PLUS Collaboration Seminar, 19 Oct 2022

The Physics of Kilonovae

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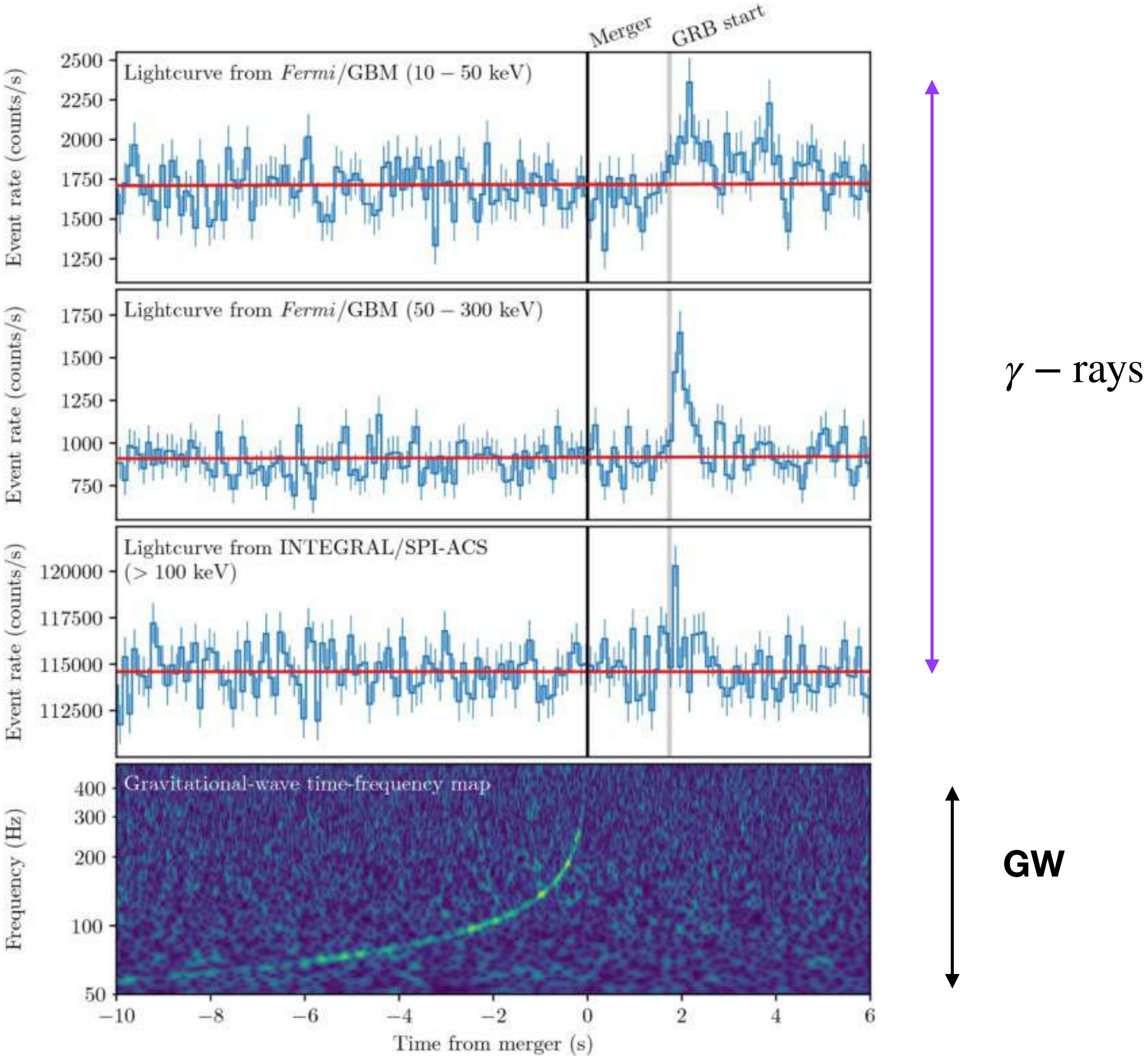
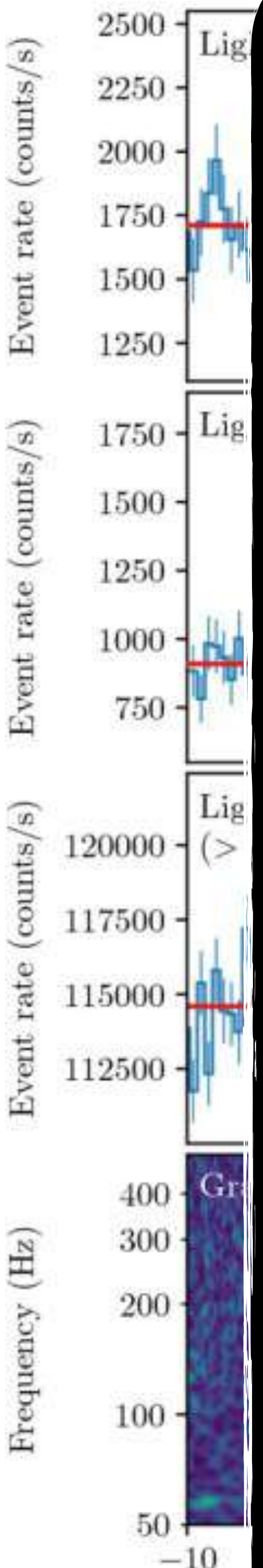
Image Credit: Mark Garlick

Stefano Ascenzi (Instituto de Ciencia del Espacio ICE-CSIC)

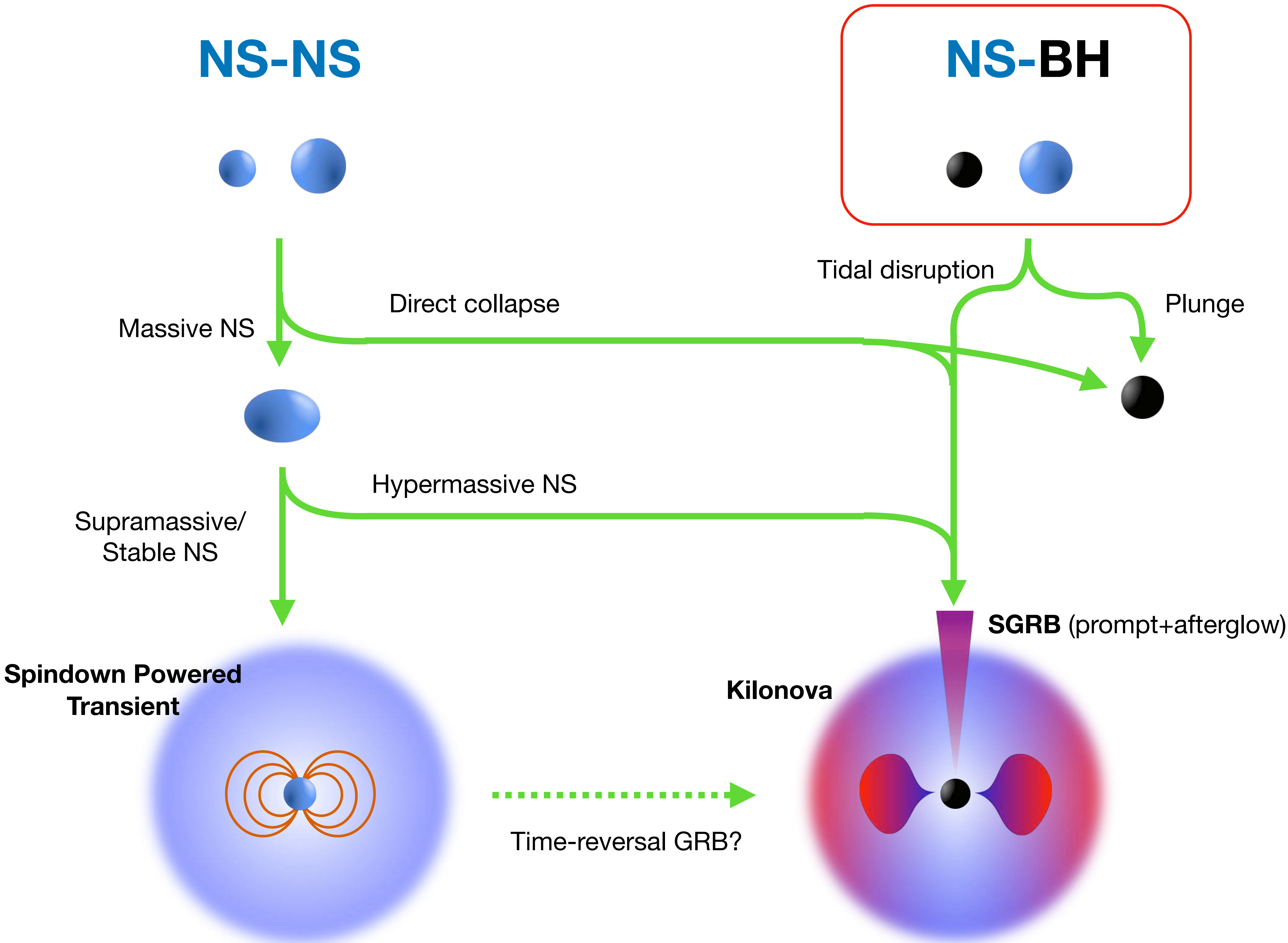


(LVC, Fermi & Integral Collaborations, 2017)



HST observations (https://www.nasa.gov/press-release/nasa-missions-catch-first-light-from-a-gravitational-wave-event)

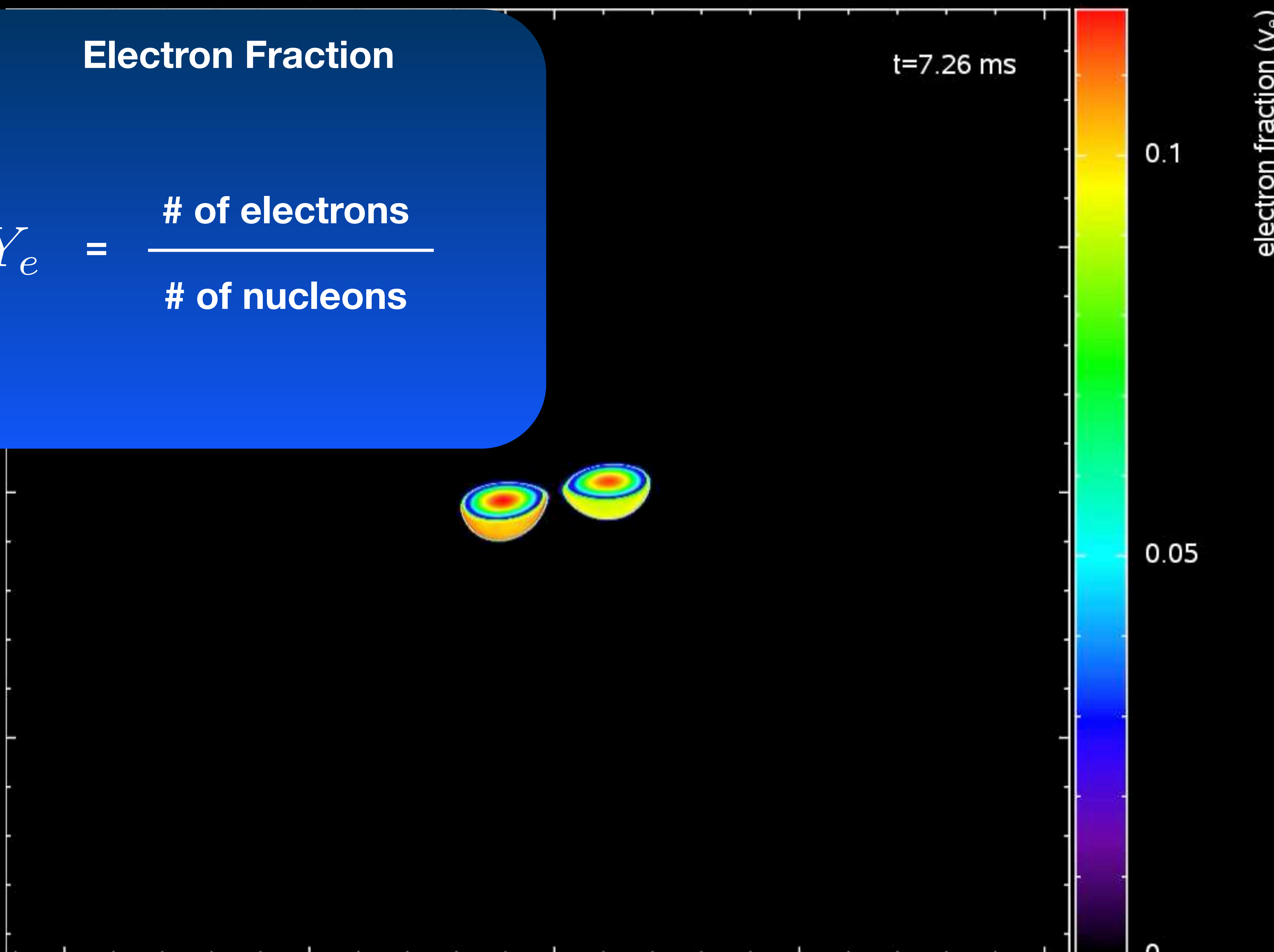
(LVC, Fermi & Integral Collaborations, 2017)


NS-NS
NS-BH
Tidal disruption
Plunge
Direct collapse
Massive NS
Hypermassive NS
Supramassive/
Stable NS
SGRB (prompt+afterglow)
Spindown Powered
Transient
Kilonova
Time-reversal GRB?

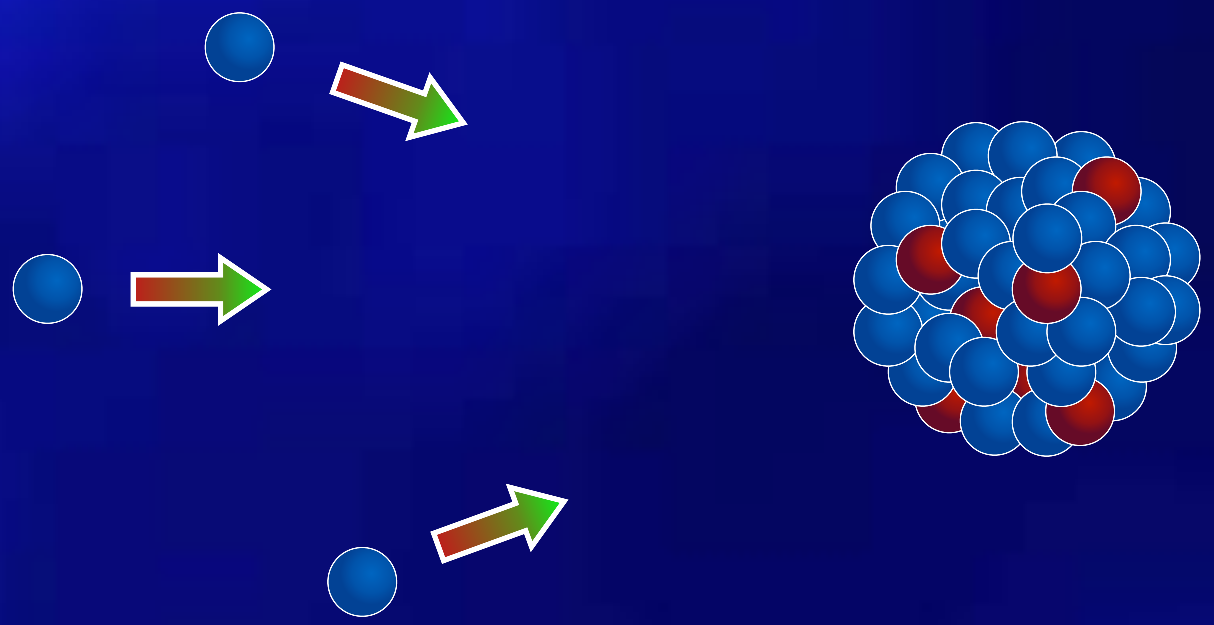
Binary Neutron Star Merger

Electron Fraction

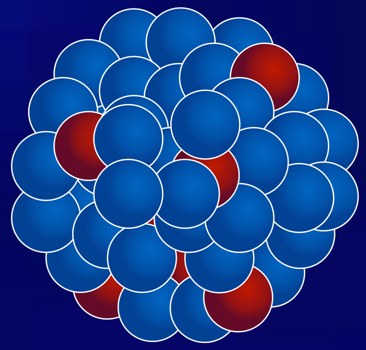
$$Y_e = \frac{\text{\# of electrons}}{\text{\# of nucleons}}$$



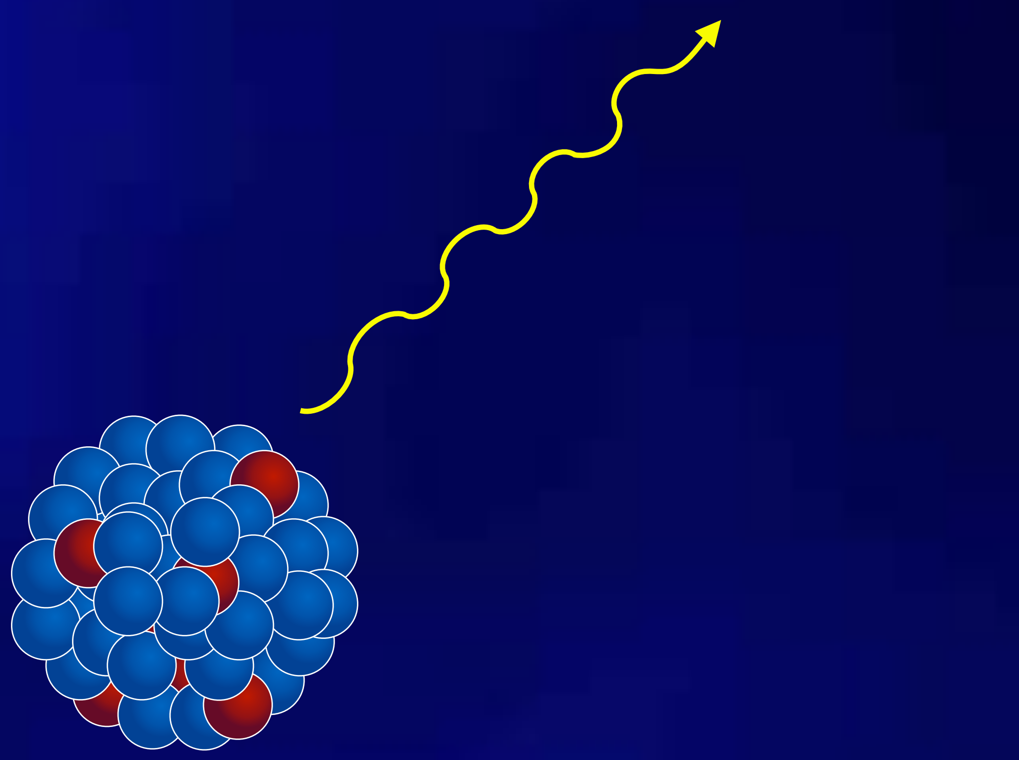
R-Process Nucleosynthesis



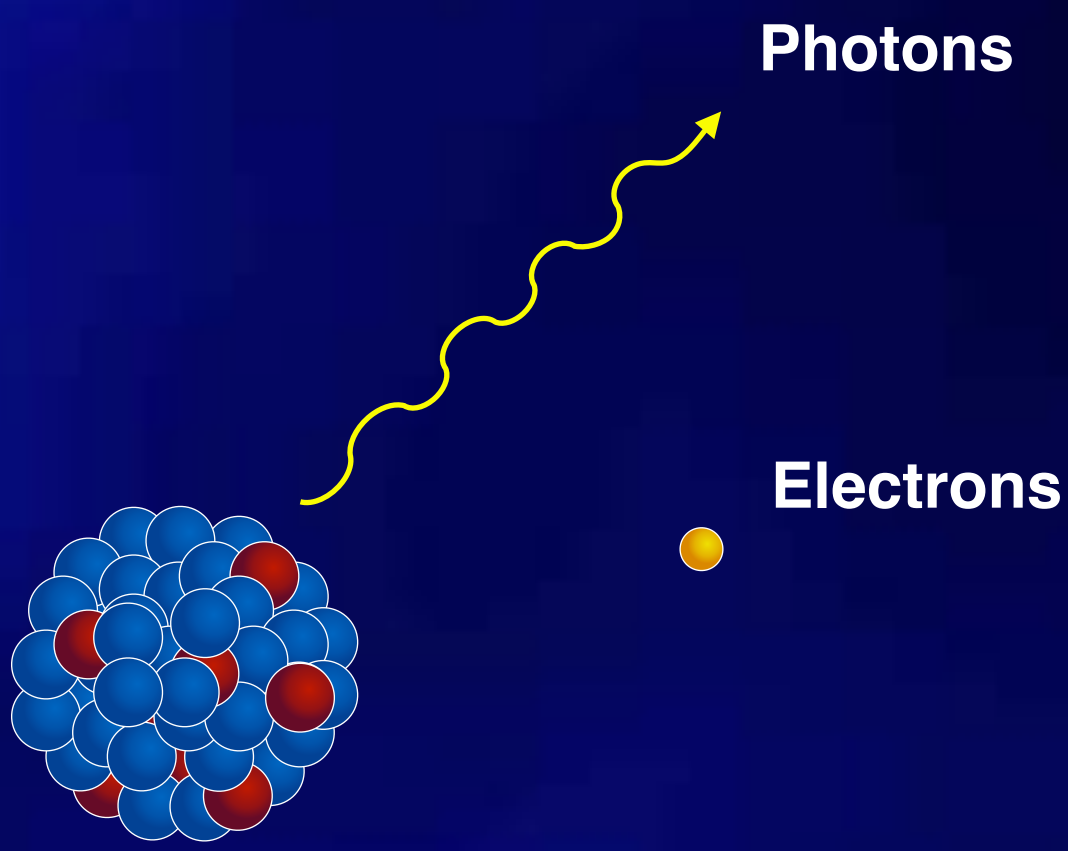
R-Process Nucleosynthesis



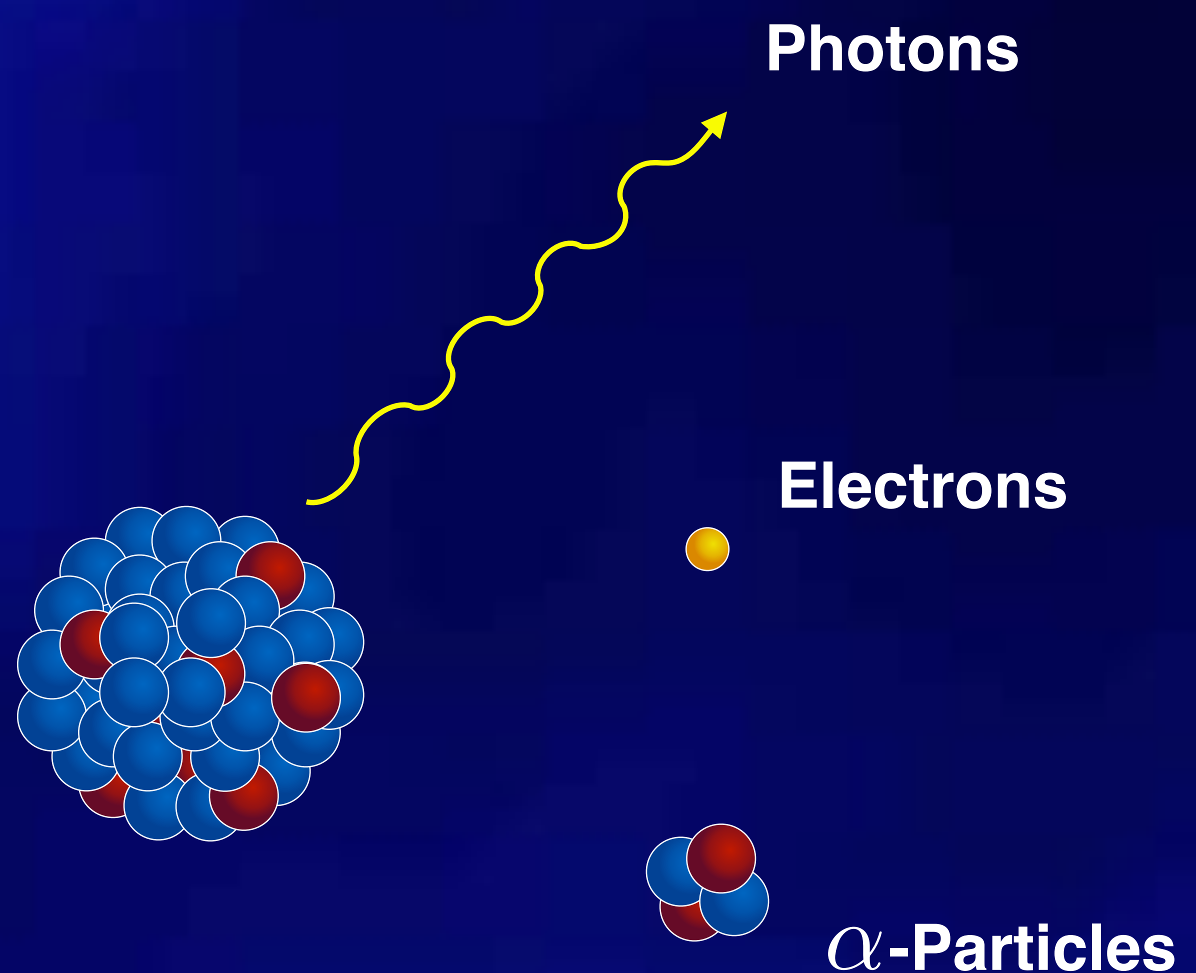
R-Process Nucleosynthesis



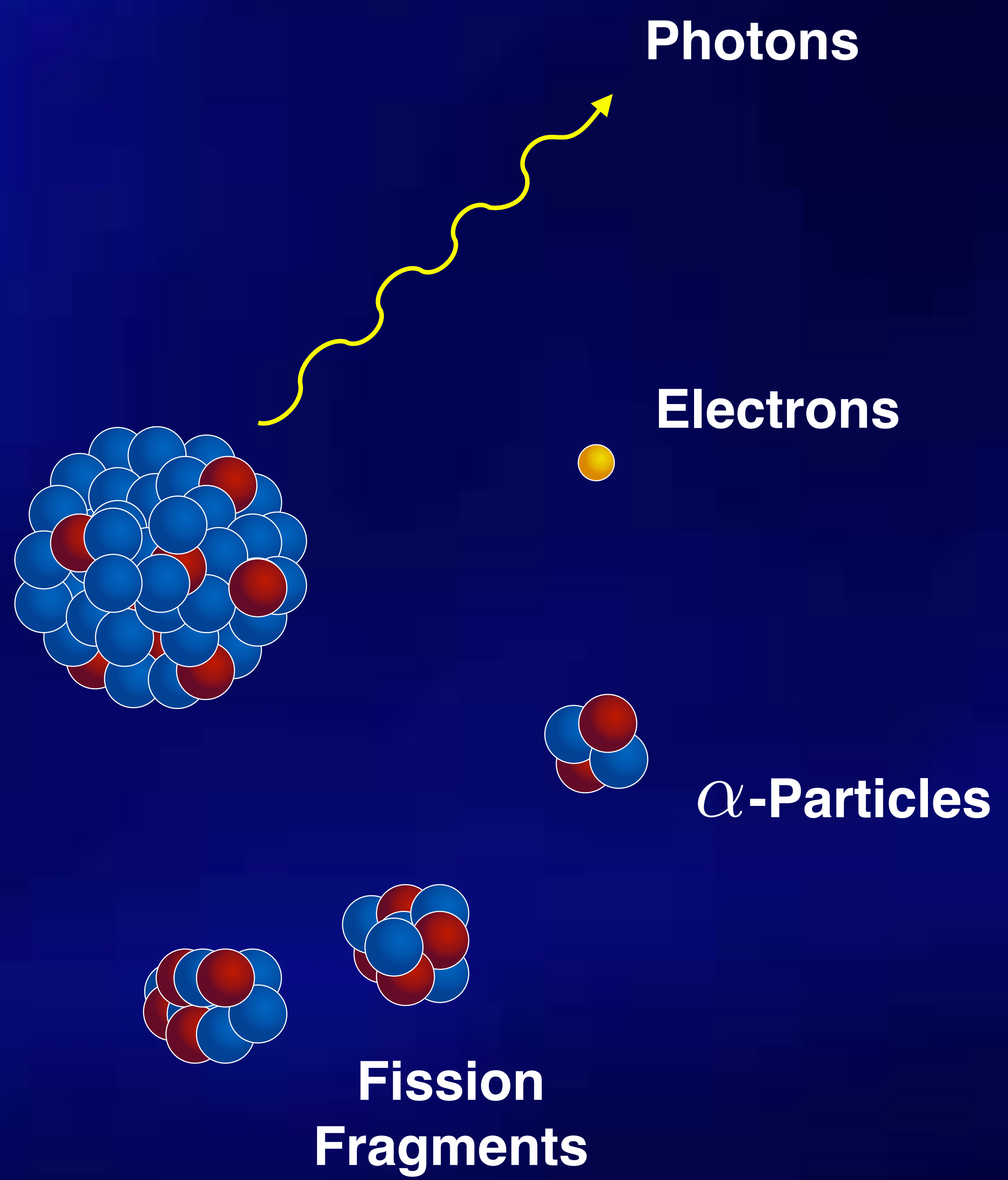
R-Process Nucleosynthesis



R-Process Nucleosynthesis



R-Process Nucleosynthesis



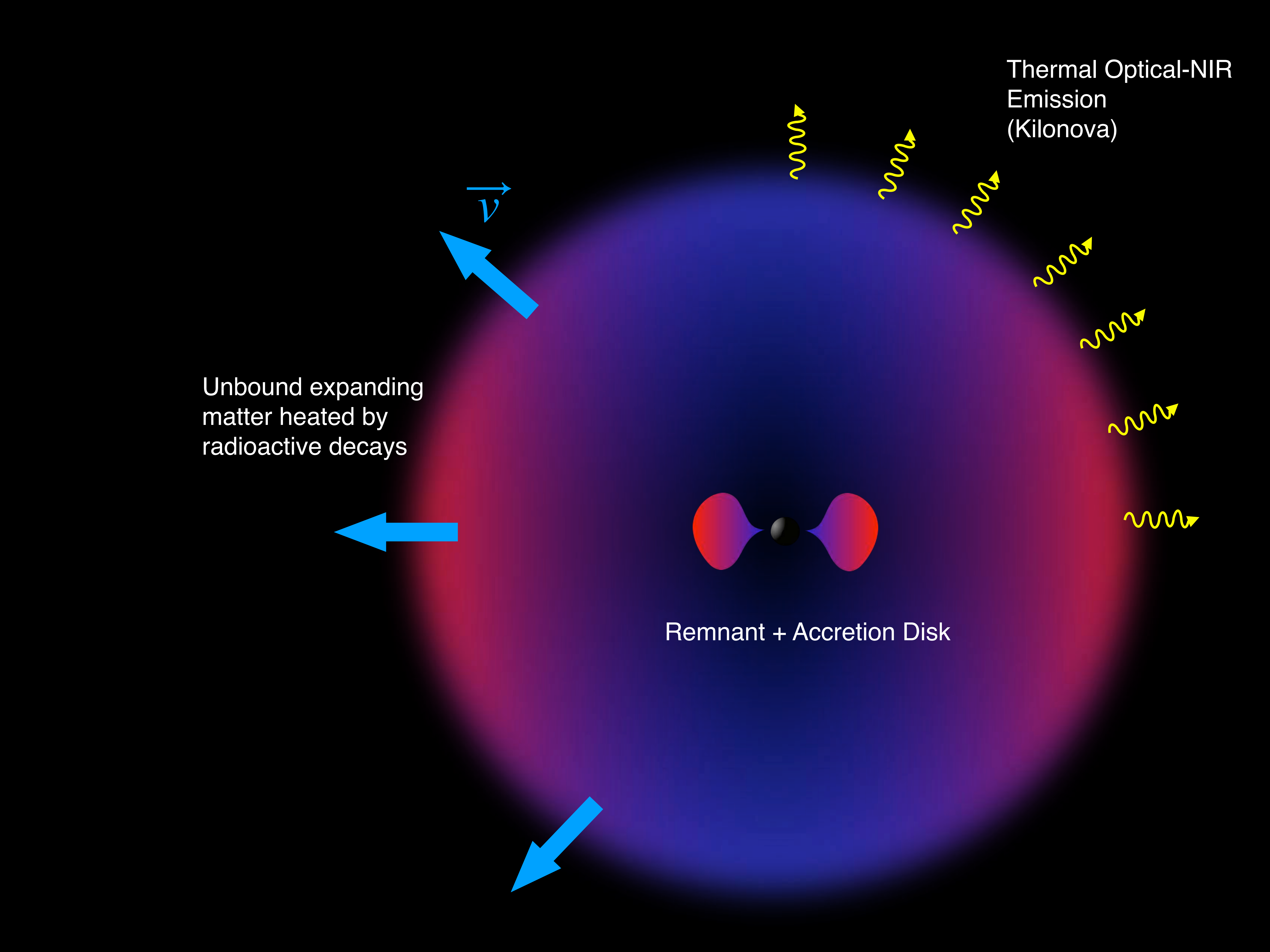
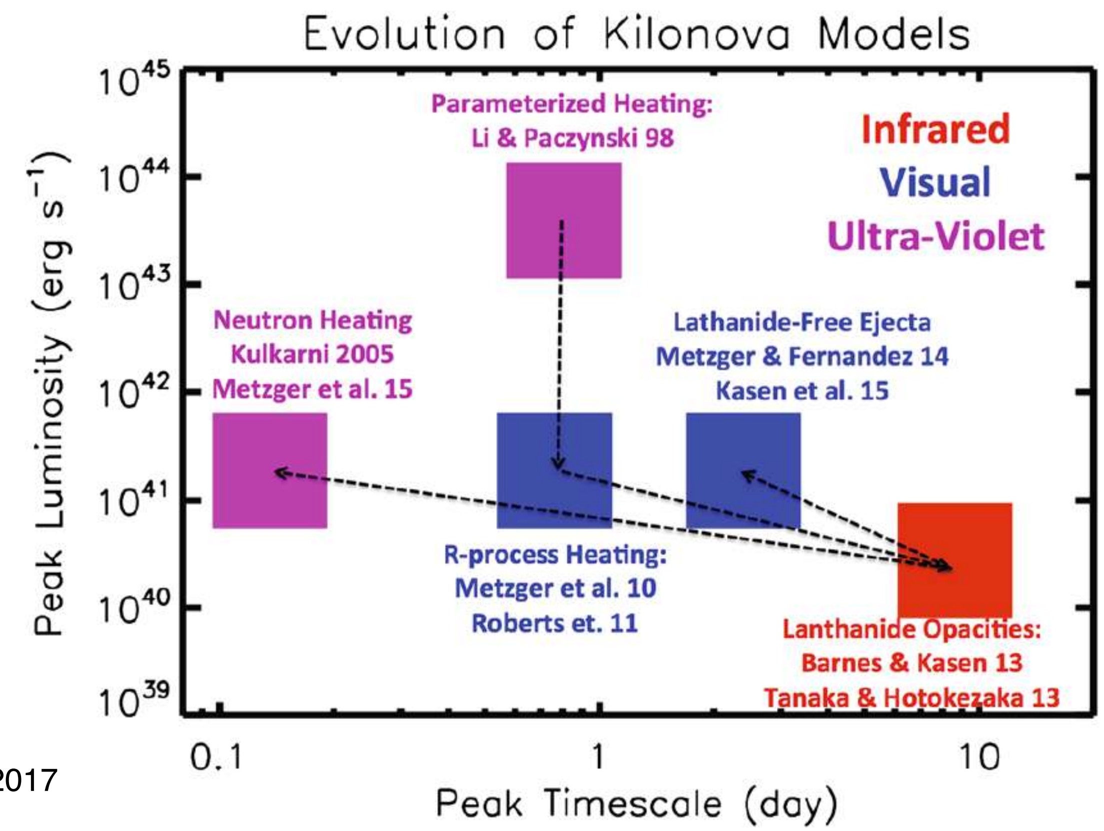

Thermal Optical-NIR
Emission
(Kilonova)
$\vec{v}$
Unbound expanding
matter heated by
radioactive decays
Remnant + Accretion Disk

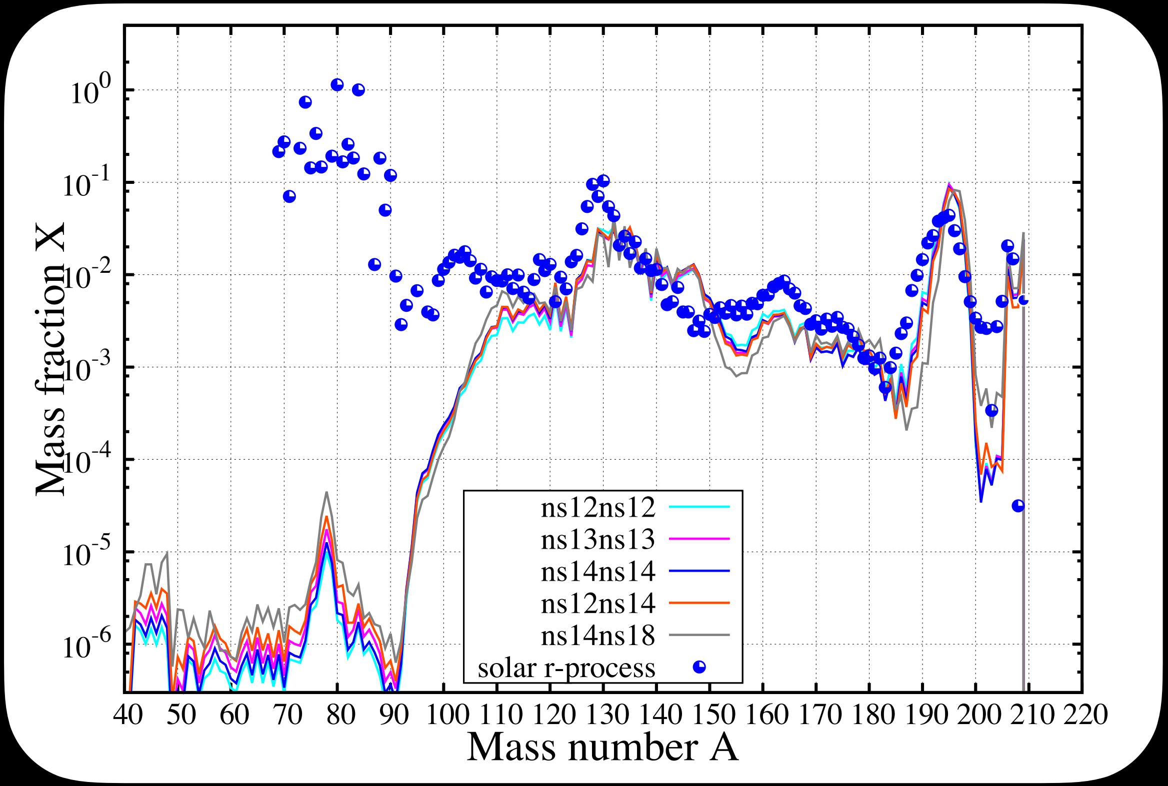
Table 1 Timeline of major developments in kilonova research

1974	Lattimer and Schramm: r-process from BH–NS mergers
1975	Hulse and Taylor: discovery of binary pulsar system PSR 1913 + 16
1982	Symbalisty and Schramm: r-process from NS–NS mergers
1989	Eichler et al.: GRBs from NS–NS mergers
1994	Davies et al.: first numerical simulation of mass ejection from NS–NS mergers
1998	Li and Paczyński: first kilonova model, with parameterized heating
1999	Freiburghaus et al.: NS–NS dynamical ejecta ⇒ r-process abundances
2005	Kulkarni: kilonova powered by free neutron-decay ("macronova"), central engine
2009	Perley et al.: optical kilonova candidate following GRB 080503 (Fig. 9)
2010	Metzger et al., Roberts et al., Goriely et al.: kilonova powered by r-process heating
2013	Barnes and Kasen, Tanaka and Hotokezaka: La/Ac opacities ⇒ NIR spectral peak
2013	Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B
2013	Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova")
2014	Metzger and Fernandez, Kasen et al.: blue kilonova from post-merger remnant disk winds



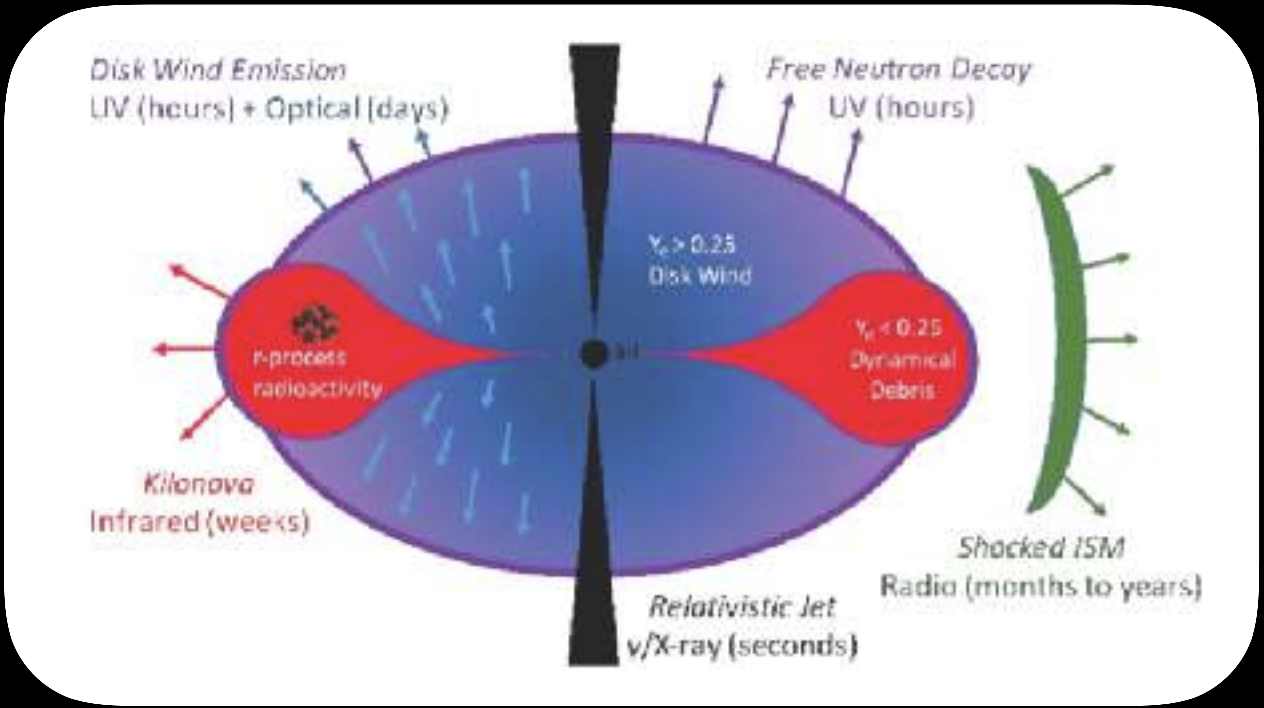
Metzger 2017

Why are they interesting?



(Rosswog et al. 2016)

R-process nucleosynthesis



Isotropic EM- counterpart of GW and sGRBs

Kilonova: Main Ingredients

k ← Opacity

m_{ej} ← Mass of the Ejecta

v_{ej} ← Velocity of the Ejecta

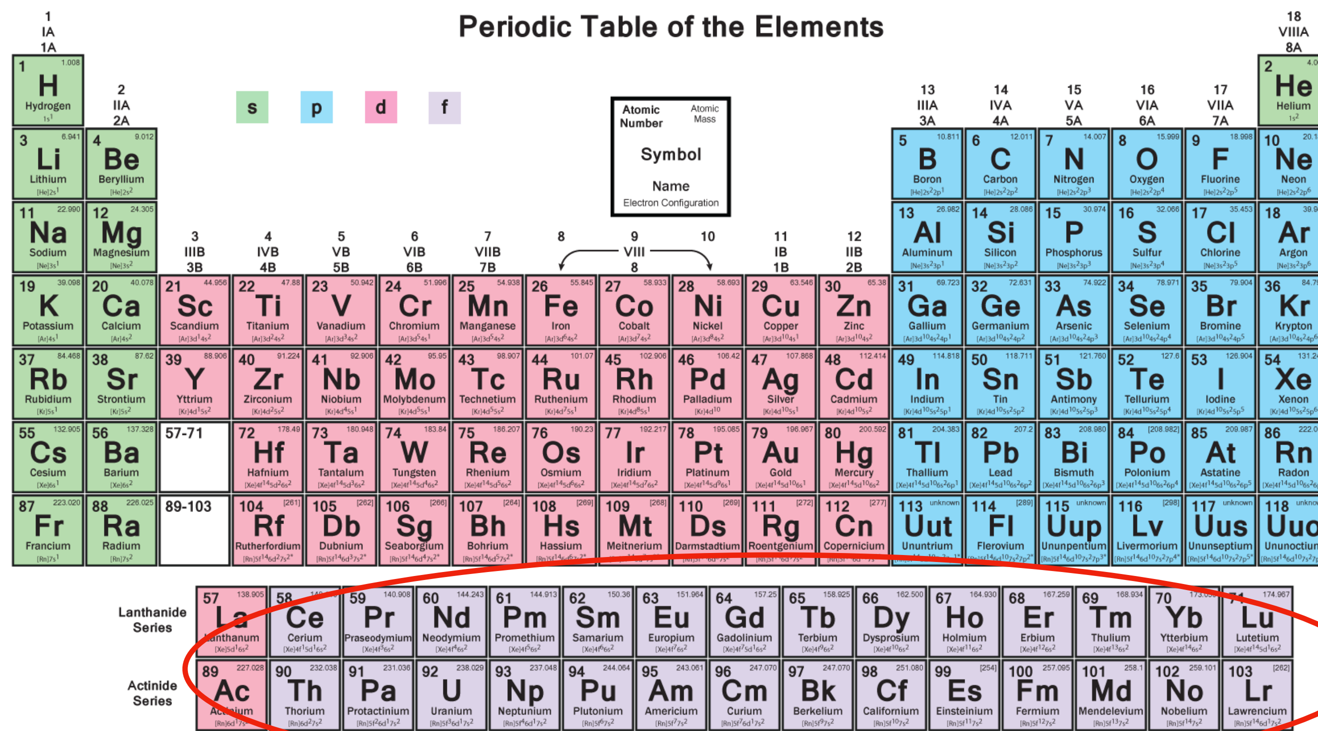
$$t_{peak} \simeq 4.9\,days \left(\frac{k}{10\,cm^2/g} \frac{m_{ej}}{0.01\,M_\odot} \frac{0.1\,c}{v_{ej}} \right)^{1/2}$$

$$L_{peak} \simeq 2.5 \times 10^{40}\,\frac{erg}{s} \left(\frac{v_{ej}}{0.1\,c} \frac{10\,cm^2/g}{k} \right)^{0.65} \left(\frac{m_{ej}}{0.01\,M_\odot} \right)^{0.35}$$

$$T_{peak} = 2200\,K \left(\frac{k}{10\,cm^2/g} \right)^{-0.41} \left(\frac{v}{0.1\,c} \right)^{-0.09} \left(\frac{m_{ej}}{0.01\,M_\odot} \right)^{-0.16}$$

(Grossman et al. 2014)

Opacity



Lanthanides & Actinides:

Open electron valence f-shell

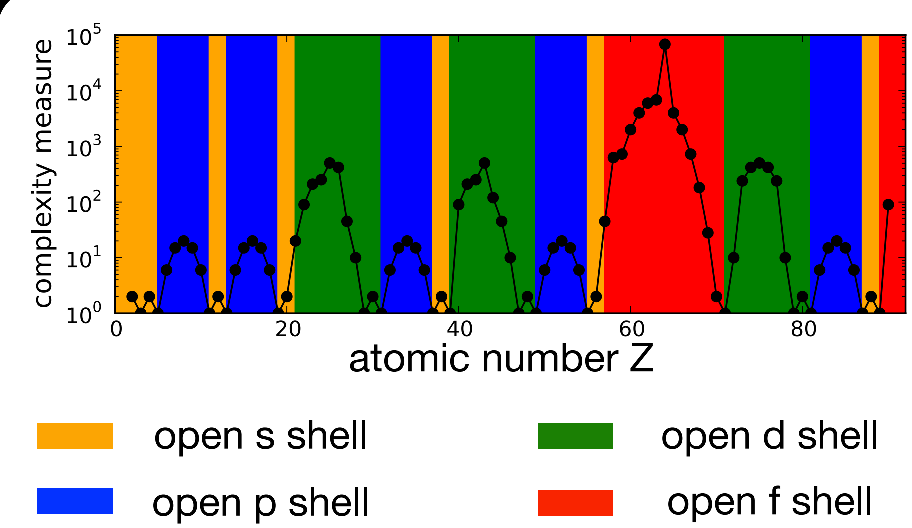
Complex electronic structure

↓

High number of transitions

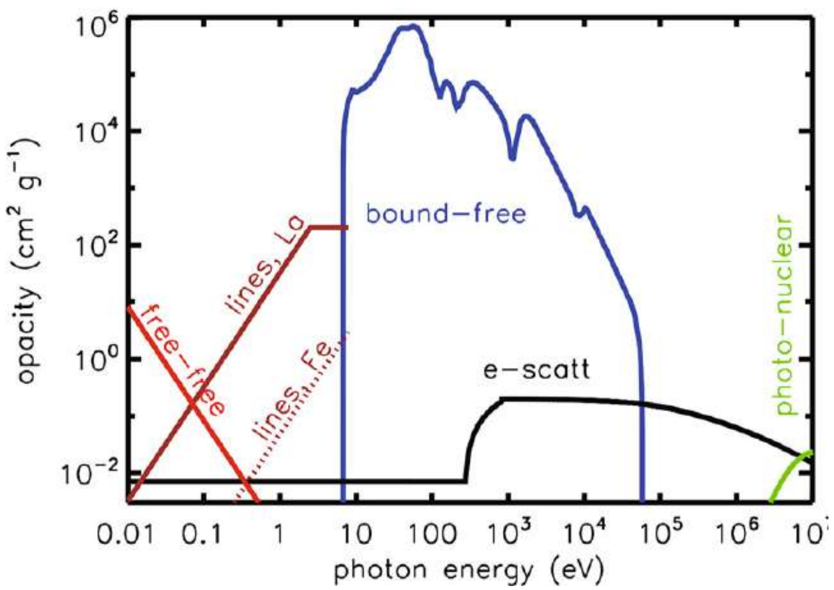
↓

High Opacity

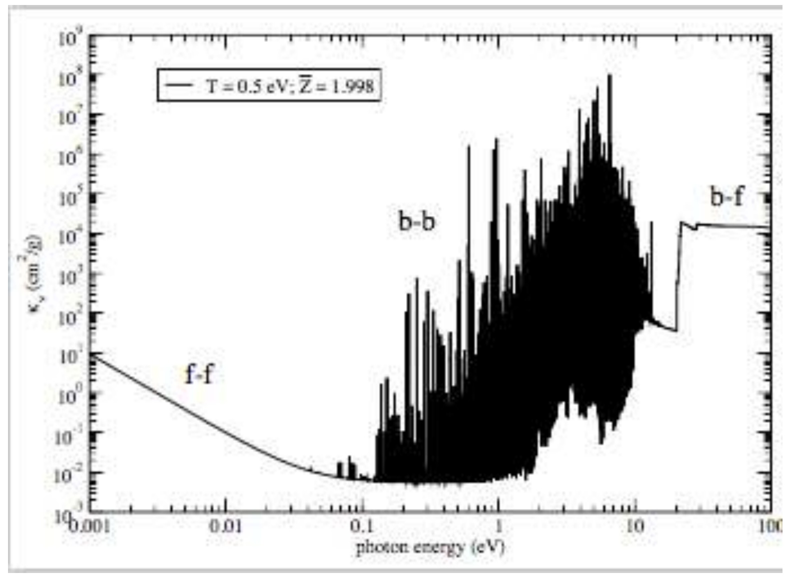


(Kasen, Badnell & Barnes 2013)

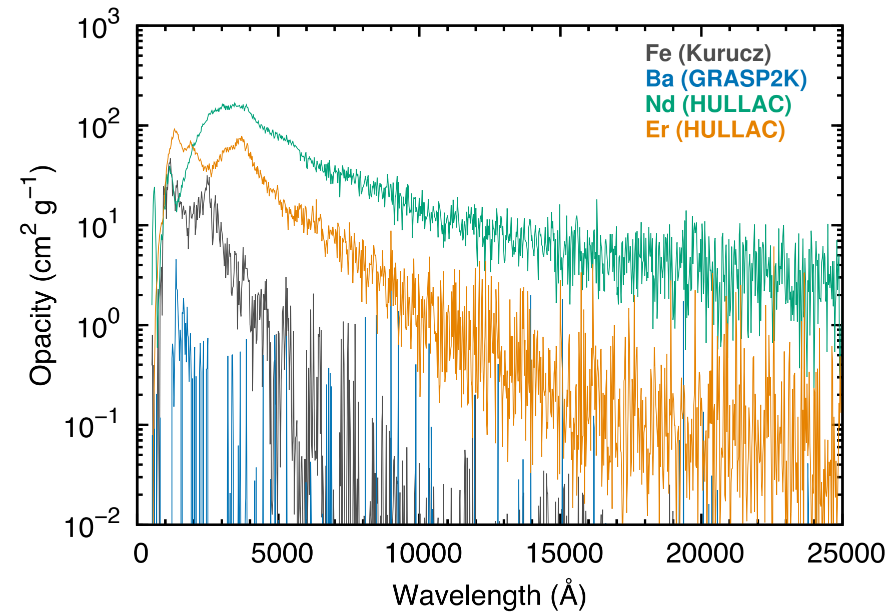
Opacity



(Metzger 2017)



(Fontes et al. 2017)



(Tanaka et al. 2017)

Radio - Far IR	→	Free - Free absorption
Near IR - Optical	→	Bound - Bound transitions
UV - X-ray	→	Bound - Free transitions
X-ray - γ-ray	→	Electron scattering

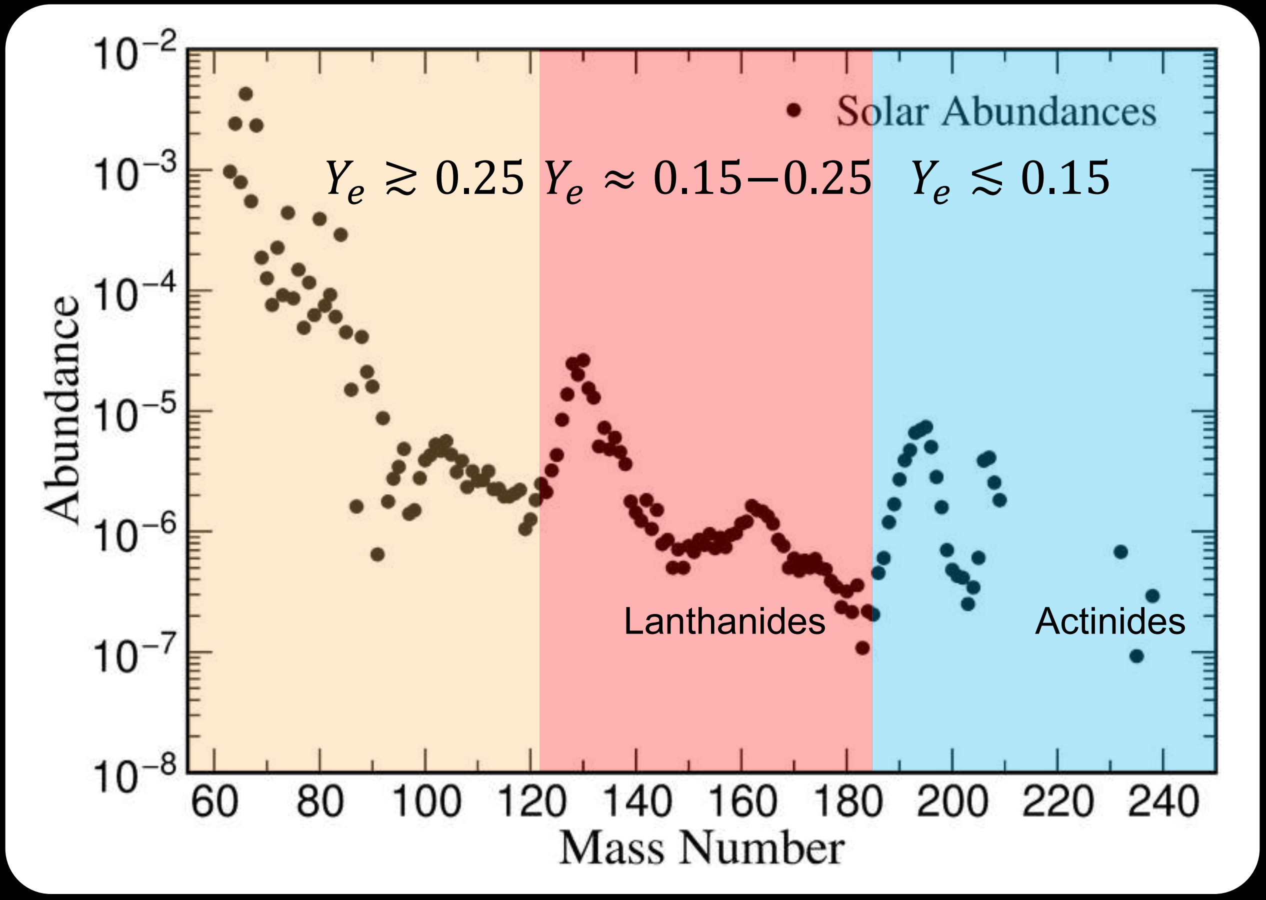
Nucleosynthesis and Opacity

$Y_e < 0.2$, r-process up to the 3rd peak $\mathrm{A} \sim 195$ (lanthanide rich) → $k < 20 - 30\,\mathrm{cm}^2/\mathrm{g}$

$0.25 < Y_e < 0.35$, r-processes up to the 2rd peak $\mathrm{A} \sim 130$ (few or no lanthanides) → $k \sim 3 - 5\,\mathrm{cm}^2/\mathrm{g}$

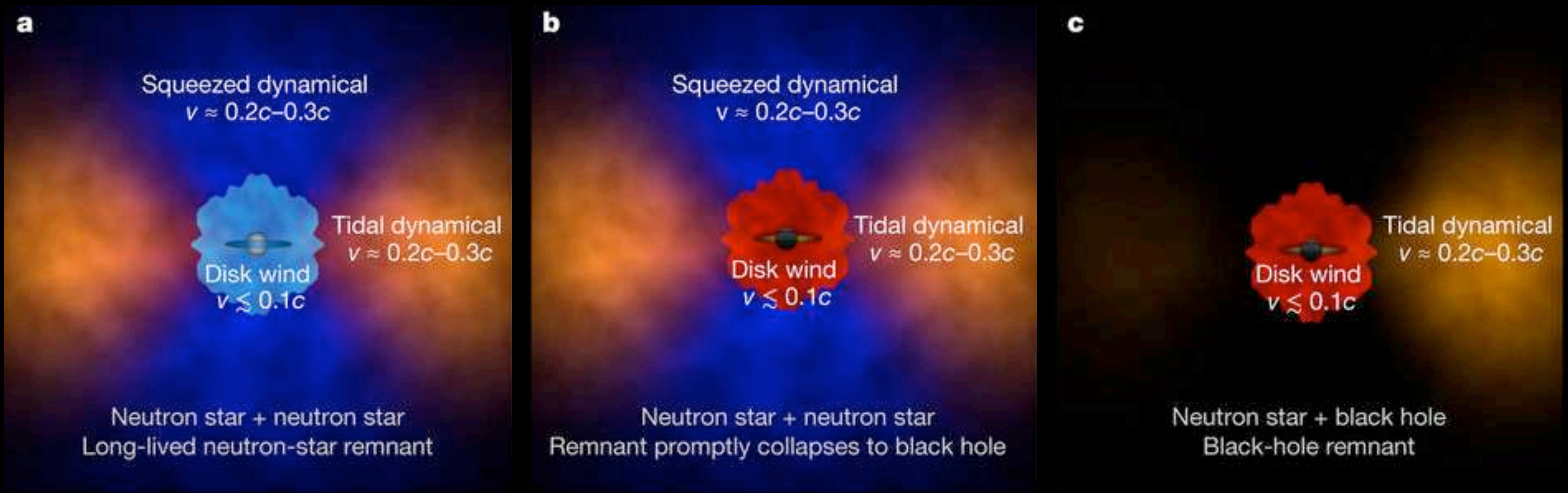
$Y_e \sim 0.40$, Fe group elements, with few or none r-process elements → $k \sim 1\,\mathrm{cm}^2/\mathrm{g}$

Tanaka+2019



Courtesy of Martinez-Pinedo

Blue & Red Kilonova



Red Kilonova

t_{peak}	Days- 1 week after the merger
L_{peak}	$< 10^{41}\ erg/s$
Spectral Range:	Optical Red/ NIR

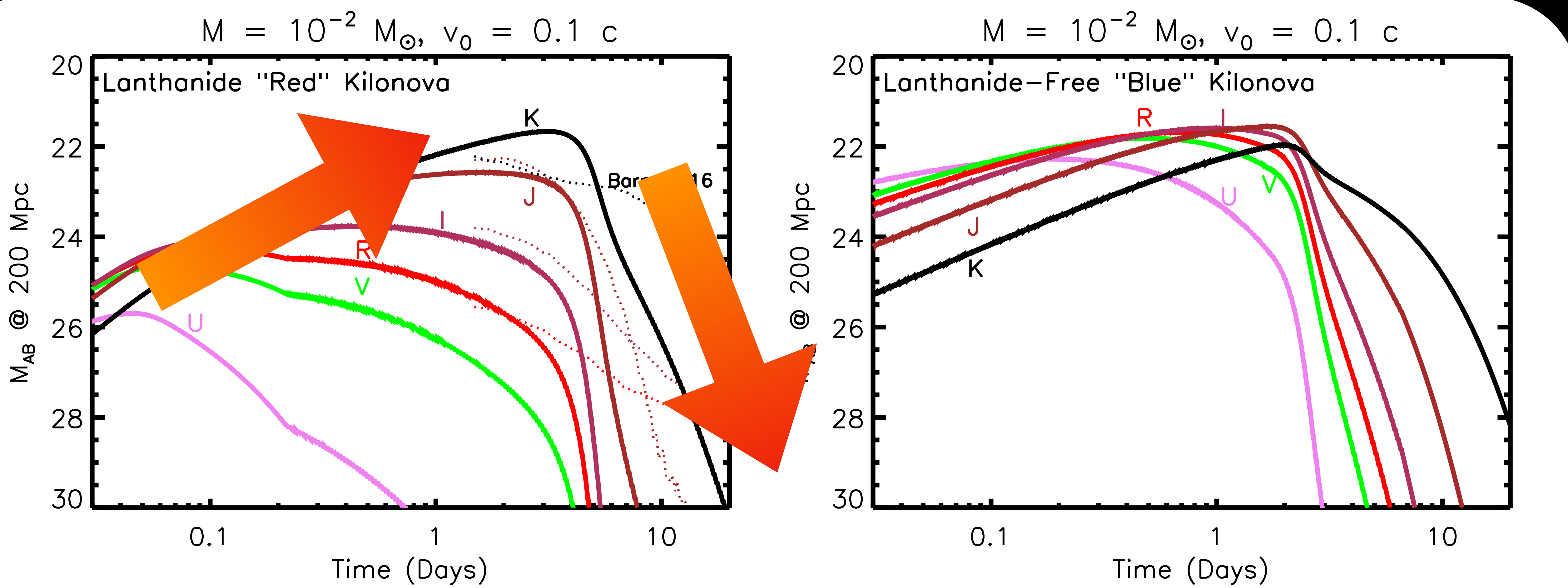
Blue Kilonova

t_{peak}	1-day after the merger
L_{peak}	$\gtrsim 10^{41}\ erg/s$
Spectral Range:	Optical

Lightcurves

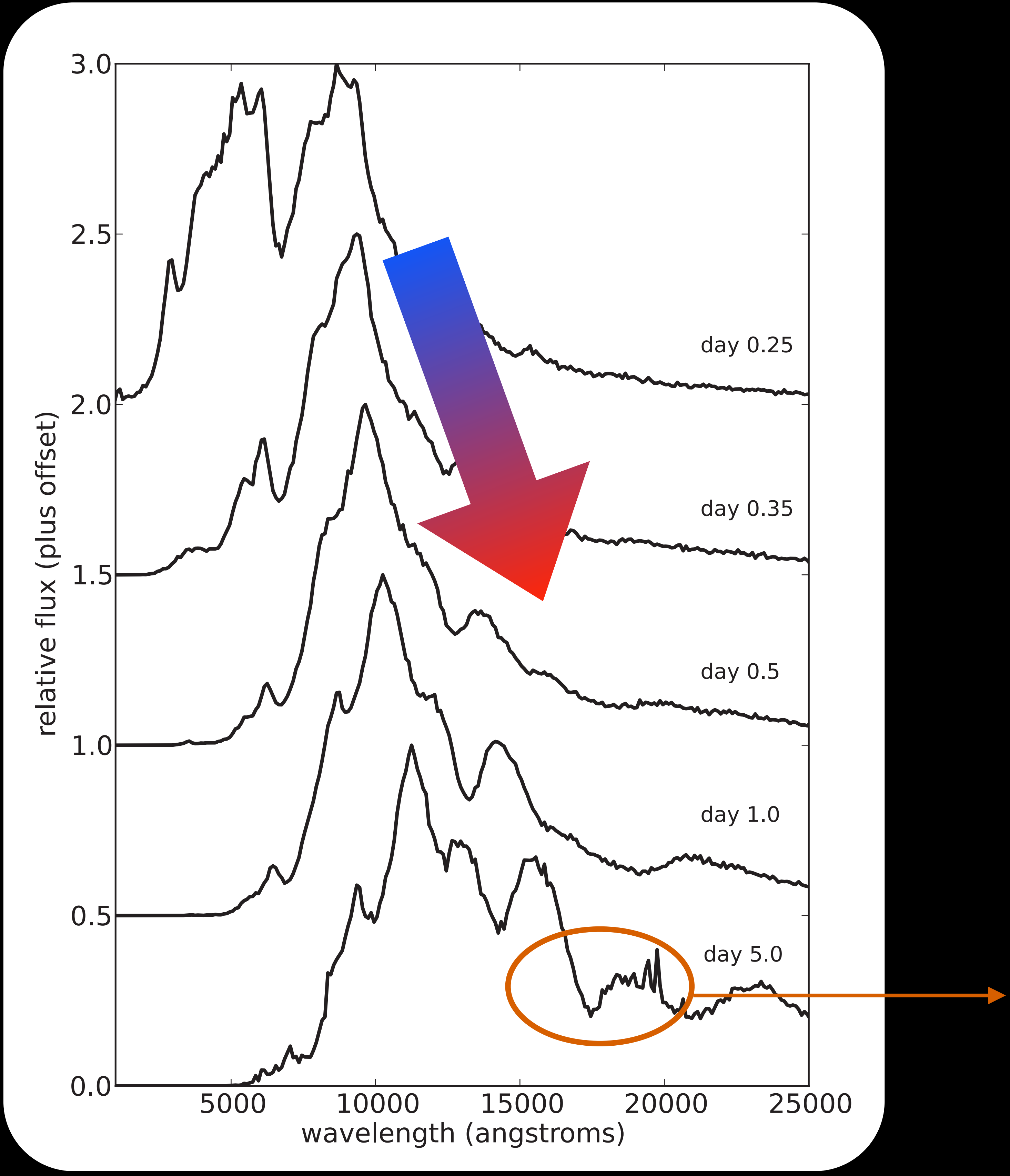
More matter becomes visible

Radioactive decay



(Metzger 2017)

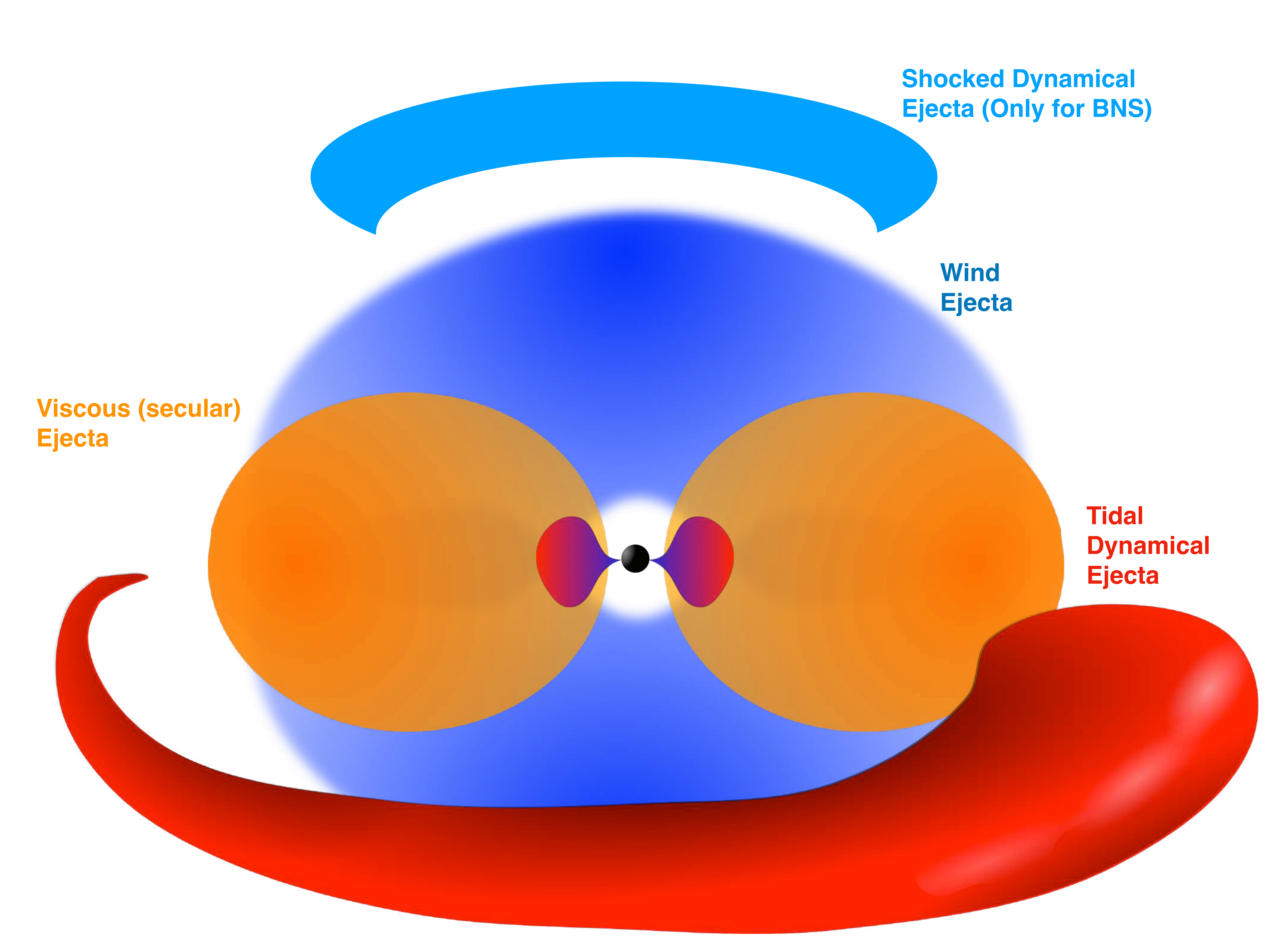
Spectra

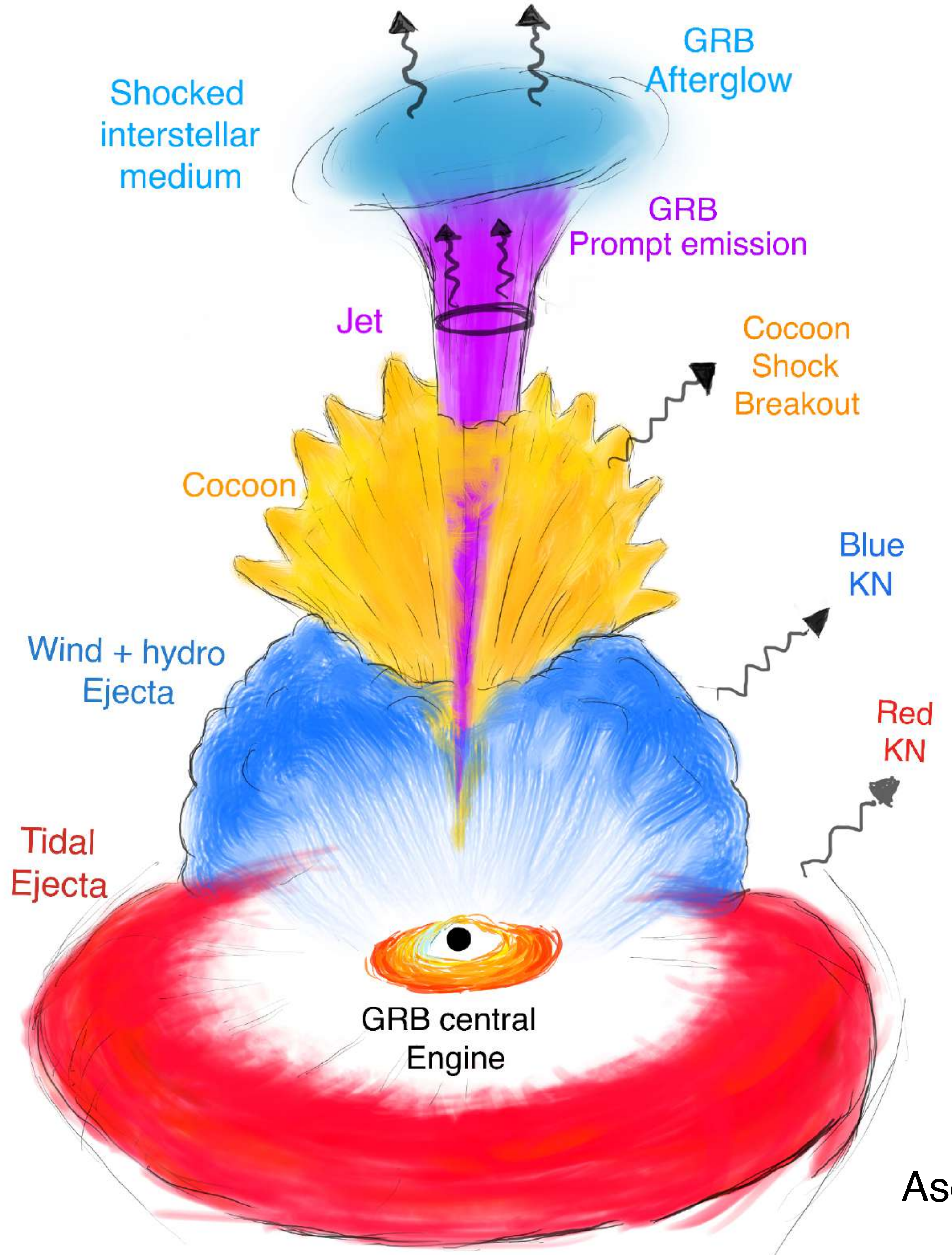


(Kasen et al. 2013)

Rapid evolution toward red colors

Broad spectral features arising from blending of many lines


Shocked Dynamical
Ejecta (Only for BNS)
Wind
Ejecta
Viscous (secular)
Ejecta
Tidal
Dynamical
Ejecta



Ascenzi et al. 2021

Dynamical Ejecta

$t \sim \mathcal{O}(ms)$ $v_{\rm dyn} \sim 0.2 - 0.3\,c$

$M_{\rm dyn}^{\rm BNS} \sim 10^{-4} - 10^{-3}\,M_{\odot}$ → Depends on mass ratio, total mass and EOS

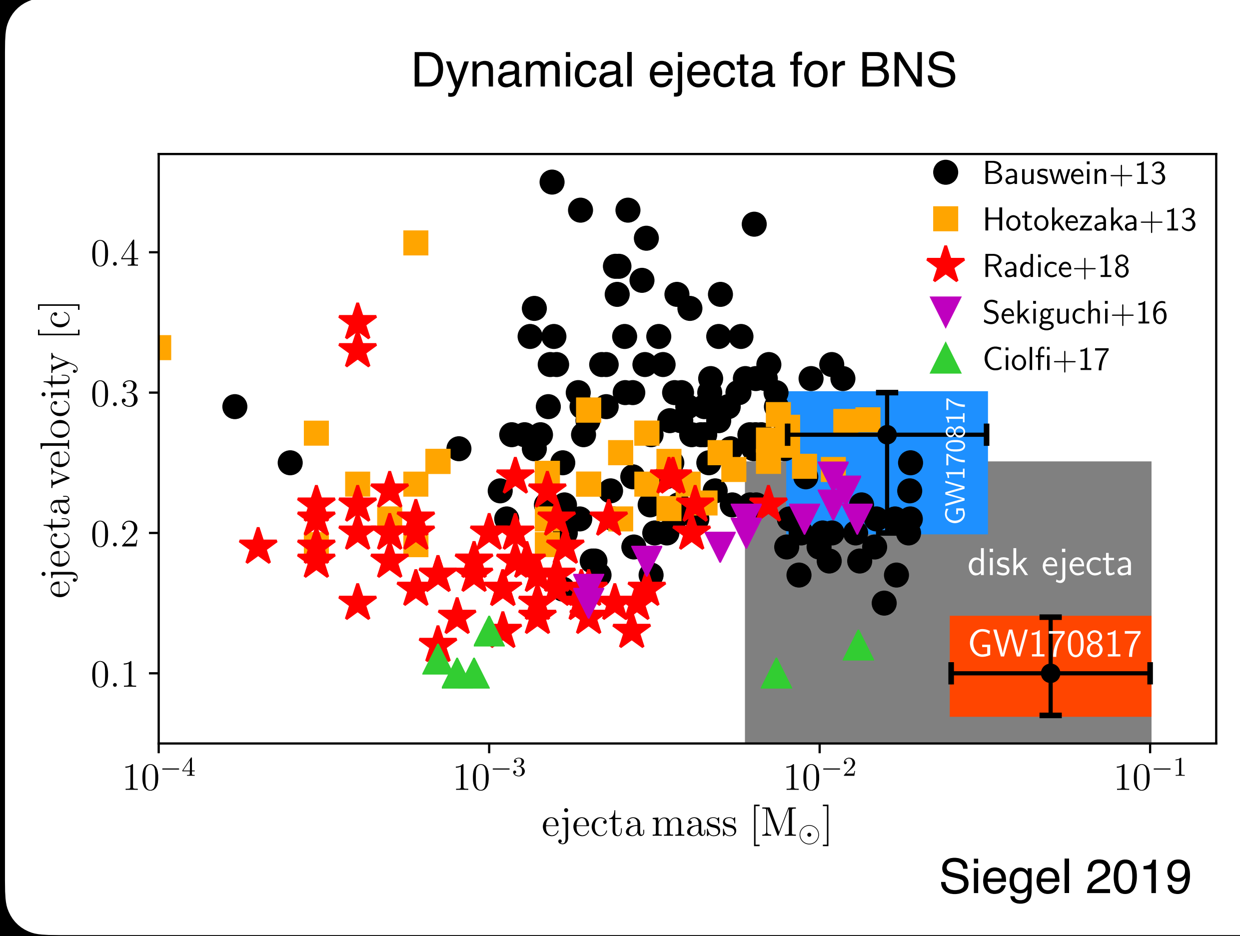
$M_{\rm dyn}^{\rm NS-BH} \sim 0 - 10^{-1}\,M_{\odot}$ → Depends on mass ratio, EOS, BH mass and spin

Tidal Ejecta →

- Both in BNS and NS-BH
- Along the equatorial plane
- Cold matter (low Y_e)
- Asymmetric binaries expelling more mass

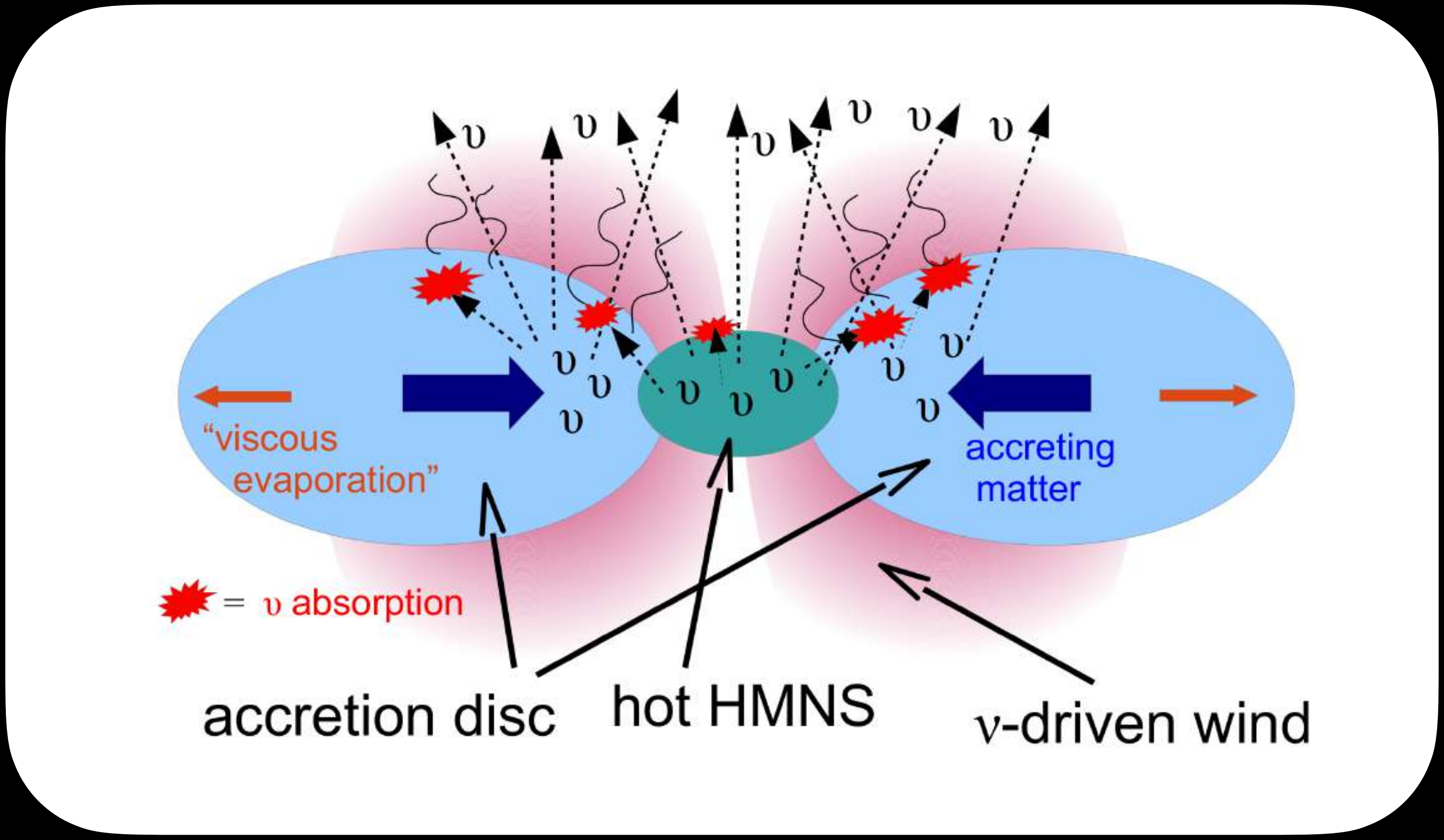
Shocked Ejecta →

- Only in BNS
- Ejected by the quasi-radial pulsation of the remnant
- All the directions
- Hot matter (high Y_e)



Wind Ejecta from the disk

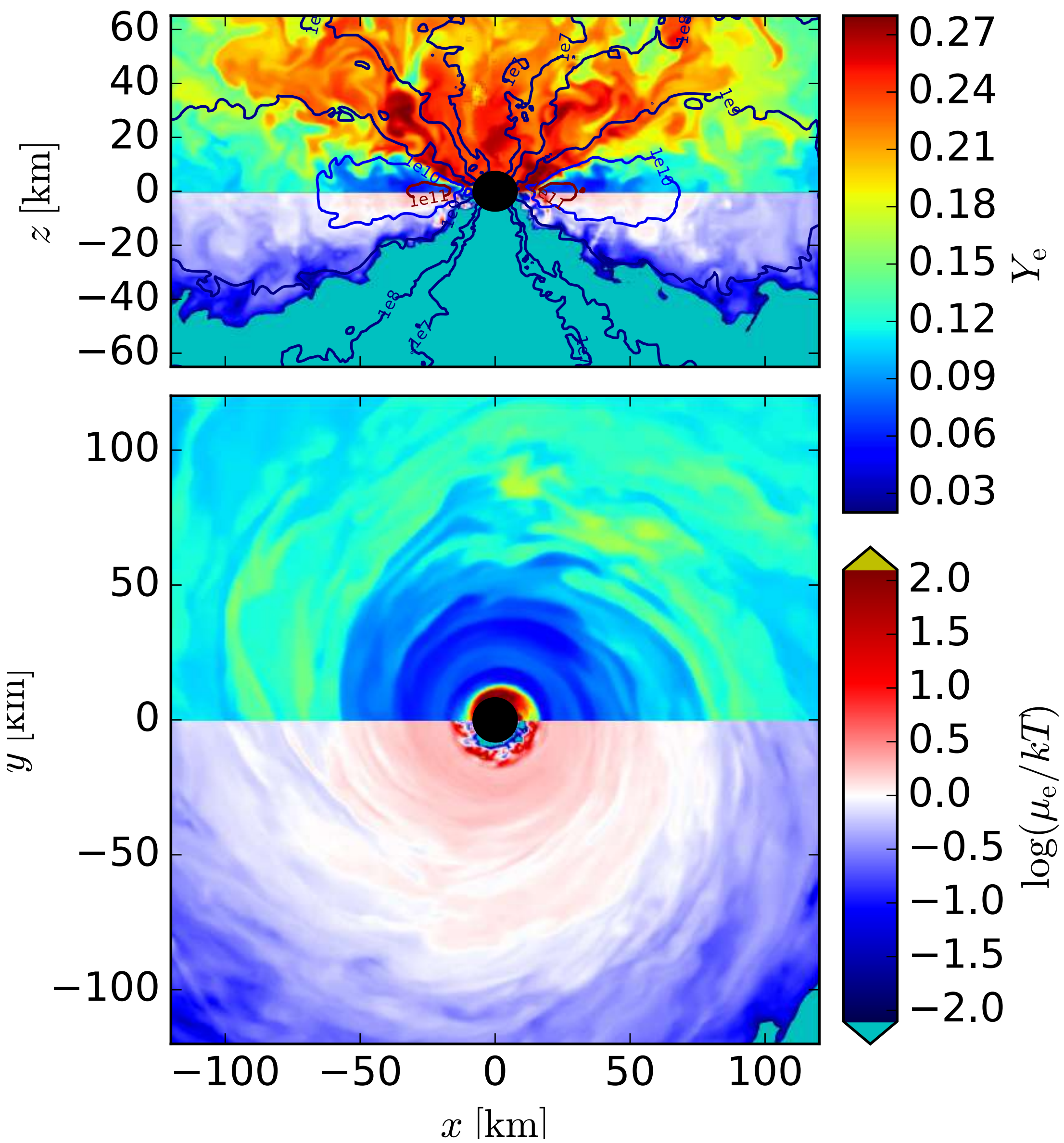
- Both the metastable NS and the accretion disk emits neutrinos with a luminosity of $L_\nu \sim 10^{53}\,\mathrm{erg/s}$
- A fraction of neutrinos are absorbed and deposit their energy in the disk
- When the deposited energy overcomes the gravitational binding energy an outflow with $\dot{M} \sim 10^{-3}\,M_\odot/s$ and $v < 0.1\,c$ is generated, this happens on a timescale of $t_{wind} \sim 10\,\mathrm{ms}$
- **5%** of disk mass unbind
- If the metastable NS survives for more than 50 ms, $\sim 10^{-3}\,M_\odot$ can be also unbound from the NS surface . This can be substantially increased if the star has a strong ordered magnetic field (Metzger+2018).
- The lifetime of the metastable NS influences the Y_e of the ejecta



Perego+2014

Viscous secular ejecta

- When the accretion rate decreases the neutrino cooling is quenched. The heating due to viscosity and nuclear recombination are not balanced anymore by the neutrino cooling and an outflow is launched.
- The disk settles in a mildly degenerate state, where the pair production is suppressed (Beloborodov 2003, Siegel & Metzger 2017). The number density of electrons overcomes that of positrons. Electron capture by protons favoured with respect to positron capture by neutrons. **The outflow is neutron rich**, with $0.1 < Y_e < 0.4$.



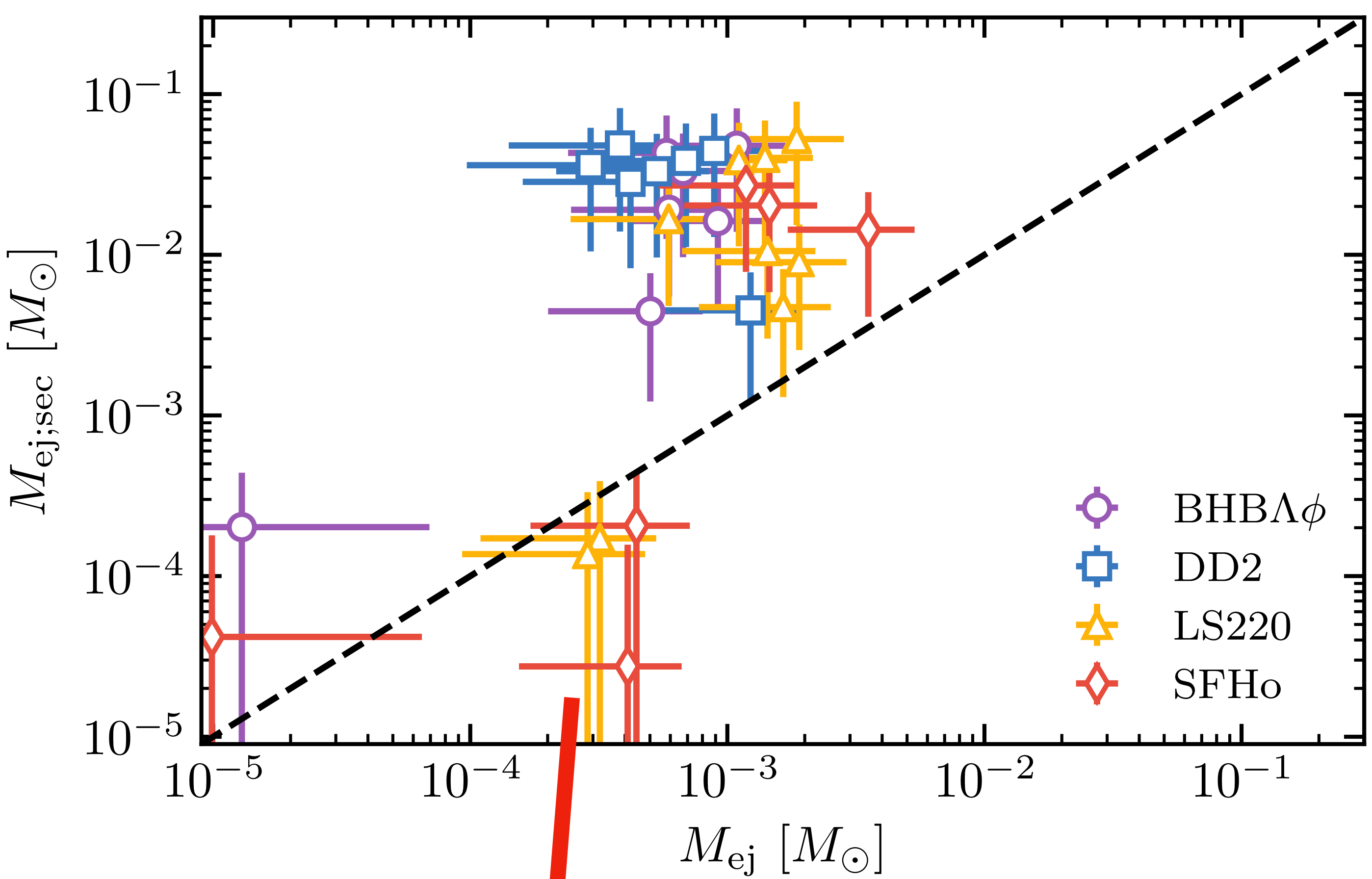
Siegel & Metzger 2017

$$p + e^- \rightarrow n + \nu_e$$ Favoured

$$n + e^+ \rightarrow p + \bar{\nu}_e$$ Disfavoured

- Up to 40% of disk mass unbound
- A long lived NS can generate an increase of Y_e

Dynamical Ejecta vs Disk Outflow



Radice+2018

Prompt BH formation

Viscous Ejecta dominates over the dynamical ejecta in therms of mass content

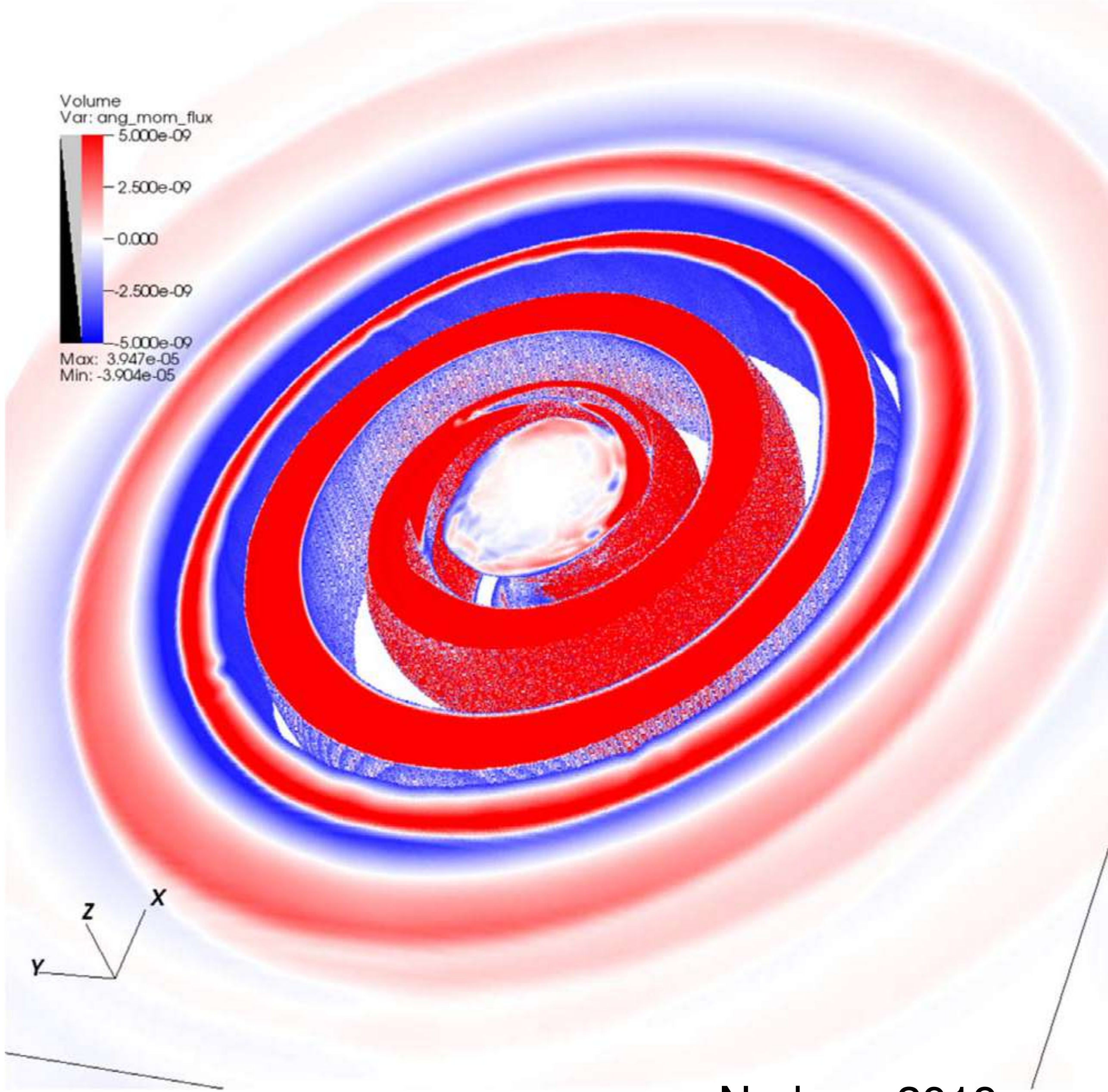
Spiral Wave Ejecta (?)

Oscillations of the remnant excite spiral waves in the disk, which contributes to the matter outflow

$Y_e \sim 0.25$

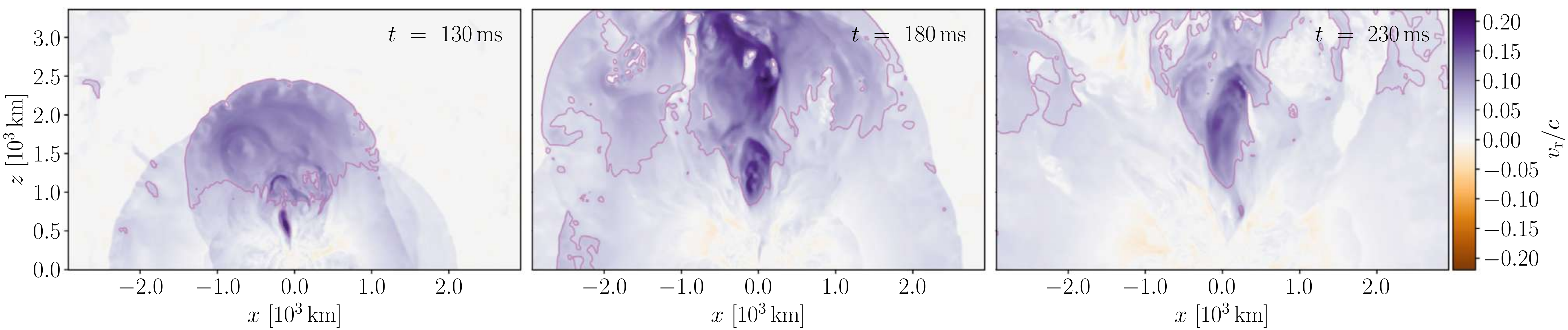
$v \sim 0.2\,c$

$M \sim 10^{-2}\,M_\odot$



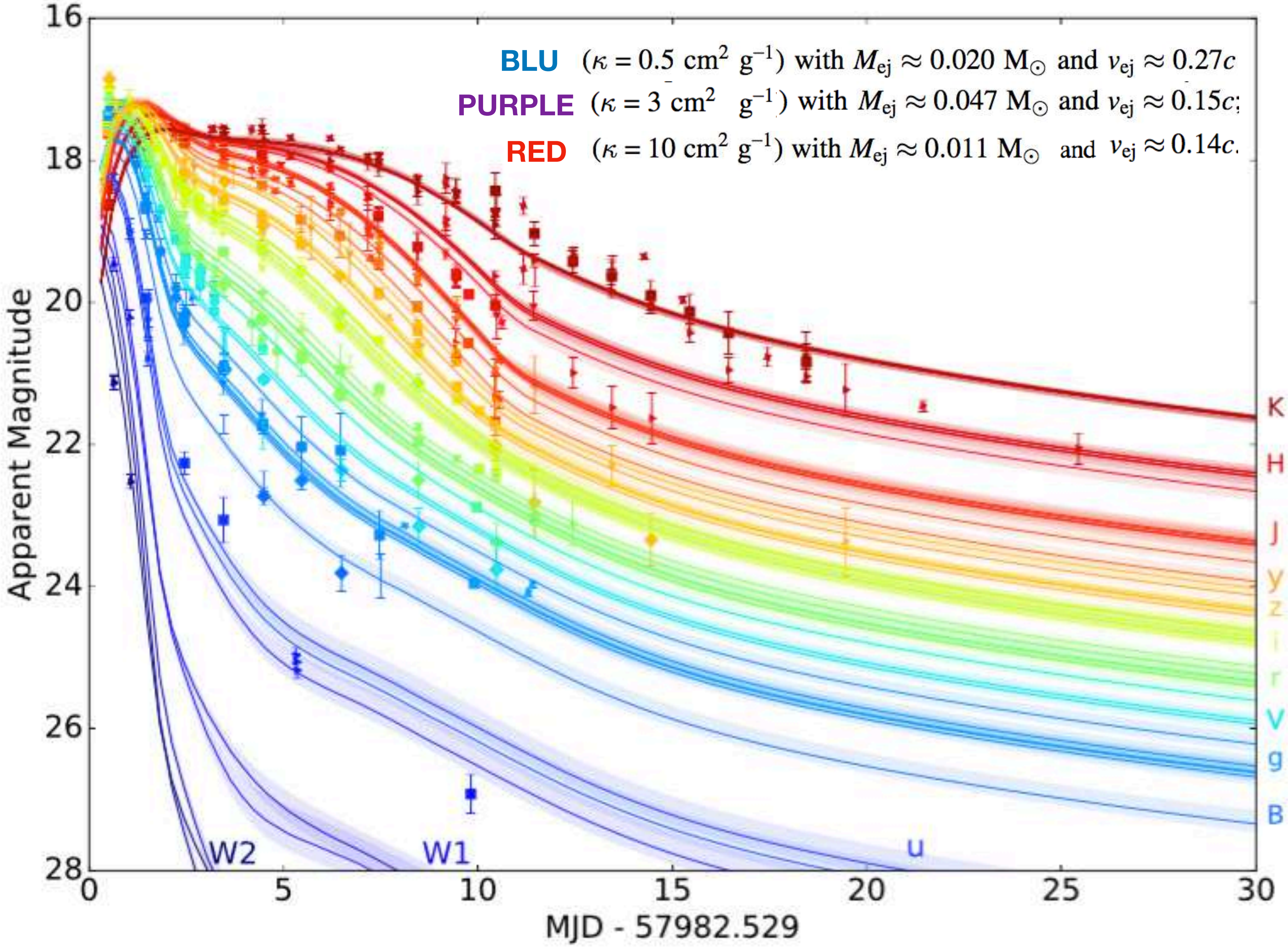
Nedora+2019

Magnetic HMNS wind



Ciolfi & Kalinani 2020

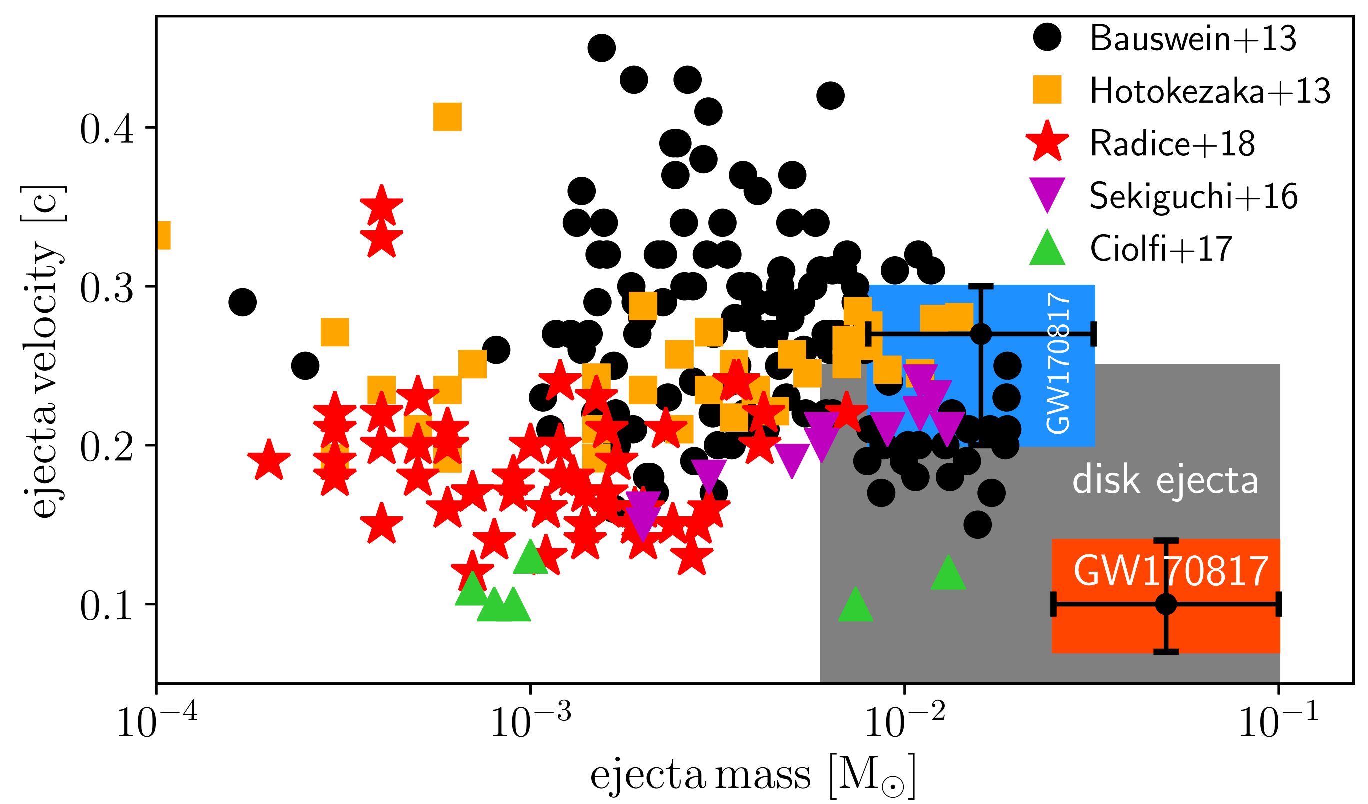
AT2017gfo Lightcurve



Villar et al. (2017)

Open Problems

What is the origin of the blue component?



Siegel 2019

Blue Component

$$k = 0.5\,\mathrm{cm^2/g}$$

$$v = 0.25\,c$$

$$M = 0.02\,M_\odot$$

- The velocity of blue component is compatible with a dynamical ejecta origin, but the mass is too high
- Part of the dynamical ejecta mass (i.e. tidal ejecta) cannot generate the blue component.

What is the origin of the blue component?

Ejecta type	Quantity?	Velocity?	Y_e?
Tidal tail dynamical	Maybe, if $q \lesssim 0.7$[a]	✓	**Too low**
Shock-heated dynamical	Maybe, if $R_{1.6} \lesssim 11$ km[b]	✓	✓ if NS long-lived
Accretion disk outflow	✓ if torus massive	**Too low**	✓ if NS long-lived
HMNS ν-driven wind	**Too low**	**Too low**	**Too high?**
Spiral wave wind	✓	Maybe	✓
Magnetized HMNS wind	✓ if NS long-lived	✓	✓

[a] Where $q \equiv M_1/M_2$ and M_1, M_2 are the individual NS masses (Dietrich et al. 2017b; Dietrich and Ujevic 2017; Gao et al. 2017)

[b] However, a small NS radius may be in tension with the creation of a large accretion disk needed to produce the red KN ejecta (Radice et al. 2018c)

Metzger+2018

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$$M = 0.02\,M_\odot$$

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- Part of the dynamical ejecta mass (i.e. tidal ejecta) cannot generate the blue component.

Does the interaction between GRB jet and ejecta play any role? (eg. see Lazzati+2017, Bromberg+2018, Piro & Kollmeier 2018)

Are BNS mergers responsible for all the r-process nucleosynthesis?

Challenges

(Siegel 2019)

- r-process abundances in the metal poor halo stars
- r-process abundances in dwarf galaxies and GC
- r-process abundances in MW disk
- r-process abundances with respect to α-element abundances

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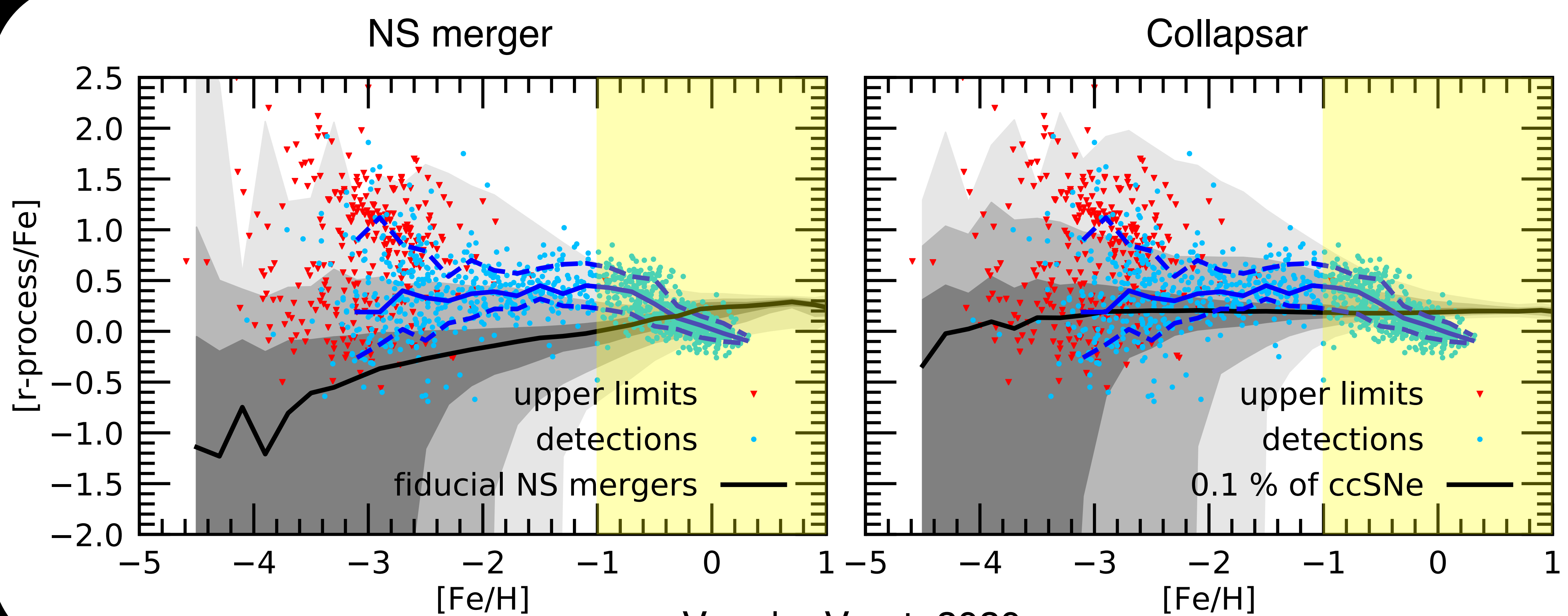
If the NS mergers were the only r-process nucleosynthesis channel, we would expect an increase median r-process abundance with metallicity, due to the delay of the merger with respect to the SFR. Instead at low metallicity the median seems flat



Van der Voort+2020

Are BNS mergers responsible for all the r-process nucleosynthesis?

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- r-process abundances in dwarf galaxies and GC
- r-process abundances in MW disk
- r-process abundances with respect to α-element abundances

- High r-process enrichment are observed in some DGs and in some stars inside GCs.
- Both DGs and GCs are characterised by a small escape velocity (10 km/s and 10-100 km/s, respectively) and very short star formation period (< 1 Gyr and 10-100 Myr, respectivelly)
- NS merger are characterised by high natal kicks and delay with respect to star formation

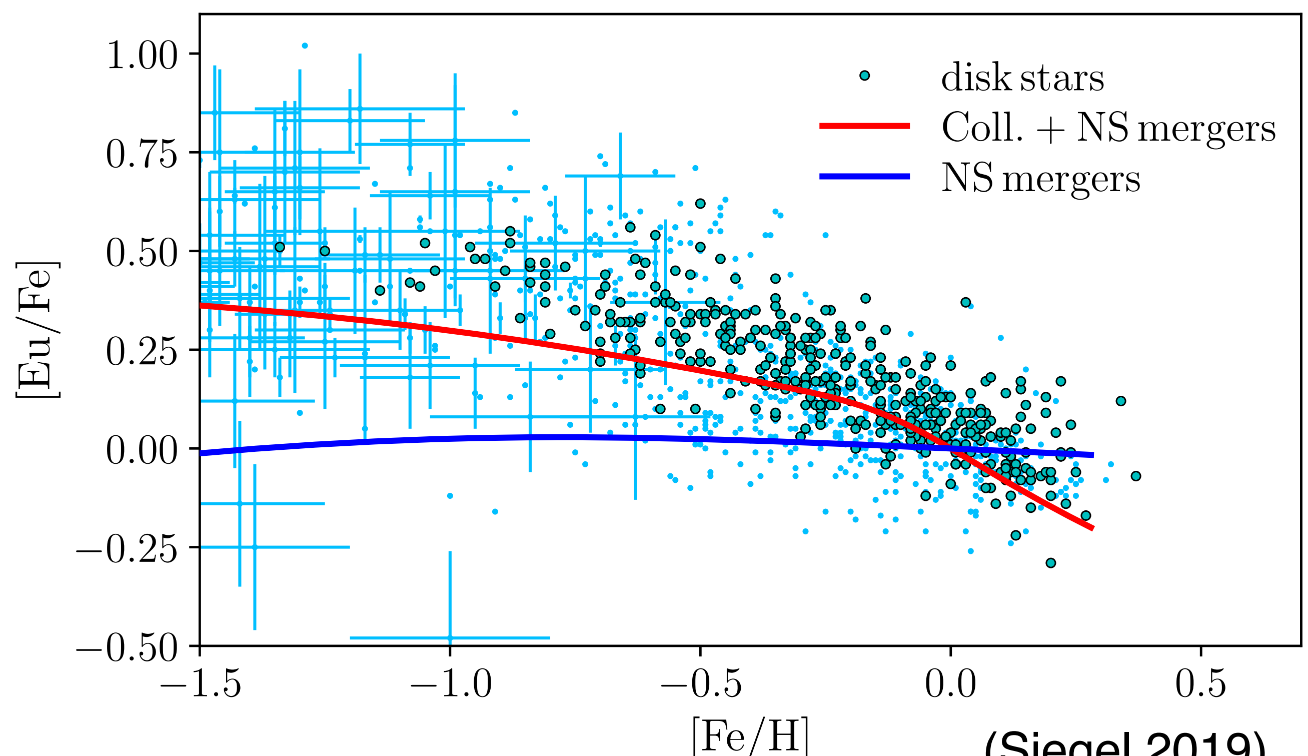
Are BNS mergers responsible for all the r-process nucleosynthesis?

Challenges

(Siegel 2019)

- r-process abundances in the metal poor halo stars
- r-process abundances in dwarf galaxies and GC
- r-process abundances in MW disk
- r-process abundances with respect to α-element abundances

At high metallicity the main Fe production channel are type Ia SNe, that has the same NS merger time delay distribution with respect to SFR. We should expect r-process abundance to be constant with respect to metallicity, instead we observe a decreasing trend. If collapsar contributes to r-process enrichment they preferentially happens at lower metallicity, explaining the decreasing trend.



(Siegel 2019)

Are BNS mergers responsible for all the r-process nucleosynthesis?

Challenges

(Siegel 2019)

- r-process abundances in the metal poor halo stars
- r-process abundances in dwarf galaxies and GC
- r-process abundances in MW disk
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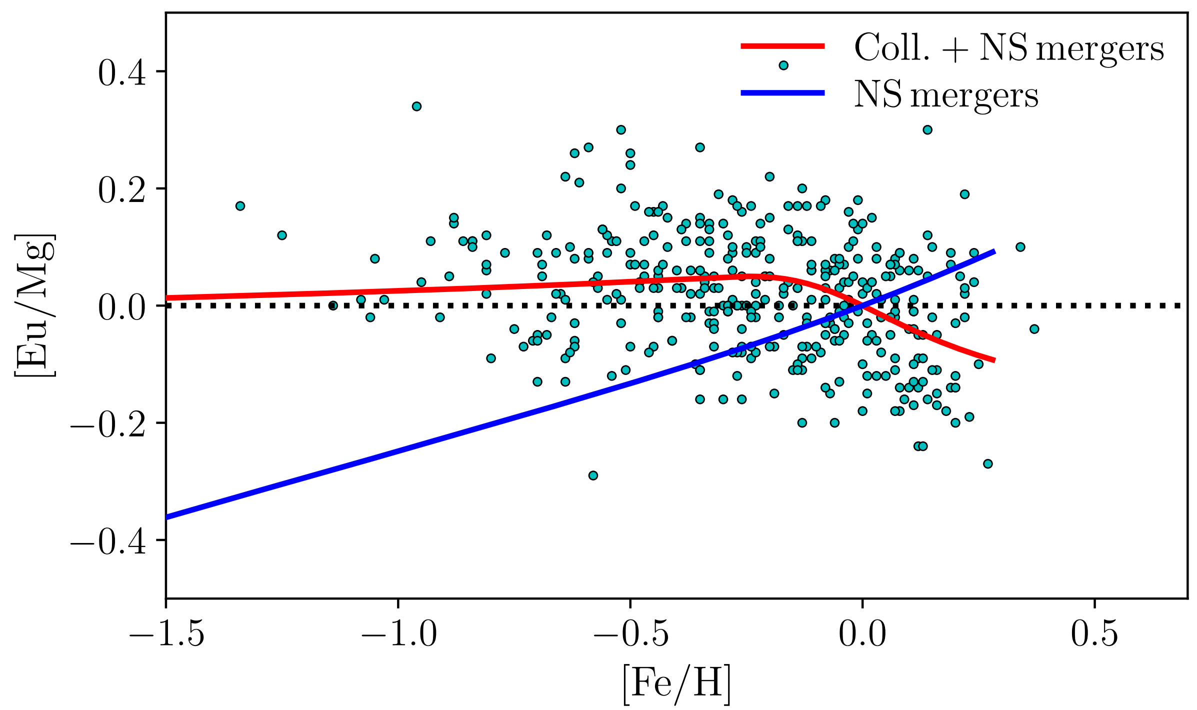
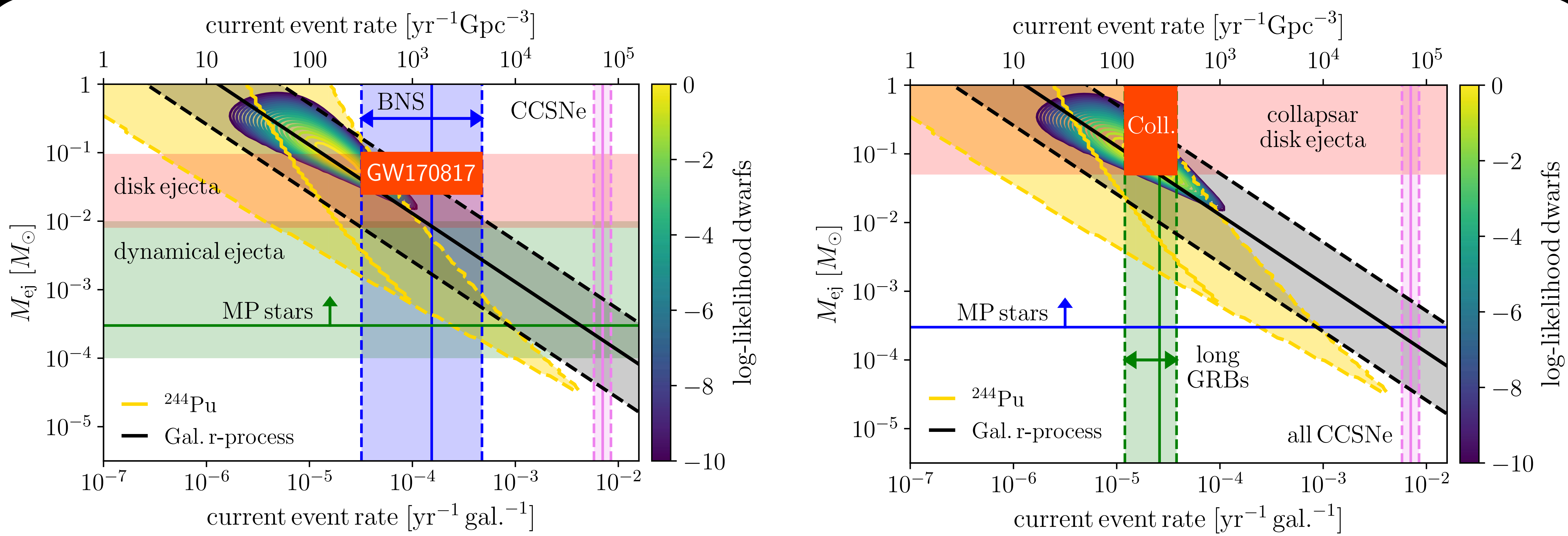
Due to the delay time between CCSN and BNS merger the production of r-process elements is expect to lag behind α-elements if BNS merger are the main r-process element produces. Instead the ratio of Eu/Mg is constant with metallicity.



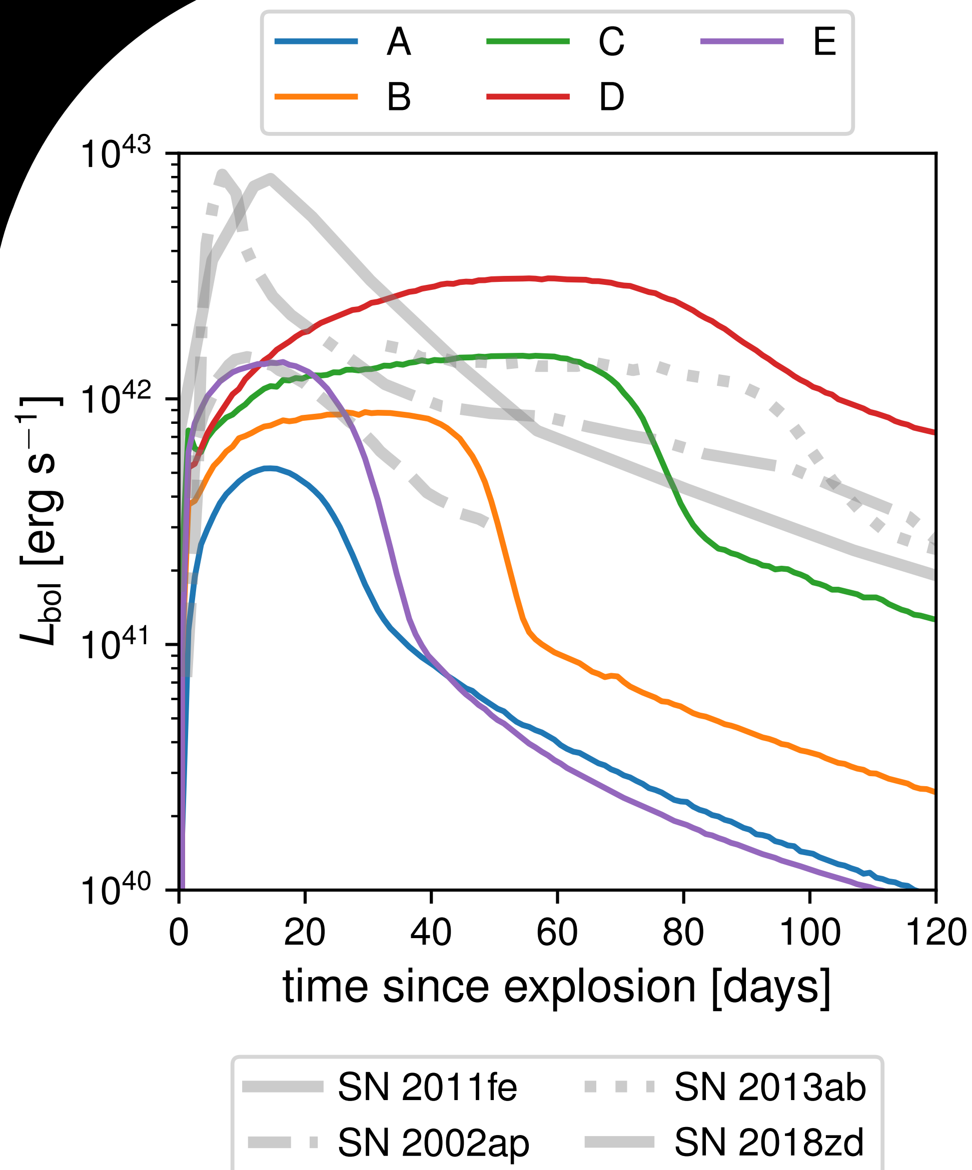
(Siegel 2019)

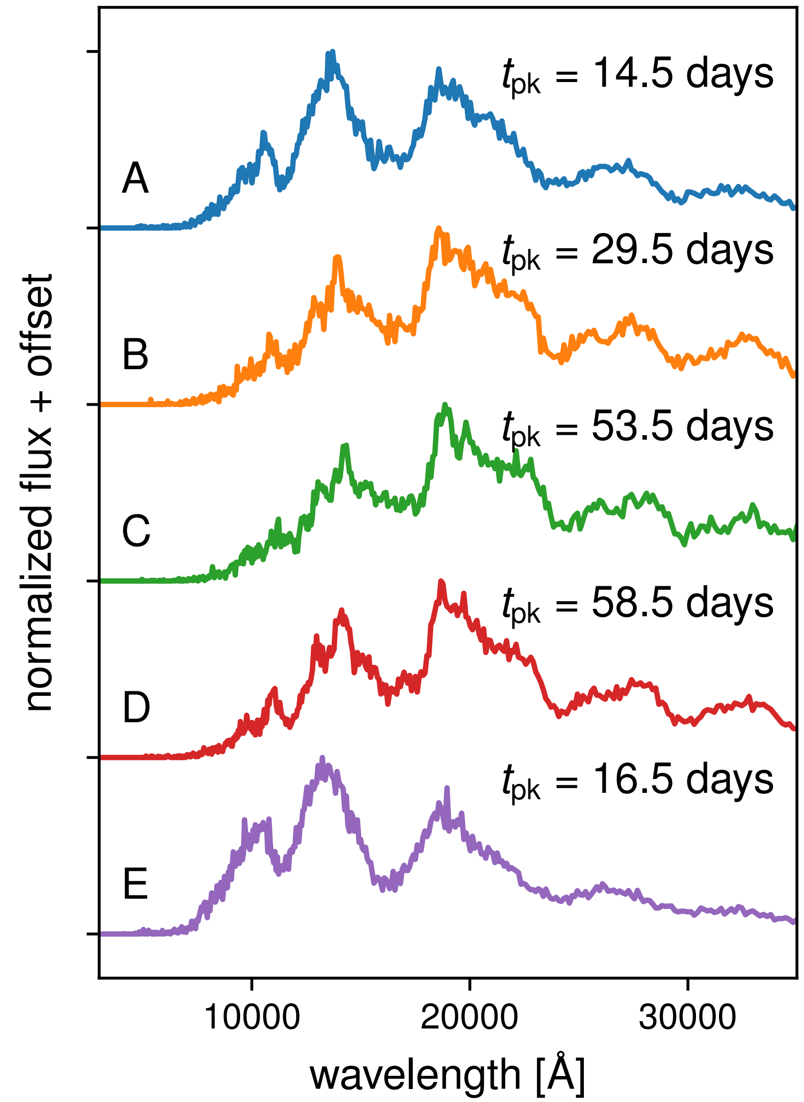
Are BNS mergers responsible for all the r-process elements nucleosynthesis?



(Siegel 2019)

Can Collapsars produce KNs ?





Model	M_{ej} ($M_\odot$)	v_{ej} (c)	M_{Ni} ($M_\odot$)	M_{lrp} ($M_\odot$)	X_{La} (10^{-3})	$R^{(a)}_{Rubin}$ (yr^{-1})	$R^{(b)}_{Roman}$ (yr^{-1})
a	8.6	0.1	0.019	0.83	1.4	0.01	0.02
b	31.0	0.1	0.012	8.28	17.0	0.03	0.4
c	35.6	0.1	0.087	23.2	4.0	0.1	2
d	50.0	0.1	0.53	9.59	0.53	0.1	4
e	60.0	0.1	0.0	5.6	0.17	0.2	0.01

(Siegel+ 2021)