Resonant Shattering Flares:
Multimessenger Probes of Neutron Star Physics

David Tsang
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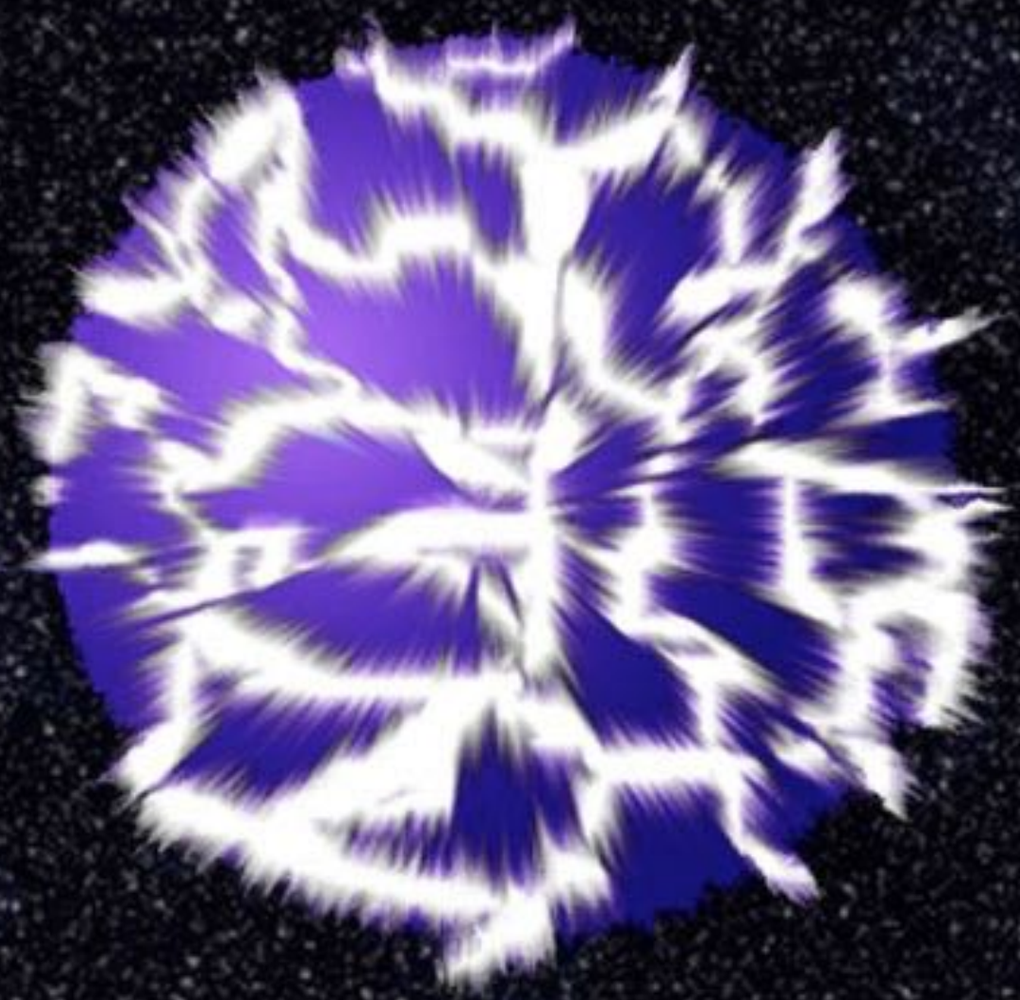


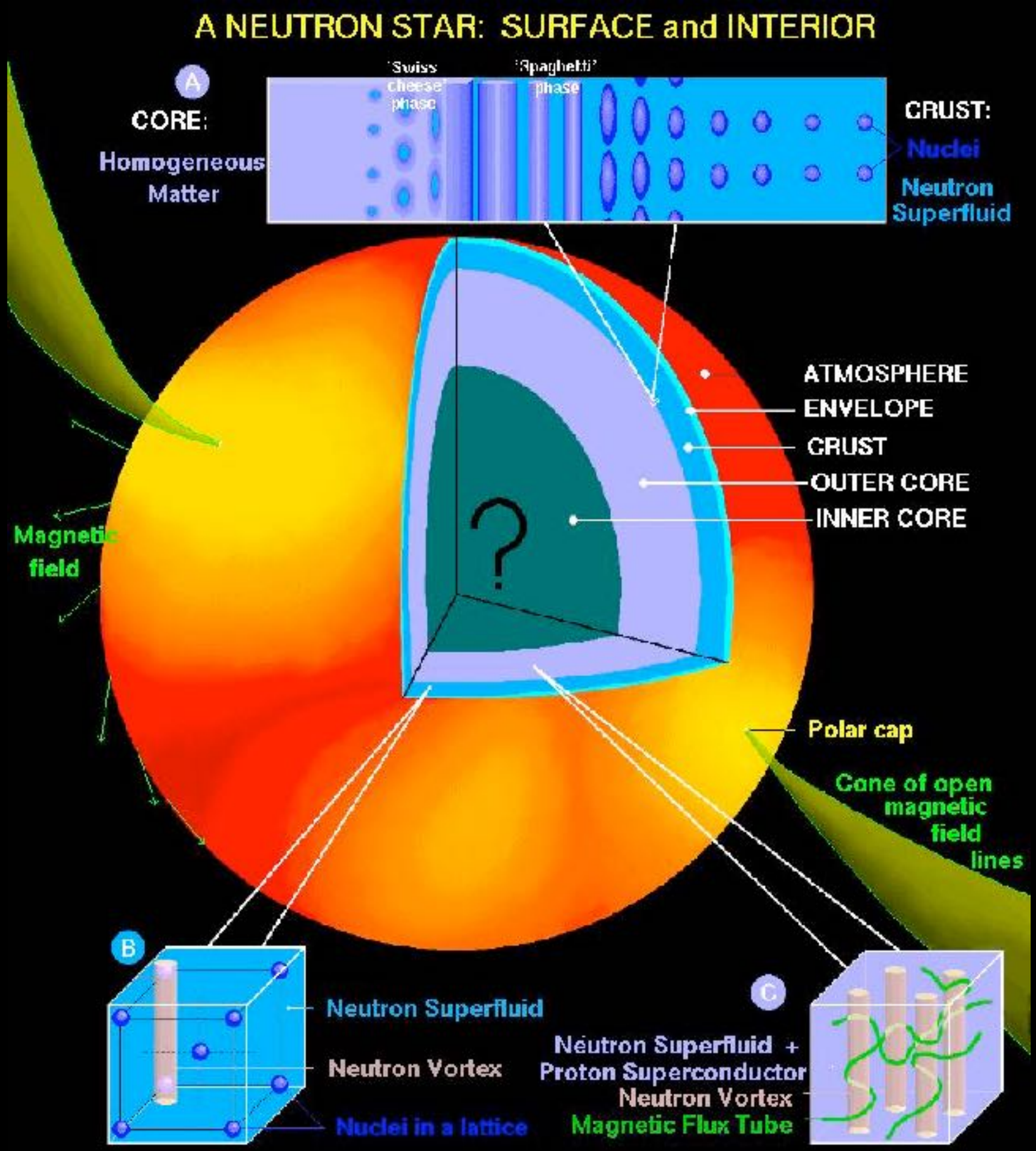
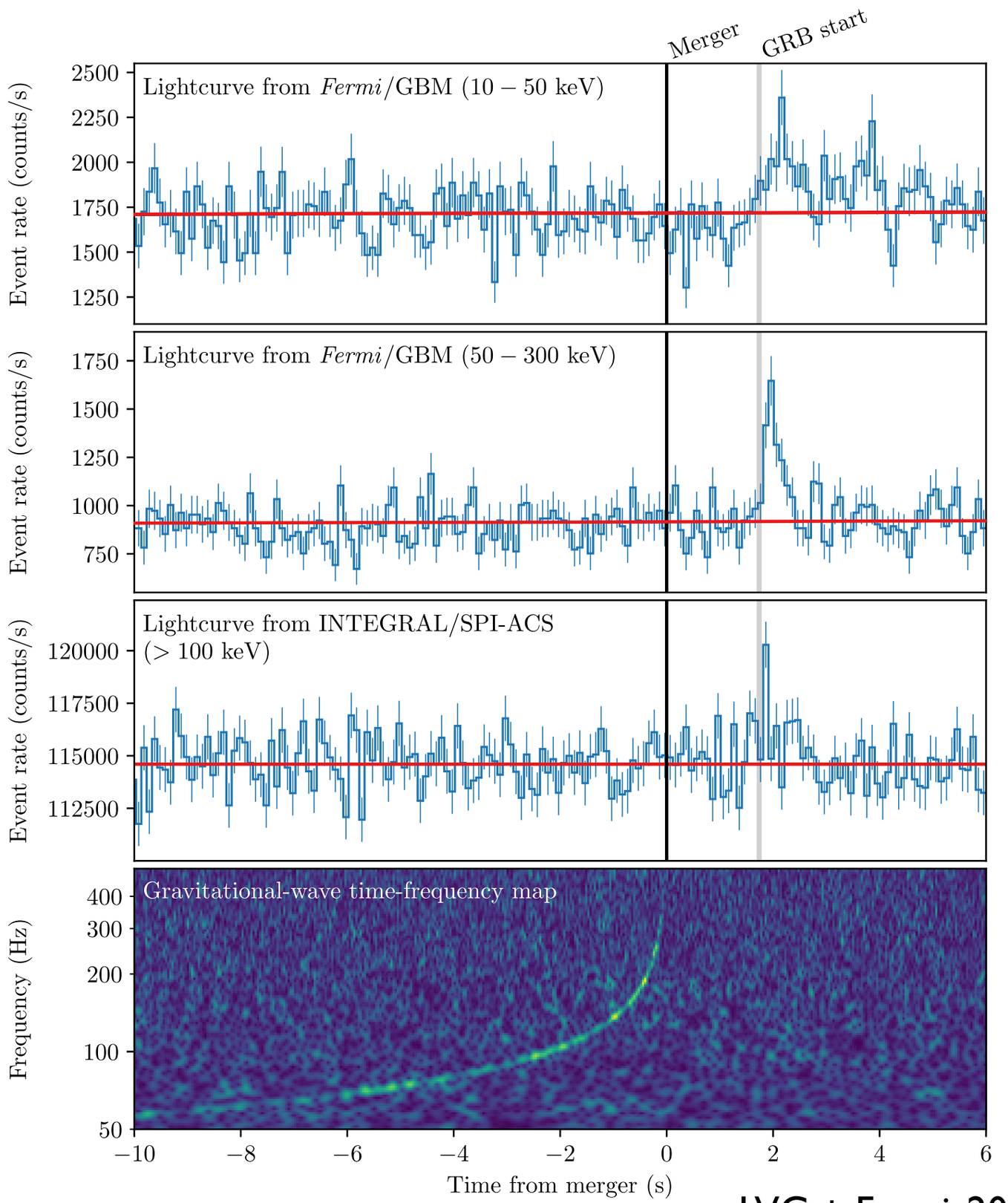


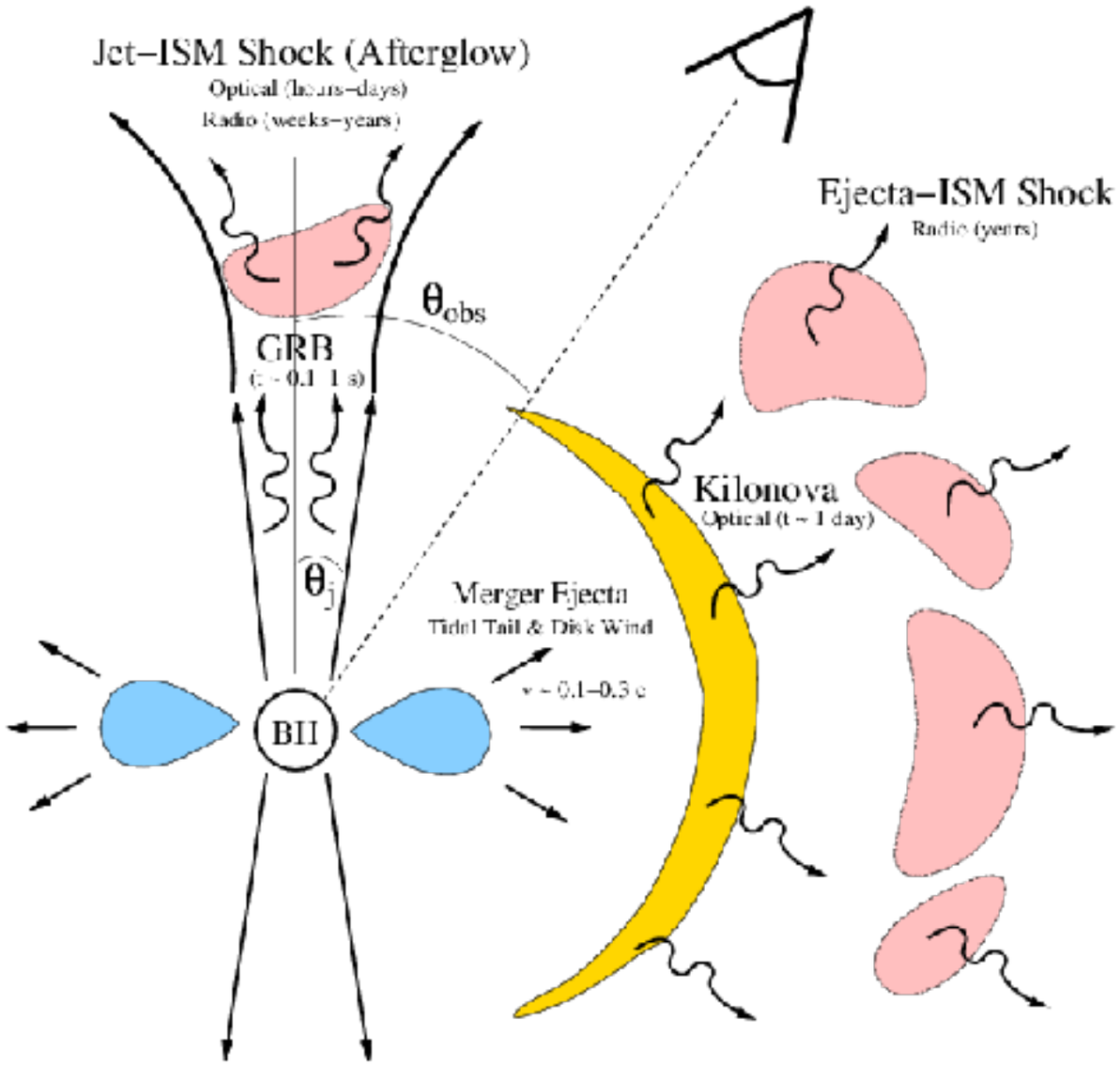
Image due to Dany Page

The Era of GW/EM Astronomy

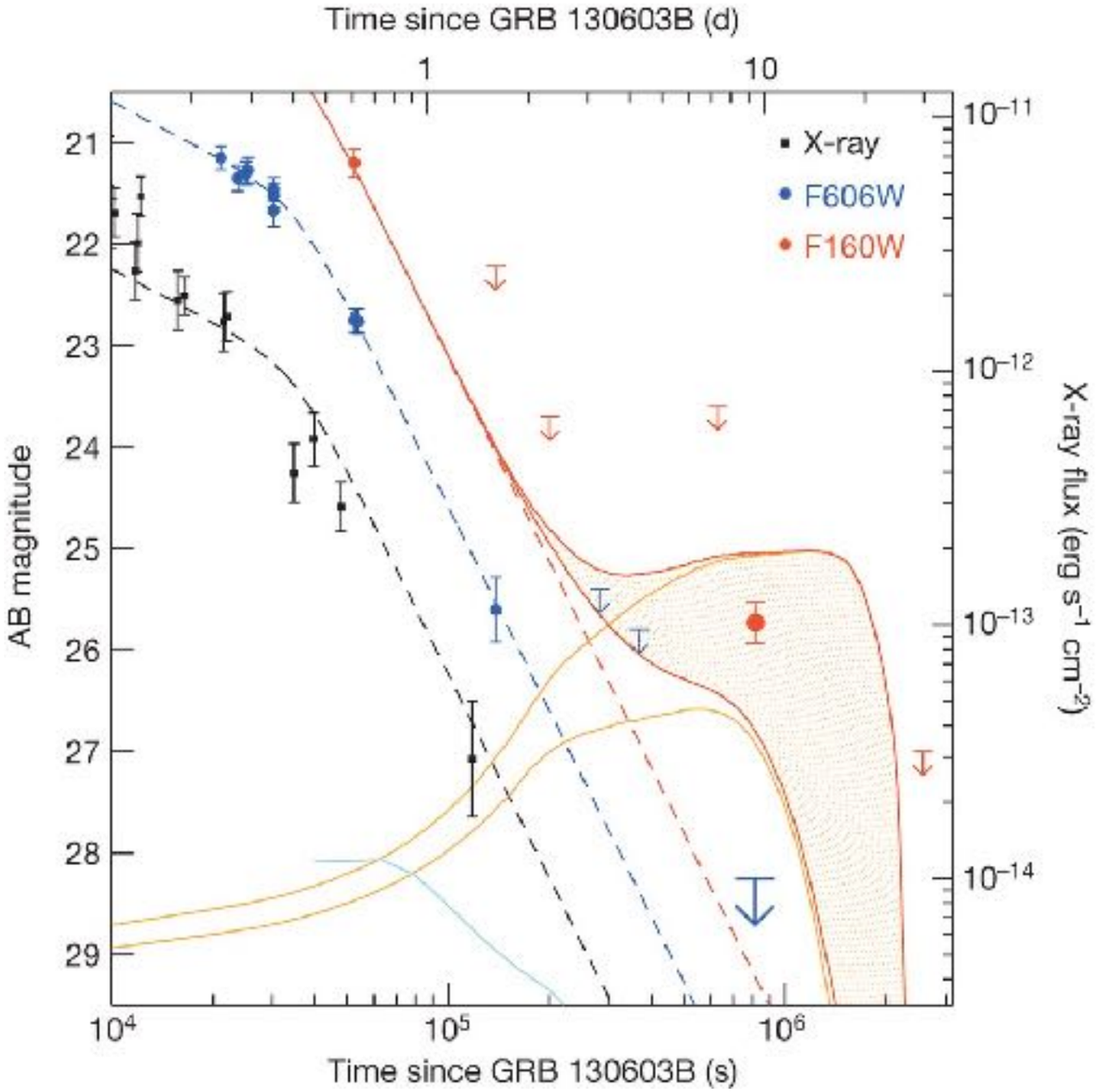


LVC + Fermi, 2017

Electromagnetic Counterparts: Kilonovae



Metzger & Berger (2011)



Tanvir et al. (2013)

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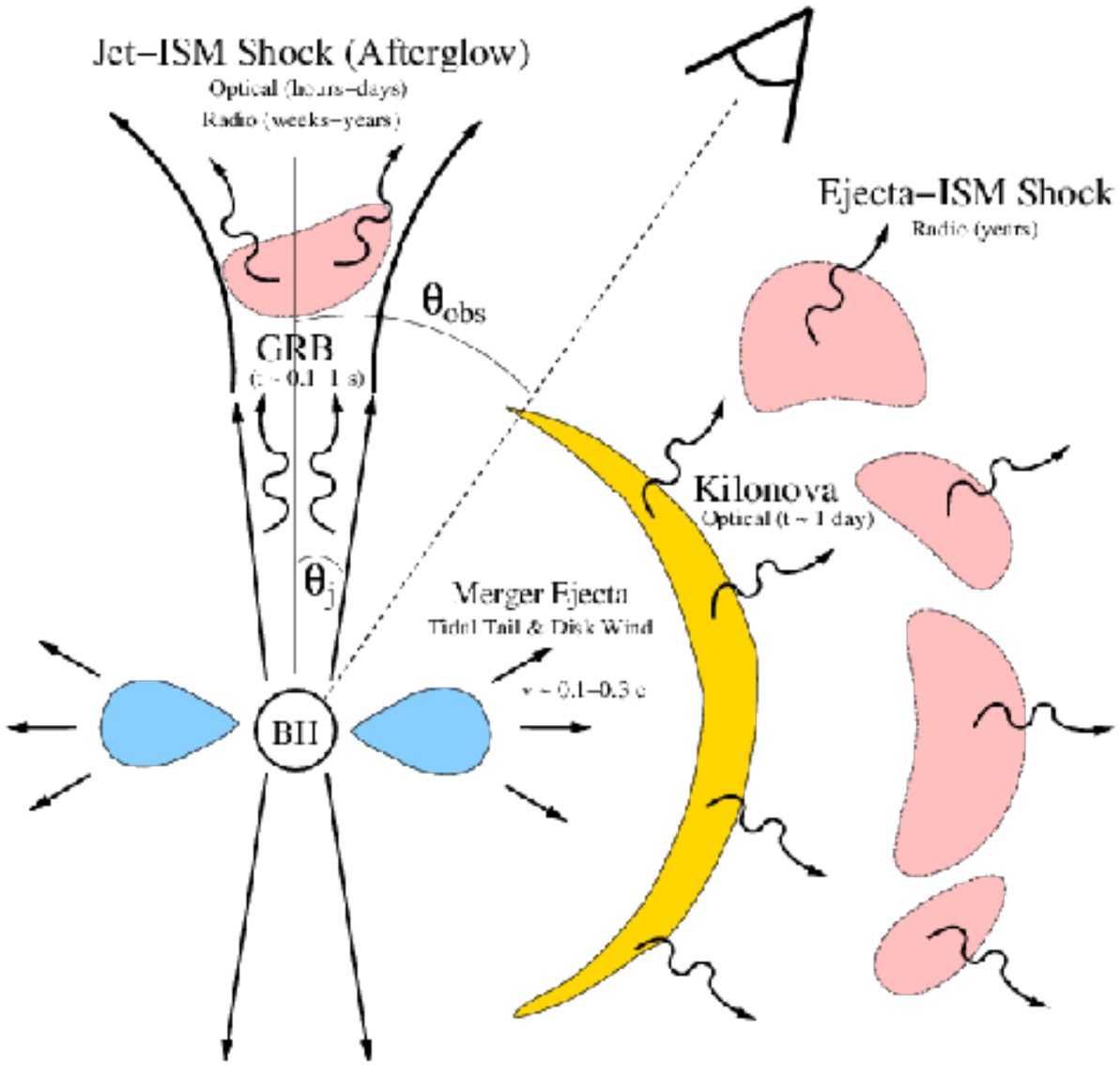

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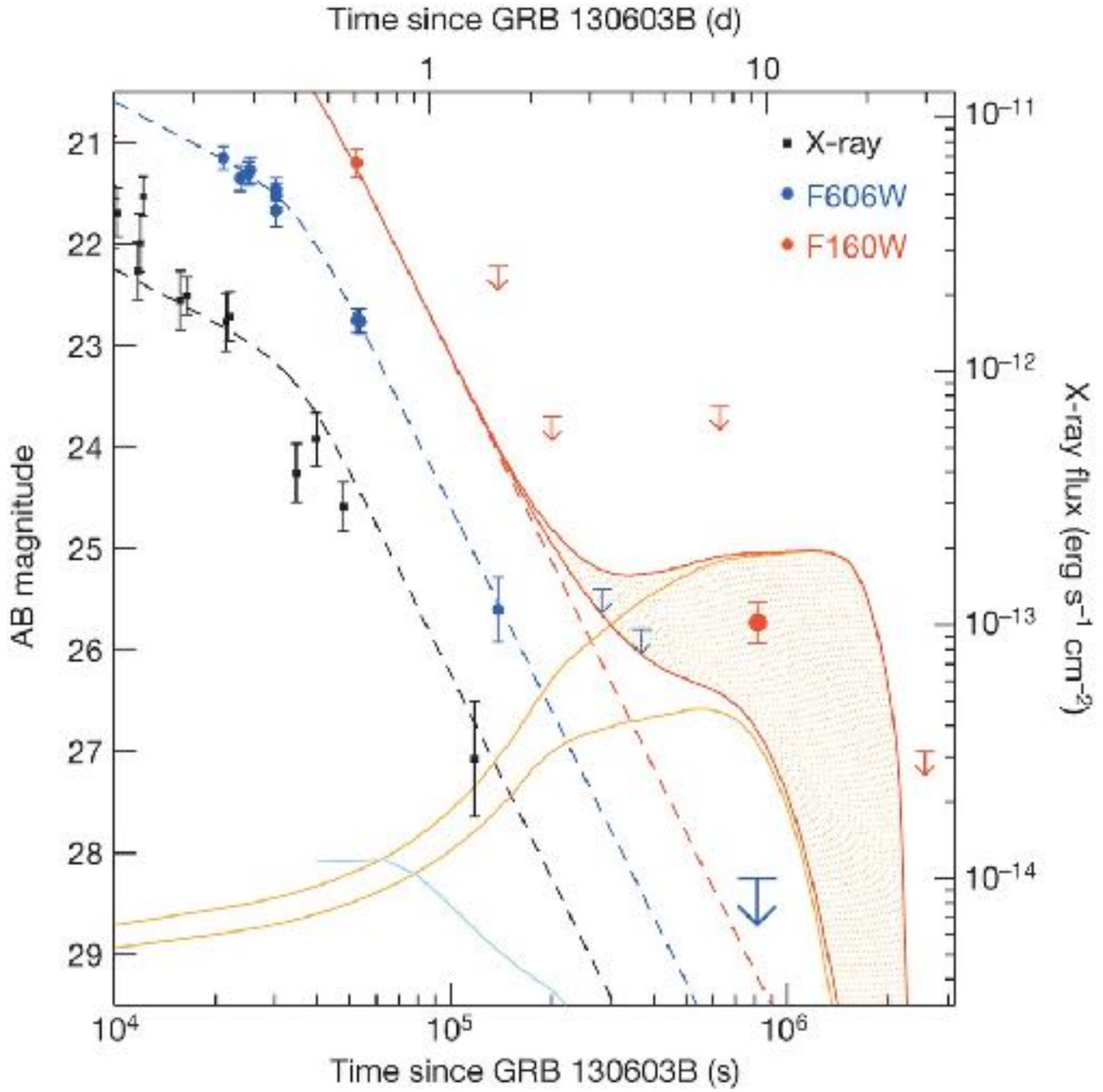
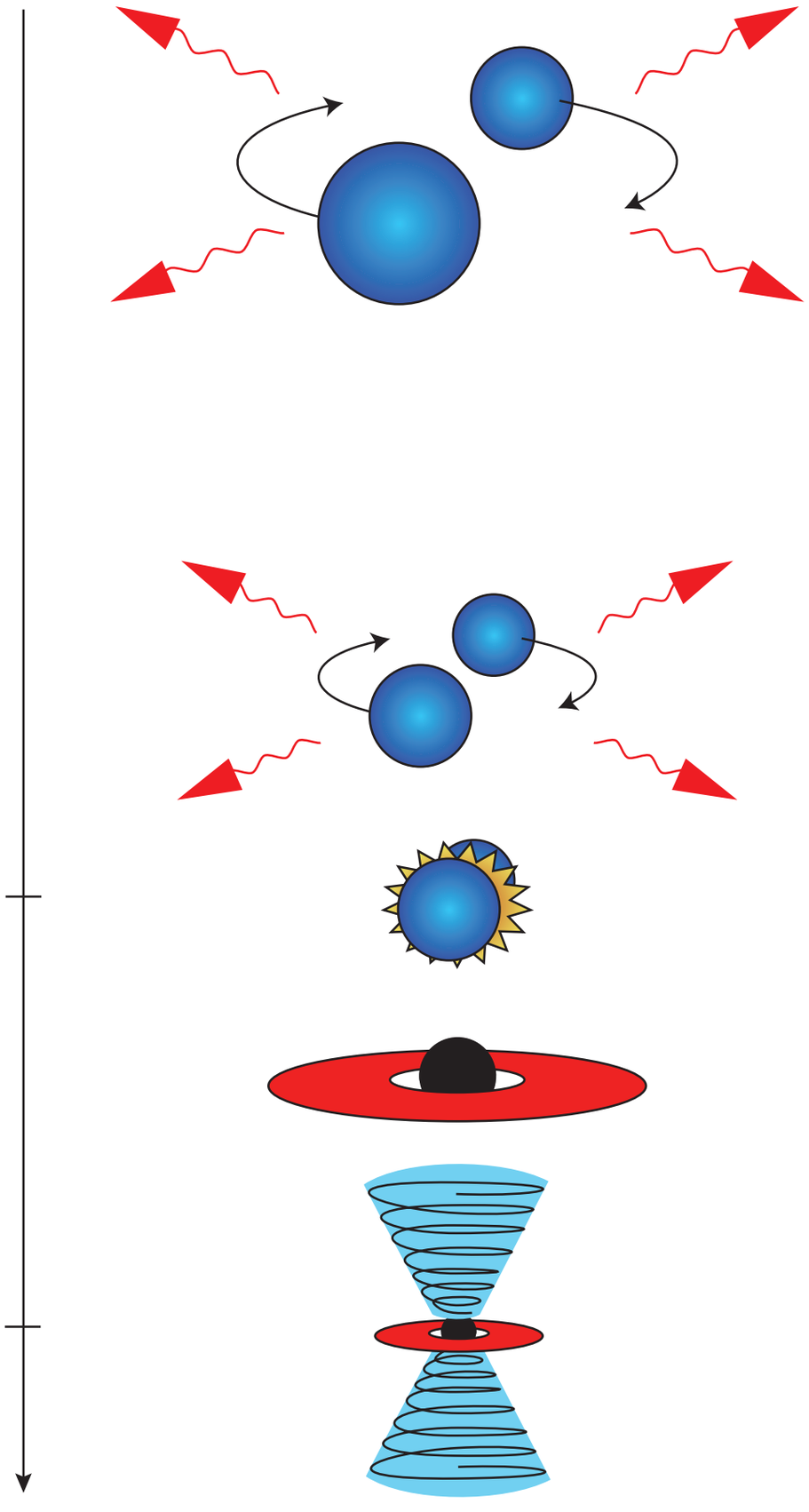
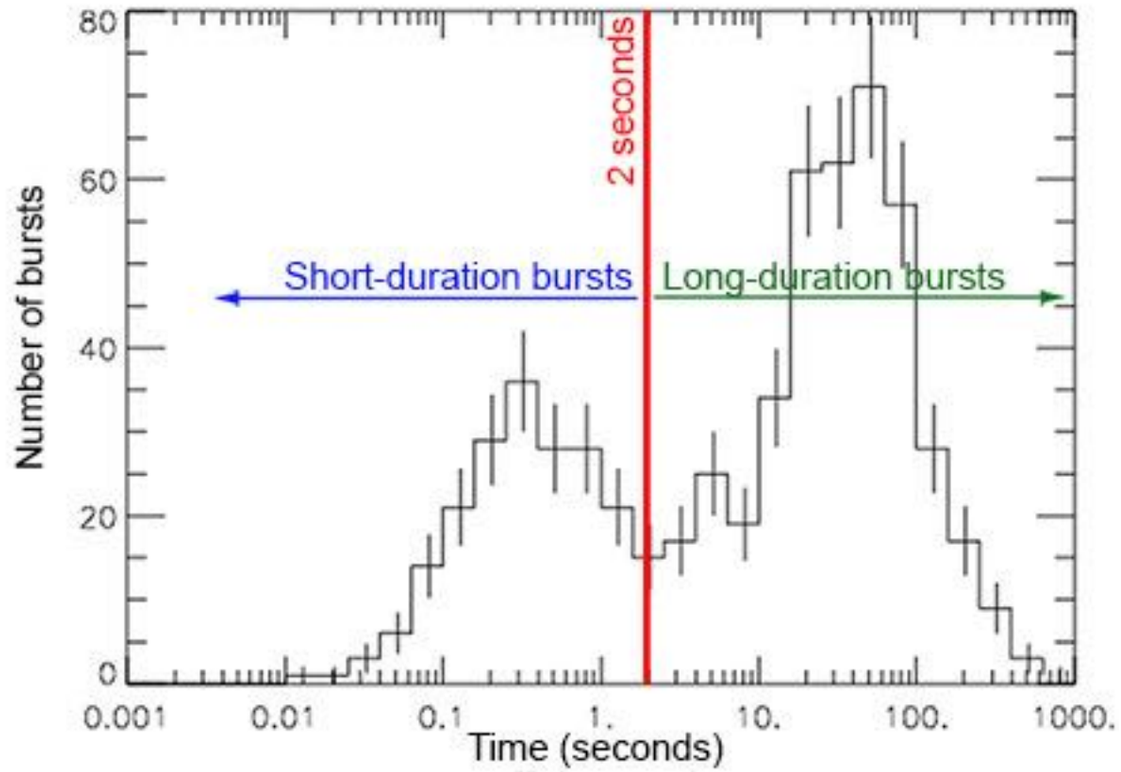


Tanvir et al. (2013)

…opacity of r-process material depends on Y_e (see Barnes & Kasen 2013, Fontes et al 2017)

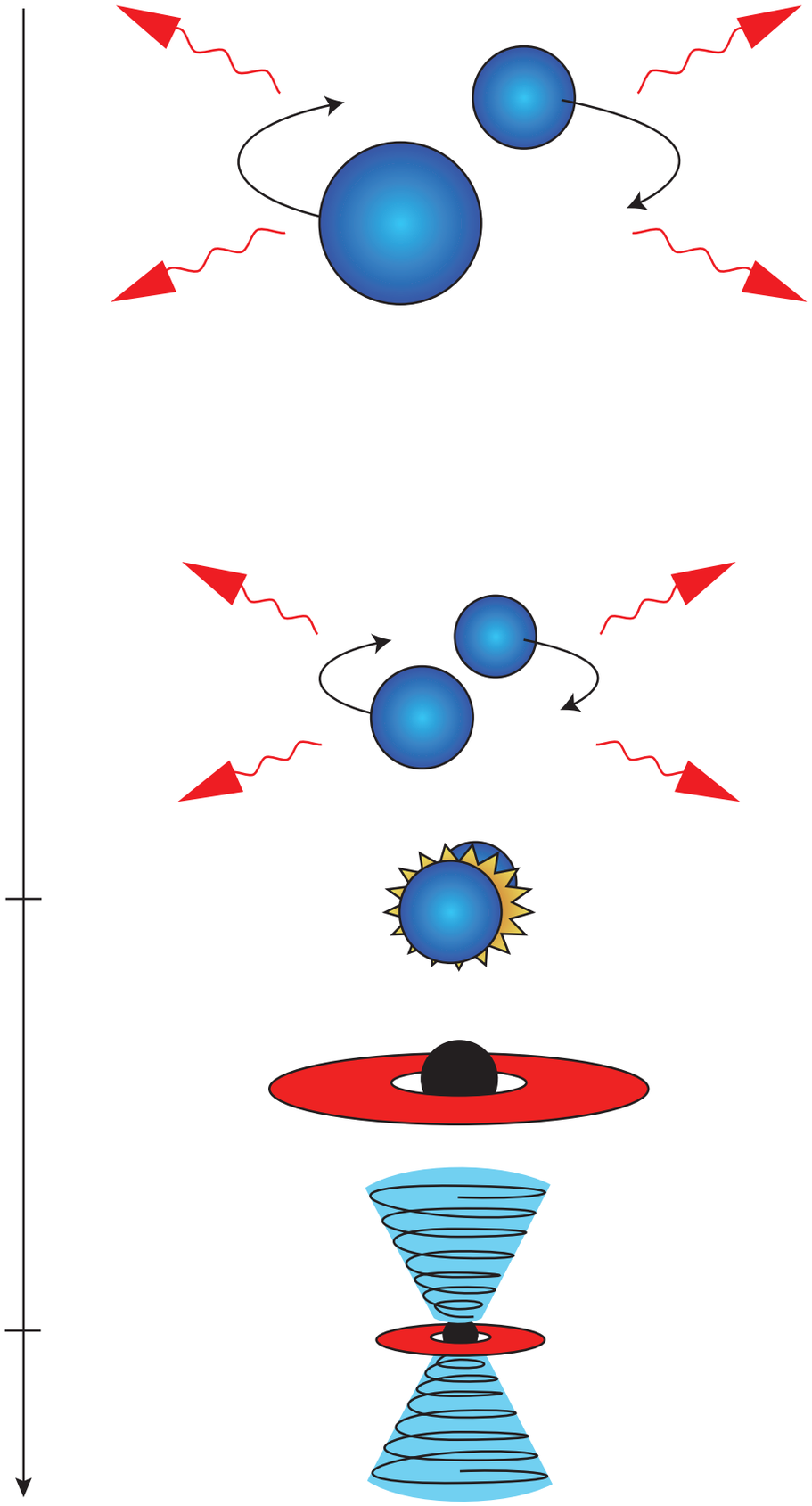
Electromagnetic Counterparts: Short Gamma Ray Bursts

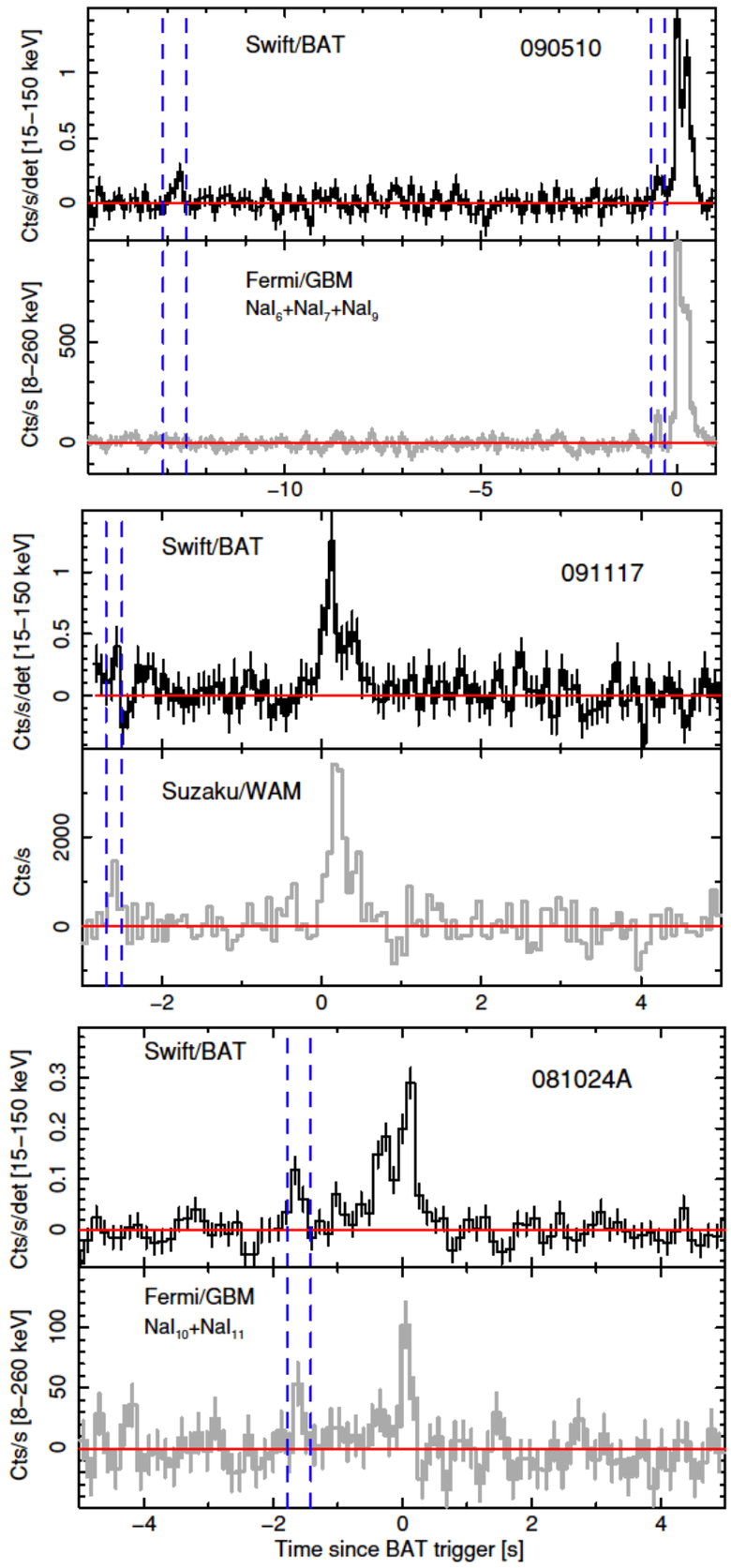




- Strongly beamed emission (~10^{o}-20^{o} opening angle?)
- Only ~1% of SGRBs beamed towards Earth! (up to ~10% of GW detections at larger distances due to GW inclination)

Some SGRBs have precursors…





Troja et al. ApJ, 723, 1711 (2010)

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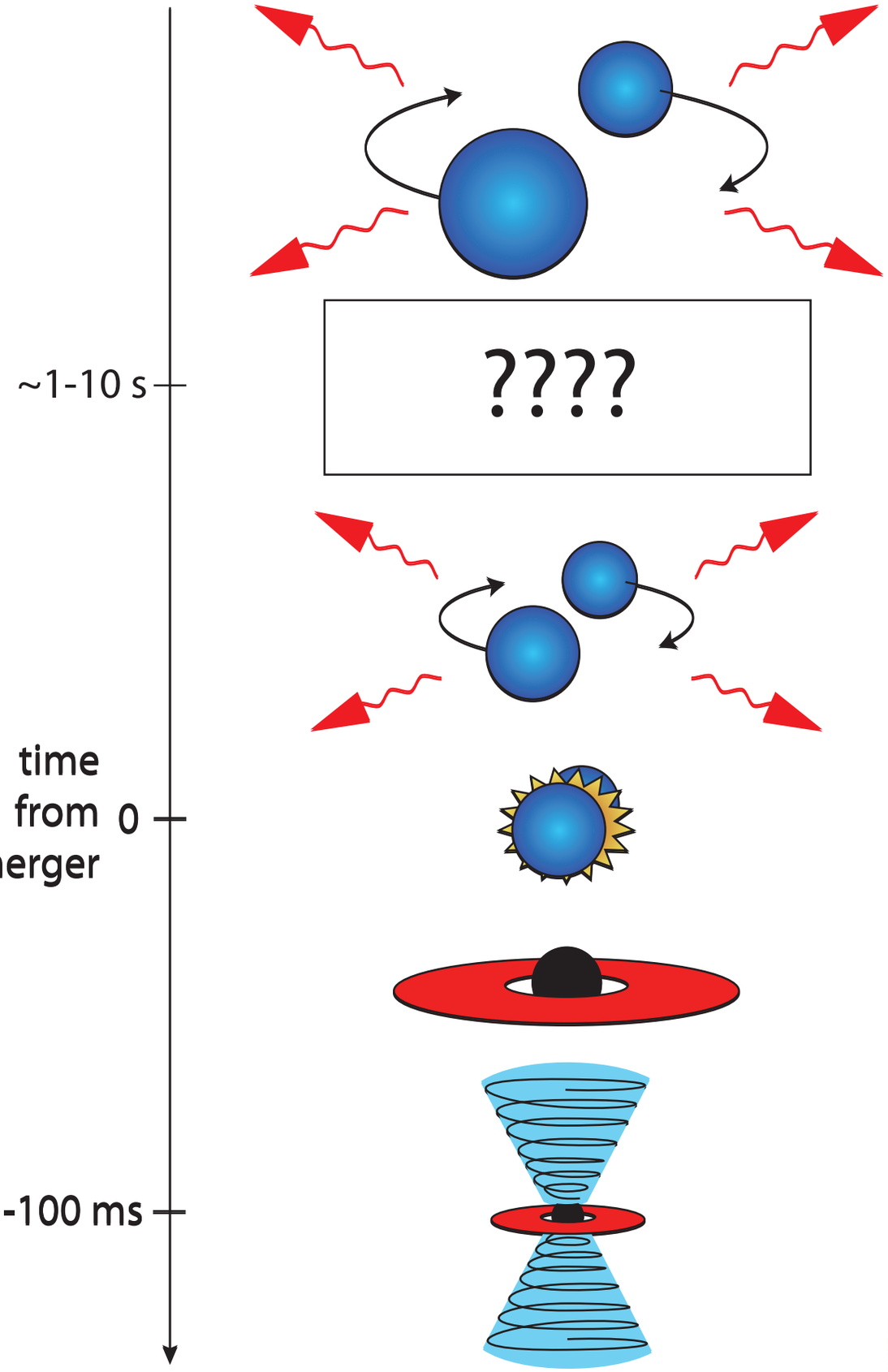

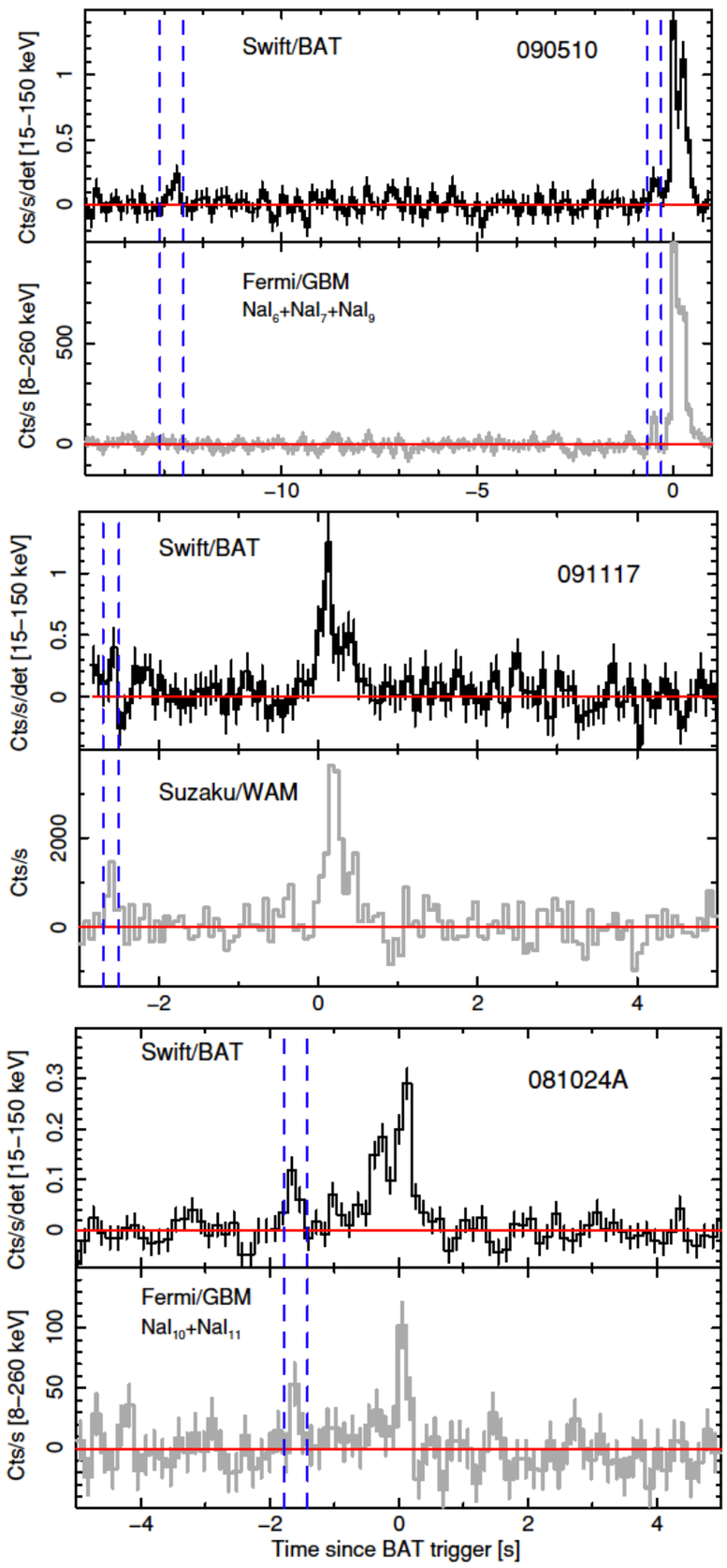

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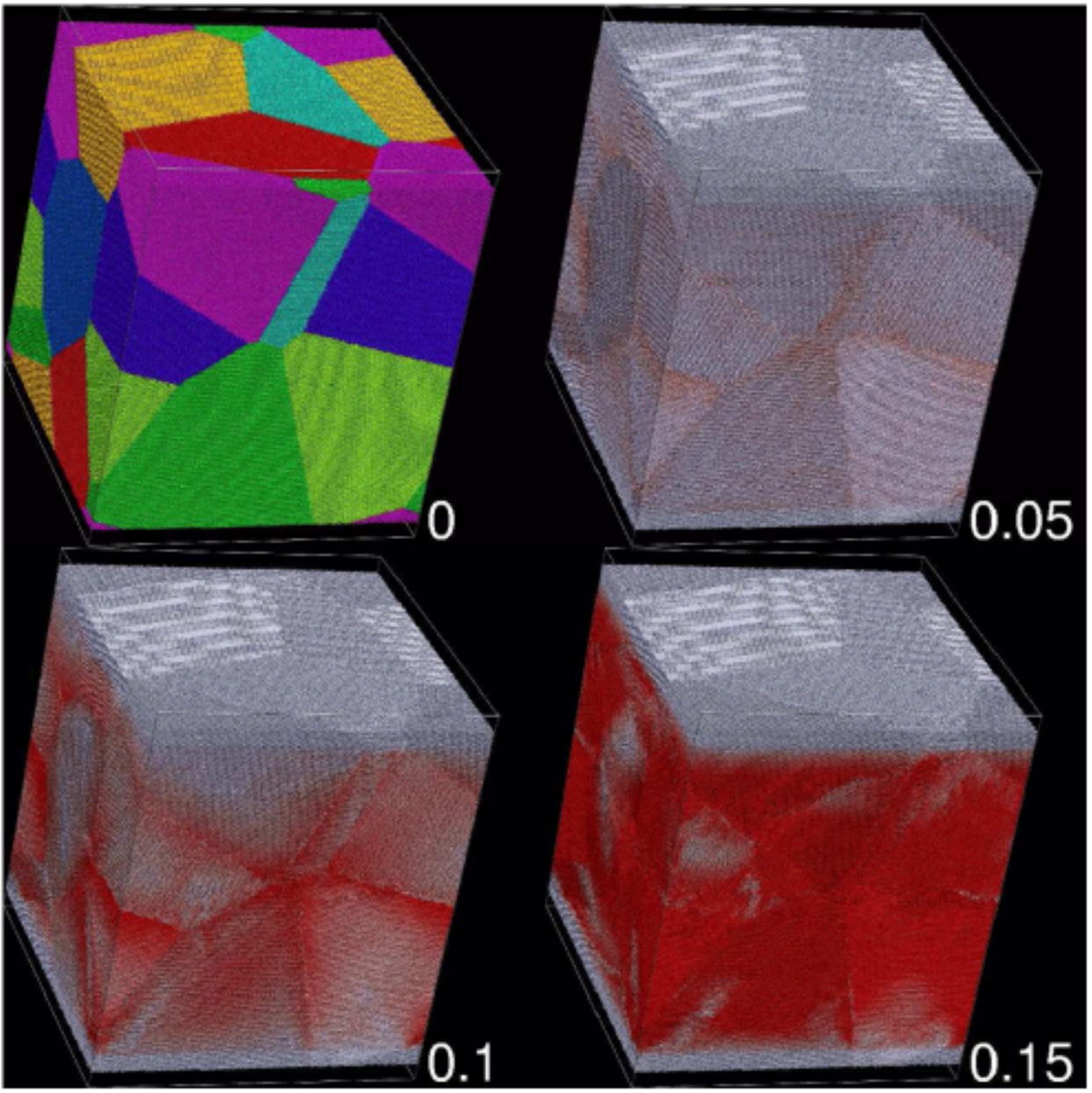
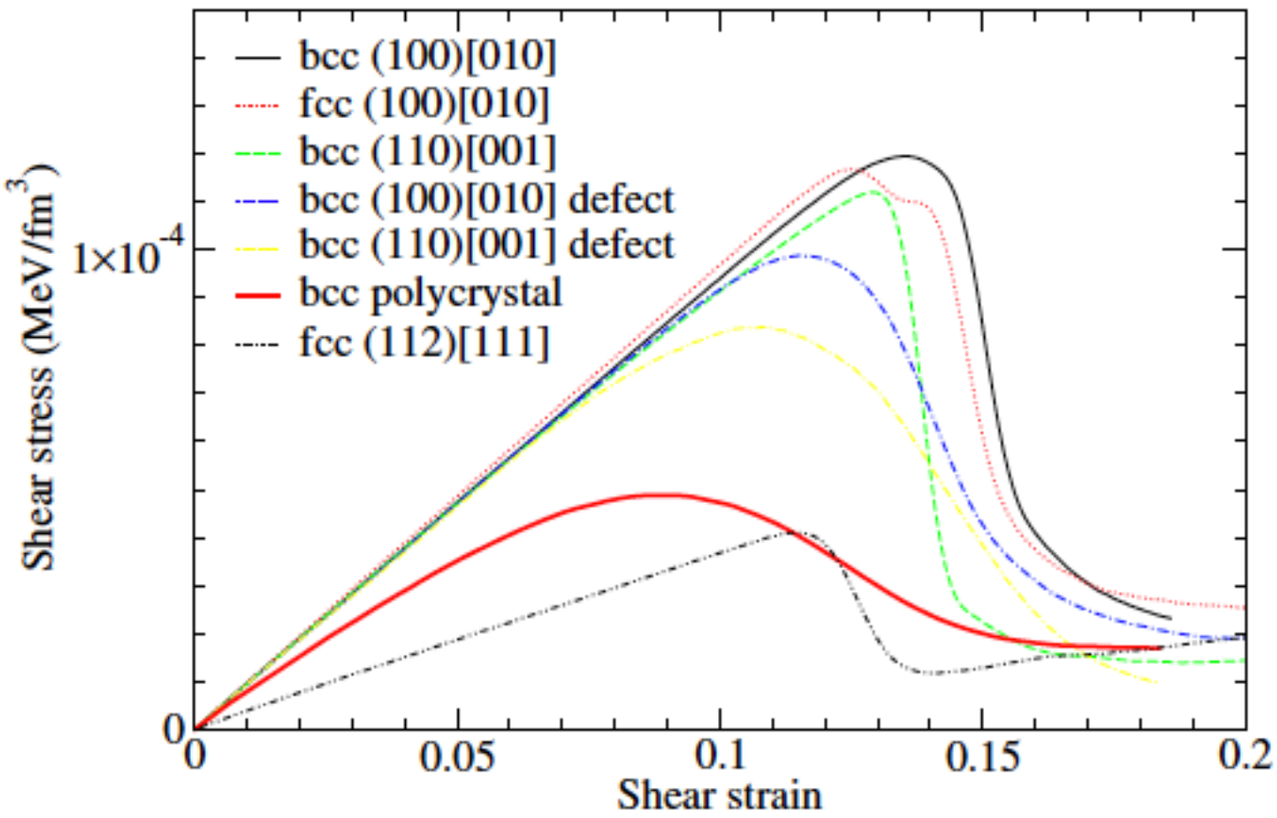
Direct Tidal Crust Cracking?





Horowitz & Kadau (2009), PRL, 102, 191102

For tidal crust cracking we need $\delta R/R \simeq \epsilon_{\rm break} \sim 0.1$

Direct crust cracking doesn't happen until just before merger (if at all). What else?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Tidal Resonance

- Tidal Resonance can transfer huge amounts of energy from orbit to modes
- Need a mode that:
  - strains the crust
  - couples to the tidal field (l=2, spheroidal)
  - hits a resonance well before merger (f < 1 kHz)

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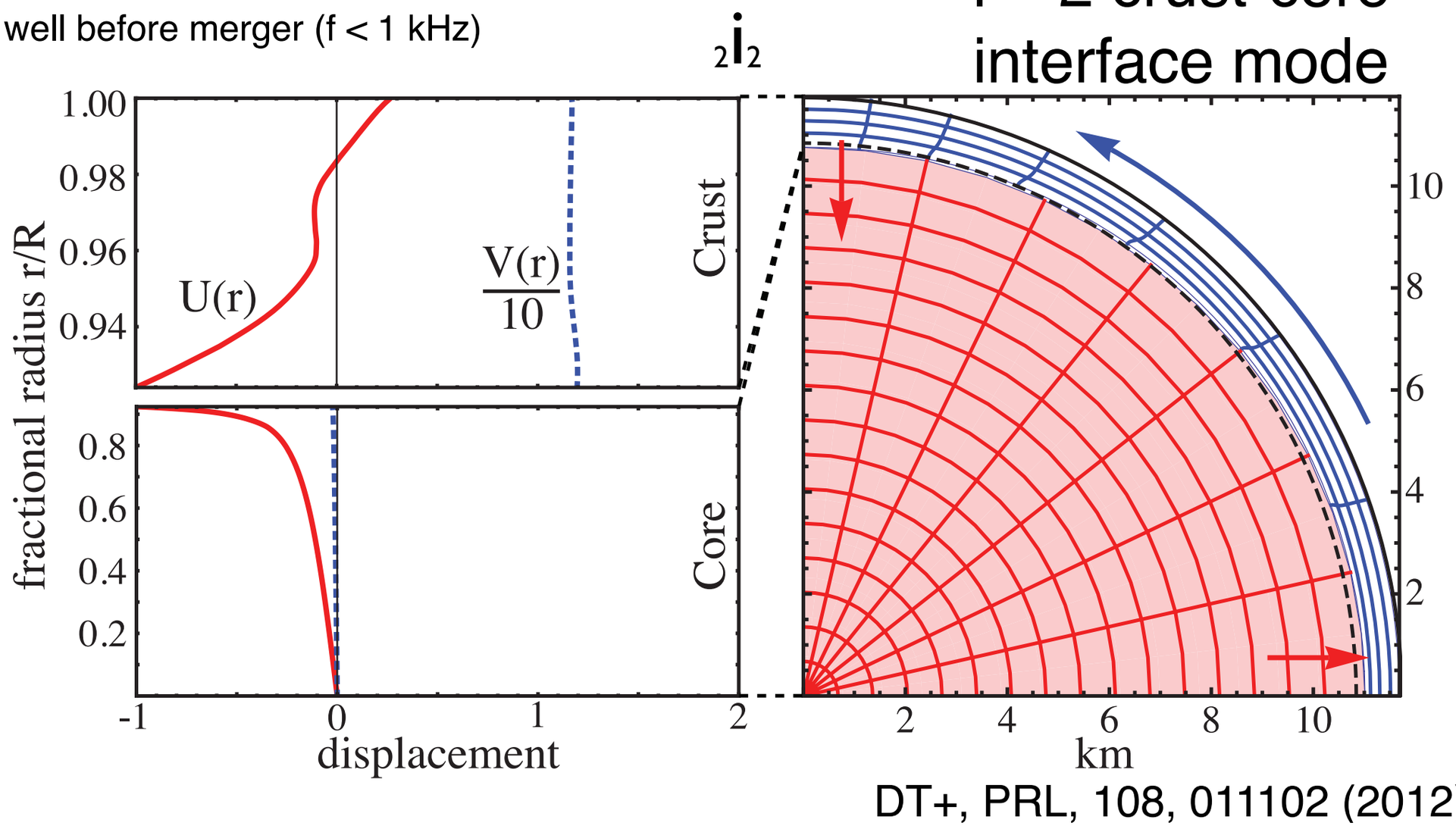


DT+, PRL, 108, 011102 (2012)

Resonant Shattering Flares

Orbit

$\dot{E}_{\rm tidal} \simeq 10^{50}{\rm erg\,s^{-1}}$

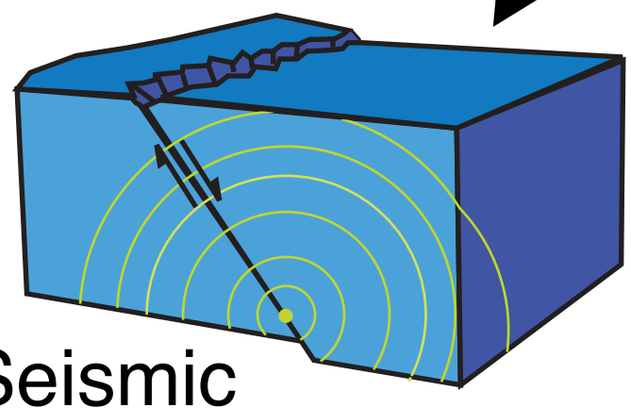
Resonance

$E_{\rm b} \simeq 10^{47}{\rm erg}$

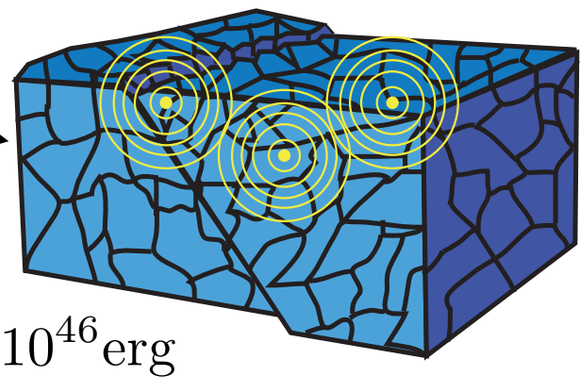
Mode

Cracking

$E_{\rm crack} \simeq \epsilon_{\rm b}^2 \mu \Delta r_{\rm crust}^3$
$\simeq 10^{43}{\rm erg}$

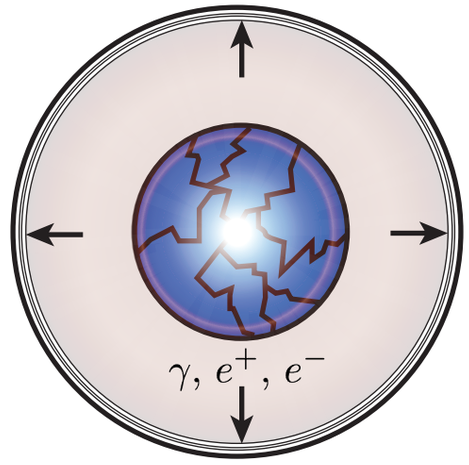


Seismic



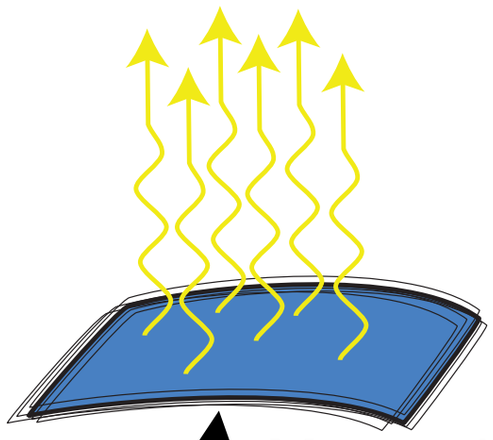
$E_{\rm elastic} = \oint dV \epsilon_b^2 \mu \sim 10^{46}{\rm erg}$

Seismic (shattered)



Pair-Fireball

10^{47}-10^{49} ergs

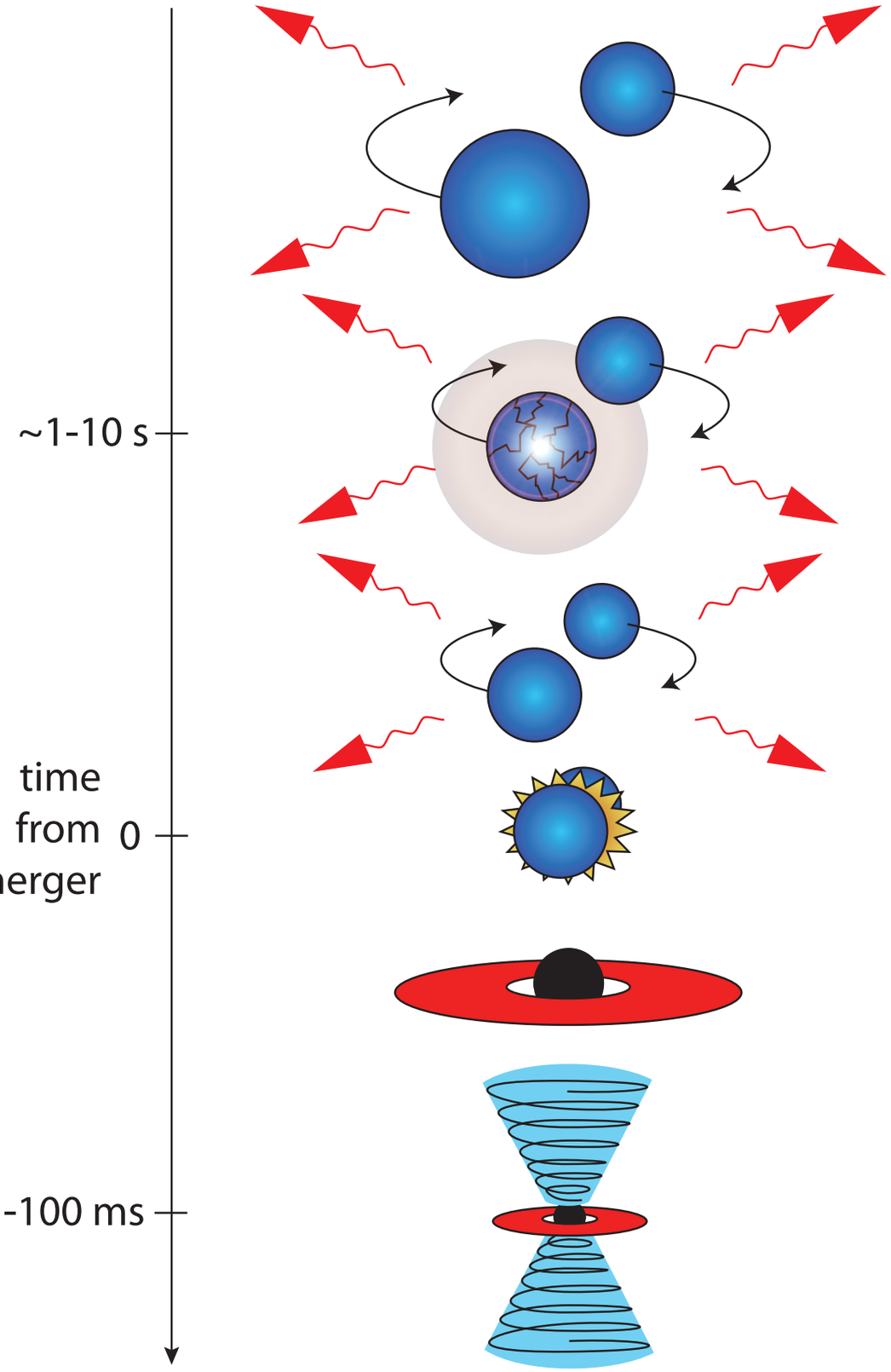


Magnetic Field

$L_{max} \sim 10^{49}{\rm erg\,s^{-1}}(v/c)$
$\times (B_{surf}/10^{14}G)^2 (R/10\,km)^2$

DT+, PRL, 108, 011102 (2012)
DT, ApJ, 777, 103 (2013)

Resonant Shattering Flares



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- RSF model can be easily **tested with EM/GW coincident timing**
  - Predicts weak GRB-like emission **seconds <u>before</u>** the chirp coalescence

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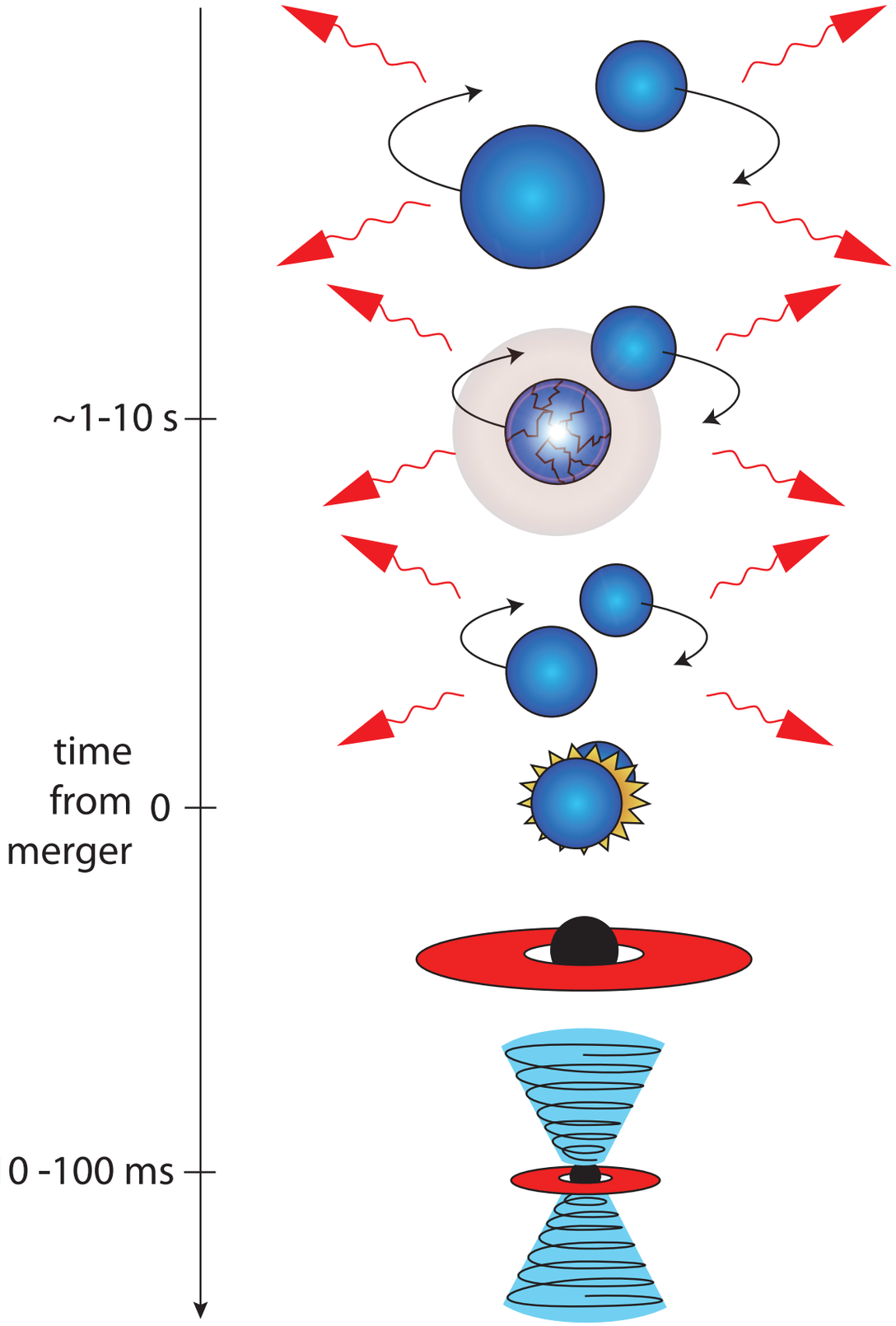

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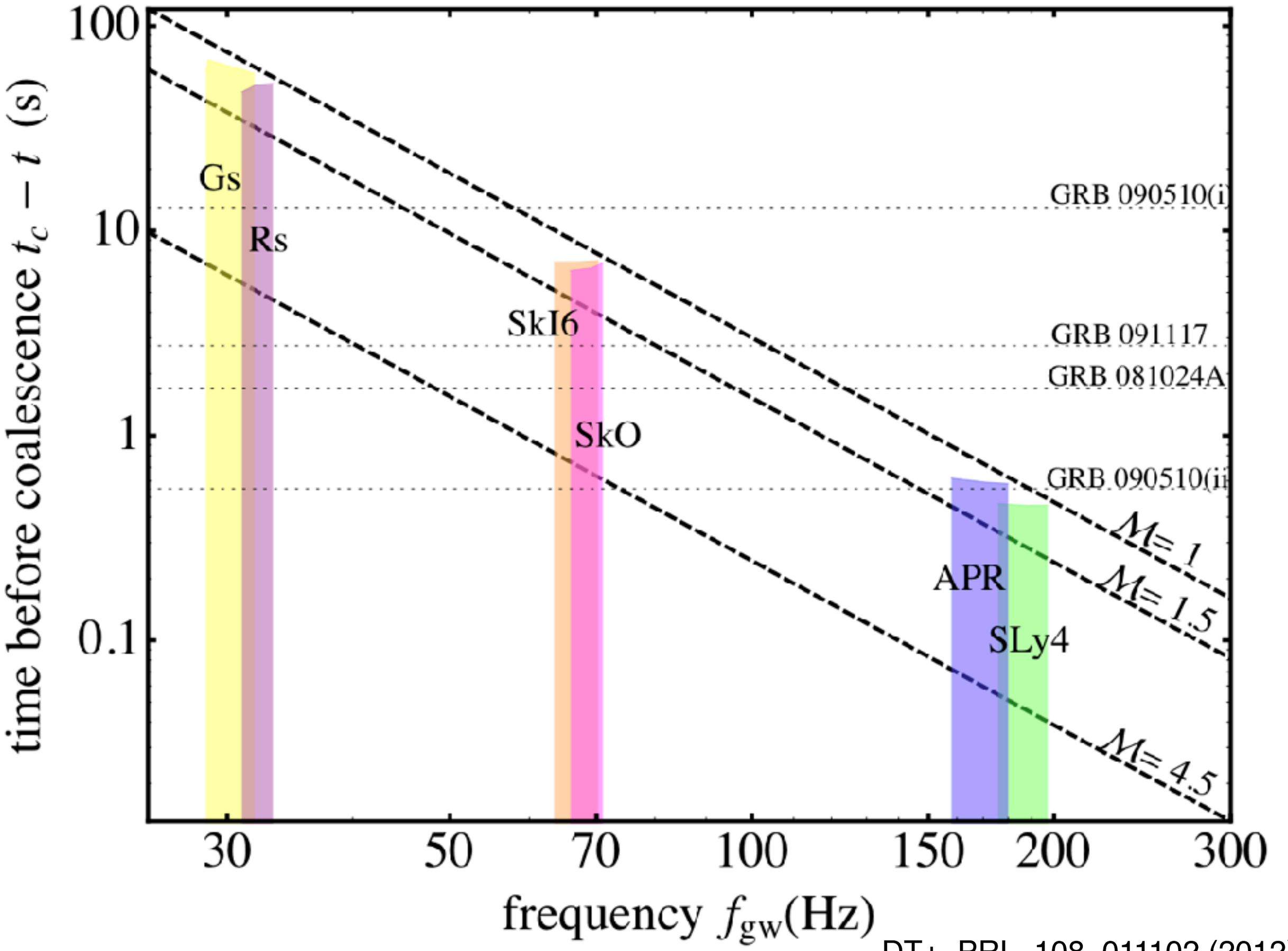

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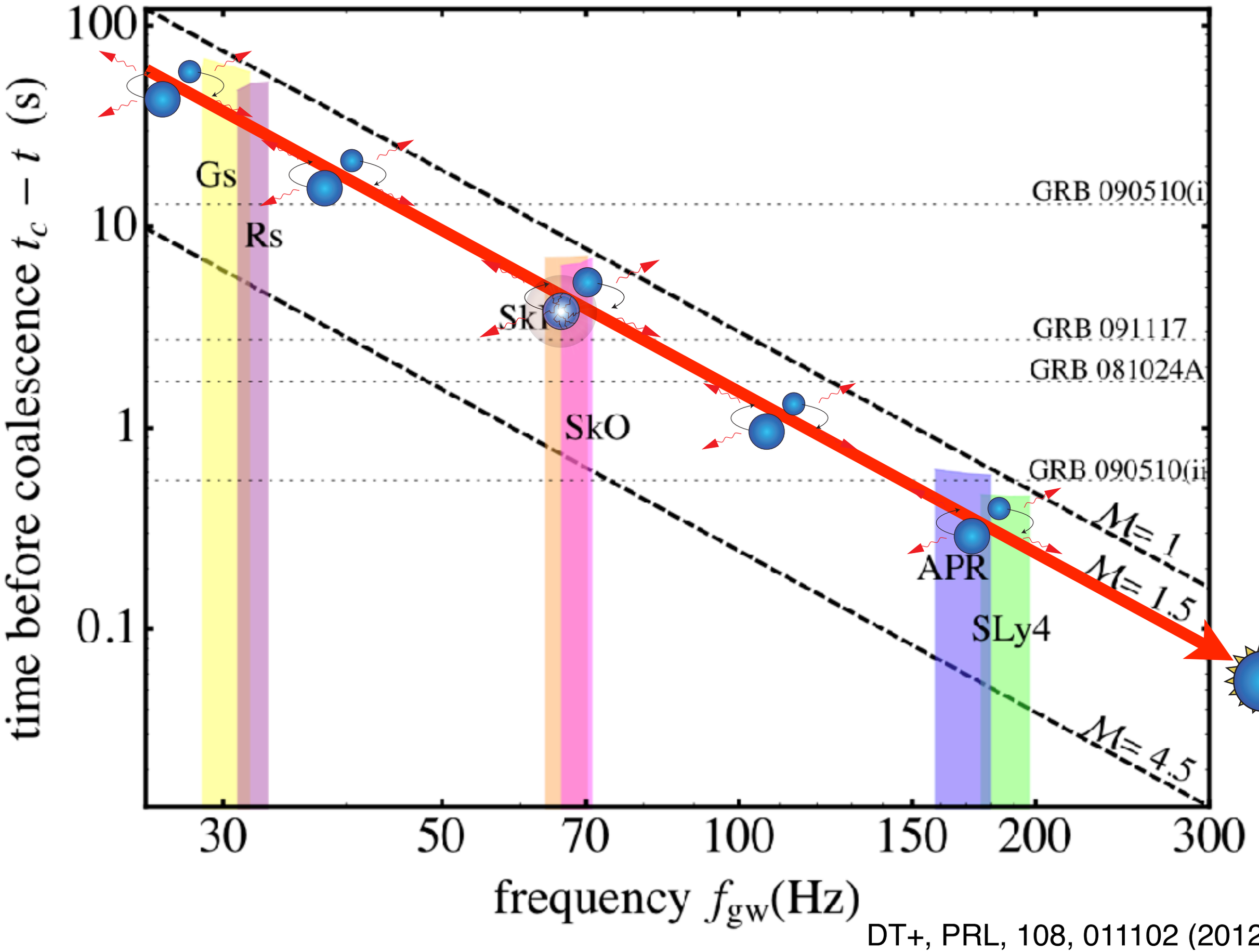

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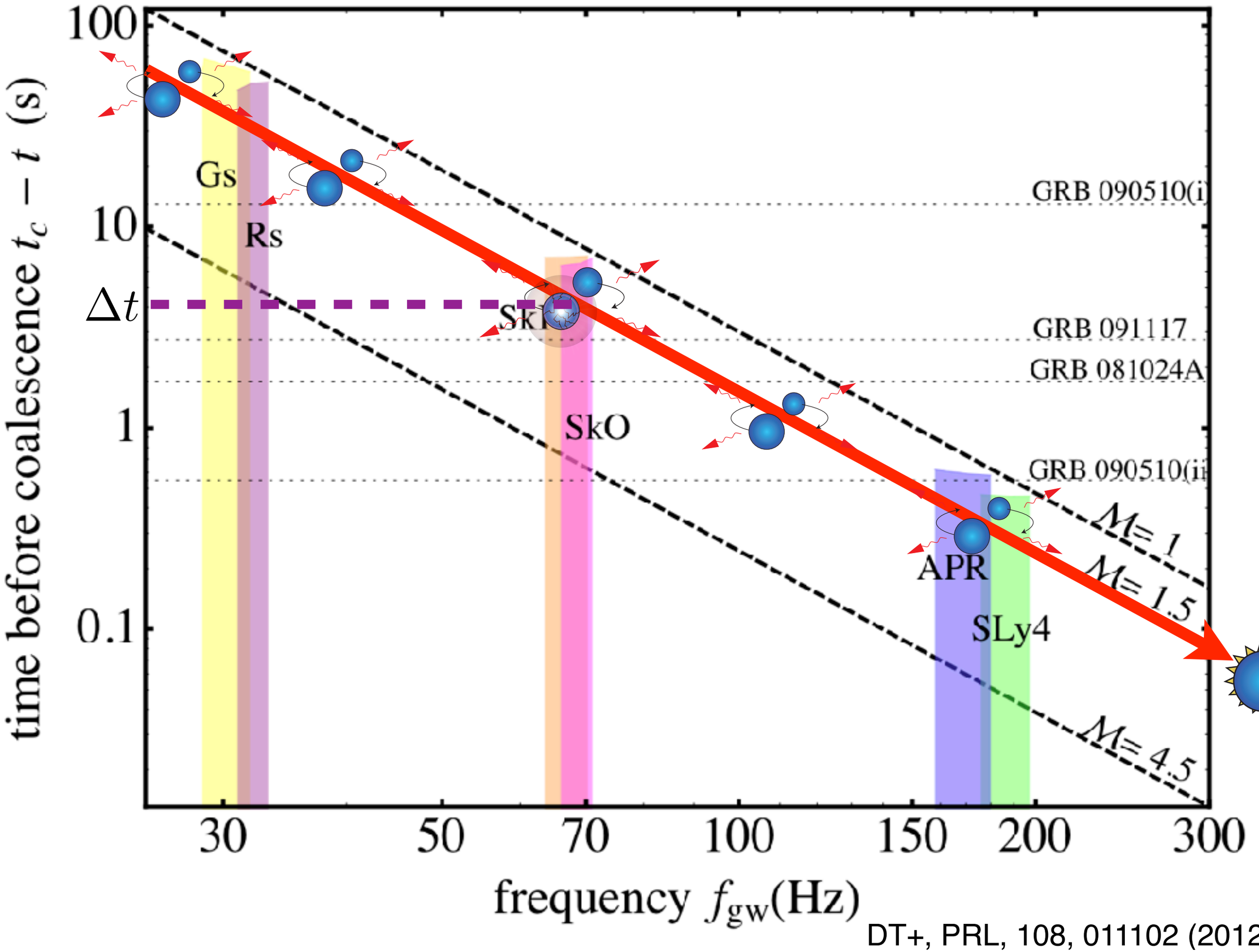

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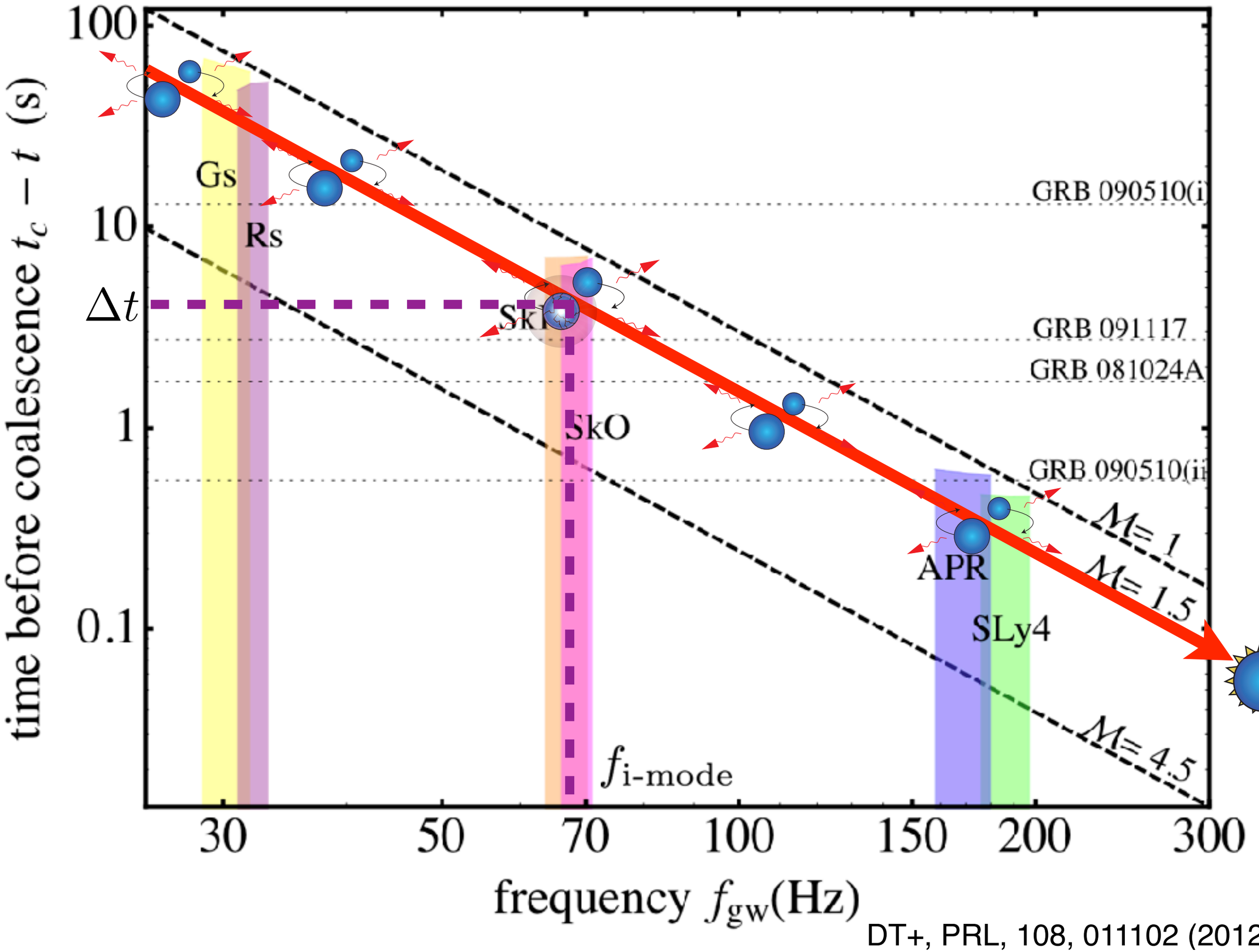

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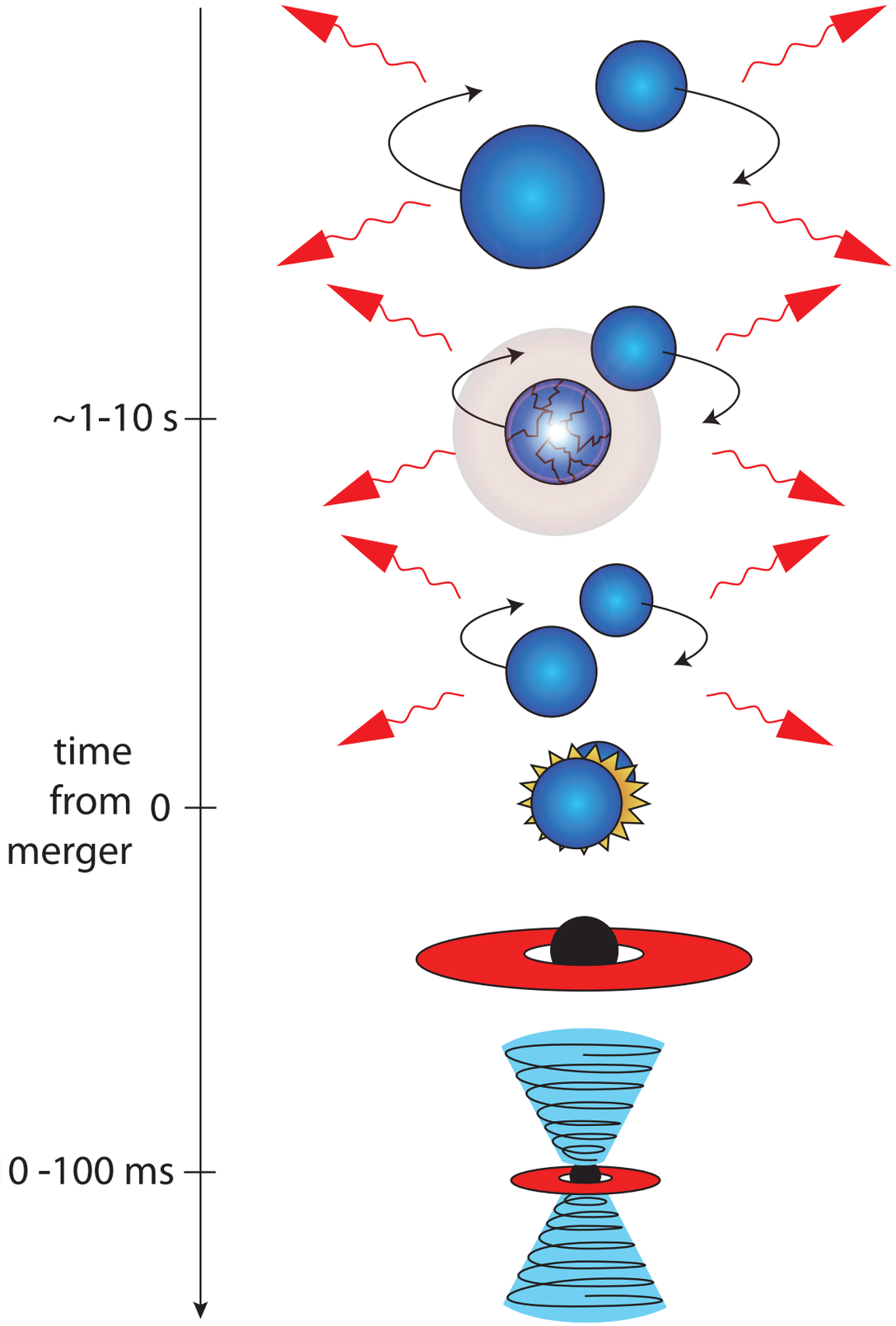

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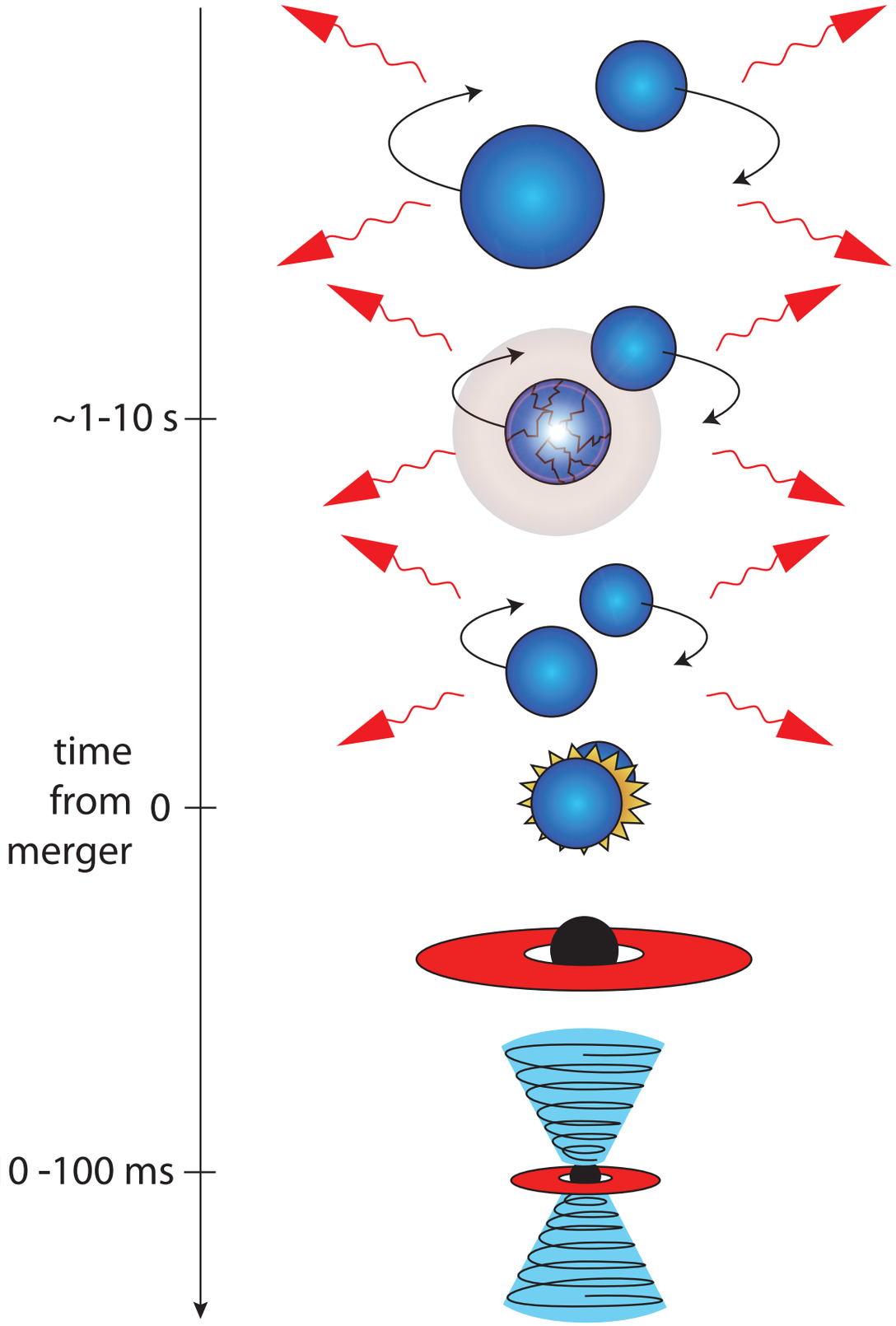

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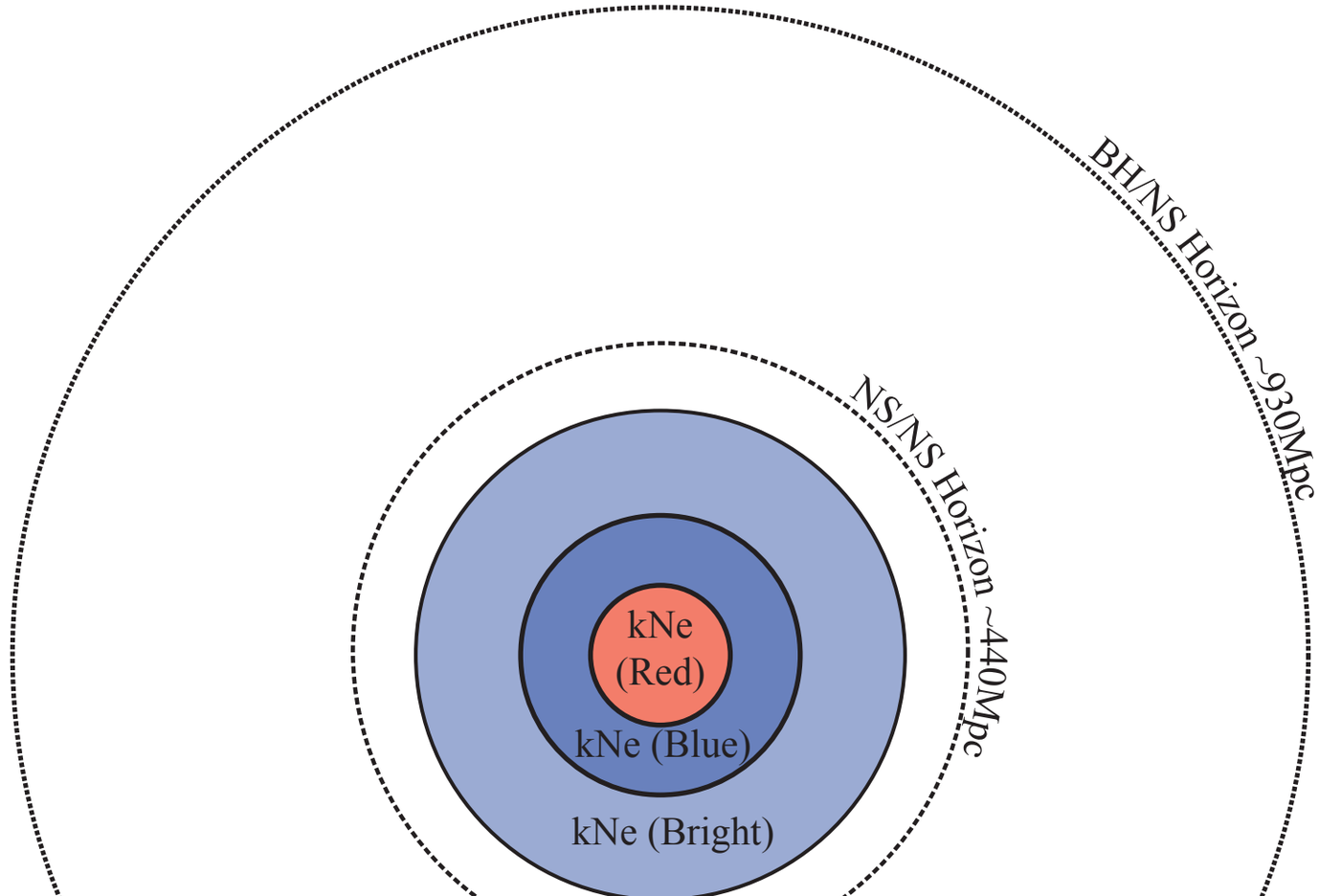
- i-mode frequency dependent on EOS, NS bulk properties and shear velocity at base of the crust
- Constrains unknown nuclear physics (Symmetry energy, EOS…)

How detectable are EM counterparts?



(kNe detectability from Kalsiwal & Nissanke, 2014)

(DT et al. in prep)

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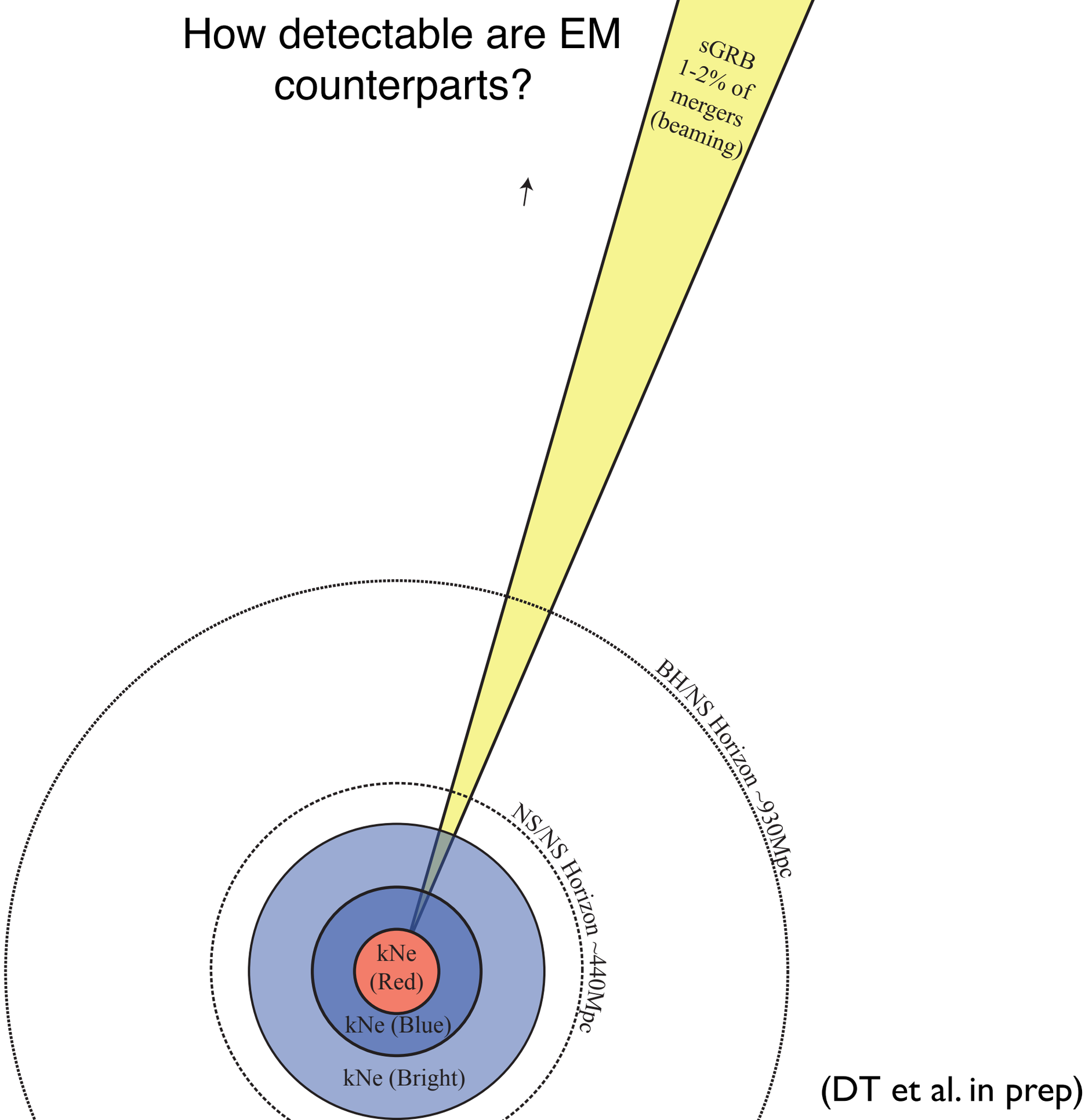

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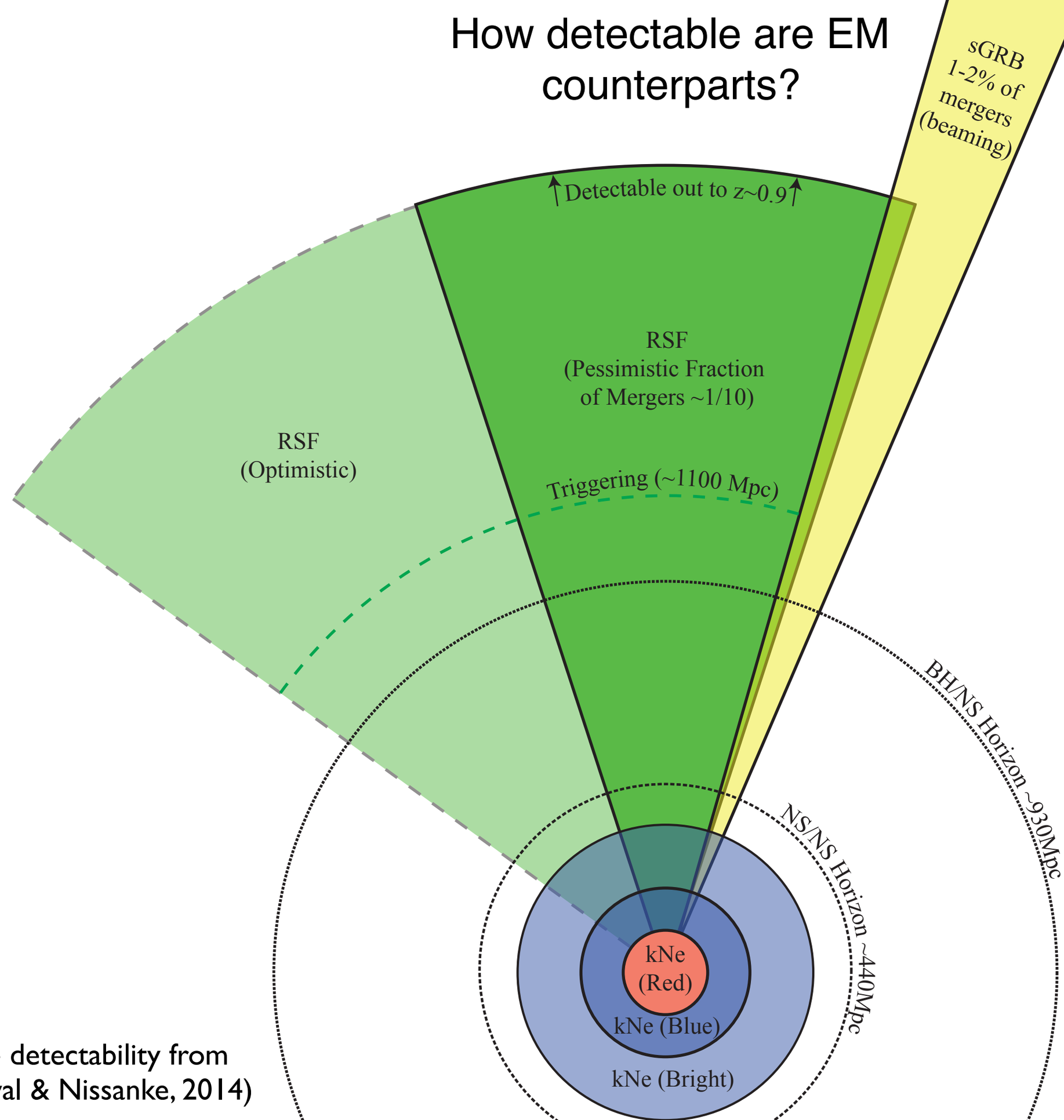

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Potential Orphan RSFs?

E_{RSF} ~ 10^{47} - 10^{49} erg, t_{RSF} ~ 0.1s

GRB	T_{90}(s)	z	BAT Fluence (10^{-7} erg cm^{-2})	$E_{BAT\ ISO}$ (erg)	Notes
150101B	0.018	0.13	0.23	2.6 x 10^{48}	High E_{kin}; Fong+(2016)
050509B	0.073	0.225	0.09	1.1x10^{48}	Gehrels+(2005)
060502B	0.131	0.287	0.4	7.9x10^{48}	Bloom+ (2006)
050906	0.128	0.031*	0.07	1.5 x 10^{46}	Levan & Tanvir (2008)

*no afterglow; host galaxy within BAT error box

Q: Is there a local orphan RSF component in SGRBs population?

Progenitor

NS NS

NS BH

BH BH

Post-Merger

NS

NS + Disk/Ejecta

BH

BH + Disk/Ejecta

BH

No Tidal Disruption

BH

No Matter

EM Counterpart

kilo/macronovae

SGRB
(prompt + afterglow)

Cocoon emission

kilo/macronovae

SGRB
(prompt + afterglow)

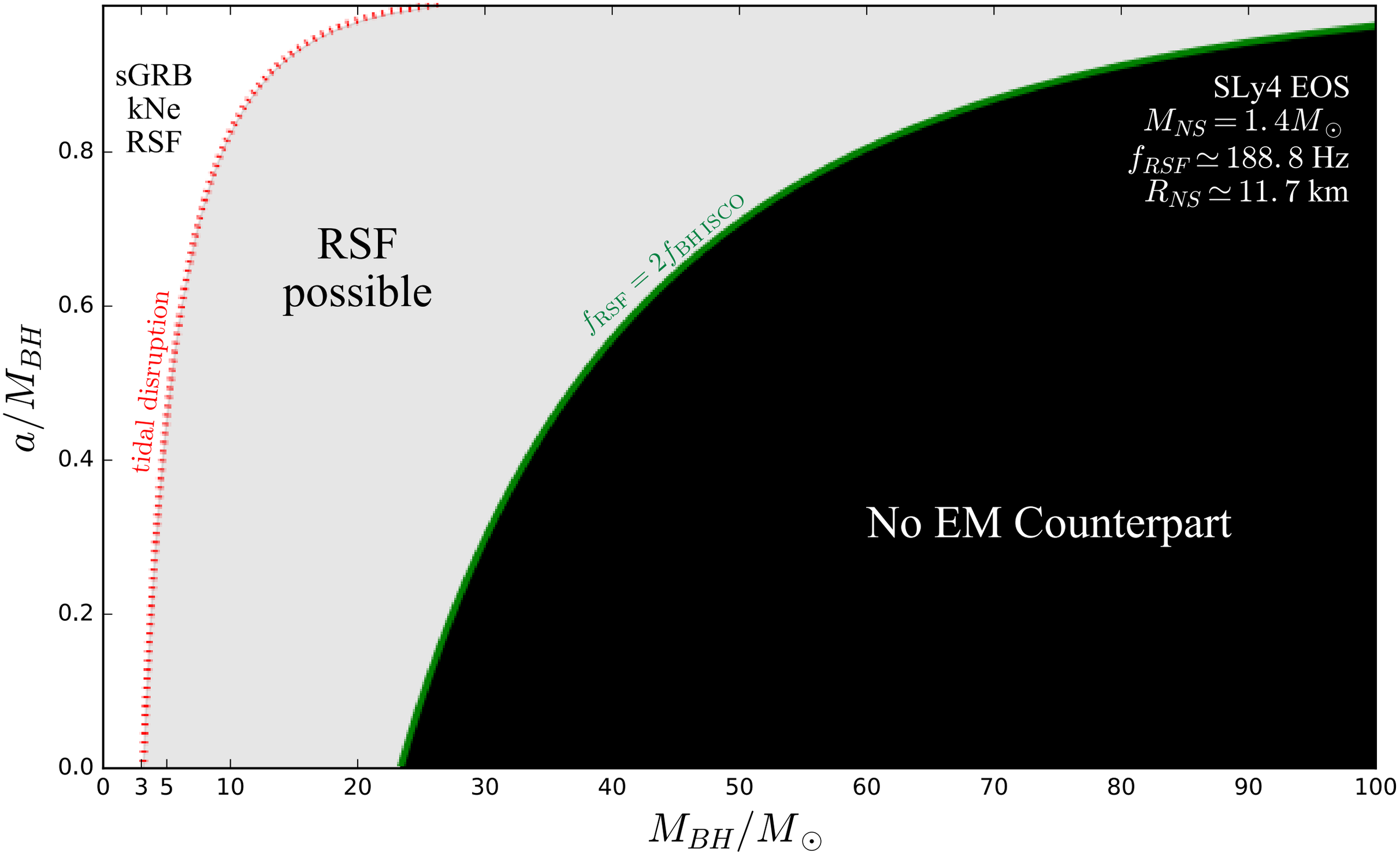
Cocoon emission

(DT et al. in prep)

Progenitor	NS NS	NS BH	BH BH
Post-Merger	NS + Disk/Ejecta	BH + Disk/Ejecta	No Tidal Disruption	No Matter
EM Counterpart	kilo/macronovae SGRB (prompt + afterglow) Cocoon emission RSF (prompt precursor + afterglow)	kilo/macronovae SGRB (prompt + afterglow) Cocoon emission RSF (prompt precursor + afterglow)	RSF (prompt precursor + afterglow)	

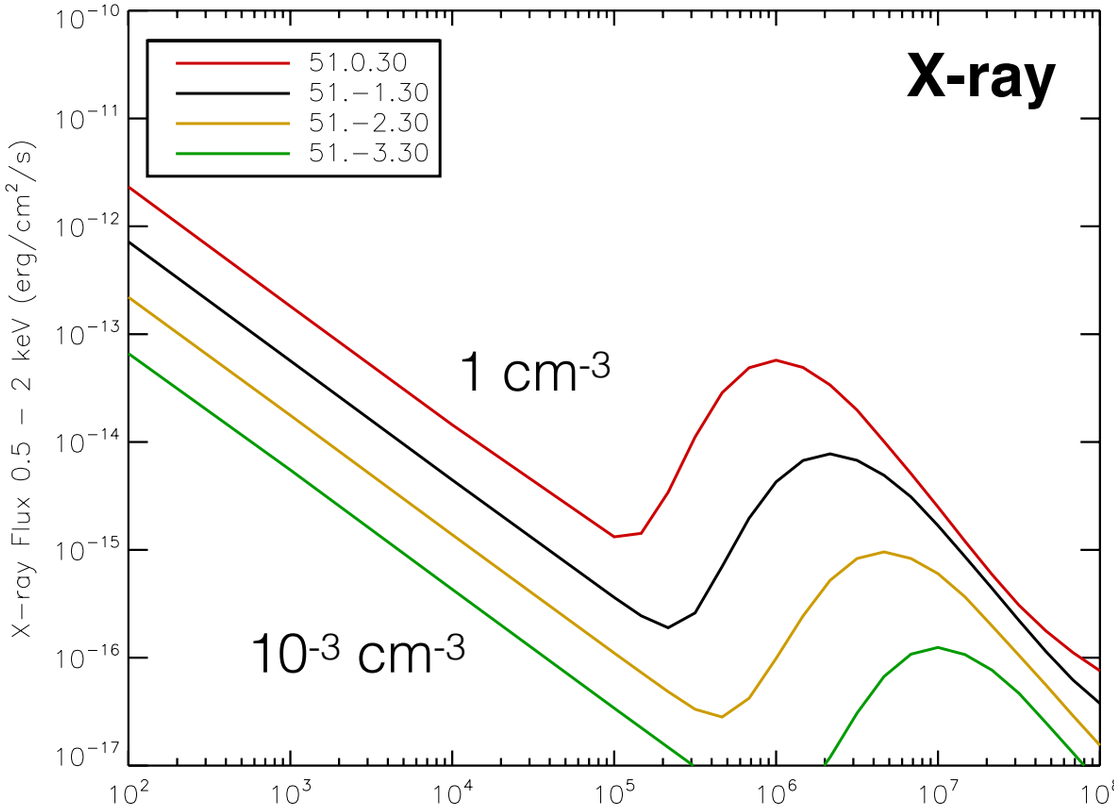
(DT et al. in prep)

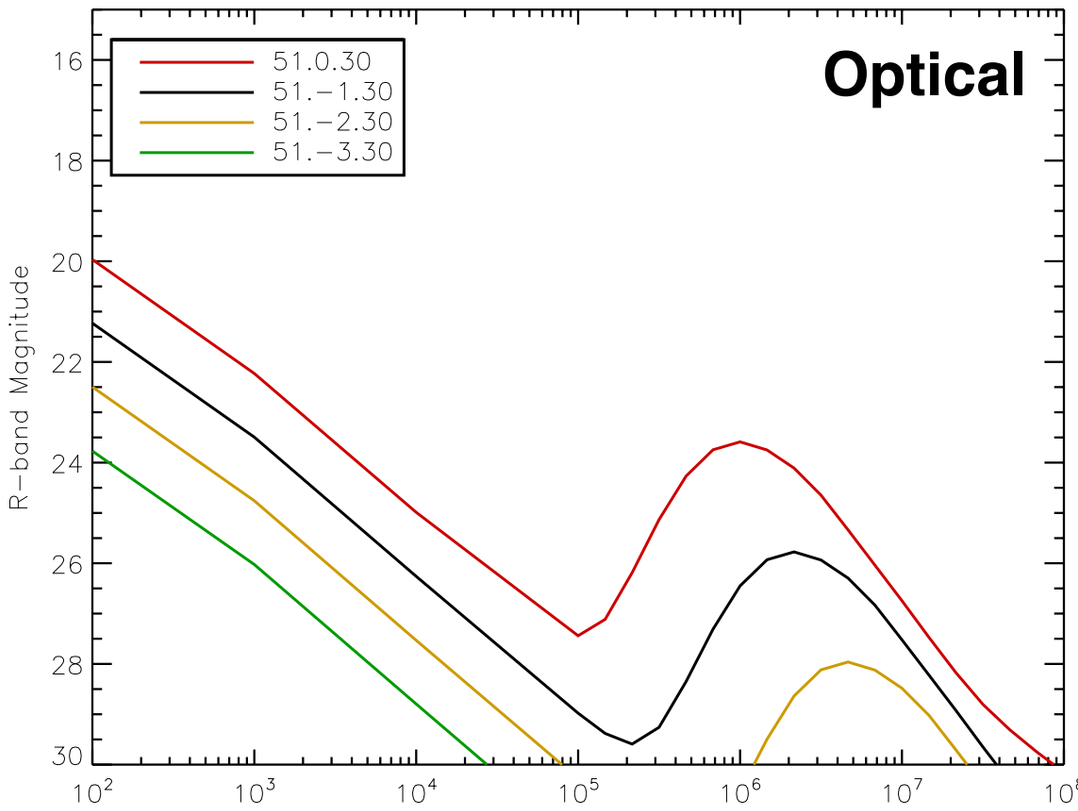
Black Hole - Neutron Star Mergers

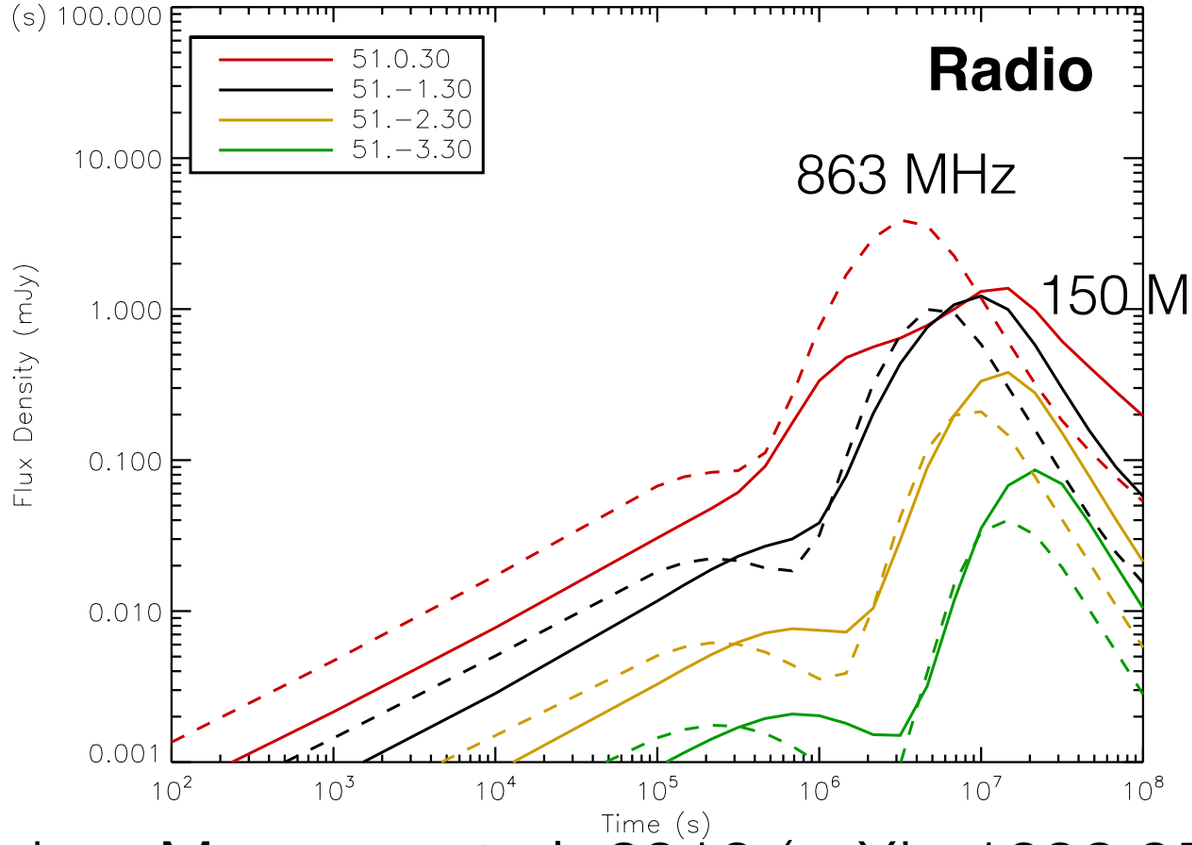


DT et al. (in prep)

RSF Afterglow



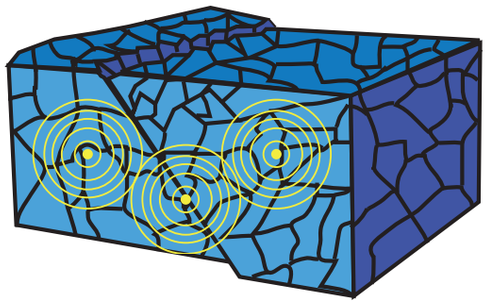




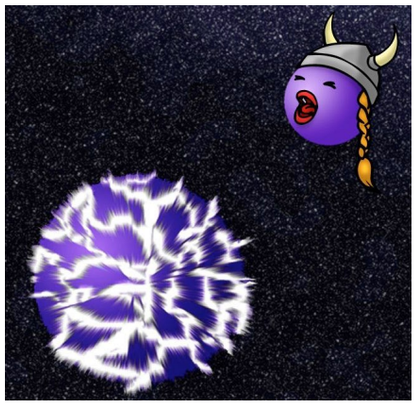
@200 Mpc
10^{48} erg isotropic
shattering flare
10^{51} erg (E_{ISO}) GRB
(30^{o} off axis)

(DT et al. in prep)

based on Morsony et al. 2016 (arXiv:1602.05529)



Summary



- RSFs caused by resonant tidal excitation of i-mode injecting energy into pair-fireball, seconds before merger
- RSFs are:
  - Isotropic
  - Bright: should be easily detectable within the LIGO horizon
  - $E_{RSF} \sim 10^{47}$ - 10^{49} ergs
  - $t_{RSF} \sim 0.1$s
- Can appear as SGRB precursors or orphan RSFs (underluminous, very short GRBs)
- Weak X-ray/Optical/Radio afterglow
- Coincident EM/GW timing will confirm RSF model and determine mode freq.
- Shear speed/nuclear physics constraints; Complementary to M, R, λ
- Does not need tidal disruption - larger fraction of NS-BH mergers
- Uncertainties
  - Surface B-field - core vs crust evolution?
  - N_{RSF}/N_{merger}?
  - Excess of nearby orphan RSFs?