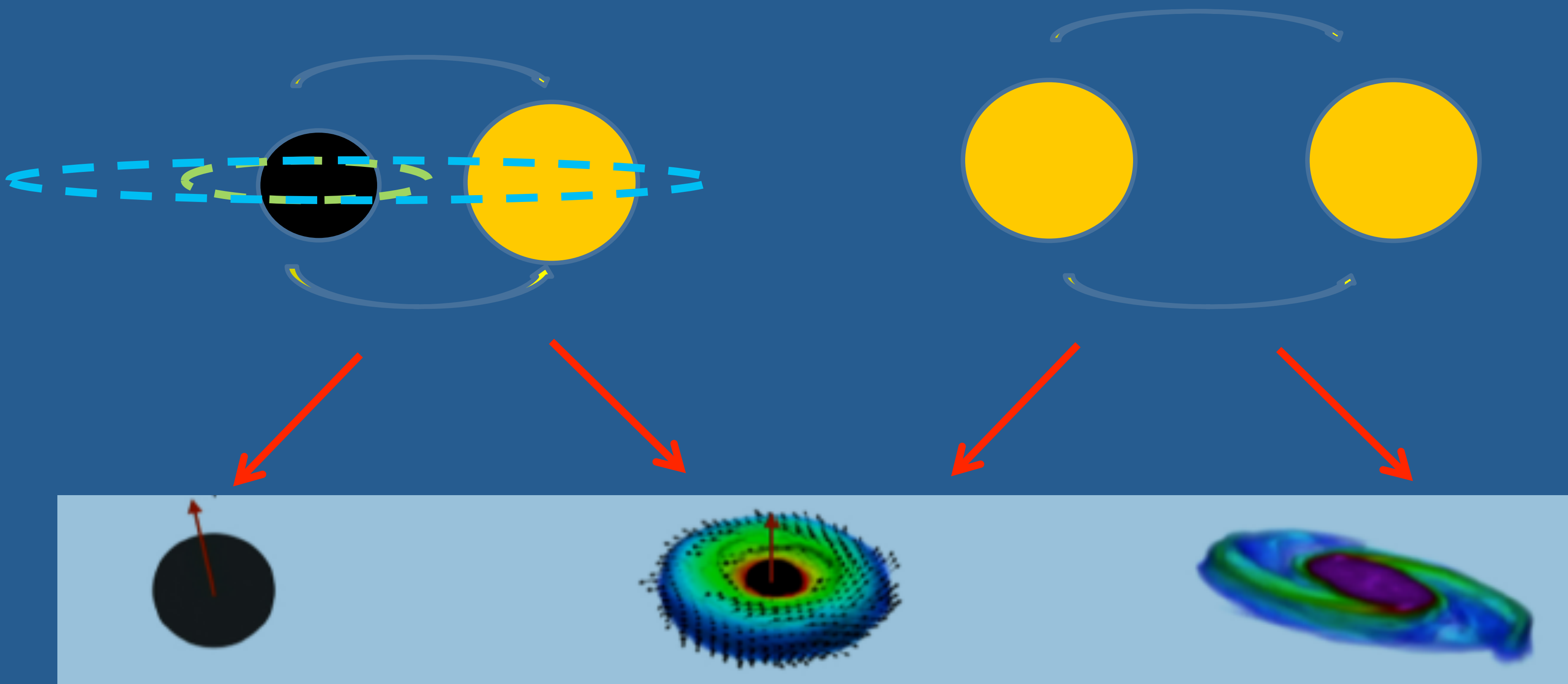
[Foucart etal ’15]

- Decoding waveforms:
  - Early on PN is enough but tidal effects visible near merger ~ $(v/c)^{10} R^5$ (Nagar etal, Hinderer etal)
  - then 'barish' structure. Strongly dependent on masses/EOS (Bausswein etal)

- Distinguishing EOS with single (few) NS-NS grav wave signals alone will be difficult (SNR dependent)

- BH-NS waveform near merger depends on competition between tidal radius and ISCO radius.
  - $R_{ISCO} \sim M$; $R_{tidal} \sim M^{1/3}$. → tidal disruption requires low BH masses and/or high BH spins. Otherwise BH-NS waveform → same as BH-BH waveform of same masses

What's the outcome? (sGRB motivated)



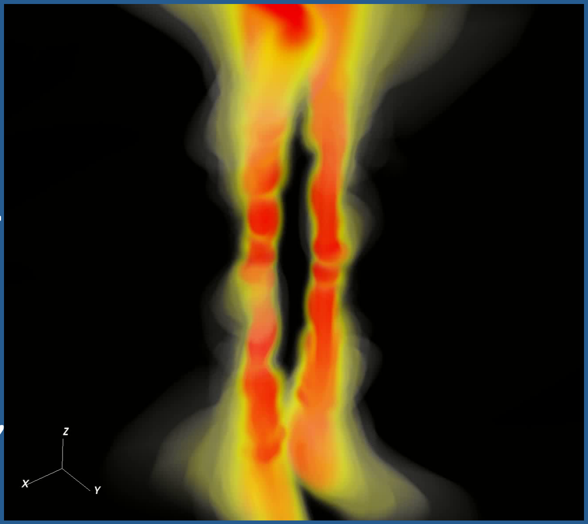
Low spin/high mass, small radius → direct plunge.
No sGRB, but could still shine.

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?

Further nuggets from simulation

System radiates ~ % of total mass, Luminosity ~$10^{7\text{-}9}$ L_{GRB} , just needs to tap a portion to shine somehow. Examples:



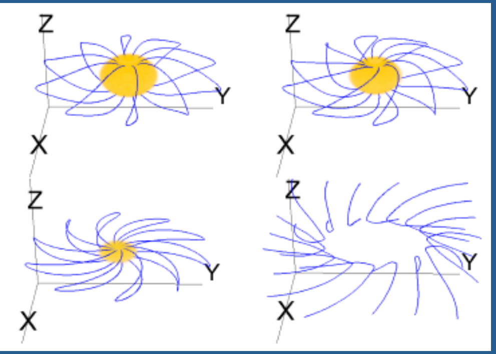
[Palenzuela,LL ,Liebling '10]

•BH-BH surrounded by plasma
['unipolar induction' works even for non spinning BHs]

BH-NS can generate a jet [Hansen-Liutikov, McWillians-Levin,Paschalidis etal]

•NS-NS merger → tap kinetic energy → Produce a magnetar!
[Anderson,LL,Liebling,Neilsen; Giacommazo-Baiotti-Rezzolla,…]

– Long-lived magnetar → sGRB model (Metzger)
– Magnetar collapse → can radiate up to even 10^{51} ergs [LL,Palenzuela,Liebling,Thompson,Hanna '12]
– Depending on loading this might come out as a GRB or precursor/extended emission [Murguia,Ramirez-Ruiz,Montes,DeColle,Lee '14]



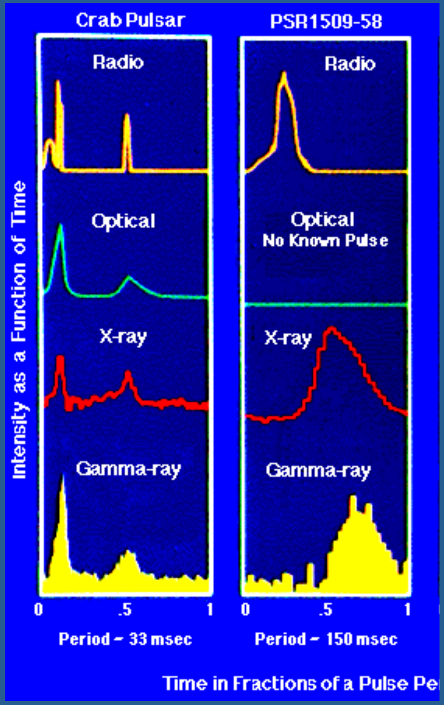
Signals: what else & wich ones might be clean enough?

1. Detectable with present or upcoming facilities within reasonable allocation
2. Accompany a high fraction of GW events
3. Be unambiguously identifiable
4. Quality of the information than can be drawn from them

The above is a tall order, non-vacuum binary mergers (BH-NS & NS-NS) can give, in principle plenty: neutrinos, EM from gamma to radio and GWs. Also, a possibility is that GW might even give ‘early-warning’ prior to merger (mins).

Among the many possible options, and bearing in mind conditions above, let’s consider 2 that could be ‘sufficiently clean’ by considering pre-merger in time, or far from the messy details of the source.

Discriminating options

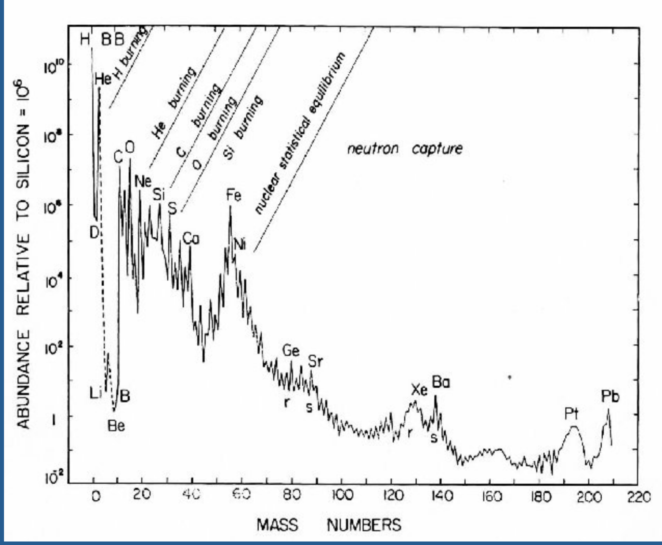


- Concentrate on premerger stage: Emission

Induced by magnetosphere's dynamics as binary tightens. Pulsar guidance → emission across many bands. High frequency 'best' understood (sidestepping optical depth issues)

- Also, 'kilonovae' related to radiactive decay

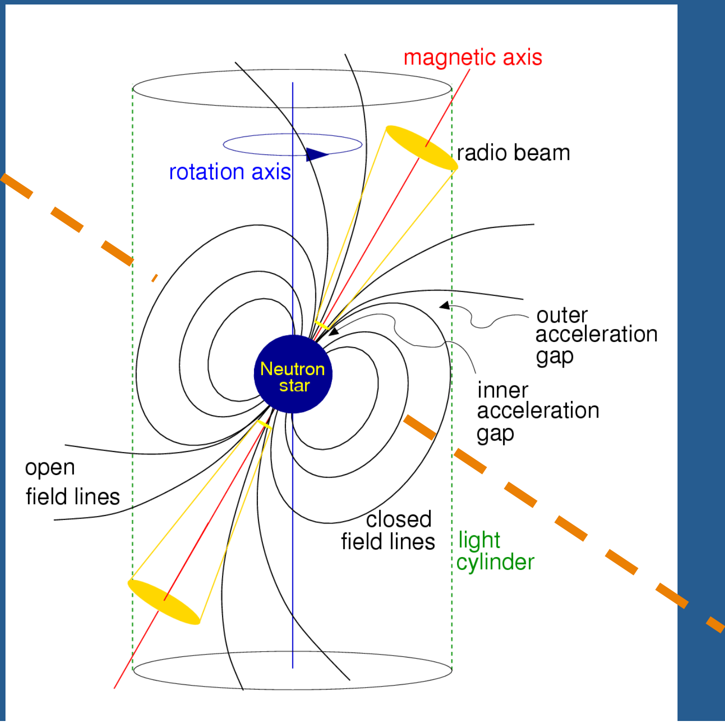
of r-processes. Distribution is tied to how neutron rich the material that powers the process is. Standard suspect: supernovae… but simulations point to ejecta not sufficiently neutron rich

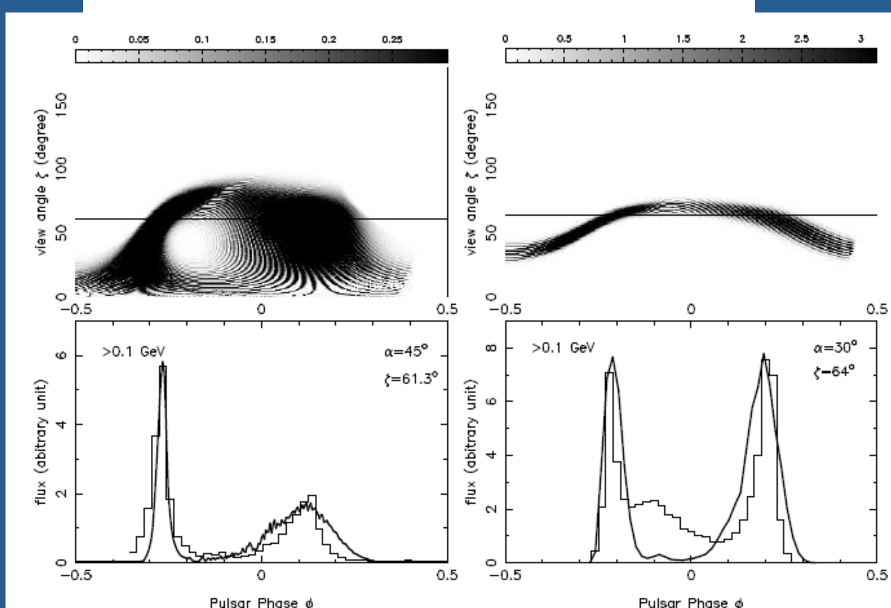


Also, one association with GRB 130603B [Tanvir etal Nature '13, Berger etal Astrophys J. Letters '13]).

infrared signal implies high neutron richness

Pulsar guidance





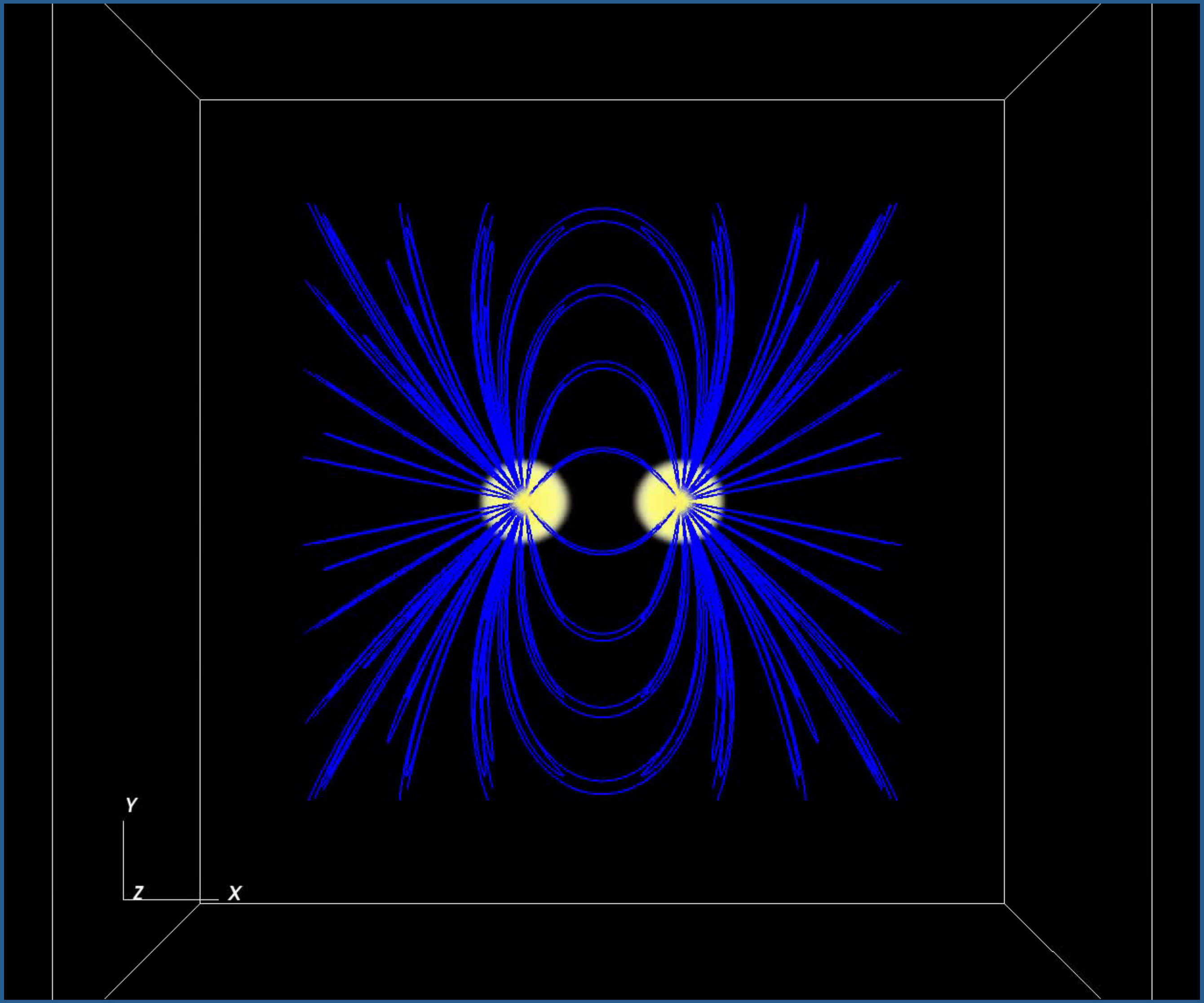
- NS isn't in vacuum. [Goldreich-Julian] Magnetosphere induced by pair creation
- Charges shorts out E.B → 'force free' condition

$$L \sim B^2\ \Omega^4\ R^6\ [1+\sin(x)^2]$$

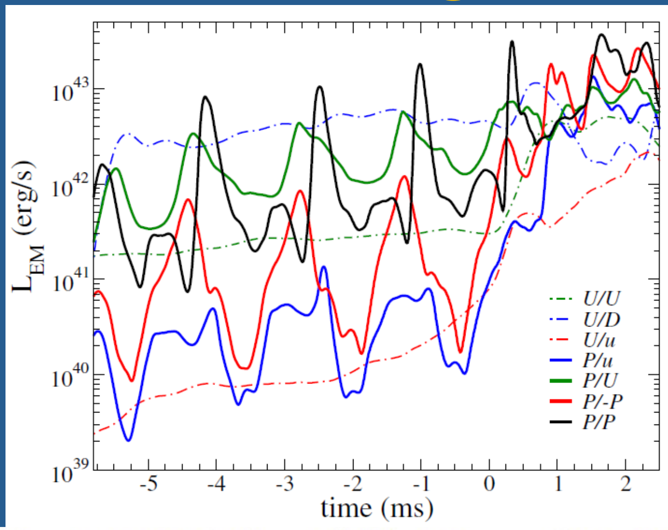
[Spitkovsky 2006]

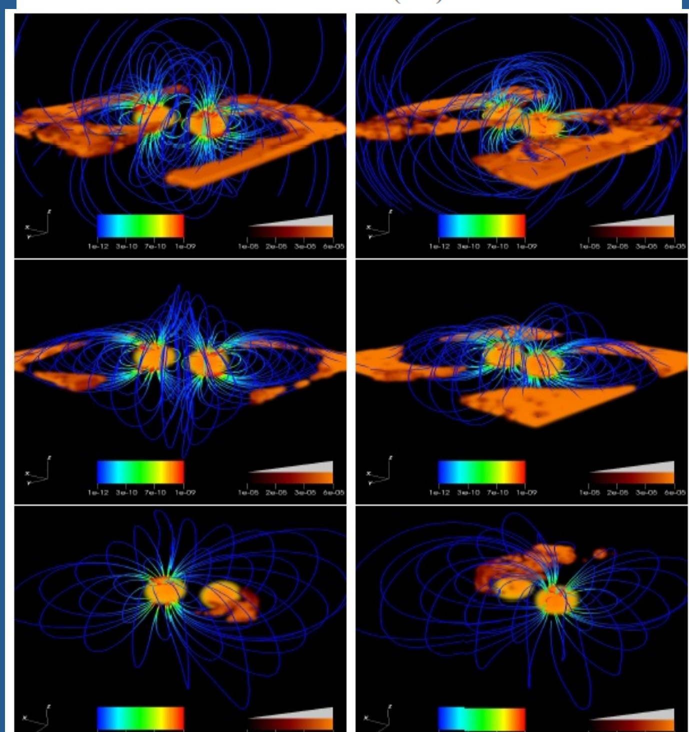
- *Gaps, current sheet : zones where particle acceleration can take place*
- Plasma arguments are 'generic' enough that should be applicable to compact binaries

spacetime rattle → Pulsar on steroids



Pre-merger: magnetosphere interactions

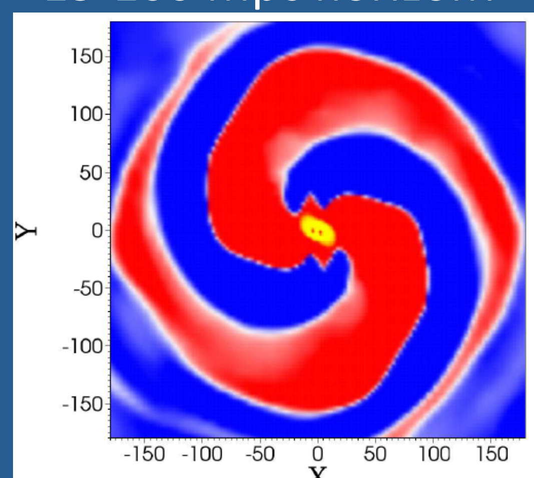


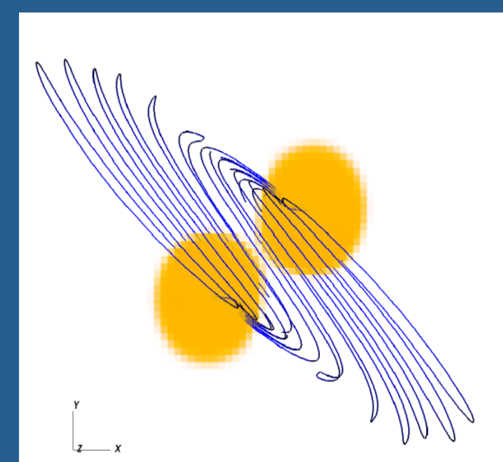


- As with pulsars, magnetosphere interactions with binaries can induce a strong Poynting flux scaling as $L \sim B^2 (1/a)^5$

- Similar structure to pulsar magnetosphere: current sheet, gaps, closed/``open'' field lines, polarity changes, etc.

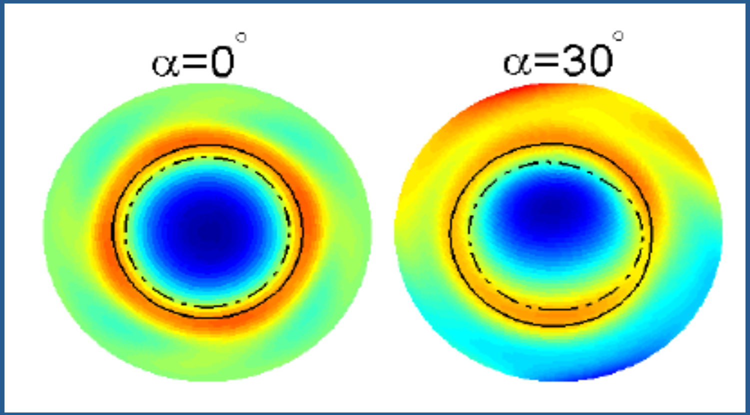
- In pulsar, radio emission poorly understood, but better handle on gamma/x-ray side. Extrapolating from current observations → 15-100 Mpc horizon?

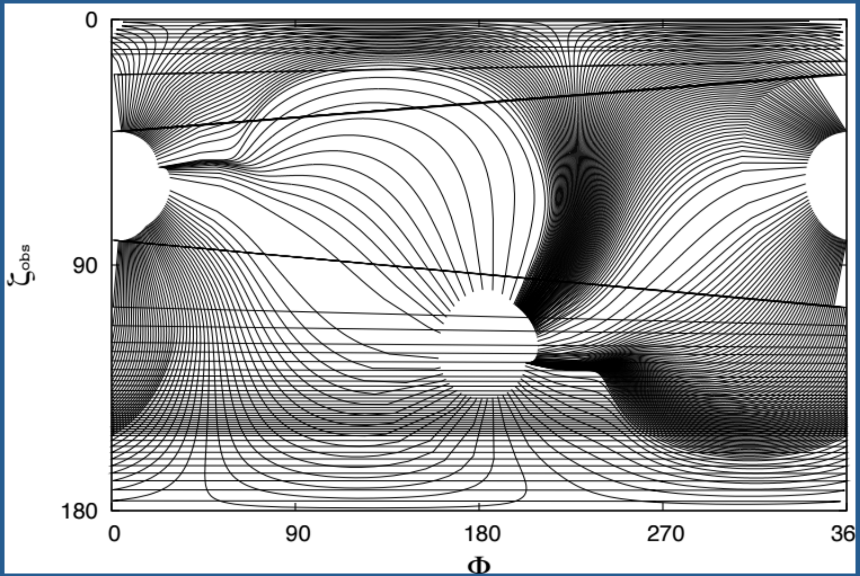


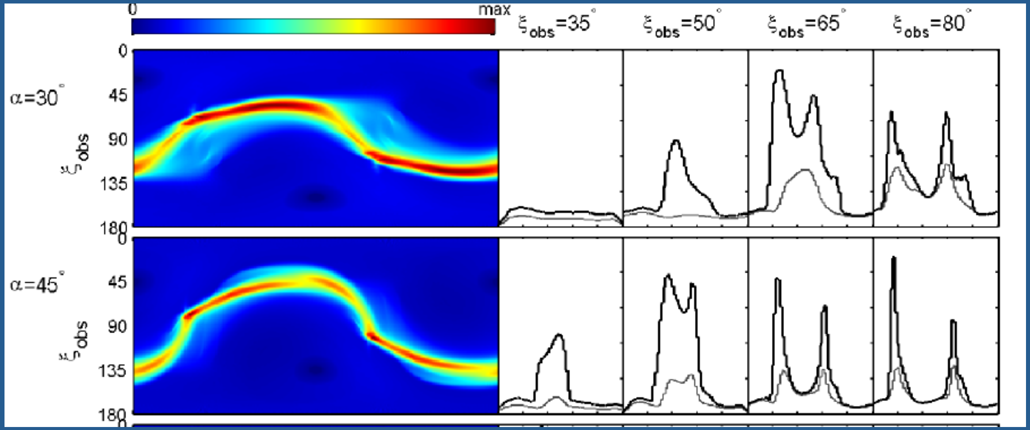


[Palenzuela,LL,Liebling,Ponce,Neilsen '14]

rather isotropic counterpart



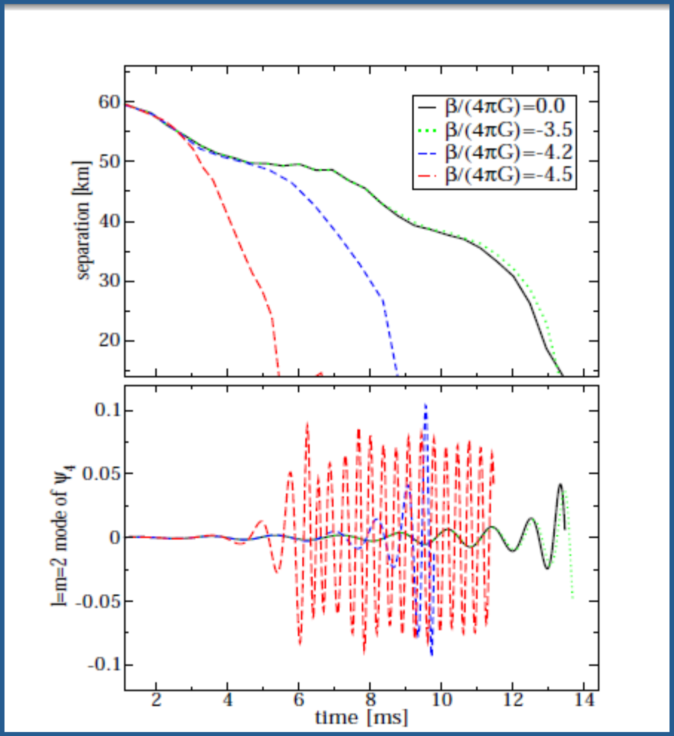




[Spitkovsky-Bai]

Added bonus (need!): what if GR is not correct? GWs might tell us so, but we might need also EM waves

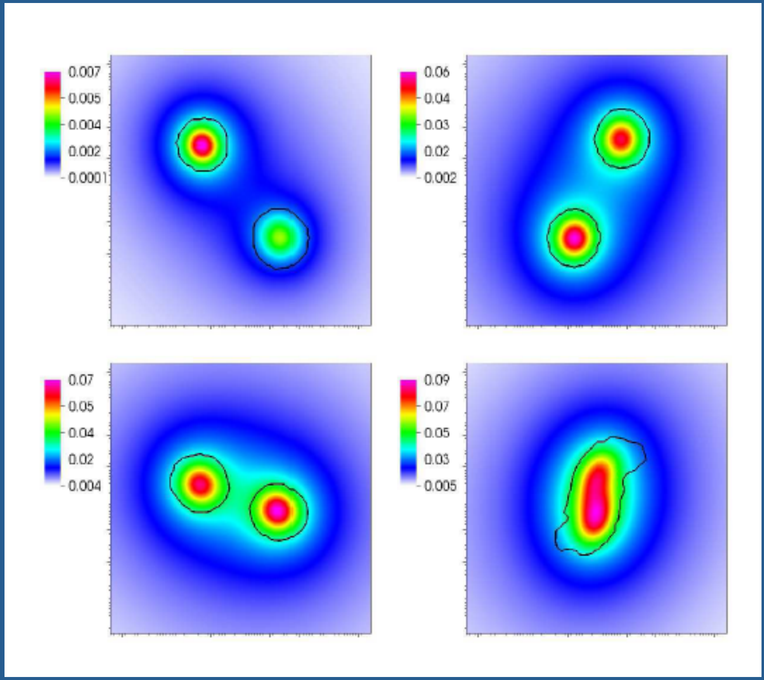
- Scalar-tensor theories [Fierz-Jordan-Brans-Dicke,Damour-Esposito-Farese,…]
  - Gravity mediated by usual tensor degrees of freedom + a non-minimally coupled scalar field
  - New phenomenology :
    - Dipole radiation
    - Spontaneous scalarization → provides a non-trivial 'scalar charge' to compact stars
    - While significantly constrained by solar and pulsar tests, interesting parameter space remains & new phenomena can arise!
    - Non-linear interactions till recently largely unexplored → more 'generic' scalarization possible (dynamical and/or induced scalarization) [Barausse,LL,Palenzuela,Ponce '14]



- Dipole radiation modifies dynamical behavior.
- Important deviations from GR behavior (eg separation and grav wave signals) which *might not be easily identified by current detectors*
- Furthermore, non-monotonic behavior of corrections (implications for, e.g. PPE)

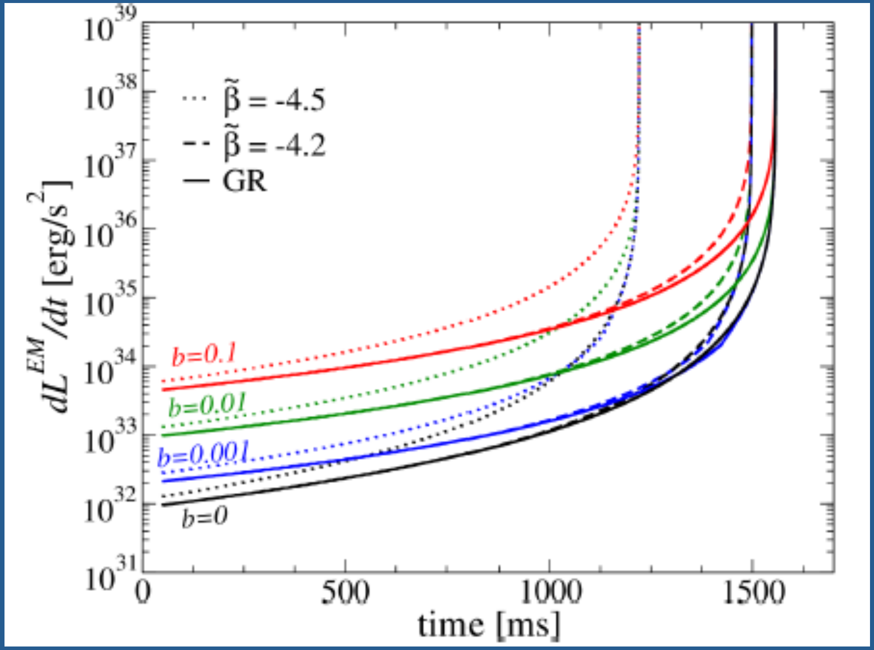
-Pheno: Interaction between differently scalarized stars induces a dynamical readjustment of charges to become equal

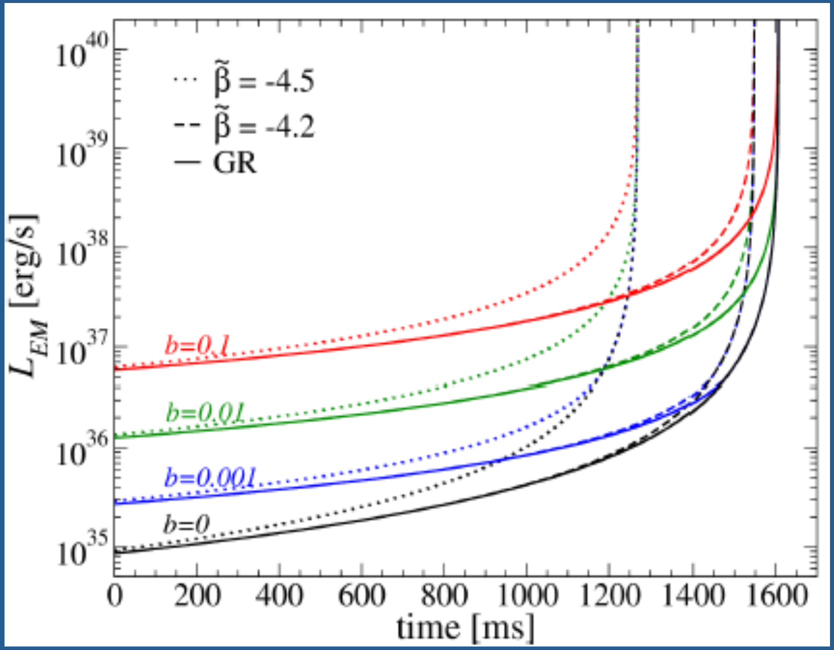
- ALIGO will have a hard time digging this out for moderate and low mass binaries
- EM signals can potentially save the day



[Barausse,Palenzuela,Ponce,LL 2013; Sampson etal 2014, also Shibata,Taniguichi, Okawa, Buonanno ‘14]

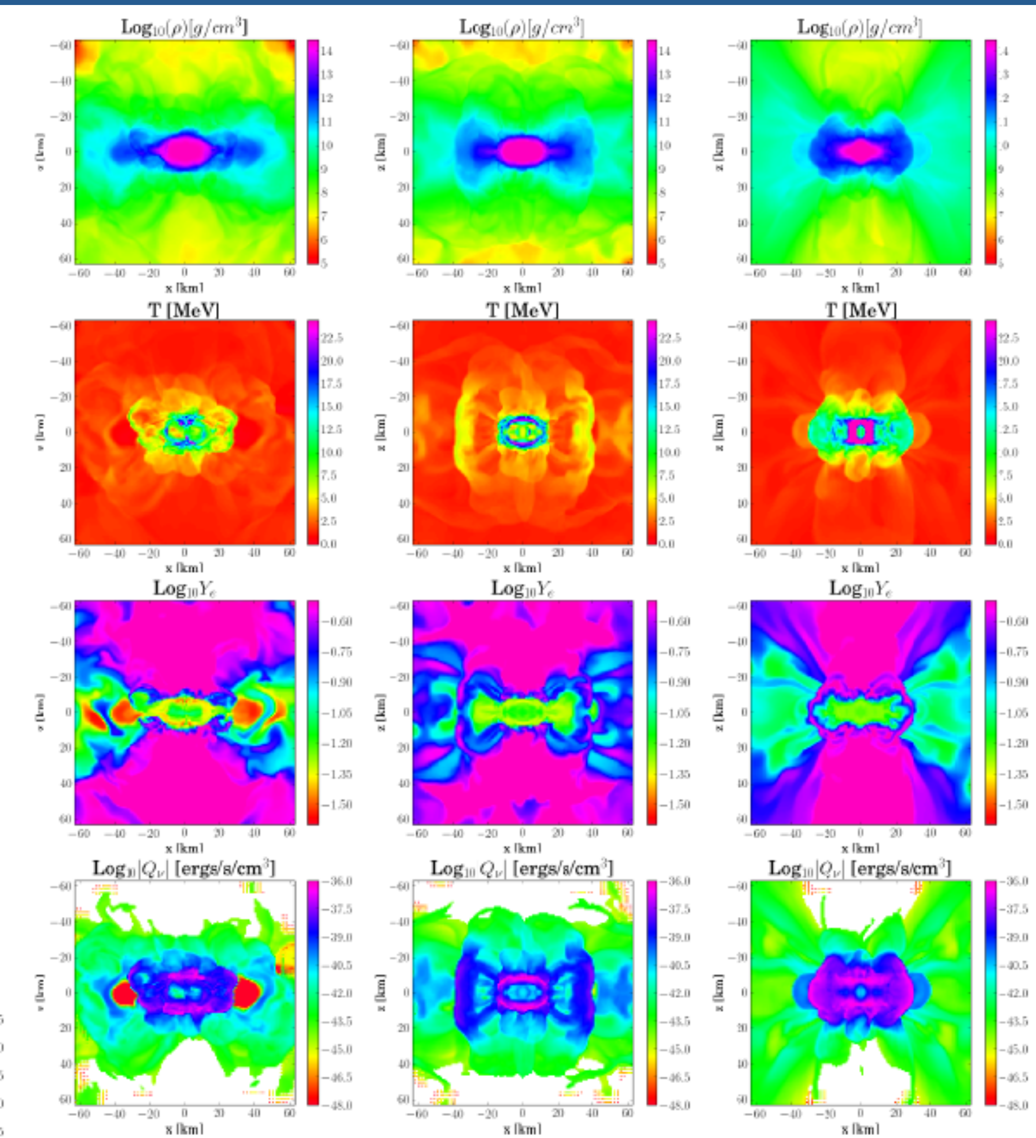
EM signals can potentially save the day

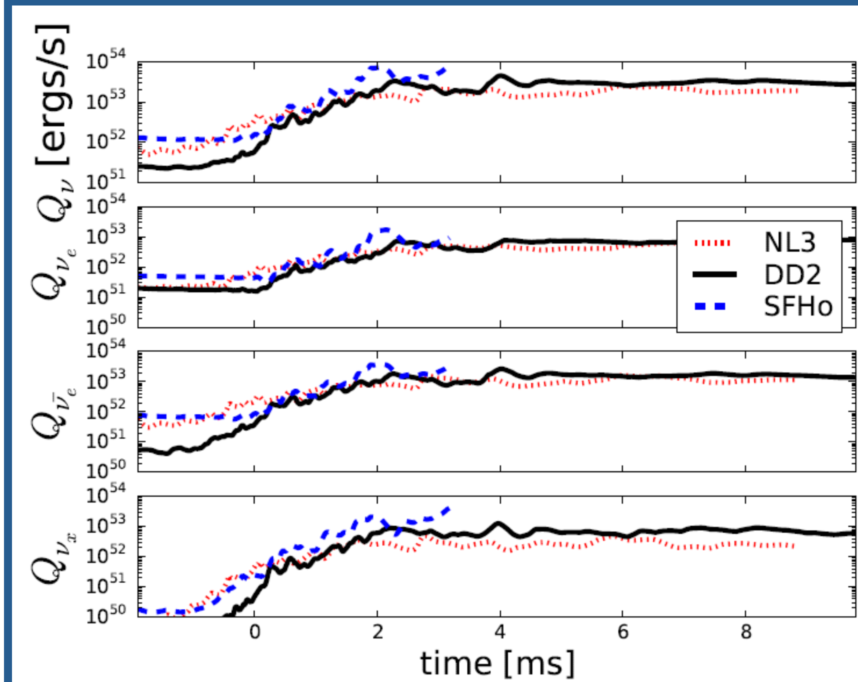




- Luminosity 'sweep-up' in frequency will be different from that of GR
- 'pulsar' observations allow (indirect) grav wave detection to continue

Fast-forward and outwards…



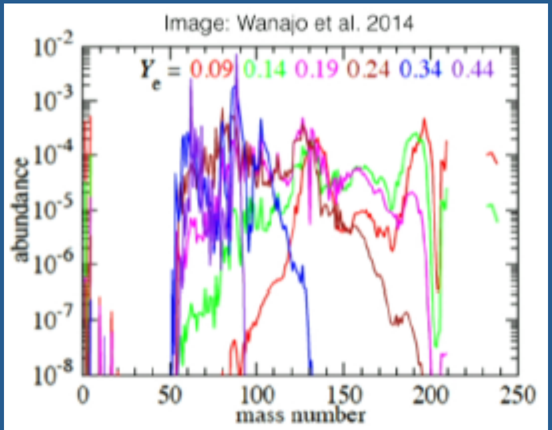


- Neutrino characteristics are similar across al EOS, but ejecta properties are *quite different*

Ejecta & possible associated emission

- Ejecta leaves the cental engine, is neutron rich → neutron capture yields radioactive elements which would decay and yield a rather isotropic signal.
- Result of nucleosynthesis depends on: velocity, amount and electron fraction (Y_e) of ejected material
  - Sufficiently small Y_e (< 0.2) strong r-processes, yields heavier nuclei (lantanides). Higher optical depth → week delay and IR counterpart.

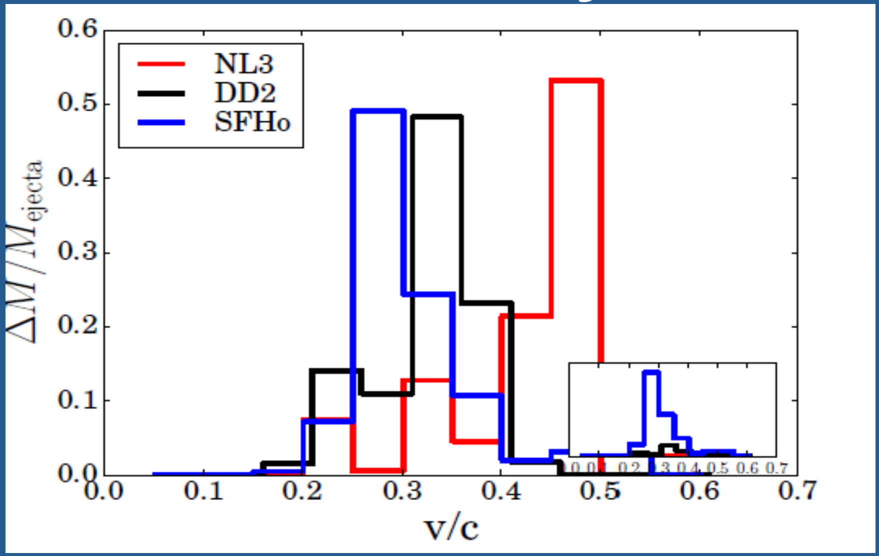
  Otherwise lighter nuclei, day delay & optical counter.

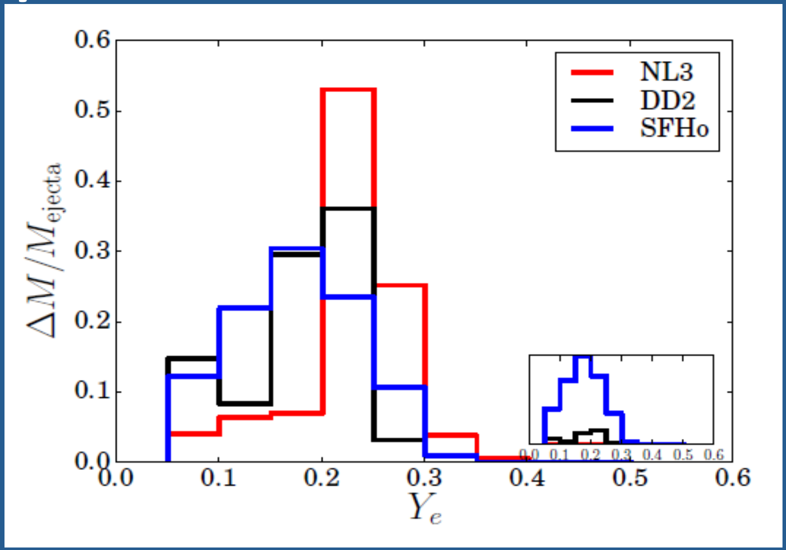


NS-NS (equal mass) mergers → large range of Y_e and temperatures, rather isotropical, but amount highly dependent on EOS (softer EOS, higher mass) [Hotokezaka etal, Palenzuela etal]. Unequal mass case more similar amount

BH-NS (if disrupted). Low Y_e , low temperatures, equatorial/axisymmetric distribution. [Foucart etal]

Ejecta & properties





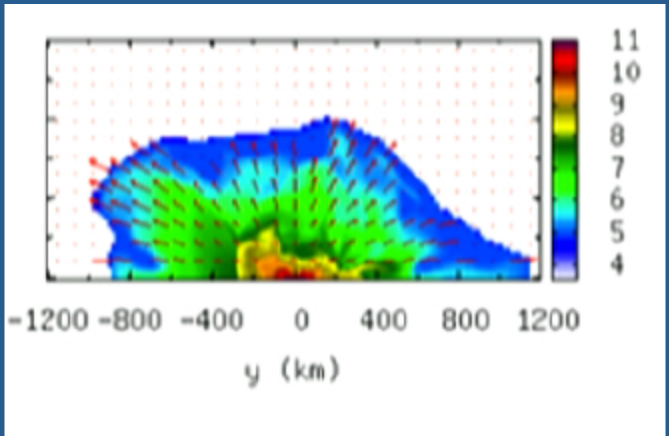


Image: Hotokezaka et al 2013

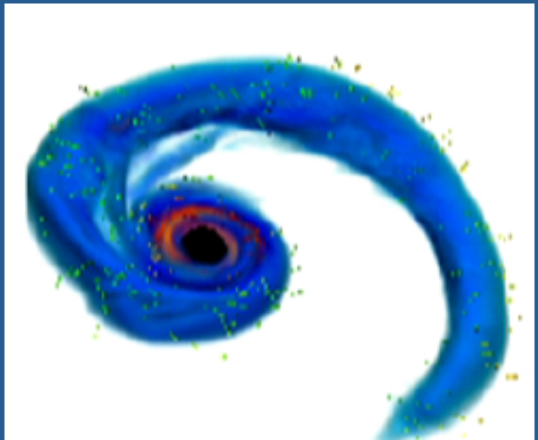


Image: Foucart et al 2015

- 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.

Summarizing results

- Amount & characteristics of ejecta quite tied to EoS.
  - Very little < 0.001 M_o for stiff EoS, velocity of ejecta ~ similar [0.1 – 0.4c] & Y_e quite peaked at ~ 0.2
  - On the other hand, enough [0.001-0.01 M_o] for soft EoS [collision takes place deeper in the potential]. Y_e peaked at ~ 0.2 with significant amounts in [0.1-0.2]

  - Supernovae simulations do not seem to get Y_e this low. Also, abundance of ^{244}Pu in deep-sea samples is 1/100 of what would be expected if supernovae does the job but consistent with binary merger rates [Wallner etal '15]

Speculations

- IF GRB130603B is a `typical case', and decay of r-processes elements indicate very neutron rich ejecta, then if produced by nearly equall neutron stars → EoS lies on the softer side [way out: low mass BHs and/or very high spins]
- Alternatively, it could be produced by a BH-NS system with low mass ratio and/or high spin. Further, this scenario favors stiff EoS.

→ A GW measurement would give masses (see however [Hannam,Brown etal '13] which will help dissentangle which system it is and provide arguments for the EoS (even if not identified in the GW side)

Final words

- Experimental front going strong, lots of activities and plans for the future
- Global efforts towards multimessenger astronomy
- Counterparts provide significant information, which might be required even to answer the most basic questions