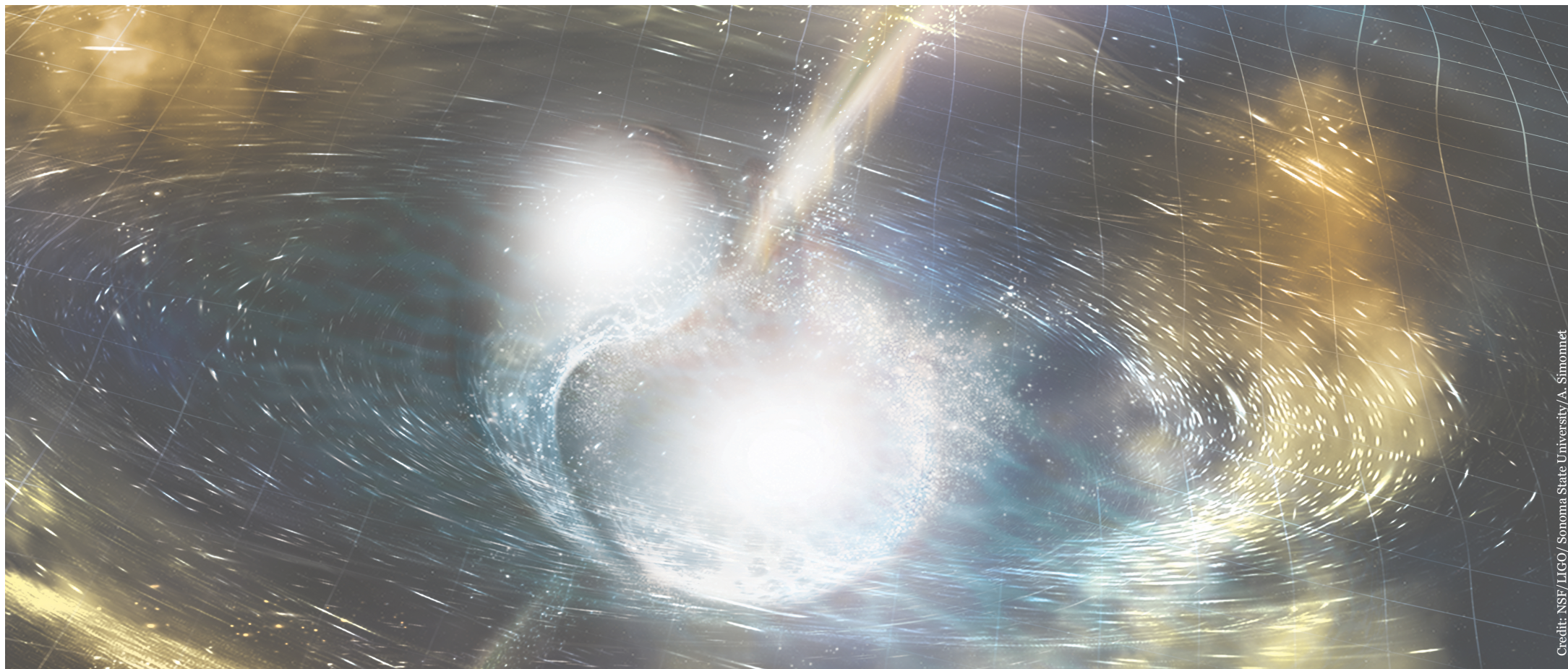




Università
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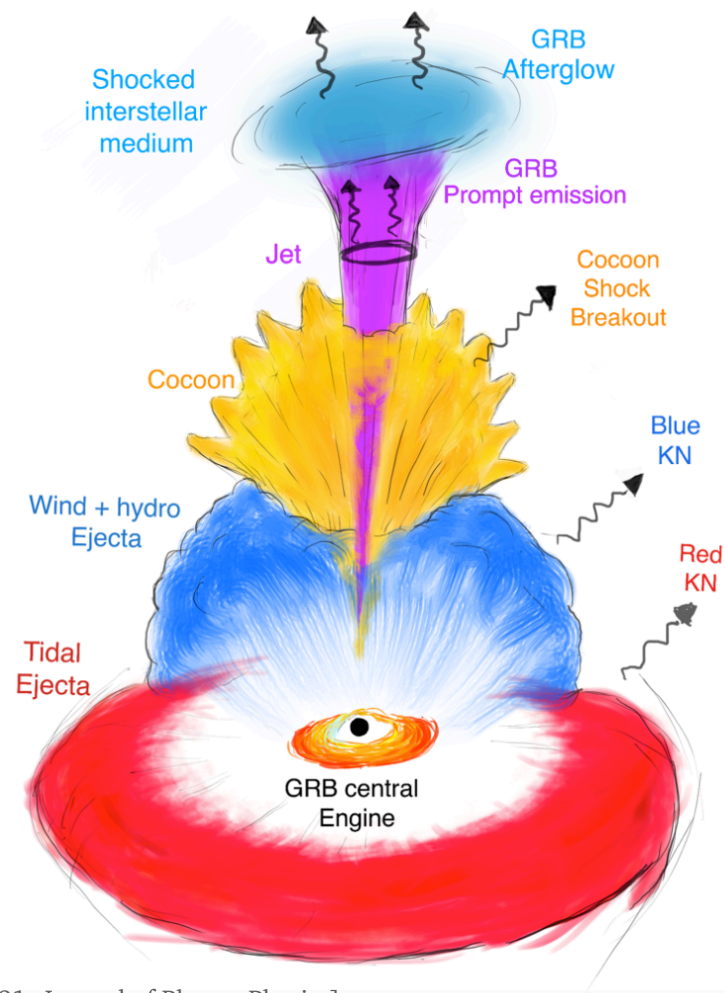
Modelling of jet-ejecta interaction in BNS mergers and the impact on the kilonova emission

Mattia Bulla



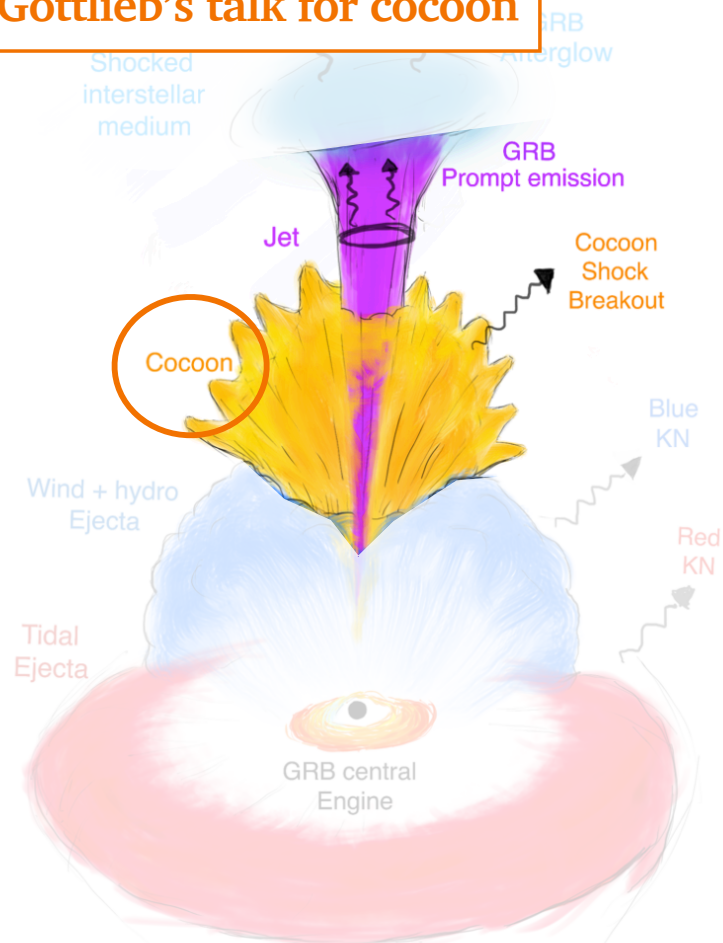
Credit: NSF/LIGO/ Sonoma State University/ A. Simonnet

A multi-messenger view of neutron star mergers

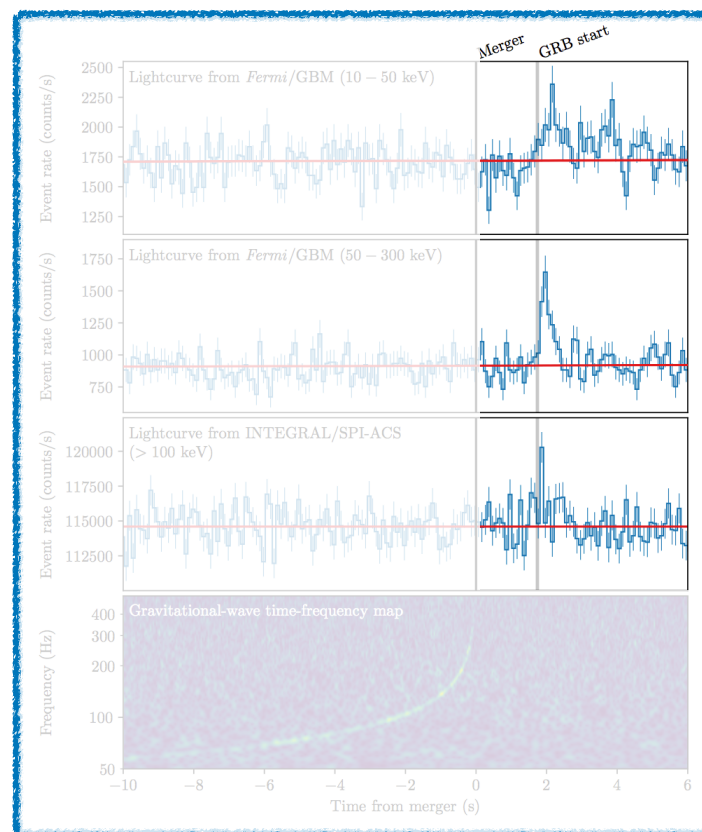


A multi-messenger view of neutron star mergers

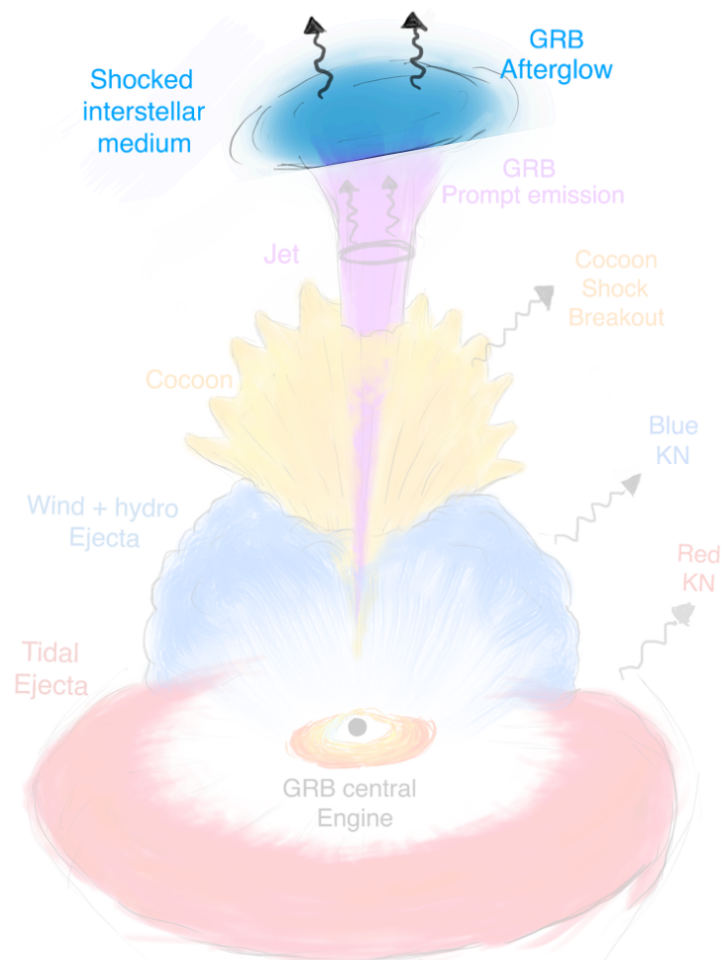
See Gottlieb's talk for cocoon



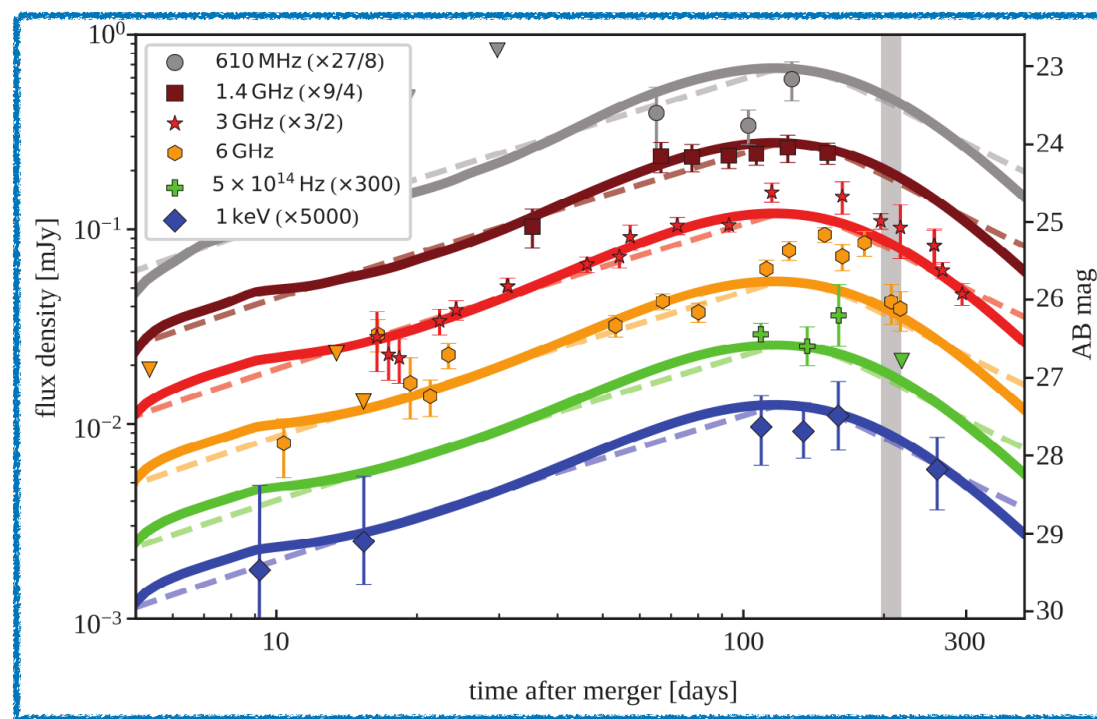
Gamma Ray Burst (GRB)



A multi-messenger view of neutron star mergers



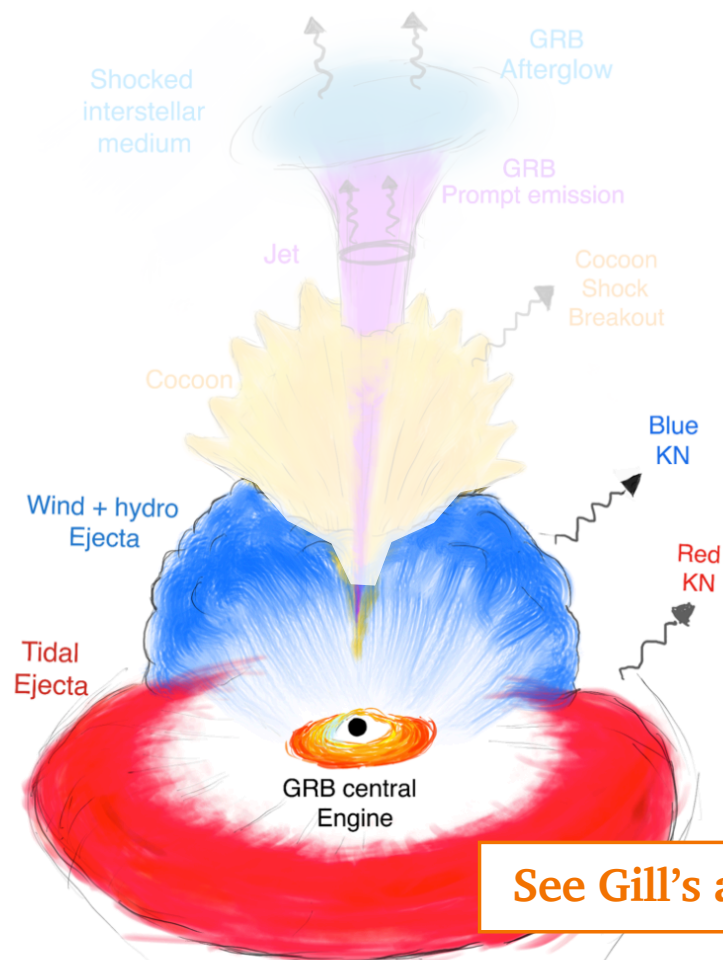
GRB afterglow



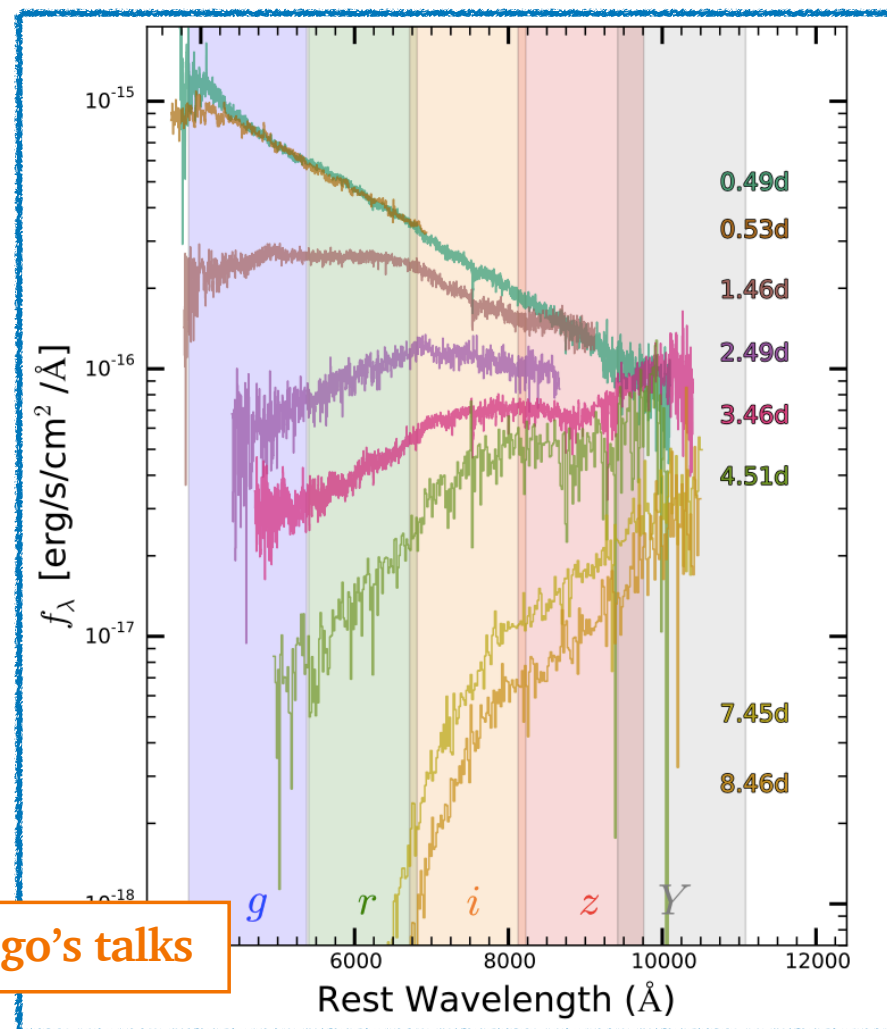
[Ghirlanda+2019, Science]

A multi-messenger view of neutron star mergers

Kilonova (KN)



See Gill's and Perego's talks



[Shappee+2017, Science]



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Kilonovae in a nutshell



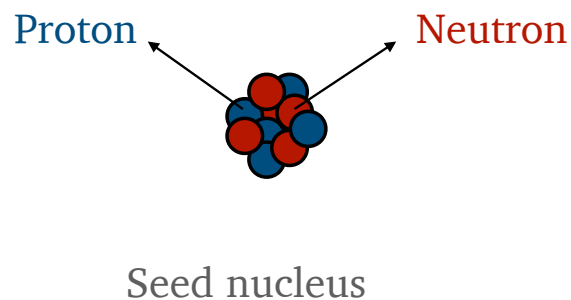
‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]

Kilonovae in a nutshell

‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

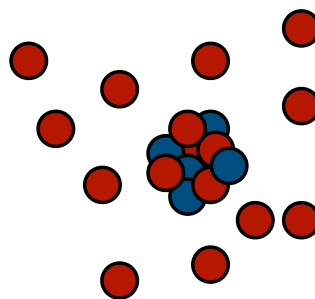
[Metzger 2020, LRR]



Kilonovae in a nutshell

‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

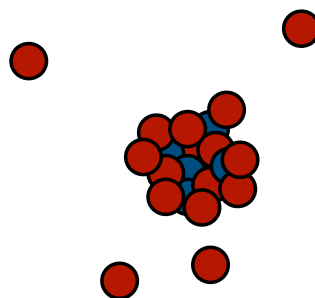
[Metzger 2020, LRR]



Kilonovae in a nutshell

‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the radioactive decay of **heavy, neutron-rich elements** synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]

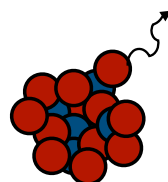


Rapid neutron captures [r-process]

Kilonovae in a nutshell

‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the **radioactive decay** of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]

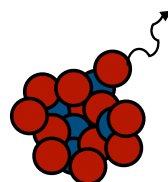


Unstable nuclei $\rightarrow$ radioactive decay

Kilonovae in a nutshell

‘Kilonovae are day to week-long thermal, supernova-like transients, which are powered by the **radioactive decay** of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]



$T \sim 5000 - 10\,000 \text{ K @1 day}$

α - and β - particles, γ -rays and fission fragments

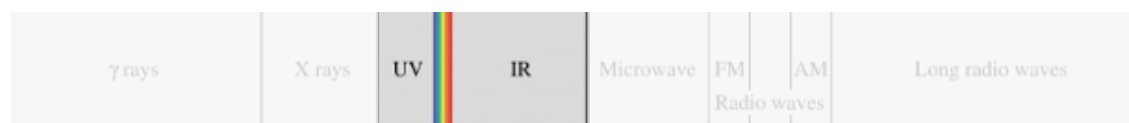


Decay products thermalise within the ejected material and set its temperature

Kilonovae in a nutshell

‘Kilonovae are day to week-long **thermal**, supernova-like transients, which are powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]

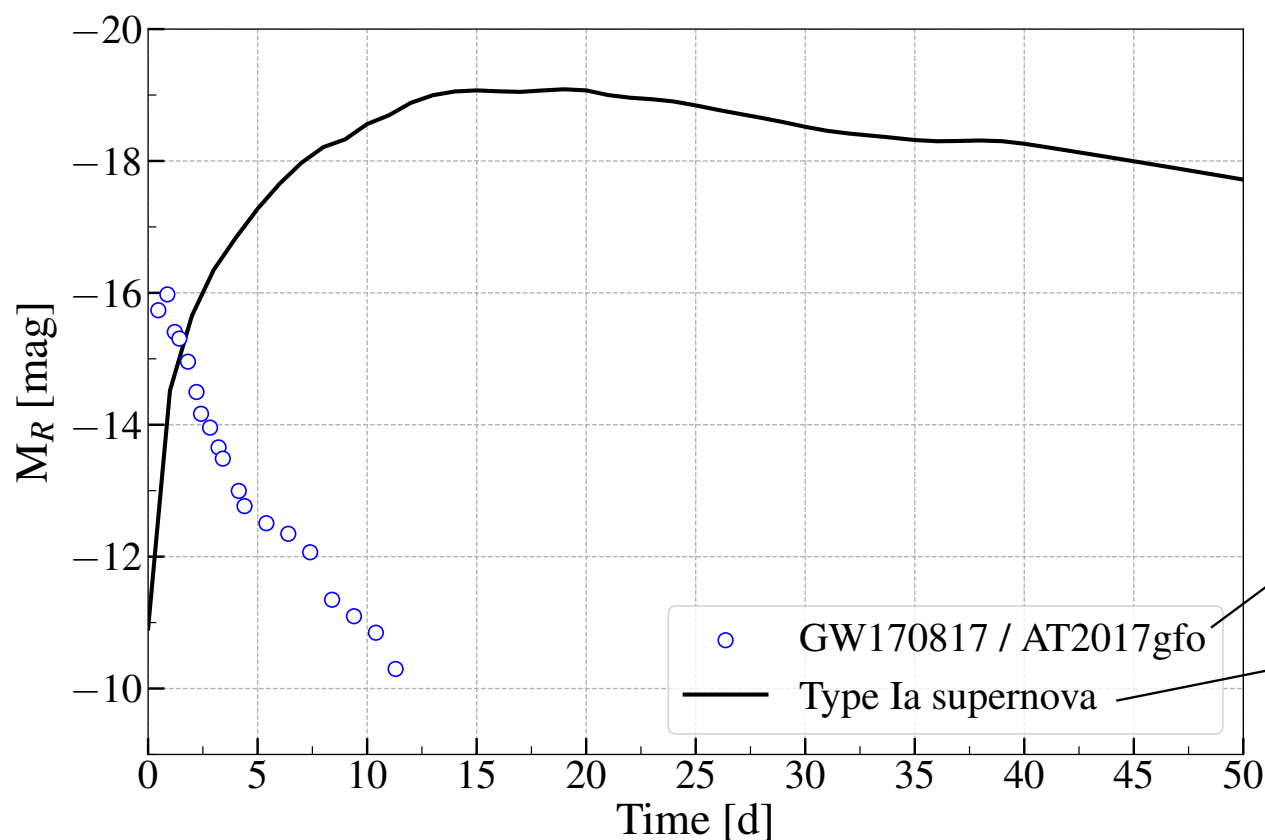


Thermal emission at ultraviolet-optical-infrared wavelengths

Kilonovae in a nutshell

‘Kilonovae are **day to week-long** thermal, **supernova-like transients**, which are powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding merger ejecta’

[Metzger 2020, LRR]



See Bianco's talks

Mass of radioactive material $\sim 0.01 M_{\odot}$

Mass ejected $\sim 0.01 M_{\odot}$

NS+NS

Mass of radioactive material $\sim 0.5 M_{\odot}$

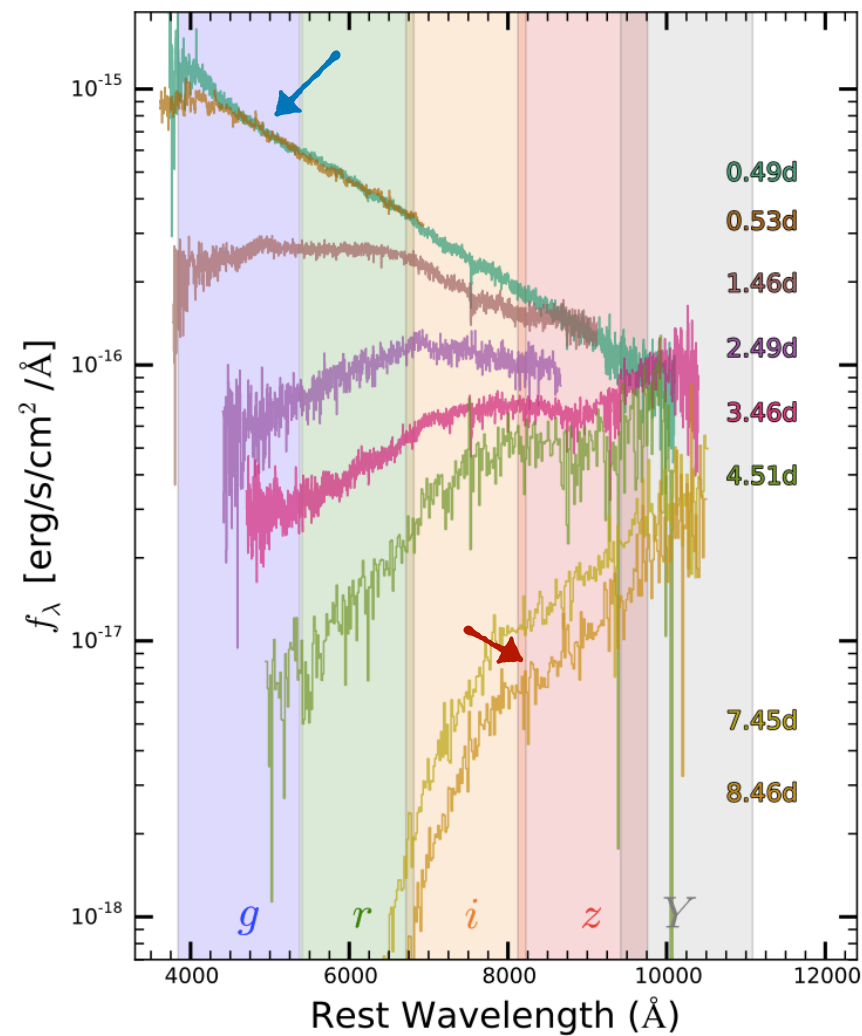
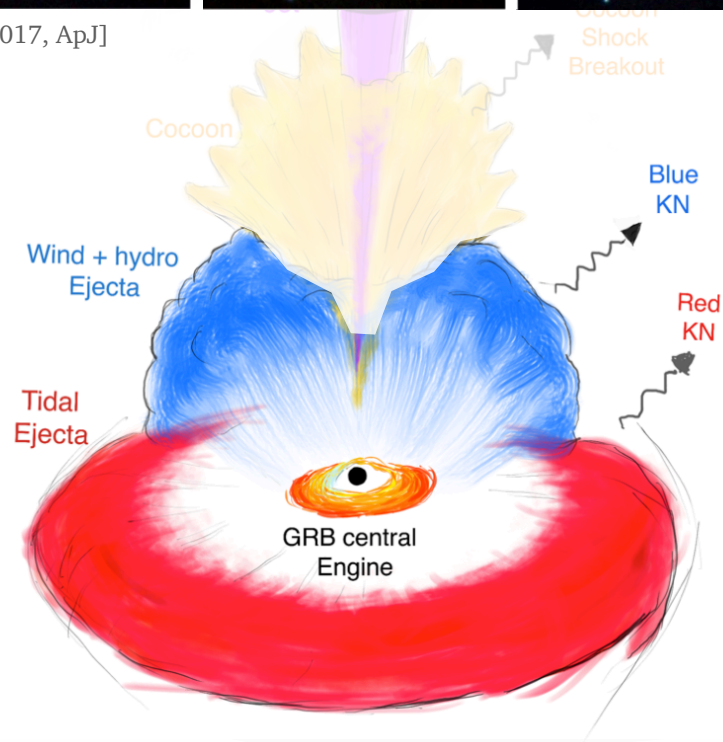
Mass ejected $\sim 1.4 M_{\odot}$

Exploding white dwarf

Multi-component asymmetric ejecta in GW170817



[Tanvir+2017, ApJ]



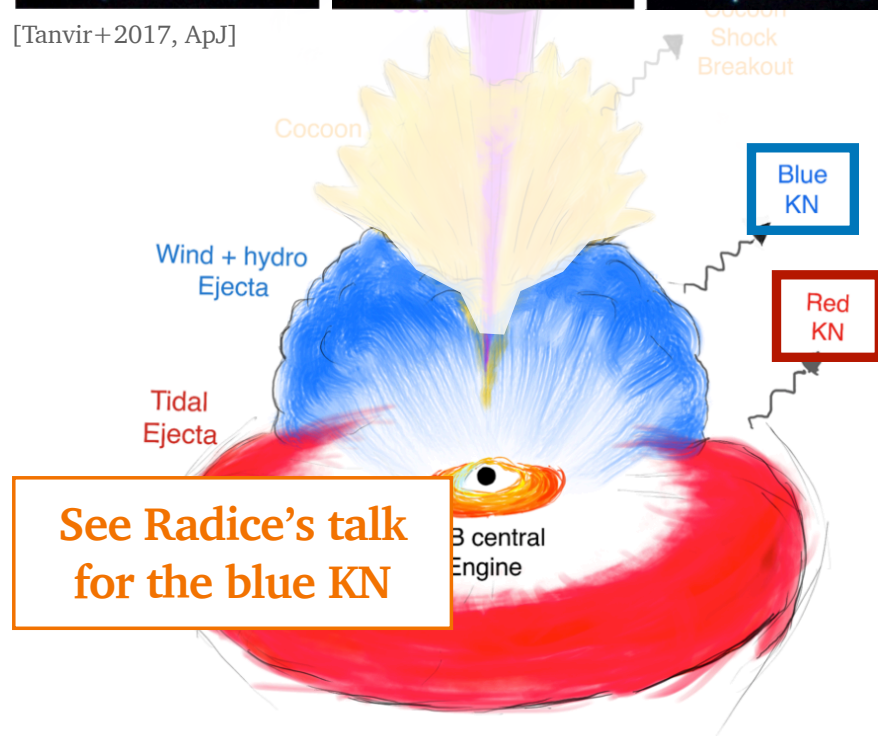
Multi-component asymmetric ejecta in GW170817



[Tanvir+2017, ApJ]

Blue KN: early times powered by decay of 'light' r-process elements with 'low' UV/optical opacities, i.e. flux escapes in UV/optical

Red KN: late times powered by decay of 'heavy' r-process elements with 'high' UV/optical opacities, i.e. flux is suppressed in UV/optical



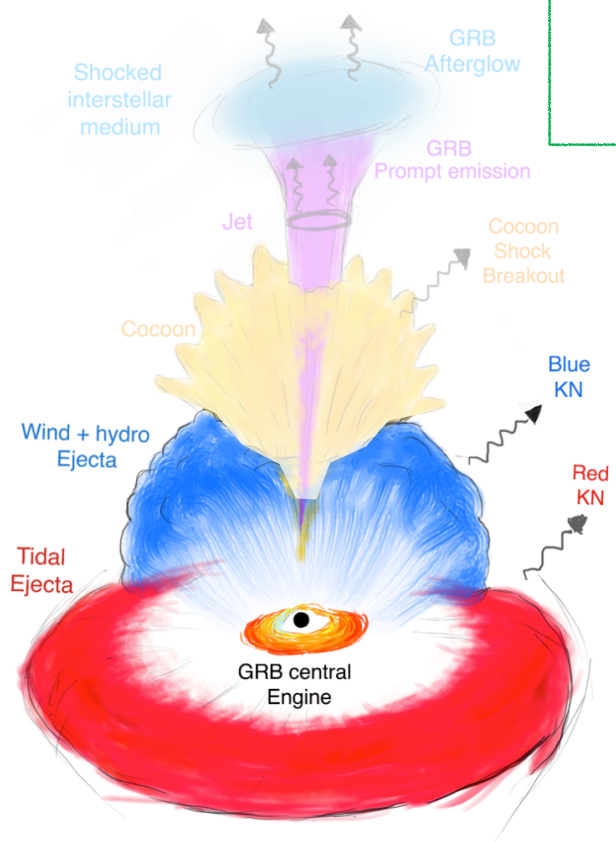
See Radice's talk
for the blue KN

H 1	Big Bang fusion Cosmic ray fission Dying low-mass stars Merging neutron stars Exploding massive stars Exploding white dwarfs Human synthesis No stable isotopes																He 2
Li 3	Be 4	B 5	C 6	N 7	O 8	F 9	Ne 10	Na 11	Mg 12	Al 13	Si 14	P 15	S 16	Cl 17	Ar 18		
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86	
Fr 87	Ra 88	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	
		Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	

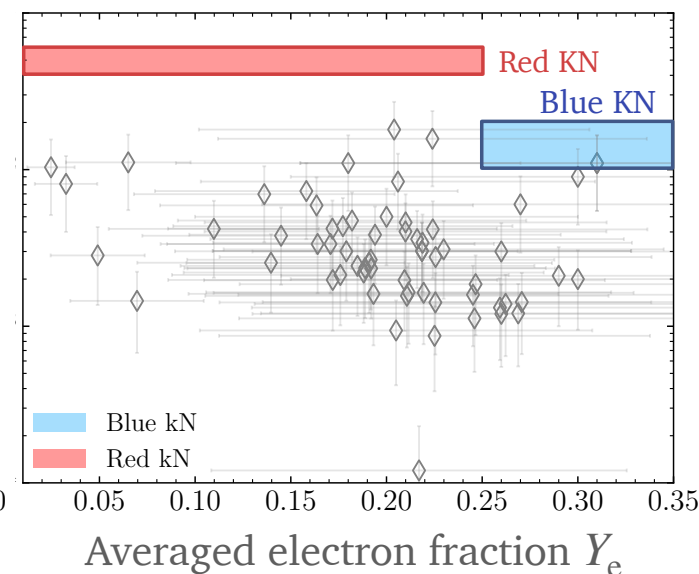
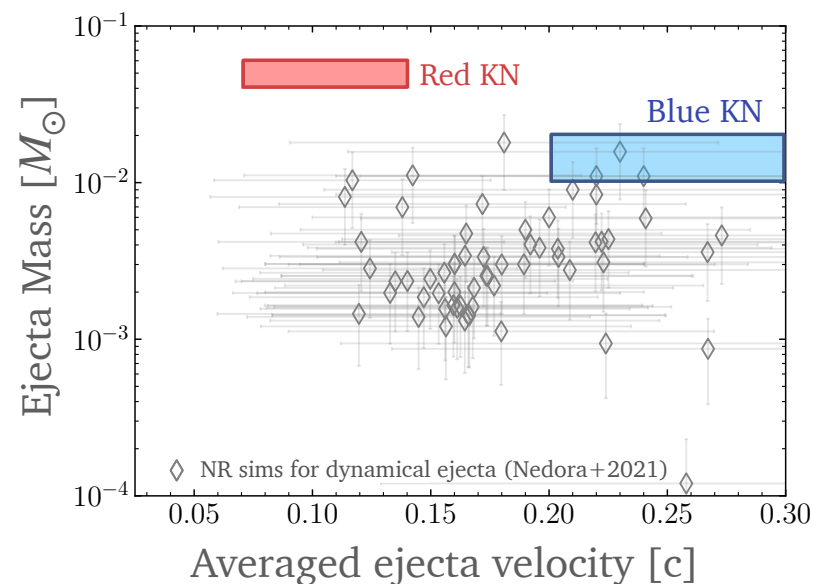
Kilonova modelling

Parameters for **red** and **blue** KNe are extracted from **1D** and/or **semi-analytical** modelling
No geometry | No viewing angle dependence | No reprocessing
Simple energy input (e.g. uniform+constant) | **Simple** opacities (e.g. uniform+grey)

Masses for **red KN** and **blue KN** are larger than predicted by numerical relativity simulations



[Ascenzi+2021, Journal of Plasma Physics]



Parameters for Red and Blue KN from [Siegel 2019, Eur. Phys. J. A.]

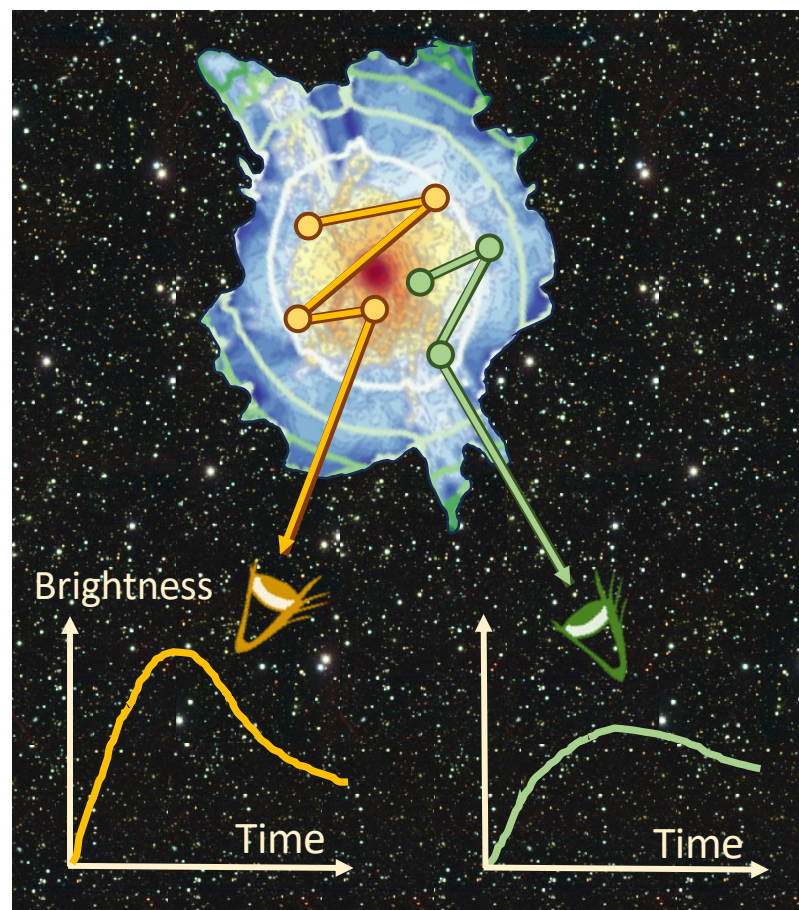
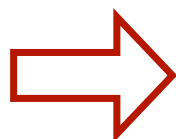
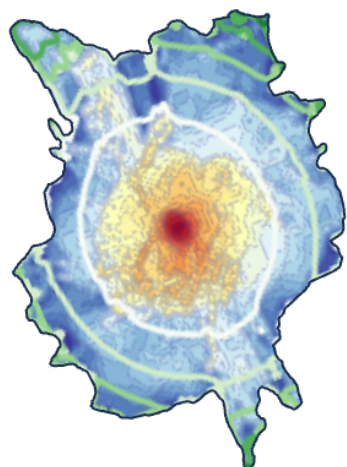
Kilonova modelling with radiative transfer

POSSIS: A 3D Monte Carlo radiative transfer code to model explosive transients

[MB+2015, MNRAS; MB 2019, MNRAS; MB 2023, MNRAS]

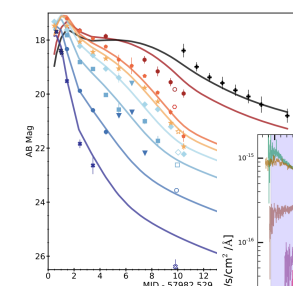
See Kerzendorf's talk

MODELS

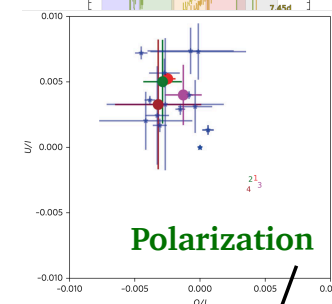
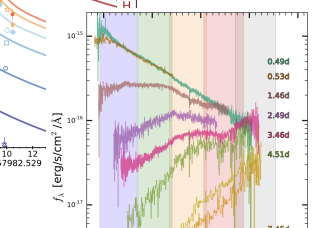


OBSERVATIONS

Light curves



Spectra



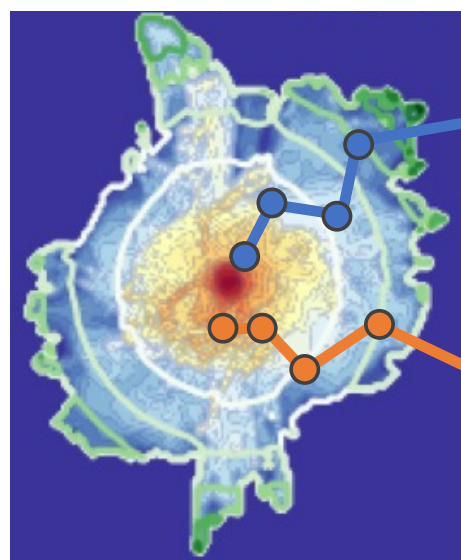
[MB+2019, Nature Astronomy] (BNS)

[MB+2021, MNRAS] (BHNS)

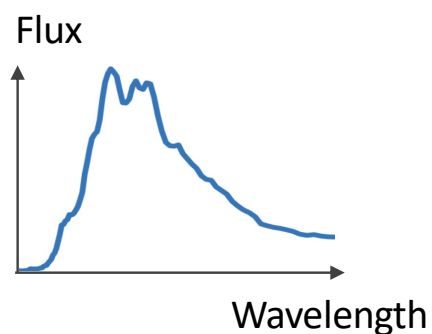
[Shrestha, MB+2023, MNRAS] (BNS with jets)

Kilonova modelling with radiative transfer

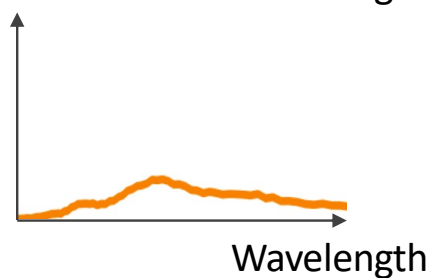
Kilonovae are viewing-angle dependent



EJECTA MODEL

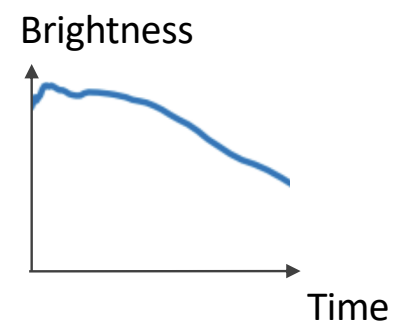


Wavelength

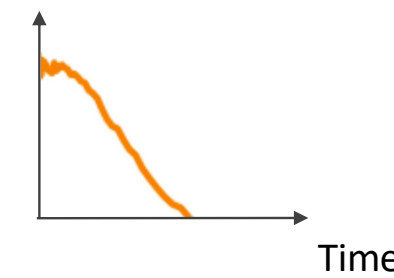


Wavelength

SPECTRA

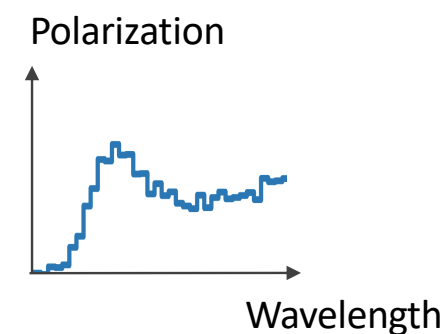


Time

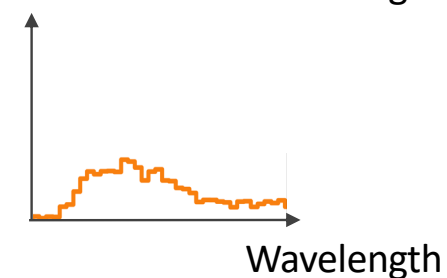


Time

LIGHT CURVES



Wavelength



Wavelength

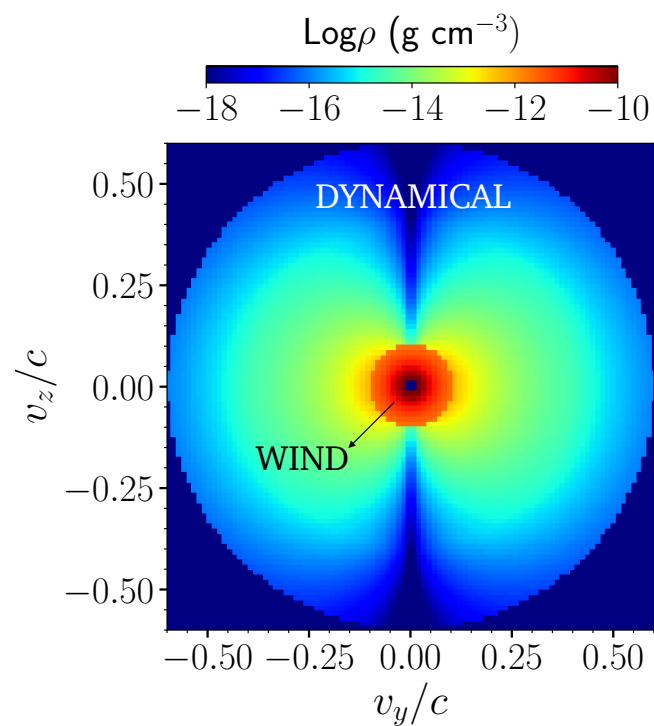
POLARIZATION

Kilonova modelling with radiative transfer

Idealised

Large grids of models (~ 1000)

Typical runtime/model ~ 100 -500 CPUh



[MB 2023, MNRAS]

Kilonova modelling with radiative transfer

6D GRID WITH POSSIS

varying ejecta parameters
(masses, velocities and compositions)

[1024 models, 11264 different KNe]

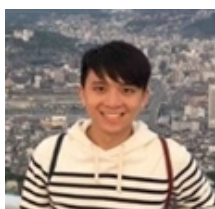
INTERPOLATING GRID WITH NMMA



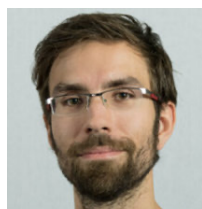
<https://github.com/nuclear-multimessenger-astronomy/nmma>

[Dietrich, Coughlin, Pang, MB+2020, Science]

[Pang, Dietrich, Coughlin, MB+2024, Nature Comms.]

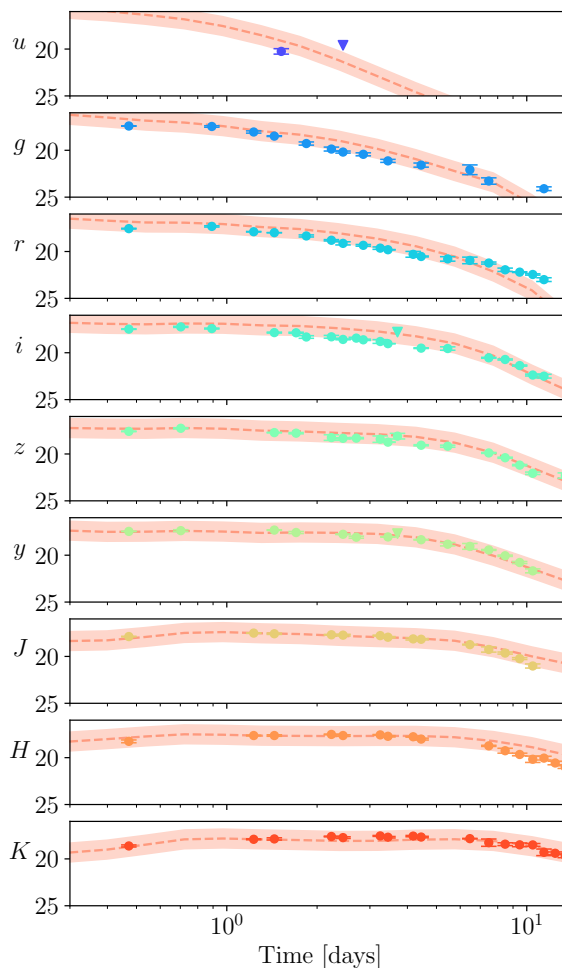


Peter Pang
PhD student



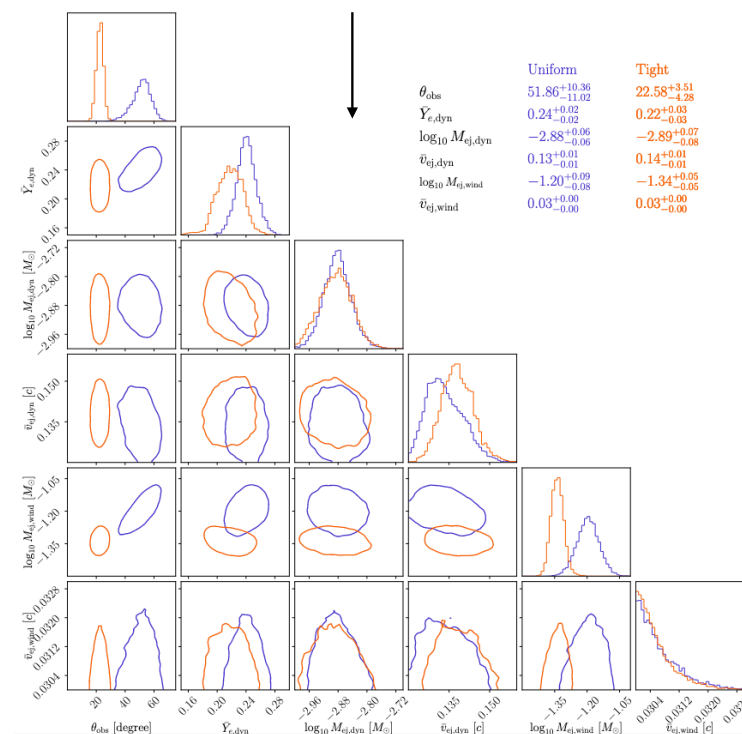
Tim Dietrich
Professor

[Anand, Pang, MB+, arXiv:2307.11080]



Light curve fit to KN
from GW170817

Inference on
ejecta parameters



Shreya Anand
PhD student

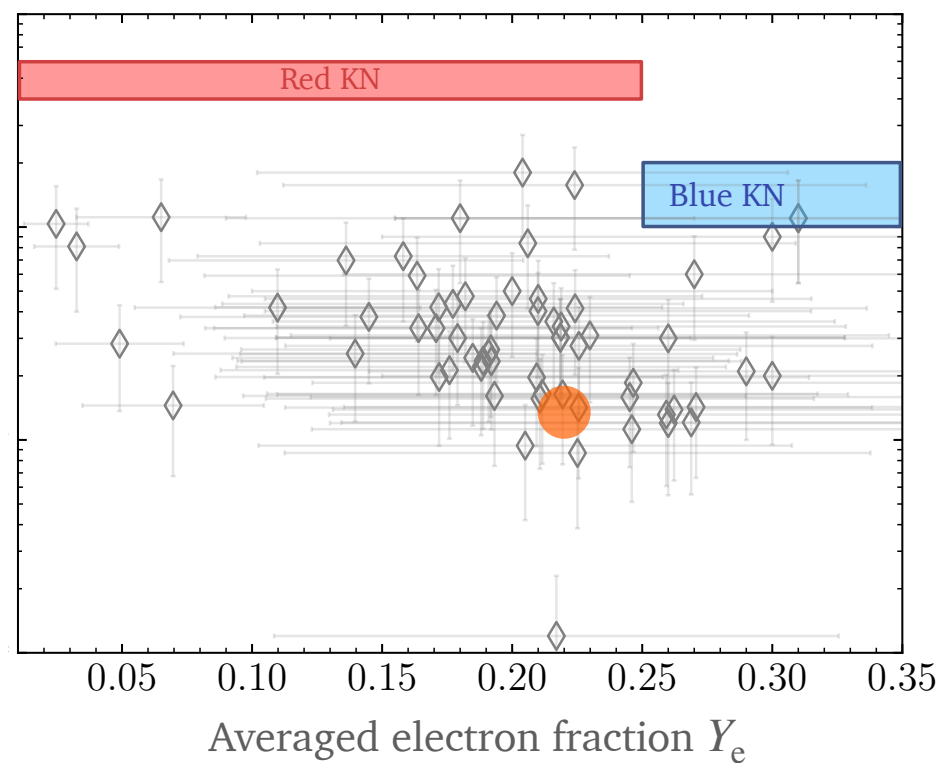
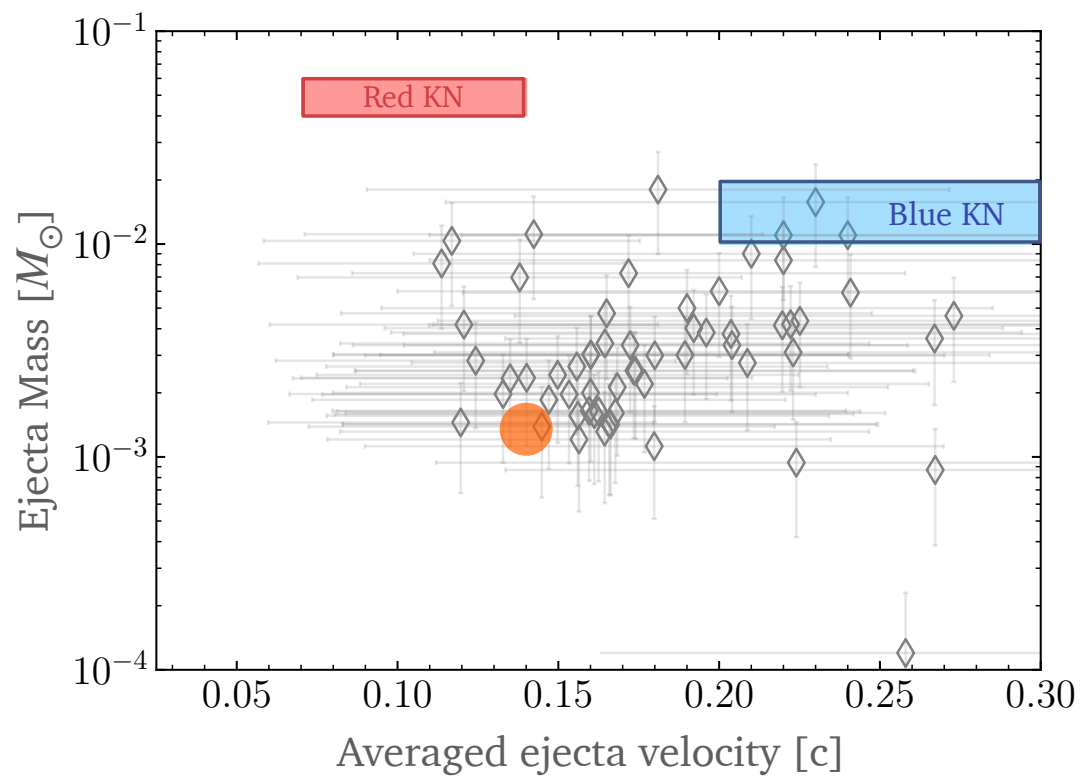
Kilonova modelling with radiative transfer

[Anand, Pang, MB+, arXiv:2307.11080]

No tension with numerical-relativity simulations



Shreya Anand
PhD student

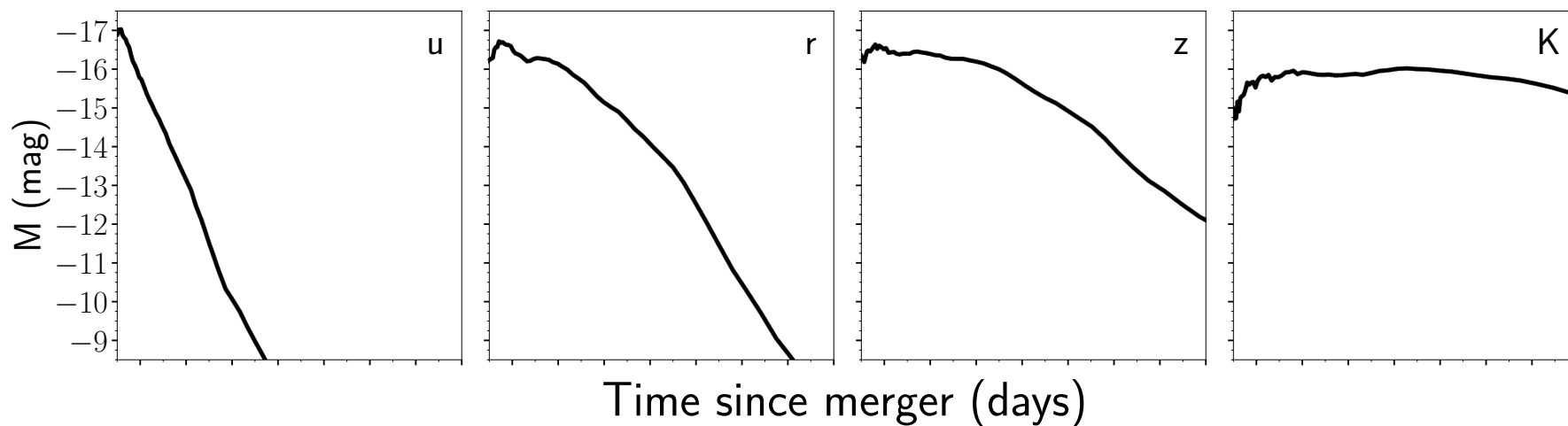


Kilonova modelling with radiative transfer

[MB 2023, MNRAS]

Fiducial model

Heating rates
(Korobkin+2021),
thermalisation
efficiencies and opacities
(Tanaka+2020)
depending on local
properties of the ejecta



Kilonova modelling with radiative transfer

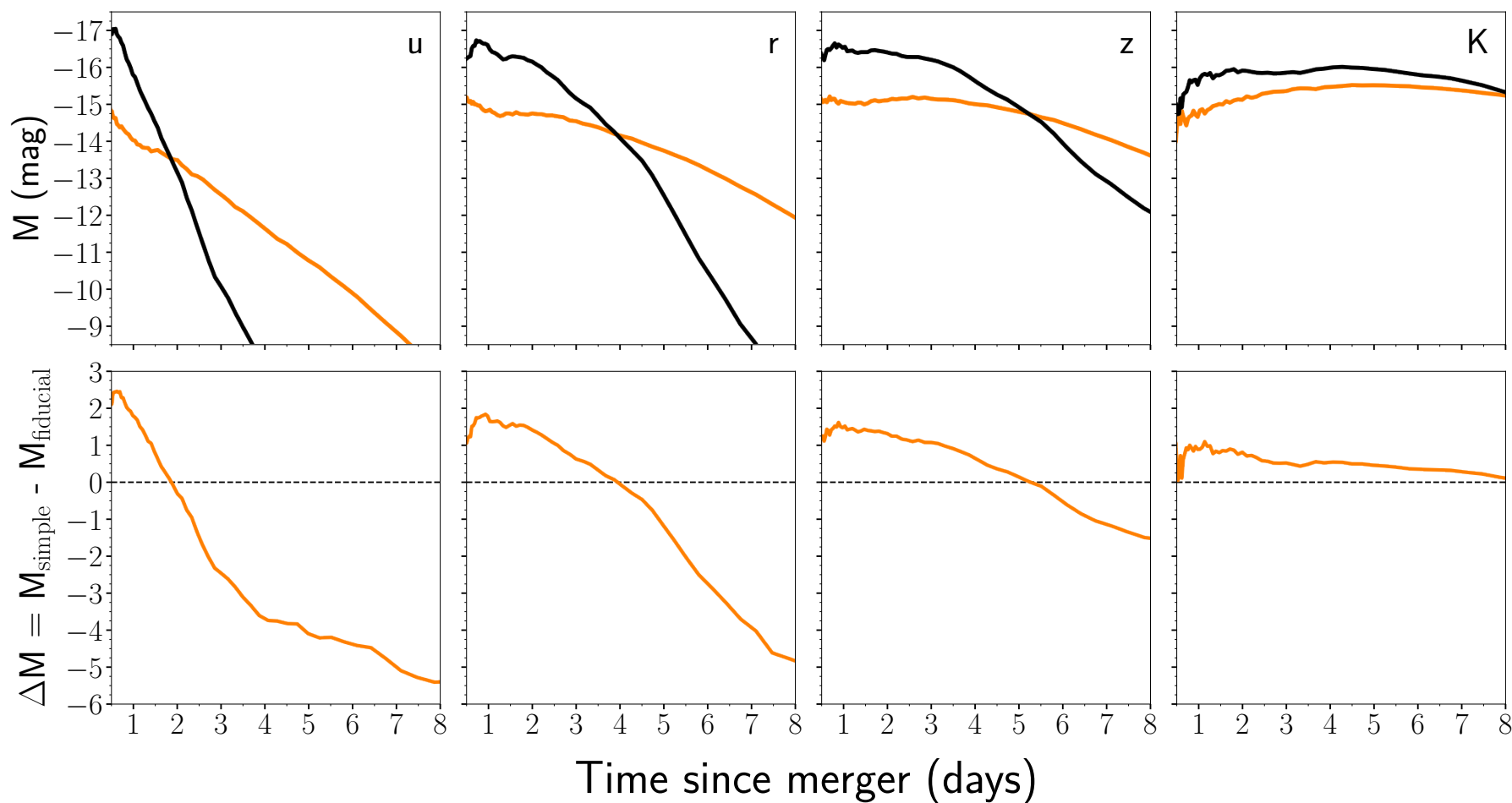
[MB 2023, MNRAS]

Fiducial model

Heating rates
(Korobkin+2021),
thermalisation
efficiencies and opacities
(Tanaka+2020)
depending on local
properties of the ejecta

Simple model

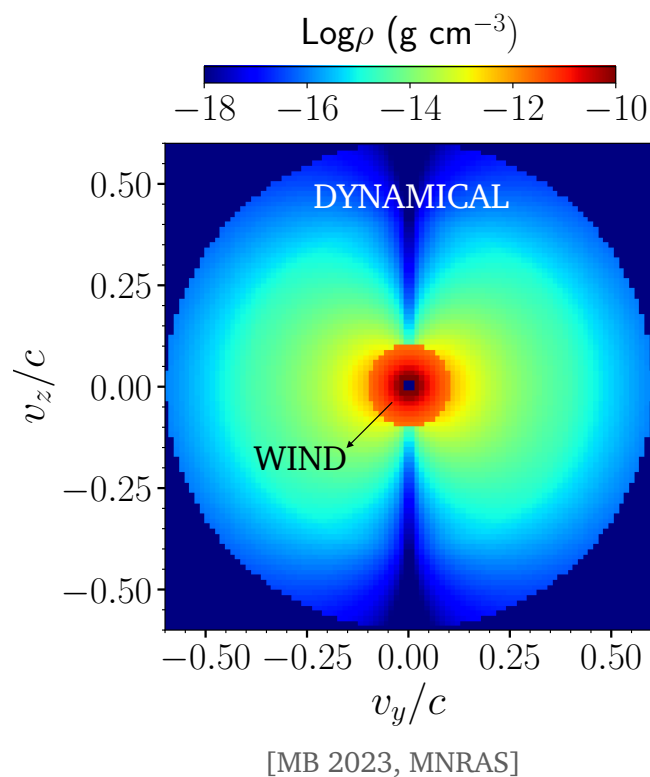
- Uniform
heating rates
(Korobkin+2012)
- Uniform & constant
thermalisation
efficiencies (0.5)
- Grey opacities
(red+blue+purple)



Kilonova modelling with radiative transfer

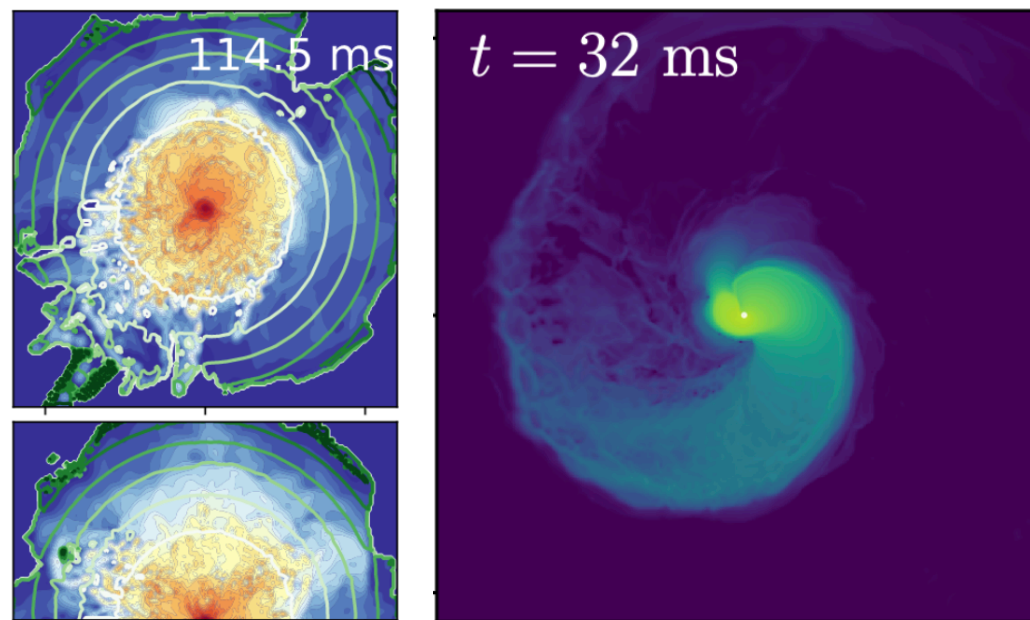
Idealised

Large grids of models (~ 1000)
Typical runtime/model ~ 100 -500 CPUh



Numerical simulations

From numerical-relativity and/or
hydrodynamic simulations



[Neuweiler, Dietrich, MB+2023, PRD]

[Markin...MB+2023, PRD]

[Schianchi...MB+2024, PRD]



Anna Neuweiler
PhD student



Ivan Markin
PhD student

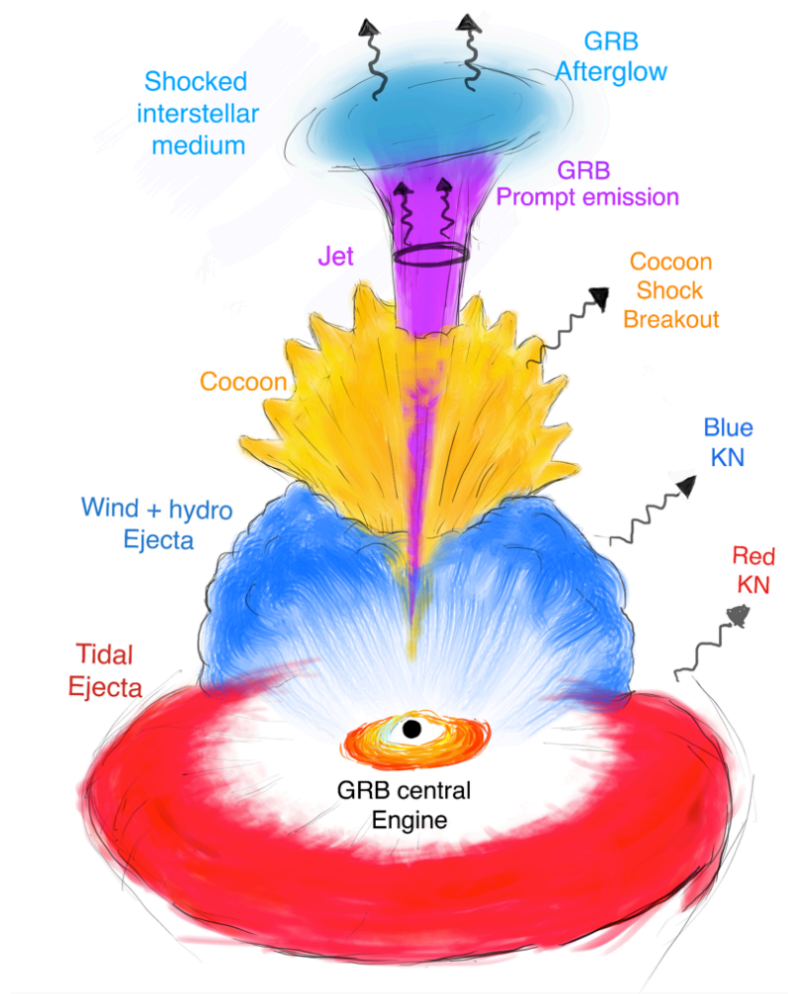


Federico Schianchi
PhD student



Tim Dietrich
Professor

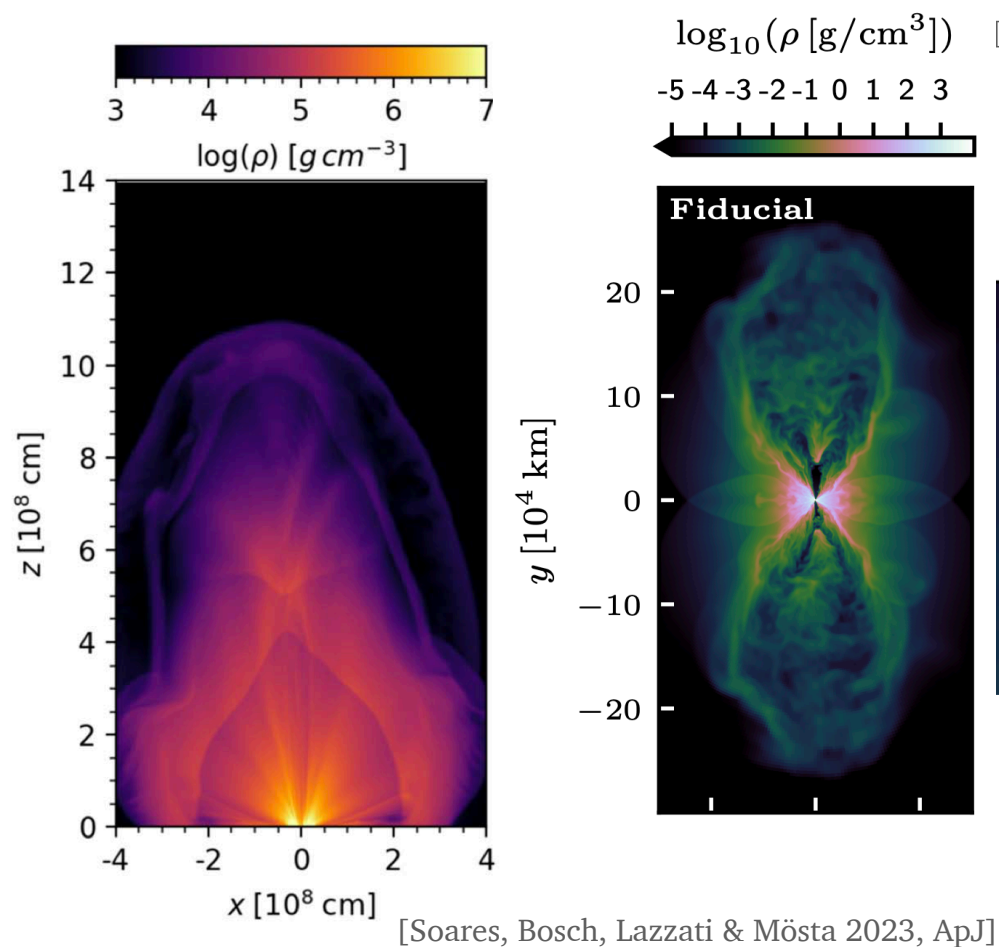
Jet-ejecta interaction and its impact on the kilonova



[Ascenzi+2021, Journal of Plasma Physics]

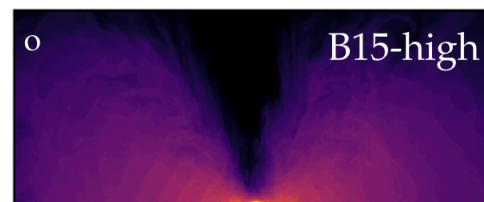
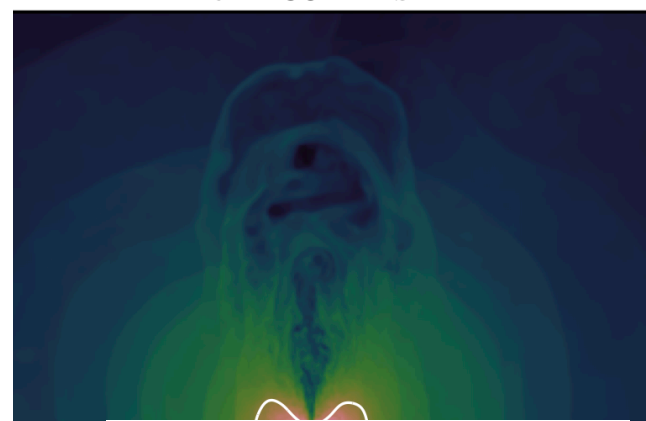
Jet-ejecta interaction and its impact on the kilonova

See Ciolfi's talk

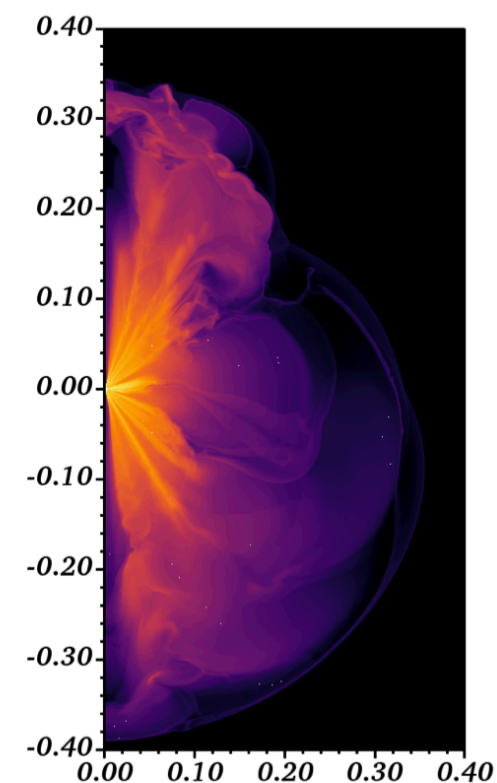


[Combi & Siegel 2023, APJ]
[Combi & Siegel 2023, PRL]

$t = 56.1 \text{ ms}$



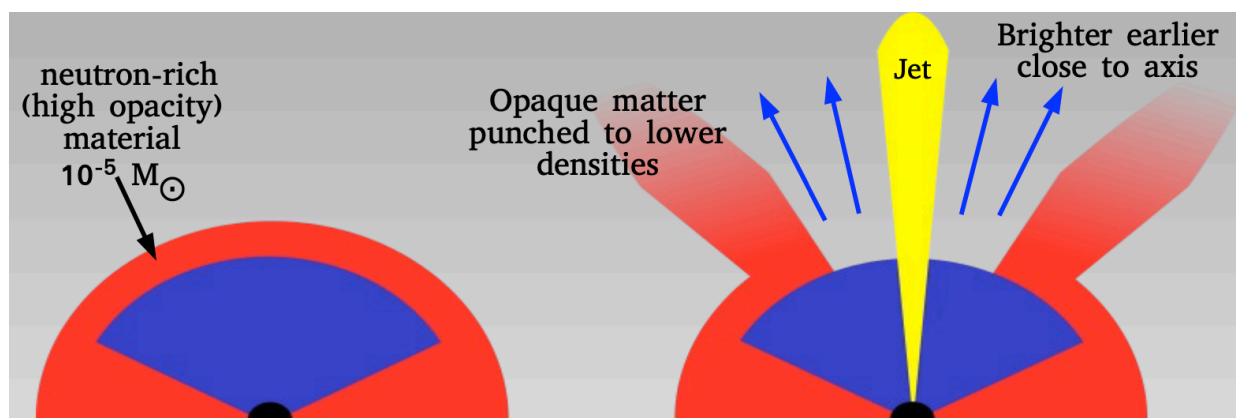
[Urrutia+ arXiv:2401.10094]



[Mösta, Radice+2020, ApJ]

Jet-ejecta interaction and its impact on the kilonova

[Nativi, MB, Lundman, Rosswog+2021, MNRAS]



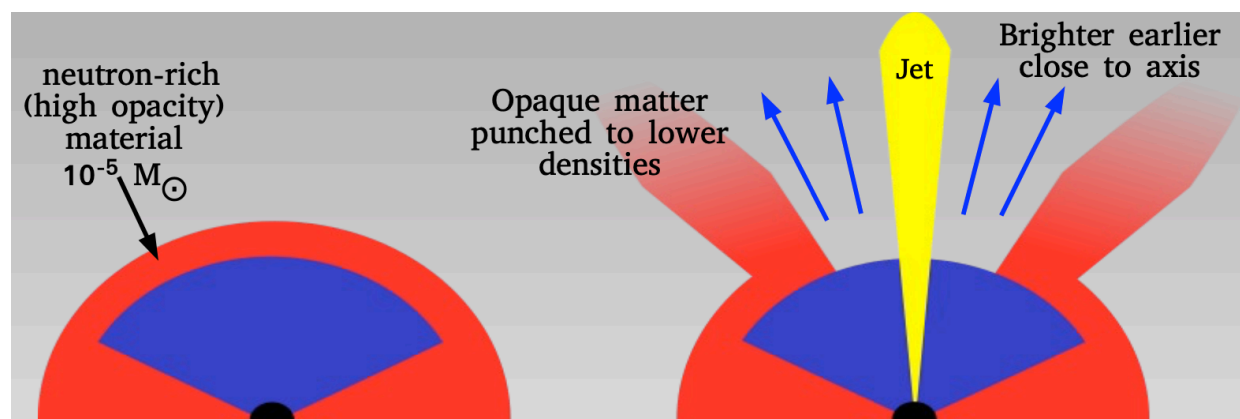
Lorenzo Nativi
PhD student

$$\tau = \int \kappa \rho dr$$

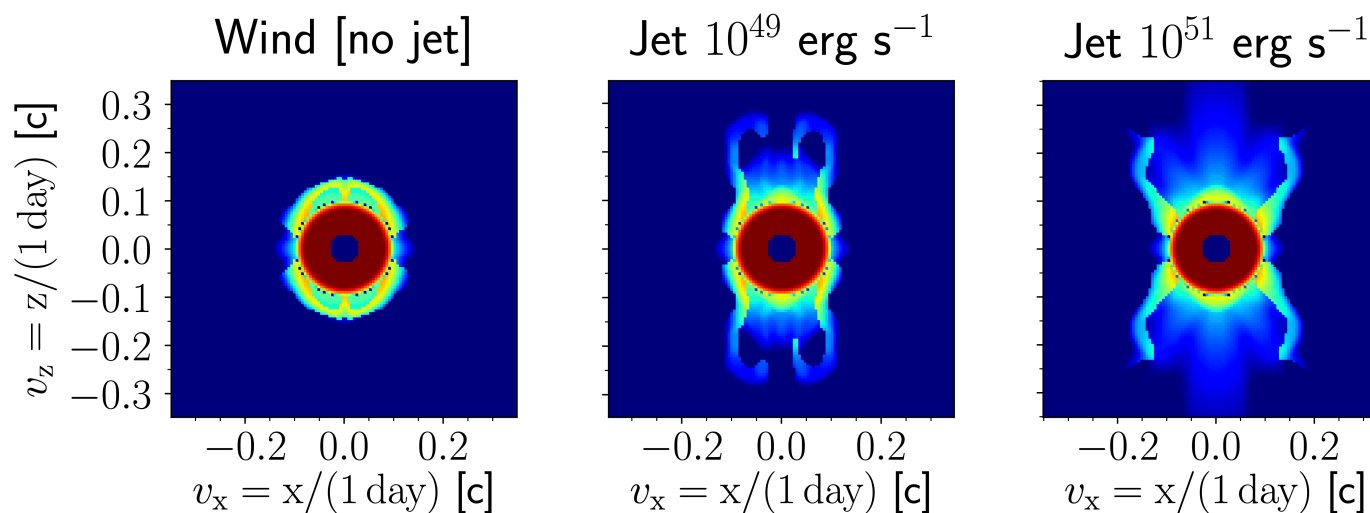
Decrease in **density** -> decrease in **optical depth**
-> optically **thin** ejecta -> photons **escaping** more easily

Jet-ejecta interaction and its impact on the kilonova

[Nativi, MB, Lundman, Rosswog+2021, MNRAS]



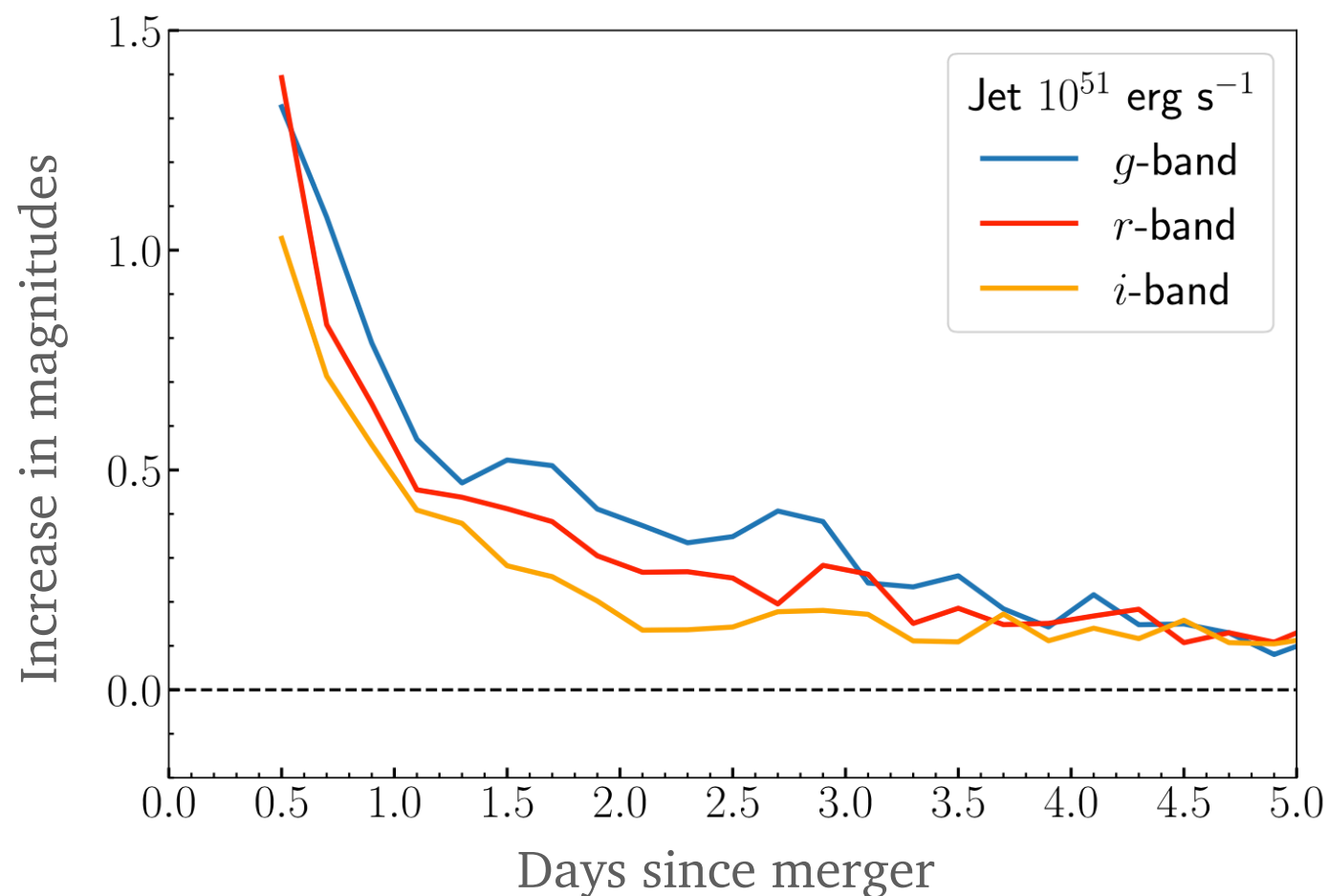
Lorenzo Nativi
PhD student



Wind models from
[Perego+2014, MNRAS]

Jet-ejecta interaction and its impact on the kilonova

[Nativi, MB, Lundman, Rosswog+2021, MNRAS]



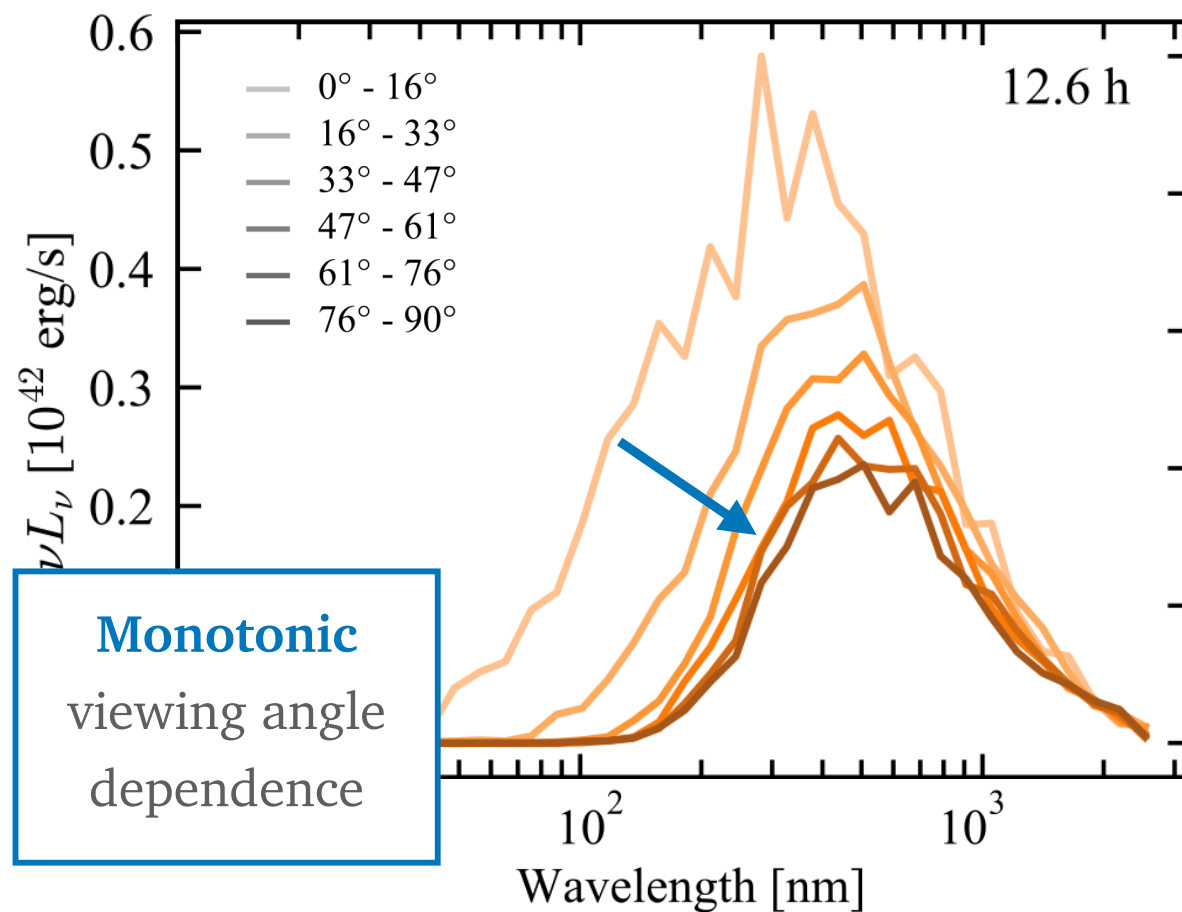
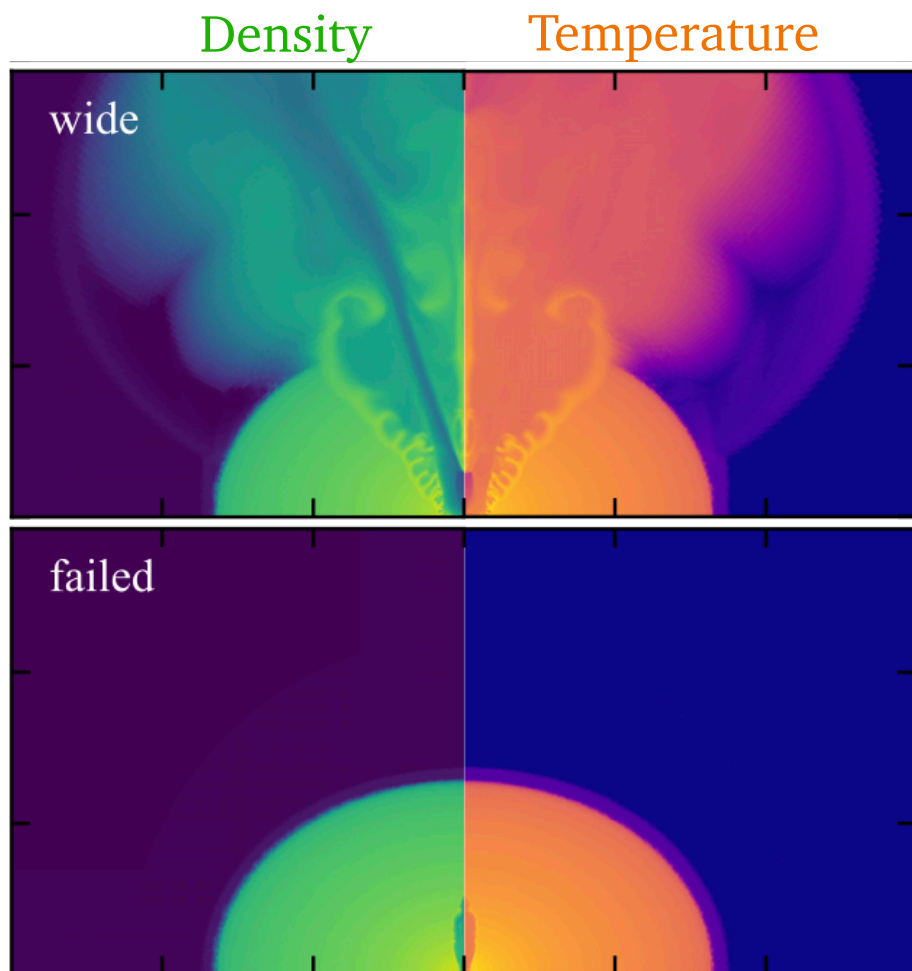
Lorenzo Nativi
PhD student

Jet making kilonova
brighter and **bluer**
along the **jet axis**

Jet-ejecta interaction and its impact on the kilonova

[Klion, Duffel, Kasen & Quataert 2021, MNRAS]

Jet making kilonova **brighter**
and **bluer** along the **jet axis**



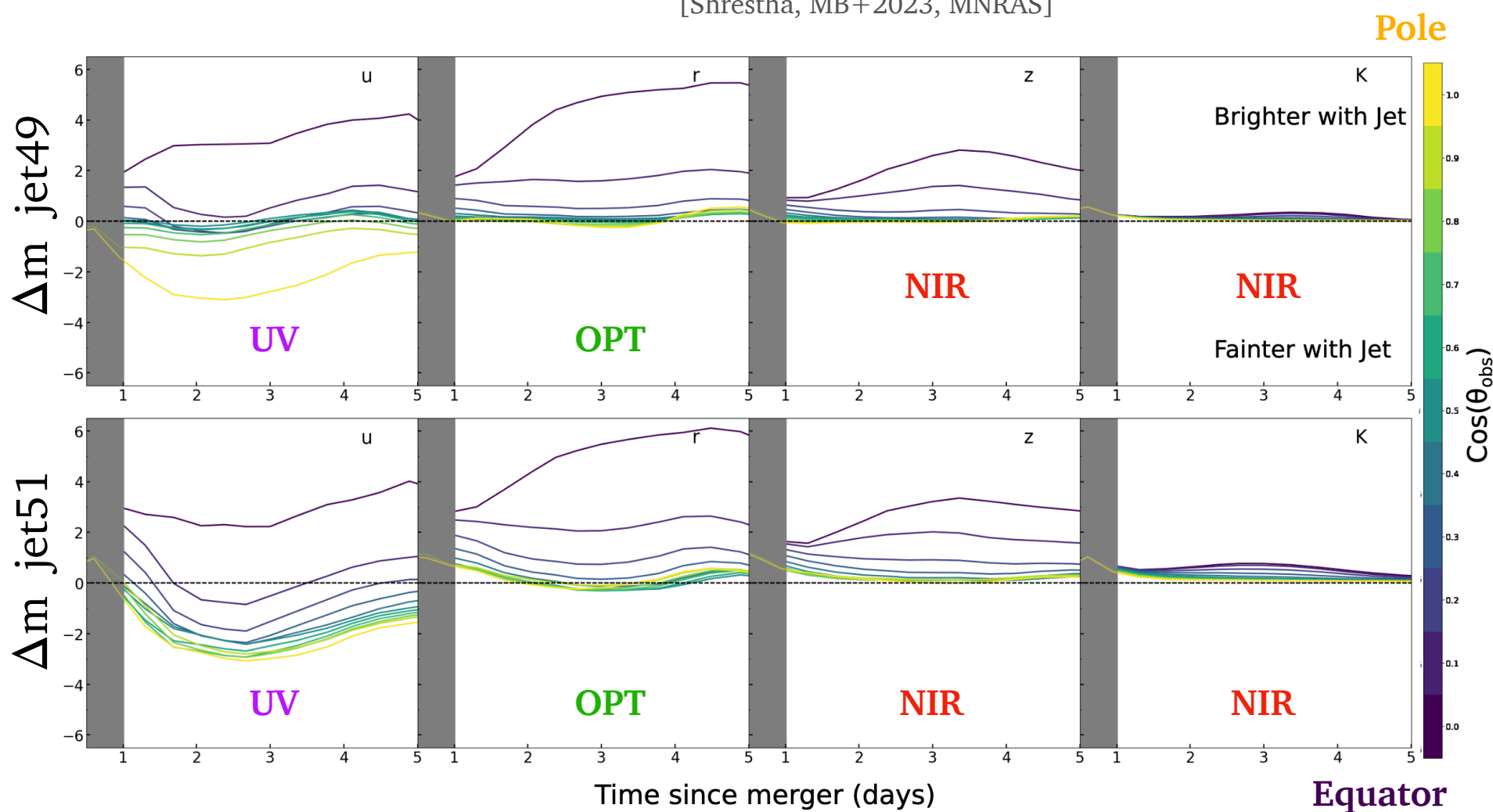
Jet-ejecta interaction and its impact on the kilonova

[Shrestha, MB+2023, MNRAS]

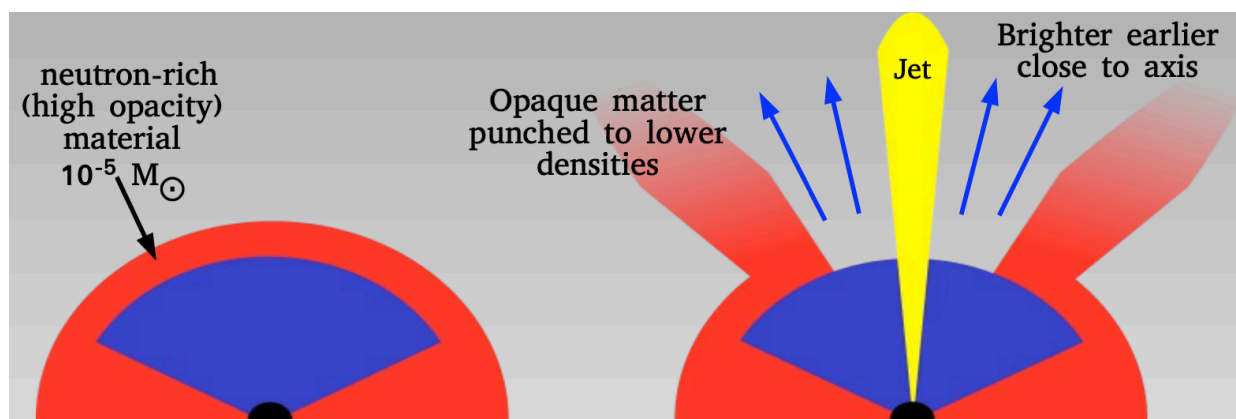


Manisha Shrestha
Postdoc

NON
monotonic
viewing
angle
dependence



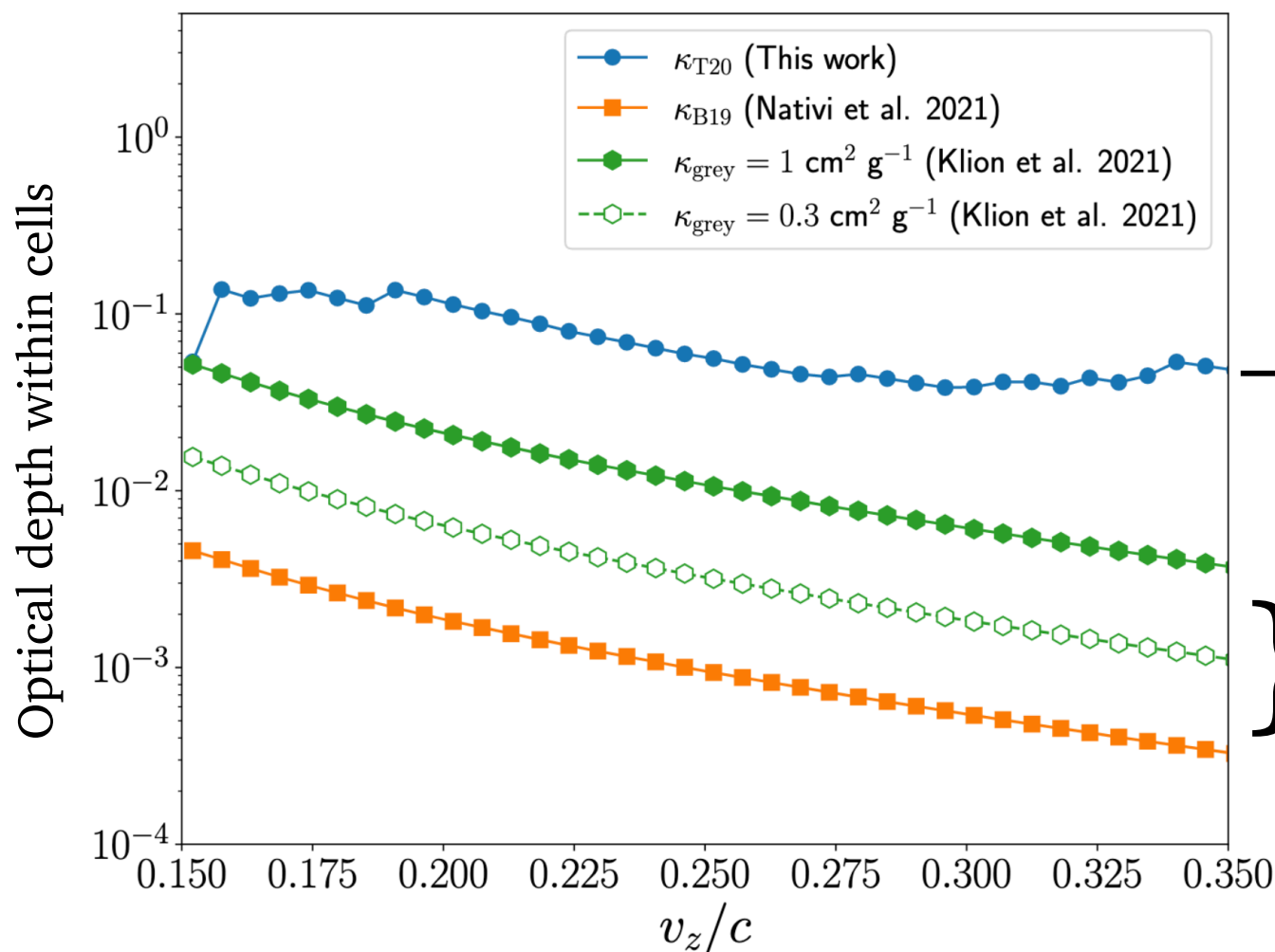
Jet-ejecta interaction and its impact on the kilonova



$$\tau = \int \kappa \rho dr$$

Jet-ejecta interaction and its impact on the kilonova

[Shrestha, MB+2023, MNRAS]



Exact impact on
kilonova depending
on **opacities!**



Manisha Shrestha
Postdoc

Shrestha, MB+2023

Ejecta along jet axis still
moderately optically **thick**

Flux redistribution to other angles

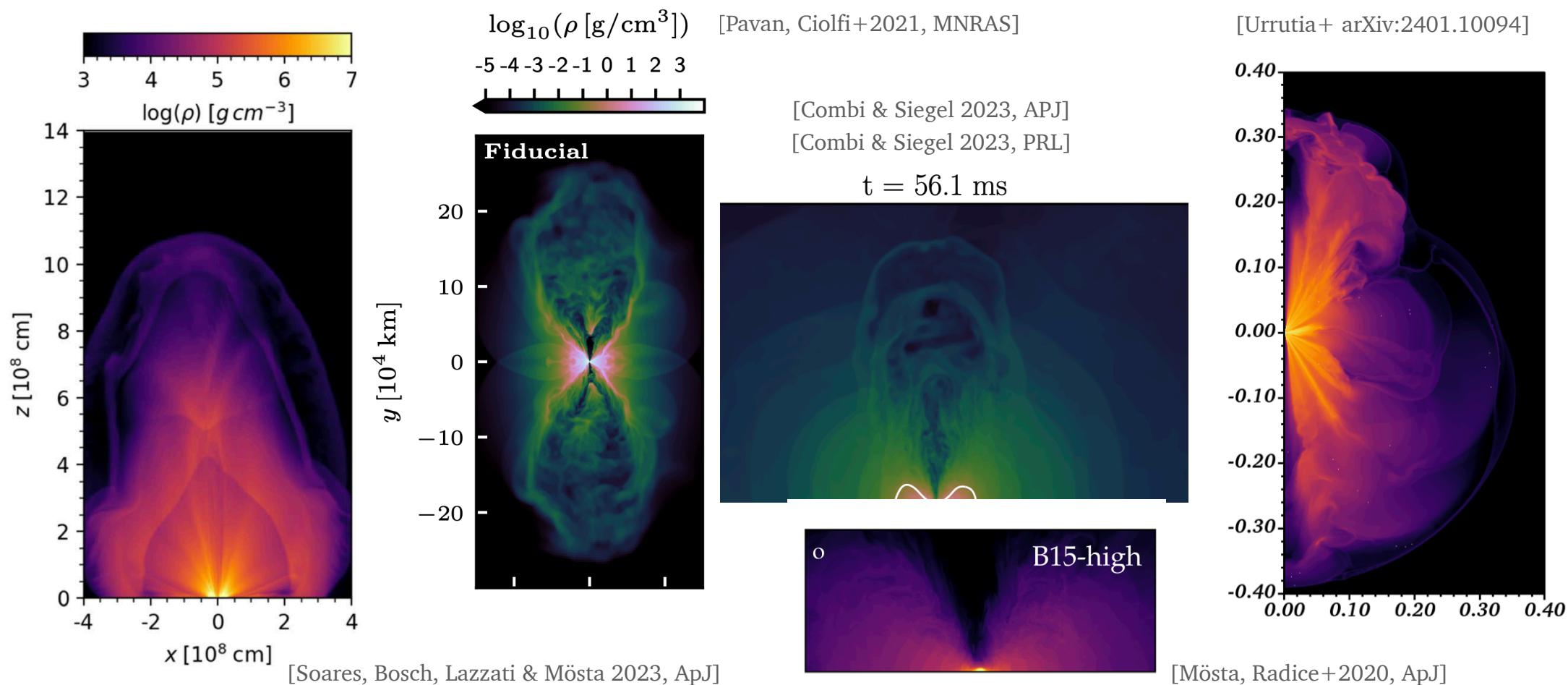
Nativi, MB+2021 Klion+2021

Ejecta along jet axis optically **thin**

Flux “freely” escaping along z

Jet-ejecta interaction and its impact on the kilonova

Exact impact on kilonova likely model-dependent!



Kilonova modelling:

- Radiative transfer simulations
- 3D models including different ejecta components
- **State-of-the-art** heating rates, thermalisation efficiencies and opacities that depend on **local** properties of the ejecta

Jet-ejecta interaction:

- Strong impact on the kilonova at early times
- Effect depending on input **models** and **opacities**